Gravity and Hadrons Spin Structure

Spin Physics at NICA: Theoretical Aspects

LHEP JINR March 4 2026

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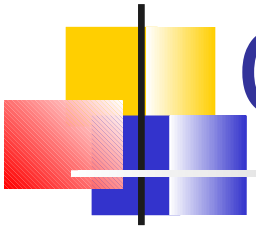
BLTP JINR

How strongest and weakest interactions are related?

- Energy-momentum tensor matrix elements describe both the hadronic structure and the coupling to gravity
- Strongly interacting matter in heavy-ion collisions is manifesting the extremely high vorticity ($\sim 10^{28}\ \Omega_{Earth}$) and acceleration ($\sim 10^{30}$ g) corresponding due to Equivalence Principle to superstrong gravity (M_{Pl} -> m_P)



Outline

Low-energy theorems for gravity: Equivalence Principle and its Extension

Hydro aspects of hadron structure: pressure, shear and viscosity

Anomalies for medium vorticity: axial current and polarization

EMT: Gravitational Formfactors (Pagels'66, Ji'97 : O (Δ)

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

- Conservation laws - zero Anomalous Gravitomagnetic Moment : $\mu_G = '\tilde{J}$ =2)

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

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

- No M_{Pl}! May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons Ji's SRs
- Describe interaction with both classical and "equivalent" gravity

Electromagnetism vs Gravity (OT'99)

- Interaction – field vs metric deviation

$$M = \langle P'|J^{\mu}_{q}|P\rangle A_{\mu}(q) \qquad M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P|J^{\mu}_{q}|P\rangle = 2e_q P^{\mu} \qquad \sum_{q,G}\langle P|T^{\mu\nu}_{i}|P\rangle = 2P^{\mu}P^{\nu}$$

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

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

- Mass as charge – equivalence principle
- Low-energy theorem

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 $h_{00} = 2\phi(x)$ nor 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

Equivalence principle

- Newtonian – "Falling elevator" – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on (quantum!) SPIN – known since 1962 (Kobzarev and Okun'; ZhETF paper contains acknowledgment to Landau: probably his last contribution to theoretical physics before car accident); rederived from conservarion laws - Kobzarev and V.I. Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way

Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW
LETTERS

VOLUME 68 | 13 JANUARY 1992 | NUMBER 2

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

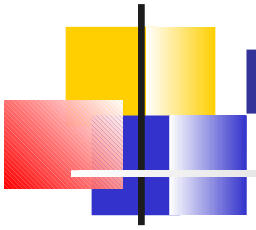
B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson
Physics Department, FM-15, University of Washington, Seattle, Washington 98195
(Received 25 September 1991)

- If (CP-odd!) GEDM (new EMT FF, also forbidden by EP: extra γ_5 in B) =0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background

