Anomalies and Asymmetries in Quark-Gluon Matter

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Outline

- Axial anomaly in medium – Chiral Magnetic Effect
- Velocity instead of EM field - Chiral Vortaic Effect
- CVE & neutron asymmetries @ NICA
- Bilinear current correlators in medium and dilepton angular distributions
- Heavy flavours and Strangeness separation and similarity to strangeness polarization in nucleon
- Other signals for (local) C/P violations – decays forbidden in vacuum

Symmetries and conserved operators

- (Global) Symmetry -> conserved current ($\partial^{\mu} J_{\mu} = 0$)
- Exact:
- U(1) symmetry – charge conservation - electromagnetic (vector) current
- Translational symmetry – energy momentum tensor $\partial^{\mu} T_{\mu\nu} = 0$

Massless fermions (quarks) – approximate symmetries

- Chiral symmetry (mass flips the helicity)

$$\partial^{\mu} J^{5}{}_{\mu} = 0$$

- Dilatational invariance (mass introduce dimensional scale – c.f. energy-momentum tensor of electromagnetic radiation)

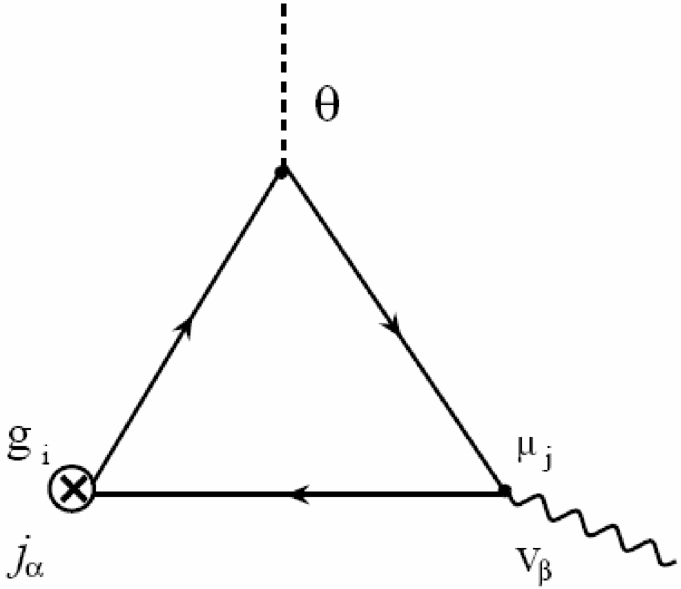
$$T_{\mu\mu} = 0$$

Quantum theory

- Not all the classical symmetries can be preserved -> anomalies
- Vector current conservation <-> chiral invariance
- Triangle VVA diagram - pion decay (generalization – transition formfactors – collective effect of hadron spectrum - Klopot , Oganesian, OT, talk at ICHEP2010 and in preparation)
- Asymmetries – e.g. polarization of decay photons
- Medium – Chiral Magnetic Effect (talks of S. Voloshin, V. Toneev)
- VVA = V(external magnetic field) + V(induced current)+A(topological QCD field)

Anomaly in medium – new external lines in VVA graph

- Gauge field -> velocity
- CME -> CVE
- Kharzeev, Zhitnitsky (07) – EM current
- Straightforward generalization: any (e.g. baryonic) current – neutron asymmeries@NICA - Rogachevsky, Sorin, OT - Arxive 1006.1331 (hep-ph)



Baryon charge with neutrons – (Generalized) Chiral Vortaic Effect

- Coupling: $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$
- Current: $J_e^\gamma = \frac{N_c}{4\pi^2 N_f} \varepsilon^{\gamma\beta\alpha\rho} \partial_\alpha V_\rho \partial_\beta (\theta \sum_j e_j \mu_j)$
- - Uniform chemical potentials: $J_i^\nu = \frac{\sum_j g_{i(j)} \mu_j}{\sum_j e_j \mu_j} J_e^\nu$
- - Rapidly (and similarly) changing chemical potentials:

$$J_i^0 = \frac{|\vec{\nabla} \sum_j g_{i(j)} \mu_j|}{|\vec{\nabla} \sum_j e_j \mu_j|} J_e^0$$

