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Chiral Imbalance in Heavy Ion collisions

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1. **Chiral charge generation**
2. **From initial stage to hadronization: chiral imbalance vacuum**
3. **Effective scalar and vector state lagrangians with chiral chemical potential**
4. **Direct observables of P(CP) parity breaking without E.-M. background**
5. **Shall / can we measure them?**

In search for <u>local</u> parity breaking in heavy ion collisions

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, A.Zhitnitsky, L. D. McLerran, K.Fukushima, H. J. Warringa (an earlier proposal: A.Vilenkin, 1980)]

- **New QCD phase** characterized by a spontaneous parity breaking due to formation of neutral pion-like background [A.A.Anselm, J.Bjorken . . . . . . A. A., V. A. Andrianov & D. Espriu]

- **DETECTION: vector meson masses depending on their polarizations**
  A.A., V,A.Andrianov, D.Espriu, X.Planells, Phys. Lett. B 710 (2012) 230, Phys. Rev. D, 90 (2014), 034024)
  Polarization asymmetry in pion-gamma production
  M. Kawaguchi, M. Harada, S. Matsuzaki, R. Ouyang ,
  PHYS. REV. C 95, 065204 (2017) ……..(generalization in this talk)

Induced chiral Imbalance

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

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

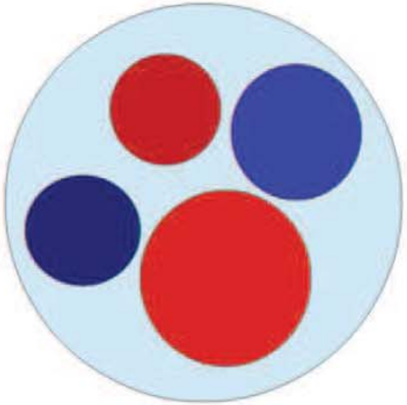
predicts the induced axial charge (for small quark masses $m_q \simeq 0$)

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

Chiral imbalance

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

Topological charge



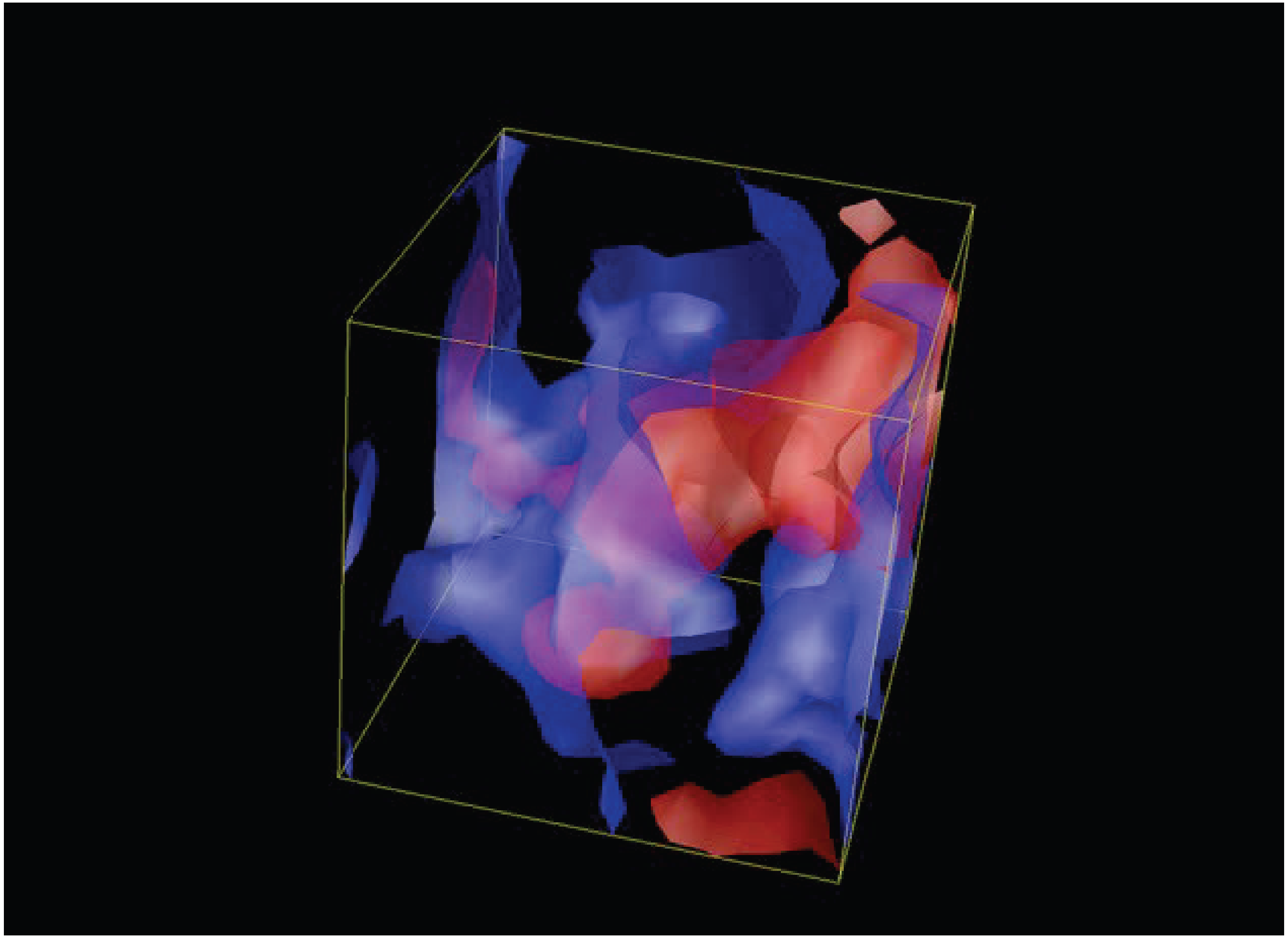
$$T_5 = \frac{1}{8\pi^2}\int_{\text{vol.}} d^3x \varepsilon_{jkl} \mathrm{Tr}\left(G^j \partial^k G^l - i\frac{2}{3} G^j G^k G^l \right)$$

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

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

Topological number fluctuations in QCD vacuum

ITEP Lattice Group



P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov

Topological vs. Chiral chemical potentials

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

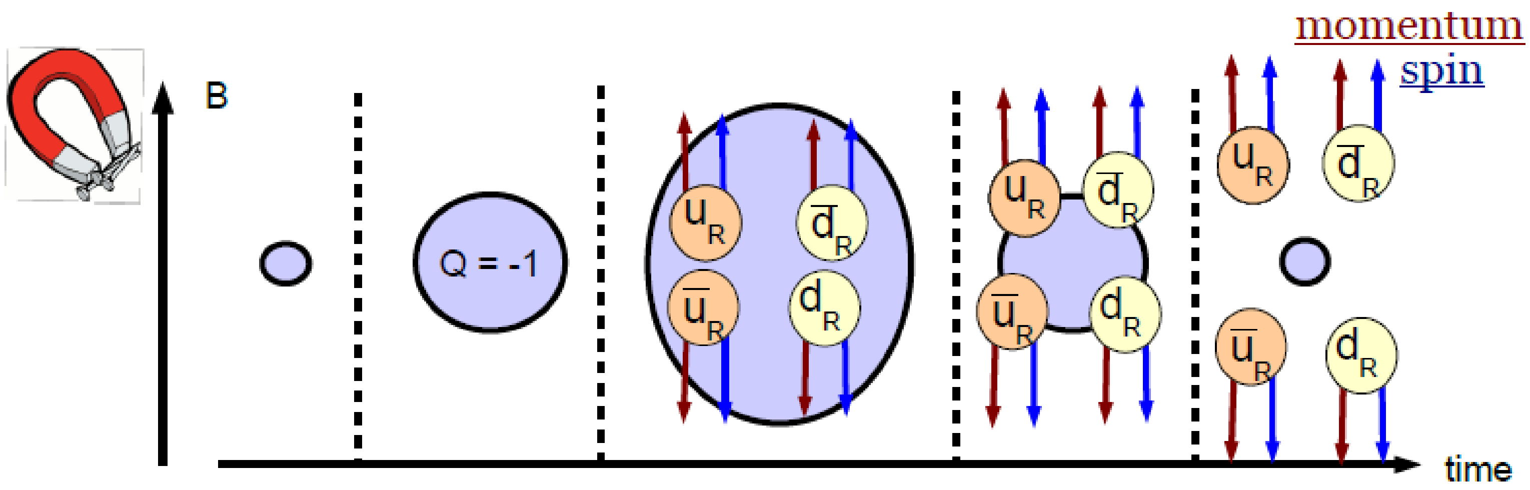
$$\boxed{\langle \Delta T_5 \rangle \simeq \frac{1}{2N_f}\langle Q_5^q \rangle \iff \mu_5 \simeq \frac{1}{2N_f}\mu_\theta,}$$

