

# Нарушение P-четности В СТОЛКНОВЕНИЯХ ТЯЖЕЛЫХ ИОНОВ

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Физика частиц при средних и высоких энергиях  
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НИЦ "Курчатовский институт" - ИФВЭ, зд.ОТФ

# CP violation in QCD

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^{\mu\nu,a}G_{\mu\nu}^a + \bar{q}(i\gamma^\mu D_\mu - m)q,$$

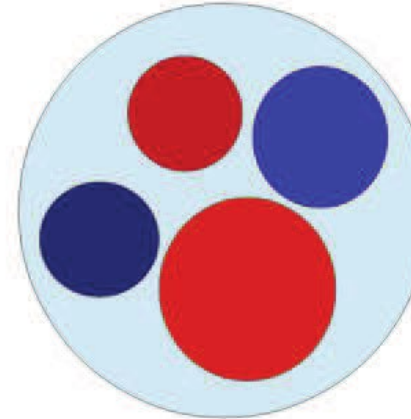
$$D_\mu = \partial_\mu - igG_\mu^a\lambda^a, \quad G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + gf^{abc}G_\mu^b G_\nu^c$$

▣  $\theta$ -term 
$$\Delta\mathcal{L}_\theta = \theta \frac{g^2}{16\pi^2} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right)$$

▣ strong CP problem  $\theta \lesssim 10^{-9}$ .

▣ P – and CP – odd bubbles may appear in a finite volume due to large topological fluctuations in a hot medium

▣ Gauge field configurations can be characterized by an integer topological (invariant) charge



## *CP violation in QCD*

▣ In QCD topologically non-trivial configurations of gauge fields can exist (instantons)

▣ Gauge field configurations can be characterized by an integer topological (invariant) charge

$$T_5 = \frac{g^2}{16\pi^2} \int_{t_i}^{t_f} dt \int_{\text{vol.}} d^3x \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right) \in \mathbb{Z}$$

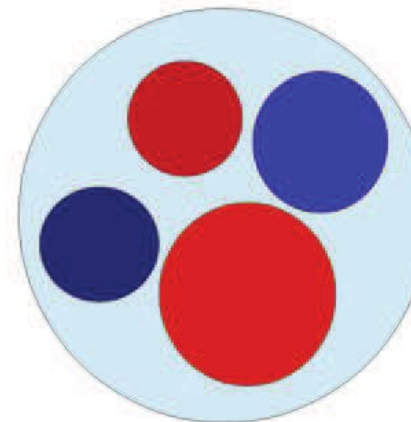
▣ Statistical treatment: with chemical potential  $\mu$

The local partial conservation of the axial current is afflicted by gluon anomaly

$$\partial^\mu J_{5,\mu} - 2i\bar{q}\hat{m}_q\gamma_5q = \frac{N_f g^2}{8\pi^2} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right),$$

$$\frac{d}{dt} (Q_5^q - 2N_f T_5) \simeq 2i \int_{\text{vol.}} d^3x \bar{q}\hat{m}_q\gamma_5q, \quad Q_5^q = \int_{\text{vol.}} d^3x \bar{q}\gamma_0\gamma_5q.$$

$$\langle T_5 \rangle = \frac{1}{2N_f} \langle Q_5^q \rangle \iff \mu_5 = \frac{1}{2N_f} \mu_\theta.$$

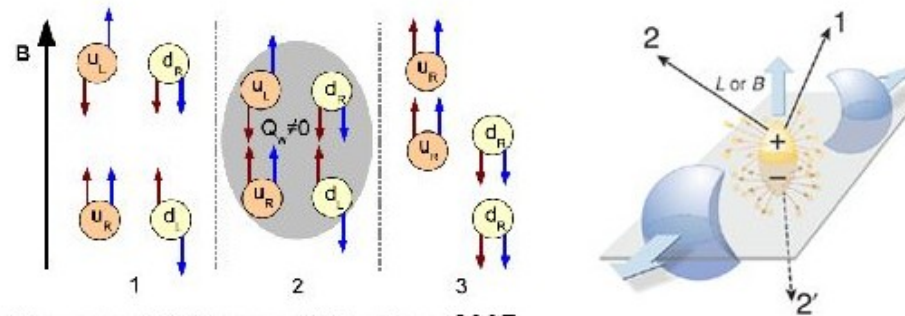


It must survive for a sizeable lifetime in a heavy-ion fireball,

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

# Observables for Local parity violation in QCD

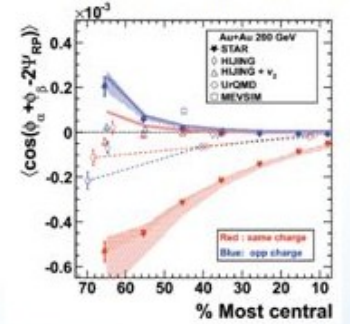
## Chiral Magnetic Effect (CME)



Kharzeev, L. McLerran, H. Warringa, 2007

Fukushima, D. Kharzeev, and H. Warringa. Phys. Rev. D, 78, 074033 (2008).

(STAR Collaboration)



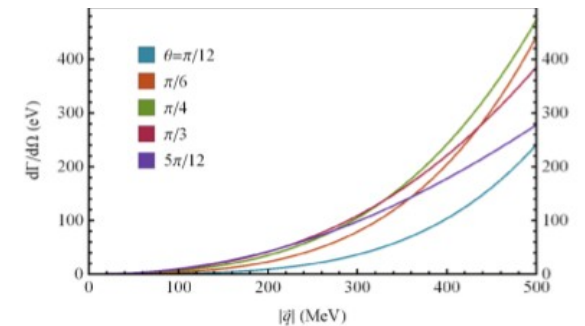
Effective meson theory in a medium with LPB

The decays  $\tilde{a}_0^\pm \rightarrow \tilde{\pi}^\pm \gamma$ ,

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

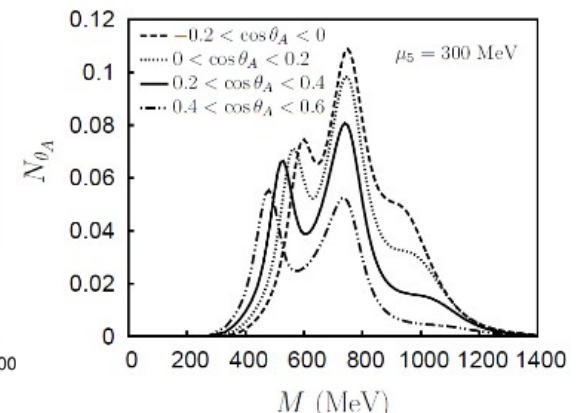
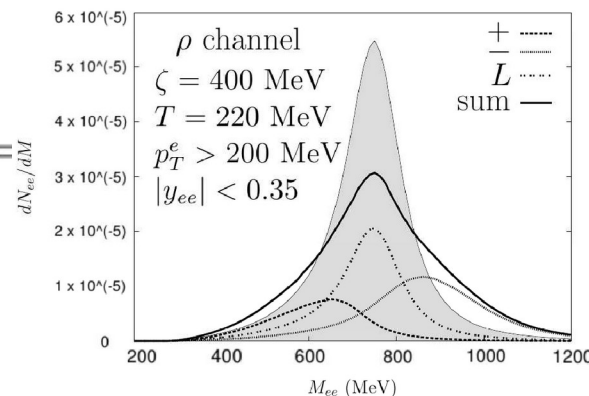
$$m_1^2 = -2[M^2 - 2(3\lambda_1 + \lambda_2)v_q^2 - \lambda_2 v_s^2 - cv_s + 2\mu_5^2]$$

$$m_2^2 = \frac{2m}{v_q} B.$$



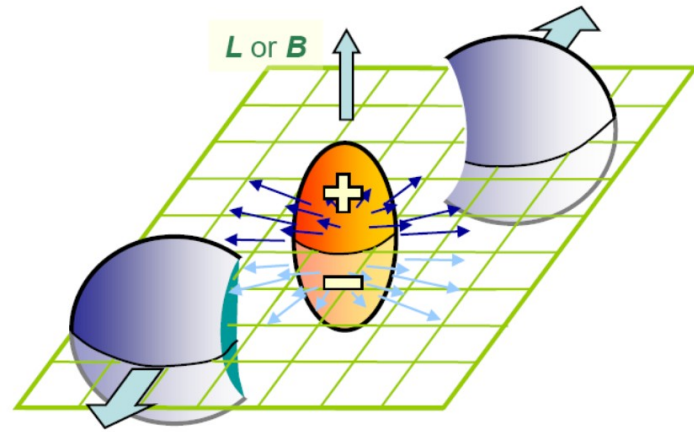
A. A. Andrianov, V. A. Andrianov, D. Espriu, A.V. Iakubovich, A.E. Putilova EPJ Web of Conf. 158, 03012 (2017)

Vector meson polarization split VMD +  $\mathcal{L}_{CS}$  angular analysis in di-lepton decays



A. Andrianov, V. Andrianov, D. Espriu, EPJ Web of Conferences 137, 01005 (2017), Xumeu Planells, arXiv:1411.3283 [hep-ph]

