Flying of vector particles from a parity breaking (Chern-Simons) medium to vacuum and back

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A.A., S.Kolevatov, R.Soldati, JHEP 11 (2011) 007

Outline

- **Maxwell-Chern-Simons Electrodynamics: possible manifestation**
  a. **Large-scale universe or galaxies**: Carroll-Field-Jackiw model (1990) and cosmic birefringence. Spontaneous generation of MCS Electrodynamics by axion condensation, A.A., R.Soldati (1995).
  b. **Parity breaking (PB) in a finite volume**: fireballs in heavy ion collisions with a non-zero topological charge and/or neutral pion condensate, chiral magnetic effect, D.Kharzeev, L. McLerran, A Zhitnitsky, K.Fukushima, H.J.Warringa et al; photons and vector mesons in Chern-Simons constant background; A.A., D.Espriu, V.A.Andrianov et al.
  c. **Compact dense star filled by axions?**
- **Finite volume effects**: passing through and reflecting from a boundary A.A., S.S.Kolevatov, R.Soldati (2011)
- **Quantization**: Bogoliubov transformation from vacuum to parity breaking medium and back.

Massive MCS electrodynamics (CFJ model)

$$\mathcal{L}_{MCS} = -\frac{1}{4} F^{\alpha\beta}(x) F_{\alpha\beta}(x) + \frac{1}{2} m^2 A_\nu(x) A^\nu(x) + \frac{1}{2} \zeta_\mu A_\nu(x) \tilde{F}^{\mu\nu}(x) + \text{g.f.}$$

In momentum space wave Eqs.

$$\begin{cases} \left[g^{\lambda\nu} \left(k^2 - m^2 \right) - k^\lambda k^\nu + i\, \varepsilon^{\lambda\nu\alpha\beta} \zeta_\alpha k_\beta \right] \mathbf{a}_\lambda(k) = 0 \\ k^\lambda \mathbf{a}_\lambda(k) = 0 \end{cases}$$

Projection onto different polarizations with the help of

$$S^\nu_\lambda = \delta^\nu_\lambda \mathtt{D} + k^\nu k_\lambda \zeta^2 + \zeta^\nu \zeta_\lambda k^2 - \zeta \cdot k \left(\zeta_\lambda k^\nu + \zeta^\nu k_\lambda \right); \quad \mathtt{D} \equiv (\zeta \cdot k)^2 - \zeta^2 k^2$$

Transversal polarizations,

$$\boldsymbol{\pi}^{\mu\nu}_\pm \equiv \frac{S^{\mu\nu}}{2\,\mathtt{D}} \pm \frac{i}{2} \varepsilon^{\mu\nu\alpha\beta} \zeta_\alpha k_\beta \mathtt{D}^{-\frac{1}{2}}; \quad \varepsilon^\mu_\pm(k) = \boldsymbol{\pi}^{\mu\lambda}_\pm \epsilon^{(0)}_\lambda$$

Scalar and longitudinal polarizations,

$$\varepsilon^\mu_S(k) \equiv \frac{k^\mu}{\sqrt{k^2}}, \qquad \varepsilon^\mu_L(k) \equiv \left(\mathtt{D}\, k^2 \right)^{-\frac{1}{2}} \left(k^2 \zeta^\mu - k^\mu \zeta \cdot k \right)$$

Transversal polarizations,

$$K^{\mu}_{\nu}\,\varepsilon^{\nu}_{\pm}(k) = \left(k^2 - m^2 \pm \sqrt{\mathrm{D}}\right)\varepsilon^{\mu}_{\pm}(k);$$

$$\omega_{\mathbf{k},\pm} = \begin{cases} \sqrt{\mathbf{k}^2 + m^2 \pm \zeta_0|\,\mathbf{k}\,|}; & \zeta_\mu = (\zeta_0, 0, 0, 0) \\ \sqrt{\mathbf{k}^2 + m^2 + \frac{1}{2}\zeta_x^2 \pm \zeta_x\sqrt{k_1^2 + m^2 + \frac{1}{4}\zeta_x^2}} & \zeta_\mu = (0, -\zeta_x, 0, 0) \end{cases}$$

CFJ model - massless photons: in observations of very remote radio galaxies left-handed and right-handed circular e.m. waves propagate with different velocities. Birefringence!