Comparing CME and CVE

- Orbital Angular Momentum and magnetic moment are proportional – Larmor theorem
- Vorticity for uniform rotation – proportional to OAM
- Same scale as magnetic field (eH/μ ~1)
- Tests are required

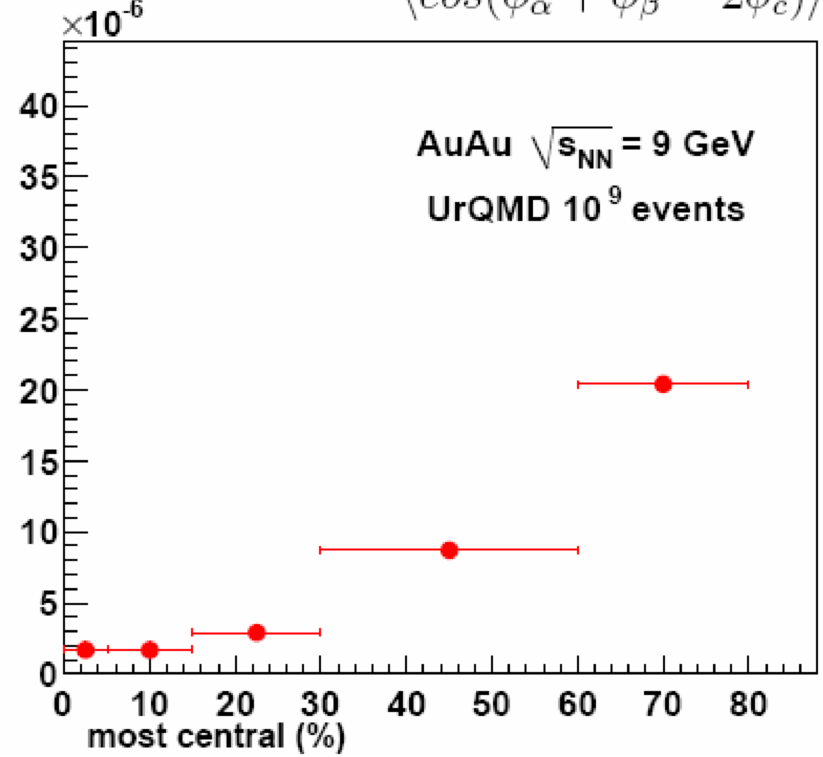
Observation of GCVE

- Sign of topological field fluctuations unknown – need quadratic (in induced current) effects
- CME – like-sign and opposite-sign correlations – S. Voloshin
- No antineutrons, but like-sign baryonic charge correlations possible
- Look for neutron pairs correlations!
- MPD may be well suited for neutrons!

Estimates of statistical accuracy at NICA MPD (months of running)

- UrQMD model : $Au + Au$ at $\sqrt{s_{NN}} = 9$ GeV
- 2-particles -> 3-particles correlations
  no necessity to fix the event plane
- 2 neutrons from mid-rapidity $(|\eta| > 3)$
- +1 from ZDC $(|\eta| < 1)$

$\langle cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle$



Other sources of quadratic effects

- Quadratic effect of induced currents – not necessary involve (C)P-violation
- May emerge also as C&P even quantity
- Complementary probes of two-current correlators desirable
- Natural probe – dilepton angular distributions

Observational effects of current correlators in medium

- McLerran Toimela’85 $W^{\mu\nu} = \int d^4x \, e^{-iq\cdot x} \langle J^\mu(x) J^\nu(0) \rangle$
- Dileptons production rate

$$\frac{d(R/V)}{d^4q \, d^3p \, d^3p'} = -\frac{1}{E_p E_{p'}} e^4 \frac{1}{(2\pi)^6} \times \delta^{(4)}(p+p'-q) L^{\mu\nu}(p,p') \times (1/q^4) W_{\mu\nu}(q) \, .$$

