Axial Anomaly and Hadron Structure

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Anomaly - phenomenon of quantum field theory

Relevance in more general context?

Nucleon couplings to gravity

Rotation in quark gluon plasma

Outline

Anomaly sum rules (example – anomaly for virtual photons and transition formfactors)

in collaboration with

Yaroslav Klopot (JINR), Armen Oganesian (ITEP)

Heavy strangeness in nucleons and nuclear/quark matter

Anomaly for medium velocity and Chiral Vortical Effect for neutrons

in collaboration with

Oleg Rogachevsky, Alexandr Sorin (JINR)

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)

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

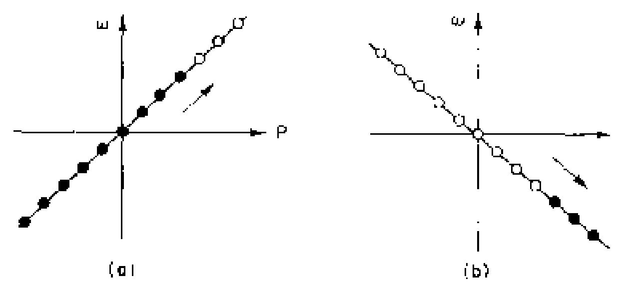
Quantum theory

- 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

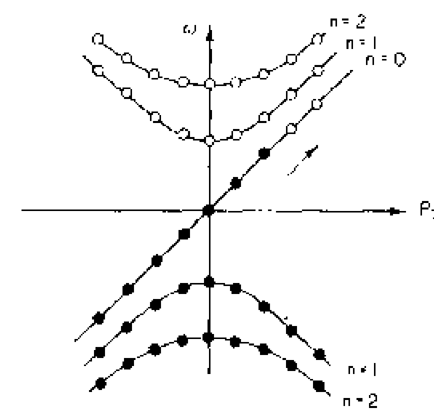
$$\partial^\mu j_{5\mu}^{(0)} = 2i\sum_q m_q \bar{q}\gamma_5 q - \left(\frac{N_f \alpha_s}{4\pi}\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$



- UV vs IR languages-

understood in physical

picture (Gribov, Feynman,
Nielsen and Ninomiya)
of Landau levels flow (E||H)



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

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

- where

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

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

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)
- Exact – powerful tool

Mesons contributions (Klopot, Oganesian, OT)

Phys.Lett.B695:130-135,2011 (1009.1120) , Phys.Rev. D84 (2011) 05190 (1106.3855) , JETP Lett. 94 (2011) 729-733 (1110.0474) and in preparation

- 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 $F^{asymp}_{\pi\gamma\gamma^*}(Q^2) - \frac{\sqrt{2} f_\pi}{Q^2} + \mathcal{O}(1/Q^4)$
- This is also true also for axial and higher spin mesons (longitudianl components are dominant)
- Heavy PS decouple in a chiral limit

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)
- For quantitative analysis – quark-hadron duality

Mesons contributions within quark hadron duality – transition FF (generalization of decay amplitude)

- Pion: $$F_{\pi\gamma\gamma*}(Q^2) = \frac{1}{2\sqrt{2}\pi^2 f_\pi}\frac{s_0}{s_0+Q^2}$$
- Cf Brodsky&Lepage, Radyushkin – comes now from anomaly!
- Axial mesons contribtion to ASR

$$\int_0^\infty A_3(s;Q^2)ds = \frac{1}{2\pi} = I_\pi + I_{a_1} + I_{cont}.$$

$$I_{a_1} = \frac{1}{2\pi}Q^2\frac{s_1-s_0}{(s_1+Q^2)(s_0+Q^2)}$$

Content of Anomaly Sum Rule ("triple point")

