QCD with chiral imbalance: models vs. lattice

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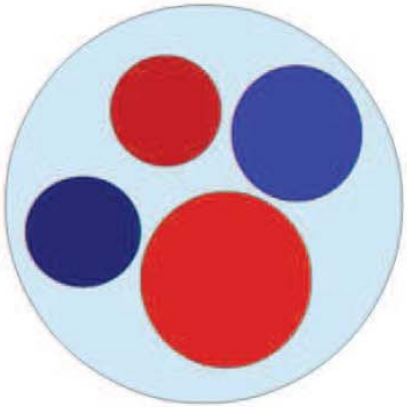
Outline of the talk

(Local) Chiral Imbalance in QCD =
different densities of left (anti)quarks and right (anti)quarks
in a particular region

1. Where does chiral imbalance appear?
2. Topological charge $\longleftrightarrow$ axial (chiral) charge:
   topological $\longleftrightarrow$ chiral chemical potentials
3. Phenomenology of chiral imbalance in QGP
4. Chiral imbalance in hadronic phase: influence on chiral symmetry breaking (*on chiral condensates*)
5. Observables sensitive to chiral imbalance: new states in scalar, pseudoscalar, vector meson spectra

Topological charge and topological chemical potential



In hot QCD (in heavy ion collisions) a metastable topological charge $\langle T_5 \rangle$ may arise in a finite volume due to sphaleron transitions [McLerran, Rubakov, Shaposhnikov,. . . , Moore]

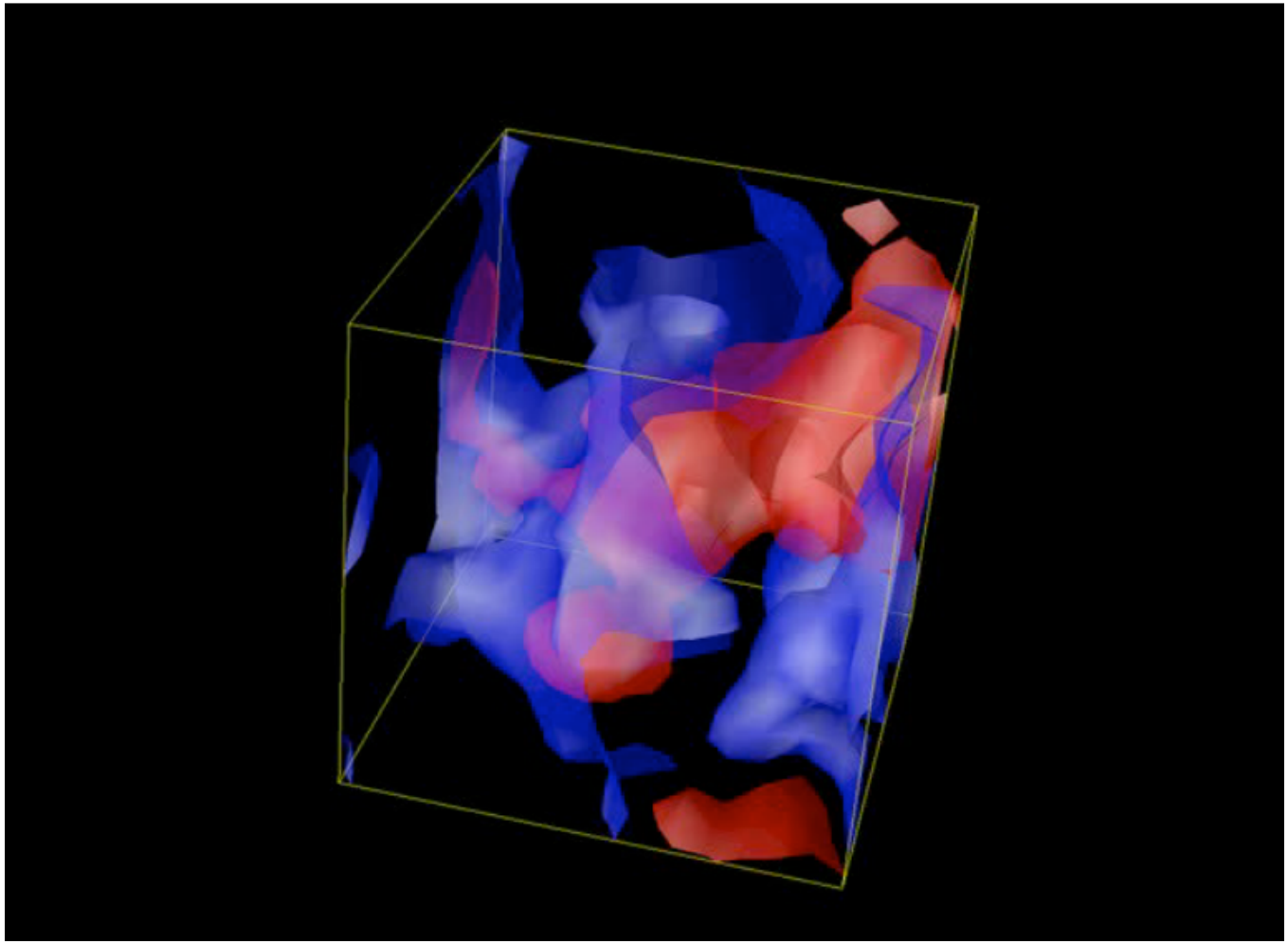
$$T_5 = \frac{1}{8\pi^2} \int_{\text{vol.}} d^3x \varepsilon_{jkl} \text{Tr} \left(G^j \partial^k G^l - i \frac{2}{3} G^j G^k G^l \right)$$

it may survive for a sizeable lifetime in a heavy-ion fireball

$$\langle \Delta T_5 \rangle \neq 0 \quad \text{for} \quad \Delta t \simeq \tau_{\text{fireball}} \simeq 5 \div 10 \text{ fm/c};$$

[$= 7 \pm 1$ fm/c, van Hees – Rapp for Au-Au PHENIX, LHC?,]

Topological charge fluctuations



Red - positive charge
Blue - negative charge

From: P.V.Buividovich, T.Kalaydzhyan and M.I.Polikarpov, Phys. Rev. D86, 074511 (2012)

Local Parity Breaking in QCD

Metastable bubbles due to Sphalerons?

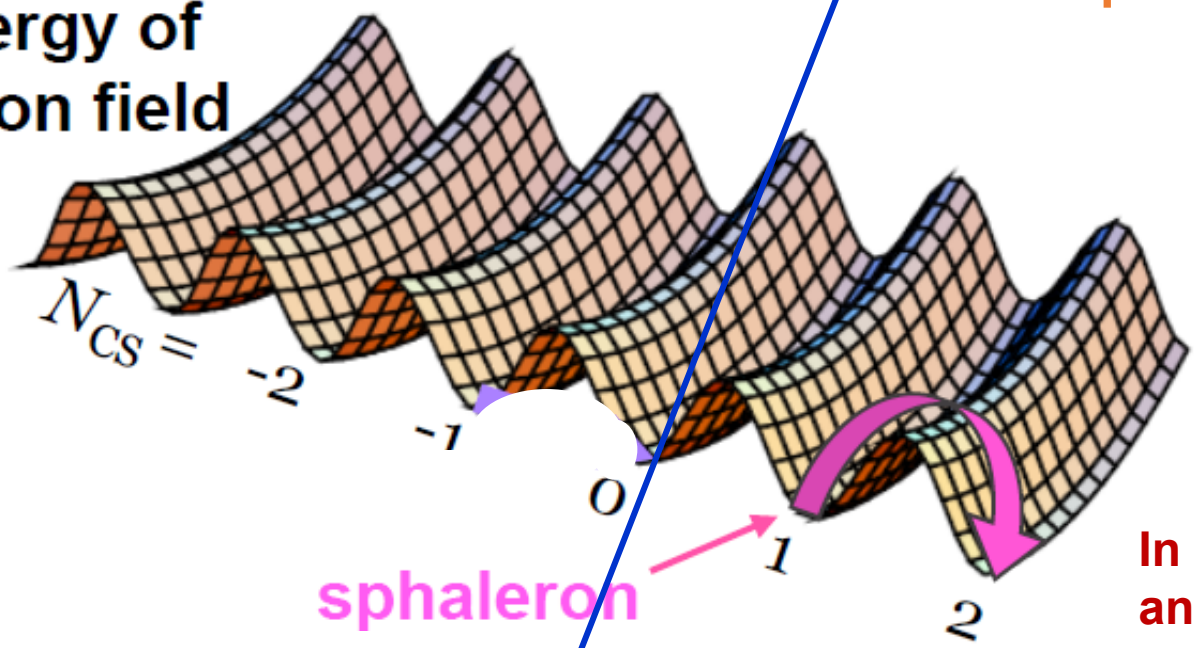
Manton, McLerran, Rubakov, Shaposhnikov,Shuryak…

$V \to \infty$?? boundaries!!

Rate $$\Gamma = \frac{1}{2} \lim_{t\to\infty} \lim_{V\to\infty} \int_0^t \langle (q(x)q(0) + q(0)q(x)) \rangle d^4x$$

Top. charge density

Energy of gluon field



sphaleron

In HIC finite time and size!

Topological charge

$$\langle T_5^2 \rangle = 2\Gamma V t, \quad t \to \infty$$

Phenomenology of local parity breaking

Local large fluctuations in the topological charge presumably exist in a hot environment.

- For *peripheral* heavy ion collisions they lead to the Chiral Magnetic Effect (CME): Large $\vec{B} \Rightarrow$ large $\vec{E} \Rightarrow$ charge separation.

  D. Kharzeev, R. D. Pisarski & M. H. G. Tytgat, Phys. Rev. Lett. 81, 512 (1998)

  D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A 803, 227 (2008)

  D. E. Kharzeev, **talk on this conference**

- For *central* collisions (and light quarks) they correspond to a phase with axial chemical potential $\mu_5 \neq 0$ located in "fluctons" of few-Fermi size. **(the subject of this talk)**

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

The two effects are complementary!

Axial baryon charge and axial chemical potential

For the fireball lifetime one can trigger the value of $\langle \Delta T_5 \rangle \neq 0$ introducing into the QCD Lagrangian a topological chemical potential μ_θ in a gauge invariant way via $\Delta \mathcal{L}_{top} = \mu_\theta \Delta T_5$, where

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

$$= \frac{1}{2\pi^2} \int_0^{t_f} dt \int_{\text{vol.}} d^3x \partial_\mu K^\mu,$$

PROVIDED THAT the flows through the boundary are negligible

$$\int_{\text{boundary}} d^2\vec{s} \cdot \vec{J_5} \simeq 0 \simeq \int_{\text{boundary}} d^2\vec{s} \cdot \vec{K}$$

that is a filter condition for relevant events = metastability of a fireball.
Topological current

$$K^\mu = \frac{1}{2} \epsilon^{\mu\nu\sigma\rho} \text{Tr} \left(G_\nu \partial_\sigma G_\rho - i \frac{2}{3} G_\nu G_\sigma G_\rho \right)$$

Axial baryon charge and axial chemical potential

The exact law in QCD, the partial conservation of axial current (broken by gluon anomaly)

$$\partial_\mu J_5^\mu - 2im_q J_5 = \frac{N_f}{2\pi^2}\partial_\mu K^\mu$$

predicts the induced axial charge (for small quark masses $m_q \simeq 0$)

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

to be conserved during $\tau_{fireball}$.

Axial baryon charge and axial chemical potential

The characteristic left-right oscillation time is governed by inverse quark masses.

- For u, d quarks $1/m_q \sim 1/5$ MeV^{-1} ~ 40 fm $\gg \tau_{\text{fireball}}$ and the left-right quark mixing can be neglected.
- For s quark $1/m_s \sim 1/150$ MeV^{-1} ~ 1 fm $\ll \tau_{\text{fireball}}$ and $\langle Q_5^s \rangle \simeq 0$ due to left-right oscillations.

For u, d quarks QCD with a topological charge $\langle \Delta T_5 \rangle \neq 0$ can be equally described at the Lagrangian level by topological chemical potential μ_θ or by axial chemical potential μ_5

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

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

Effective meson theory in a medium with LPB

- Scalar (and pseudoscalar) mesons

The scalar sector can be estimated by using the spurion technique in the chiral Lagrangian

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

Similar to isospin chemical potential!