# Chiral Magnetic Effect (CME)



CME searches is the charge-dependent three-point azimuthal correlator

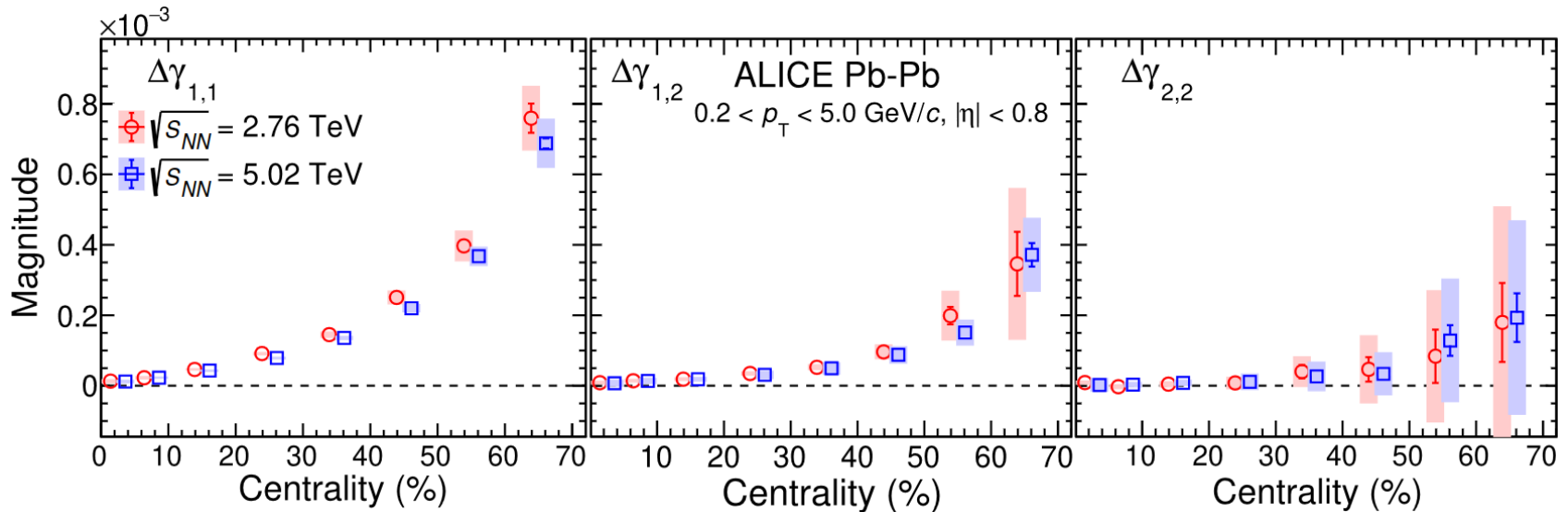
$$\begin{aligned}\gamma_{\alpha\beta} &\equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{\text{RP}}) \rangle \\ &= \langle \cos \tilde{\phi}_\alpha \cos \tilde{\phi}_\beta \rangle - \langle \sin \tilde{\phi}_\alpha \sin \tilde{\phi}_\beta \rangle\end{aligned}$$

$$\tilde{\phi} = \phi - \psi_{\text{RP}}.$$

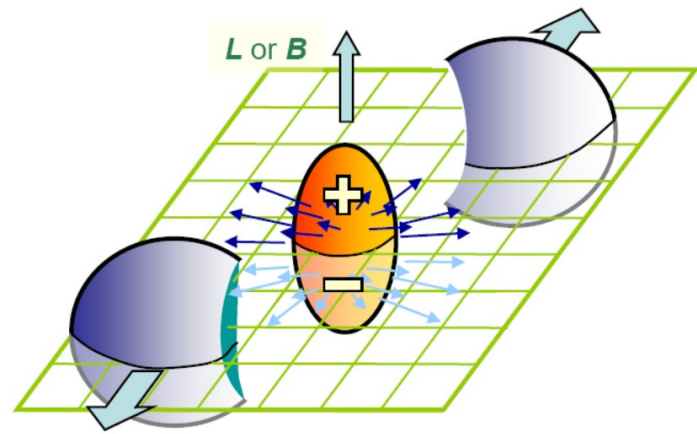
$$\Delta\gamma \equiv \gamma_{\text{OS}} - \gamma_{\text{SS}} \quad f_{\text{CME}} \equiv \frac{\Delta\gamma_{\text{CME}}}{\Delta\gamma}.$$

FIG. 1. Schematic view of a heavy-ion collision. The charge separation happens along the magnetic field indicated by the upward arrow. The direction of the charge separation fluctuates in accord with the sign of the topological charge. Drawing is from Ref. [22].

[22] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 81, 054908 (2010).



# Chiral Magnetic Effect (CME)



## Backgrounds

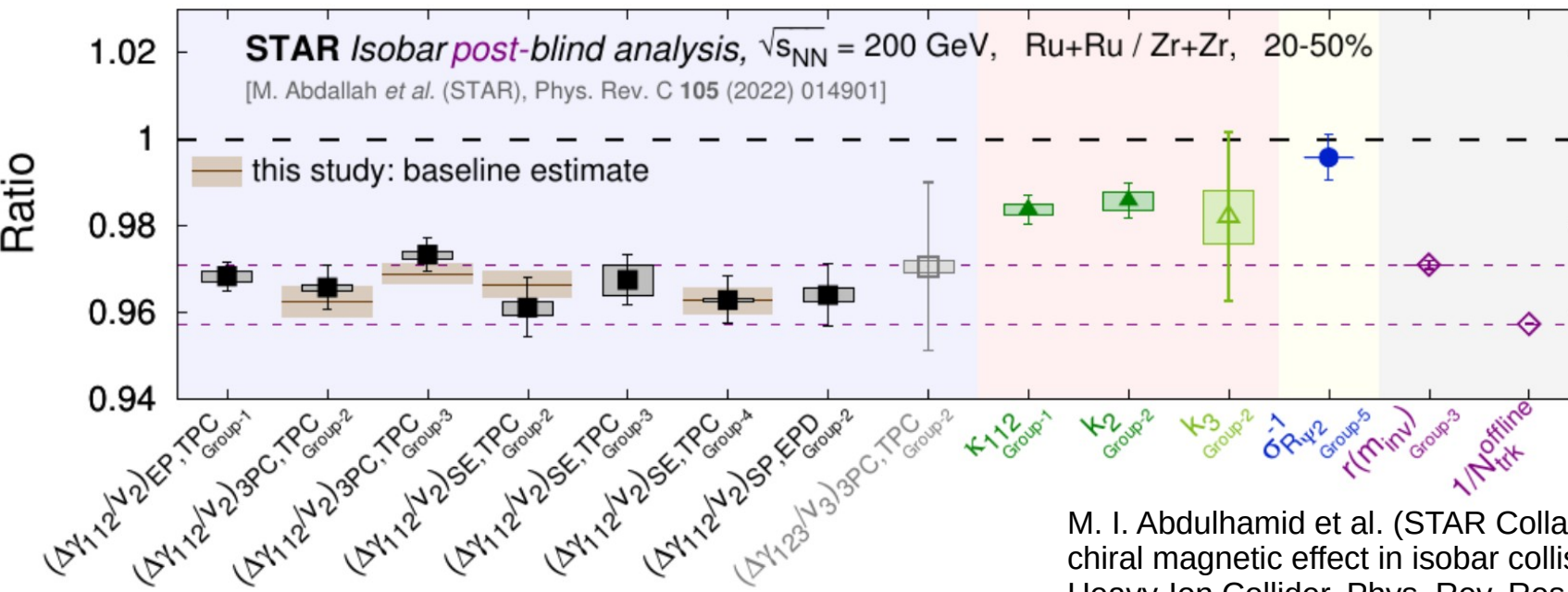
### Major backgrounds

1. Reaction-plane-dependent (flow-induced) background: local charge conservation in flowing clusters
2. Nonflow and reaction-plane-independent background: (mini-)jets, resonance decays, etc
3. Vector meson spin alignment ( $\phi$ ,  $\rho^0$ -meson)

## Solution: isobar collisions ?

same background, different magnetic-field-dependent contribution

FIG. 1. Schematic view of a heavy-ion collision. The charge separation happens along the magnetic field indicated by the upward arrow. The direction of the charge separation fluctuates in accord with the sign of the topological charge. Drawing is from Ref. [22].  
[22] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 81, 054908 (2010).



M. I. Abdulhamid et al. (STAR Collaboration), Upper limit on the chiral magnetic effect in isobar collisions at the Relativistic Heavy-Ion Collider, Phys. Rev. Res. 6, L032005 (2024).

