

η' production in nucleus-nucleus collisions as a probe of chiral dynamics

Giorgio Torrieri*

IFGW, State University of Campinas, Brazil



(Received 28 February 2018; revised manuscript received 27 May 2018; published 5 July 2018)

I argue that, because of the peculiar properties of the η' meson, it is a promising probe of chiral dynamics. In particular, I show that a rotating gluon-dominated plasma might lead to an enhanced production of η' with respect to statistical model expectations. The presence of a strong topological susceptibility might give a similar effect. In both cases, unlike the statistical model, I expect a nontrivial dependence on event geometry, such as initial volume and impact parameter. Hence, an observation of η'/π ratio depending strongly on impact parameter might be a good indication of chiral effects, either from vorticity or topological phases of QCD.

 DOI: [10.1103/PhysRevC.98.014901](https://doi.org/10.1103/PhysRevC.98.014901)

I. INTRODUCTION

A recent topic that has been the subject of a lot of theoretical and experimental investigation is chiral dynamics, a class of phenomena involving the transfer of angular momentum between collective angular momentum and spin, in the context of the strongly coupled system created in heavy-ion collisions.

Two main effects are thought to be taking place: One is the temporary breaking of CP symmetry, in a randomly fluctuating direction, due to topologically nontrivial configurations. The other, CP conserving, is the transfer of angular momentum between vorticity and spin due to near-equilibrium statistical mechanics. The phenomenological manifestations of this are known as chiral magnetic and vortical effects, as well as global polarization [1–16]. The two effects are very different (one anomalously breaks the symmetries of QCD, the other does not and should appear in the ideal hydrodynamic limit [7,8]), but the experimental signatures developed so far are generally insensitive to this distinction [17].

Indeed, the immediate problem with these observables is that heavy-ion events are messy both from a theoretical and experimental perspectives. The experimental probes of these effects are typically very complicated and subject to production by background nonchiral processes [2–4]. The theory is typically strongly coupled and opaque to effective expansions, making reliable quantitative calculations difficult [5–8].

In this work, I would like to propose a seemingly indirect but promising observable as a probe for the presence of these type of effects. While it is not trivial to measure, it is a chemical abundance, and hence might be less susceptible to hydrodynamic background effects plaguing other observables: the momentum-integrated abundance of the η' resonance, reconstructed by peak identification, relative to particles of similar composition (experimentally the best choice is the π^0), and the dependence of this relative abundance on impact parameter.

The η' meson is considerably heavier than similar pseudoscalar states, such as the π , K and η . The reason is believed to be that the η' acquires mass via the presence of nonperturbative objects such as instantons in the QCD vacuum, and consequent breaking of $U_A(1)$ symmetry by these objects, which contribute to the triangle anomaly [18–20].

If this is true, this anomaly also allows for a new mechanism for generating η' from gluon-gluon fusion, with free gluons fusing into an η' via a topologically nontrivial field configuration (Fig. 1).

From symmetry considerations the effective vertex for gluon-gluon- η' must be [21]

$$T_{ab}^{\alpha\beta}(p, q, P) = H_f(p^2, q^2, P^2) \delta_{ab} P(p, q, \alpha, \beta), \quad (1)$$

where p and q are the momenta of the gluons, P is the momentum of the produced η' and

$$P(p, q, \alpha, \beta) = \epsilon_{\mu\nu\lambda\gamma} p^\mu q^\nu \epsilon^\lambda(p, \alpha) \epsilon^\gamma(q, \beta). \quad (2)$$

Here, $\epsilon_\lambda(p, \alpha)$ is the polarization vector of a gluon with momentum p and helicity $\alpha = \pm 1$. The Kronecker delta δ_{ab} picks the color-neutral combination of the gluons. The hadronic form factor $H_f(p^2, q^2, P^2)$, as usual, gives the momentum structure of the hadron in terms of the quark wave functions. The corresponding cross section is

$$d\hat{\sigma}_{ab, \alpha\beta}^{gg \rightarrow \eta'} = M \delta^4(P - p - q) \frac{d^3 P}{(2\pi)^3 2P^0},$$

$$M = \frac{1}{4\sqrt{(p_\mu q^\mu)^2}} |T_{ab}^{\alpha\beta}|^2 (2\pi)^4. \quad (3)$$

