Happy Birthday, Dima!

Phenomenology of local parity breaking

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Outline

- Motivation of local parity breaking (LPB): *P*-odd bubbles, neutral pion condensate, cold axion background
- Axial baryon charge and chiral chemical potential
- Vector Meson Dominance (VMD) approach to LPB (**with V. A. Andrianov, D. Espriu and X. Planells**)
- Manifestation of LPB in heavy ion collisions (HIC)
- Finite volume effects: passing through a boundary (**with S.S.Kolevatov**)
- Conclusions: in hunting for LPB.

Motivation of LPB

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

Recent investigations:

- **quantum fluctuations of θ parameter** (P-odd bubbles [T. D. Lee and G. C. Wick ...]: their manifestation in Chiral Magnetic Effect (CME))[D. E. Kharzeev, L. D. McLerran, A.Zhitnitsky, H. J. Warringa]
- **New QCD phase** characterized by a spontaneous parity breaking due to formation of neutral pion-like background [A.A.Anselm ... A. A. Andrianov, V. A. Andrianov & D. Espriu]
- **Axion background** in dense stars and/or as the dark matter [E.W. Mielke, P. Sikivie et al, A.A.Andrianov, D.Espriu et al]
- *Our special interest*:
  LPB background inside a hot dense nuclear fireball in HIC !?

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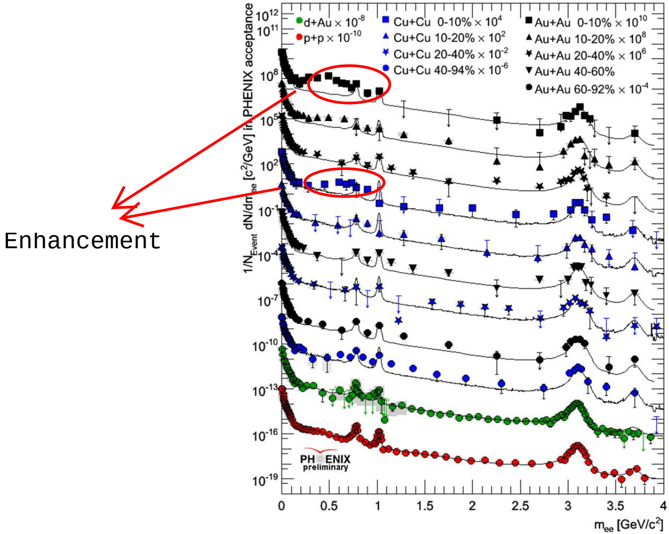
Motivation of LPB

PHENIX anomaly: abnormal e^+e^- excess in central HIC at low p_t !?



Hint to LPB?

[PHENIX Data Plot (id p1147) 2011]

Topological charge

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

in a finite volume it may arise from quantum fluctuations in hot QCD medium
(due to sphaleron transitions!? [Manton, Rubakov, Shaposhnikov, McLerran])
and survive for a sizeable lifetime in a heavy-ion fireball,

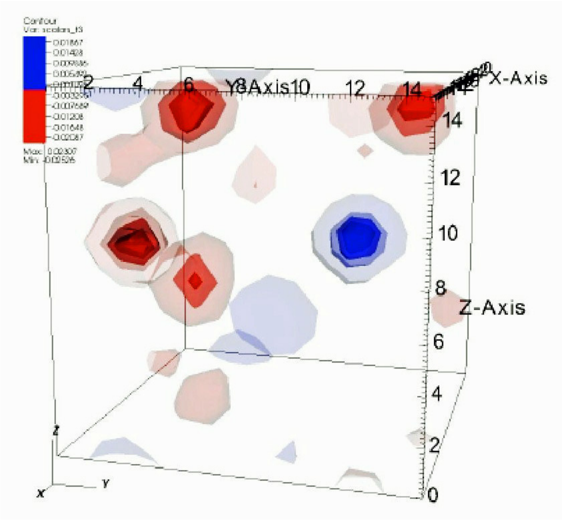
$$\langle T_5 \rangle \neq 0 \quad \text{for} \quad \Delta t \simeq \tau_{\text{fireball}} \simeq 5 - 10 \text{ fm},$$

For this period one can control the value of $\langle T_5 \rangle$ introducing into the QCD Lagrangian a topological chemical potential

$$\Delta L = \mu_\theta \ T_5$$

.