# Observables for Local parity violation in QCD

## in central AA collisions

Parity forbidden decays  
of light scalar mesons

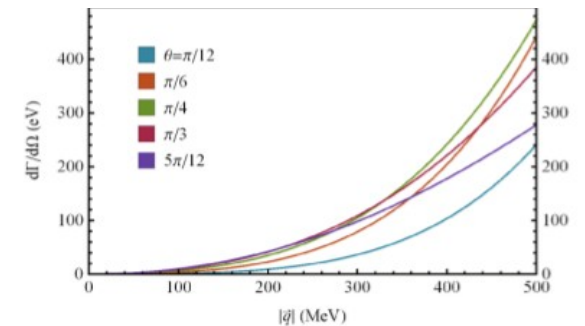
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$$m_1^2 = -2[M^2 - 2(3\lambda_1 + \lambda_2)v_q^2 - \lambda_2 v_s^2 - cv_s + 2\mu_5^2]$$

$$m_2^2 = \frac{2m}{v_q} B.$$

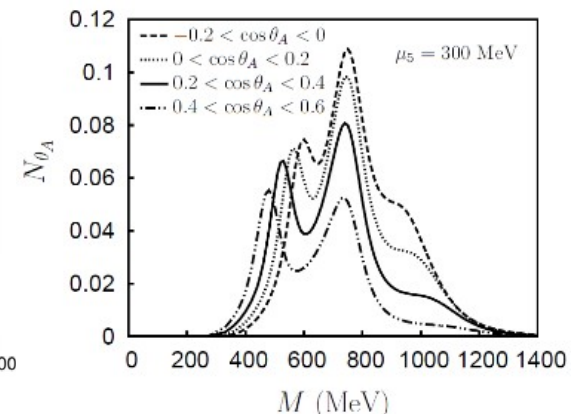
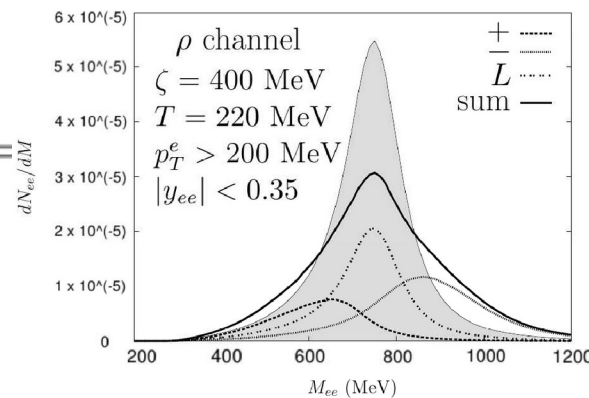
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A. A. Andrianov, V. A. Andrianov, D. Espriu, A.V. Iakubovich, A.E. Putilova EPJ Web of Conf. 158, 03012 (2017)

Vector meson  
polarization split  
angular analysis  
in di-lepton decays

VMD  
VDM +  $\mathcal{L}_{CS}$



A. Andrianov, V. Andrianov, D. Espriu, EPJ Web of Conferences 137, 01005 (2017), Xumeu Planells, arXiv:1411.3283 [hep-ph]

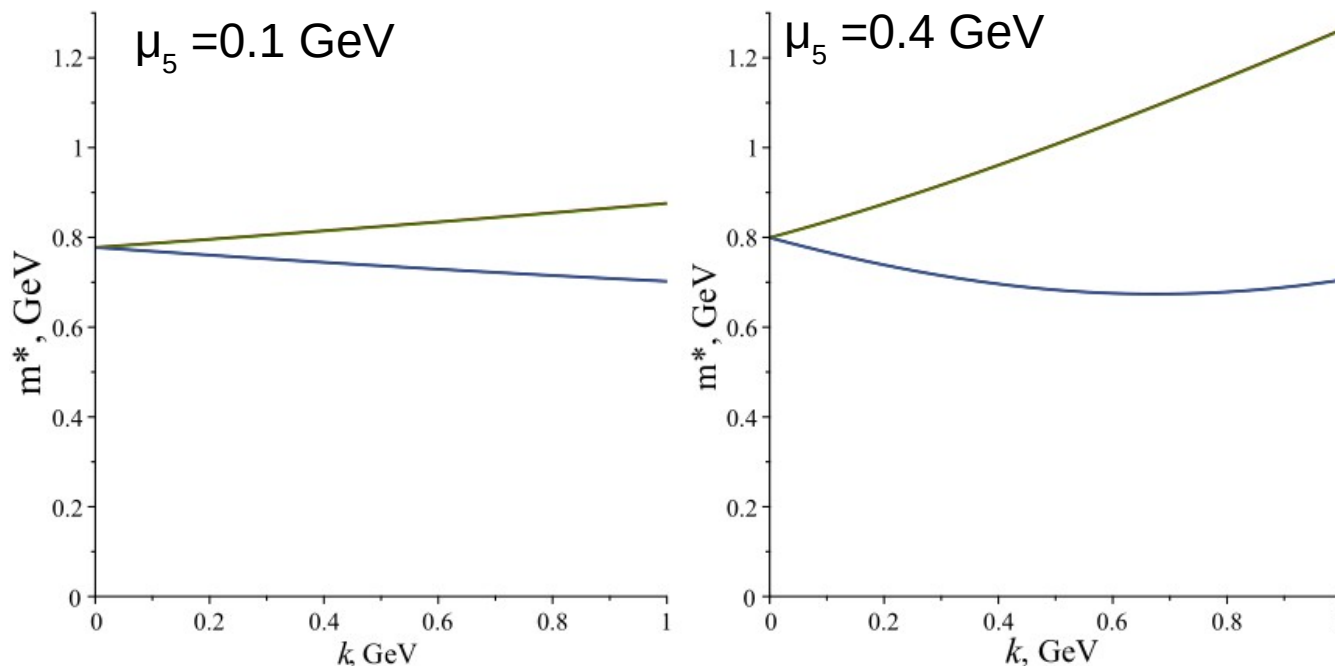
## Vector meson dominance in LPB medium

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

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{kin}} - \frac{1}{4}\varepsilon V_{\mu\nu}\varepsilon V^{\mu\nu} + \frac{1}{2}\varepsilon m^2 V_\nu V^\nu + \varepsilon \frac{b^\lambda b^\nu}{2b^2} V_{\lambda\rho} V_\nu^\rho - \frac{N_c}{8\pi^2} b_\mu V_\nu \varepsilon^{\mu\nu\lambda\rho} V_{\lambda\rho}$$

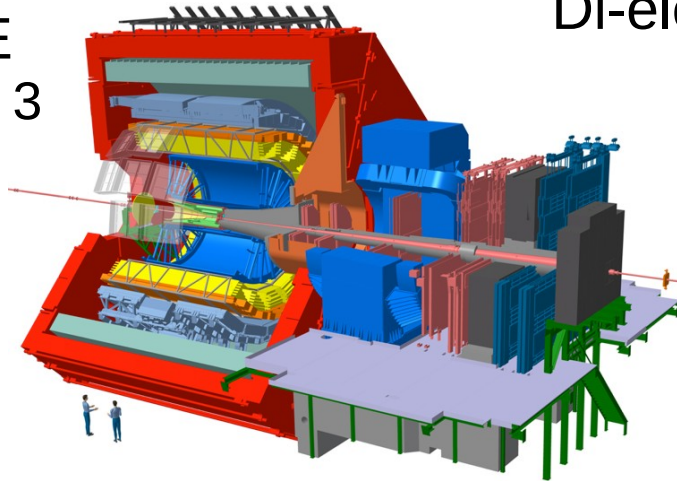
Mass of the transverse polarisations for  $\rho$  and  $\omega$  mesons

$$k_0^2 - |\vec{k}|^2 \equiv m_*^2 = \bar{m}^2 \pm \zeta b_0 |\vec{k}| + \xi b_0^2 |\vec{k}|^2 / m^2$$



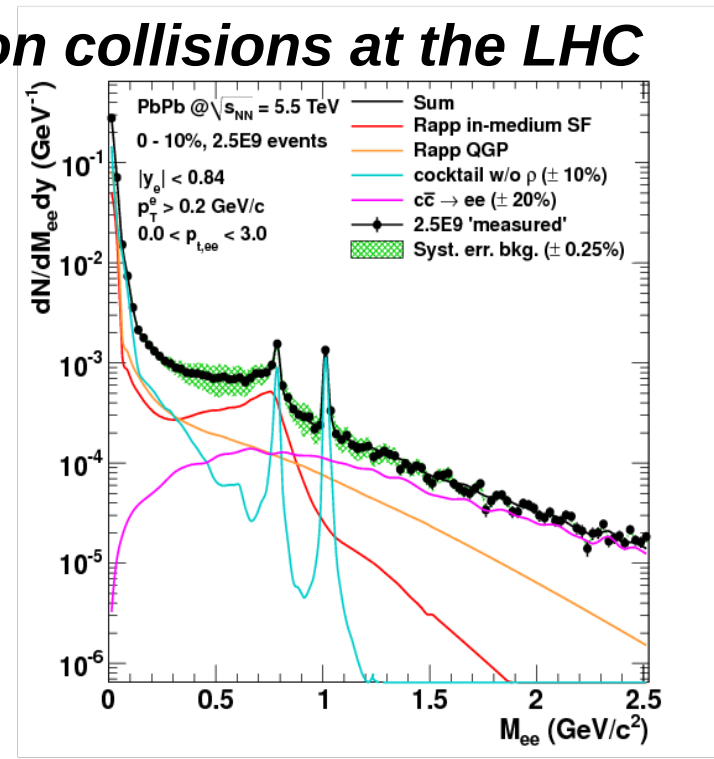
# Experimental possibilities in heavy ion collisions at the LHC