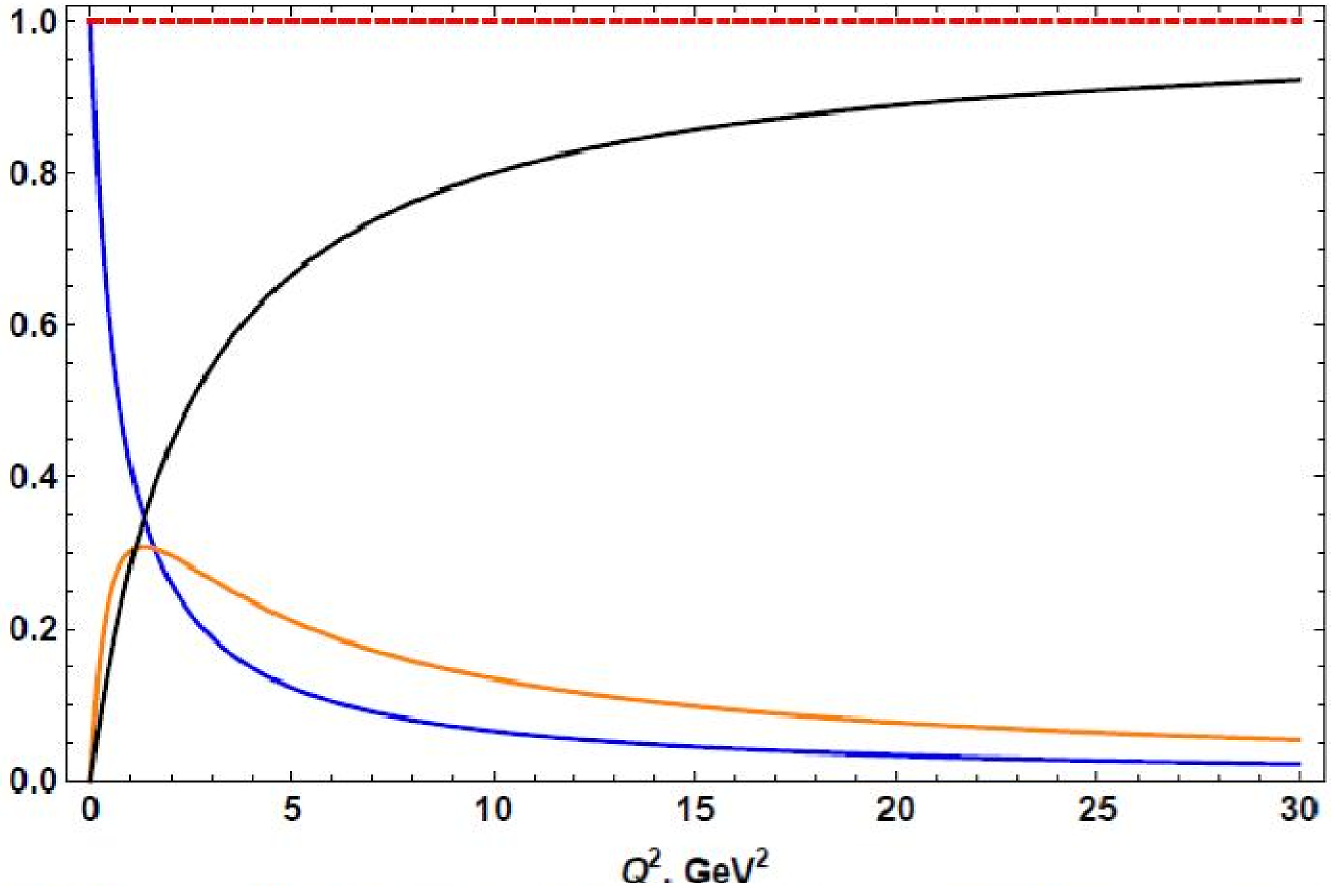


Figure 1: Relative contributions of π (blue line) and a_1 (orange line) mesons, intervals of duality are $s_0 = 0.7\ GeV^2$ and $s_1 - s_0 = 1.8\ GeV^2$ respectively, and continuum (black line), continuum threshold is $s_1 = 2.5\ GeV^2$

ASR and BaBar data

- In the BaBar(2009) region – main contribution comes from the continuum
- Small relative correction to continuum –due to exactness of ASR must be compensated by large relative contributions to lower states!
- Amplification of corrections

$$\frac{\delta I_{cont}/I^0_{cont}}{\delta I_\pi / I^0_\pi} = \frac{s_0}{Q^2} \simeq \frac{1}{30} \quad Q^2 = 20\ GeV^2,\ s_0 = 0.7\ GeV^2$$

- Smaller for eta because of larger duality interval (supported by BaBar)

Corrections to Continuum

- Perturbative – zero at 2 loops level (massive-Pasechnik&OT – however cf Melnikov; massless-Jegerlehner&Tarasov)
- Non-perturbative (e.g. instantons)
- The general properties of ASR require decrease at asymptotically large Q^2 (and $Q^2=0$)

$$\delta I = \frac{1}{2\sqrt{2}\pi^2 f_\pi}\frac{\lambda s_0 Q^2}{(s_0+Q^2)^2}(\ln\frac{Q^2}{s_0}+\sigma)$$

- Corresponds to logarithmically growing pion contribution (cf Radyushkin, Polyakov, Dorokhov).

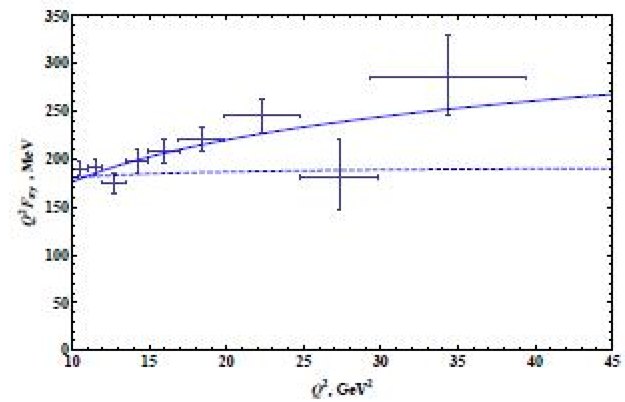
Modelling of corrections

- Continuum vs pion

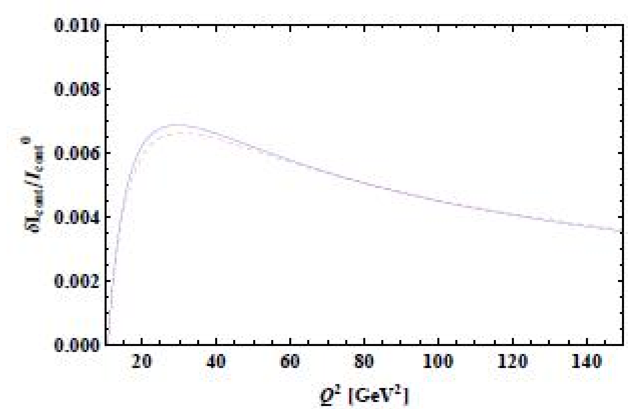
$$I_{cont} = \frac{1}{2\pi}\frac{Q^2}{s_0+Q^2} - c s_0 \frac{\ln(Q^2/s_0)+b}{Q^2},$$

$$I_{\pi} = \frac{1}{2\pi}\frac{s_0}{s_0+Q^2} + c s_0 \frac{\ln(Q^2/s_0)+b}{Q^2}.$$