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

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

Chiral magnetic effect

Topological Charge + Magnetic field = Chirality + Polarization =



Q < -1: Positively charged particles move parallel to magnetic field, negatively charged antiparallel

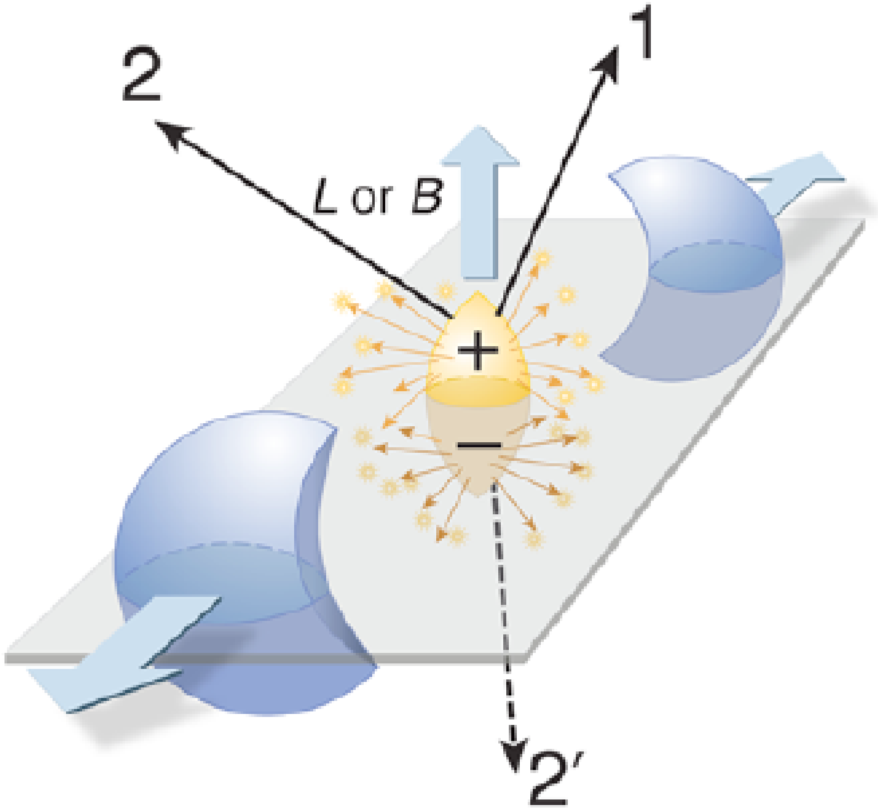
... = Electromagnetic Current

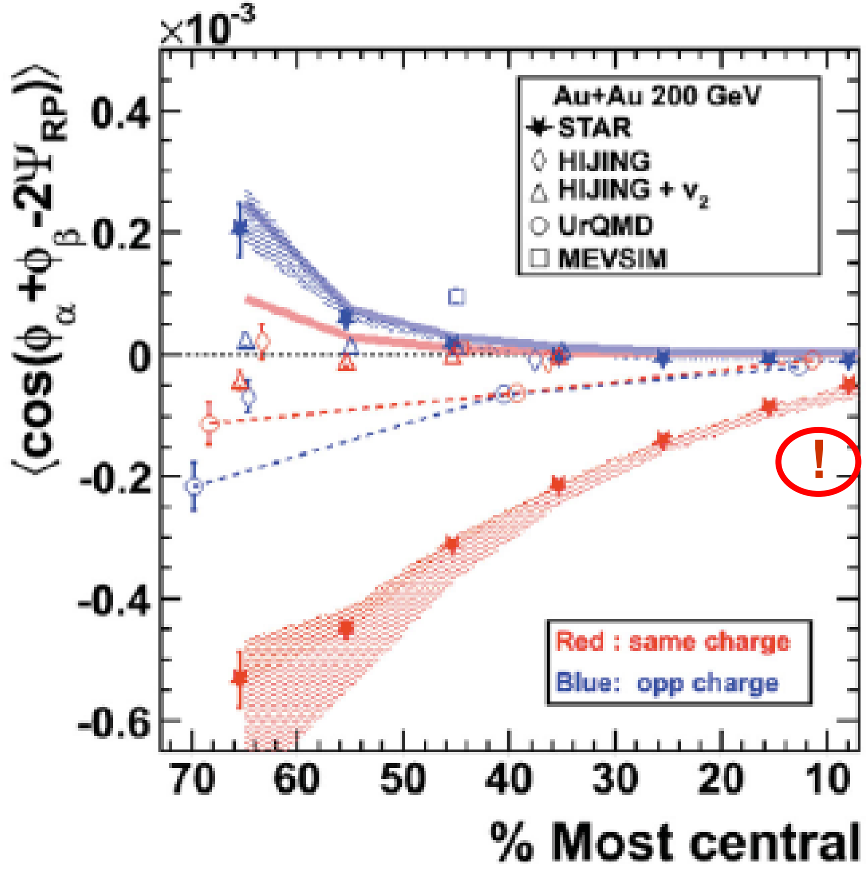
P- and CP-odd effect --> Chiral Magnetic Effect: Kharzeev, McLerran & HJW ('08)

D.Kharzeev, L.McLerran, K.Fukushima, H.Warringa,…

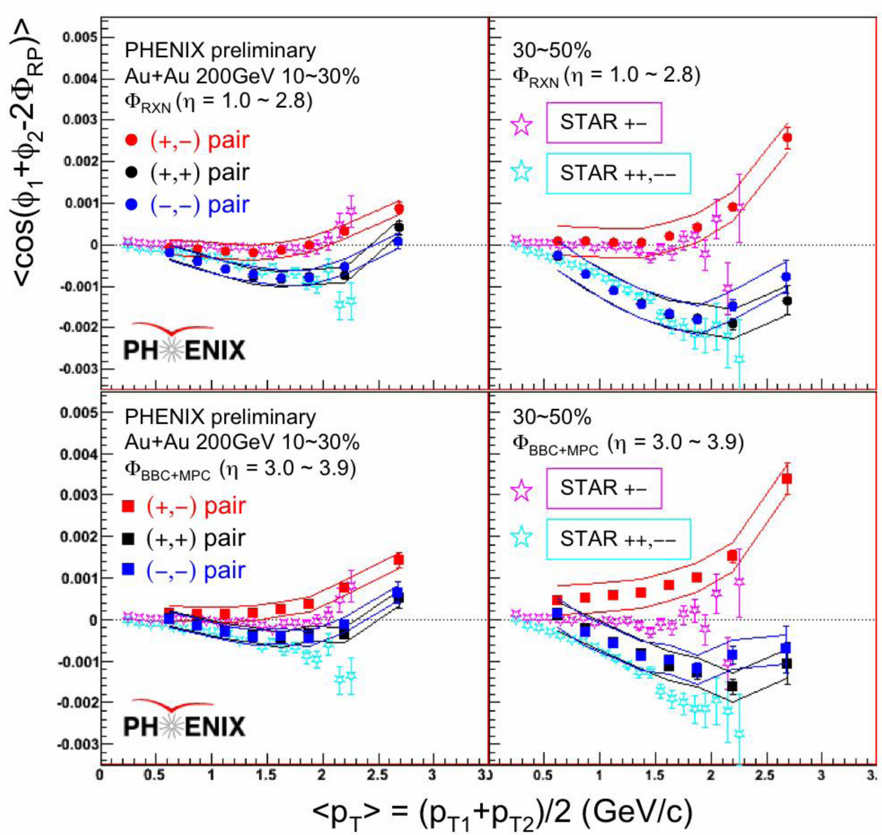
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)





Asymmetry comparison: STAR vs. PHENIX



Close examinations revealed that the INTERPRETATION of the nice data is complicated by backgrounds.