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

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

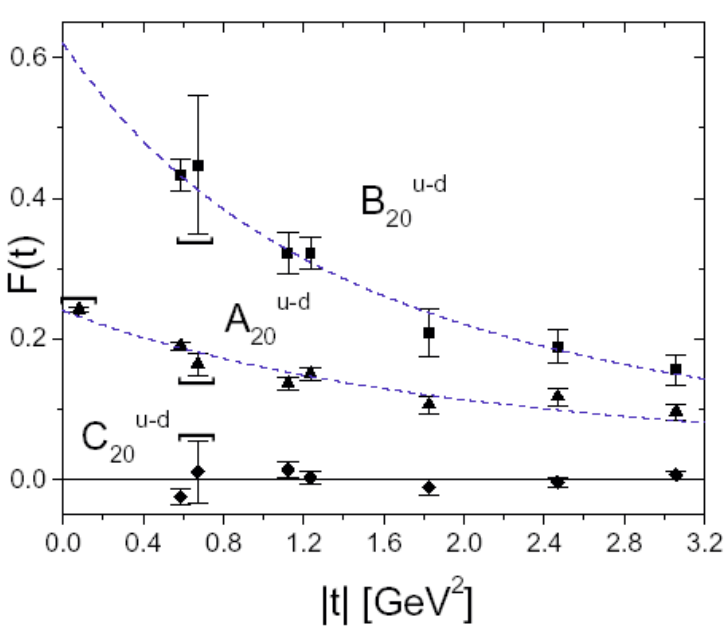
EP and quantum measurement

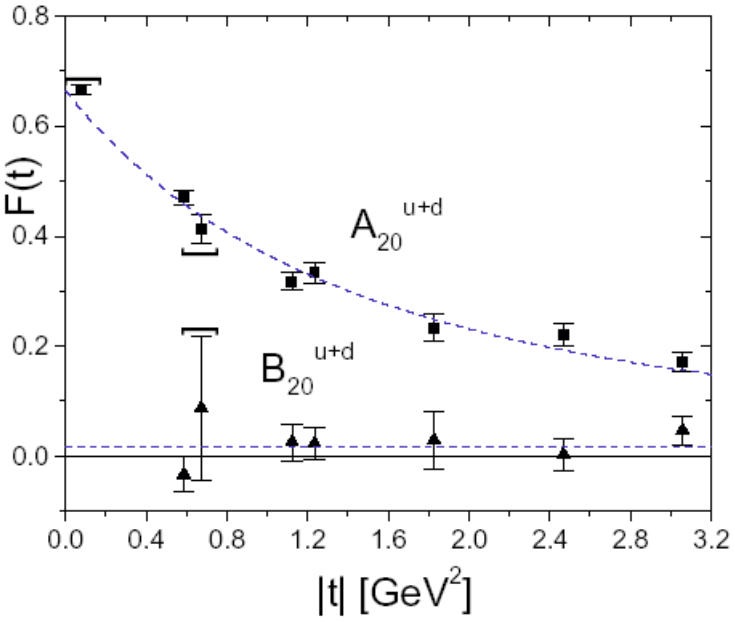


- If spin is just a geometric vector, EP for Earth's rotation is "trivial": looking from stars, spin rotates with Earth's angular velocity like Foucault pendulum
- Non-trivial if quantum measurement (quite practical here) is performed in the rotating frame
- Cf with Unruh effect: measurement in accelerated frame is crusial, medium as an (active) detector

Extension of Equivalence principle

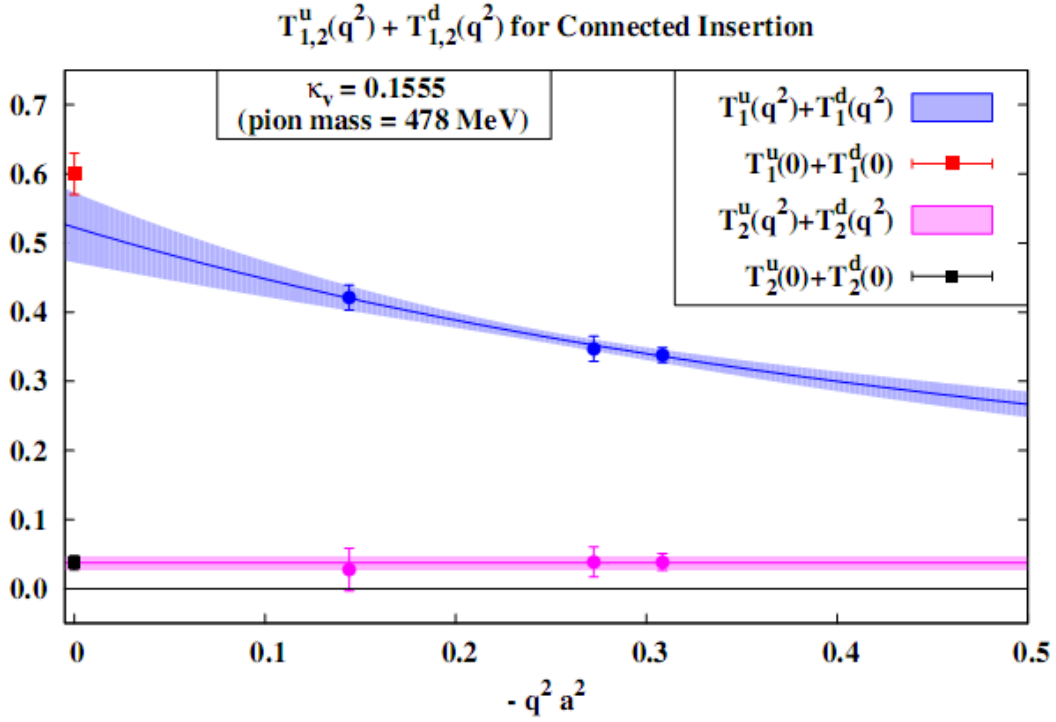
- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





