Abnormal enhancement of dilepton yield in central heavy-ion collisions from local parity breaking

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Abstract

We propose a novel explanation for the dilepton excess observed in dense/hot nuclear matter at invariant masses below 1 GeV. We argue that the presence of local parity breaking due to a time-dependent isosinglet and/or isotriplet pseudoscalar condensate may substantially modify the dispersion relation of photons and vector mesons propagating in such a medium, resulting in an abnormally large excess of e^+e^- with respect to the common theoretical predictions based in a 'cocktail' of hadronic processes. Various signatures to prove or disprove this effect are proposed.

During the last decade several experiments in heavy ion collisions have indicated an abnormal yield of lepton pairs of invariant mass < 1 GeV in the region of small rapidities and moderate transversal momenta [1, 2] (reviewed in [3, 4]). This effect is visible only for collisions that are central or nearly central. Most studies refer to e^+e^- pairs but dimuon pairs have also been found to be produced in excess beyond the dimuon threshold. From comparison to proton-proton and proton-nucleus collisions it has been well established that such an enhancement is undoubtedly a nuclear medium effect [3]. For the energies accessible at GSI (of few GeV per nucleon in HADES experiments [3]) the effect was interpreted as being due to enhanced η meson production in proton-neutron scattering [5]. For the higher energies accessible at CERN SPS and BNL RHIC (of order of 100 GeV per nucleon, in CERES, HELIOS/3, NA60 [1] and PHENIX [2] experiments) the abnormal dilepton yield has not been yet explained satisfactorily by any mechanisms known in hadron phenomenology [3, 4].

Following [2] we shall divide the range of invariant masses into high (beyond 3.2 GeV), low (below 1.2 GeV) and intermediate. The low mass region (LMR) is in turn divided into LMR I with $M_{ee} < 0.3$ GeV and LMR II with $0.3 \text{ GeV} < M_{ee} < 1.2$ GeV. In the LMR I the enhancement could be explained by possible modification of meson properties in nuclear medium [6, 7, 8, 9] as well as by proton-neutron scattering [5]. But in the LMR II the ρ meson decay dominates and the in-medium effects of a dropping mass and/or broadening resonance are insufficient to explain the spectacular dilepton enhancement by a 4 to 7 factor, depending on p_T and centrality.

In this letter we propose a radically different explanation of this enhancement. We suggest that the effect may be a manifestation of local parity breaking (LPB) in colliding nuclei due to

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generation of pseudoscalar, isosinglet or neutral isotriplet, classical background whose magnitude depends on the dynamics of the collision. It has been suggested that such a background could appear as the result of large-scale fluctuation of topological charge leading to the so-called Chiral Magnetic Effect (CME)[10] studied by lattice QCD simulations [13] and seemingly detected in the STAR experiments on RHIC [14], although the issue is far from being settled. It may be also related to pseudoscalar domain walls [12]. However the fact that the observed dilepton excess is absent for peripheral collisions (where the CME should be more visible) and maximized in cental collisions makes us believe that it may rather correspond to the ephemeral formation of a locally bona-fide thermodynamic phase where parity is broken, a possibility that has been argued for in [11].

It has been shown in [15] that a pseudoscalar field slowly evolving in time changes drastically the electromagnetic properties of the vacuum. In particular an energetic photon propagating in this background may decay on shell into dileptons. This same mechanism extended to vector mesons is proposed here as the source for abnormal yield of e^+e^- pairs both the LMR I and LMR II, i.e. in the range 0.15 GeV $< M_{ee} <$ 1 GeV, for centrality $0 \div 20\%$ and for moderate $p_T < 1$ GeV [2]. In this letter we will concentrate in the LMR II where the discrepancy between theory and experiment is more puzzling.