This was used in Refs. [22,23] to propose the η' as a probe of the double spin asymmetry in the parton distribution function, since the above expressions would have lead to a finite difference $\Delta\sigma^{gg\eta'} = d\sigma_{++} - d\sigma_{+-} \neq 0$ where $d\sigma_{++}$ denotes the cross section where both protons have their spins parallel to their momenta while $d\sigma_{+-}$ denotes the cross section when one proton has its spin antiparallel to its momentum. The difference would be directly dependent on the polarized part of the parton distribution function ΔG given the usual deep

*torrieri@ifi.unicamp.br

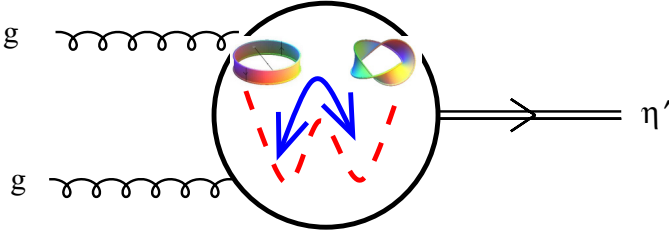


FIG. 1. The production mechanism of the η' from free gluons via a topologically nontrivial field configuration.

inelastic scattering cross sections

$$\begin{aligned} d\Delta\sigma^{pp\rightarrow\eta'X} \\ = \int dx_1 dx_2 \Delta G(x_1, Q_f^2) \Delta G(x_2, Q_f^2) d\Delta\sigma^{gg\rightarrow\eta'}. \end{aligned}$$

Thus, the form of Eq. (1) directly leads to the link between the absolute η' meson abundance and the presence of chiral QCD fields at the quark level. This is at first confusing, since η' is a spin (pseudo)scalar state, but the matrix element of Eq. (1) ensures that any momentum vorticity in a gluon-rich medium leads to an enhanced production of η' . Such momentum vorticity is exactly what most chiral processes examined in the literature lead to.

I will assume the form of Eq. (1) has analogs during hadronization of the quark gluon plasma and show that the abundance of the η' meson can function as a probe of chiral dynamics in this context.

I note that the measurement of the η' to study parity-odd bubbles has been proposed long ago [1,24–32]. Most of the proposed measurements had to do with the experimentally difficult to detect direct interaction of the η' field with the modified chiral condensate, leading to meson mass shifts, η' - η mixings, and new decay modes.

Direct measurements of the cross section of η' photoproduction in nuclear matter [33] do offer evidence of vacuum-driven changes in cross section. However, even medium-modified η' might be too long lived to experience a mass and width shift observable in experiment, due to the η' large lifetime and weak interaction with the medium. In this case, the in-medium η' spectral function would relax to its vacuum value before decay. Other proposals [30] bypass this difficulty by an indirect measurement of the η' abundance via π - π momentum space correlations. Many dynamical effects, from flow to Coulomb corrections, are likely to affect these correlations, but past searches in this direction seem to suggest enhanced production and in-medium mass modification do occur [31,32].

Given these encouraging indications I argue that, given the subsequent phenomenological success of the statistical model in describing momentum-integrated particle ratios [34–37], the lack of a conclusive signature for resonance mass shifts [38,39] and no solid evidence for a long hadronic phase, a simple chemical ratio centrality dependence might be enough, both in the presence of a vortical medium and of topologically nontrivial regions. In the next two sections I will show how each of these mechanisms will result in a centrality-dependent enhancement, with respect to (w.r.t.) statistical model expectations, of ratios such as η'/π and η'/ϕ .

II. η' FROM VORTICAL HYDRODYNAMICS

I will adopt the arguments of the previous section, and apply the concepts behind Eq. (1) and Eq. (2) to a rotating thermal quark-gluon plasma. To do this, one must treat Eq. (1) as a kernel for thermal gluons to coalesce into η' at hadronization, thereby neglecting the loss term [23]. Because I am interested in an estimate, I will make some simplifying assumptions such as neglecting mass and coupling temperature dependence computed carefully in Ref. [23]. The number of η' will then be given by

$$\begin{aligned} n(P) = \sum_{\alpha,\beta} \int \frac{d^3p}{p^0} \frac{d^3q}{q^0} M(p,q) \\ \times \int d^3x_p d^3x_q \delta_{ab} f_g(x_p, p) f_g(x_q, q). \end{aligned} \quad (4)$$

Here, $f_g(x, p)$ is the gluon distribution in phase space, assumed to be a Juttner-type distribution controlled by a temperature field $T(x)$ and a velocity field $u_\mu(x)$ given by a hydrodynamic simulation. Up to normalization

$$f_g(x, p) \sim T^{-3} \exp \left[\frac{u_\mu(x) p^\mu}{T(x)} \right]. \quad (5)$$

