Dilepton excess from local parity breaking in baryon matter

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Outline

- Motivation of local parity breaking (LPB)
- Axial baryon charge and chiral chemical potential
- Vector Meson Dominance (VMD) approach to LPB
- Manifestation of LPB in heavy ion collisions (HIC)
- Numerical results for dilepton excess
- Conclusions

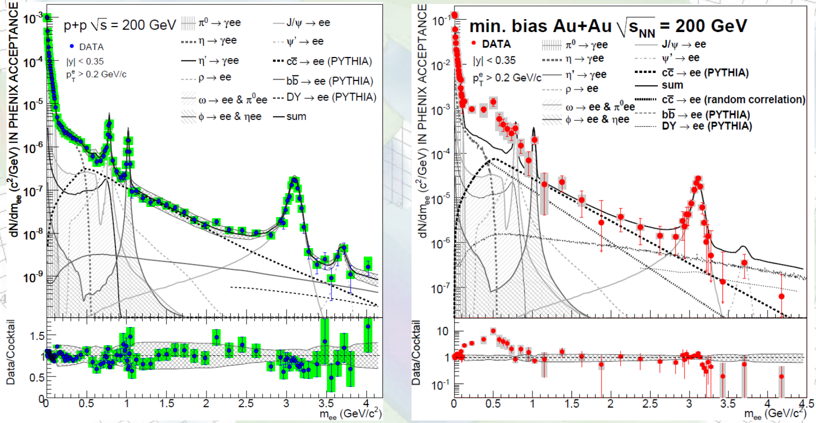
Motivation of local parity breaking
P-breaking

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)]

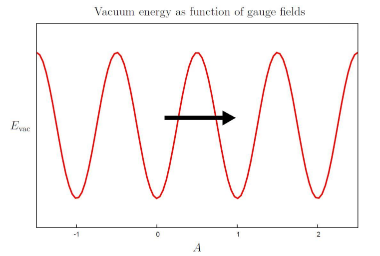
LPB background $\Longleftrightarrow$ hot dense nuclear fireball in HIC

- Hint to LPB?



[A. Adare et al. [PHENIX collaboration], Phys. Rev. C81, 034911 (2010)]

Axial baryon charge and chiral chemical potential

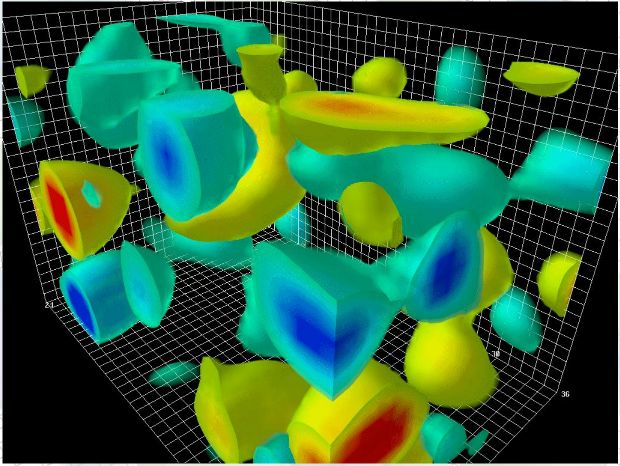


Topological charge T_5 may arise due to quantum fluctuations in hot medium due to sphaleron transitions [Manton, McLerran, Rubakov, Shaposhnikov]. PCAC leads

$$Q_5^q = \int_{\text{vol.}} d^3x \bar{q}\gamma_0\gamma_5 q, \;\; T_5 = \frac{1}{8\pi^2}\int_{\text{vol.}} d^3x \varepsilon_{jkl} \mathrm{Tr}\left(G^j \partial^k G^l - i\frac{2}{3} G^j G^k G^l\right)$$

$$\frac{d}{dt}\left(Q_5^q - 2N_f T_5\right) \simeq 0, \;\; m_q \simeq 0 \implies \mu_5^q Q_5^q$$

Axial baryon charge and chiral chemical potential



Lattice simulation of topological charge in QCD vacuum
[Leinweber]

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 $\zeta \sim \alpha\mu_5 \sim \alpha\tau^{-1} \sim 1$ MeV

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

Vector Meson Dominance approach to LPB

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

$$(V_{\mu,a}) \equiv \left(A_\mu,\, \omega_\mu,\, \rho^0_\mu, \phi_\mu\right), \quad g_\omega \simeq g_\rho \equiv g \simeq 6 < g_\phi$$