ALICE  
in Run 3



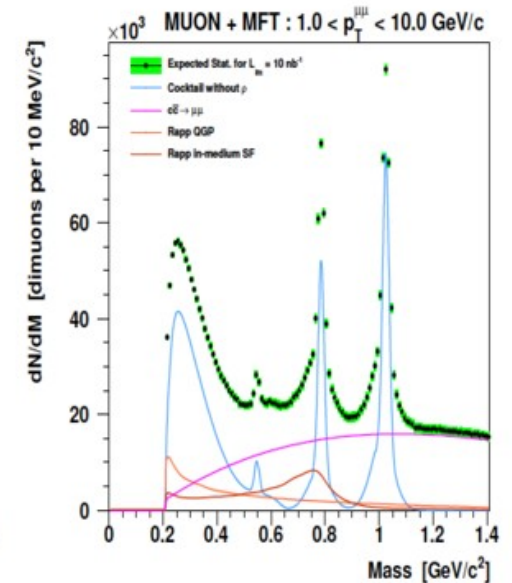
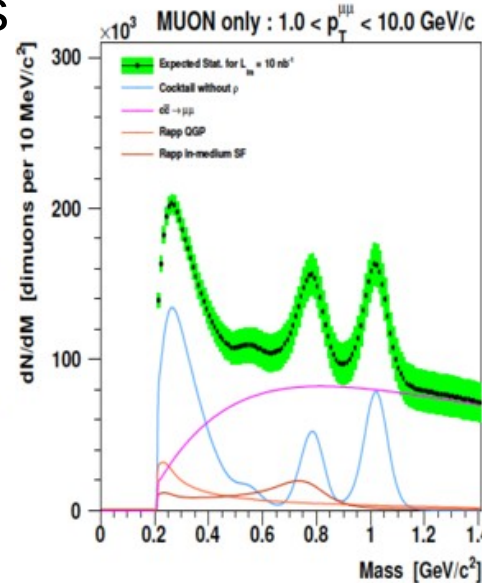
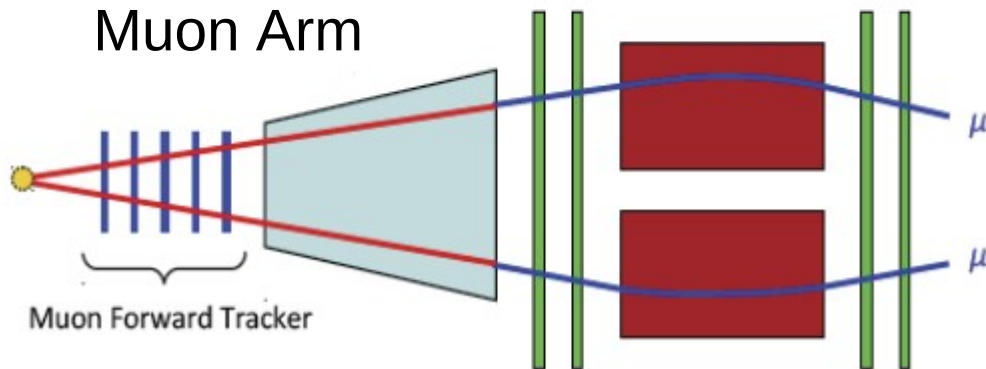
Di-electrons

e+ e- in ITC+TPC,  
combined PID + MVA (ml) methods



Technical Design Report for the Upgrade of the ALICE Inner Tracking System

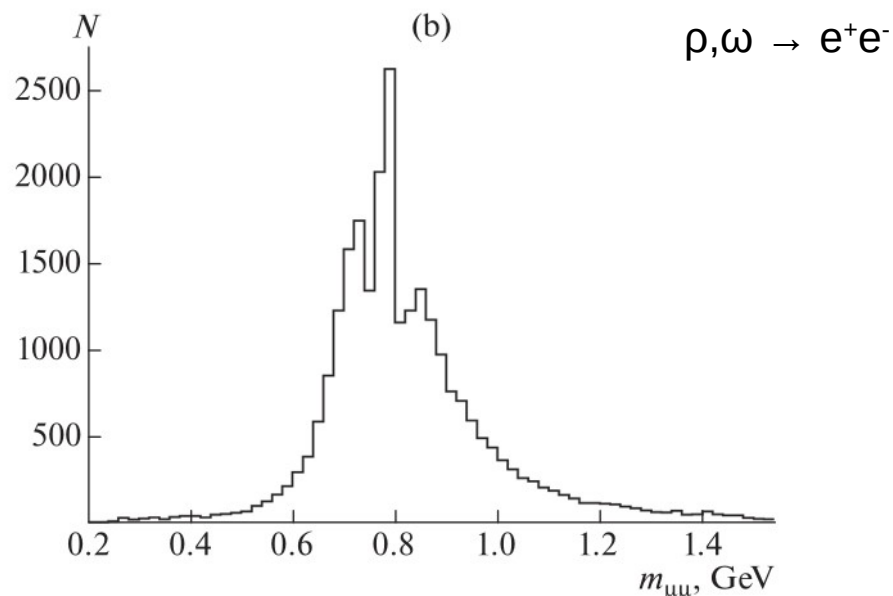
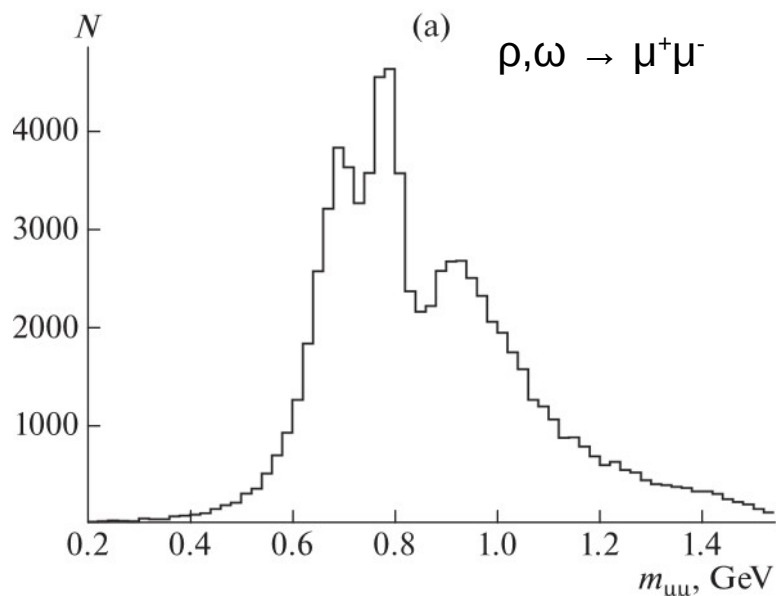
Di-muons



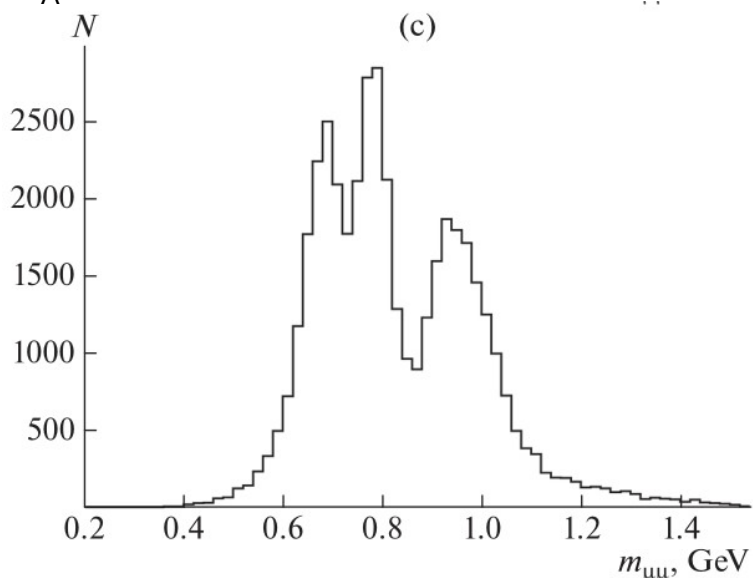
# Pythia 8.2, Monte Carlo in ALICE Run 3 conditions (with detector response resolution) - Pb-Pb at 5.02 TeV