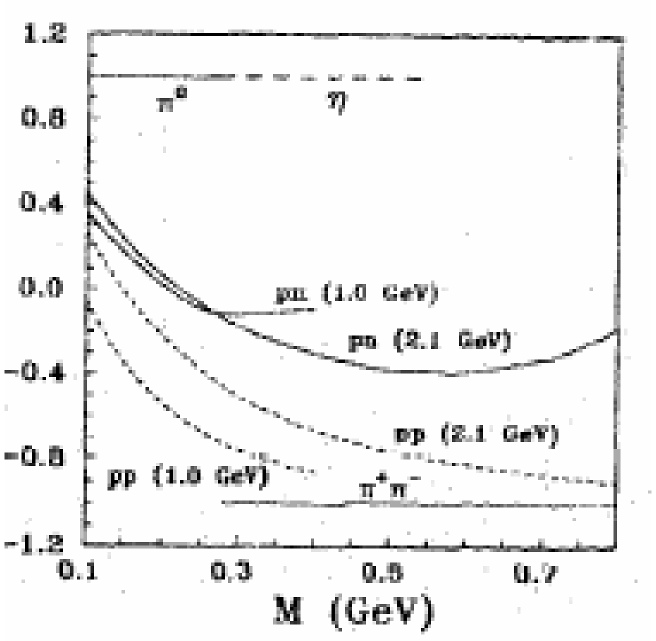
- Structures –similar to DIS F1, F2 (p ->v)

Tensor polarization of in-medium vector mesons (Bratkovskaya, Toneev, OT'95)

- Hadronic in-medium tensor – analogs of spin-averaged structure functions: p -> v
- Only polar angle dependence
- Tests for production mechanisms

$$W^{\mu\nu} = W_1(q^2, vq)\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) + W_2(q^2, vq)\left(v^\mu - q^\mu \frac{vq}{q^2}\right)\left(v^\nu - q^\nu \frac{vq}{q^2}\right)$$

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \frac{|v|^2}{2W_1/W_2 + 1 - (vq)^2/q^2} \cos^2\theta$$



Effect of EM fields

- New structures

$$W_1(-g^{\mu\nu}+q^\mu q^\nu/q^2)+W_2\tilde{v}^\mu\tilde{v}^\nu\ (\tilde{v}=v-q(vq)/q^2)$$

$$+W_3(FF,(F\tilde{F})^2)F^{q\mu}\tilde{v}^\nu+(\mu<->\nu)+W_4\tilde{F}^{q\mu}\tilde{v}^\nu+(\mu<->\nu)$$

$$+W_5F^{q\mu}F^{q\nu}+W_6\tilde{F}^{q\mu}\tilde{F}^{q\nu}+W_7(F\tilde{F})F^{q\mu}\tilde{F}^{q\nu}+(\mu<->\nu)$$

- CG type relations in the real photon limit
- Linear terms – zero real photon limit
- Effect on polar and azimuthal asymmetries – in progress (V. Shmakova, OT)

$$W_2=-W_1q^2/(vq)^2, W_1\sim const$$

$$W_3, W_4\sim q^2 const$$

General hadronic tensor and dilepton angular distribution

- Angular distribution

$$d\sigma \propto 1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi+\rho\sin 2\theta\sin\phi+\sigma\sin^2\theta\sin 2\phi$$

- Positivity of the matrix (= hadronic tensor in dilepton rest frame)

$$\begin{pmatrix} \frac{1-\lambda}{2} & \mu & \rho \\ \mu & \frac{1+\lambda+\nu}{2} & \sigma \\ \rho & \sigma & \frac{1+\lambda-\nu}{2} \end{pmatrix}$$

$$|\lambda|\le 1,\ |\nu|\le 1+\lambda,\ \mu^2\le\frac{(1-\lambda)(1+\lambda-\nu)}{4}$$

$$\rho^2\le\frac{(1-\lambda)(1+\lambda+\nu)}{4},\ \sigma^2\le\frac{(1-\lambda)^2-\nu^2}{4}$$

- \+ cubic – det M> 0
- 1st line – Lam&Tung by SF method

Magnetic field conductivity and asymmetries

- Magnetic field along z: zz-component of conductivity (~hadronic) tensor dominates
- Dilepton at rest: λ =-1 ->
- Longitudinal polarization with respect to magnetic field axis
- Effects of dilepton motion – work in progress

Other signals of rotation

- Hyperons (in particular, Λ) polarization (self-analyzing in weak decay)
- Searched at RHIC (S. Voloshin et al.) – oriented plane (slow neutrons) - no signal observed
- No tensor polarizations as well

Why rotation is not seen?