Topological charge fluctuations, QCD with 2+1 flavors



Domain Wall Fermions on a lattice of size $16^3 \times 8$,
T. Blum et al. LAT2009, 0911.1348 [hep-lat]

Chiral (axial) baryon charge

Partial conservation of isosinglet axial current broken by gluon anomaly (consider the light quarks only),

$$\partial_\mu J_5^\mu - 2im_q J_5 = \frac{N_f}{8\pi^2} \mathrm{Tr}\left(G^{\mu\nu} \widetilde{G}_{\mu\nu} \right)$$

predicts the induced **chiral (axial) charge**

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

to be conserved $\dot{Q}_5^q \simeq 0$ (in the chiral limit $m_q \simeq 0$) during $\tau_{fireball}$.

Chiral chemical potential

Chiral chemical potential can be associated with approximately conserved Q_5^q (for u, d quarks!)

$$\Delta L_q = \mu_5^q Q_5^q,$$

to reproduce a corresponding

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

For the s quark introducing of μ_5^q is problematic as $1/m_s \sim 1$ fm and several left-right oscillations occur during the fireball lifetime $\sim 5-10$ fm, i.e. one cannot consider the s quark chiral charge as conserved. As well the heavier is a quark the larger is screening of anomaly ($\rightarrow$ topological charge) by the pseudoscalar density J_5 (decoupling effect in vector gauge theories). Thus one expects suppression of strange meson contributions into LPB.

Chiral chemical potential in hadron Lagrangians

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

- e.m. interaction implies

$$Q_5^q \to \tilde{Q}_5 = Q_5^q - T_5^{em}, \quad T_5^{em} = \frac{1}{16\pi^2}\int_{vol.} d^3x \varepsilon_{jkl} A^j \partial^k A^l$$

- μ_5 is conjugated to (nearly) conserved $\tilde{Q}_5$
- ***Bosonization*** of Q_5^q following VMD prescription
  Extra term in Lagrangian

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

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

$$\boxed{\langle T_5 \rangle \iff \mu_\theta \implies \mu_5 \implies \zeta}$$

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$$\boxed{\langle T_5 \rangle \Longleftrightarrow \mu_\theta \Longrightarrow \mu_5 \Longrightarrow \zeta}$$

Vector Meson Dominance approach to LPB

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

$$(V_{\mu,a}) \equiv \left(A_\mu,\, \omega_\mu,\, \rho^0_\mu, \phi_\mu\right), \quad g_\omega \simeq g_\rho \equiv g \simeq 6 < g_\phi \simeq 7.8$$

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

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

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

VDM approach to LPB: reduction of $3 \to 2$ flavors

P-odd interaction

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

- $\tau_\phi \gg \tau_{fireball}$, non-negligible L-R oscillations due to s-quark mass term $\Longrightarrow \langle Q_5^s\rangle \simeq 0$. Correspondingly the reduction of $3 \to 2$ flavors makes sense.

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

[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)]

VDM approach to Local P-breaking

Mixing matrix N:

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

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

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

- Pion-like condensate ($\mu \gg T$) [FAIR, NICA]

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Manifestation of LPB in heavy ion collisions

Enhanced dilepton production

contribution of different polarizations $L, \pm$ for vector mesons in the hot pion gas:

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

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

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 $\zeta = 0$ the ratio $c_\rho / c_\omega \sim 10$ holds.

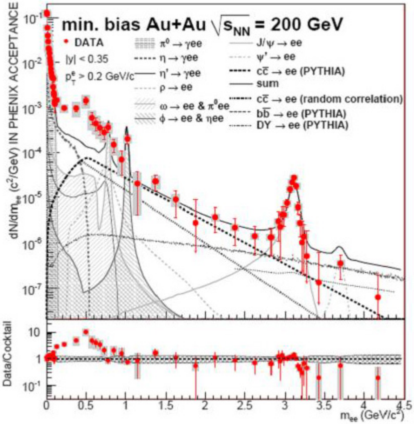
Manifestation of LPB in heavy ion collisions

Cocktail of hadron decays

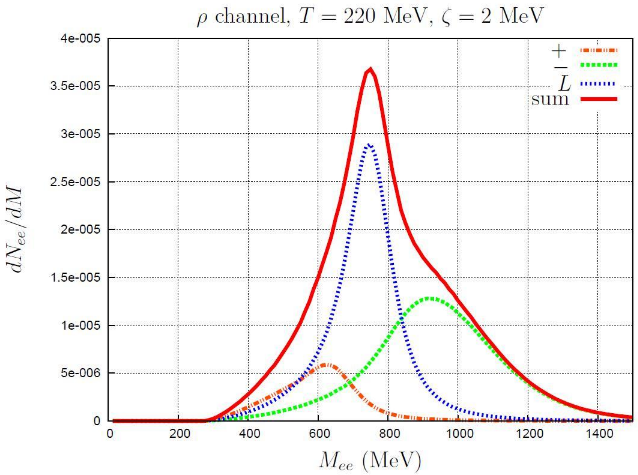
PHENIX data for Au-Au collisions

Cocktail of hadron decays:

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



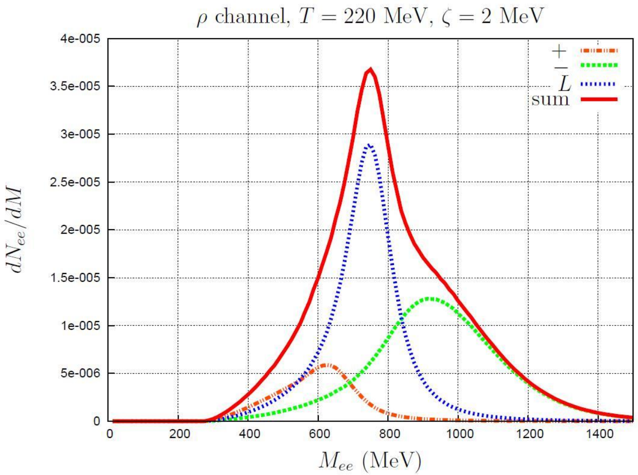
ρ spectral function



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

POLARIZATION ASYMMETRY!!

ρ spectral function



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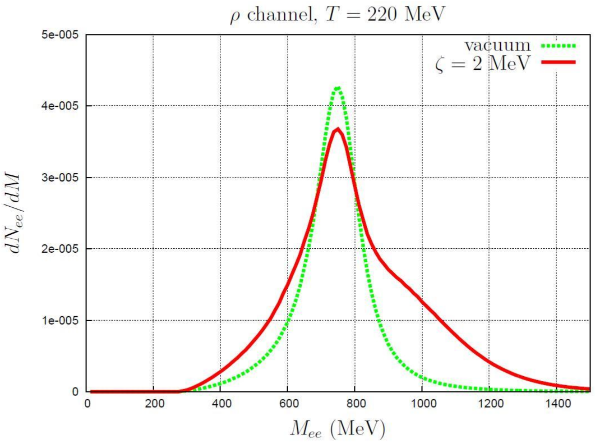
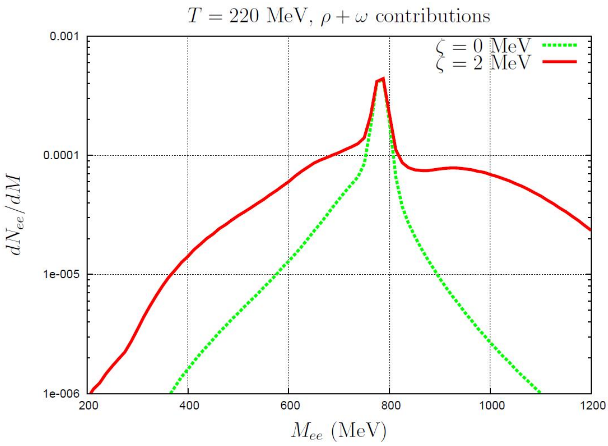


Comparison ρ spectral function in vacuum and for LPB $\zeta = 2$ MeV. In-medium calculation is pushed up by factor 1.8 due to $\pi\pi$ recombination into ρ

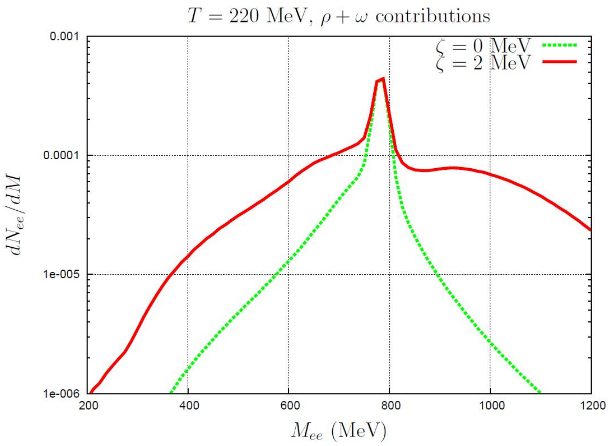
Numerical results for dilepton excess around $\rho + \omega$ peak



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

ENHANCEMENT OF DILEPTON YIELD!!

Numerical results for dilepton excess around $\rho + \omega$ peak



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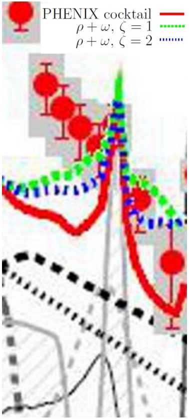
Numerical results for dilepton excess

PHENIX anomaly



Comparison of PHENIX cocktail with modified cocktail using $\rho + \omega$ contributions for LPB with ζ =1, 2 MeV.