All:  $\mu_5 = 0.1$  GeV

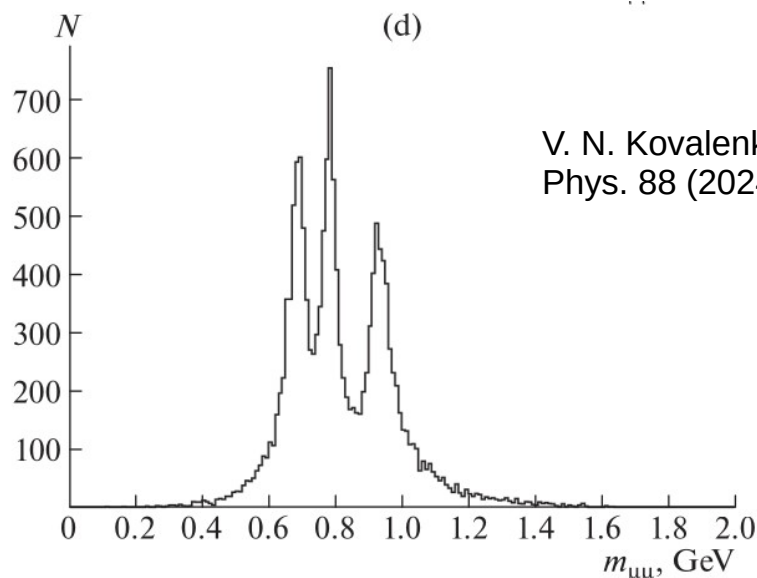
No angular  $\theta_A$  selection



$0.4 < \cos \theta_A < 0.5$  (for muons — boost to midrapidity applied)



$p_{T\mu} > 0.2$  GeV,  $p_{T\mu\mu} > 0.4$  GeV

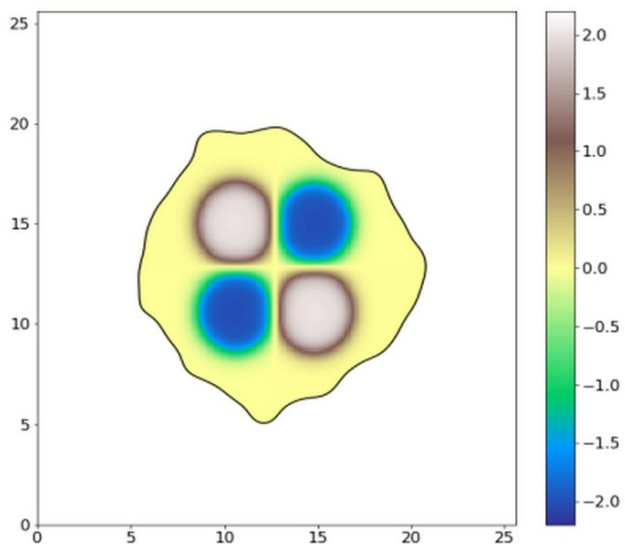


$p_{Te} > 0.1$  GeV,  $p_{Te\mu\mu} > 0.4$  GeV

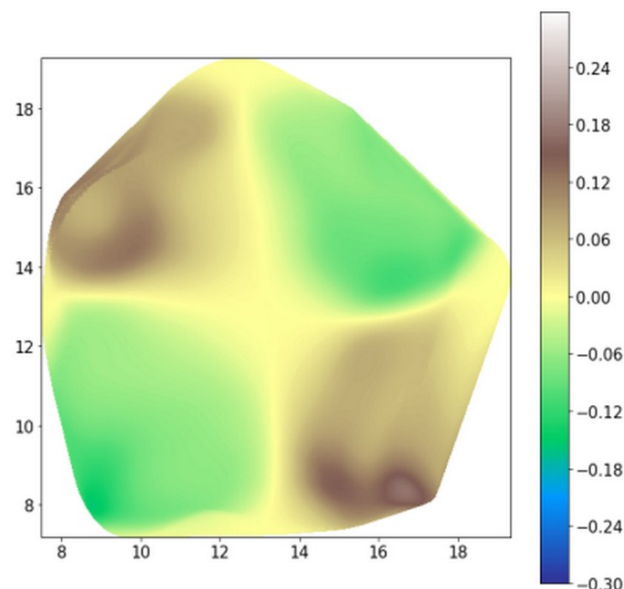
V. N. Kovalenko, Bull. Russ. Acad. Sci. Phys. 88 (2024) 11, 1800-1805.

# Axial charge density evolution

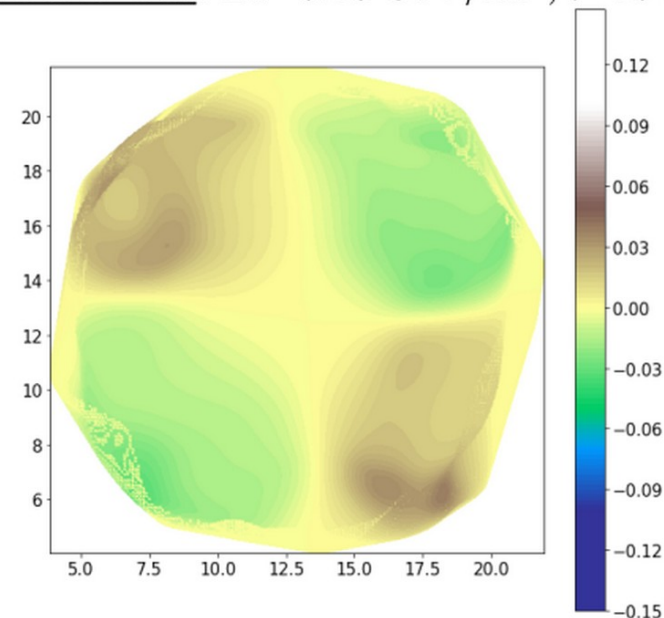
Initial  $Ed \sim 60 \text{ GeV}/\text{fm}^3$   $\tau = 0.6 \text{ fm}$



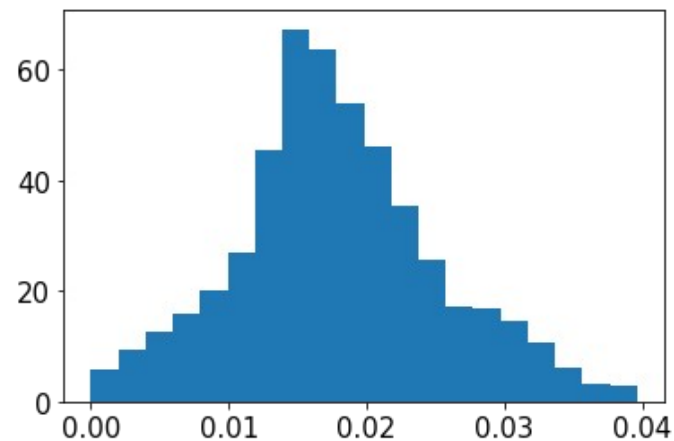
$Ed = 0.98 \text{ GeV}/\text{fm}^3$ ,  $\tau \approx 6 \text{ fm}$



freeze-out:  $Ed = 0.18 \text{ GeV}/\text{fm}^3$ ,  $\tau \approx 10 \text{ fm}$



Regions of local axial charge excess survive throughout the entire hydro-dynamical evolution of the medium



V. Kovalenko, Int. J. Mod. Phys. E 33, 2450037 (2024).

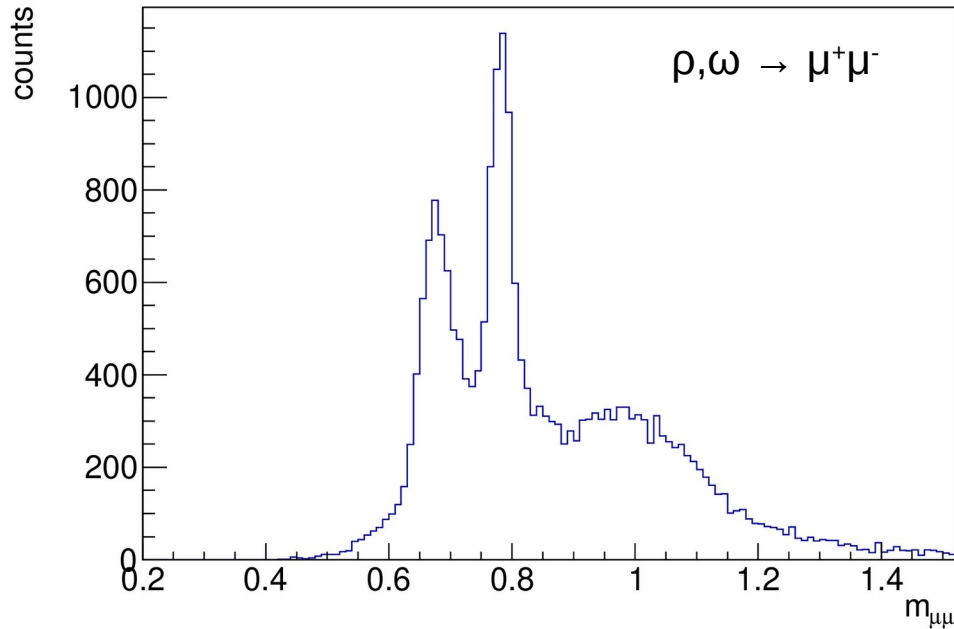
$\langle |\rho_5| \rangle = 0.018 \text{ fm}^{-3}$ ,  $\sigma = 0.007 \text{ fm}^{-3}$   
 relative error  $\sigma_{|\rho_5|} / \langle |\rho_5| \rangle = 0.4$