In the context of Eq. (1) and deep inelastic scattering, H_f was a form factor. However, there is no reason it cannot be straightforwardly generalized to a different environment. Here, therefore, I will use $H(\dots)$ analogously to the previous section, but treat it as a Wigner function. In particular, just as with form factors, it is reasonable to assume it can be expressed in position or momentum space

$$\begin{aligned} H(p, q, P^2) = \int \exp[i(p_\mu x_p^\mu + q_\mu x_q^\mu) \tilde{H}(x_p, x_q, P^2)] \\ \times d^3x_p d^3x_q. \end{aligned} \quad (6)$$

For a qualitative estimate, one assumes that gluons in a comoving frame are approximately unpolarized, i.e., the direct transfer of vorticity to spin studied in Refs. [7,8] is a small effect. Now, since thermal fluctuations cancel out one has that

$$\int \left[\frac{d^3p}{p^0} \right] f(x, p) p^\mu \propto T u^\mu(x) \quad (7)$$

further assuming $H(\dots)$ to be small w.r.t. the variation in u_μ

$$|\tilde{H}(x_p, x_q)|^2 \sim \Theta[(x_p - x_q)^2 - \Delta^2]. \quad (8)$$

One can directly relate the η' production from such anomalous coalescence to the vorticity

$$\Delta n(P) \sim T^2 \Delta^3 |\Omega|^2, \quad (9)$$

where $\Omega_{\alpha\beta} = \epsilon_{\alpha\beta\gamma\mu} \partial^\gamma u^\mu$ is the vorticity.

Normal particles, whose production is not straightforwardly related to instantons, will not experience any effect from vorticity and their abundance will simply depend, in either a statistical model or coalescence from a thermal medium, on mass, temperature, and hadronization volume V [34–37]. For systems where the freeze out is fast enough, and the volume is large enough that dynamical Bose-Einstein correlations are

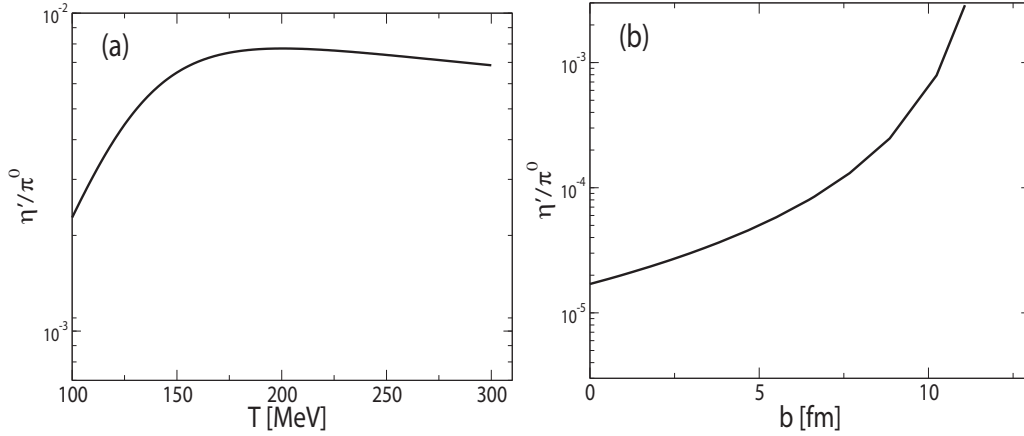


FIG. 2. Predictions for η'/π dependence, assuming a zero isospin chemical potential. The left panel (a) has a background statistical model estimate, temperature driven and independent on volume and impact parameter, calculated in Ref. [35]. The right panel (b) a vorticity-driven calculation using the methods of Sec. II.

negligible one gets that [34]¹

$$n_{m \ll T} \sim VT^3, \quad n_{m \geq T} \sim VTm^2 K_2\left(\frac{m}{T}\right).$$

Hence, relating the η' to another particle, say η'/π , a clear effect should be seen in more vorticose events. The thermal production of π^0 is completely insensitive to flow and will be, in the massless limit, simply $\sim VT^3$ where V is the total volume.

$$\frac{\eta'}{\pi} \sim \frac{\Delta^3 \sum_j |\Omega_j|^2}{VT} + \frac{\eta'}{\pi} \Big|_{\text{thermal}}, \quad (10)$$

where Ω_i is the vorticity associated with an fluid cell j of size Δ^3 , summed over the whole event and the thermal background, $\frac{\eta'}{\pi} \Big|_{\text{thermal}} \sim \exp\left[\frac{-m_{\eta'} + m_{\pi}}{T}\right]$ is expected to only depend on the freeze-out temperature T and, in particular, be independent of the production volume.