For $M_{ee} > 300$ MeV we include the lightest vector mesons ρ_0 and ω in the $SU(2)$ flavor sector (we don't include ϕ meson being less relevant for the selected M_{ee} region). The appropriate framework to describe electromagnetic interactions of hadrons at low energies is the Vector Dominance Model (VDM) [7]. We shall assume that a time dependent but approximately spatially homogeneous background of pseudoscalar field $a(t)$ is induced at the densities reached in heavy ion collisions and we will define a 4-vector related to it, $\zeta_\mu \simeq \partial_\mu a$, for later use. We contemplate the possibility that $a(t)$ is either isosinglet or isotriplet or even a mixture of the two, but detailed calculations will be presented for the case of isosinglet background only.

The appropriate kinetic Lagrangian for vector fields $V_\mu(x)$ in a pseudoscalar time-dependent background contains the Maxwell and mass terms supplemented by a Chern-Simons (CS) interaction

$$\begin{aligned} &\mathcal{L}_{int} = \bar{q}\gamma_\mu V^\mu q; \quad V_\mu \equiv -eA_\mu Q + \frac{1}{2} g_\omega \omega_\mu \mathbf{I} + g_\rho \rho_\mu \frac{\tau_3}{2}, \\ &(V_{\mu,a}) \equiv (A_\mu,\, \omega_\mu,\, \rho_\mu \equiv (\rho_0)_\mu)\,, \end{aligned} \tag{1}$$

where $Q = \frac{\tau_3}{2} + \frac{1}{6}\mathbf{I}, \qquad g_\omega \simeq g_\rho \equiv g \simeq 6$. These values are extracted from vector meson decays. Vector fields are normalized to the usual kinetic terms in vacuum

$$\begin{aligned} &\mathcal{L}_{kin} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} + \rho_{\mu\nu}\rho^{\mu\nu}\right) + \frac{1}{2} V_\mu \hat{m}^2 V^\mu, \\ &m^2_{a,b} = m_V^2 \begin{pmatrix} \frac{10e^2}{9g^2} & -\frac{e}{3g} & -\frac{e}{g} \\ -\frac{e}{3g} & 1 & 0 \\ -\frac{e}{g} & 0 & 1 \end{pmatrix}, \ \det\left(\hat{m}^2\right) = 0, \end{aligned}$$

where $m_V^2 = m_\rho^2 = 2g_\rho^2 f_\pi^2 \simeq m_\omega^2$. The mass matrix reflects the VMD relations at the quark model level [16, 7].

The parity-odd contribution is provided by the CS term

$$\mathcal{L}_{CS}(k) = -\frac{1}{4}\varepsilon^{\mu\nu\rho\sigma}\, \mathrm{tr}\, \hat{\zeta}_\mu\, V_\nu(x)\, V_{\rho\sigma}(x) = \frac{1}{2}\mathrm{tr}\, \hat{\zeta}\, \epsilon_{jkl}\, V_j\, \partial_k V_l = \frac{1}{2}\, \zeta\, \epsilon_{jkl}\, V_{j,a}\, N_{ab}\, \partial_k V_{l,b}, \tag{2}$$

which produces the mixing between photons and vector mesons induced by LPB. For isosinglet pseudoscalar background $\hat{\zeta} = \frac{9}{5}\zeta\mathbf{I}$, and the mixing matrix reads

$$N_{ab} \simeq \begin{pmatrix} 1 & -\frac{3g}{10e} & -\frac{9g}{10e} \\ -\frac{3g}{10e} & \frac{9g^2}{10e^2} & 0 \\ -\frac{9g}{10e} & 0 & \frac{9g^2}{10e^2} \end{pmatrix}, \quad \det\left(\hat{N}\right) = 0, \tag{3}$$

Remarkably, $\hat{N} \sim \hat{m}^2$. Simple order-of-magnitude considerations indicate that $\zeta \sim \alpha\tau^{-1} \sim 1$ MeV, taking $\tau = 1$ fm.