Calculations in relativistic viscous hydrodynamics MUSIC (boost-invariant) + AVFD

# Influence of the $\mu_5$ fluctuation on the observation of polarization splitting

$$\mu_5 \sim \exp\left(-\frac{1}{2} \frac{(\mu_5 - \langle \mu_5 \rangle)^2}{\sigma_{\mu_5}^2}\right) \quad \text{with mean } \mu_5 = 0.15 \text{ GeV and } \sigma = 0.06 \text{ GeV}$$

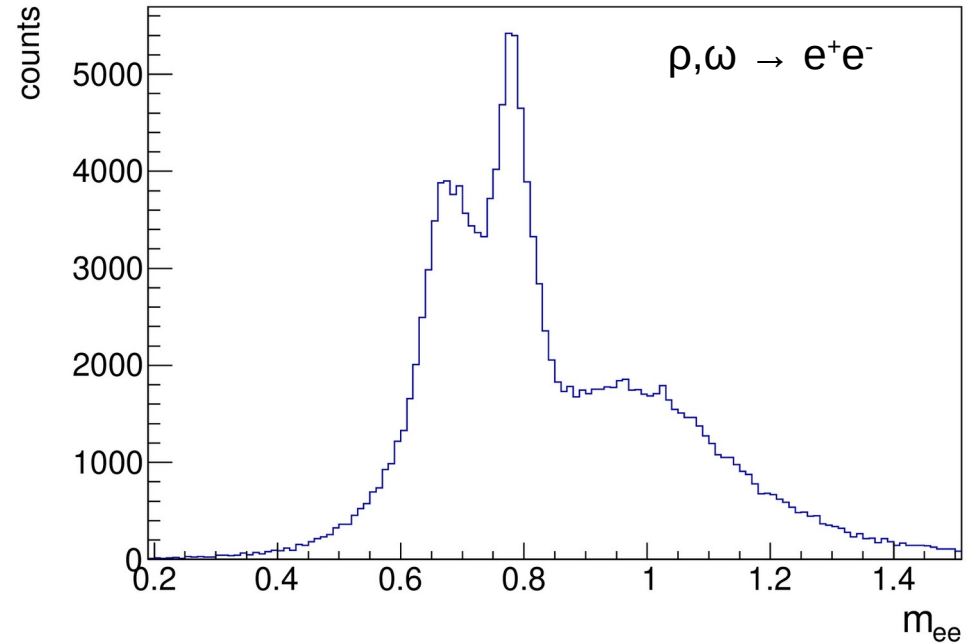
( or  $\sigma/\langle \mu_5 \rangle = 0.4$  )



$p_{T\mu} > 0.5 \text{ GeV}, p_{T\mu\mu} > 0.5 \text{ GeV}$

$0.4 < \cos \theta_A < 0.5$

ALICE Run 3 experimental conditions



$p_{Te} > 0.15 \text{ GeV}, p_{Te e} > 0.4 \text{ GeV}$

$0.4 < \cos \theta_A < 0.5$

Smearing:

Viscous effects

Chern-Simons relaxation:

Charge separation survives

# New Possibilities

## Parity forbidden decays

Effective meson theory in a medium with LPB

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

$$m_1^2 = -2[M^2 - 2(3\lambda_1 + \lambda_2)v_q^2 - \lambda_2 v_s^2 - cv_s + 2\mu_5^2]$$

$$m_2^2 = \frac{2m}{v_q} B.$$

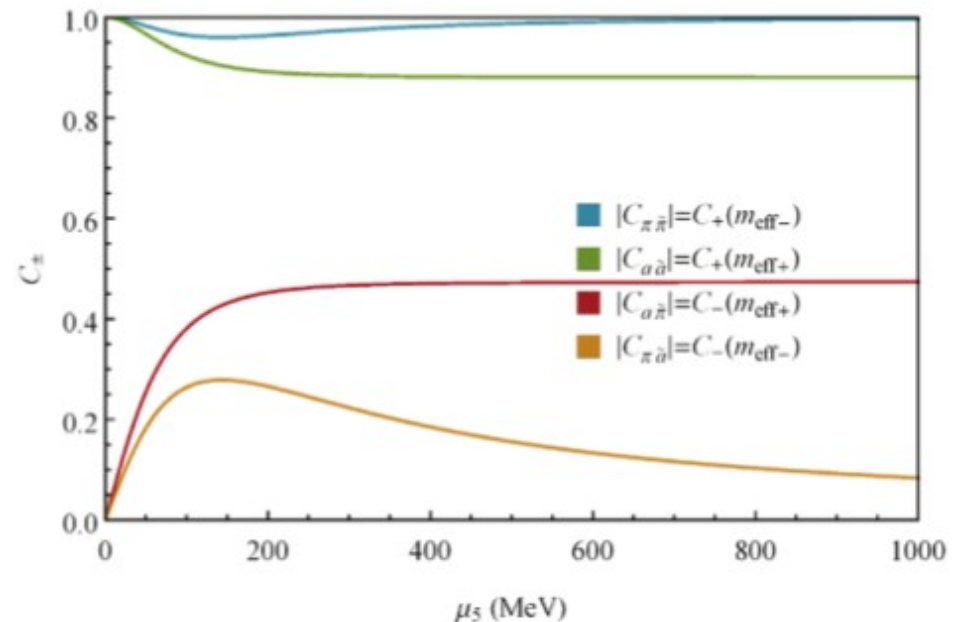
After diagonalization the new eigen-states appear:  $\tilde{\pi}$  and  $\tilde{a}_0$ .

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

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

with

$$C_{\pm} = \frac{1}{\sqrt{2}} \sqrt{1 \pm \frac{m_a^2 - m_{\pi}^2}{\sqrt{(m_a^2 - m_{\pi}^2)^2 + (8 b^{\mu} k_{\mu})^2}}}.$$



mixing coefficients dependence on chemical potential  $\mu_5$

# New Possibilities

## Parity forbidden decays

Effective meson theory in a medium with LPB

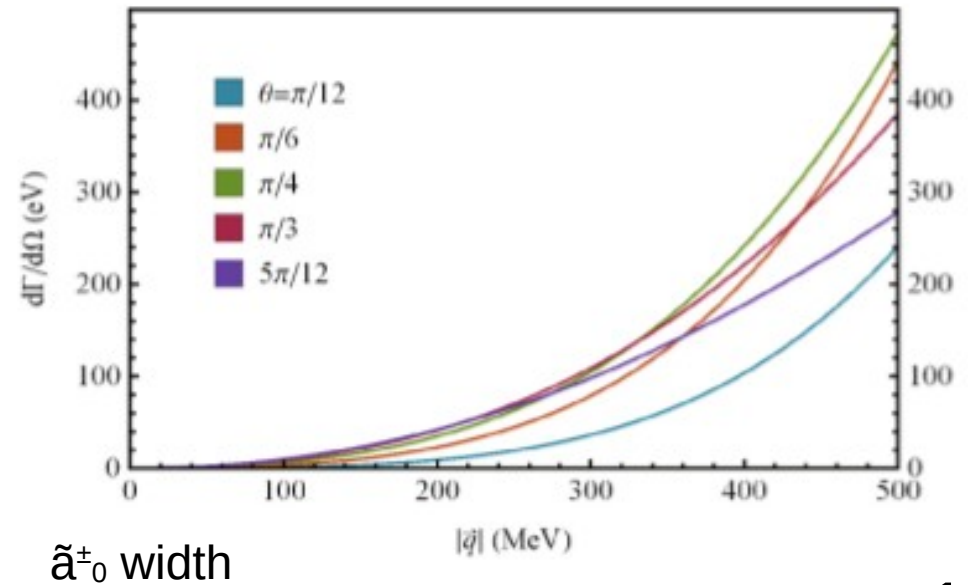
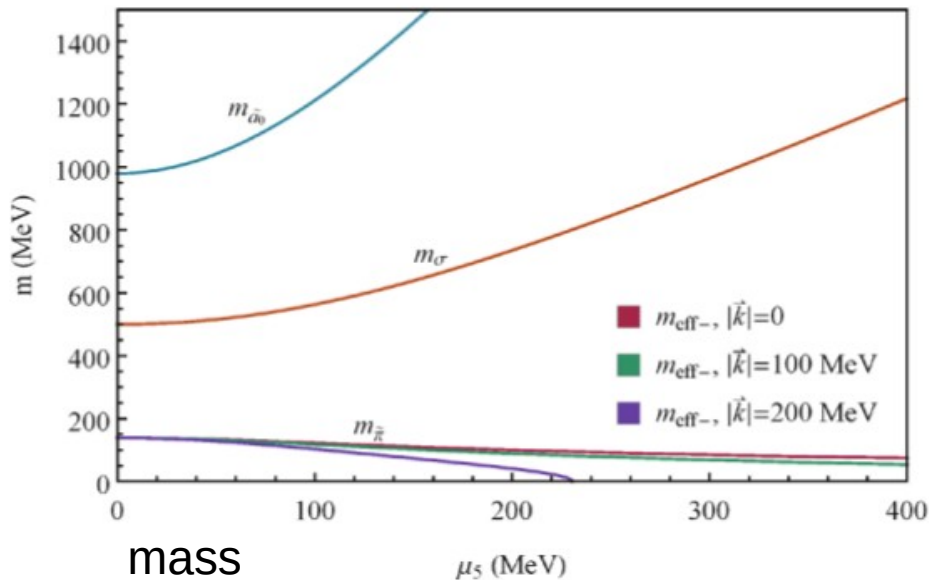
$$\mathcal{L} = \frac{1}{2}(\partial a_0)^2 + \frac{1}{2}(\partial\pi)^2 - \frac{1}{2}m_1^2 a_0^2 - \frac{1}{2}m_2^2 \pi^2 - 4\mu_5 a_0 \dot{\pi},$$