In other words, there would be a direct dependence of η'/π on the impact parameter (as opposed to multiplicity, like strangeness), something that can be seen in scans with system size or in event engineering. This estimate is shown in Fig. 2(b) for top RHIC energies, assuming a $\Delta = 1 \text{ fm}$ and a $T = 170 \text{ MeV}$. The angular momentum and volume are taken from Fig. 3 of Ref. [42]. For the π I use the statistical model implemented in SHARE [35]. As an estimate of the statistical model background I also include [Fig. 2(a)] an estimate, as a function of temperature, of the statistical model value of this ratio, which is of course constant with volume. The relation between centrality and number of participants was further

estimated using the formulas in Ref. [43]. It should be reiterated that this is an illustrative estimate, and it is the impact parameter dependence, rather than the ratio's absolute value, that will provide the experimental probe.

In this respect, it is important to emphasize that I expect η'/π yield due to the mechanism described in this section to increase strongly with decreasing centrality. This dependence is both physically obvious and markedly different from other mechanisms, where particle ratios are typically independent of centrality or, as in the case of strangeness, rise with centrality [44]. Thus, a strong η'/π as a function of impact parameter could signal vorticity at the level of a gluon-rich quark-gluon plasma.

III. η' FROM TOPOLOGICAL CHARGE FLUCTUATIONS

In a topologically nontrivial thermal QCD environment [2] the Hamiltonian acquires an effective term

$$\begin{aligned} \Delta H &= \hat{\theta} F_{\mu\nu} \tilde{F}^{\mu\nu} = \hat{\theta} \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} \tilde{F}^{\alpha\beta} \\ &= \hat{\theta} \epsilon_{\mu\nu\alpha\beta} \epsilon^{\mu\nu\zeta\iota} \epsilon^{\alpha\beta\rho\omega} \partial_\zeta A_\iota \partial_\rho A_\omega, \end{aligned} \quad (11)$$

where $\hat{\theta}$ is the random value of the effective θ angle, approximately Gaussian centered around zero and with width related to the topological susceptibility $\langle \theta^2 \rangle$. Explaining the fact that the distribution of $\hat{\theta}$ is centered around zero is known as the strong CP problem, but in a topologically nontrivial medium $\hat{\theta}$ should fluctuate randomly in space time, something seen in lattice calculations [45,46].

As discussed in Sec. I, the fact that η' production is closely associated with this topological term has been noted a long time ago and explored with a variety of techniques involving spectral functions and particle correlations. Here, I wish to take the simple approach argued for in Sec. I and show that, even assuming that the η' is produced, and decays unmodified from its vacuum state by a coalescence-type process, topologically nontrivial states will still leave an imprint in the momentum-integrated η'/π ratio as a function of multiplicity, which can be looked for in an invariant mass $\eta' \rightarrow \gamma\gamma$ reconstruction and consequent η'/π measurement.

¹This assumption is not physically guaranteed. For example, it would not apply to halo-dominated models [40] where freeze-out time scales are comparable with expansion. In this work I calculate p_T integrated abundances, where the π seems to not have centrality-dependent deviations from the statical model [41], so assuming these effects are small is justifiable. To check their size, the dependence of the η'/ϕ as well as the η'/π ratio might be used, since the ϕ is less susceptible to these effects

I will therefore decompose the A fields in momentum modes (the time constraint and gauge constraint are here absorbed in the \tilde{A} definition for brevity)

$$A^\mu(x) = \int dx (\tilde{A}^\mu(k)e^{ikx} + (\tilde{A}^\mu)^*(k)e^{-ikx}). \quad (12)$$

Assuming that regions defined by the same topological susceptibility are large enough for field configurations to be approximately in this momentum eigenstate, one gets a thermal occupation number

$$f(p, q) = \exp \left[V_\theta \sum_i \frac{\hat{\theta}_i \tilde{Z}(p, q)}{T} \right], \quad (13)$$

where

$$\tilde{Z}(p, q) = \epsilon_{\alpha\beta\mu\nu} Z^{\alpha\beta}(p) Z^{\mu\nu}(q), \quad Z^{\mu\nu}(p) = \epsilon^{\mu\nu\zeta\iota} p_\zeta \tilde{A}_\iota(p). \quad (14)$$