For isotriplet pseudoscalar background the $\hat{\zeta} = 3\zeta\tau_3$, and the corresponding CS matrix takes the form

$$N^{\pi}_{ab} \simeq \begin{pmatrix} 1 & -\frac{3g}{2e} & -\frac{g}{2e} \\ -\frac{3g}{2e} & 0 & \frac{3g^2}{2e^2} \\ -\frac{g}{2e} & \frac{3g^2}{2e^2} & 0 \end{pmatrix}, \quad \det\left(\hat{N}^{\pi}\right) = 0. \tag{4}$$

The VMD coefficients in (3),(4) are obtained from the anomalous Wess-Zumino action [17] and related to the phenomenology of radiative decays of vector mesons [18]. The ratios of matrix elements for isotriplet condensate in (4) are in direct agreement with experimental decay constants for processes $\pi_0 \to \gamma\gamma, \quad \omega \to \pi_0\gamma, \quad \rho_0 \to \pi_0\gamma$ [17] and for the decay $\omega \to \pi\pi\pi$ [19] taken from [20]. Likewise the elements in (3) can be, in principle, estimated from the decays $\eta \to \gamma\gamma, \quad \eta' \to \gamma\gamma, \quad \omega \to \eta\gamma, \quad \rho_0 \to \eta\gamma$. However, phenomenologically there exists a strong $\eta_8 - \eta_0$ mixing effect which must be finally resolved in the SU(3) flavor scheme [21]. Only the ratio of the decay widths $\omega \to \eta\gamma, \quad \rho_0 \to \eta\gamma$ is little sensitive to the mixing and confirms the off-diagonal elements of (3). In this letter we ignore the above mixing and restrict ourselves to SU(2). Furthermore as mentioned previously we restrict ourselves to an isosinglet pseudoscalar background $a(t)$. In this case one can find the mass-shell equations for vector mesons

$$\begin{aligned} &K^{\mu\nu}_{ab} V_{\nu,b} = 0; \quad k^{\nu}\, V_{\nu,b} = 0, \\ &K^{\mu\nu} \equiv g^{\mu\nu}(k^2\mathbf{I} - m^2) - k^{\mu}k^{\nu}\mathbf{I} - i\varepsilon^{\,\mu\nu\rho\sigma}\,\zeta_{\rho}k^{\sigma}\hat{N}, \end{aligned} \tag{5}$$

selecting out three physical polarizations for massive vector fields. In fact, these three polarizations contribute into the vector field propagators as they couple to conserved fermion currents. The longitudinal polarization ε^{μ}_{L} is orthogonal to k_{μ} and to the CS term

$$\varepsilon^{\mu}_{L} = \frac{\zeta^{\mu}k^2 - k^{\mu}(\zeta\cdot k)}{\sqrt{k^2\left((\zeta\cdot k)^2 - \zeta^2 k^2\right)}}, \quad \varepsilon_L \cdot \varepsilon_L = -1, \tag{6}$$

for $k^2 > 0$. The mass of this state remains undistorted. The transversal (circular) polarizations $\varepsilon^{\mu}_{\pm}$ on the other hand satisfy

$$K^{\mu}_{\nu}\varepsilon^{\nu}_{\pm} = \left(k^2\mathbf{I} - m^2 \pm \sqrt{(\zeta\cdot k)^2 - \zeta^2k^2}\;\hat{N}\right)\varepsilon^{\mu}_{\pm}. \tag{7}$$

The spectrum can be found after the simultaneous diagonalization of matrices $\hat{m}^2, \hat{N}$ and particularizing to the case $\zeta_{\mu} \simeq (\zeta, 0, 0, 0)$

$$\begin{aligned} \hat{N} &= \mathrm{diag}\left[0,\, \frac{9g^2}{10e^2},\, \frac{9g^2}{10e^2} + 1\right] \sim \\ \hat{m}^2 &= m_V^2\,\mathrm{diag}\left[0,\, 1,\, 1 + \frac{10e^2}{9g^2}\right], \end{aligned} \tag{8}$$

namely

$$k_0^2 - \vec{k}^2 = m_V^2 \pm \frac{9g^2}{10e^2}\zeta|\vec{k}| \simeq m_V^2 \pm 360\zeta|\vec{k}| \equiv m^2_{V,\pm}. \tag{9}$$