- Vector mesons

Low energy QCD can be described by Vector Meson Dominance. In this framework, the following term appears

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

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

Two different cases of isospin structure for μ_5:

- Isosinglet pseudoscalar background ($T \gg \mu$) [RHIC, LHC]
- Pion-like (isotriplet) background (not considered) ($\mu \gg T$) [FAIR, NICA]

Effective scalar/pseudosalar meson theory with μ_5

Effective Lagrangian:

$$\mathcal{L} = \frac{1}{4}\mathrm{Tr}\left(D_\mu H D^\mu H^\dagger\right) + \frac{b}{2}\mathrm{Tr}\left[M(H+H^\dagger)\right] + \frac{M^2}{2}\mathrm{Tr}\left(HH^\dagger\right)$$
$$-\frac{\lambda_1}{2}\mathrm{Tr}\left[(HH^\dagger)^2\right] - \frac{\lambda_2}{4}\left[\mathrm{Tr}\left(HH^\dagger\right)\right]^2 + \frac{c}{2}(\det H + \det H^\dagger)$$
$$+\frac{d_1}{2}\mathrm{Tr}\left[M(HH^\dagger H + H^\dagger HH^\dagger)\right] + \frac{d_2}{2}\mathrm{Tr}\left[M(H+H^\dagger)\right]\mathrm{Tr}\left(HH^\dagger\right)$$

where

$$H = \xi\Sigma\xi, \quad \xi = \exp\left(i\frac{\Phi}{2f}\right), \quad \Phi = \lambda^a\phi^a, \quad \Sigma = \lambda^b\sigma^b.$$

The v.e.v. of the neutral scalars are defined as $v_i = \langle\Sigma_{ii}\rangle$ where $i = u, d, s$, and satisfy the following gap equations:

$$M^2 v_i - 2\lambda_1 v_i^3 - \lambda_2 \vec{v}^2 v_i + c\frac{v_u v_d v_s}{v_i} = 0.$$

Multiplets under consideration

$$\Phi = \begin{pmatrix} \eta_q + \pi^0 & \sqrt{2}\pi^+ & 0 \\ \sqrt{2}\pi^- & \eta_q - \pi^0 & 0 \\ 0 & 0 & \sqrt{2}\eta_s \end{pmatrix}, \Sigma = \begin{pmatrix} v_u + \sigma + a_0^0 & \sqrt{2}a_0^+ & 0 \\ \sqrt{2}a_0^- & v_d + \sigma - a_0^0 & 0 \\ 0 & 0 & v_s \end{pmatrix}$$

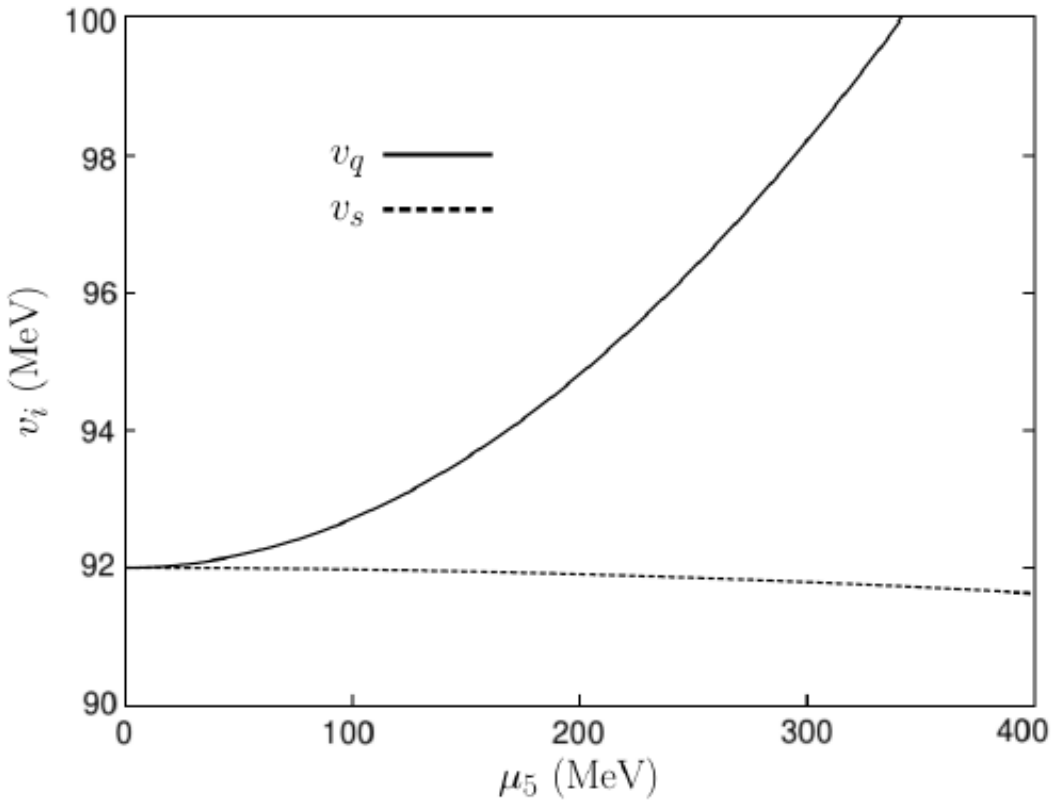
$$\begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix} \begin{pmatrix} \eta \\ \eta' \end{pmatrix}$$

For $\mu_5 = 0$, we assume $v_u = v_d = v_s = v_0 \equiv f_\pi \approx 92$ MeV.

Weak decay constants ~ dynamic masses ~ condensates

$$v_q^2 = \frac{2\mu_5^2 + M^2 + \frac{c^2}{4\lambda^2}}{2(\lambda_1 + \lambda_2)} + O(1/\mu_5^2),$$

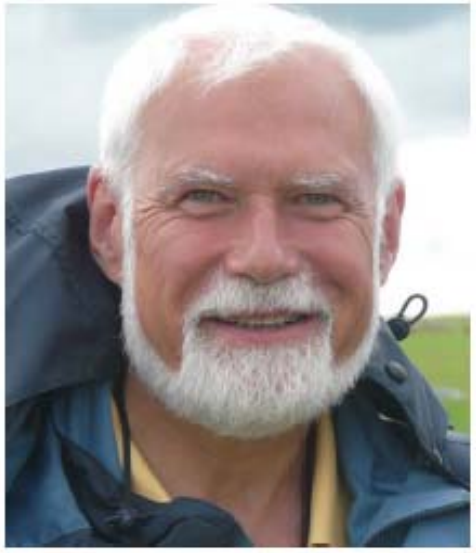
$$v_s = \frac{c}{2\lambda_2} + O(1/\mu_5^2)$$



v_q and v_s dependence on μ_5

From: **A.A.Andrianov, D.Espriu and X.Planells, Eur. Phys. J. C73, 2294 (2013)**

Lattice for condensates



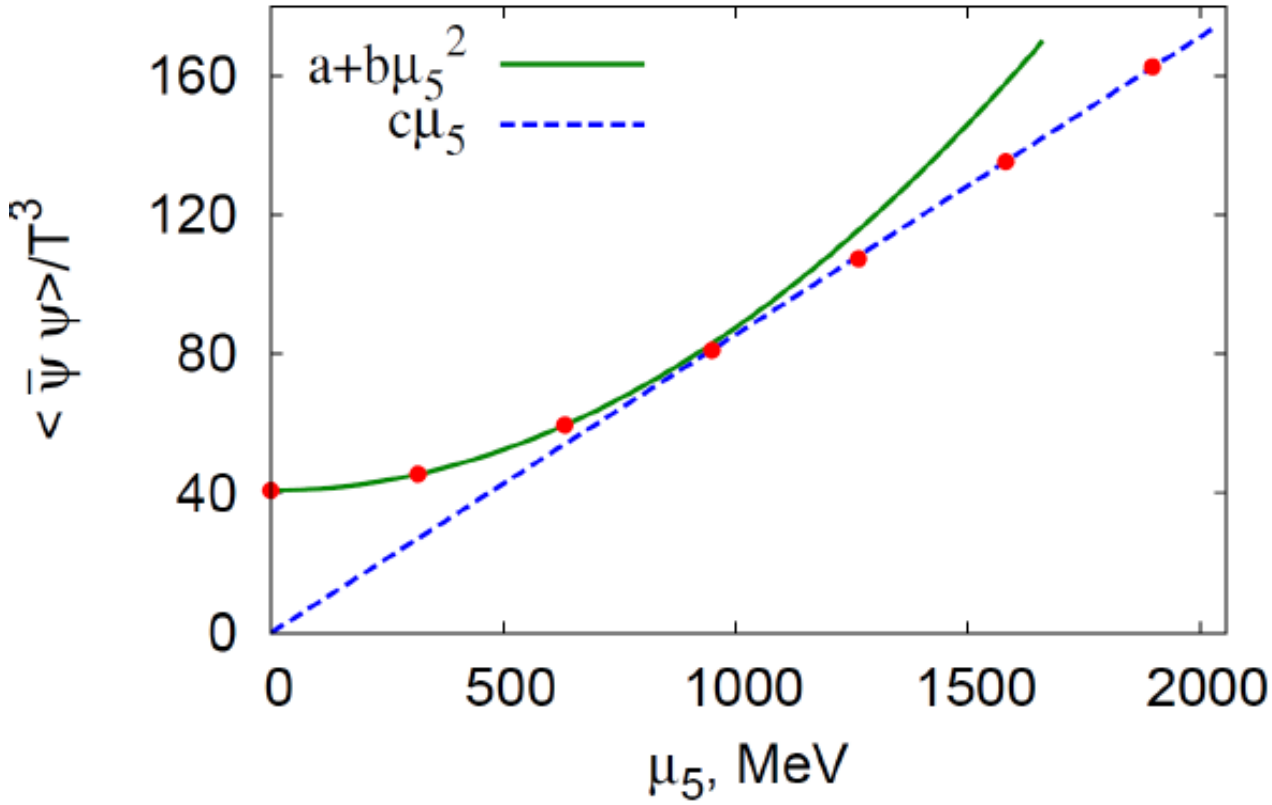


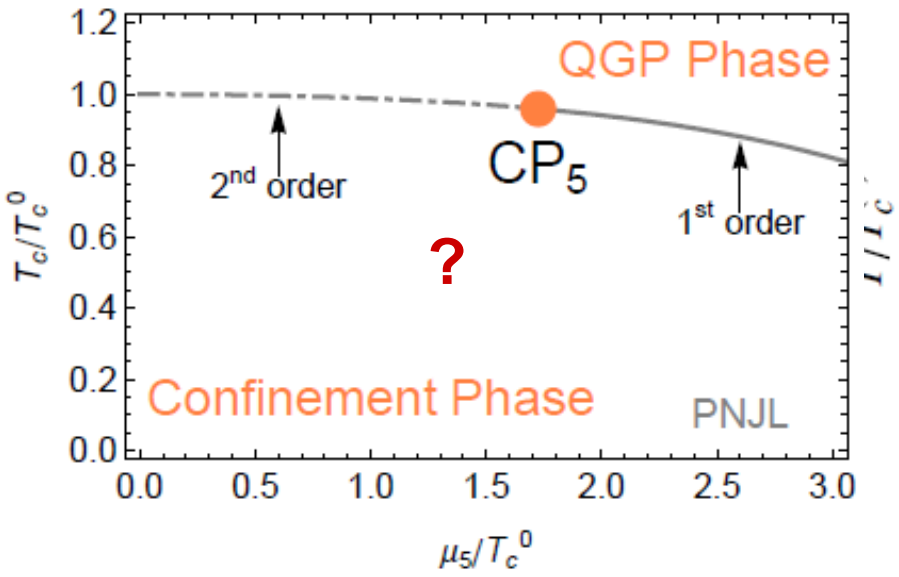
FIG. 1. Chiral condensate as a function of μ_5 in the confinement phase ($T = 158$ MeV).

V. V. Braguta, V. A. Goy, E.-M. Ilgenfritz, A. Y. Kotov, A. V. Molochkov, M. Muller-Preussker, and B. Petersson, J. High Energy Phys. 06 (2015) 094.

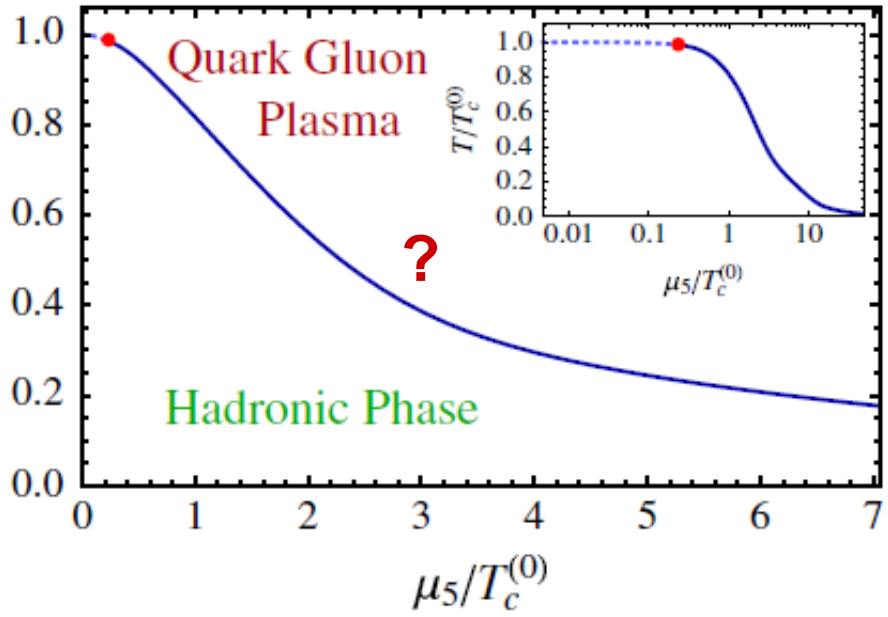
V.V.Braguta and A.Y.Kotov, Phys. Rev. D 93, 105025 (2016)

Critical temperatures in quark models of (P)NJL type: do they reveal critical end points?