Note that $\hat{\theta}_i$ is a random variable that can be positive or negative, and the sum is taken over topological correlation lengths regions, each of volume V_θ . Both the variance $\langle \theta^2 \rangle$ and V_θ are parameters that need to be computed from non-perturbative QCD. Since this dynamics is nonperturbative, it is expected, and Refs. [45,46] confirm, that $\langle \theta^2 \rangle$ goes rapidly down above the deconfinement temperature (in Fig. S28 of Ref. [46] $\langle \theta^2 \rangle \sim \chi/T^4$). V_θ should be ~ 1 fm in size but the quantitative value is not known.

Now, $\tilde{A}^\nu(k)$ and $\epsilon^\mu(k, \alpha)$ are parallel for $\alpha = 1$ and antiparallel for $\alpha = -1$. I also consider that for an η' to form, spins of gluons have to point in opposite directions. Hence, following Eq. (1) then, the number of η' produced will have an abundance $\Delta n(p)$ w.r.t. equilibrium expectation values $n(P)$ scaling as

$$\frac{\Delta n(p)}{n(p)} \sim \int d^3 p d^3 q |H(p^2, q^2, P^2) \tilde{Z}(p, q)|^2 \times \sum_i \exp \left[\frac{V_\theta}{T} \hat{\theta}_i \tilde{Z}(p, q) \right]. \quad (15)$$

The gluon momentum distributions $\tilde{A}^\mu(k)$ in \tilde{Z} are either given by the same Juttner distributions of Eq. (5)

$$|\tilde{A}(p)|^2 \sim \int dx f_g(x, p)$$

or perhaps given by a glasma description [47] (which should enhance topological configurations). Note that both positive and negative values of $\hat{\theta}$ deviate from the equilibrium value. This is consistent with the fact that η' is a pseudoscalar particle, insensitive to the actual value of spin. It is only either when $\hat{\theta} = 0$ or cancels out to zero that production is fully the one expected from thermal equilibrium.

Here, the main dependence driving η' abundance is the topological susceptibility $\hat{\theta}/T$ and the number of regions V_θ . Because of our complete lack of knowledge of the distribution of $\hat{\theta}$ and its correlation length in space time V_θ , I feel I cannot give a quantitative estimate, even an elementary one like in the previous section, of Eq. (15). If one follows the chiral chemical potential ansatz (μ_5 with topological charge density n_5) developed in Ref. [2] and assumes $V_\theta \sim n_5^{-1}$ dimensional

analysis would lead to a formula of the type

$$\frac{\eta'}{\pi} \sim \frac{\Delta^3(m'_\eta)^2}{VT^2} K_2 \left(\frac{m'_\eta}{T} \right) \sum_{i=1}^{V n_5} \exp \left[\frac{\mu_5}{T} \hat{\theta}_i \right], \quad (16)$$

where once again I have a nonextensive volume dependence due to the appearance of clusters with the same value of $\hat{\theta}$ and charge density n_5 .

Equation (16) allows us to make some qualitative considerations. Reference [46] suggests $\langle \theta^2 \rangle$ remains approximately constant for $T = 100$ – 200 MeV and falls very rapidly at higher temperatures. Thus, at the temperature commonly associated with statistical hadronization the effects described in this section should be prevalent unless too many regions of V_θ size will cause topological configurations to cancel out in the $\sum_i \hat{\theta}_i$ of Eq. (15).

Since the statistical model assumes the Hamiltonian expectation value to be given by the particle mass, without the inclusion of a term such as Eq. (11), the most straightforward prediction of relevance of chiral susceptibilities in particle production is a strong deviation of η' from the statistical model expectation value, perhaps for a characteristic momentum at which the integral in Eq. (15) becomes particularly peaked.

If V_θ is of the order of the nucleon size, this deviation should be prominent in small (pp, pA) systems but would go away for systems larger than the nucleus, i.e., central collisions, due to the cancellation in Eq. (15) of various $\hat{\theta}$ terms. So far η' was compared to statistical models just in ee collisions [37], where it appears to fit reasonably well, but not other systems. Hence even such a qualitative prediction is not open to verification without further experimental measurements. Enhanced event-by-event fluctuations of η' would be a more direct probe of $\langle \theta^2 \rangle$, but, as clearly shown in the next section, it is most likely impossible to measure these in experiment.