More recent lattice study (M. Deka,…K.-F. Liu et al. Phys.Rev. D91 (2015) no.1, 014505)

- Sum of u and d for Dirac (T1) and Pauli (T2) FFs



Extended Equivalence Principle=Exact EquiPartition

- In NLO pQCD – violated (LF:S.Brodsky et al.)
- Reason – in the case of ExEP- no smooth transition for zero fermion mass limit (Milton, 71)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Gravityproof confinement?! Nucleons are not broken even by black holes?!

Effective QCD coupling from Bjorken SR

- Effective QCD coupling from BjorkeN SR (Deur,Brodsky,de Teramond,Roberts),
- Slope at $Q^2=0$ from (Lapidus-Zhou-Guanzhao) Gerasimov-Drell-Hearn SR

SOVIET PHYSICS JETP VOLUME 11, NUMBER 1 JULY, 1960

SCATTERING OF GAMMA-RAY QUANTA BY NUCLEONS NEAR THE THRESHOLD FOR MESON PRODUCTION

L. I. LAPIDUS and CHOU KUANG-CHAO

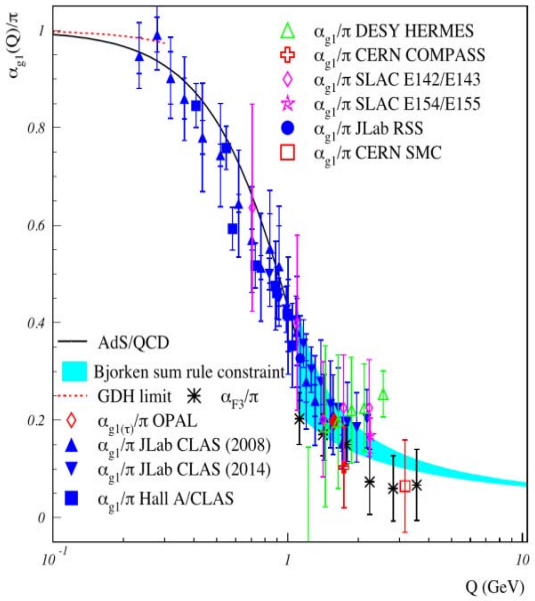
Joint Institute for Nuclear Research

Submitted to JETP editor July 9, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 201-211 (January, 1960)

The elastic scattering of γ-ray quanta near the threshold for single meson production is treated by means of dispersion relations. It is shown that when one takes into account meson production in the s state there are appreciable departures from monotonic variation with energy of the scattering amplitudes, cross sections, and other observable quantities near the threshold of the reaction. On definite assumptions about the analysis of photoproduction in the range of γ-ray energies up to 220 Mev, calculations are made of the scattering amplitude and the differential and total cross sections for elastic scattering of polarized and unpolarized γ-rays by protons, and also of the polarization of the recoil protons above the photoproduction threshold.