Finite volume: passing through boundary

A.A., S.Kolevatov, 1109.3440[hep-ph]

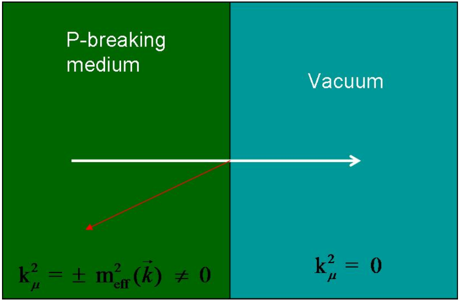
Mean free paths for vector mesons:

- $L_\rho \sim 0.8fm \ll L_{fireball} \sim 5-10fm$
- $L_\omega \sim 16fm \gg L_{fireball}$ Why it is relevant in medium? (PHENIX confirms!)

LPB "vacuum" $\neq$ empty vacuum $=$ coherent state of vacuum mesons Bogoliubov transformation!

Matching on $\zeta \cdot x = 0$

$$\delta(\zeta{\cdot}x)\,[\,A^\mu_{\rm vacuum}(x) - A^\mu_{\rm LPB}(x)\,] = 0$$



Thus to save energy-momentum conservation transmission must be accompanied by reflection back

Conclusions

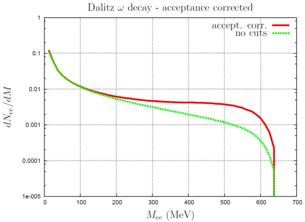
- LPB not forbidden by any physical principle in QCD at finite temperature/density
- The effect leads to unexpected modifications of the in-medium properties of vector mesons and photons
- LPB seems capable of explaining in a natural way the PHENIX 'anomaly'
- *Event-by-event* measurements of the lepton polarization asymmetry may reveal in an unambiguous way the existence of LPB
- Lattice simulations triggered by topological vs. chiral chemical potentials could shed light on the local P-breaking in QCD (work in progress with M. D'Elia, D. Espriu and A. Papa)

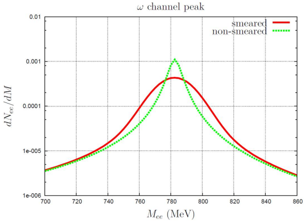
Back up slides

Manifestation of LPB in heavy ion collisions

Acceptance

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





Invariant mass smearing: gaussian with width 10 MeV

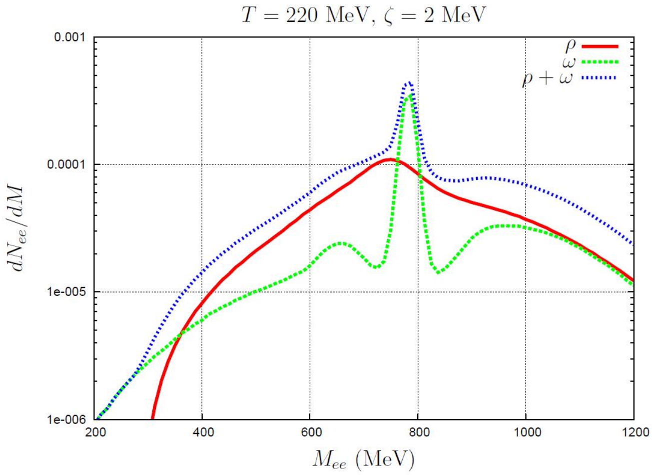
Acceptance correction breaks Lorentz invariance. Phase space calculation becomes a non-trivial task $\Longrightarrow$ VEGAS

Explicit formula for the simulation with acceptance correction:

$$\frac{dN}{d^4x dM} = \int d\tilde{M} \frac{1}{\sqrt{2\pi}\Delta} \exp\left[-\frac{(M-\tilde{M})^2}{2\Delta^2}\right] c_V \frac{\alpha^2}{24\pi\tilde{M}} \left(1 - \frac{n_V^2 m_\pi^2}{\tilde{M}^2}\right)^{3/2}$$
$$\times \sum_\epsilon \int_{\text{acc.}} \frac{k_t dk_t dy d^2\vec{p}_t}{|E_k p_{||} - k_{||} E_p|} \frac{1}{e^{\tilde{M}_t/T} - 1} P_\epsilon^{\mu\nu} \left(\tilde{M}^2 g_{\mu\nu} + 4 p_\mu p_\nu\right)$$
$$\times \frac{m_{V,\epsilon}^4}{\left(\tilde{M}^2 - m_{V,\epsilon}^2\right)^2 + m_{V,\epsilon}^4 \frac{\Gamma_V^2}{m_V^2}}$$

Numerical results for dilepton excess

PHENIX anomaly



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