Polarizations of linearly polarized radio waves could be rotated with distance L!

$$\zeta_0 \ll |\,\mathbf{k} \quad k_\pm \simeq \omega_{\mathbf{k}} \mp \frac{1}{2}\zeta_0; \quad \Delta\phi_{rotation} = \frac{1}{2}(\phi_L - \phi_R) = \frac{1}{2}\zeta L.$$

Distances are of order the Hubble scale $\sim 10^{10}$ l.y. and from the analysis of 160 galaxies with linearly polarized radio waves $\Rightarrow |\zeta| < 10^{-33}\mathrm{eV} \sim 1/R_{Universe}$

Large-scale Universe is not birefringent! (at low energies)

Motivation of local PB

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

- **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, K.Fukushima, H. J. Warringa]

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- *Our special interest*:
  PB background inside a hot dense nuclear fireball in HIC !?

Topological charge

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

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,

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

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

$$\Delta L = \mu_\theta \Delta T_5, \quad \Delta T_5 = T_5(t_f) - T_5(0) = \frac{1}{8\pi^2} \int_0^{t_f} \int_{\text{vol.}} d^3x \text{Tr} \left(G^{\mu\nu} \widetilde{G}_{\mu\nu} \right)$$

in a gauge invariant way.

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**

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

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

Axial chemical potential

Axial 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

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

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

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

- μ_5 is conjugated to (nearly) conserved $\tilde{Q}_5$

Axial chemical potential in hadron Lagrangians

Bosonization of Q_5^q following VMD prescription

$$\mathcal{L}_{\text{int}} = \bar{q}\gamma_\mu \hat{V}^\mu q; \quad \hat{V}_\mu \equiv -eA_\mu Q + \frac{1}{2}g_\omega \omega_\mu \mathbb{I} + \frac{1}{2}g_\rho \rho^0_\mu \tau_3,$$
$$(V_{\mu,a}) \equiv \left(A_\mu,\, \omega_\mu,\, \rho^0_\mu, \phi_\mu\right), \quad g_\omega \simeq g_\rho \equiv g \simeq 6$$

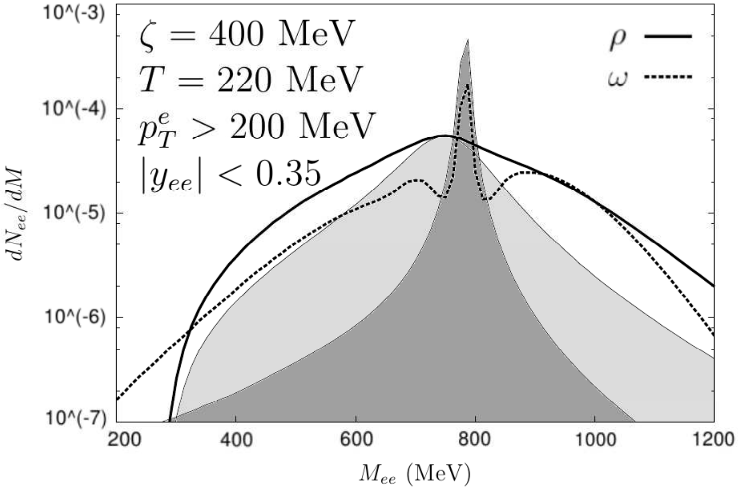
$$\mathcal{L}_{\text{kin}} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} + \rho_{\mu\nu}\rho^{\mu\nu} + \phi_{\mu\nu}\phi^{\mu\nu}\right) + \frac{1}{2}V_{\mu,a}(\hat{m}^2)_{a,b}V_b^\mu$$

P-odd interaction

$$\mathcal{L}_{\text{mix}} \propto -\frac{1}{4}\varepsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\hat{\zeta}_\mu V_\nu V_{\rho\sigma}\right] = \frac{1}{2}\text{Tr}\left(\hat{\zeta}\varepsilon_{jkl}\hat{V}_j\partial_k\hat{V}_l\right) = \frac{1}{2}\zeta\varepsilon_{jkl}V_{j,a}N_{ab}\partial_k V_{l,b}$$

with $\hat{\zeta}_\mu = \hat{\zeta}\delta_{\mu 0}$, spatially homogeneous and isotropic background.