[Bzdak, Koch, JL; FQ Wang; Pratt, Schlichting; Teaney, Yan;…]

Several backgrounds were identified:

transverse momentum conservation;

local charge conservation;

dipolar fluctuations; …

Generalized "Ohm Table" for QGP

$$\begin{pmatrix} \vec{\mathrm{J}} \\ \vec{\mathrm{J}}_5 \end{pmatrix} = \begin{pmatrix} \sigma & \sigma_5\mu_5 \\ \sigma_{\chi e}\mu\mu_5 & \sigma_5\mu \end{pmatrix} \begin{pmatrix} \vec{\mathrm{E}} \\ \vec{\mathrm{B}} \end{pmatrix}$$

* Chiral Magnetic Effect (CME)
[Vilenkin, 1980; Kharzeev 2004;
McLerran, Fukushima, Warringa; Voloshin….]

$$\boxed{\vec{\mathrm{J}} = \sigma_5\mu_5\vec{\mathrm{B}}}$$

Etc. …..

Not in this talk!

How to "measure" parity odd effects theoretically? Chiral chemical potential/chiral flow vector

$$\mathcal{L}_{\mathrm{LIV}} = \frac{1}{2}\eta_\alpha A_\beta(x)\tilde{F}^{\alpha\beta}(x) + b_\mu\bar{\psi}(x)\gamma_5\gamma^\mu\psi(x)$$

Vector mesons

Scalars?

Fermions

Split transversal polarizations in masses

$$\boxed{\begin{aligned} k^2 - m_\gamma^2 \pm \sqrt{\mathtt{D}} &= 0 \\ \mathtt{D} \equiv (\eta\cdot k)^2 - \eta^2 k^2 & \end{aligned}}$$

Split positive and negative fermion helicities in masses

$$\boxed{p_0^2 = \left(|\vec{p}| \pm b_0\right)^2 + m^2}$$

jhep022002030,

Lorentz and CPT violations from Chern-Simons modifications of QED

Alexander A. Andrianov,* Paola Giacconi and Roberto Soldati

Large chiral imbalance

Initial Stage
After
HI collision

Hadronization:
phase with chiral imbalance
inherited from quark vacuum

< 1 fm/c

1 fm/c < 7-10 fm/c

Vacuum quark-hadron continuity (Fukushima talk!)

Topological vs.Chiral chemical potentials

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

- For u, d quarks $1/m_q \sim 1/5\ \mathrm{MeV}^{-1} \sim 40$ fm $\gg \tau_{\mathrm{fireball}}$ and the left-right quark mixing can be neglected.
- k $1/m_s \sim 1/150\ \mathrm{MeV}^{-1} \sim 1$ fm $\ll \tau_{\mathrm{fireball}}$ 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

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

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

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

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

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

- 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]

QCD inspired effective meson lagrangian (SU(2) case)

current quark mass

$$L = \frac{1}{4} Tr\,(D_\mu H\,(D^\mu H)^\dagger) + \frac{b}{2} Tr\,[\,m(H + H^\dagger)] + \frac{M^2}{2} Tr\,(HH^\dagger)$$
$$- \frac{\lambda_1}{2} Tr\,[(HH^\dagger)^2] - \frac{\lambda_2}{4}[Tr\,(HH^\dagger)]^2 + \frac{c}{2}(\det H + \det H^\dagger)$$

$$\boxed{H = \xi\,\Sigma\,\xi}$$

pions

$$U = \xi\xi = \exp\left(i\frac{\vec{\pi}\vec{\tau}}{f_\pi}\right) \qquad \vec{\pi}\vec{\tau} = \begin{bmatrix} \pi^0 & \sqrt{2}\,\pi^+ \\ \sqrt{2}\,\pi^- & -\pi^0 \end{bmatrix}$$

$$\Sigma = \begin{bmatrix} v+\sigma+a_0^0 & \sqrt{2}\,a^+ \\ \sqrt{2}\,a_0^- & v+\sigma-a_0^0 \end{bmatrix}$$

scalar mesons (isosingles + isotriplets)

$$\boxed{D_\mu H = \partial_\mu H - i\mathcal{L}_\mu H + iH\mathcal{R}_\mu}$$

$$\mathcal{R}_\mu = e\,Q_{em}A_\mu - \mu_5\delta_{\mu,0}\cdot 1_{2\times 2}; \quad \mathcal{L}_\mu = e\,Q_{em}A_\mu + \mu_5\delta_{\mu,0}\cdot 1_{2\times 2}$$

$$Q_{em} = \tfrac{1}{2}\tau_3 + \tfrac{1}{6}1_{2\times 2}.$$

Chiral chemical potential
= time-component of axial field

Mass spectrum in vacuum

Take

$$\mu_5 = 0,\ M = 300\ \mathrm{MeV},\ v = 92\ \mathrm{MeV}$$

Obtain

$$\boxed{m_\pi = 139\ \mathrm{MeV},\ m_a = 980\ \mathrm{MeV},\ m_\sigma = 500\ \mathrm{MeV},\ m = 5.5\ \mathrm{MeV},}$$

for

$$\boxed{\lambda_1 = 16.4850,\ \lambda_2 = -13.1313,\ c = -4.46874 \times 10^4\ \mathrm{MeV}^2,\ b = 1.61594 \times 10^5\ \mathrm{MeV}^2}$$

Mass spectrum

σ meson,

$$\tfrac{1}{2}\,\partial_\mu\sigma\,\partial^\mu\sigma - \tfrac{1}{2}\,m_\sigma^2\sigma^2$$

Neutral meson sector,

$$\tfrac{1}{2}\,\partial_\mu a_0^0\,\partial^\mu a_0^0 + \tfrac{1}{2}\,\partial_\mu\pi^0\partial^\mu\pi^0 - \tfrac{1}{2}m_a^2\,(a_0^0)^2 - \tfrac{1}{2}m_\pi^2\,(\pi^0)^2 - 4\mu_5\,\dot{\pi}^0 a_0^0$$

Charged meson sector,

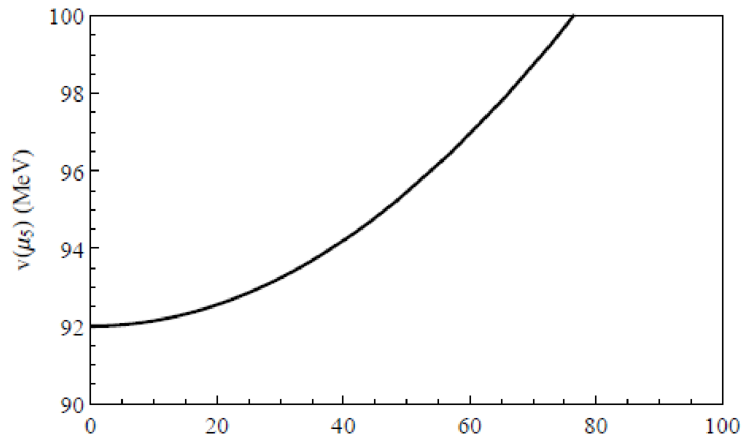
$$\partial_\mu a_0^-\,\partial^\mu a_0^+ + \partial_\mu\pi^-\partial^\mu\pi^+ - m_a^2 a_0^- a_0^+ - m_\pi^2\pi^-\pi^+ - 4\mu_5\,\dot{\pi}^+ a_0^- - 4\mu_5\,\dot{\pi}^- a_0^+$$

mass matrix
and
chiral condensate

$$\begin{cases} m_\sigma^2 = -2\left(M^2 - 6\,(\lambda_1+\lambda_2)v^2 + c + 2\mu_5^2\right) \\ m_a^2 = -2\left(M^2 - 2\,(3\lambda_1+\lambda_2)v^2 - c + 2\mu_5^2\right) \\ m_\pi^2 = \dfrac{2\,b\,m}{v} \\ v(\mu_5) = \sqrt{\dfrac{M^2+2\mu_5^2+c}{2(\lambda_1+\lambda_2)}} + \dfrac{b}{2(M^2+2\mu_5^2+c)}\,m \end{cases}$$

