Anomalous dilepton production from hot and dense nuclear matter

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Outline

- Motivation of local parity breaking (LPB)
- Axial baryon charge and chiral chemical potential
- Effective meson theory with chiral charge
- Manifestation of LPB in heavy ion collisions (HIC)
- PHENIX/STAR anomaly
- Conclusions and outlook

Parity: well established global symmetry of strong interactions. Reasons to believe it may be broken in a finite volume. Recent investigations:

- Chiral Magnetic Effect (CME): quantum fluctuation of θ parameter (P-odd bubbles) [D. E. Kharzeev, L. D. McLerran & H. J. Warringa, Nucl. Phys. A803, 227 (2008)]
- **New QCD phase** characterised by a local parity breaking due to pseudoscalar background [A. A. Andrianov, V. A. Andrianov & D. Espriu, Phys. Lett. B 678, 416 (2009)]

HIC may trigger LPB inside the hot dense nuclear fireball

[A. Andrianov, V. Andrianov, D. Espriu, X. Planells, Phys. Lett. B 710 (2012) 230]

Axial baryon charge and chiral chemical potential

Topological charge T_5 may arise due to quantum fluctuations in hot medium due to sphaleron transitions [Manton, McLerran, Rubakov, Shaposhnikov]

$$T_5 = \frac{1}{8\pi^2} \int_{\text{vol.}} d^3x \varepsilon_{jkl} \text{Tr} \left(G^j \partial^k G^l - i\frac{2}{3} G^j G^k G^l \right)$$

PCAC leads

$$Q_5^q = \int_{\text{vol.}} d^3x \bar{q}\gamma_0\gamma_5 q, \quad \frac{d}{dt}\left(Q_5^q - 2N_f T_5\right) \simeq 0, \quad m_q \simeq 0$$

Lagrangian with topological or axial chemical potential (μ_θ, μ_5)

$$\langle \Delta T_5 \rangle \simeq \frac{1}{2N_f} \langle Q_5^q \rangle \iff \mu_5 \simeq \frac{1}{2N_f} \mu_\theta,$$

$$\Delta\mathcal{L}_{top} = \mu_\theta \Delta T_5 \iff \Delta\mathcal{L}_q = \mu_5 Q_5^q$$

Axial baryon charge and chiral chemical potential

LPB investigated in e.m. interactions of leptons and photons with hot/dense nuclear matter via heavy ion collisions.

- e.m. interaction implies $Q_5^q \to Q_5 = Q_5^q + Q_5^{em}$
- New μ_5 conjugated to Q_5
- ***Bosonization*** of Q_5^q following VMD prescription

Extra term in Lagrangian

$$\Delta\mathcal{L} \sim -\frac{1}{4}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left[\hat{\zeta}_\mu V_\nu V_{\rho\sigma}\right],$$

with $\hat{\zeta}_\mu = \hat{\zeta}\delta_{\mu 0}$ due to spatially homogeneous and isotropic background ($\hat{}$ $\equiv$ isospin content) and $\zeta \propto \mu_5$

$$\boxed{\langle T_5 \rangle \quad \Longleftrightarrow \quad \zeta}$$

Effective meson theory with chiral charge

Scalar part of the effective Lagrangian estimated using spurion technique

$$D_\nu \Longrightarrow D_\nu - i\{\mu_5 \delta_{0\nu}, \cdot\} = D_\nu - 2i\mu_5\delta_{0\nu}$$

New processes are relevant inside the fireball: $\eta, \eta' \to \pi\pi$ (strictly forbidden in QCD on parity grounds). Such particles could reach thermal equilibrium.

Need to include the lightest iso-scalar degrees of freedom in effective Lagrangian.

$$\downarrow$$

New eigenstates mixing $\sigma - \eta - \eta'$ and $a_0 - \pi$, with effective masses depending on μ_5 and $\vec{k}$. Work on their main properties in progress.

Vector Meson Dominance bosonization:

$$\mathcal{L}_{\text{int}} = \bar{q}\gamma_\mu \hat{V}^\mu q; \quad \hat{V}_\mu \equiv -eA_\mu Q + \frac{1}{2}g_\omega \omega_\mu \mathbb{I} + \frac{1}{2}g_\rho \rho^0_\mu \tau_3,$$

$$(V_{\mu,a}) \equiv \left(A_\mu,\, \omega_\mu,\, \rho^0_\mu\right)$$

where $Q = \frac{\tau_3}{2} + \frac{1}{6}$, $g_\omega \simeq g_\rho \equiv g \simeq 6$.