- Fit $b = -2.74, \quad c = 0.045.$



- Continuum contribution similar for Radyushkin’s approach

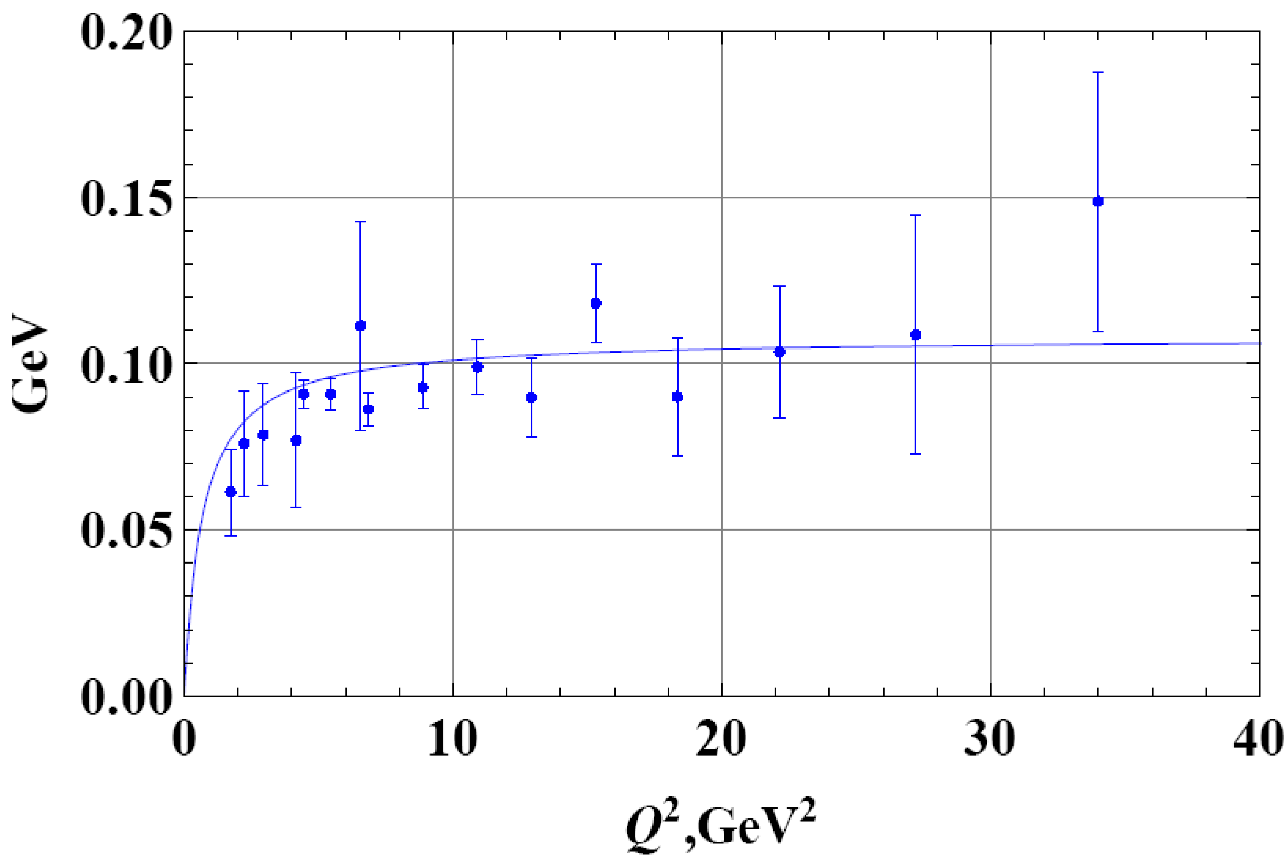


Interplay of pion with lower resonances

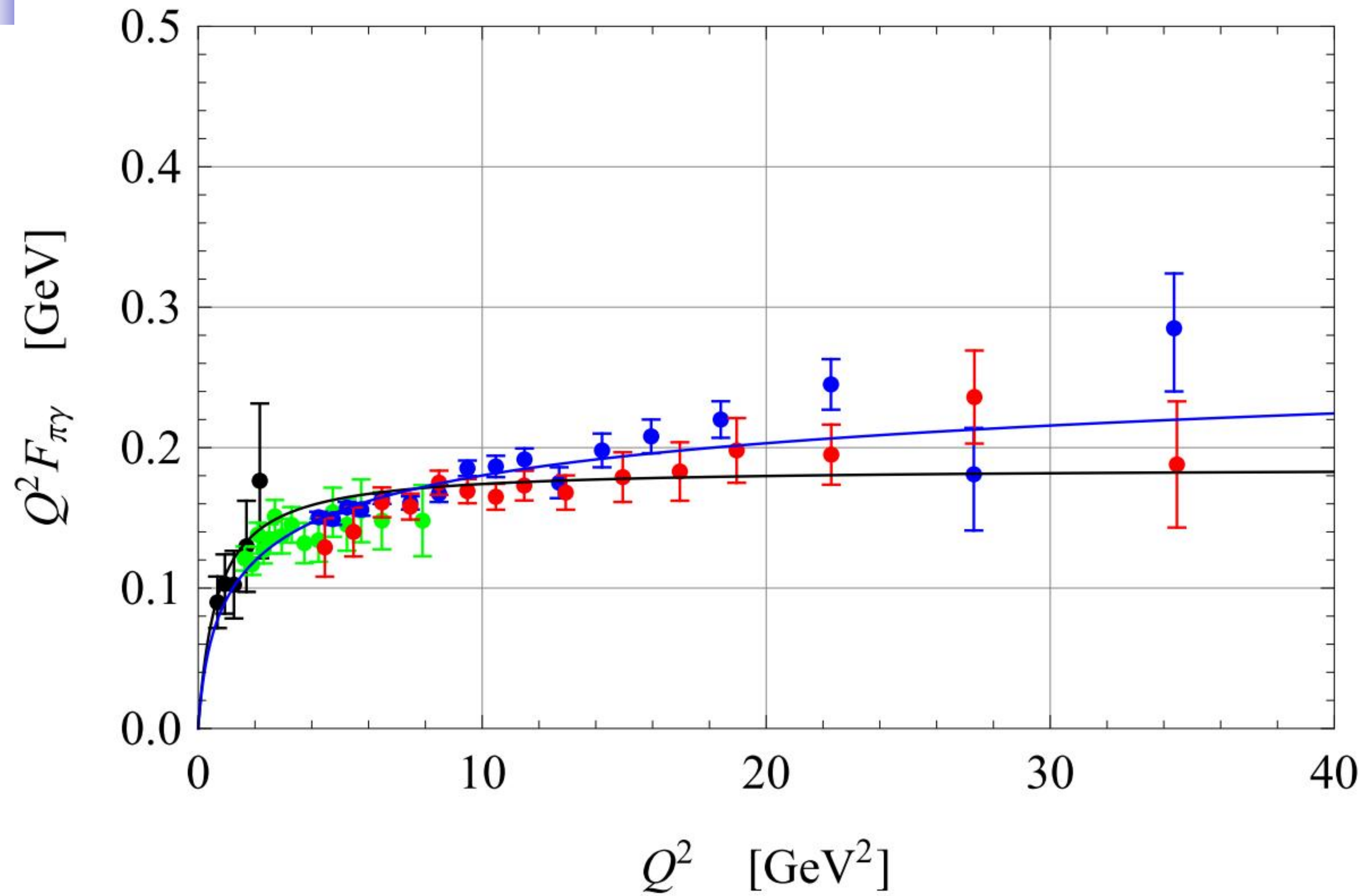
- Small (NP) corrections to continuum – interplay of pion with higher states
- A1 – decouples for real photons
- Relation between transition FF’s of pion and A1 (testable!)