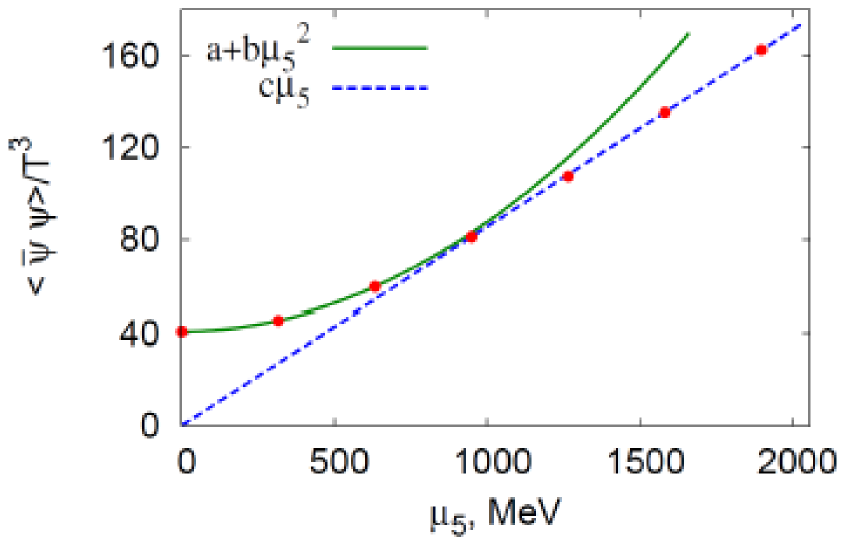
In the above model **quark condensate is governed by the decay constant v**

T = 0



SU(2) effective Lagrangian
this talk

T = 158 MeV



NJL model
V.Braguta, A.Kotov.
PRD, 93,105025(2016)

SU(2) QCD
V.Braguta et al
JHEP 06 (2015) 094)

Masses with chiral imbalance

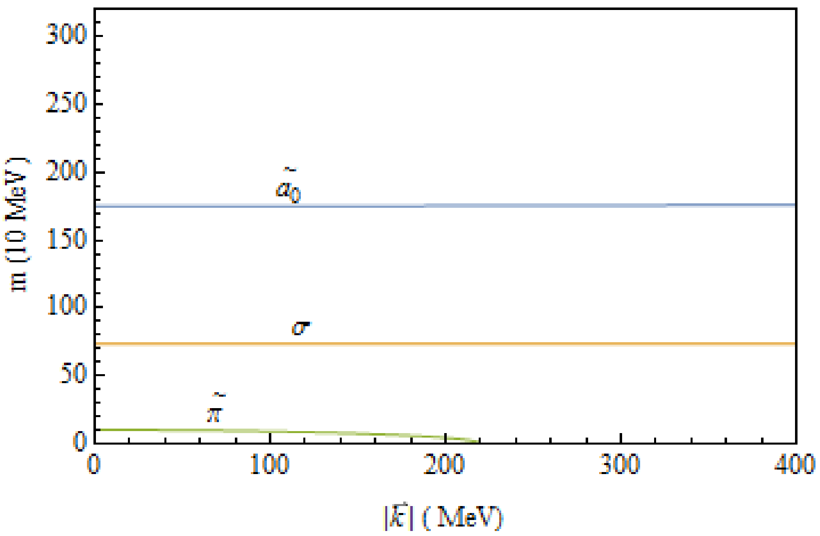
$$m^2_{eff-} = \frac{1}{2}\left(16\,\mu_5^2 + m_a^2 + m_\pi^2 - \sqrt{(16\mu_5^2 + m_a^2 + m_\pi^2)^2 - 4\left(m_a^2\, m_\pi^2 - 16\mu_5^2\,|\vec{k}|^2\right)}\ \right)$$

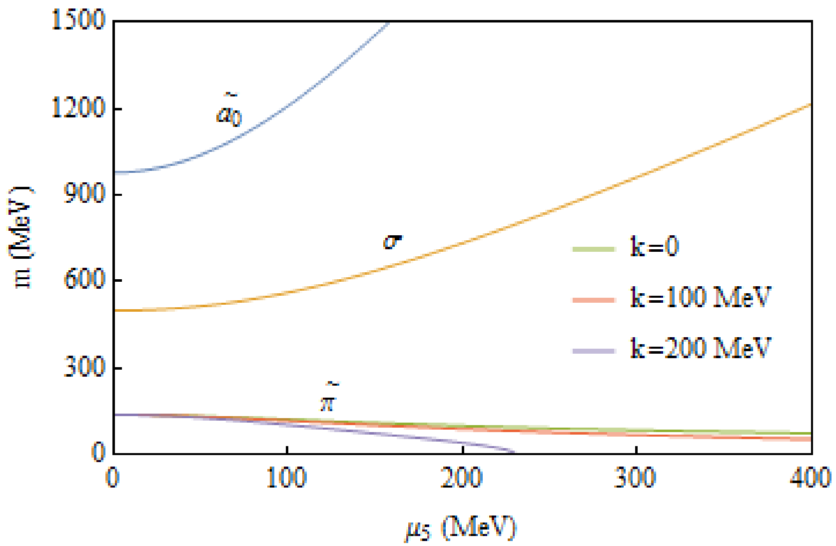
$$m^2_{eff+} = \frac{1}{2}\left(16\,\mu_5^2 + m_a^2 + m_\pi^2 + \sqrt{(16\mu_5^2 + m_a^2 + m_\pi^2)^2 - 4\left(m_a^2\, m_\pi^2 - 16\mu_5^2\,|\vec{k}|^2\right)}\ \right)$$

When $|\vec{k}| > m_1 m_2/(4\mu_5) \equiv k_\pi^c$ $m^2_{eff-} < 0$ but no instability!

"tachyon" in flight

Effective masses of scalar and pseudoscalar states states





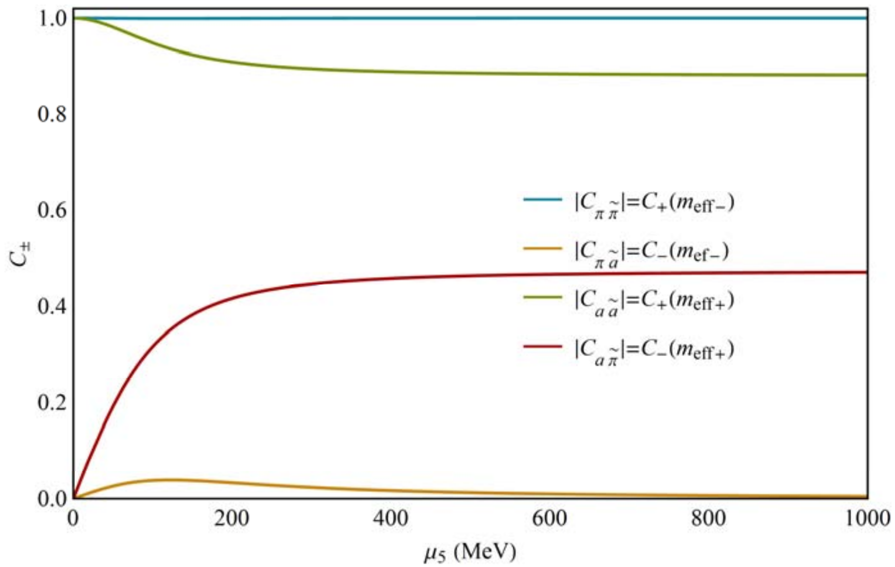
Inflight masses at $\mu_5 = 200\,\mathrm{MeV}$