Of course, coalescence should happen around hadronization temperature the turnoff seen on the lattice at higher temperature should not, naively, impact on the η' abundance. However, if the in-QGP production mechanism argued for in Refs. [48,49] is applicable to the η' , this particle becomes a very important probe of chiral susceptibility, although in this case the loss term [23] becomes important.

IV. DISCUSSION

The obvious observable here is the global abundance of η' compared to another particle, such as the π or the ϕ . Which of these two should be the denominator in the ratio is a decision best left to experimentalists. The ϕ meson, through its dimuon decay, can be reconstructed with greater reliability than $\pi^0 \rightarrow \gamma\gamma$, does not have a background autocorrelation due to the same decay mode, and has a similar mass to the η' . However, it is also a much rarer particle than the π^0 and it also strongly depends on γ_s , which has a nontrivial dependence on centrality. If the isospin chemical potential does not depend on centrality, something true for most experimentally accessible energies, η'/π^{+-} provides a relatively reliable denominator free of autocorrelation.

The signature for nontrivial dynamics is a variation of the ratio specifically on impact parameter. Usually particle ratios

are constant in the thermodynamic limit; strangeness seems to depend on multiplicity rather than initial geometry. This can be experimentally probed either by comparing different system sizes same multiplicity bins, or by event engineering, using event bins with similar event-by-event v_2 . A strong obstacle in the analysis suggested in this work is the difficulty of reconstruction. The only promising decay for the η' seems to be [50] the 2.2% $\eta' \rightarrow \gamma\gamma$ decay, although perhaps the $\eta' \rightarrow \rho^0\gamma$ is achievable (its branching ratio is much larger, 30%). This is considerably larger than the $\phi \rightarrow \mu\mu$ decays ($\sim 10^{-4}$) observed by NA50 [51] and CERES [52]. The comparative abundance of the two particles, from thermal considerations should be similar since the mass of the η' is of the order of the temperature around hadronization, which compensates of the ϕ s higher degeneracy.

That said, the $\pi^0 \rightarrow \gamma\gamma$ decays will provide a truly formidable background to this measurement. However, an array of techniques can be used to separate this background from the signal. The macroscopic lifetime of the π^0 , the lower momentum of the $\pi^0 \rightarrow \gamma\gamma$ decay products and the larger opening angle of this decay can all be used to distinguish $\eta' \rightarrow \gamma\gamma$ candidates from $\pi^0 \rightarrow \gamma\gamma$ background and the direct photon production from the collision. A detector with good electromagnetic calorimetry in the range of the η' decay kinematics, capable of estimating both the momentum and direction of each γ with sufficient precision, should be able to reconstruct the η' peak given sufficient luminosity, unless the η' has been considerably modified in medium.

The obvious theoretical background to the effects examined here are other mechanisms of η' production. Indeed, I interpreted the production as a kind of coalescence at hadronization, neglecting kinetic production and in-medium modification of the sort examined in Ref. [23]. To what extent this is a good approximation is highly dependent on how hadronization actually occurs. If it occurs mostly through coalescence, and if symmetries distinguishing the η' from other particles are not altered by the medium, then the mechanism proposed here might be dominant since statistical coalescence from other quarks will be suppressed by parity conservation. If these assumptions do not hold, or if the system is at chemical equilibrium around hadronization, the background will be that of Fig. 2(b).

This is why I would like to concentrate on the variation with centrality and system size rather than the absolute value when finding a signature. As is well known, the statistical model in the thermodynamic limit does not depend on volume [36]. A residual volume dependency on strangeness seems to scale with multiplicity but reach a plateau for high-multiplicity AA collisions [44]. While a suppression has been seen in resonances in high-multiplicity events [53], explained either by rescattering [53] or initial-state effects [54–56], this suppression seems to be specific to some short-lived Regge excitations, which are longer lived but also strongly interact with the

hadron gas (the $\Lambda(1520)$ and K^* appear suppressed, but the Σ^* and Ξ^* do not [55,56]). The long-lived and nonstrange η' , with a comparatively weak in-medium cross section [32] will thus be less affected by hadronic in-medium rescatterings and will therefore conserve more memory of the production mechanism.

Both of the mechanisms examined in the preceding two sections, when applied to high-multiplicity collisions, go directly against these trends. High multiplicity means high-centrality events, where vorticity is expected to be lower. The anticorrelation between vorticity and impact parameter, together with the yield of π and ϕ linearly increasing with volume in the statistical model leads to the strong decrease with centrality seen in Fig. 2(b). No other phenomenon, to the author's knowledge, gives the same dependence for a particle ratio.