Generalization for eta(')

- Octet channel sum rule (gluon anomaly free)



New situation – 2 sets of data (BaBar,BELLE)



Conclusions/Discussion-I

- New manifetsation of Axial Anomaly - Anomaly Sum Rule – exact NPQCD tool- do not require QCD factorization
- Anomaly for virtual photons – collective effect (with fast excitation of collective mode)
- Similar collective effect is expected for finite temperature and/or chemical potential
- Exactness of ASR – very unusual situation when small pion contribution can be studied on the top of large continuum – amplification of corrections to continuum
- BaBar(BELLE) data – small(very) negative correction to continuum

Equivalence principle

- Newtonian – “Falling elevator” – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’); rederived from conservarion laws - Kobzarev and Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- - not checked on purpose but in fact checked in atomic spins experiments at % level (Silenko,OT’07)

Gravitational Formfactors

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle = \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M]u(p)$$

- Conservation laws - zero Anomalous Gravitomagnetic Moment : $\mu_G = J$ (g=2)

$$P_{q,g} = A_{q,g}(0) \qquad A_q(0) + A_g(0) = 1$$

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right] \qquad A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1$$

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons
- Describe interaction with both classical and TeV gravity

Generalized Parton Diistributions (related to matrix elements of non local operators) – models for both EM and Gravitational Formfactors (Selyugin,OT '09)

- Smaller mass square radius (attraction vs repulsion!?)

$$\rho(b) = \sum_q e_q \int dx q(x,b) \qquad = \int d^2q F_1(Q^2 = q^2) e^{i\vec{q}\,\vec{b}}$$

$$= \int_0^\infty \frac{q dq}{2\pi} J_0(qb) \frac{G_E(q^2) + \tau G_M(q^2)}{1+\tau}$$

$$\rho_0^{\mathrm{Gr}}(b) = \frac{1}{2\pi} \int_\infty^0 dq q J_0(qb) A(q^2)$$

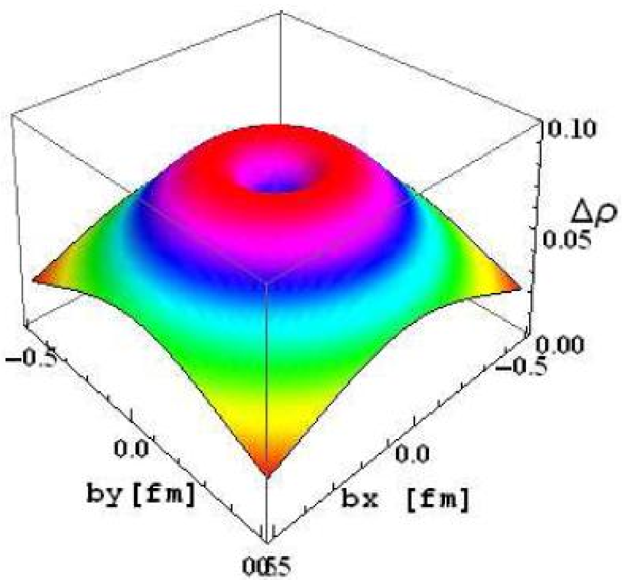


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)

Electromagnetism vs Gravity

- Interaction – field vs metric deviation

$$M = \langle P'|J_q^\mu|P\rangle A_\mu(q) \qquad M = \frac{1}{2}\sum_{q,G}\langle P'|T_{q,G}^{\mu\nu}|P\rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P|J_q^\mu|P\rangle = 2e_q P^\mu \qquad \sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle = 2P^\mu P^\nu$$

$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P|J_q^\mu|P\rangle A_\mu = 2e_q M\phi(q) \qquad M_0 = \frac{1}{2}\sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle h_{\mu\nu} = 2M\cdot M\phi(q)$$

- Mass as charge – equivalence principle

Gravitomagnetism

- Gravitomagnetic field (weak, except in gravity waves) – action on spin from $M = \frac{1}{2}\sum_{q,G} \langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$

$$\vec{H}_J = \frac{1}{2} rot \vec{g}; \ \vec{g}_i \equiv g_{0i}$$

spin dragging twice smaller than EM

- Lorentz force – similar to EM case: factor ½ cancelled with 2 from $h_{00} = 2\phi(x)$ Larmor frequency same as EM

$$\omega_J = \frac{\mu_G}{J} H_J = \frac{H_L}{2} = \omega_L \ \vec{H}_L = rot \vec{g}$$

- Orbital and Spin momenta dragging – the same - Equivalence principle

Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW LETTERS

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Search for a Coupling of the Earth's Gravitational Field to Nuclear Spins in Atomic Mercury

B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson
Physics Department, FM-15, University of Washington, Seattle, Washington 98195
(Received 25 September 1991)

- If (CP-odd!) GEDM=0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious background

$$\mathcal{H} = -g\mu_N \boldsymbol{B}\cdot\boldsymbol{S} - \zeta\hbar\boldsymbol{\omega}\cdot\boldsymbol{S}, \quad \zeta = 1+\chi$$

$$|\chi(^{201}\mathrm{Hg}) + 0.369\chi(^{199}\mathrm{Hg})| < 0.042 \quad (95\%\mathrm{C.L.})$$