Maxwell and mass terms

$$\mathcal{L}_{\text{kin}} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} + \rho_{\mu\nu}\rho^{\mu\nu}\right) + \frac{1}{2}V_{\mu,a}(\hat{m}^2)_{a,b}V^\mu_b$$

$$\hat{m}^2 \simeq m_V^2 \begin{pmatrix} \frac{10e^2}{9g^2} & -\frac{e}{3g} & -\frac{e}{g} \\ -\frac{e}{3g} & 1 & 0 \\ -\frac{e}{g} & 0 & 1 \end{pmatrix}$$

P-odd interaction

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

- Isosinglet pseudoscalar background ($T \gg \mu$) [RHIC, LHC]

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

$\rightarrow$ undistorted γ and polarization splitting in meson masses:

$$m^2_{V,\epsilon} = m^2_V - \epsilon\zeta|\vec{k}|$$

- Pion-like condensate (not considered) ($\mu \gg T$) [FAIR, NICA]

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

Manifestation of LPB in heavy ion collisions

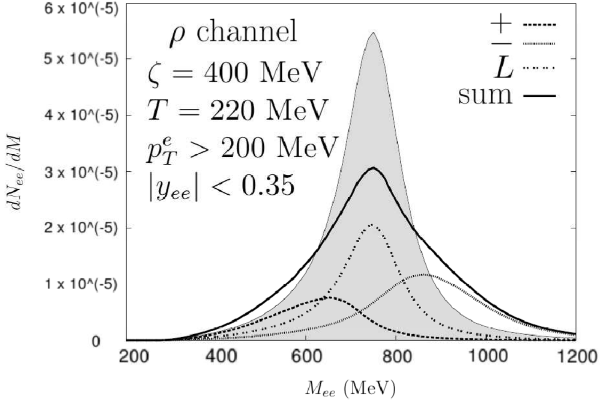
$L, \pm$ contribution for vector mesons before acceptance corrections:

$$\frac{dN^{\epsilon}_{ee}}{d^4x dM} \simeq c_V \frac{\alpha^2 \Gamma_V m_V^2}{3\pi^2 g^2 M^2} \left(\frac{M^2 - n_V^2 m_\pi^2}{m_V^2 - n_V^2 m_\pi^2} \right)^{3/2}$$

$$\times \sum_{\epsilon} \int_M^\infty dk_0 \frac{\sqrt{k_0^2 - M^2}}{e^{k_0/T} - 1} \frac{m^4_{V,\epsilon}}{\left(M^2 - m^2_{V,\epsilon}\right)^2 + m^4_{V,\epsilon} \frac{\Gamma_V^2}{m_V^2}},$$

where $n_V = 2, 0$; $|\vec{k}| = \sqrt{k_0^2 - M^2}$ and $M^2 > n_V^2 m_\pi^2$. c_V absorbs combinatorial factors different for ρ and ω, μ_V, finite volume suppression. Empirically for $\mu_5 = 0$ the ratio $c_\rho / c_\omega \sim 10$ holds.

Simulations implemented with PHENIX acceptance: $|y_{ee}| < 0.35$, $|\vec{p}^{\,e}_t| > 200$ MeV, gaussian M_{ee} smearing (width=10 MeV)

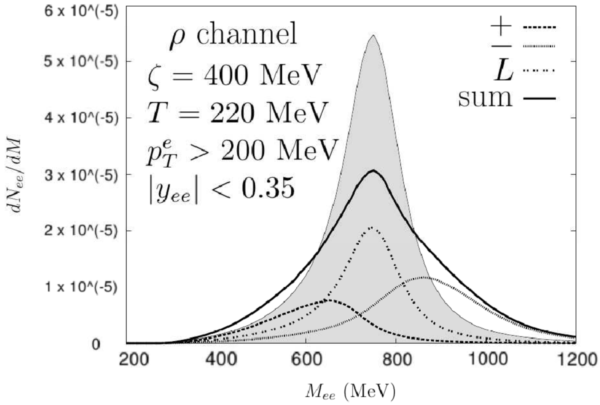


Polarization splitting in ρ spectral function for LPB $\zeta = 400$ MeV ($\mu_5 = 290$ MeV) compared with $\zeta = 0$ (shaded region).

POLARIZATION ASYMMETRY!!