Resonance splitting in polarizations (corrected for PHENIX acceptance)



Finite volume: passing through boundary

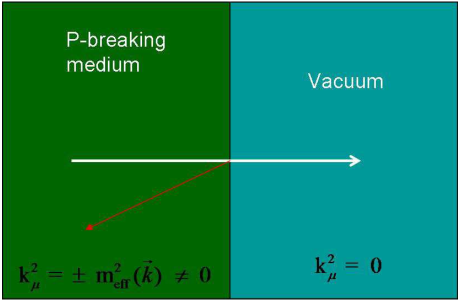
A.A., S.Kolevatov, R.Soldati, JHEP 11 (2011) 007

Mean free paths for vector mesons:

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

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

Matching on $\zeta \cdot x = 0$



Thus to save energy-momentum conservation transmission must be accompanied by reflection back. Enhancement of in-medium decays of ω mesons!

MCS electrodynamics in a half space

A possible gauge-invariant choice,

$$-\frac{1}{4}\,F^{\mu\nu}(x)\widetilde{F}_{\mu\nu}(x)\,\zeta_\lambda x^\lambda\,\theta(-\,\zeta\cdot x) \Rightarrow \frac{1}{2}\,\zeta_\mu A_\nu(x)\widetilde{F}^{\mu\nu}(x)\,\theta(-\,\zeta\cdot x),$$

which however associates a space-like boundary with a space-like CS vector $(\zeta_\mu)(x) = \zeta(0,\vec{a})\theta(-\,\vec{a}\cdot\vec{x}), \quad |\vec{a}| = 1$.

Compact dense stars filled by axions with density degrading to their surface?!

Another choice: time-like CS vector and space-like boundary $(\zeta_\mu)(x) = \zeta\big(\theta(-\,\vec{a}\cdot\vec{x}), -\vec{a}x_0\delta(-\,\vec{a}\cdot\vec{x})\big)$ gauge invariance condition $\partial_\nu\zeta_\mu = \partial_\mu\zeta_\nu$. Singular interaction on a space-like boundary!

Axial chemical potential for a fireball

$\star\ \star\ \star\ \star\ \star\star$

Matching on the boundary $\zeta\cdot x = 0$

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

Classical solutions

Spatial Chern-Simons vector $\zeta_\mu = (0, -\zeta_x, 0, 0)$ and orthogonal planes $\hat{k} = (\omega, k_2, k_3)$, $\hat{x} = (x_0, x_2, x_3)$
In the entire space,

$$A_1 = \int \frac{d^3\hat{k}}{(2\pi)^3}\, \theta(\omega^2 - k_\perp^2 - m^2)\, (\tilde{u}_{1\rightarrow}(\omega, k_2, k_3) e^{ik_{10}x_1} + \tilde{u}_{1\leftarrow}(\omega, k_2, k_3) e^{-ik_{10}x_1}) e^{i\hat{k}\hat{x}}$$

where $\quad k_{10}^2 = \omega^2 - m^2 - k_\perp^2,\ k_\perp^2 = k_2^2 + k_3^2$
Two solutions for other components in the different half-spaces taken both on entire axis.
For $x_1 > 0$ $(\nu = 0, 2, 3)$

$$A_\nu = \int \frac{\mathrm{d}^3\hat{k}}{(2\pi)^3}\, \theta(\omega^2 - k_\perp^2 - m^2)\, (\tilde{u}_{\nu\rightarrow}(\omega, k_2, k_3) e^{ik_{10}x_1} + \tilde{u}_{\nu\leftarrow}(\omega, k_2, k_3) e^{-ik_{10}x_1}) e^{i\hat{k}\hat{x}}$$

Arrows $\rightarrow$, $\leftarrow$ for directions of particle propagation.
For $x_1 < 0$ $(A = L, \pm$ eigenstates of suitable polarizations)

$$\tilde{A}_\nu = \sum_A [\tilde{v}_{\nu A\rightarrow}(k_2, k_3, \omega)\delta(k_1 - k_{1A}) + \tilde{v}_{\nu A\leftarrow}(k_2, k_3, \omega)\delta(k_1 + k_{1A})]$$

MCS dispersion laws and polarizations

The MCS dispersion laws for different polarizations,

$$\begin{cases} k_{1L} = k_{10} = \sqrt{\omega^2 - m^2 - k_\perp^2} \\ k_{1+} = \sqrt{\omega^2 - m^2 - k_\perp^2 + \zeta_x \sqrt{\omega^2 - k_\perp^2}} \\ k_{1-} = \sqrt{\omega^2 - m^2 - k_\perp^2 - \zeta_x \sqrt{\omega^2 - k_\perp^2}} \end{cases}$$