Thus in the case of isosinglet pseudoscalar background the massless photons are not distorted when mixed with massive vector mesons. In turn, massive vector mesons split into three polarizations with masses $m^2_{V,-} < m^2_{V,L} < m^2_{V,+}$. This splitting unambiguously signifies local parity breaking as well as breaking of Lorentz invariance due to the time-dependent background. For large enough $|\vec{k}| \geq 10e^2m_V^2/9g^2\zeta \simeq m_V^2/360\zeta$ vector meson states with negative polarization

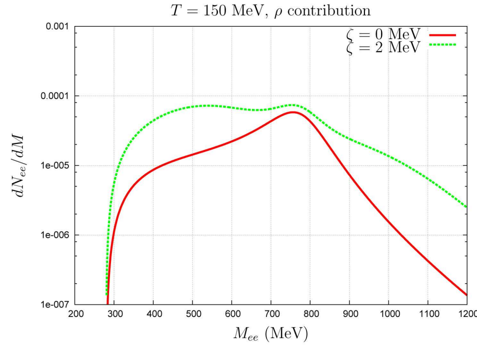

Figure 1: The ρ meson contribution into the dilepton production is shown for parity symmetric nuclear matter $\zeta = 0$ and for local parity breaking with $\zeta = 2MeV$. The units of vertical axis are normalized on those for the PHENIX experimental data [2].

become tachyons. However their group velocity remains less than the light velocity [22] provided that $\zeta < 20e^2 m_V/9g^2 \simeq m_V/180 \approx 4.3$ MeV. For higher values of ζ the vacuum state becomes unstable, namely, polarization effects give an imaginary part for the vacuum energy.

It is crucial to note that the position of resonance poles for $\pm$ polarized mesons is moving with wave vector $|\vec{k}|$ and therefore they reveal themselves as "giant" resonances. This feature is responsible for a substantial amplification of their contribution into dilepton production.

The production rate of e^+e^- pairs mediated by ρ and ω mesons takes a form similar to [7] but with modified propagators due to the LPB according to our previous discussion

$$\frac{dN_{ee}}{d^4x dM} \simeq \sum_V c_V \frac{\alpha^2 \Gamma_V m_V^2}{3\pi^2 g^2 M^2} \left(\frac{M^2 - n_V^2 m_\pi^2}{m_V^2 - n_V^2 m_\pi^2} \right)^{3/2} \Theta(M^2 - n_V^2 m_\pi^2)$$
$$\times \sum_\epsilon \int_M^\infty dk_0 \frac{\sqrt{k_0^2 - M^2}}{e^{k_0/T} - 1} \frac{m_{V,\epsilon}^4 \left(1 + \frac{\Gamma_V^2}{m_V^2}\right)}{\left(M^2 - m_{V,\epsilon}^2\right)^2 + m_{V,\epsilon}^4 \frac{\Gamma_V^2}{m_V^2}}, \tag{10}$$

where $n_V = 2, 3$ for ρ and ω mesons respectively. A simple thermal average over the pion gas energies (assumed to represent the fireball created after the heavy ion collision) has been included. The coefficient c_V absorbs some combinatorial factors different for ρ and ω mesons as well as the production rate per unit volume of thermal pions responsible for vector meson creation and dependence on meson chemical potential [7]. Empirically for $\zeta = 0$ the ratio $c_\rho/c_\omega \sim 10 \sim \Gamma_\rho/2\Gamma_\omega$ (see [2]).

The enhancement due to LPB with respect to the usual 'cocktail' estimates is shown on Fig.1 for $T = 150$ MeV. In the region 300 MeV $< M <$ 900 MeV virtual ρ mesons contribute substantially to the production of e^+e^- from $\pi\pi$ fusion. ω mesons decays are also important but give a subdominant contribution as compared to ρ meson ones, except for the very vicinity of the resonance peak of the ω. In addition there is a contribution from the Dalitz decay of the η meson, to which we shall return later.

The ρ meson has a strong coupling to the $\pi\pi$ channel, and its mean free path (1.3 fm) is essentially shorter than the expected size of the hadronic gas fireball (5-10 fm). Thus in-medium effects for ρ meson must be the most important ones for managing the abnormal dilepton yield.