M.R.Ruggieri, Phys.Rev.D84, 014011 (2011)



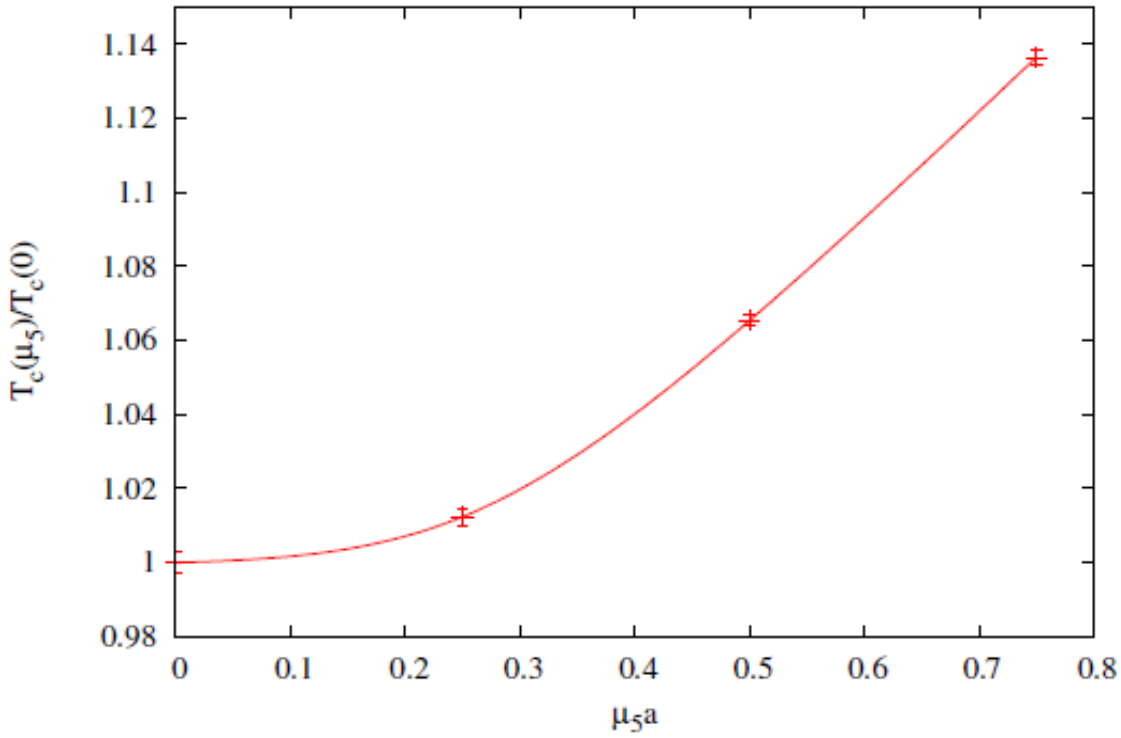
M.N.Chernodub and A.S.Nedelin, Phys. Rev. D 83, 105008 (2011)



! There is **no CP5 on the divide line induced by** μ_5 **in EFT and lattice**

Rising critical temperature (lattice)

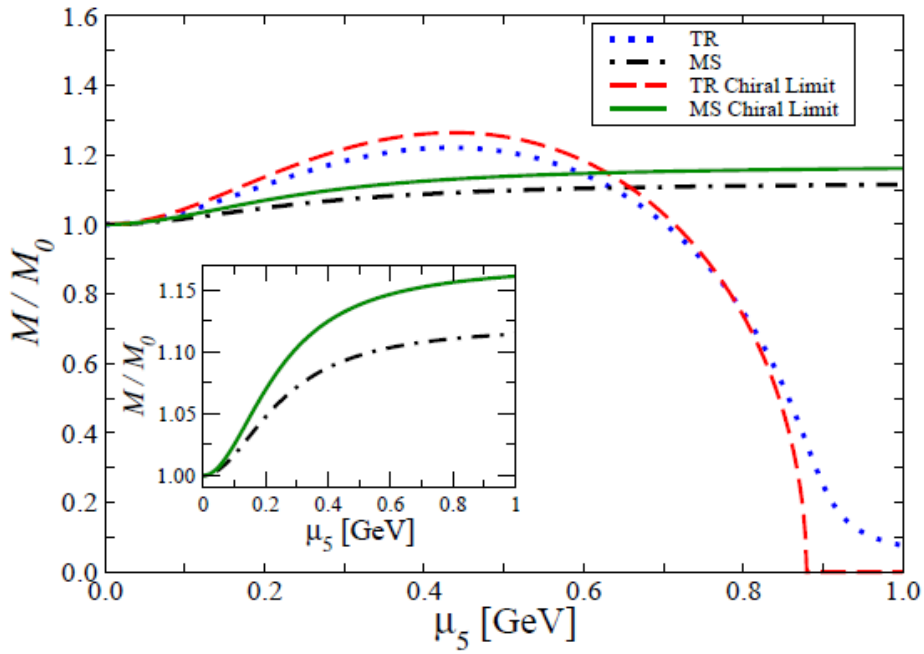
Wilson fermions to introduce the chiral chemical potential in a local exponential form



V.V.Braguta, E.M.Ilgenfritz, A.Y.Kotov, B.Petersson and S.A.Skinderev
Phys. Rev. D 93, no. 3, 034509 (2016)

V.Braguta, talk on this conference

NJL prediction (appropriate regularization)



TR= traditional regularization

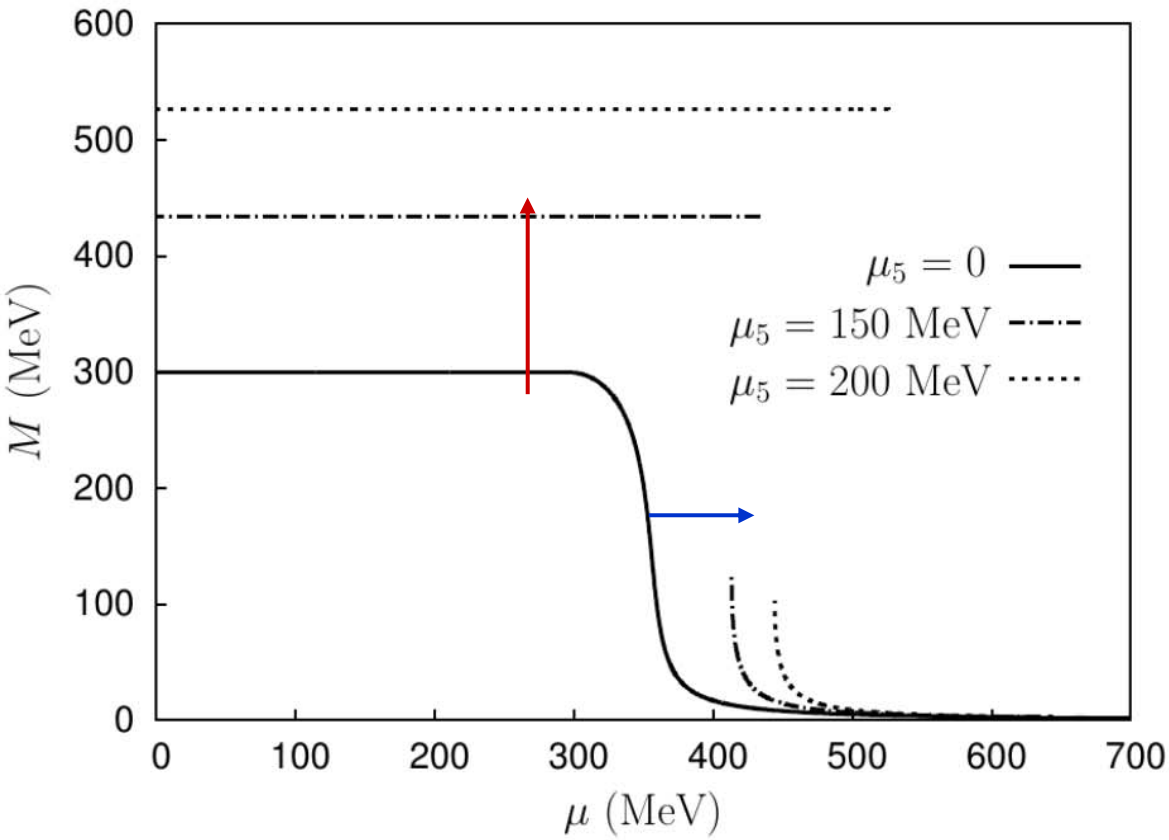
MS= medium separation scheme

The zero temperature quark mass M, normalized by its respective vacuum value M_0, as a function of chiral chemical potential μ_5. The results obtained using the TR scheme are given by the dashed (chiral limit) and dotted lines. In the MS scheme the results are given by the solid (chiral limit, $m_c = 0$) and dash-dotted lines.

From: **R.L.S.Farias, D.C.Duarte, G.Krein and R.O.Ramos, 1604.04518**

See also **M.Ruggieri and G.X.Peng, 1602.03651**

NJL models with chiral and baryon chemical potentials



Evolution of the constituent quark mass M depending on μ for different values of the axial chemical potential μ_5 setting $m = -5$ MeV, $G_1 = -40/\Lambda^2$ and $G_2 = -45/\Lambda^2$. The drawn lines correspond to locally stable phases and accordingly the absence of a continuous line in the cases where $\mu_5 \neq 0$ is due to the fact that the Hessian matrix is not positive definite. The transition to a chirally restored phase changes to a first order one as μ_5 increases.

From: **A.A.Andrianov, D.Espriu and X.Planells, Eur.Phys. J. C 74, 2776 (2014)**

Scalar/pseudoscalar sector with chiral chemical potential

As already stressed, in the scalar sector we use the spurion technique (μ_5 as the time component of some external axial-vector field) in the chiral Lagrangian with an isosinglet μ_5

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

Two new processes are likely to appear inside the fireball: the decays $\eta, \eta' \to \pi\pi$ that are strictly forbidden in QCD on parity grounds.

$$\mathcal{L}_{\eta\pi\pi} \sim \frac{16\mu_5}{F_\eta f_\pi^2} L\, \partial\eta\, \partial\pi \partial\pi,$$

where $L \sim 10^{-3}$ strong dependence on μ_5 as $\Gamma_{\eta\to\pi\pi} \propto \mu_5^2$