Matching on boundary

Matching,

$$\begin{cases} -k_{10}^2(-\frac{\tilde{u}_{0\rightarrow}-\tilde{u}_{0\leftarrow}}{ik_{10}}+\sum_A \frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}}) = i\zeta_x(k_2\sum_A \frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}} - k_3\sum_A \frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}}) \\ -k_{10}^2(-\frac{\tilde{u}_{2\rightarrow}-\tilde{u}_{2\leftarrow}}{ik_{10}}+\sum_A \frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}}) = -i\zeta_x(k_3\sum_A \frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}} + \omega\sum_A \frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}}) \\ -k_{10}^2(-\frac{\tilde{u}_{3\rightarrow}-\tilde{u}_{3\leftarrow}}{ik_{10}}+\sum_A \frac{\tilde{v}_{3A\rightarrow}-\tilde{v}_{3A\leftarrow}}{ik_{1A}}) = i\zeta_x(\omega\sum_A \frac{\tilde{v}_{2A\rightarrow}-\tilde{v}_{2A\leftarrow}}{ik_{1A}} + k_2\sum_A \frac{\tilde{v}_{0A\rightarrow}-\tilde{v}_{0A\leftarrow}}{ik_{1A}}) \end{cases}$$

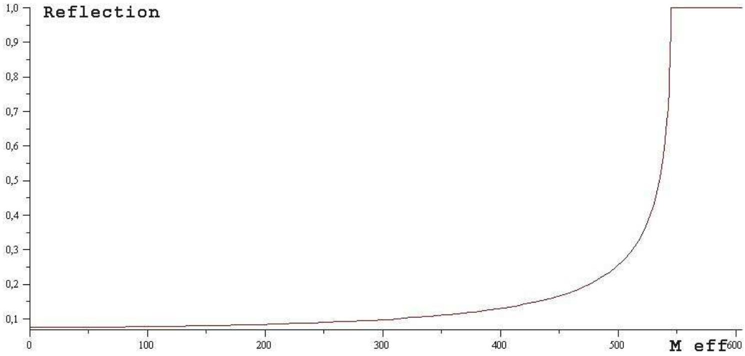
Continuity of A,

$$\begin{aligned} \tilde{u}^{(L)}_{\nu\rightarrow} + \tilde{u}^{(L)}_{\nu\leftarrow} &= \tilde{v}_{\nu L\rightarrow} + \tilde{v}_{\nu L\leftarrow} \\ \tilde{u}^{(+)}_{\nu\rightarrow} + \tilde{u}^{(+)}_{\nu\leftarrow} &= \tilde{v}_{\nu+\rightarrow} + \tilde{v}_{\nu+\leftarrow} \\ \tilde{u}^{(-)}_{\nu\rightarrow} + \tilde{u}^{(-)}_{\nu\leftarrow} &= \tilde{v}_{\nu-\rightarrow} + \tilde{v}_{\nu-\leftarrow} \end{aligned}$$

Final relations

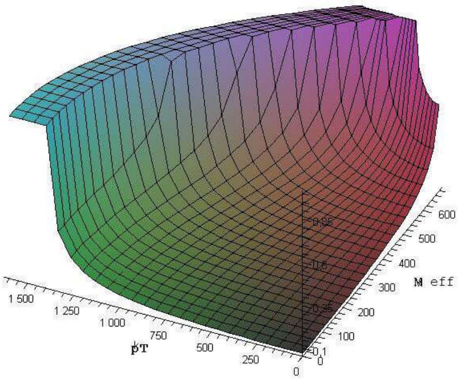
$$\begin{aligned} \tilde{u}^{(A)}_{\nu\rightarrow} &= \frac{1}{2}(\tilde{v}_{\nu A\rightarrow}(\frac{k_{1A}+k_{10}}{k_{10}}) - \tilde{v}_{\nu A\leftarrow}(\frac{k_{1A}-k_{10}}{k_{10}})) \\ \tilde{u}^{(A)}_{\nu\leftarrow} &= \frac{1}{2}(-\tilde{v}_{\nu A\rightarrow}(\frac{k_{1A}-k_{10}}{k_{10}}) + \tilde{v}_{\nu A\leftarrow}(\frac{k_{1A}+k_{10}}{k_{10}})) \end{aligned}$$

