# Axial vortical effect and hyperon polarization

**Helmholtz - DIAS International Summer School “Hadron Structure, Hadronic Matter and Lattice“, JINR, Dubna**

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## Global $\Lambda$ hyperon polarization in nuclear collisions: evidence for the most vortical fluid



**The extreme temperatures and energy densities generated by ultra-relativistic collisions between heavy nuclei produce a state of matter with surprising fluid properties[1]. Non-central collisions have angular momentum on the order of $1000\hbar$, and the resulting fluid may have a strong vortical structure[2–4] that must be understood to properly describe the fluid. It is also of particular interest because the restoration of fundamental symmetries of quantum chromodynamics is expected to produce novel physical effects in the presence of strong vorticity[15]. However, no experimental indications of fluid vorticity in heavy ion collisions have so far been found. Here we present the first measurement of an alignment between the angular momentum of a non-central collision and the spin of emitted particles, revealing that the fluid produced in heavy ion collisions is by far the most vortical system ever observed. We find that $\Lambda$ and $\overline{\Lambda}$ hyperons show a positive polarization of the order of a few percent, consistent with some hydrodynamic predictions[5]. A previous measurement[6] that reported a null result at higher collision energies is seen to be consistent with the trend of our new observations, though with larger statistical uncertainties. These data provide the first experimental access to the vortical structure of the "perfect fluid"[7] created in a heavy ion collision. They should prove valuable in the development of hydrodynamic models that quantitatively connect observations to the theory of the Strong Force. Our results extend the recent discovery[8] of hydrodynamic spin alignment to the subatomic realm.**

*Polarization data has often been the graveyard of fashionable theories.*
*If theorists had their way, they might just ban such measurements altogether out of self-protection.*
*J.D. Bjorken*
*St. Croix, 1987*

# Outline

- QCD factorization and hadronic polarization (Lecture 1)
- Axial anomaly and transport in hadronic media (Lecture 2)
- Vorticity and hyperon polarization (Lecture 3)

# Outline of Lecture 2

- Quantum anomalies
- Anomaly  and Landau levels flow
- Dispersive approach to anomaly and t'Hooft principle
- Induced currents from anomaly

# 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 )

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

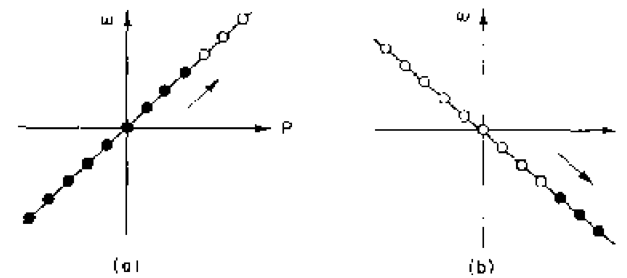
# Quantum theory

- Currents -> operators
- Not all the classical symmetries can be preserved -> anomalies
- Enter in pairs (triples?...)
- Vector current conservation <-> chiral invariance
- Translational invariance <-> dilatational invariance

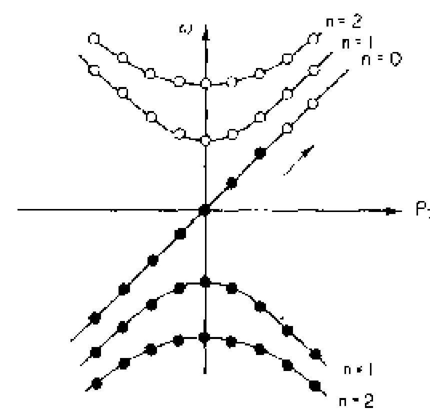
# Calculation of anomalies

- Many various ways
- All lead to the same operator equation

$$\partial^\mu j^{(0)}_{5\mu} = 2i\sum_q m_q \bar{q}\gamma_5 q - \left(\frac{N_f\alpha_s}{4\pi}\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$




- UV vs IR languages- understood in physical picture (Gribov, Feynman, Nielsen and Ninomiya) of Landau levels flow (E||H)



# Degeneracy of Landau levels and Chirality

- Degeneracy rate of Landau levels
- "Transverse" HS/(1/e) (Flux/flux quantum)
- "Longitudinal" Ldp= eE dt L (dp=eEdt)
- Anomaly – coefficient in front of 4-dimensional volume - $e^2$ EH

# Topological current

- Anomaly implies new current conservation
- $\partial_\mu (J-K)^\mu=0$
- Preserved by QCD evolution
- Controls the anomalous gluon contributions to nucleon spin structure (Lecture 1)