- Possible origin – distributed orbital angular momentum and local spin-orbit coupling
- Only small amount of collective OAM is coupled to polarization
- The same should affect lepton polarization
- Global (pions) momenta correlations (handedness)

New sources of Λ polarization coupling to rotation

- Bilinear effect of vorticity – generates quark axial current (Son, Surowka)
- Strange quarks - should lead to Λ polarization
- Proportional to chemical potential – small at RHIC – may be probed at FAIR & NICA

Anomaly for massive quarks

- One way of calculation – finite limit of regulator fermion contribution (to TRIANGLE diagram) in the infinite mass limit
- The same (up to a sign) as contribution of REAL quarks
- For HEAVY quarks – cancellation!
- Anomaly – violates classical symmetry for massless quarks but restores it for heavy quarks

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Heavy quarks polarisation

- Non-complete cancellation of mass and anomaly terms (97)

$$\partial^\mu j^c_{5\mu} = \frac{\alpha_s}{48\pi m_c^2}\partial^\mu R_\mu ,$$

$$R_\mu = \partial_\mu(G^a_{\rho\nu}\tilde{G}^{\rho\nu,a}) - 4(D_\alpha G^{\nu\alpha})^a\tilde{G}^a_{\mu\nu}$$

$$\langle N(p,\lambda)|j^{(c)}_{5\mu}(0)|N(p,\lambda)\rangle$$

$$= \frac{\alpha_s}{12\pi m_c^2}\langle N(p,\lambda)|g\sum_{f=u,d,s}\bar{\psi}_f\gamma_\nu\tilde{G}_\mu{}^\nu\psi_f|N(p,\lambda)\rangle$$

$$= \frac{\alpha_s}{12\pi m_c^2}2m_N^3 s_\mu f_S^{(2)} .$$

- Gluons correlation with nucleon spin – twist 4 operator NOT directly related to twist 2 gluons helicity BUT related by QCD EOM to singlet twist 4 correction (colour polarisability) f2 to g1
- “Anomaly mediated” polarisation of heavy quarks

Numerics

- Small (intrinsic) charm polarisation

$$\overline{G}^{c}_{A}(0) = -\frac{\alpha_s}{12\pi} f_S^{(2)} \left(\frac{m_N}{m_c}\right)^2 \approx -5 \times 10^{-4}$$

- Consider STRANGE as heavy! – CURRENT strange mass squared is ~100 times smaller – -5% - reasonable compatibility to the data! (But problem with DIS and SIDIS)

Can s REALLY be heavy?!

- Strange quark mass close to matching scale of heavy and light quarks – relation between quark and gluon vacuum condensates (similar cancellation of classical and quantum symmetry violation – now for trace anomaly). BUT - common belief that strange quark cannot be considered heavy,
- In nucleon (no valence “heavy” quarks) rather than in vacuum - may be considered heavy in comparison to small genuine higher twist – multiscale nucleon picture

Comparison : Gluon Anomaly for massless and massive quarks

- Mass independent
- Massless (Efremov, OT ’88) – naturally (but NOT uniquely) interpreted as (on-shell) gluon circular polarization
- Small gluon polarization – no anomaly?!
- Massive quarks – acquire “anomaly polarization”
- May be interpreted as a sort of correlation of quark current to chromomagnetic field
- Qualitatively similar to CME
- Very small numerically
- Small strange mass – partially compensates this smallness and leads to % effect

Heavy unpolarized Strangeness: vector current

- Follows from Heisenberg-Euler effective lagrangian
  Published in **Z.Phys.98:714-732,1936**.
  e-Print: **physics/0605038**
- FFFF -> FGGG -> Describes strangeness contribution to nucleon magnetic moment and pion mean square radius
- FFFF->FFGG -> perturbative description of chiral magnetic effect for heavy (strange) quarks in Heavy Ion collisions – induced current of strange quarks

Induced current for (heavy - with respect to magnetic field strength) strange quarks

- Effective Lagrangian

$$L = c(F\tilde{F})(G\tilde{G})/m^4 + d(FF)(GG)/m^4$$

- Current and charge density from c (~7/45) – term $j^\mu = 2c\tilde{F}^{\mu\nu}\partial_\nu(G\tilde{G})/m^4$
- $\rho \sim \vec{H}\vec{\nabla}\theta$ (multiscale medium!)