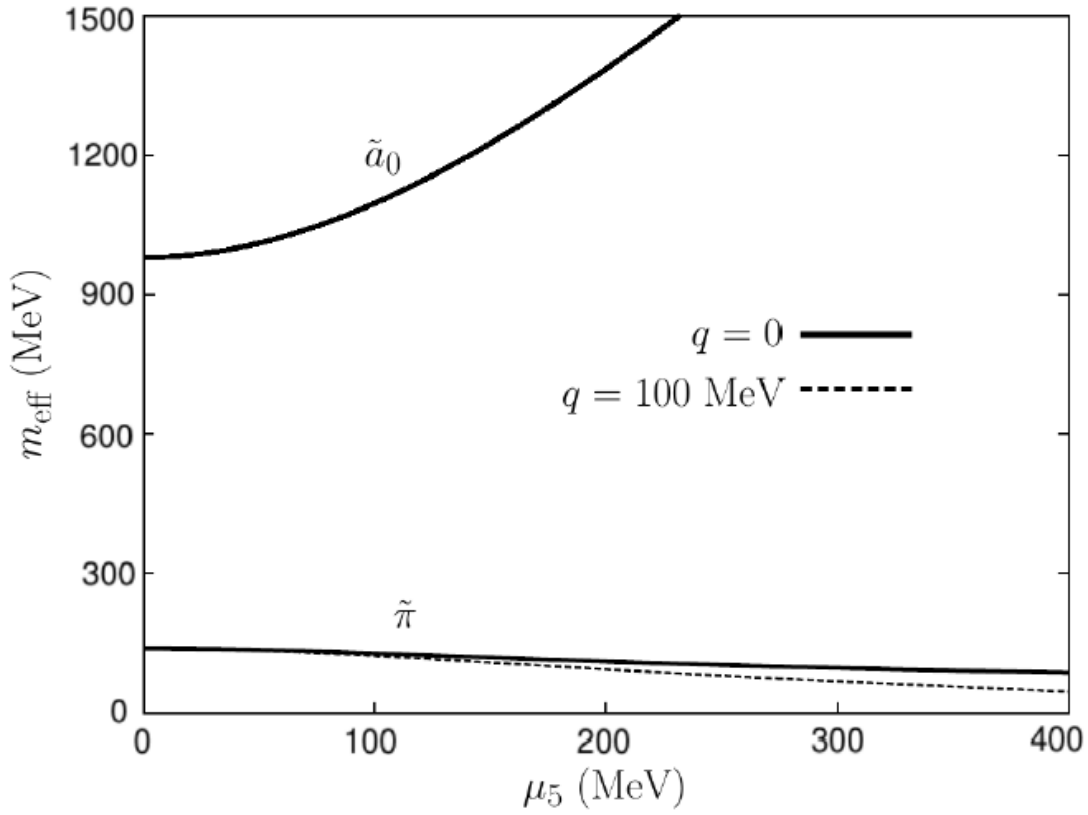
More details in

A.A.Andrianov, D.Espriu and X.Planells, Eur. Phys. J. C73 (2013) 1, 2294

New eigenstates of strong interactions with LPB (isotriplet)

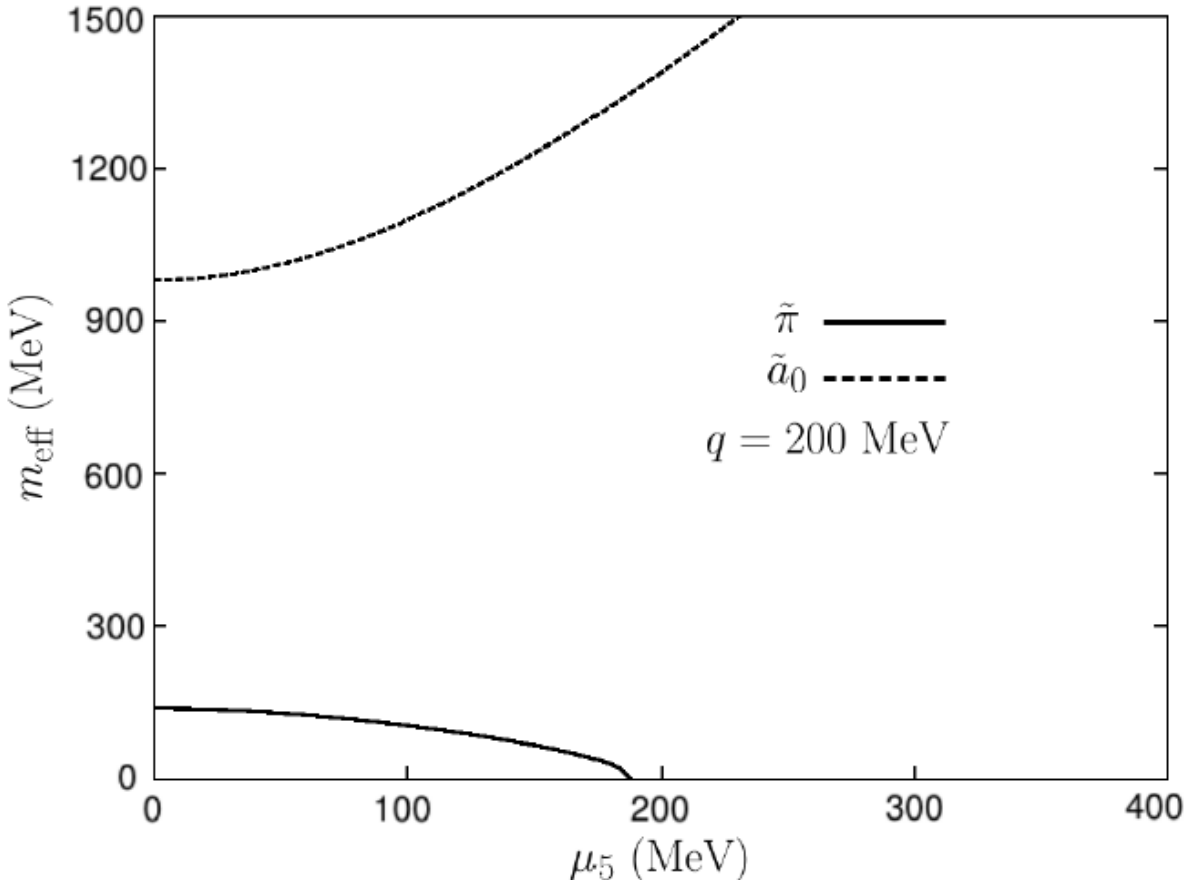
$$\mathcal{L} = \frac{1}{2}(\partial a_0)^2 + \frac{1}{2}(\partial \pi)^2 - \frac{1}{2}m_1^2 a_0^2 - \frac{1}{2}m_2^2 \pi^2 - 4\mu_5 a_0 \dot{\pi},$$

New eigenstates $\tilde{\pi}$ and $\tilde{a}_0$



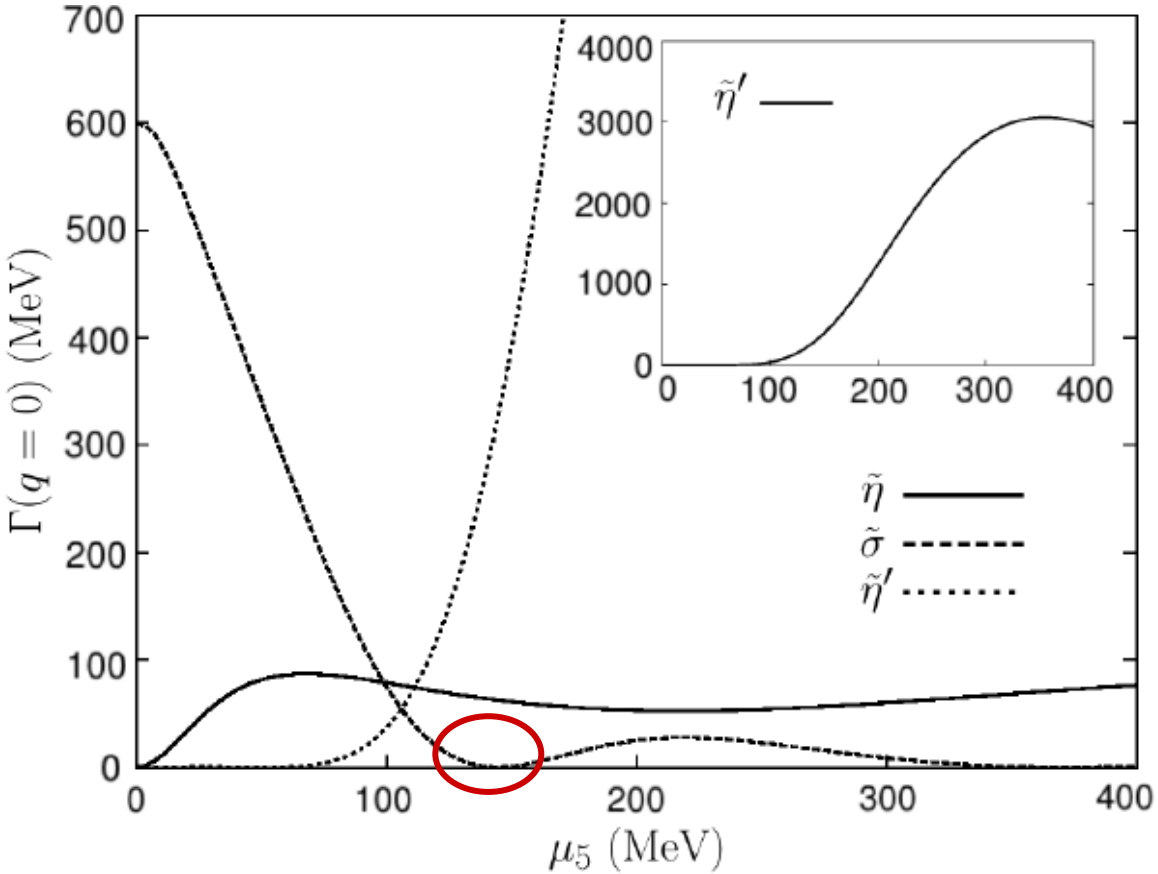
Effective mass in flight

For high energies $k_0, |\vec{k}| > m_1 m_2/(4\mu_5) \equiv k^c_{\tilde{\pi}}$, in-medium $\tilde{\pi}$ goes tachyonic. Nevertheless, energies are always positive (no vacuum instabilities). Group velocities < c



Decay widths (at rest)

$\tilde{\eta}$ exhibits a smooth behaviour with $\langle \Gamma_{\tilde{\eta}} \rangle \sim 60$ MeV $\leftrightarrow$ mean free path ~ 3 fm $\lesssim L_{\text{fireball}} \sim 5 \div 10$ fm. Possible thermalization! Down to $\mu_5 \sim 100$ MeV, $\tilde{\sigma}$ width decreases and becomes stable.



Axial charge + photons $\longrightarrow$ vector mesons

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

- e.m. interaction implies

$$Q_5^q \to \tilde{Q}_5 = Q_5^q - T_5^{\text{em}}, \quad T_5^{\text{em}} = \frac{N_c}{8\pi^2} \int_{\text{vol.}} d^3x\, \varepsilon_{jkl}\, \text{Tr}\left(\hat{A}^j \partial^k \hat{A}^l\right).$$

- μ_5 is conjugated to (nearly) conserved $\tilde{Q}_5$
- Bosonization of $\tilde{Q}_5$ with chiral Lagrangian, VMD...

$$\boxed{\langle \Delta T_5 \rangle \quad \Longleftrightarrow \quad \mu_5}$$

How does $\tilde{Q}_5$ affect the hadronic phenomenology?

Effective meson theory in a medium with LPB

Low energy QCD can be described with the help of Vector Meson Dominance

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

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

where $Q = \frac{\tau_3}{2} + \frac{1}{6}$, $g_\omega \simeq g_\rho \equiv g \simeq 6$.
In this framework, the following term is generated in the effective lagrangian for vector mesons

$$\boxed{\Delta\mathcal{L} \simeq \varepsilon^{\mu\nu\rho\sigma} \text{Tr}\left[\hat{\zeta}_\mu V_\nu V_{\rho\sigma}\right]}$$

with $\hat{\zeta}_\mu = \hat{\zeta}\delta_{\mu 0}$ for a spatially homogeneous and isotropic background ($\hat{} \equiv$ isospin content) and $\zeta \propto \mu_5$.
Two different cases of isospin structure for μ_5:

- Isosinglet pseudoscalar background ($T \gg \mu$) [RHIC, LHC]
- Pion-like (isotriplet) background ($\mu \gg T$) [FAIR, NICA]

Effective vector meson theory in a medium with LPB

Energy spectrum:

Transversal polarizations

$$\omega_{\mathbf{k},\pm} = \sqrt{\mathbf{k}^2 + m^2 \pm \zeta|\mathbf{k}|}$$

Longitudinal polarization

$$\omega_{\mathbf{k},L} = \sqrt{\mathbf{k}^2 + m^2}$$

Three polarizations with masses $m^2_{V,+} < m^2_{V,L} < m^2_{V,-}$.
The position of the poles for $\pm$ polarized mesons is changing with wave vector $|\vec{k}|$.

More details in: **A.A., V.A. Andrianov, D. Espriu and X.Planells, Phys. Lett. B 684 (2010) 101; B 710 (2012) 230,...**

This splitting unambiguously signifies LPB.