# 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

# Dilatational anomaly

- Classical and anomalous terms

$$\theta_{\mu\mu} = [\beta(\alpha_s)/4\alpha_s]\, G^a_{\mu\nu} G^a_{\mu\nu}$$

$$+ m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s + \sum_{h=c,b,\ldots} m_h \bar{h}h$$

- Beta function – describes the appearance of scale dependence due to renormalization
- For heavy quarks – cancellation of classical and quantum violation -> decoupling

# Anomaly and virtual photons

- Often assumed that only manifested in real photon amplitudes
- Not true – appears at any $Q^2$
- Natural way – dispersive approach to anomaly (Dolgov, Zakharov'70) - anomaly sum rules
- One real and one virtual photon – Horejsi,OT'95
- where $$\int_{4m^2}^{\infty} A_3(t;q^2,m^2)dt = \frac{1}{2\pi}$$

$$F_j(p^2) = \frac{1}{\pi}\int_{4m^2}^{\infty} \frac{A_j(t)}{t-p^2}dt, \qquad j=3,4$$

$$\begin{aligned} T_{\alpha\mu\nu}(k,q) &= F_1\,\varepsilon_{\alpha\mu\nu\rho}k^\rho + F_2\,\varepsilon_{\alpha\mu\nu\rho}q^\rho \\ &+ F_3\,q_\nu\varepsilon_{\alpha\mu\rho\sigma}k^\rho q^\sigma + F_4\,q_\nu\varepsilon_{\alpha\mu\rho\sigma}k^\rho q^\sigma \\ &+ F_5\,k_\mu\varepsilon_{\alpha\nu\rho\sigma}k^\rho q^\sigma + F_6\,q_\mu\varepsilon_{\alpha\nu\rho\sigma}k^\rho q^\sigma \end{aligned}$$

# Dispersive derivation

- Axial WI $F_2 - F_1 = 2mG + \frac{1}{2\pi^2}$
- GI $F_2 - F_1 = (q^2 - p^2)F_3 - q^2 F_4$
- No anomaly for imaginary parts

$$(q^2 - t)A_3(t) - q^2 A_4(t) = 2mB(t) \qquad F_j(p^2) = \frac{1}{\pi}\int_{4m^2}^{\infty} \frac{A_j(t)}{t - p^2} dt, \qquad j = 3, 4$$

- Anomaly as a finite subtraction

$$F_2 - F_1 - 2mG = \frac{1}{\pi}\int_{4m^2}^{\infty} A_3(t) dt \qquad \int_{4m^2}^{\infty} A_3(t; q^2, m^2) dt = \frac{1}{2\pi}$$

# Properties of anomaly sum rules

- Valid for any $Q^2$ (and quark mass)
- No perturbative QCD corrections (Adler-Bardeen theorem)
- No non-perturbative QCD correctioons (`t Hooft consistency principle)
- Massless pole in quark triangle – massless pion (complementary to CSB)

# Mesons contributions

- Pion – saturates sum rule for real photons $ImF_3 = \sqrt{2} f_\pi \pi F_{\pi\gamma\gamma*}(Q^2)\delta(s - m_\pi^2)$ $F_{\pi\gamma^*\gamma}(0) = \frac{1}{2\sqrt{2}\pi^2 f_\pi}$
- For virtual photons – pion contribution is rapidly decreasing $F^{\mathrm{asymp}}_{\pi\gamma\gamma^*}(Q^2) = \frac{\sqrt{2} f_\pi}{Q^2} + \mathcal{O}(1/Q^4)$
- This is also true also for axial and higher spin mesons (longitudianl components are dominant)
- Heavy PS decouple in a chiral limit