Massless "pions"
at large chemical potentials

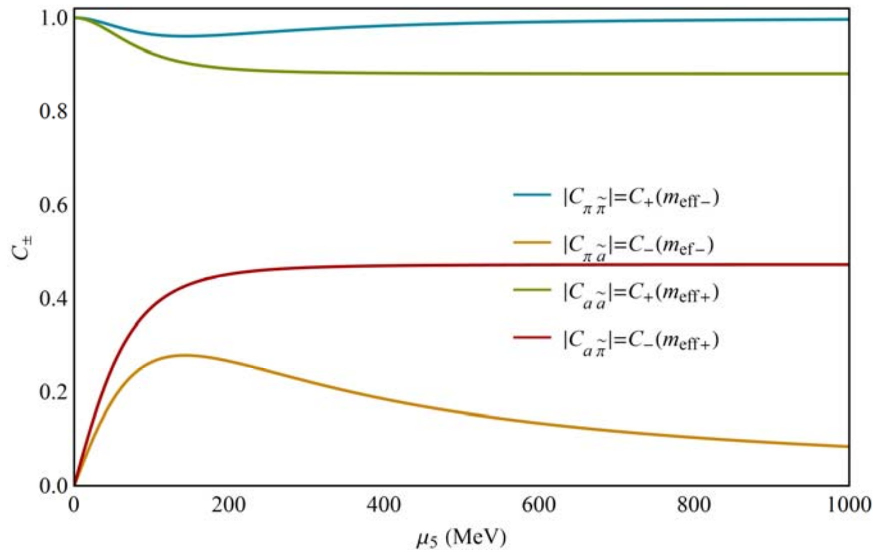
Mixing of scalars and pseudoscalars and their decays
(depending on velocity)

$$\mathrm{a_0 = C_{a\tilde{a}}\tilde{a} + C_{a\tilde{\pi}}\tilde{\pi}}, \quad \pi = \mathrm{C_{\pi\tilde{a}}\tilde{a} + C_{\pi\tilde{\pi}}\tilde{\pi}},$$
$$\mathrm{C_{a\tilde{a}} = iC_{\pi\tilde{\pi}} = C_+}, \quad \mathrm{C_{a\tilde{\pi}} = -iC_{\pi\tilde{a}} = -C_-}$$

$$\mathrm{C_\pm} = \frac{1}{\sqrt{2}}\sqrt{1 \pm \frac{\mathrm{m_a^2 - m_\pi^2}}{\sqrt{(\mathrm{m_a^2 - m_\pi^2})^2 + (8\mu_5 \mathrm{k_0})^2}}}.$$

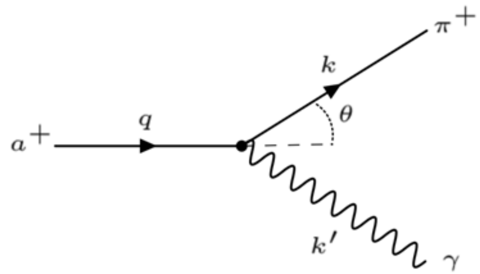


k = 0



k = 1000 MeV

Decays with chiral imbalance: P-even vertices



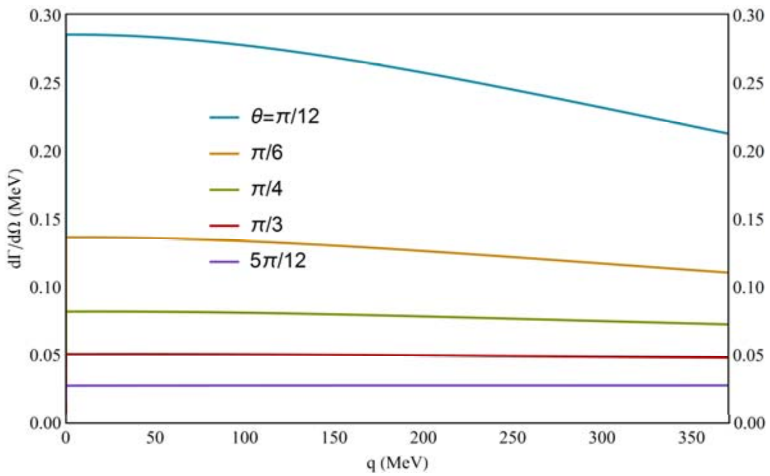
$$\frac{d\Gamma}{d\Omega} = \frac{e^2}{2(2\pi)^2}\frac{1}{f_+(q_{0_+})}\frac{1}{f_-(q'_{0_-}(q'))}\frac{\left(C_-(q_{0_+}^2)\,C_+(q_{0_-}'^2) - C_-(q_{0_-}'^2)\,C_+(q_{0_+}^2)\right)^2}{\sqrt{|q|^2 + |q'^*|^2 - 2\,|q|\,|q'^*|\cos\theta}}\,\frac{|q'|^2}{|Z|}\cdot$$

$$\cdot\left(m_{\mathrm{eff}+}^2 + m_{\mathrm{eff}-}^2 + 2\sqrt{|q|^2 + m_{\mathrm{eff}+}^2(|q|)}\sqrt{|q'|^2 + m_{\mathrm{eff}-}^2(|q'|)} - 2\,|q|\,|q'|\cos\theta\right)$$

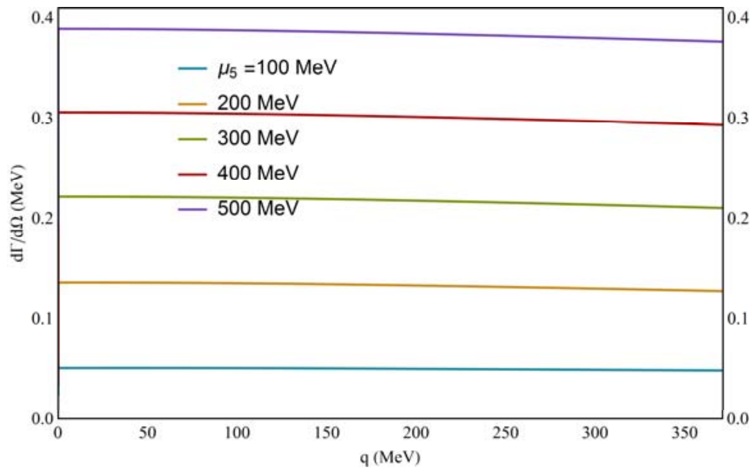
$$Z = \frac{-|q'| + |q|\cos\theta}{\sqrt{|q|^2 + |q'|^2 - 2\,|q|\,|q'|\cos\theta}} - \frac{|q'|}{\sqrt{|q'|^2 + m_{\mathrm{eff}-}^2}\left(1 + \frac{8\mu_5^2}{m_{\mathrm{eff}-}^2 - \frac{1}{2}(m_a^2 + m_\pi^2 + 16\mu_5^2)}\right)}$$

$$f_-(q_{0_-}) = 2q_{0_-} + \frac{32 q_{0_-}\mu_5^2}{\sqrt{(8q_{0_-}\mu_5)^2 + (m_a^2 - m_\pi^2)^2}}$$

Decays with chiral imbalance: P-even vertices



Inflight decays at $\mu_5 = 100$ Mev

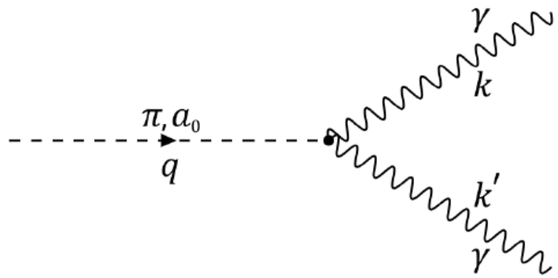


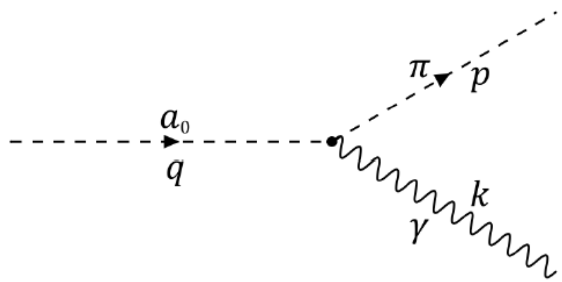
Inflight decays for the angle between a_0 and π equal to 60^o