  $\theta \sim (G\tilde{G})/m^4 \to \int d^4x G\tilde{G}$
- Light quarks -> matching with D. Kharzeev et al' -> correlation of density of electric charge with a gradient of topological one (Lattice ?)

Properties of perturbative charge separation

- Current carriers are obvious - strange quarks -> matching -> light quarks?
- NO obvious relation to chirality – contribution to axial current starts from pentagon (!) diagram
- No relation to topollogy (also pure QED effect exists)
- Effect for strange quarks is of the same order as for the light ones if topological charge is localized on the distances ~ $1/m_s$, strongly (4th power!) depends on the numerical factor : Ratio of strange/light – sensitive probe of correlation length
- Universality of strange and charm quarks separation - charm separation suppressed as $(m_s /m_c)^4 \sim 0.0001$
- Charm production is also suppressed – relative effects may be comparable at moderate energies (NICA?) – but low statistics

Comparing CME to strangeness polarization

- Strangeness polarization – correlation of
- (singlet) quark current
- (chromo)magnetic field
- (nucleon) helicity
- Chiral Magnetic Effect - correlation of
- (electromagnetic) quark current
- (electro)magnetic field
- (Chirality flipping) Topological charge gradient

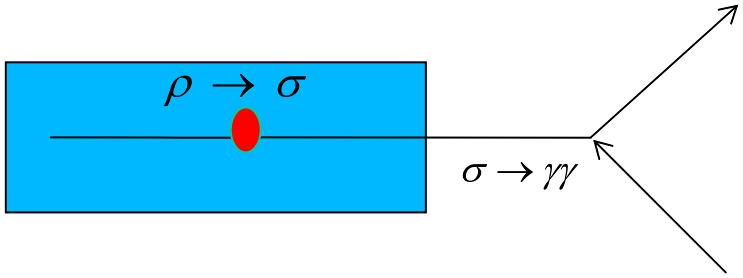
Local symmetry violation

- CME – assumed to be the sign of local P(C) violation
- BUT Matrix elements of topological charge, its density and gradient are zero
- Signs of real C(P) violation – forbidden processes

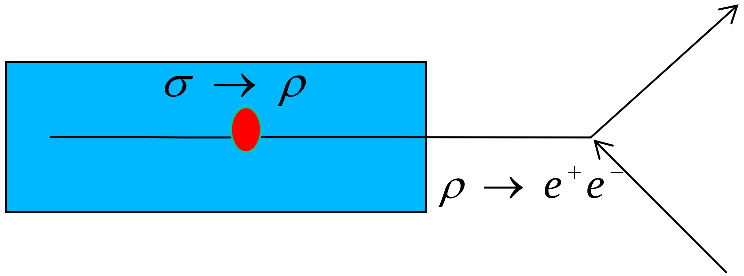
Forbidden decays in vacuum – allowed in medium

- C-violation by chemical potential -> (Weldon ’92) $\sigma \to e^+e^-$
- $\rho \to \gamma\gamma$ (OT’96; Radzhabov, Volkov, Yudichev ’05,06 - NJL)
- New (?) option: $\pi \to e^+e^-$ in magnetic field $\frac{\Gamma_{\pi \to e^+e^-}}{\Gamma_{\pi \to \gamma\gamma}} \sim \frac{H^2}{m_\pi^4}$
- Polarization (angular distribution in c.m. frame) of dilepton $\sim 1 + \cos^2\theta$ (with respect to field direction!)

Approximation: EM part – vacuum value Two-stage forbidden decays - I



Two-stage forbidden decays - II



Relating forbidden and allowed decays

- In the case of complete mass degeneracy (OT'05, unpublished):

$$\frac{\Gamma_{\sigma\to e^+e^-}}{\Gamma_{\rho\to\gamma\gamma}} = \frac{9}{4}\frac{\Gamma_{\rho\to e^+e^-}}{\Gamma_{\sigma\to\gamma\gamma}}$$

- Tests and corrections – in progress

Conclusions

- Axial anomaly in medium is a fundamental property of QCD and may be manifested in the angular and spin asymmetries
- Chiral Vortaic Effect may be probed in the neutron asymmetries at NICA
- Bilinear current correlator may be probed in dilepton asymmetries
- CME/CVE for (heavy) strange quarks is similar to their polarization in a nucleon
- Various medium-induced decays may be related to each other