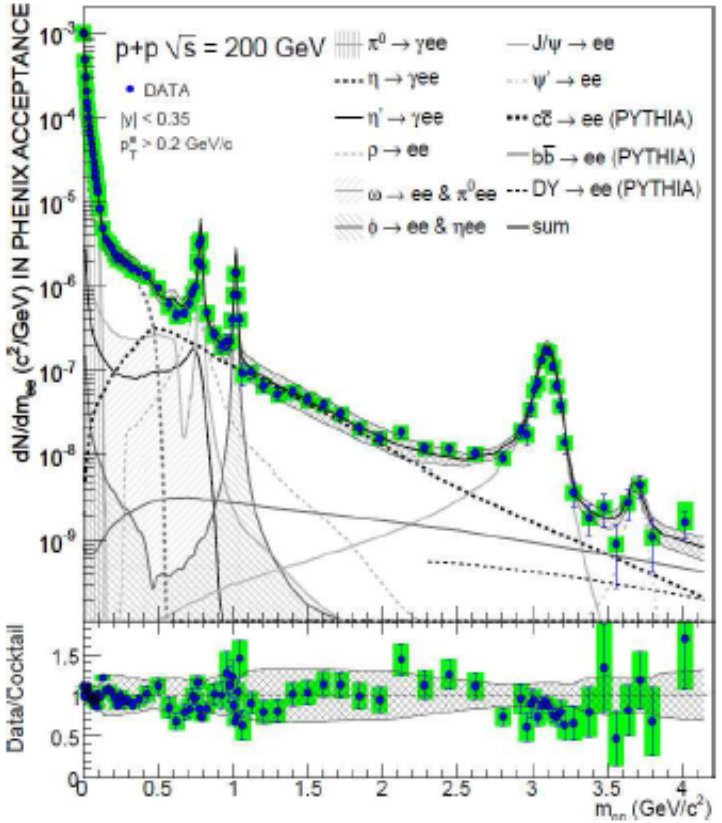
Thus arises the question.

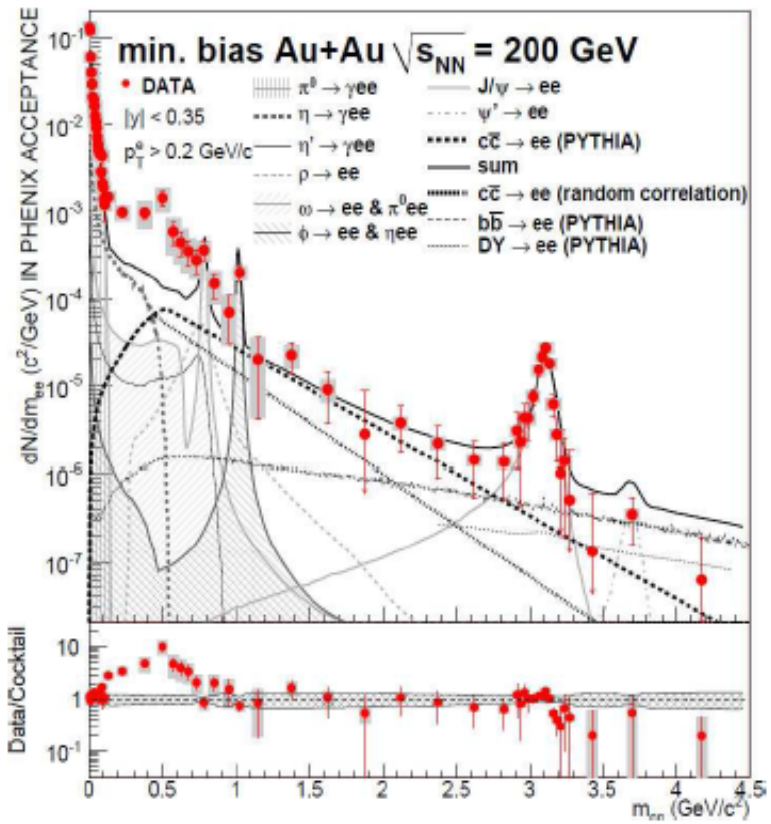
Can these effects somehow be registered in the experiments with heavy ion collisions and thereby assert the existence of the local parity breaking phase?

(details see **A.A. Andrianov, V. A. Andrianov, D. Espriu, and X. Planells, Phys. Rev. D, 90 (2014), 034024).**

Manifestation of LPB in heavy ion collisions

PHENIX/STAR anomaly - Abnormal e^+e^- excess in central HIC

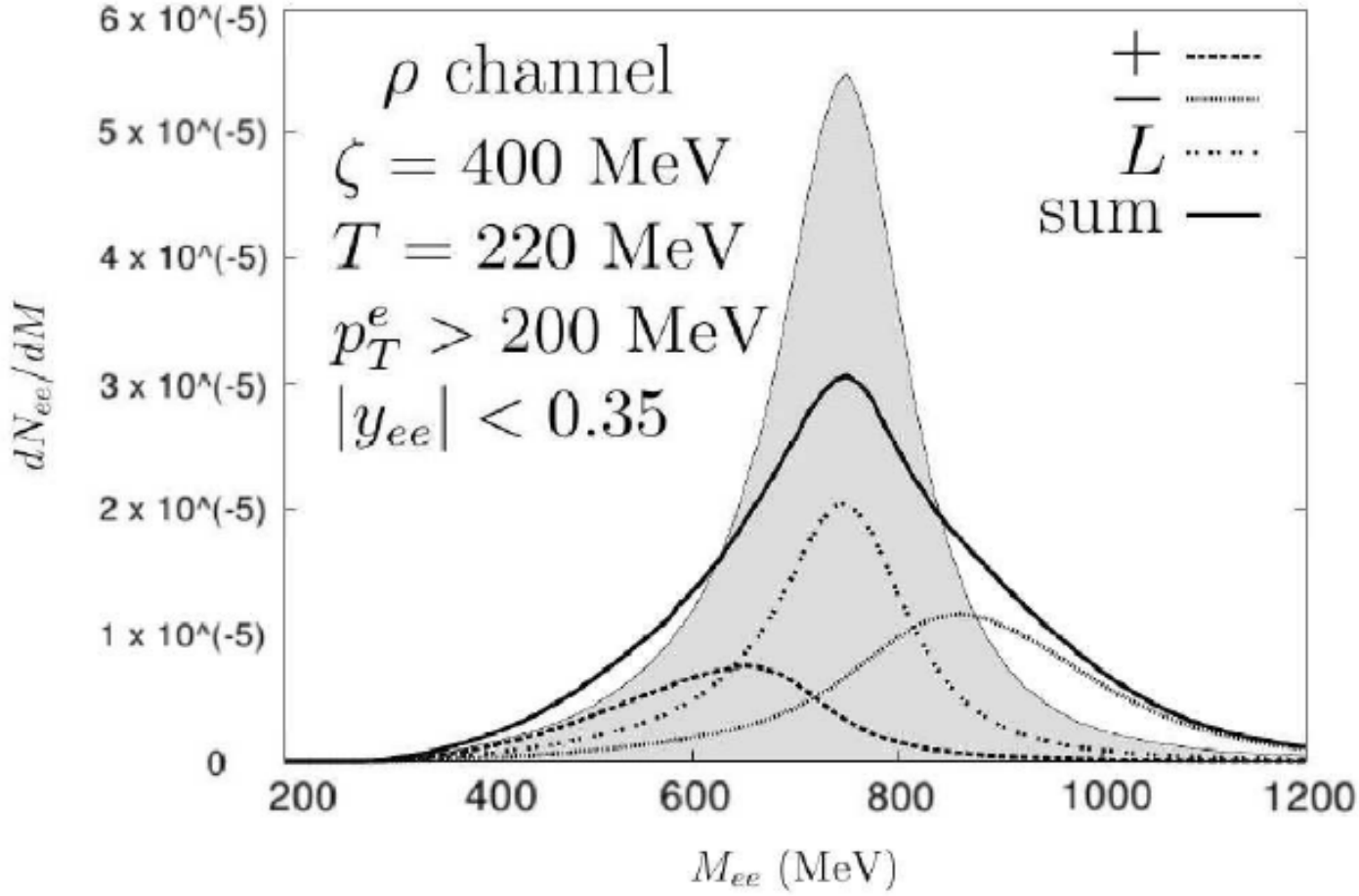




Anomalous dilepton yield in Au+Au collisions in PHENIX

Manifestation of LPB in heavy ion collisions

ρ spectral function

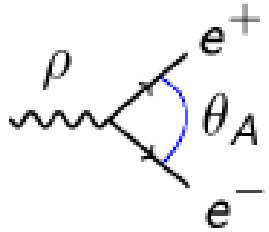


Polarization splitting in ρ spectral function for LPB $\zeta = 400$ MeV ($\mu_5 = 290$ MeV) compared with $\zeta = 0$ (shaded region).

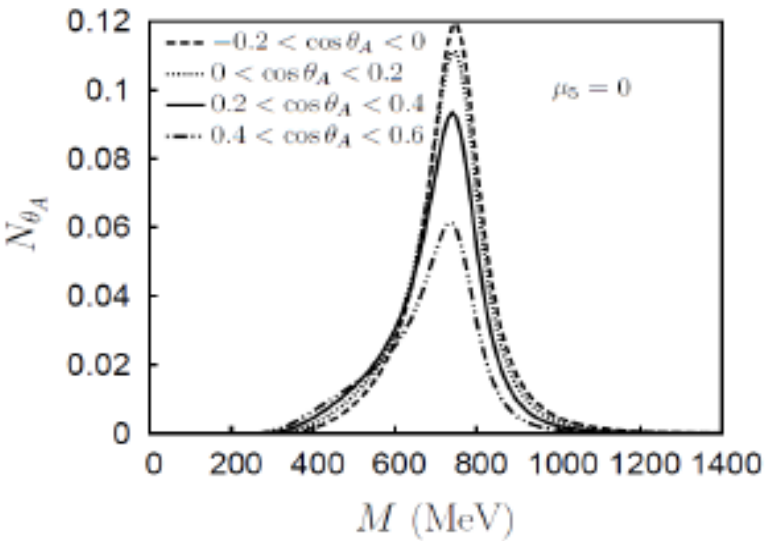
Contaminated with thermal effects and low statistics

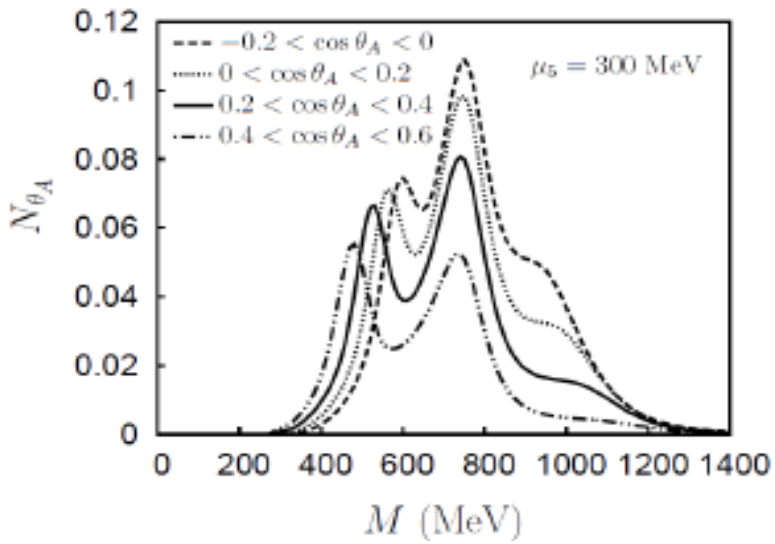
Observables sensitive to P-odd effects

- We study the angular distributions for the polarizations in the mentioned reactions when the angle between the two outgoing leptons in the decay of meson constrained with the laboratory frame.



In order to select the transverse polarizations in the spectrum, we will perform the different cuts for each angle and study the variations of the \rho (and \omega)- spectral function.





Conclusions and outlook

1. Topological charge fluctuations transmit their influence to hadron physics via axial chemical potential: in this way local parity breaking (LPB) occurs in hadron sector

2. LPB enhances dynamical chiral symmetry breaking in QCD: chiral condensates, critical temperature of chiral symmetry restoration are increasing with chiral chemical potential

3. Axial chemical potential triggers parity-odd condensation for large baryon chemical potential in first-order phase transition ("chiral catalysis")

4. LPB modifies dispersion laws for scalar and vector mesons: lightest "pseudoscalar" mesons tend to massless states in flight, vector meson polarizations split with different in-flight masses

5. <u>There are observables unambiguously indicating LPB</u> (ALICE LHC?)