Equivalence principle for moving particles

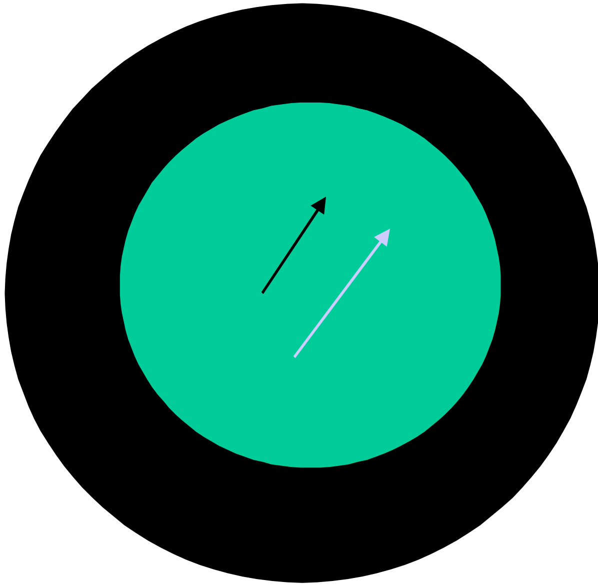
- Compare gravity and acceleration: gravity provides EXTRA space components of metrics $h_{zz} = h_{xx} = h_{yy} = h_{00}$
- Matrix elements DIFFER

$$\mathcal{M}_g = (\epsilon^2 + p^2) h_{00}(q), \qquad \mathcal{M}_a = \epsilon^2 h_{00}(q)$$

- Ratio of accelerations: $R = \frac{\epsilon^2 + p^2}{\epsilon^2}$ - confirmed by explicit solution of Dirac equation (Silenko, OT, '05)
- Non-stationary (weak approximation to Kerr) – Obukhov, Silenko, OT '09

Cosmological implications of PNEP

- Necessary condition for Mach's Principle (in the spirit of Weinberg's textbook) -
- Lense-Thirring inside massive rotating empty shell (=model of Universe)
- For flat "Universe" - precession frequency equal to that of shell rotation
- Simple observation-Must be the same for classical and quantum rotators – PNEP!
- More elaborate models - Tests for cosmology ?!



Gravitational FF and QCD anomaly (quarks – long ago: **hep-ph/9303228; gluons – in progress**)

- BELINFANTE (relocalization) invariance :

decreasing in coordinate –

$$M^{\mu,\nu\rho} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} J^5_{S\sigma} + x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu}$$

smoothness in momentum space

$$M^{\mu,\nu\rho} = x^\nu T^{\mu\rho}_B - x^\rho T^{\mu\nu}_B$$

- Leads to absence of massless pole in singlet <J> – U_A(1)

$$\epsilon_{\mu\nu\rho\alpha} M^{\mu,\nu\rho} = 0.$$

- Delicate effect of NP QCD

$$(g_{\rho\nu} g_{\alpha\mu} - g_{\rho\mu} g_{\alpha\nu}) \partial^\rho (J^\alpha_{5S} x^\nu) = 0$$

- Gluon – ghost pole

$$q^2 \frac{\partial}{\partial q^\alpha} \langle P | J^\alpha_{5S} | P + q \rangle = (q^\beta \frac{\partial}{\partial q^\beta} - 1) q_\gamma \langle P | J^\gamma_{5S} | P + q \rangle$$

- VIOLATES EP!!

$$\langle P, S | J^5_\mu(0) | P + q, S \rangle = 2MS_\mu G_1 + q_\mu (Sq) G_2,$$
$$q^2 G_2|_0 = 0$$

Possible solutions

- Realistic: Ghost pole is zero – <J-K> =0 for massless quarks -> as <K> is small <J> is small – small quark contribution to nucleon spin (defined mostly by strange quark mass); Exp ~ 0.3 (x 1/2)
- Romantic: EP for nucleon is violated at ~10% level – testable for deuteron EDM searches at BNL and COSY
- Trivial: Gluon angular momentum tensor can not be decomposed to spin and orbital parts

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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PHYSICAL REVIEW D 60 051502

Heavy quarks polarisation

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

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

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

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

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

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

- 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

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

- Consider STRANGE as heavy! – CURRENT strange mass squared is ~100 times smaller – -5% - reasonable compatibility to the data! May solve the problem with DIS and SIDIS (talk of M. Sapozhnikov)

Strangeness Polarization IN DIS and SIDIS

- Seen in DIS (fits) and not in SIDIS
- Global fit – polarization concentrated at small x ~0.02
- Models – typically larger
- Gluons – natural candidates for low x polarization (OT’09)

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

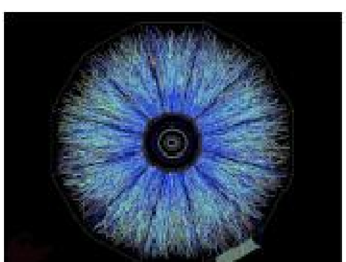
Heavy unpolarized Strangeness: vector current

- 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
- Starting point – very strong magnetic fields in heavy ions coliisions (D. Kharzeev et al. – next slide)

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	4.5×10^5 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



At BNL we beat them all!

Off central Gold-Gold Collisions at 100 GeV per nucleon

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

Anomaly in Heavy Ion Collisions - Chiral Magnetic Effect

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

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

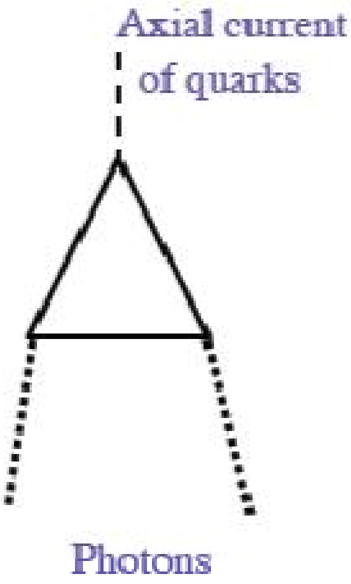
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu\theta = (M, \vec{P})$$

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

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

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

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



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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