In turn, the mean free path for ω is 17 times longer, therefore the probability of its decay within the fireball is not as high and the in-medium enhancement due to LPB of the dilepton production is relatively reduced (finite volume suppression). Neglecting this reduction the amplification of dilepton yield is presented on Fig.2 .

Nevertheless the resonance peak is mostly saturated by ω decays and the net effect is depicted on Fig.3. Comparison with the results from PHENIX indicate that a value for ζ between 1 and 2 MeV provides enough enhancement in this region to explain the dilepton excess.

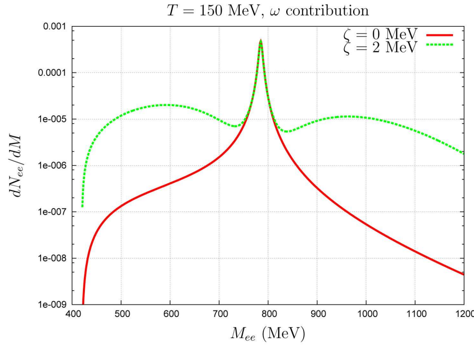

Figure 2: The ω meson contribution into the dilepton production is shown for parity symmetric nuclear matter $\zeta = 0$ and for local parity breaking with $\zeta = 2MeV$. The limit of very large fireball is taken.

At lower invariant masses < 300 MeV the Dalitz processes $\pi_0 \to \gamma e^+e^-, \eta \to \gamma e^+e^-$ nearly saturate the e^+e^- production. As before, for an isosinglet background only the spectral densities of virtual ρ and ω states are modified by the pseudoscalar background resulting from LPB. In this case the analog of the Kroll-Wada formula [25] describes the partial decay widths from the $L, \pm \to \epsilon = 0, \pm 1$ polarizations for distorted vector states

$$\frac{dN_{ee}}{dMd^4xd^3q} \simeq \sum_{V,P} c_P \frac{\alpha^3 m_P^3 M^2}{144\pi^4 f_P^2 M} \left(1 - \frac{M^2}{m_P^2}\right)^3 \sum_\epsilon |F(M, m_{V,\epsilon})|^2 \equiv \frac{d\Gamma_{\gamma ee}}{dM} \tag{11}$$

$$F(M, m_{V,\epsilon}) \equiv \left[\left(1 - \frac{M^2}{m_{V,\epsilon}^2}\right)^2 - i\frac{\Gamma_{Vee}}{m_V}\right]^{-1}, \tag{12}$$

where for massive vector mesons (9)

$$m_{V,\epsilon}^2 \simeq M_\rho^2 + \epsilon\ 360\ \zeta|\vec{k}|,\ m_V^2 \equiv m_{V,0}^2 \simeq M_\rho^2,$$

and

$$\Gamma_{\rho ee}/m_\rho \simeq 10^{-5};\ \Gamma_{\omega ee}/m_\omega \simeq 0.8 \cdot 10^{-6}.$$

The coefficients c_P correct the ratio of π, η two-photon decays, $c_\eta : c_\pi \simeq 4.3$ and also includes the production rate per unit volume of pseudoscalar mesons . This production rate must be also averaged over the thermal distribution of pseudoscalar mesons. The positions of resonances $m_{V,\pm}^2$ move with the wave vector $\vec{k}$ and therefore convolution with photon thermal distribution makes them broader. In Eq.(12) the enhancement is calculated for very large nuclear matter fireballs and it is definitely overestimated . As the meson resonance life time is essentially larger than the collision time $\tau \sim 5 \div 10$ fm one should expect a strong finite volume suppression. Still one could expect a visible enhancement $\sim \tau^2\ m_{V,\epsilon}^2 > 1$ for $m_{V,\epsilon} > 100$ MeV. This estimate is valid for $\Gamma_{Vee}\tau \ll 1$. An additional reduction is caused by convolution with the thermal distribution.