Backup slides

QED anomaly

$$Q_5^q \to \tilde{Q}_5 = Q_5^q - T_5^{\rm em}, \quad T_5^{\rm em} = \frac{N_c e^2}{8\pi^2} \int_{\rm vol.} d^3x\, \varepsilon_{jkl}\, {\rm Tr}\left(\hat{A}^j \partial^k \hat{A}^l\right)$$

Instabilities

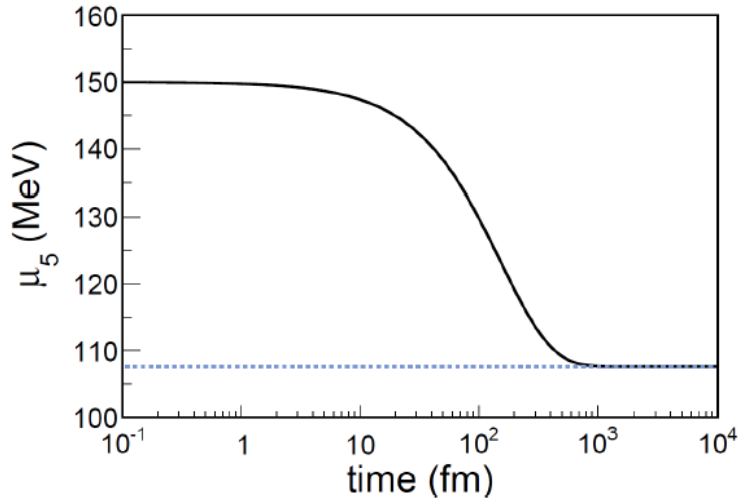
$$\frac{dn_5}{dt} = -\frac{C\alpha}{\pi}\frac{d\mathcal{H}}{dt} - \Gamma_f n_5$$

$$\mathcal{H}(t) = \frac{1}{V}\int_V d^3x\, \mathbf{A}\cdot\mathbf{B}$$

magnetic helicity density

helicity-flipping rate $\Gamma_f \to 0$

$$\frac{d\mu_5}{dt} = -c_\Delta C\alpha \frac{d\mathcal{H}}{dt} - \cancel{\Gamma_f \mu_5}$$



From: **C.Manuel and J.M.Torres-Rincon, Phys.Rev. D92, 074018 (2015)**

Parity-breaking in strong interactions at extreme conditions

Chiral Imbalance

A.Vilenkin, Phys. Rev. D 22, 3080 (1980)

Chiral Magnetic Effect

D. Kharzeev, R. D. Pisarski, and M. H. G. Tytgat, Phys. Rev. Lett. 81, 512 (1998). D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nucl. Phys. A 803, 227 (2008). K. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D 78, 074033 (2008);)…

Local Parity Breaking due to parity-odd condensate field

A.A.Ansel'm, Pis'ma Zh.Eksp.Teor.Fiz. 48, 49-53 (1988) …

A.A., V.A. Andrianov's and D. Espriu, Phys.Lett. B663 (2008) 450-455; Phys.Lett. B678 2009) 416-421; …

Hadronization of Chiral Imbalance

A.A., V.A. Andrianov's, D. Espriu and X.Planells, Phys. Lett. B 684 (2010) 101; B 710 (2012) 230,…

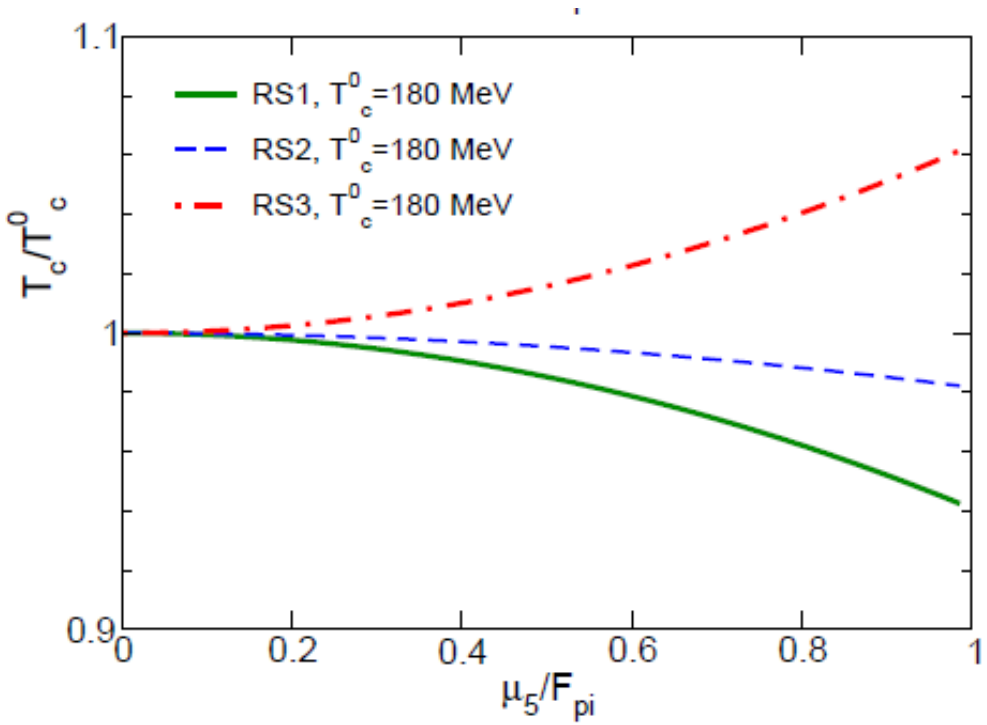
Lattice search for CME and LPB

P. Buividovich, M. Chernodub, E. Luschevskaya, and M. Polikarpov, Phys. Rev. D, 80, 054503 (2009); V.V.Braguta, V.A.Goy, E.M.Ilgenfritz, A.Y.Kotov, A.V.Molochkov, M.Muller-Preussker and B.Petersson, JHEP 1506, 094 (2015) …

Renormalization scheme dependence

$$\sigma = F_\pi \left(1 + \frac{\mu_5^2}{F_\pi^2}\frac{g^2 N_c N_f}{\pi^2}\frac{F_\pi^2}{M_\sigma^2}\right), \quad \text{RS3}$$

for T = 0

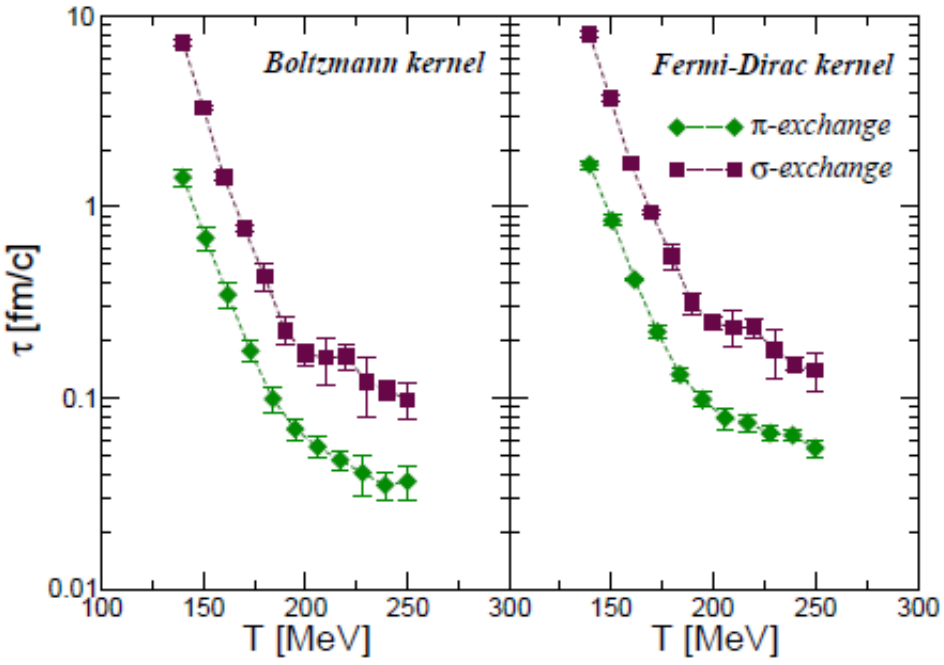


$\xi = 0,\ 1/2$ and $3/2$ for RS1, RS2 and RS3

$$T_c(\mu_5) = T_c^0 + \mu_5^2 \frac{3}{\pi^2 T_c^0}\left(\xi + \gamma_E + \frac{1}{2} - \log\frac{\pi T_c^0}{F_\pi}\right)$$

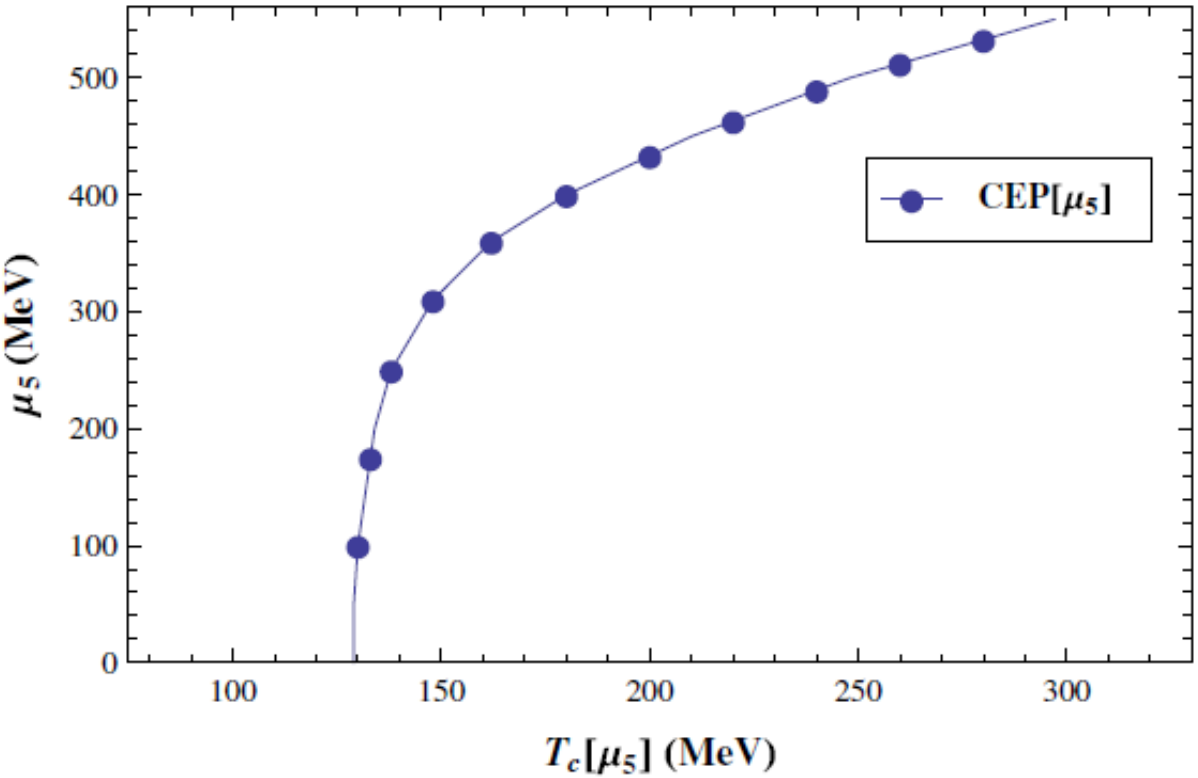
From: **M.Ruggieri and G.X.Peng, 1602.03651**

Relaxation time



Relaxation time of chiral density

From: **M.Ruggieri, G.X.Peng and M.Chernodub, 1606.03287**



The relation between μ_5 and the corresponding $T_c[\mu_5]$ in the $T-\mu$ plane.