On the other hand, a strong variation of η'/π with multiplicity reaching a statistical model plateau for more central events can be seen as an indication that topological fluctuations might be contributing to η' abundance. A further disentanglement between multiplicity and impact parameter, possible with event engineering or simply system size scan (which can also disentangle rescattering from initial-state effects, which scale as the transverse multiplicity density), can shed light on the exact mechanism. The estimates in Fig. 2 show that it is the impact parameter dependence, rather than the absolute value, that need to be probed for new physics.

The particle correlation studies presented in Refs. [31,32] makes one hopeful a detectable contribution from chiral mechanisms to production of η' does indeed occur, but the methods used there can not easily isolate the source of centrality variation advocated in this paper from other dynamical mechanisms, present throughout the fireball's evolution, affecting pion correlations. This is why a system size scan of η' ratios obtained from direct resonance reconstruction is both a promising probe of chiral physics and likely to yield a positive result.

In conclusion, the impact parameter dependence of the η'/π ratio is a possible probe for the emergence of both vortical effects (transference between quark gluon plasma angular momentum and spin) and possibly the presence of topological excitations. I hope experimentalists, especially those with precise electromagnetic calorimetry, will soon find if such an observable merits further phenomenological and theoretical investigation.

ACKNOWLEDGMENTS

I acknowledge support from FAPESP Proc. No. 2017/06508-7, participation in FAPESP tematico 2017/05685-2 and CNPQ bolsa de produtividade 301996/2014-8. This work is a part of the project INCT-FNA Proc. No. 464898/2014-5. I wish to thank Sangyong Jeon and David Chinellato for discussions.

[1] D. Kharzeev, R. D. Pisarski, and M. H. G. Tytgat, *Phys. Rev. Lett.* **81**, 512 (1998).

[2] K. Fukushima, D. E. Kharzeev, and H. J. Warringa, *Phys. Rev. D* **78**, 074033 (2008).