When $\hat{\zeta} \neq 0$ and its isospin content is arbitrary $\hat{\zeta} = A\mathbf{I} + B\tau_3$ the photons of "+" polarization behave as narrow resonances [15] with the width $\Gamma_\gamma \simeq \alpha\zeta/3$ and decay into e^+e^- above the threshold at $|\vec{k}| > 4m_e^2/\zeta$. This mechanism of enhancement could be dominant for relatively low invariant masses < 300 MeV when the Dalitz processes $\pi_0 \to \gamma e^+e^-, \eta \to \gamma e^+e^-$ saturate the e^+e^- production.

We now summarize the signatures and outline the searches of local parity breaking.

Polarization: As the amplification of dilepton yield at a given value of their invariant mass is owed to photons/vector mesons with a definite polarization one could search for polarization

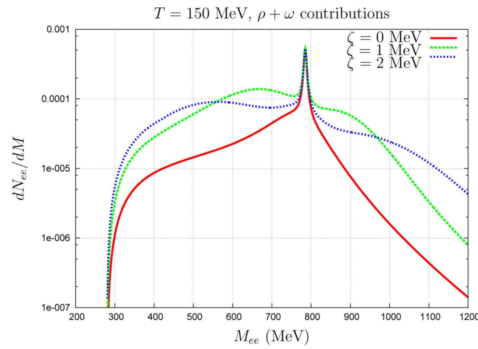

Figure 3: The net meson contribution into the dilepton production is shown for parity symmetric nuclear matter $\zeta = 0$ and for local parity breaking with $\zeta = 1, 2 MeV$. The normalization of the $\rho + \omega$ peak is chosen on the PHENIX data.

asymmetry in event-by-event measurements. These measurements may reveal in an unambiguous way the existence of parity violation .

Electrons versus muons: For distorted photons with '+' polarization there are different thresholds $\sim 4m_l^2/\zeta$ to start a resonant behavior for different dilepton species (five orders of magnitude between e^+e^- and $\mu^+\mu^-$). For massive vector mesons such a difference in thresholds are smeared out and one could expect also an abnormal dimuon excess for invariant masses $> 300 MeV$ (presumably seen in [26]).

The nature of the condensate: Mixing of photons with vector mesons is sensitive to isospin of pseudoscalar condensate and therefore the fraction of distorted photon decays helps to disentangle its isospin content.

To summarize, in a time-dependent pseudoscalar background massless photons of '+' polarization and massive vector mesons behave as giant resonances after averaging over thermal distribution. They naturally tend to produce an overabundance of dilepton pairs. For an isosinglet pseudoscalar background only the massive vector mesons ρ and ω propagators are distorted due to vector state mixing. At relatively low invariant masses < 300 MeV when the Dalitz processes $\pi_0 \to \gamma e^+e^-, \eta \to \gamma e^+e^-$ saturate the e^+e^- production the distorted intermediate vector meson states enhance dilepton production considerably. However, due to very large lifetimes the suppression due to the finite volume of fireball must be taken into account. Still a moderate enhancement takes place for large enough effective masses. In the region 300 MeV $< M <$ 900 MeV virtual ρ and ω mesons again generate a surplus of e^+e^- for isosinglet pseudoscalar background. They come from different processes including Dalitz decays and, predominantly in this region, thermal pion fusion. The latter process opens strong interaction decays and therefore their width becomes much larger and the enhancement lower, but for ρ mesons practically there will be no finite volume suppression and a noticeable enhancement of dilepton production arises. The only free parameter is ζ that characterizes the time variation of the pseudoscalar condensate. A good fit to the data is obtained for natural values of ζ. The possibility that the LPB condensate is an isotriplet or an admixture of isotriplet and isosinglet has been discussed and ways to distinguish between these possibilities have been proposed. Finally, experimental signals of the manifestation of LPB in heavy ion collisions have been suggested.

Thus local parity breaking seems capable of explaining in a natural way the PHENIX/CERES/NA60 'anomaly' and search for its manifestation in dilepton production represents a good piece of physics program for the future.

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