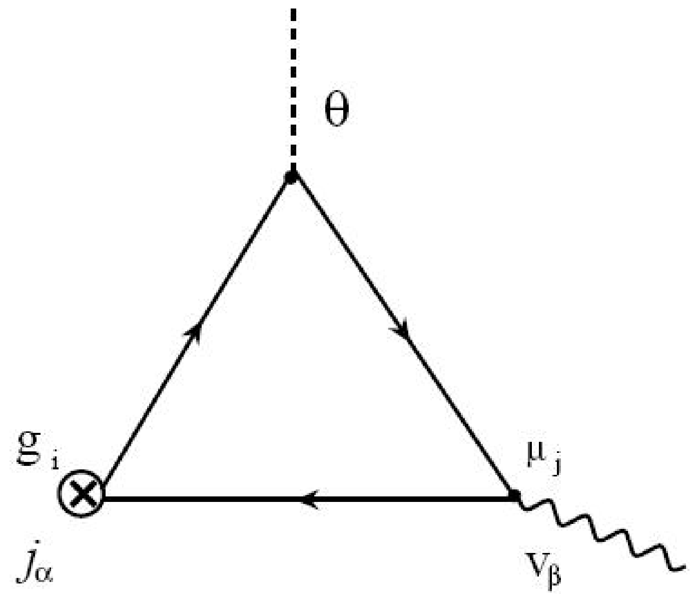
- Current carriers are obvious - strange quarks -> matching -> light quarks?
- No relation to topology (also pure QED effect exists)
- Effect for strange quarks is of the same order as for the light ones if topological charge is localized on the distances ~ $1/m_s$, strongly (4^{th} power!) depends on 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

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 - 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:

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

Comparing CME and CVE

- Orbital Angular Momentum and magnetic moment are proportional – Larmor theorem
- No antibaryons – no mirror correlations
- CME for 3 flavours – no baryon charge separation (2/3-1/3-1/3=0!) (Kharzeev, Son) - but strange mass!
- Same scale as magnetic field

Relativistic Vorticity and Chaos
(A.S.Sorin, OT, in prepration)

- “Maximal” vorticity/helicity - Beltrami flows $\omega_i \equiv \epsilon_{ijk} \partial_j v_k = m\, v_i$

$$\partial_i \phi = 0 .$$

- For ideal fluid – Bernoulli condition in the 3D region ~ chaos (normally only along streamlines ~ integrability)