# Content of Anomaly Sum Rule ("triple point")

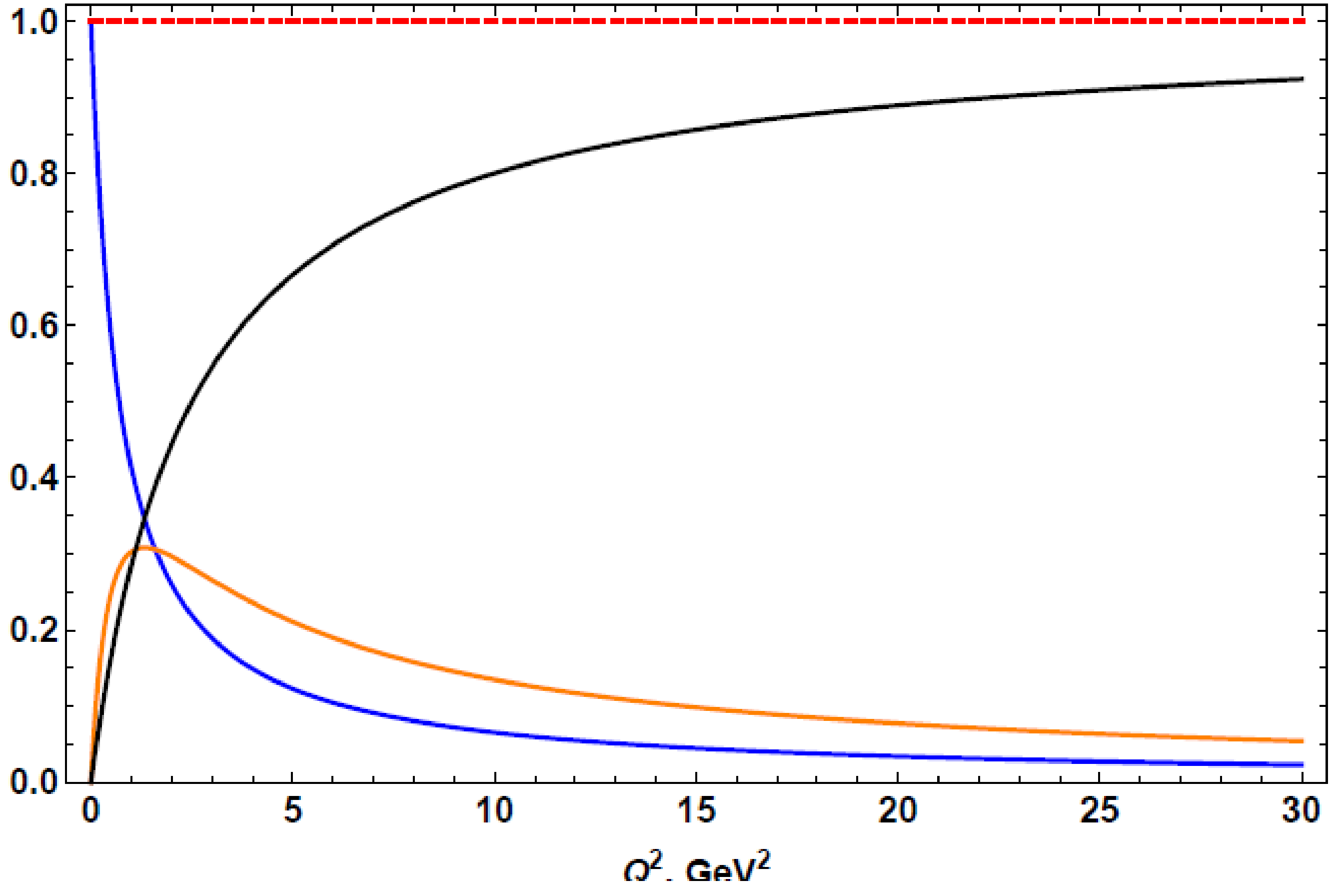



Figure 1: Relative contributions of $\pi$ (blue line) and $a_1$ (orange line) mesons, intervals of duality are $s_0 = 0.7\ GeV^2$ and $s_1 - s_0 = 1.8\ GeV^2$ respectively, and continuum (black line), continuum threshold is $s_1 = 2.5\ GeV^2$

# Anomaly as a collective effect

- One can never get constant summing finite number of decreasing function
- Anomaly at finite $Q^2$ is a collective effect of meson spectrum
- General situation –occurs for any scale parameter (playing the role of regulator for massless pole)
- Chemical potential?! Quarkyonic phase?!

# Anomaly in Heavy Ion Collisions - Chiral Magnetic Effect

## From QCD back to electrodynamics: Maxwell-Chern-Simons theory

$$\mathcal{L}_{\mathrm{MCS}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu J^\mu + \frac{c}{4}\,P_\mu J^\mu_{CS}.$$

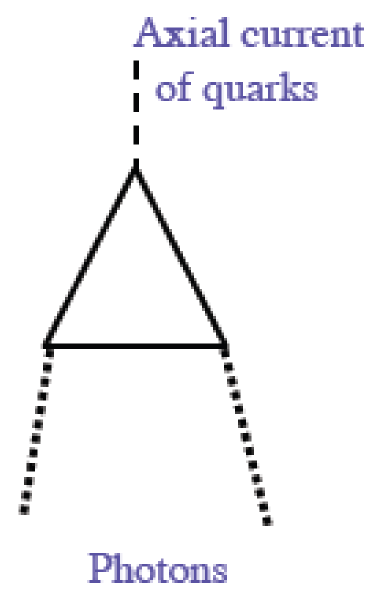
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu\theta = (M, \vec{P})$$