$$m_1^2 = -2[M^2 - 2(3\lambda_1 + \lambda_2)v_q^2 - \lambda_2 v_s^2 - cv_s + 2\mu_5^2]$$

$$m_2^2 = \frac{2m}{v_q} B.$$

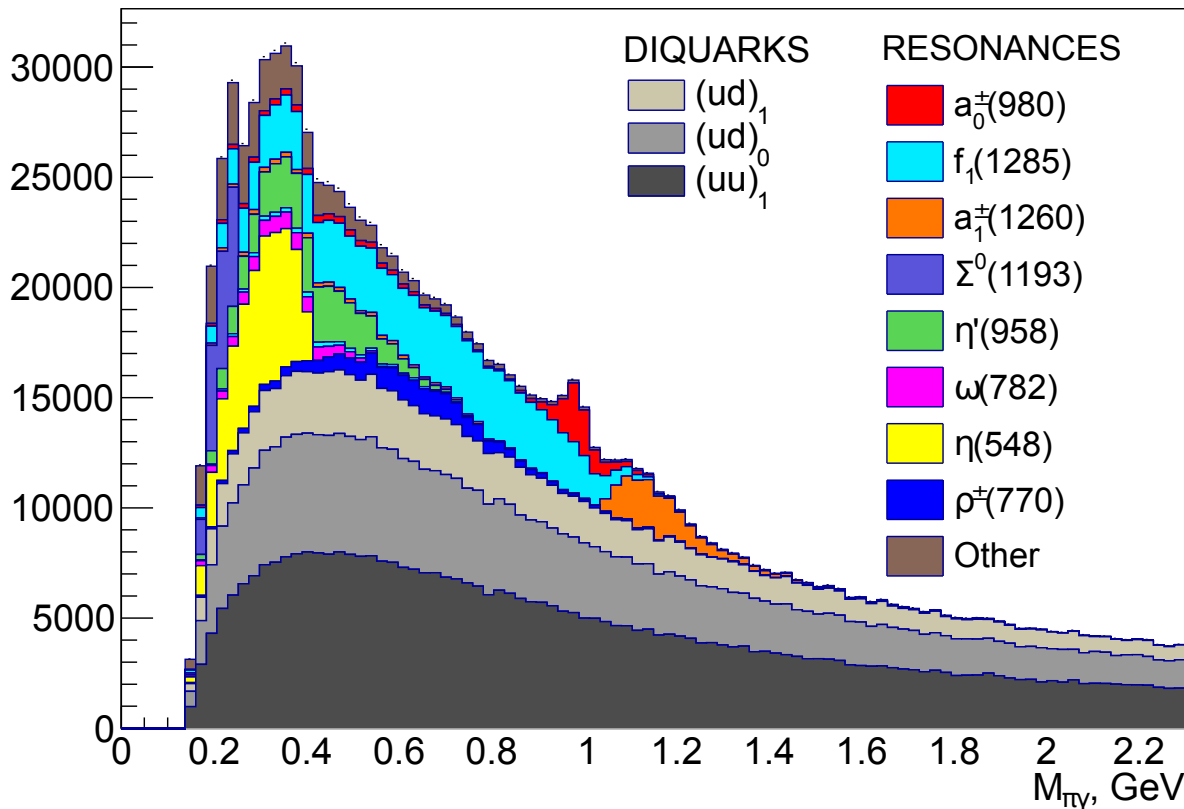
After diagonalization the new eigen-states appear:  $\tilde{\pi}$  and  $\tilde{a}_0$ .

**The decays  $\tilde{a}_0^\pm \rightarrow \tilde{\pi}^\pm \gamma$ ,**



# Parity forbidden decays of $a_{\pm}$

$$a_0^{\pm} \rightarrow \pi^{\pm} + \gamma$$

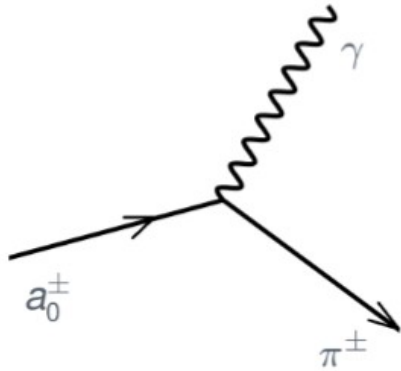


Mixed-event correction and the selection of  $\gamma$  gives the possibility to observe the peak of  $a_0^{\pm} \rightarrow \pi^{\pm} + \gamma$  decay with branching ratio = 5%.

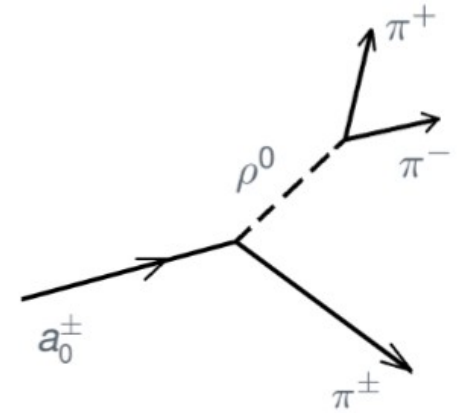
However the predicted branching ration is 0.001%, which leads to the need to analyze large statistics ( $\sim 10^{13}$  pp collisions).

the minimal number of events would be of the order of  $10^{11}$  for Pb–Pb collisions.

# Analysis of $a_0^\pm$ to $3\pi^\pm$ decay



$$W(a_0^\pm \rightarrow \pi^\pm + \gamma) \sim \left(\frac{1}{137}\right)^2$$



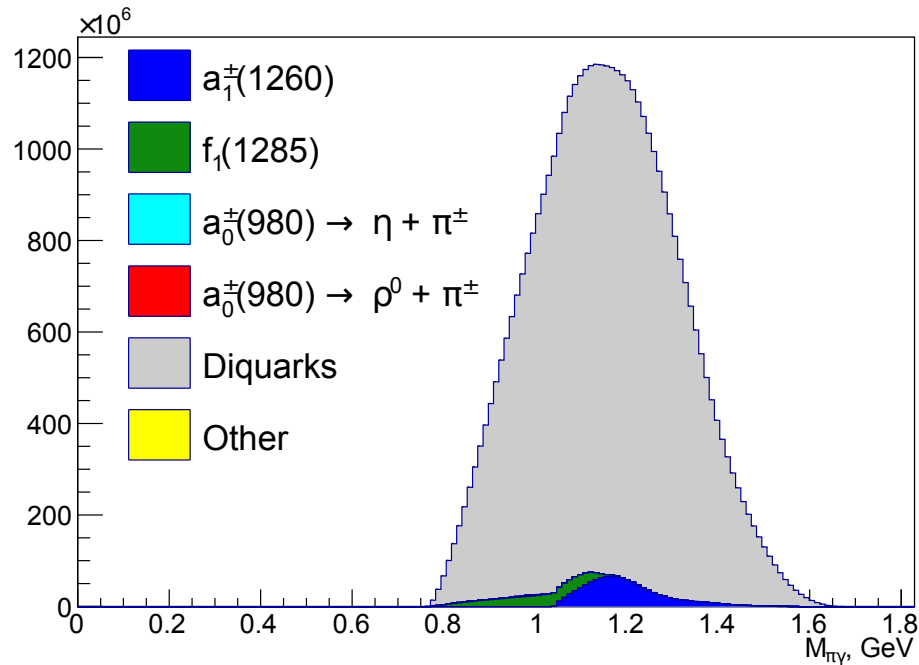
$$W(a_0^\pm \rightarrow \rho^0 + \pi^\pm) \sim 1$$

$$V_\mu \equiv -eA_\mu Q + \frac{1}{2}g_\omega\omega_\mu\mathbf{I}_q + \frac{1}{2}g_\rho\rho_\mu\lambda_3$$