- [3] V. Koch, S. Schlichting, V. Skokov, P. Sorensen, J. Thomas, S. Voloshin, G. Wang, and H. U. Yee, *Chin. Phys. C* **41**, 072001 (2017).
- [4] L. E. Finch and S. J. Murray, *Phys. Rev. C* **96**, 044911 (2017).
- [5] D. T. Son and P. Surowka, *Phys. Rev. Lett.* **103**, 191601 (2009).
- [6] M. A. Stephanov and Y. Yin, *Phys. Rev. Lett.* **109**, 162001 (2012).
- [7] D. Montenegro, L. Tinti, and G. Torrieri, *Phys. Rev. D* **96**, 056012 (2017); **96**, 079901(E) (2017).
- [8] D. Montenegro, L. Tinti, and G. Torrieri, *Phys. Rev. D* **96**, 076016 (2017).
- [9] W. Florkowski, A. Kumar, and R. Ryblewski, [arXiv:1806.02616](https://arxiv.org/abs/1806.02616) [hep-ph].
- [10] W. Florkowski, B. Friman, A. Jaiswal, and E. Speranza, *Phys. Rev. C* **97**, 041901 (2018).
- [11] B. Betz, M. Gyulassy, and G. Torrieri, *Phys. Rev. C* **76**, 044901 (2007).
- [12] Z. T. Liang and X. N. Wang, *Phys. Rev. Lett.* **94**, 102301 (2005).
- [13] F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, *Ann. Phys. (N.Y.)* **338**, 32 (2013).
- [14] L. Adamczyk *et al.* (STAR Collaboration), *Nature (London)* **548**, 62 (2017).
- [15] F. Becattini, L. P. Csernai, and D. J. Wang, *Phys. Rev. C* **88**, 034905 (2013); **93**, 069901 (2016).
- [16] I. Karpenko and F. Becattini, *Eur. Phys. J. C* **77**, 213 (2017).
- [17] O. V. Teryaev and V. I. Zakharov, *Phys. Rev. D* **96**, 096023 (2017).
- [18] G. 't Hooft, *Phys. Rev. Lett.* **37**, 8 (1976).
- [19] E. Witten, *Nucl. Phys. B* **156**, 269 (1979).
- [20] H. Forkel, [arXiv:hep-ph/0009136](https://arxiv.org/abs/hep-ph/0009136).
- [21] D. Atwood and A. Soni, *Phys. Lett. B* **405**, 150 (1997).
- [22] S. Jeon and J. Jalilian-Marian, *Nucl. Phys. A* **710**, 145 (2002).
- [23] S. Jeon, *Phys. Rev. C* **65**, 024903 (2002).
- [24] D. Ahrensmeier, R. Baier, and M. Dirks, *Phys. Lett. B* **484**, 58 (2000).
- [25] K. Buckley, T. Fugleberg, and A. Zhitnitsky, *Phys. Rev. C* **63**, 034602 (2001).
- [26] T. Kunihiro, *Phys. Lett. B* **219**, 363 (1989); **245**, 687(E) (1990).
- [27] J. I. Kapusta, D. Kharzeev, and L. D. McLerran, *Phys. Rev. D* **53**, 5028 (1996).
- [28] Z. Huang and X. N. Wang, *Phys. Rev. D* **53**, 5034 (1996).
- [29] S. Benic, D. Horvatic, D. Kekez, and D. Klabucar, *Phys. Rev. D* **84**, 016006 (2011).
- [30] S. E. Vance, T. Csorgo, and D. Kharzeev, *Phys. Rev. Lett.* **81**, 2205 (1998).
- [31] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. C* **97**, 064911 (2018).
- [32] T. Csorgo, R. Vertesi, and J. Sziklai, *Phys. Rev. Lett.* **105**, 182301 (2010).
- [33] M. Nanova *et al.* (CBELSA/TAPS Collaboration), *Phys. Lett. B* **710**, 600 (2012).
- [34] J. Letessier and J. Rafelski, *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* **18** (2002).
- [35] G. Torrieri, S. Jeon, J. Letessier, and J. Rafelski, *Comput. Phys. Commun.* **175**, 635 (2006).
- [36] P. Braun-Munzinger, K. Redlich, and J. Stachel, *Quark-Gluon Plasma 3*, edited by R. C. Hwa and X.-N. Wang (World Scientific, Singapore, 2004), pp. 491–599.
- [37] F. Becattini, P. Castorina, J. Manninen, and H. Satz, *Eur. Phys. J. C* **56**, 493 (2008).
- [38] S. Damjanovic *et al.* (NA60 Collaboration), *Nucl. Phys. A* **783**, 327 (2007).
- [39] P. Fachini, *J. Phys. G* **35**, 044032 (2008).
- [40] T. Csorgo, B. Lorstad, and J. Zimanyi, *Z. Phys. C* **71**, 491 (1996).
- [41] S. Acharya *et al.* (ALICE Collaboration), [arXiv:1803.05490](https://arxiv.org/abs/1803.05490) [nucl-ex].
- [42] F. Becattini, F. Piccinini, and J. Rizzo, *Phys. Rev. C* **77**, 024906 (2008).
- [43] W. Broniowski and W. Florkowski, *Phys. Rev. C* **65**, 024905 (2002).
- [44] J. Adam *et al.* (ALICE Collaboration), *Nat. Phys.* **13**, 535 (2017).
- [45] P. Petreczky, H. P. Schadler, and S. Sharma, *Phys. Lett. B* **762**, 498 (2016).
- [46] S. Borsanyi *et al.*, *Nature (London)* **539**, 69 (2016).
- [47] L. McLerran, *Phys. Part. Nucl. Lett.* **8**, 673 (2011).
- [48] C. Markert, R. Bellwied, and I. Vitev, *Phys. Lett. B* **669**, 92 (2008).
- [49] R. Bellwied and C. Markert, *Phys. Lett. B* **691**, 208 (2010).
- [50] C. Patrignani *et al.* (Particle Data Group), *Chin. Phys. C* **40**, 100001 (2016).
- [51] B. Alessandro *et al.* (NA50 Collaboration), *Phys. Lett. B* **555**, 147, (2003); **561**, 294(E) (2003).
- [52] D. Adamova *et al.* (CERES Collaboration), *Phys. Rev. Lett.* **96**, 152301 (2006).
- [53] C. Markert, G. Torrieri, and J. Rafelski, *AIP Conf. Proc.* **631**, 533 (2002).
- [54] R. Acconcia, D. D. Chinellato, R. D. de Souza, J. Takahashi, G. Torrieri, and C. Markert, *Phys. Rev. D* **97**, 036010 (2018).
- [55] B. I. Abelev *et al.* (STAR Collaboration), *Phys. Rev. Lett.* **97**, 132301 (2006).
- [56] S. Kiselev (ALICE Collaboration), *EPJ Web Conf.* **138**, 01022 (2017).