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

$$\hat{m}^2 \simeq m_V^2 \begin{pmatrix} \frac{4e^2}{3g^2} & -\frac{e}{3g} & -\frac{e}{g} & \frac{2eg_\phi}{g^2} \\ -\frac{e}{3g} & 1 & 0 & 0 \\ -\frac{e}{g} & 0 & 1 & 0 \\ \frac{2eg_\phi}{g^2} & 0 & 0 & \frac{2g_\phi^2}{g^2} \end{pmatrix}$$

$\Longrightarrow$ mixing of $\gamma, \rho, \omega, \phi$

Vector Meson Dominance approach to LPB

P-odd interaction

$$\mathcal{L}_{\mathrm{mix}} \propto \frac{1}{2}\mathrm{Tr}\left(\hat{\zeta}\varepsilon_{jkl}\hat{V}_j\partial_k\hat{V}_l\right) = \frac{1}{2}\zeta\varepsilon_{jkl}V_{j,a}N_{ab}\partial_k V_{l,b}$$

- $\tau_\phi \gg \tau_f$, non-negligible L-R oscillations due to s-quark mass term $\Longrightarrow$ $\langle Q_5^s\rangle \simeq 0$ $(3 \to 2$ flavors$)$

$$\hat{\zeta} = a\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} + b\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

[A. A. Andrianov, V. A. Andrianov, D. Espriu and X. Planells, *Abnormal dilepton yield from local parity breaking in heavy-ion collisions*, arXiv:1010.4688 [hep-ph]; PoS, QFTHEP2010, 053 (2010)]

Vector Meson Dominance approach to LPB

Mixing matrix N:

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

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

$$m^2_{V,\epsilon} = m^2_V - \epsilon \frac{9g^2}{10e^2} \zeta |\vec{k}| \implies |\zeta|$$

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

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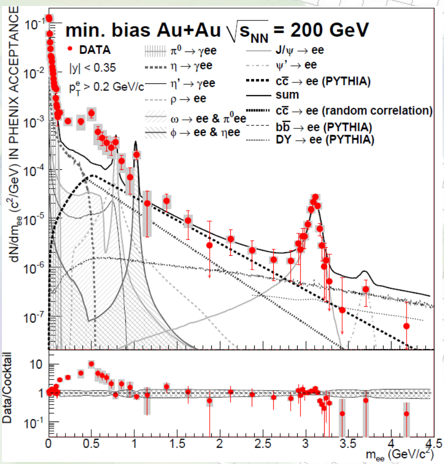
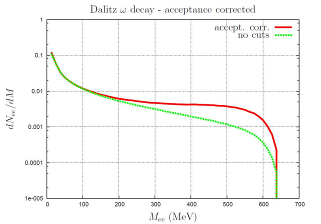
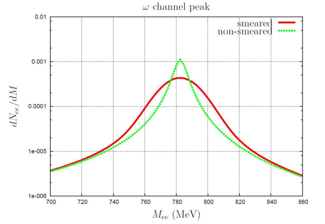
Cocktail of hadron decays:

- $\pi^0 \rightarrow \gamma e^+ e^-$
- $\eta \rightarrow \gamma e^+ e^-$
- $\eta' \rightarrow \gamma e^+ e^-$
- $\rho \rightarrow e^+ e^-$
- $\omega \rightarrow e^+ e^-$
- $\omega \rightarrow \pi^0 e^+ e^-$
- *background* $\bar{c}c$





Experimental detector cuts:
$|\vec{p}_t| > 200\ MeV,\ |y| < 0.35$



Invariant mass smearing: gaussian with width 10 MeV

Acceptance correction breaks Lorentz invariance. Phase space calculation becomes a non-trivial task $\Longrightarrow$ VEGAS

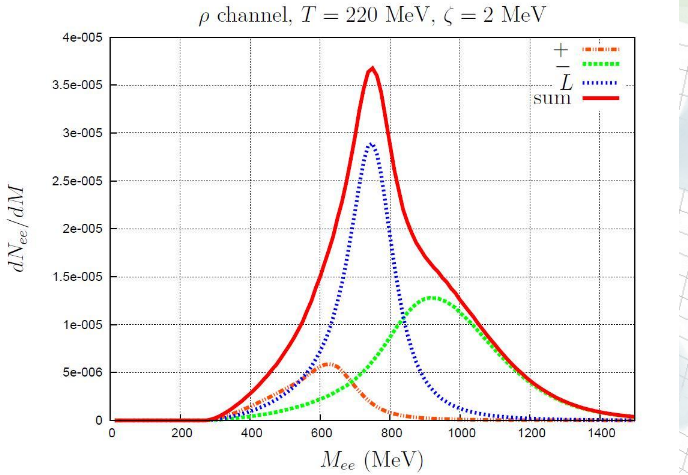
$L, \pm$ contribution for vector mesons before acceptance corrections:

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

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

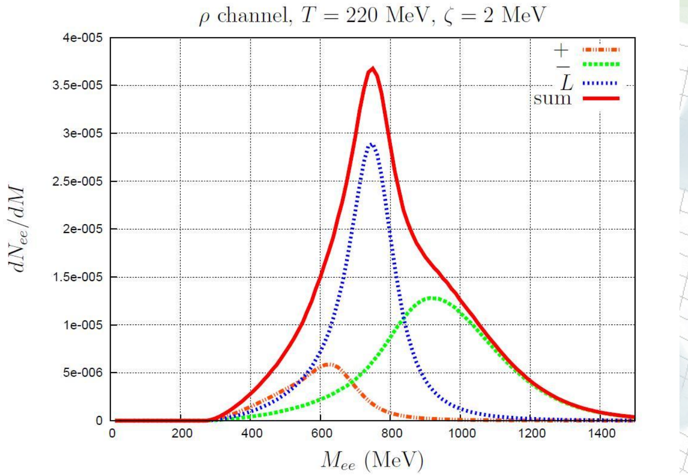
where $n_V = 2, 0$; $|\vec{k}| = \sqrt{k_0^2 - M^2}$ and $M^2 > n_V^2 m_\pi^2$. c_V absorbs combinatorial factors different for ρ and ω, μ_V, finite volume suppression. Empirically for $\zeta = 0$ the ratio $c_\rho / c_\omega \sim 10$ holds.

Numerical results for dilepton excess
ρ spectral function



Polarization splitting in ρ spectral function for LPB $\zeta = 2$ MeV.

POLARIZATION ASYMMETRY!!



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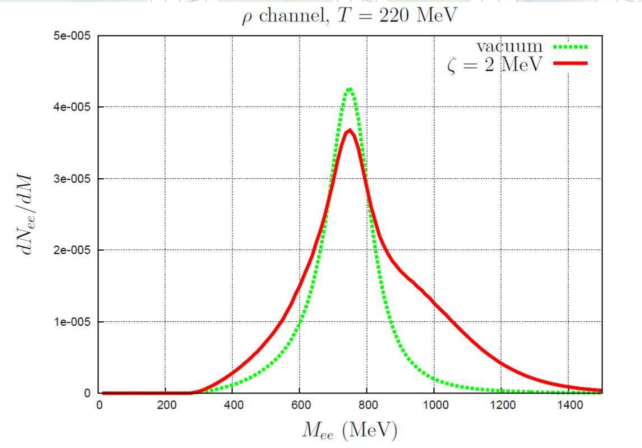
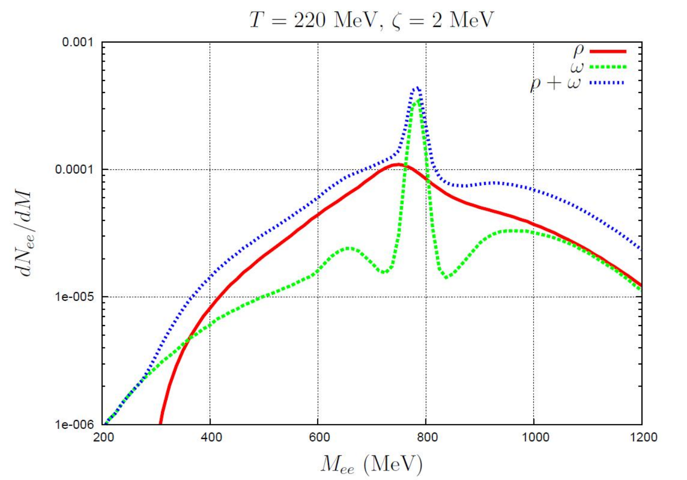


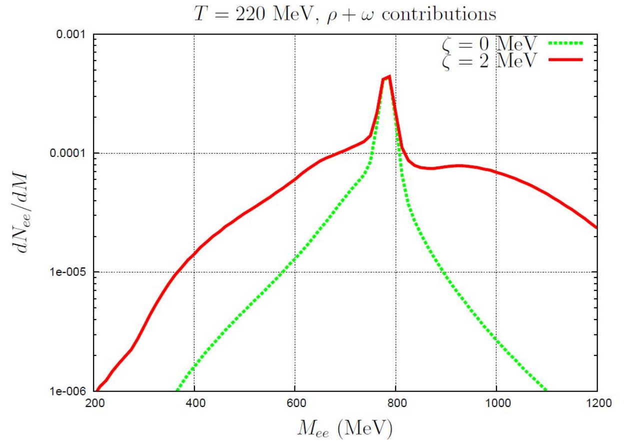
Comparison ρ spectral function in vacuum and for LPB $\zeta = 2$ MeV. In-medium calculation is pushed up by factor 1.8 due to $\pi\pi$ recombination into ρ

Numerical results for dilepton excess
PHENIX anomaly



ρ and ω contributions to dilepton yield for LPB $\zeta = 2$ MeV.