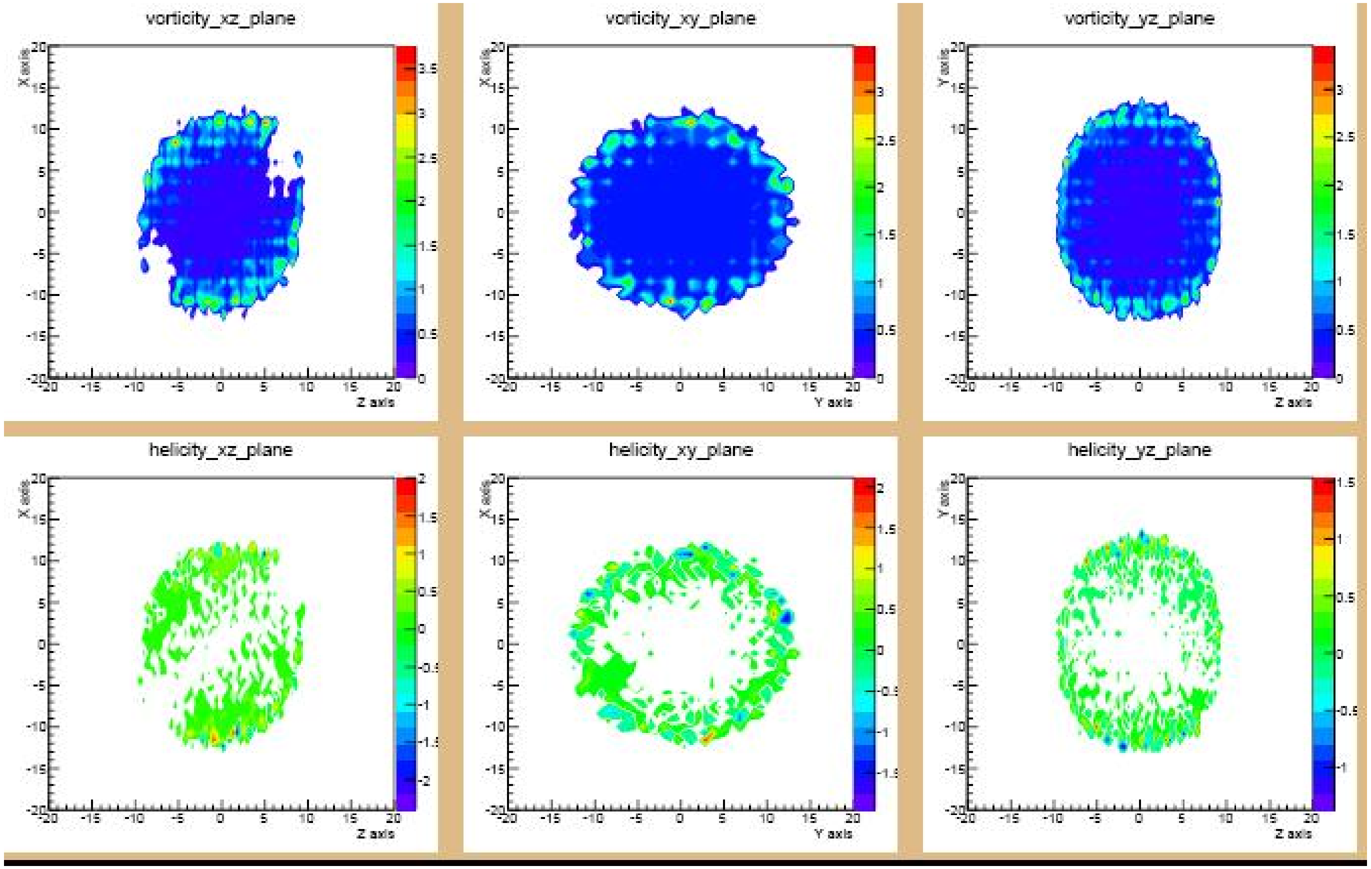
$$\phi = w + \frac{v^2}{2}$$

$$\partial_i w = \frac{1}{\rho} \partial_i p .$$

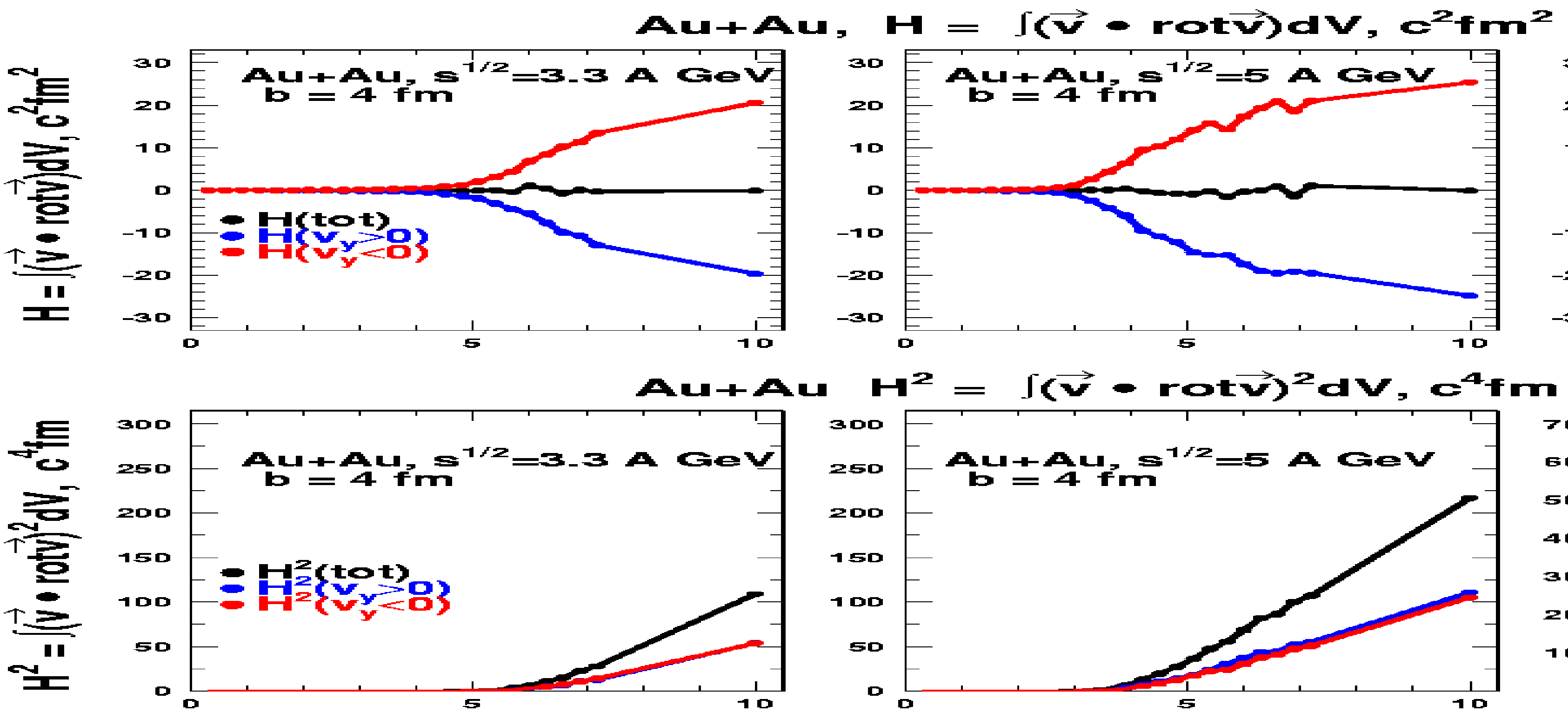
- Relativistic generalization for isentropic “steady”($\eta^\mu \partial_\mu \frac{w\, u_\nu}{\rho} = 0$)flows $\epsilon^{\mu\nu\alpha\beta} \eta_\mu \partial_\alpha \frac{w\, u_\beta}{\rho} = m \left(g^{\nu\mu} - \frac{\eta^\nu \eta^\mu}{\eta^2} \right) \frac{w\, u_\mu}{\rho}$
- Relativistic Bernoulli condition in 4D region

$$\partial_\mu \frac{w\, u^\nu \eta_\nu}{\rho} = 0$$

Model calculations (Baznat,Gudima,Sorin,OT)



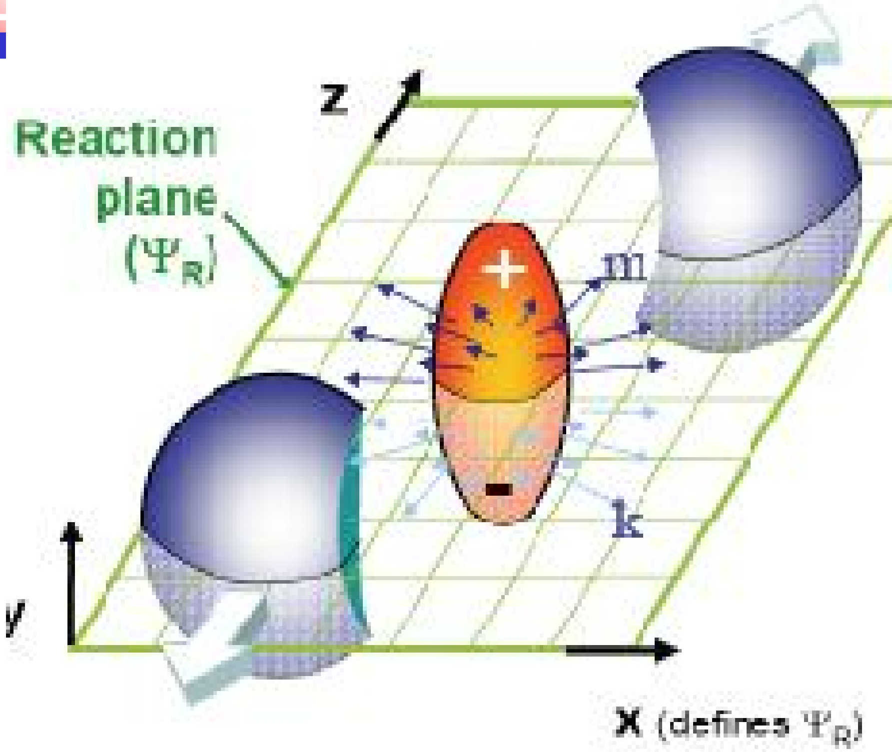
Hydrodynamical Helicity separation



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@NICA (talk of A. Sorin) may be well suited for neutrons!