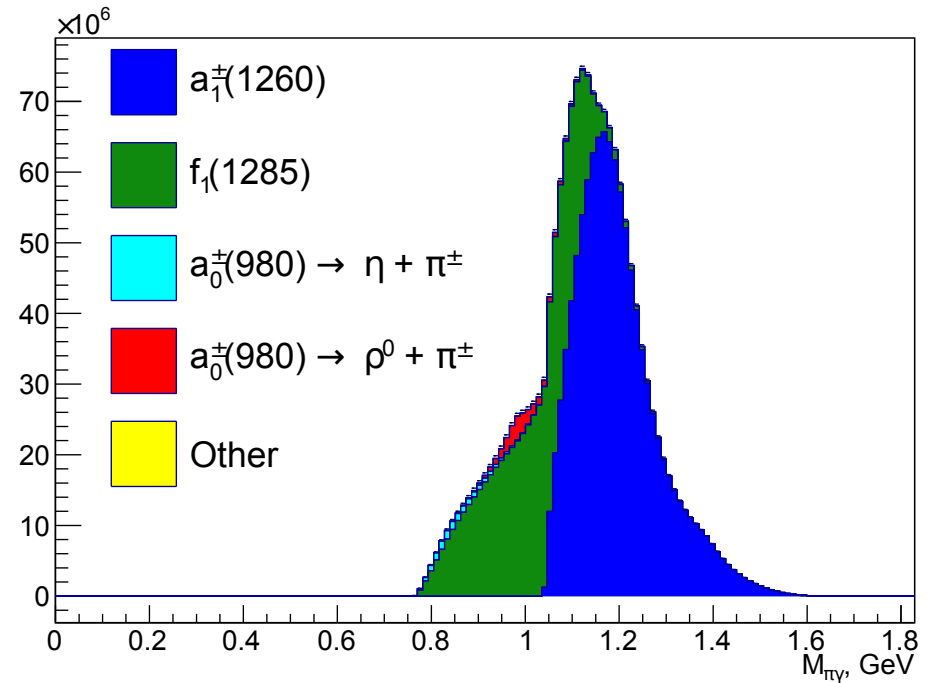
$$e^2 = 4\pi \cdot 1/137, \quad g_\omega \simeq g_\rho \equiv \underline{\underline{g}} \simeq \underline{\underline{6}}$$

We estimate branching ratio  $a_0^\pm \rightarrow \rho^0 + \pi^\pm$  of the order of 5%

# Analysis of $a_0^\pm$ to $3\pi^\pm$ decay



The composition of invariant-mass spectrum.  
Diquarks (PYTHIA8) / minijets (experiment)  
dominance.



The composition of invariant-mass spectrum  
without diquarks.

# Additional ideas

Direct search for vector meson polarization splitting using partial wave analysis in di-lepton decays

Estimation of background in hadronic decays of vector mesons and possibilities of correlation studies

Search for the photon polarization asymmetry driven by pion-gamma rescattering

$$\mathcal{A} = \left| \frac{M_+^2 - \mathcal{P}[M_+]^2}{\sum_{m=\pm} (M_m^2 + \mathcal{P}[M_m]^2)} \right|$$

$$\mathcal{A}^{\text{s-channel}} \approx \frac{\mu_5 N_c}{12\pi^2 f_\pi^2} \frac{E_\gamma (E_\pi^2 - m_\pi^2) \sin^2 \theta}{m_\pi^2 + E_\gamma E_\pi \left(1 - \sqrt{1 - \frac{m_\pi^2}{E_\pi^2}} \cos \theta\right)}$$

A.A.Andrianov, V.A.Andrianov, D.Espriu, A.V.Iakubovich, A.E.Putilova  
Phys. Part. Nucl. Lett. 16 (2019) 5, 493-497

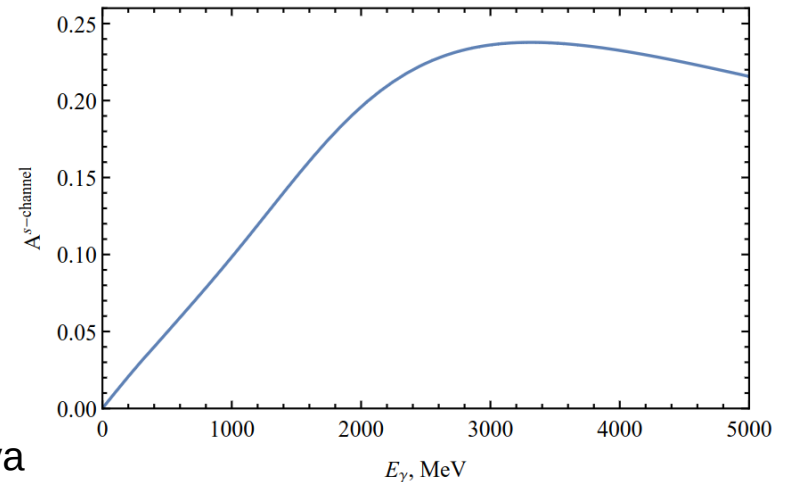


Figure 3: Asymmetry,  $\mu_5 = 100$  MeV,  $E_{\pi_2} = 1$  GeV

# Energy range

Advantages of intermediate and NICA energies are the following:

The chiral imbalance effects could be severely suppressed at ultra-high energies due to thermal and magnetic screening that breaks perturbative scaling, shifting the focus for observation to high baryon density regimes [R. A. Abramchuk, arXiv:2503.18404].

Topological susceptibility and gluon fluctuations are strongly modulated by finite baryon density, which stabilizes local CP-odd domains in dense matter [Simon Hands, Philip Kenny, Phys.Lett.B 701 (2011) 373-377, arXiv:1104.0522].

High baryon density energies provide the optimal environment for detecting chiral imbalance by maximizing density and reducing backgrounds

# Conclusions

**Chiral Magnetic Effect (CME):** Faces major challenge due to strong, flow-induced and non-flow backgrounds.

**Local Domains:** Local domains of axial charge excess survive the entire hydrodynamic evolution, leading to additional signatures in central AA collisions.

**Central Collisions:** The following manifestations of the local parity violation can be considered:

1. The polarization mass splitting of light vector mesons, which leads to angular-dependent splitting of the spectral function in the di-lepton decays (di-muon and di-electron case).
2. The parity-violating decays of light scalar mesons in em channel:  $a^0_{\pm} \rightarrow \pi^{\pm} + \gamma$
3. Hadronic parity-violating decays  $a^0_{\pm} \rightarrow \rho^0 + \pi^{\pm} \rightarrow \pi^{\pm} + \pi^{\pm} + \pi^{\pm}$

**Additional ideas:** Direct searches using partial wave analysis, background estimation in hadronic decays, and photon polarization asymmetry studies.

**Energy Range:** Intermediate and NICA energies are optimal, as high baryon density stabilizes local CP-odd domains, enhances chiral imbalance effect and reduces backgrounds compared to ultra-high energies.

# Backup

## CP violation in QCD

Vafa-Witten theorem: vector-like global symmetries such as parity, charge conjugation, isospin and baryon number in vector-like gauge theories like QCD cannot be spontaneously broken while the  $\theta$  angle is zero

However this theorem does not apply to dense QCD matter where the partition function is not any more positive definite due to the presence of a highly non-trivial fermion determinant. In addition, out-of-equilibrium symmetry-breaking effects driven by finite temperatures are not forbidden by the Vafa-Witten theorem.

Lorentz–non-invariant P -odd operators are allowed to have non-zero expectation values at finite density  $\mu > 0$  and finite temperature if the system is out of Equilibrium.

P – and CP – odd bubbles may appear in a finite volume due to large topological fluctuations in a hot medium

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^{\mu\nu,a}G_{\mu\nu}^a + \bar{q}(i\gamma^\mu D_\mu - m)q,$$

$$D_\mu = \partial_\mu - igG_\mu^a\lambda^a, \quad G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + gf^{abc}G_\mu^b G_\nu^c$$

$$\theta \lesssim 10^{-9}.$$

$$\theta\text{-term} \quad \Delta\mathcal{L}_\theta = \theta \frac{g^2}{16\pi^2} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right)$$

# Topological fluctuations as a source for parity breaking.

## Quasi-equilibrium treatment

The local partial conservation of the axial current (PCAC) relation is afflicted with the gluon anomaly

$$\partial^\mu J_{5,\mu} - 2i\bar{q}\hat{m}_q\gamma_5q = \frac{N_f g^2}{8\pi^2} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right) ,$$

$$K_\mu = \frac{g^2}{2} \epsilon_{\mu\nu\rho\sigma} \text{Tr} \left( G^\nu \partial^\rho G^\sigma - i \frac{2}{3} g G^\nu G^\rho G^\sigma \right) , \quad \partial_\mu K^\mu = \frac{g^2}{4} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right)$$

$$T_5 = \frac{g^2}{16\pi^2} \int_{t_i}^{t_f} dt \int_{\text{vol.}} d^3x \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right) \in \mathbb{Z} ,$$

$$\frac{d}{dt} (Q_5^q - 2N_f T_5) \simeq 2i \int_{\text{vol.}} d^3x \bar{q}\hat{m}_q\gamma_5q , \quad Q_5^q = \int_{\text{vol.}} d^3x \bar{q}\gamma_0\gamma_5q .$$

$$\langle T_5 \rangle = \frac{1}{2N_f} \langle Q_5^q \rangle \quad \iff \quad \mu_5 = \frac{1}{2N_f} \mu_\theta .$$