Manifestation of LPB in heavy ion collisions

ρ spectral function



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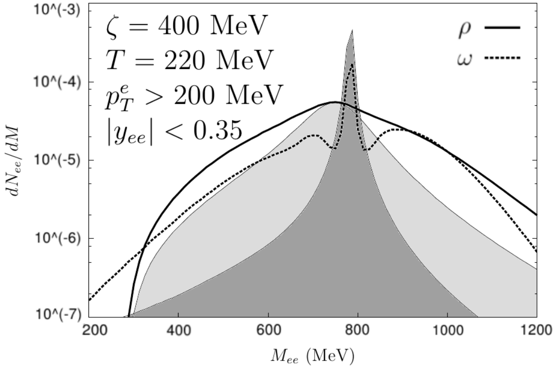
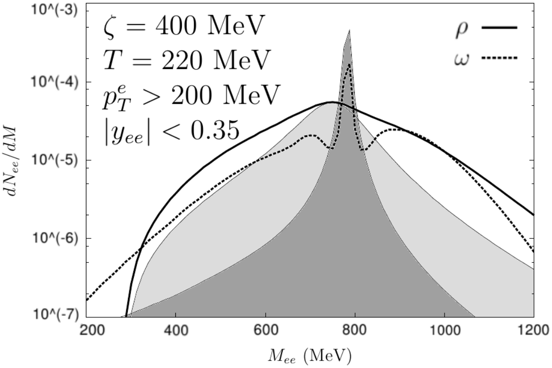


In-medium ρ and ω channels (solid and dashed line) and their vacuum contributions (light and dark shaded regions) for $\zeta = 400$ MeV. In-medium ρ is enhanced by a factor 1.8 due to $\pi\pi$ regeneration into ρ.

ENHANCEMENT OF DILEPTON YIELD!!



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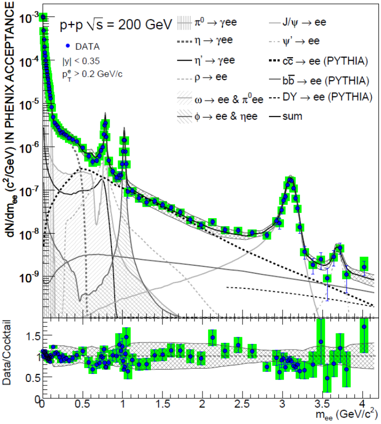
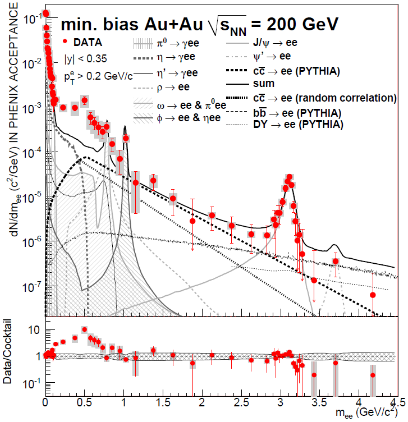
ENHANCEMENT OF DILEPTON YIELD!!

PHENIX/STAR anomaly

Abnormal e^+e^- excess in central HIC





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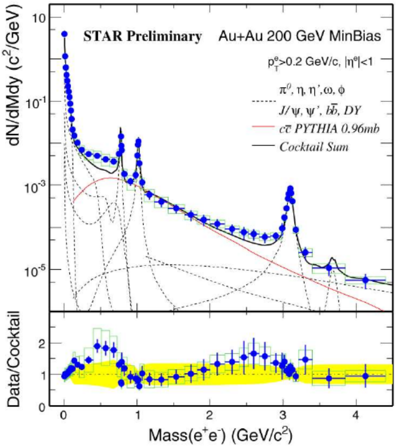

Conclusions and outlook

- LPB not forbidden by any physical principle in QCD at finite temperature/density
- The effect leads to unexpected modifications of the in-medium properties of vector mesons and photons
- LPB may help explaining the observed lepton spectrum in the LMR of PHENIX and STAR
- *Event-by-event* measurements of the lepton polarization asymmetry may reveal in an unambiguous way the existence of LPB
- Dalitz ω and η, η' (mixed with σ) decays and isotriplet condensate could be the responsible cases for the enhancement at $300 < M < 700$ [work on progress]

Thank you for your attention!

Explicit formula for the simulation with acceptance correction:

$$\frac{dN}{d^4x dM} = \int d\tilde{M} \frac{1}{\sqrt{2\pi}\Delta} \exp\left[-\frac{(M-\tilde{M})^2}{2\Delta^2}\right] c_V \frac{\alpha^2}{24\pi\tilde{M}} \left(1 - \frac{n_V^2 m_\pi^2}{\tilde{M}^2}\right)^{3/2}$$

$$\times \sum_\epsilon \int_{\text{acc.}} \frac{k_t dk_t dy d^2\vec{p}_t}{|E_k p_{||} - k_{||} E_p|} \frac{1}{e^{\tilde{M}_t/T} - 1} P_\epsilon^{\mu\nu} \left(\tilde{M}^2 g_{\mu\nu} + 4 p_\mu p_\nu\right)$$

$$\times \frac{m_{V,\epsilon}^4}{\left(\tilde{M}^2 - m_{V,\epsilon}^2\right)^2 + m_{V,\epsilon}^4 \frac{\Gamma_V^2}{m_V^2}}$$