$$\vec{\nabla}\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = \vec{J} + c\left(M\vec{B} - \vec{P}\times\vec{E}\right),$$

$$\vec{\nabla}\cdot\vec{E} = \rho + c\vec{P}\cdot\vec{B},$$

$$\vec{\nabla}\times\vec{E} + \frac{\partial\vec{B}}{\partial t} = 0,$$

$$\vec{\nabla}\cdot\vec{B} = 0,$$

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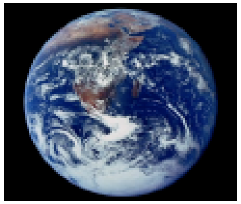
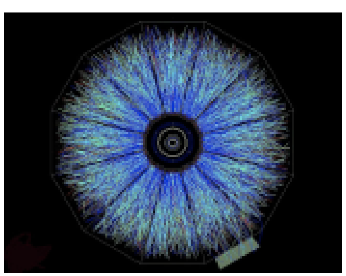
# Comparison of magnetic fields



| | |
|---|---|
| The Earths magnetic field | 0.6 Gauss |
| A common, hand-held magnet | 100 Gauss |
| The strongest steady magnetic fields achieved so far in the laboratory | $4.5 \times 10^5$ Gauss |
| The strongest man-made fields ever achieved, if only briefly | $10^7$ Gauss |
| Typical surface, polar magnetic fields of radio pulsars | $10^{13}$ Gauss |
| Surface field of Magnetars | $10^{15}$ Gauss |

http://solomon.as.utexas.edu/~duncan/magnetar.html



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$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

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

- Effective Lagrangian

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

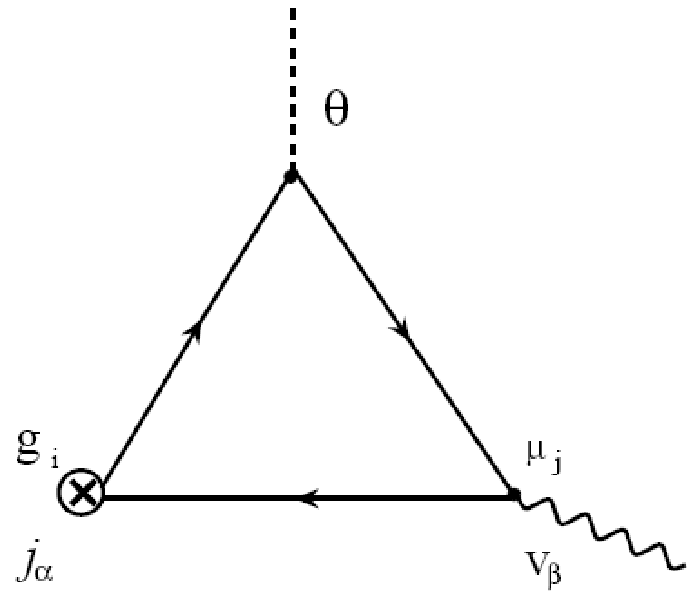
- Current and charge density from c (~7/45) – term $j^{\mu} = 2c\tilde{F}^{\mu\nu}\partial_{\nu}(G\tilde{G})/m^4$
- $\rho \sim \vec{H}\vec{\nabla}\theta$ (multiscale medium!)

$$\theta \sim (G\tilde{G})/m^4 \rightarrow \int d^4x G\tilde{G}$$

- Light quarks -> matching with D. Kharzeev et al’

# Anomaly in medium – new external lines in VVA graph

- Gauge field -> velocity
- CME -> CV(ortical)E
- Kharzeev, Zhitnitsky (07) – EM current
- Straightforward generalization: any (e.g. baryonic) current – neutron asymmeries@NICA - Rogachevsky, Sorin, OT - **Phys.Rev.C82:054910,2010**.



# Baryon charge with neutrons – (Generalized) Chiral Vortical 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:

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

# Dissipationless transport

- Time reversal: E -> E, H-> -H, j -> -j

- Electric Conductance: $j = \sigma_E E$
- Change sign under time reversal -> (anti)dissipation

- Magnetic Conductance: $j = \sigma_H H$
- Stable under time reversal – no dissipation!

# Summary of lecture 2

- Anomaly – quantum violation of classical symmetries
- Many derivations – Landau level flow: UV and IR faces
- Dispersive approach and ‘tHooft principle: collective effect for extra parameter( virtuality, chemical potential…)
- Dissipationless transport in HIC