Charge asymmetry w.r.t. reaction plane: how to detect it?



$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle =$$
$$= \langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle - \langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle$$
$$- [\langle v_{1,\alpha} v_{1,\beta} \rangle + D^{in}] - [\boxed{\langle a_\alpha a_\beta \rangle} + D^{out}],$$

S.Voloshin, hep-ph/0406311

A sensitive measure of the asymmetry:

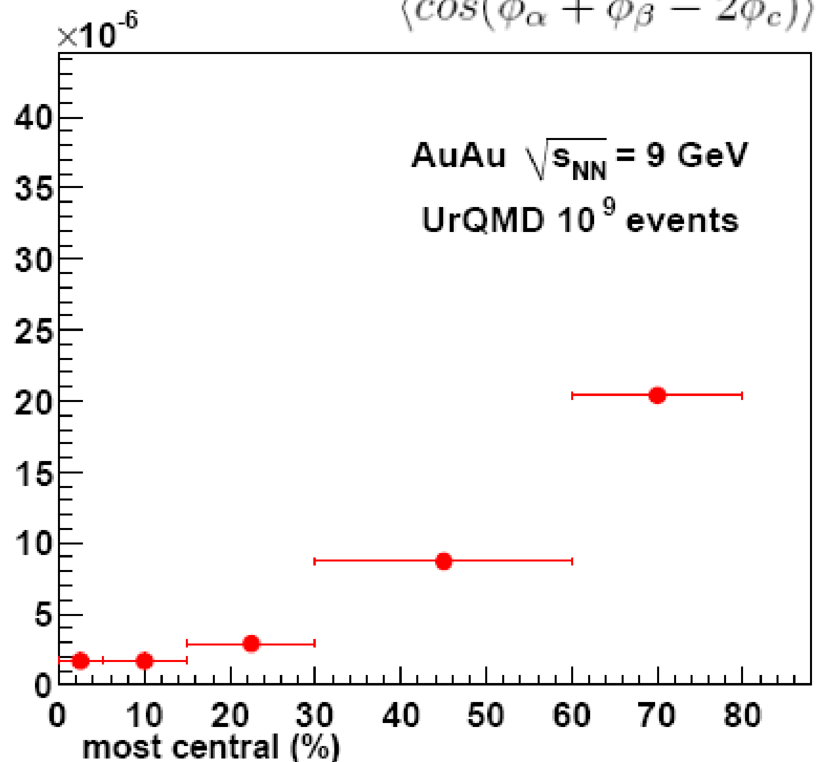
$$a^k a^m = \langle \sum_{ij} \sin(\varphi_i^k - \Psi_R)\, \sin(\varphi_j^m - \Psi_R) \rangle$$

Expect $a^+a^+ = a^-a^- > 0; \;\; a^+a^- < 0$

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

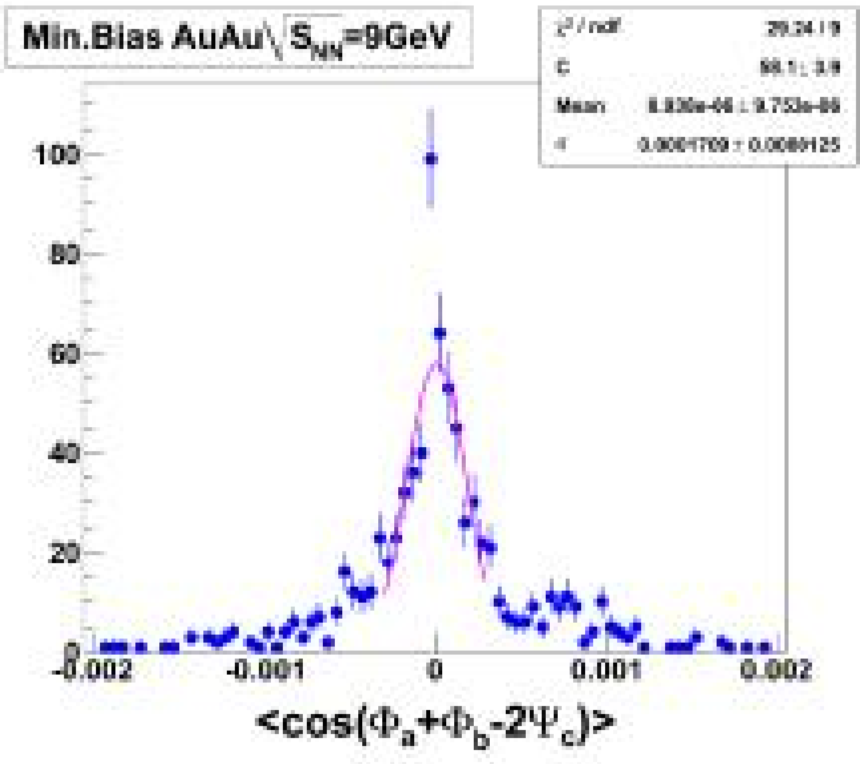
- UrQMD model : $Au + Au$ at $\sqrt{s_{NN}} = 9$ GeV
- 2-particles -> 3-particles correlations
  no necessity to fix the event plane
- 2 neutrons from mid-rapidity $(|\eta| < 1)$
- +1 from ZDC $(|\eta| > 3)$

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



Background effects

- Can correlations be simulated by UrQMD generator?



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 square of chemical potential – small at RHIC – may be probed at FAIR & NICA

$$j_A^{\mu} \sim \mu^2 \left(1 - \frac{2\,\mu\,n}{3\,(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho}\, V_\nu\, \partial_\lambda V_\rho$$

Conclusions/Discussion - II

- Anomalous coupling to fluid vorticity – new source of neutron asymmetries
- Related to the new notion of relativistic chaotic flows

- New source of hyperon polarization in heavy ions collisions