A. Deur et al. / Progress in Particle and Nuclear Physics 90 (2016) 1–74



Conformality and ExEP

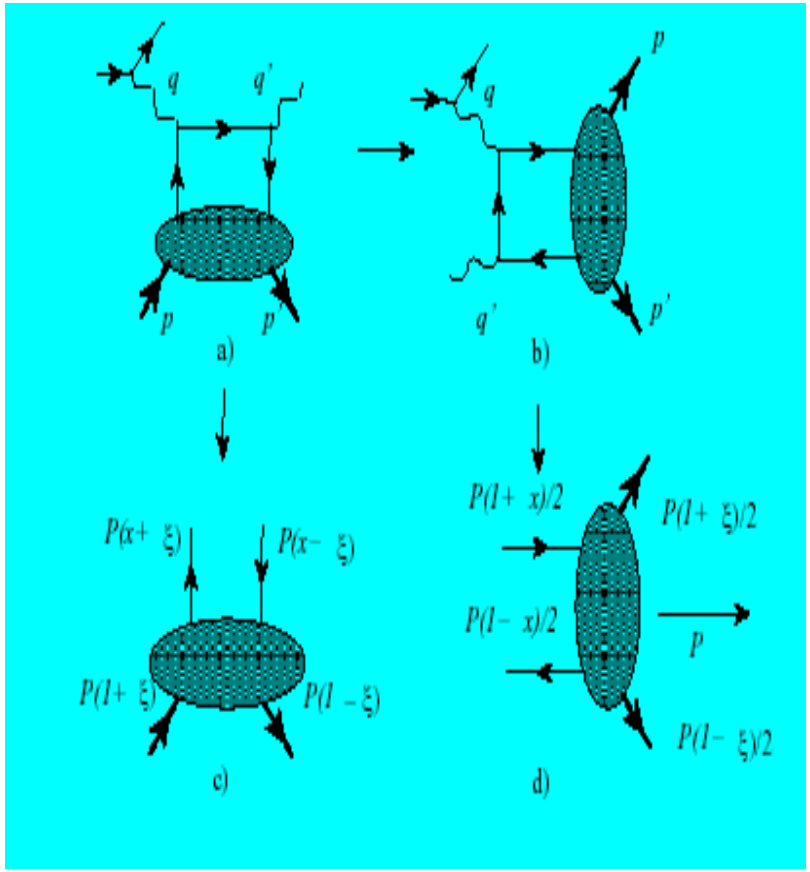
- Closeness of AMMs of proton (1.79) and neutron (-1.91) squared

$$\frac{d\alpha_{g_1}(Q^2)}{dQ^2}|_{Q^2=0} = \frac{3\pi}{4g_A}\left(\frac{\kappa_n^2}{M_n^2} - \frac{\kappa_p^2}{M_p^2}\right)$$

- Smallness of singlet AMM is related to ExEP (OT'99): 1st and 2nd moments (with different parity: antiquarks subtracted for AMM and added for AGMM) of GPD $E(x,\xi)_{u+d}$
- Relation between higher dimensional (in AdS QCD) and real gravity

Road to timelike GrFFs: Crossing for DVCS and GPD (cf e+e- and HICs: small systems)

- DVCS -> hadron pair production in the collisions of real and virtual photons
- GPD -> Generalized Distribution Amplitudes (Diehl,Gousset, Pire,OT'98)



Gravitational FFs from Belle data on GDAs

S. Kumano, Qin-Tao Song and O. Teryaev, PRD **97** (2018) 014020. 1711.10086

- Gravitational FFs are related to twist-2 GDAs

$$A_{\lambda_1\lambda_2} = T_{\mu\nu}\varepsilon^{\mu}(\lambda_1)\varepsilon^{\nu}(\lambda_2)/e^2$$

$$A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz \frac{2z-1}{z(1-z)}\Phi^q\left(z,\xi,W^2\right)$$

$$\int dz(2z-1)\Phi_q^+\left(z,\xi,W^2\right) = \frac{2}{(P^+)^2}\left\langle \pi^+(p_1)\pi^-(p_2)\left|T_q^{++}(0)\right|0\right\rangle$$

$$\left\langle \pi^0(p_1)\pi^0(p_2)\left|T^{\mu\nu}(0)\right|0\right\rangle = \frac{1}{2}\left[\left(sg^{\mu\nu}-P^{\mu}P^{\nu}\right)\Theta_1 + \Delta^{\mu}\Delta^{\nu}\Theta_2\right]$$