Reflection from boundary depending on effective mass: negative chirality

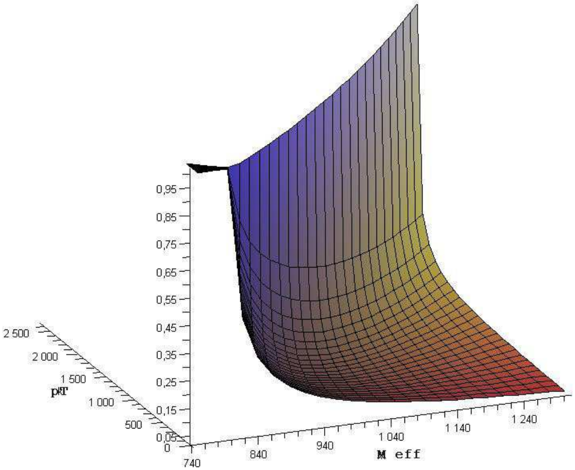


Dependence on effective mass for zero p_T, CS vector $\zeta = 400$ MeV

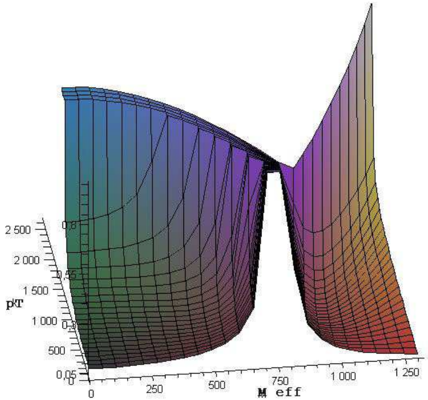
Reflection from boundary: negative chirality, $p_T \neq 0$



Reflection from boundary: positive chirality, $p_T \neq 0$



Reflection from boundary: both chiralities, $p_T \neq 0$



Quantization of MCS in a half-space: Bogolyubov transformation

In vacuum,

$$A^{\mu}_{\rm vacuum}(x) = \int \mathrm{d}^3\hat{k}\,\theta(\omega^2 - k_\perp^2 - m^2)\sum_{r=1}^{3}\left[\mathbf{a}_{\hat{k},r}\,u^{\mu}_{\hat{k},r}(x) + \mathbf{a}^{\dagger}_{\hat{k},r}\,u^{\mu\,*}_{\hat{k},r}(x)\right],$$

Canonical commutation relations $[\mathbf{a}_{\hat{k},r}, \mathbf{a}^{\dagger}_{\hat{k}',s}] = \delta(\hat{k} - \hat{k}')\,\delta_{rs}$

In P-breaking medium ($A \in \{L, +, -\}$),

$$A^{\nu}_{\rm MCS}(x) = \int \mathrm{d}^3\hat{k}\,\theta(\omega^2 - k_\perp^2 - m^2)\sum_{A}\left[c_{\hat{k},A}\,v^{\nu}_{\hat{k}\,A}(x) + c^{\dagger}_{\hat{k},A}\,v^{\nu *}_{\hat{k}\,A}(x)\right]$$

Canonical commutation relations, $\left[c_{\hat{k},A}, c^{\dagger}_{\hat{k}',A'}\right] = -g_{AA'}\,\delta(\hat{k} - \hat{k}')$

Matching,

$$v^{\nu}_{\hat{k},A}(\hat{x}) = \sum_{s=1}^{3}\left[\alpha_{sA}(\hat{k})\,u^{\nu}_{\hat{k},s}(\hat{x}) - \beta_{sA}(\hat{k})\,u^{\nu *}_{\hat{k},s}(\hat{x})\right]$$

Bogoliubov transformation

$$\mathbf{a}_{\hat{k},r} = \sum_{A=\pm,L}\left[\alpha_{rA}(\hat{k})\,c_{\hat{k},A} - \beta^{*}_{rA}(\hat{k})\,c^{\dagger}_{\hat{k},A}\right] \quad c_{\hat{k},A} = \sum_{r=1}^{3}\left[\alpha^{*}_{Ar}(\hat{k})\,\mathbf{a}_{\hat{k},r} + \beta^{*}_{Ar}(\hat{k})\,\mathbf{a}^{\dagger}_{\hat{k},r}\right]$$