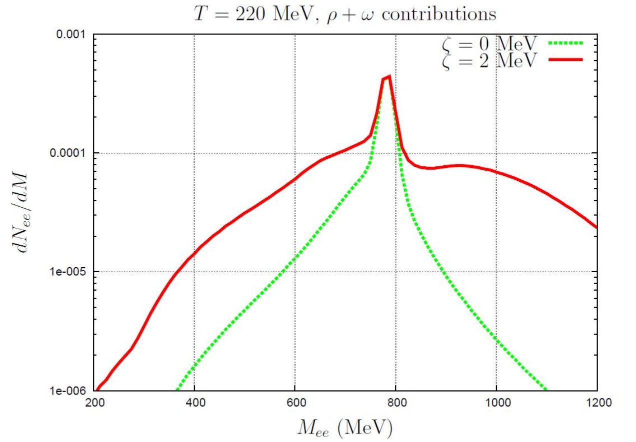
Numerical results for dilepton excess
PHENIX anomaly



$\rho + \omega$ contributions in vacuum and for LPB $\zeta = 2$ MeV (normalization given by the ω peak).

ENHANCEMENT OF DILEPTON YIELD!!

Numerical results for dilepton excess
PHENIX anomaly



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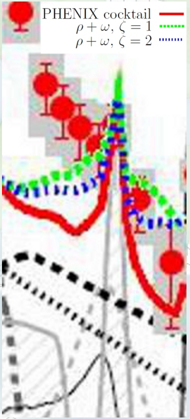


Comparison of PHENIX cocktail with modified cocktail using ρ + ω contributions for LPB with ζ =1, 2 MeV.

Conclusions

- 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 seems capable of explaining in a natural way the PHENIX 'anomaly'
- *Event-by-event* measurements of the lepton polarization asymmetry may reveal in an unambiguous way the existence of LPB
- Dalitz ω and η decays and γ in isotriplet condensate could be the main responsibles of the enhancement at $300 < M < 700$ [work on progress]

Thank you for your attention!

Backup I

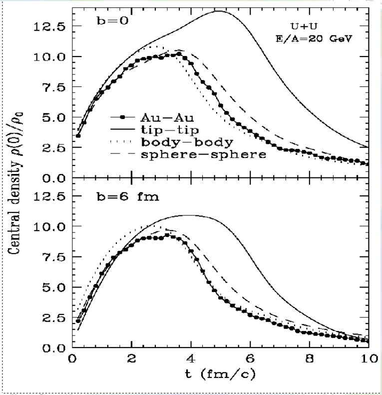
Explicit formula for the simulation with acceptance correction:

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

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

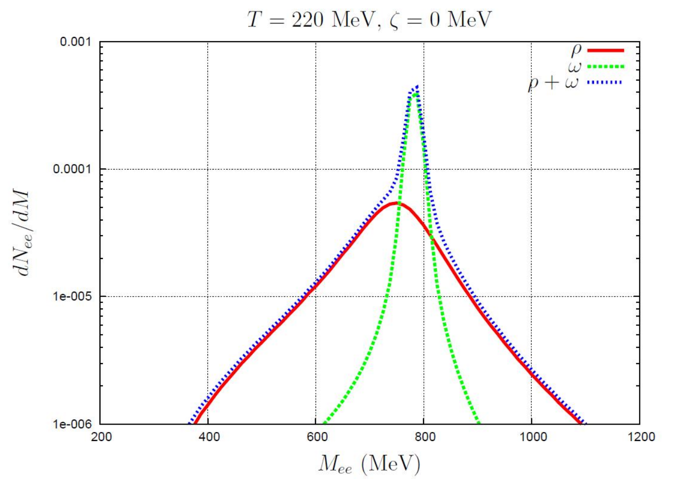
$$\times \frac{m_{V,\epsilon}^4}{\left(\tilde{M}^2 - m_{V,\epsilon}^2\right)^2 + m_{V,\epsilon}^4 \frac{\Gamma_V^2}{m_V^2}}$$

Backup II



Typical evolution of baryon density in a HIC (similar to temperature). ζ should show the same behavior.

Backup III



ρ and ω contributions to dilepton yield in vacuum.