Wess-Zumino-Witten action

Describing of anomalous decay of strong interaction $\pi \to \gamma\gamma$ and other interaction: $\gamma\pi^- \to \pi^0\pi^-$ and $\gamma \to \pi\pi\pi$

$$-\frac{e^2 N_c}{24\pi^2 f_\pi}\epsilon^{\nu\sigma\lambda\rho}\partial_\sigma A_\lambda \partial_\nu A_\rho \pi^0 \quad (1) \qquad -\frac{ie\mu_5 N_c}{6\pi^2 f_\pi^2}\epsilon_0^{\ \sigma\lambda\rho} A_\rho \partial_\sigma \pi^+ \partial_\lambda \pi^- \quad (2)$$





$\pi^0 \to \gamma\gamma, \quad a_0^0 \to \gamma\gamma$ $\qquad a_0^\pm \to \pi^\pm\gamma$

Wess-Zumino-Witten action

$$\mathbf{W_- = -\frac{iN_c}{96\pi^2}\int_0^1 dx_5 \int d^4x\epsilon^{\mu\nu\sigma\lambda\rho}\, Tr\Big[-j^-_\mu F^L_{\nu\sigma}F^L_{\lambda\rho} - j^+_\mu F^R_{\nu\sigma}F^R_{\lambda\rho}}$$
$$\mathbf{-\frac{1}{2}j^+_\mu F^L_{\nu\sigma}\,U(x_5)F^R_{\lambda\rho}\,U^\dagger(x_5) - \frac{1}{2}j^+_\mu F^R_{\nu\sigma}\,U^\dagger(x_5)F^L_{\lambda\rho}\,U(x_5)}$$
$$\mathbf{+iF^L_{\mu\nu}\,j^-_\sigma j^-_\lambda j^-_\rho + iF^R_{\mu\nu}\,j^+_\sigma j^+_\lambda j^+_\rho + \frac{2}{5}j^-_\mu j^-_\nu j^-_\sigma j^-_\lambda j^-_\rho\Big]}$$

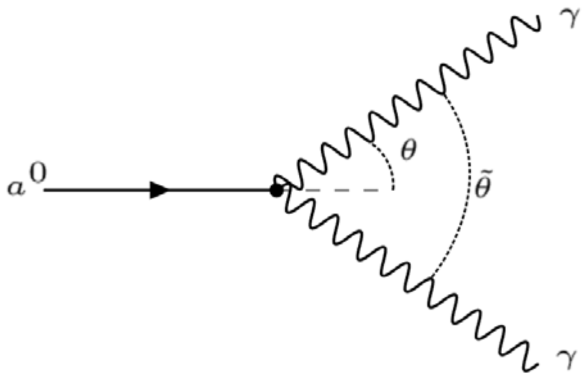
The two vertices are of most interest,

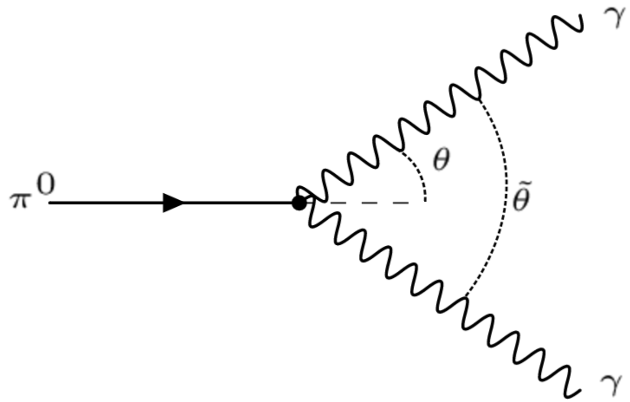
$$\mathbf{\frac{ie\,\mu_5 N_c}{6\pi^2\,v^2}\,\epsilon_4{}^{5\sigma\lambda\rho}\,A_\rho\partial_\sigma\pi^+\,\partial_\lambda\pi^- - \frac{e^2N_c}{24\,\pi^2 v}\,\epsilon^{5\nu\sigma\lambda\rho}\,\partial_\sigma A_\lambda\partial_\nu A_\rho\pi^0}$$

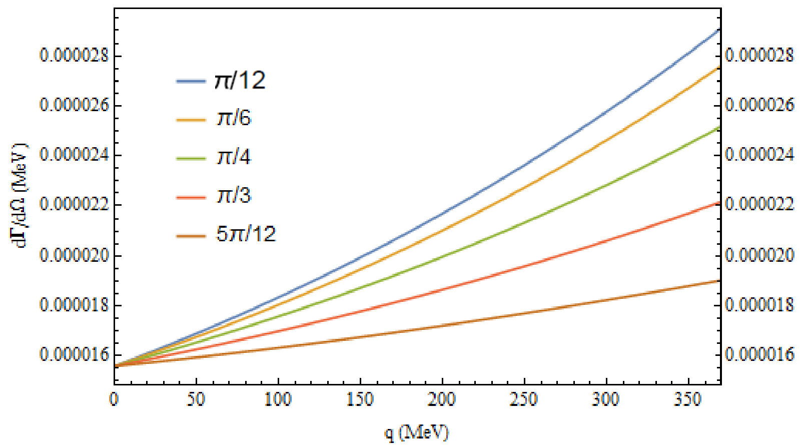
M. Kawaguchi, M. Harada, S. Matsuzaki and R. Ouyang, 1612.00616 [nucl-th].

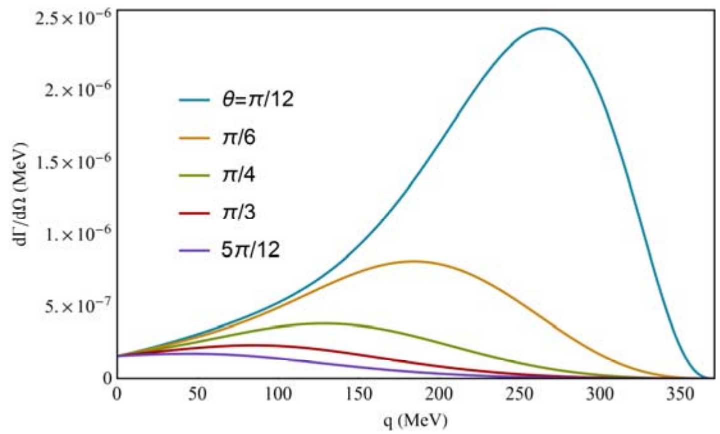
More inspirations of chiral effects induced by WZW action see in: K.Fukuzhima and K.Mameda, Phys.Rev. D86 (2012) 071501