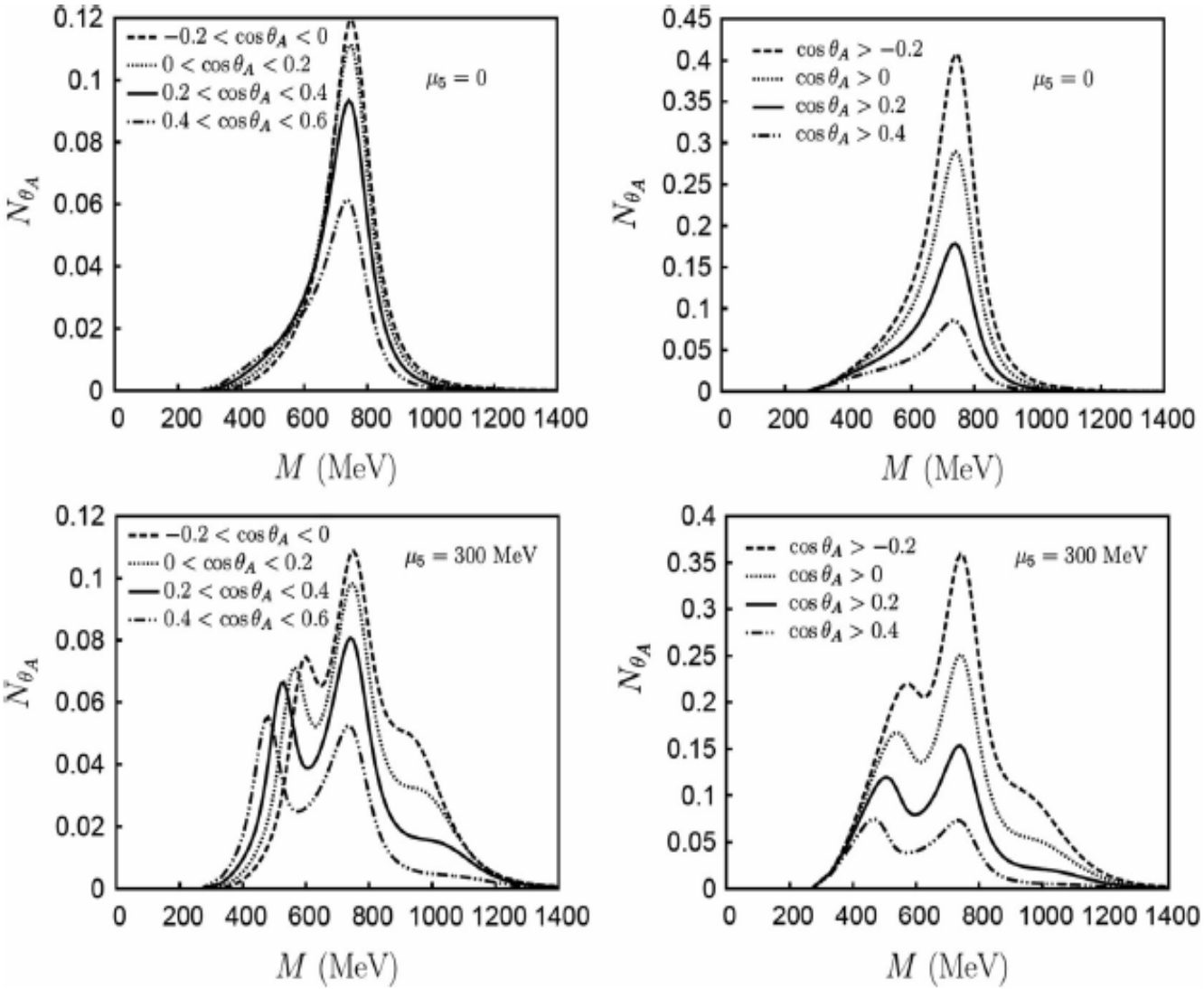


FIG. 1. The ρ spectral function is presented depending on the invariant mass M in vacuum ($\mu_5 = 0$) and in a parity-breaking medium with $\mu_5 = 300$ MeV (upper and lower panels, respectively) for different ranges of the angle between the two outgoing leptons in the laboratory frame θ_A. We display the curves corresponding to $\cos\theta_A \in [-0.2, 0], [0, 0.2], [0.2, 0.4], [0.4, 0.6]$ and $[0.6, 0.8]$ in the left panels, and $\cos\theta_A \geq -0.2, 0, 0.2, 0.4$ in the right ones. The total production at the vacuum peak is normalized to 1 when the entire phase space is considered. Results are presented for the experimental cuts quoted by PHENIX [24].

Comment on Polyakov loop NJL vs. lattice

M.R.Ruggieri

M.R., **Phys. Rev. D84 (2011)**

The Model

NJL Model with the Polyakov Loop

$$\mathcal{L} = \bar{q}\left(i\gamma^{\mu}D_{\mu} - m\right)q + G\left[(\bar{q}q)^2 + (i\bar{q}\gamma_5\boldsymbol{\tau}q)^2\right] + \mu_5\bar{q}\gamma^0\gamma^5 q$$

$$G = g\left[1 - \alpha_1 LL^{\dagger} - \alpha_2(L^3 + (L^{\dagger})^3)\right]$$

Coupling to quarks via:
) Coupling constant
) Covariant derivative

Polyakov Loop:
sensitive to confinement – deconfinement transition

$$L = \frac{1}{3}\mathrm{Tr}_c \exp\left(i\beta\lambda_a A_4^a\right)$$

K. Fukushima, **Phys.Lett. B591 (2004) 277-284**
W. Weise *et al.*, **Phys.Rev. D73 (2006) 014019**
M. Yahiro *et al.*, **Phys.Rev. D82 (2010) 076003**

Coupling dependent on L inspired by:
K. Kondo, **Phys.Rev. D82 (2010) 065024**

Controversy!!

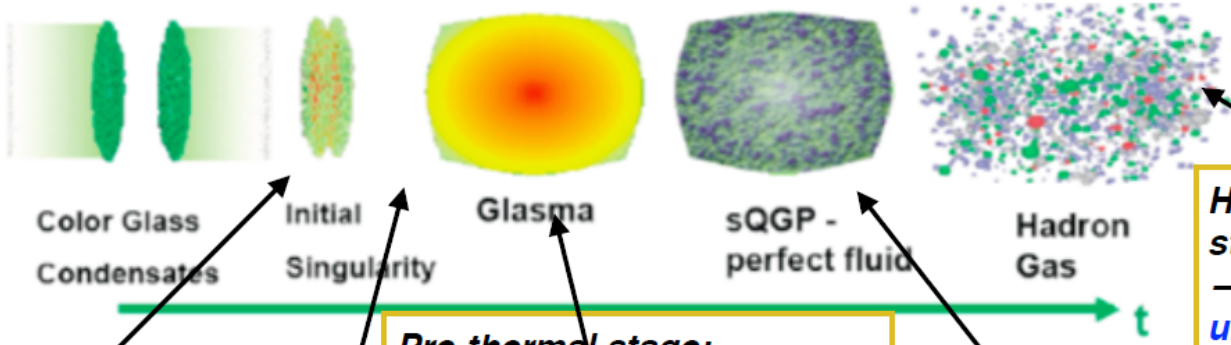
Critical temperature decreases with chemical potential whereas it increases in lattice simulations

Talk by Jinfeng Liao

Outlook: A Well-Defined To-Do List

We are at a "critical point" for transitioning from the phase of "new ideas, qualitative estimates, rough trends in exp. data" toward the phase of "quantitative modelings, and experimental validations".

We are ready to take that up!



Initial conditions:
for CHARGES!!!
(flavor-wise & Axial)
—> need theory/model

Pre-thermal stage:
important if all effects occur early!
—> need pre-thermal model (combined efforts with thermalization studies?)

Driving "forces"
(E,B fields, vorticity)
—> need precise implementation of space and time dependence (M-V-C-A-Hydro)

Hydrodynamic evolution:
—> need to implement "in-flight NOISE" of C and A charges (hydro with C/A fluctuations)

Hadronic stage:
—> need to understand its impact on observables

Focused and major efforts: A Chiral Magneto-Hydrodynamics (CMHD) simulation for wide beam energy!

Back to Models:

Structural constants: guess with NJL

A.A.Andrianov, D.Espriu and X.Planells, Eur.Phys. J. C 74, no. 2, 2776 (2014)

$$\mathcal{L} = \bar{\psi}[\partial\!\!\!/ + m - \mu\gamma_0 - \mu_5\gamma_0\gamma_5 + g_1(\sigma + i\gamma_5\vec{\tau}\vec{\pi}) + g_2(i\gamma_5\eta + \vec{\tau}\vec{a})]\psi + \frac{Ng_1^2}{4G_1}(\sigma^2 + \vec{\pi}^2) + \frac{Ng_2^2}{4G_2}(\eta^2 + \vec{a}^2)$$

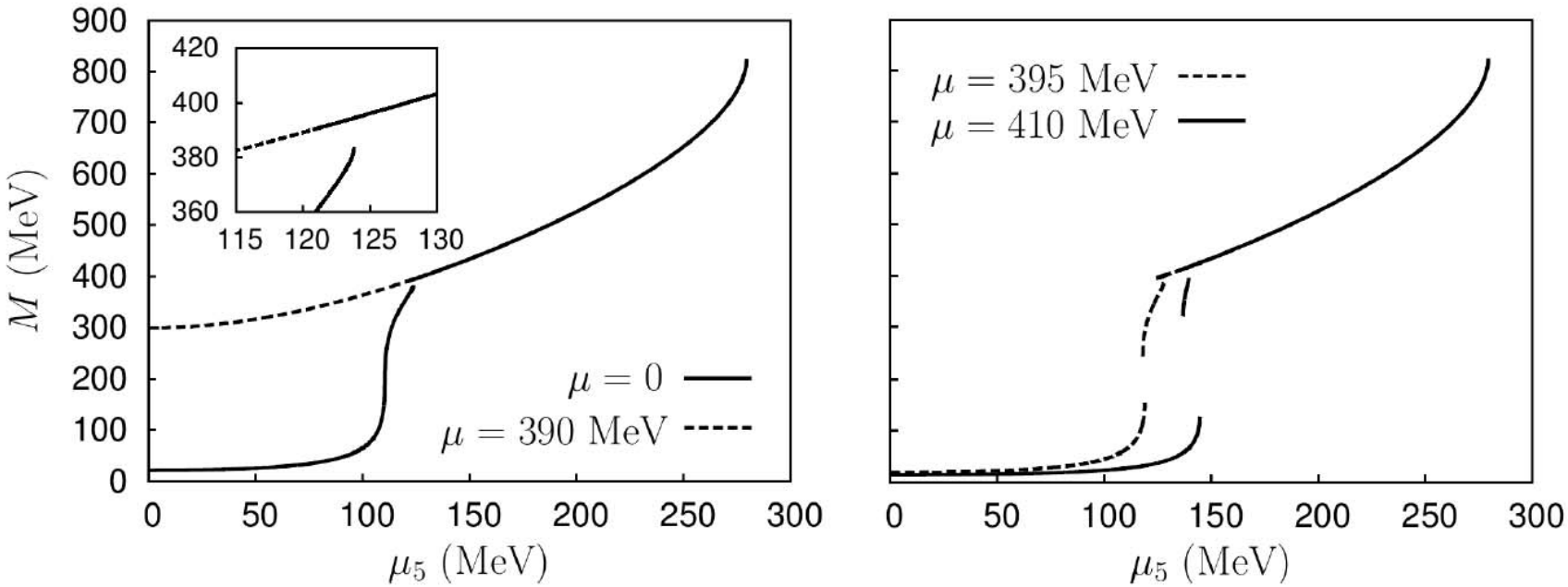
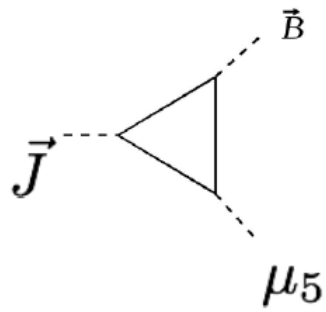


Figure 4: Evolution of the constituent quark mass M depending on μ_5 for different values of the chemical potential μ setting $m = -5$ MeV, $G_1 = -40/\Lambda^2$ and $G_2 = -45/\Lambda^2$. Both graphics show the regions where all the second derivatives are positive. Certain values of μ_5 exhibit coexisting solutions implying first order phase transitions. In the left panel, we show a plot for $\mu = 0$ (or indeed for any $\mu < M$) and $\mu = 390$ MeV. The second curve exhibits a small jump that is shown more detailed in the inset. The right panel corresponds to $\mu = 395$ (two jumps) and 410 MeV (probably only one jump).

Chiral Magnetic Effect in a chirally imbalanced plasma

Chiral chemical potential is formally equivalent to a background chiral gauge field: $\mu_5 = A_5^0$

In this background, and in the presence of B, vector e.m. current is not conserved:



$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2}\left(F_L^{\mu\nu}\tilde{F}_{L,\mu\nu} - F_R^{\mu\nu}\tilde{F}_{R,\mu\nu}\right)$$

Compute the current through

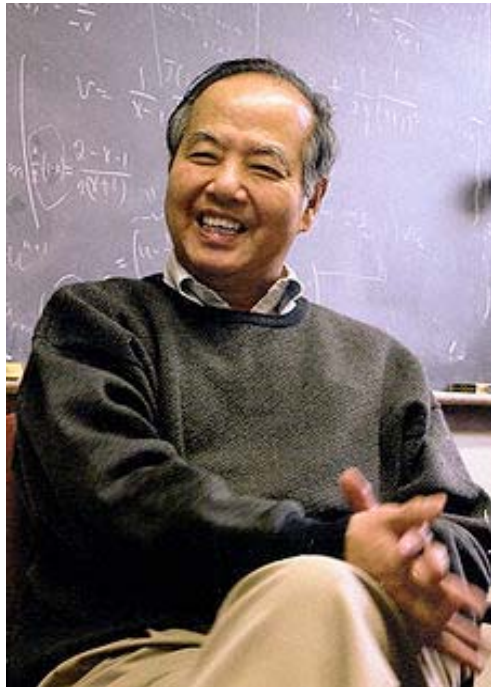
$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

The result:

$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}}$$

Coefficient is fixed by the axial anomaly, no corrections

A bit of history

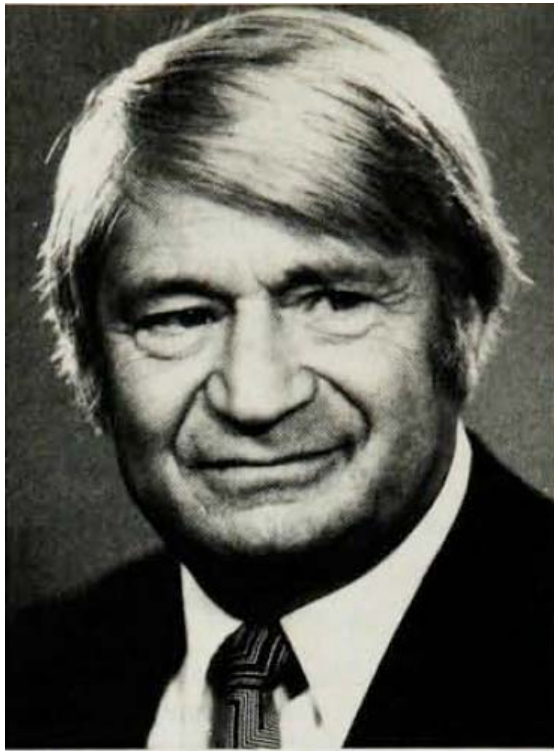


T.D.Lee

A possible formation of abnormal superdense nuclei and the possibility of *pi*-condensation was proposed by Lee and Wick that can be associated with high energy heavy ion physics.