Vacuums as coherent states

Two different Fock vacua

$$\mathbf{a}_{\hat{k},\,r}|0\rangle = 0 \qquad c_{\hat{k},A}\,|\,\Omega\,\rangle = 0$$

From Bogoliubov tranformation,

$$|0\rangle = \mathcal{N}\exp\Bigg[\int \mathrm{d}^3\hat{k}\,\theta(\omega^2 - k_\perp^2 - m^2)\times$$
$$\times\left\{\frac{\beta^*_{r+}(\hat{k})}{2\alpha_{r+}(\hat{k})}(c^{\dagger}_{\hat{k},+})^2 + \frac{\beta^*_{r-}(\hat{k})}{2\alpha_{r-}(\hat{k})}(c^{\dagger}_{\hat{k},-})^2 + \frac{\beta^*_{rL}(\hat{k})}{2\alpha_{rL}(\hat{k})}(c^{\dagger}_{\hat{k},L})^2\right\}\Bigg]\;|\,\Omega\,\rangle$$

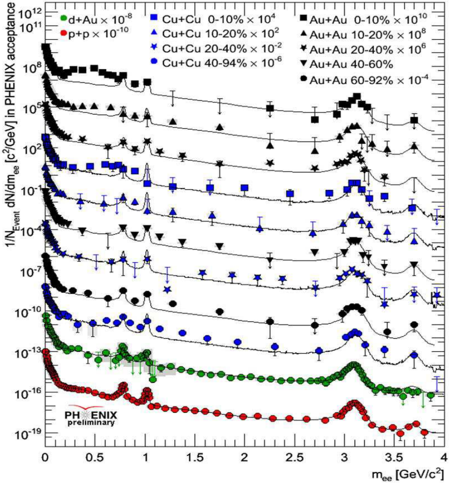
and inversely

$$|\,\Omega\,\rangle = \tilde{\mathcal{N}}\exp\Bigg[\int \mathrm{d}^3\hat{k}\,\theta(\omega^2 - k_\perp^2 - m^2)\times$$
$$\times\left\{\frac{-\beta^*_{A1}(\hat{k})}{2\alpha^*_{A1}(\hat{k})}(\mathbf{a}^{\dagger}_{\hat{k},\,1})^2 + \frac{-\beta^*_{A2}(\hat{k})}{2\alpha^*_{A2}(\hat{k})}(\mathbf{a}^{\dagger}_{\hat{k},\,2})^2 + \frac{-\beta^*_{A3}(\hat{k})}{2\alpha^*_{A3}(\hat{k})}(\mathbf{a}^{\dagger}_{\hat{k},\,3})^2]\right\}\Bigg]\;|0\rangle$$

Conclusions

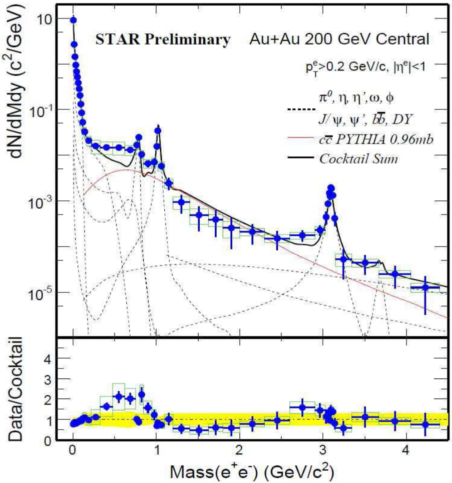
- Local (finite-volume) PB is not forbidden by any physical principle in QCD at finite temperature/density
- The effect leads to unexpected modifications of the in-medium properties of vector mesons and photons
- LPB seems to be capable of explaining in a natural way the PHENIX 'anomaly'
- Boundary enhancement of in-medium ω decays + LPB $\rightarrow$ broadening of ω resonance in fireballs (observed on PHENIX!)
- Axion stars discovery from exotic photon spectra (boundary effects)??

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



Hint to LPB? [PHENIX Data Plot (id p1147) 2011]

STAR anomaly: abnormal e^+e^- excess in central HIC at low p_t



Hint to LPB? [STAR Collaboration, J.Phys.G G38 (2011) 124134]

Resonance splitting in polarizations (corrected for PHENIX acceptance)