Decays with chiral imbalance: P-odd vertices



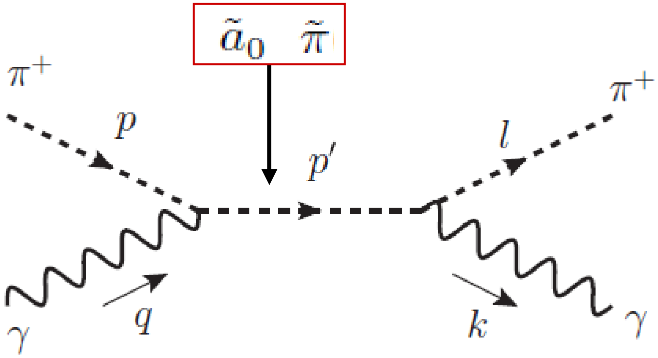


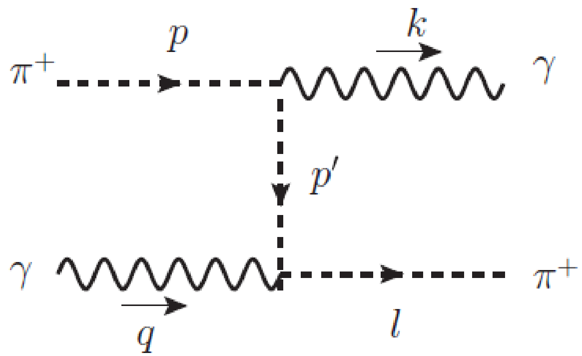




$$\mu_5 = 100MeV$$

M. Kawaguchi, M. Harada, S. Matsuzaki, R. Ouyang , PHYS. REV. C 95, 065204 (2017)





processes are parity conjugate:

$$\pi^{\pm}(\vec{p}) + \gamma(\vec{q}) \to \pi^{\pm}(\vec{l}) + \gamma_{+}(\vec{k}),$$
$$\pi^{\pm}(-\vec{p}) + \gamma(-\vec{q}) \to \pi^{\pm}(-\vec{l}) + \gamma_{-}(-\vec{k}),$$

where $\pm$ attached on photons in the final state denote photon helicities.

asymmetry ($\mathcal{A}$) can be evaluated as

$$\mathcal{A} = \left| \frac{\mathcal{N}_{+} - \mathcal{P}[\mathcal{N}_{+}]}{\sum_{\lambda}\{\mathcal{N}_{\lambda} + \mathcal{P}[\mathcal{N}_{\lambda}]\}} \right|,$$

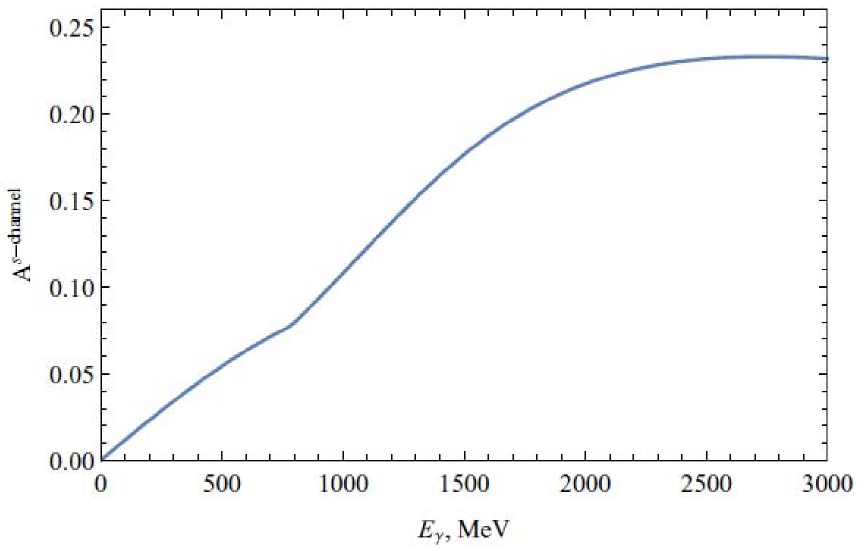
where $\mathcal{N}_{\lambda}$ stands for the number of events per the phase space, $d\,E_{\gamma}\,d\cos\theta\,d\phi$, for the parity conjugate processes with the helicity λ and the photon energy E_{γ} in the final state. The symbol $\mathcal{P}$ acts as the parity conjugation projection. The denominator represents the total number of the $\pi^{\pm}\gamma$ emission events with unpolarized photons per the phase space.

Our prediction:
Scalar resonance enhancement!

$$\mathcal{A}^{s\text{-channel}}\Big|_{\max} = \frac{\mu_5 E_{\pi} N_c}{6\pi^2 f_{\pi}^2} \simeq 0.2 \times \left(\frac{\mu_5}{200\ \text{MeV}}\right)\left(\frac{E_{\pi}}{1\ \text{GeV}}\right)$$

Asymmetry in photon polarizations

$\pi^+\gamma \to a_0^{+*} \to \pi^+\gamma$



Asymmetry, $\mu_5 = 200$ MeV, $E_{\pi 2} = 1$ GeV

Effective meson theory in a medium with LPB

- Vector mesons

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

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

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 ($\mu \gg T$) [FAIR, NICA]

Effective meson theory in a medium with LPB

Massive MCS electrodynamics for vector mesons

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

In momentum space wave Eqs.

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

Energy spectrum:

Transversal polarizations

$$\begin{aligned} K^\mu_\nu\,\varepsilon^\nu_\pm(k) &= \left(k^2 - m^2 \pm \sqrt{\mathtt{D}}\right)\varepsilon^\mu_\pm(k); \\ \omega_{\mathbf{k},\pm} &= \sqrt{\mathbf{k}^2 + m^2 \pm \zeta_0|\mathbf{k}|}; \quad \zeta_\mu = (\zeta_0, 0, 0, 0) \end{aligned}$$

Longitudinal polarization

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

Vector Meson spectrum in PB medium

After diagonalization of mass matrix

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

where $\epsilon = 0, \pm 1$ is the meson polarization.
The photon itself happens to be unaffected by a **singlet** $\hat{\zeta}$.
The position of the poles for $\pm$ polarized mesons is changing with wave vector $|\vec{k}|$.
Massive vector mesons split into three polarizations with masses $m^2_{V,+} < m^2_{V,L} < m^2_{V,-}$.

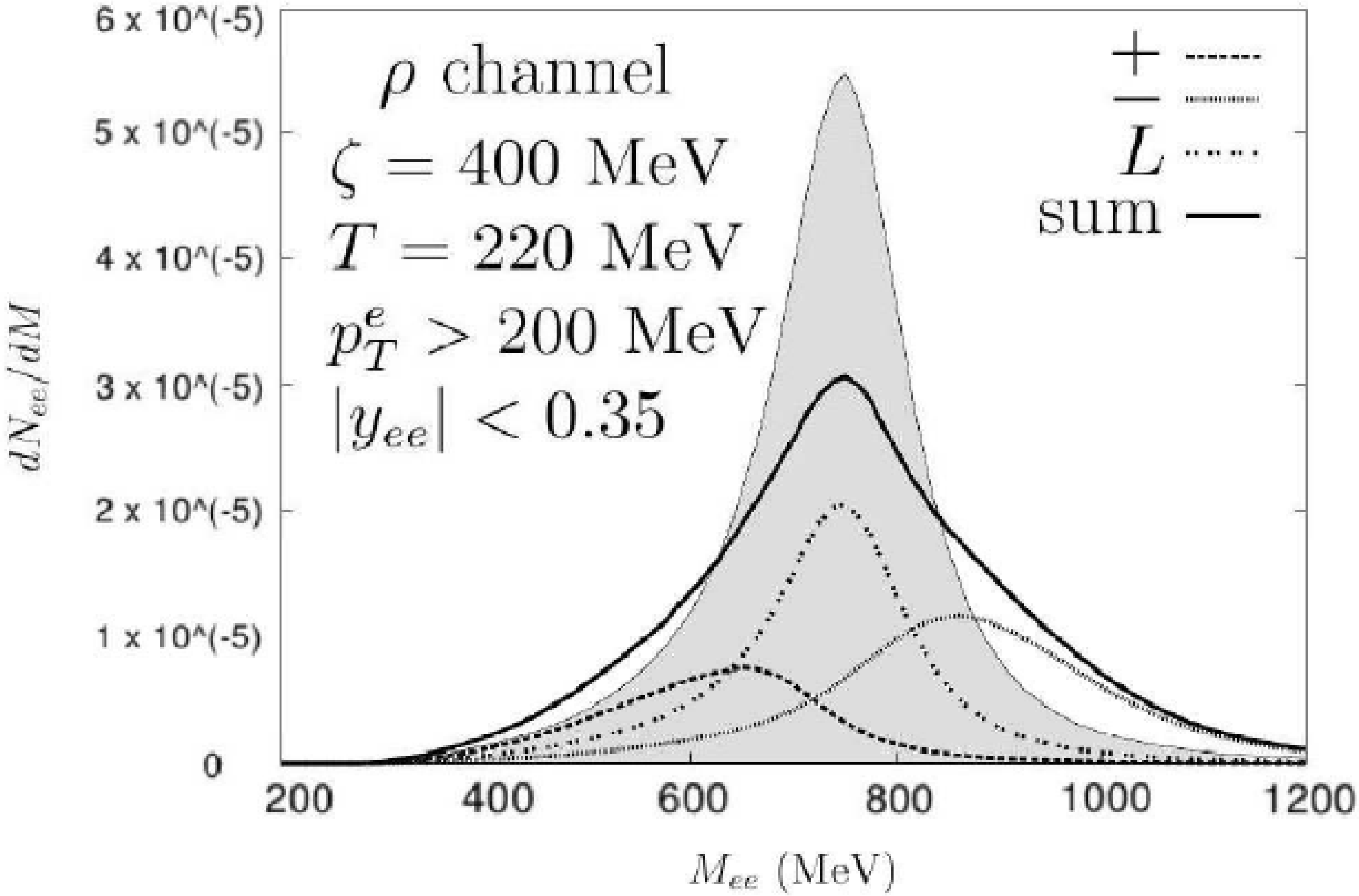
This splitting unambiguously signifies LPB. Can it be measured?