T. D. Lee and G. C. Wick, Phys. Rev. D 9, 2291 (1974). T. D. Lee, Rev. Mod. Phys. 47, 267 (1975)

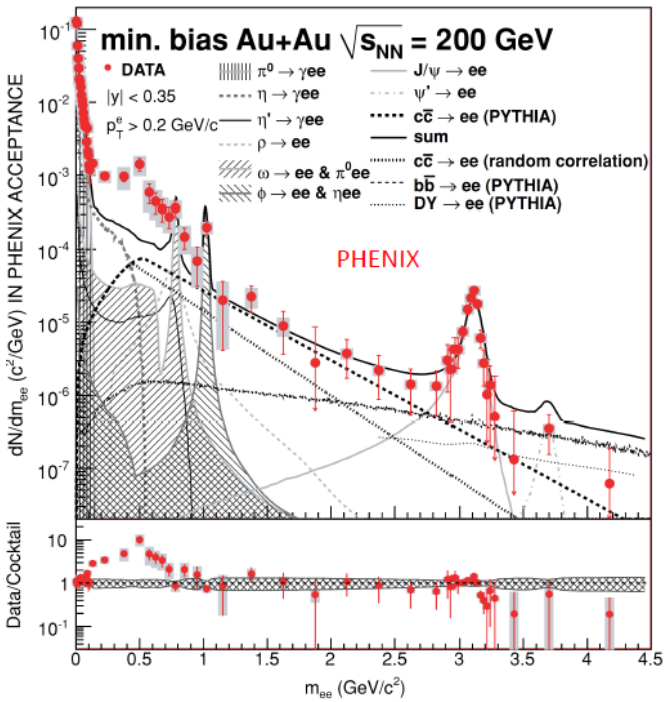
SPONTANEOUS PARITY BREAKING IN NUCLEAR MATTER

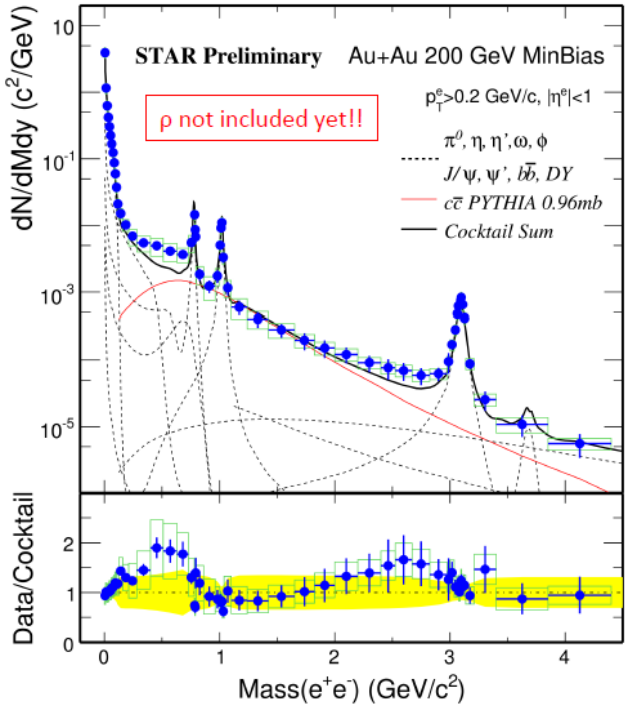


A.B.Migdal

Migdal's theory of pi-condensation predicts, at a certain density, the onset of an inhomogeneous classical pion field in the ground state of nuclear matter.

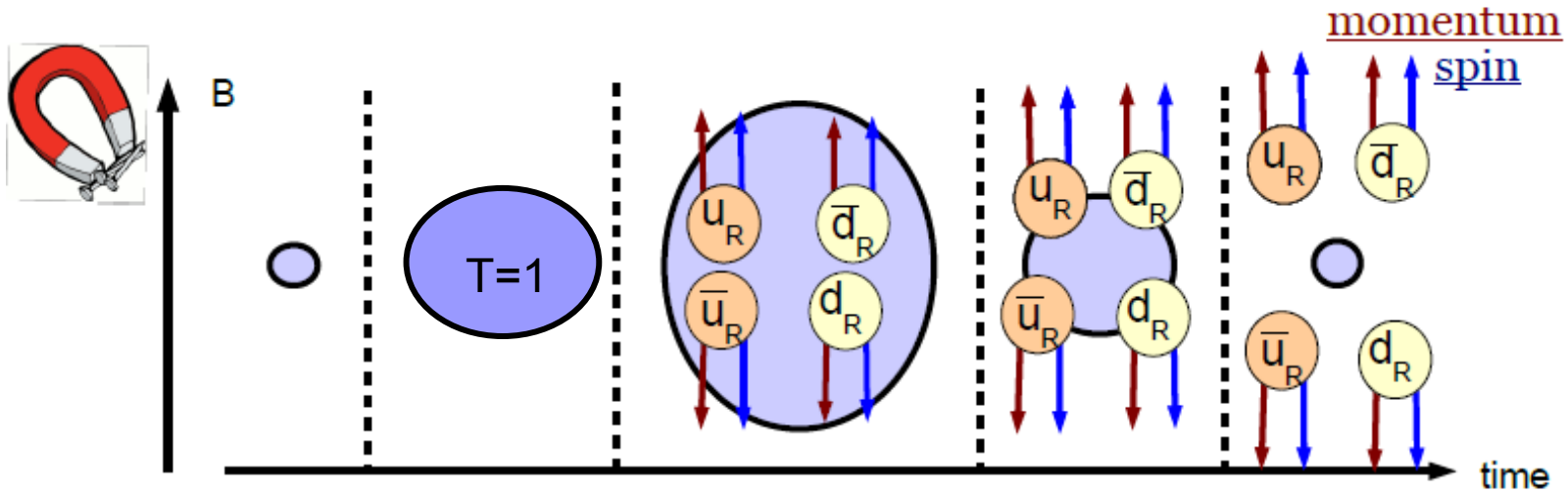
A.B. Migdal, Sov. Phys. JETP 34, 1184 (1972); 36, 1052 (1973); Nucl. Phys. A 210, 421 (1973) .





- **Au-Au minimum bias measurements:** strong excess at low masses for PHENIX after all expected sources are included

Topological Charge + Magnetic field = Chirality + Polarization =



Positively charged particles move parallel to magnetic field, negatively charged antiparallel

... = Electromagnetic Current

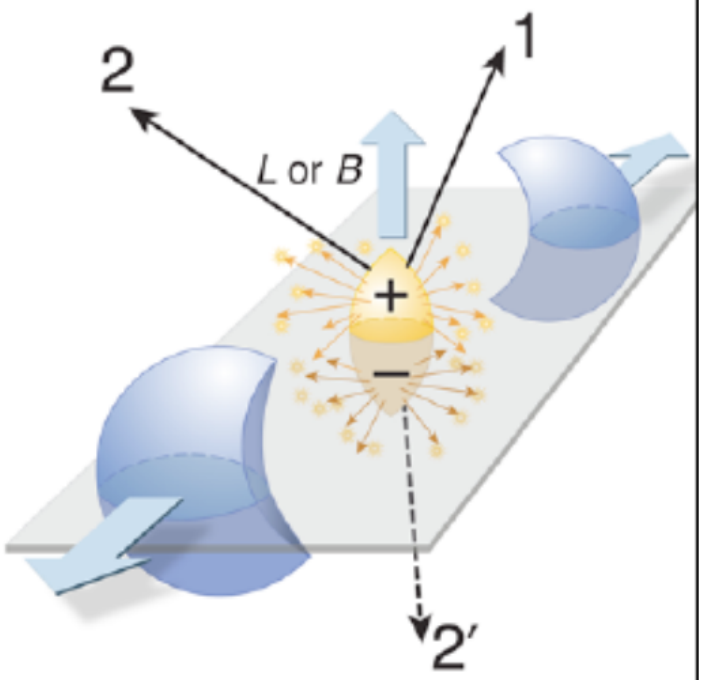
P- and CP-odd effect --> Chiral Magnetic Effect: Kharzeev, McLerran 2006-2010

PRL **103**, 251601 (2009)

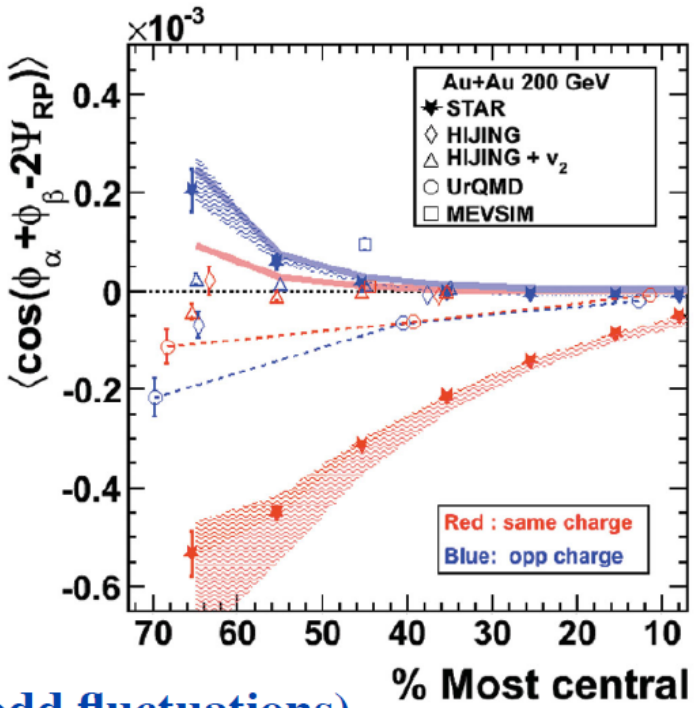
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation



(STAR Collaboration)



NB: P-even quantity (strength of P-odd fluctuations)

Lagrangian of vector meson dominance model in matter

After the bosonization of the quark sector QCD the corresponding kinetic term for the lagrangian of the vector fields V(x) in the pseudoscalar background field contains the Maxwell and mass terms supplemented by the term of the Chern- Simons interaction

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

$$m^2_{ab} = m^2_V \begin{pmatrix} \frac{4e^2}{3g^2} & -\frac{e}{3g} & -\frac{e}{g} & \frac{\sqrt{2}eg_\phi}{3g^2} \\ -\frac{e}{3g} & 1 & 0 & 0 \\ -\frac{e}{g} & 0 & 1 & 0 \\ \frac{\sqrt{2}eg_\phi}{3g^2} & 0 & 0 & \frac{g^2_\phi}{g^2} \end{pmatrix}, \quad \det\left(m^2\right) = 0,$$

$$\left(V_{\mu,a}\right) \equiv \left(A_\mu,\, \omega_\mu,\, \rho^0_\mu \equiv \rho_\mu,\, \phi_\mu\right) \qquad m^2_V = m^2_\rho = 2g^2_\rho f^2_\pi \simeq m^2_\omega$$

The quark-meson interaction is described by

$$\mathcal{L}_{\rm int} = \bar{q}\gamma_\mu V^\mu q; \quad V_\mu \equiv -eA_\mu Q + \frac{1}{2}g_\omega\omega_\mu \mathbf{I}_q + \frac{1}{2}g_\rho\rho_\mu\lambda_3 + \frac{1}{\sqrt{2}}g_\phi\phi_\mu \mathbf{I}_s$$