$\rightarrow$ dilepton production in HIC from the decays $\rho, \omega \rightarrow e^+e^-$

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

Manifestation of LPB in heavy ion collisions

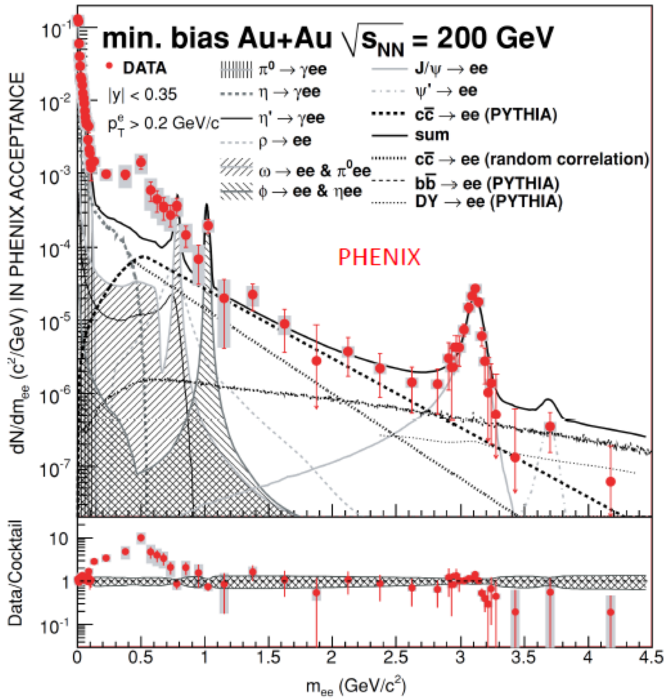
ρ spectral function

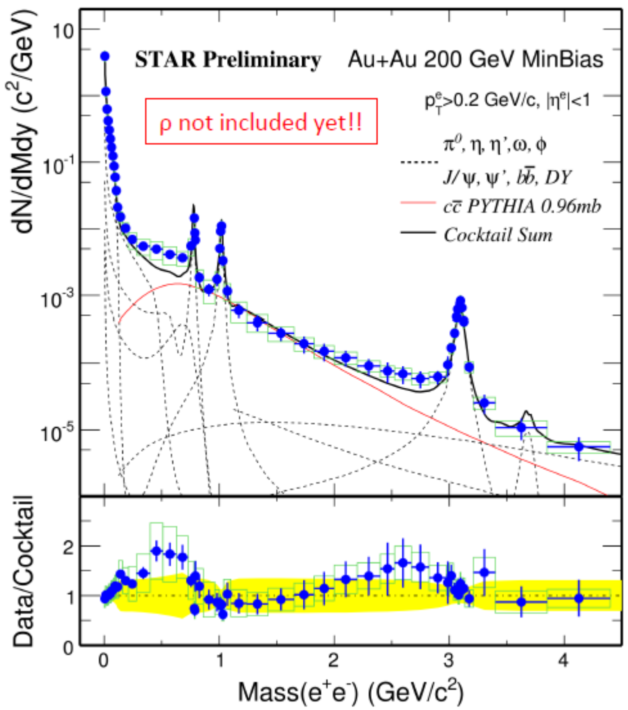


Polarization splitting in ρ spectral function for LPB $\zeta = 400$ MeV ($\mu_5 = 290$ MeV) compared with $\zeta = 0$ (shaded region).

POLARIZATION ASYMMETRY!!

Hints in dilepton excess?





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

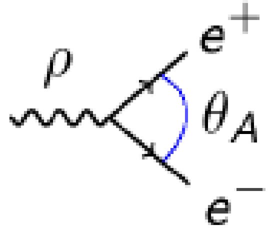
Thus arises the question.

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

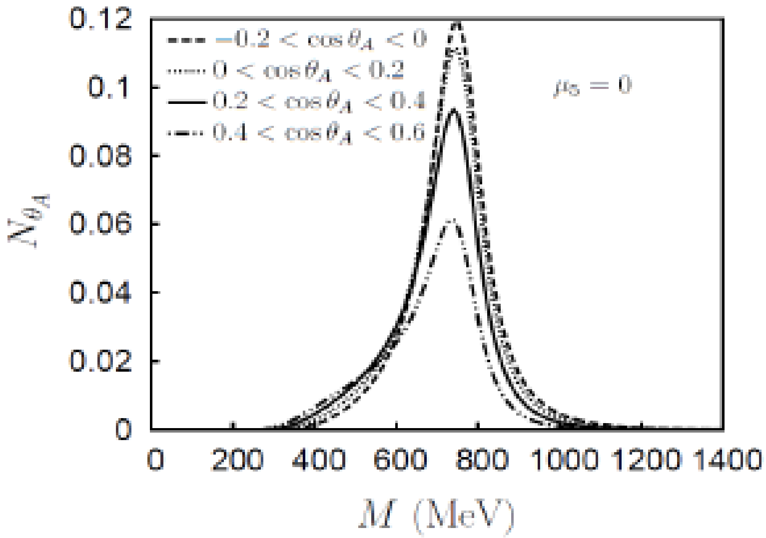
(details see **A.A. Andrianov, V. A. Andrianov, D. Espriu, and X. Planells, Phys. Rev. D, 90 (2014), 034024).**

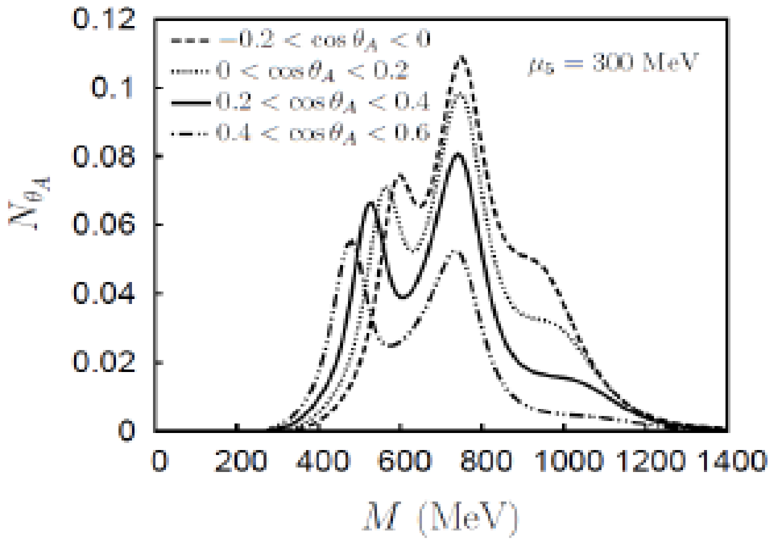
Observables sensitive to P-odd effects

- 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 transitions ("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. There are observables unambiguously indicating LPB (ALICE LHC?)