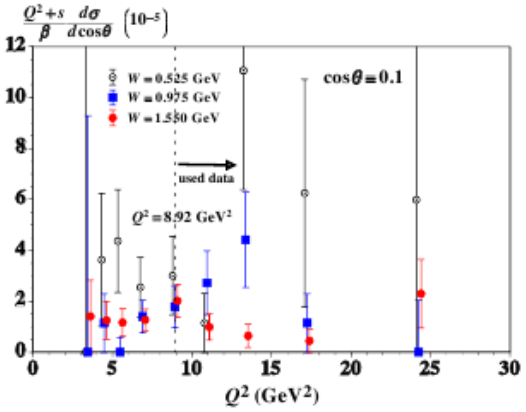
$$P = p_1 + p_2\,,\ \Delta = p_1 - p_2$$

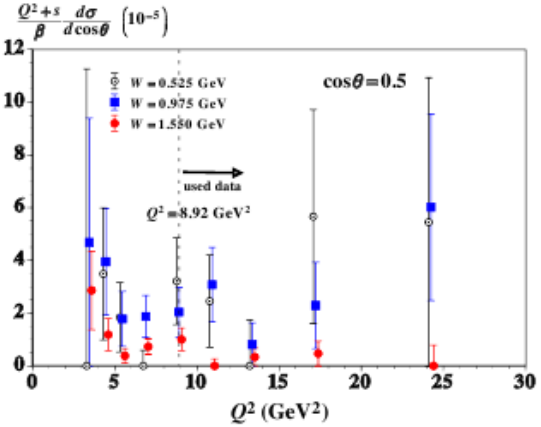
M. Masuda et al. [Belle Collaboration], PRD 93 (2016), 032003

- Belle data and scaling : W=0.525,

$$\frac{(Q^2+s)d\sigma}{\beta d|\cos\theta|} \propto \left|\Phi^{\pi^0\pi^0}(z,\cos\theta,W,Q)\right|^2$$

$$\sqrt{\langle r^2\rangle_{\rm mass}} = 0.39\,{\rm fm},\ \sqrt{\langle r^2\rangle_{\rm mech}} = 0.82\,{\rm fm}$$





New EMT formfactor : "Shear viscosity" (OT'2020)

- From spherically symmetric object to fluid (EoS!)
- $T^{\mu\lambda} = (e+p)\, v^{\mu} v^{\lambda} - p\, g^{\mu\lambda}$
- $V^{\mu} = P^{\mu}/M$: correct normalization but no coordinate dependence
- Another suggestion (OT'19):
- $V^{\mu} = (P^{\mu} + a(t)\, k_T^{\mu}) / (M^2 + a^2(t)\, k_T^2)^{1/2}$
- Viscosity: $\eta\, dv^{\mu}/d\, x_T^{\lambda} \sim E_{\eta}\, p^{[\mu} \Delta^{\lambda]}$
- NO such term in total EMT (but can be for quarks separately)

- Naïve T-oddness: phases in GPD channel from decays in TDA
- Phases <-> dissipation: polarization in pionic superfluidity model (V. I. Zakharov, OT' 17)

Timelike GrFF: Viscosity in GDA channel

- Viscosity:will correspond to Exotic $J^{PC}=1^{-+}$ meson (studied long ago without mentioning gravity: Anikin, Pire, Szymanowski,OT, Wallon'06)
- Spin: related to structure of matrix element: One index of EMT (0th in rest frame) is carried by momentum and other by polarization vector - just what we need for viscosity
- NO for conserved EM: zero coupling for (G)DA!
- $\pi\eta$ pairs observation instead of $\pi\,\pi$ required
- Smallness of viscosity: related to smallness of exotic GDAs and ExEP violation?!

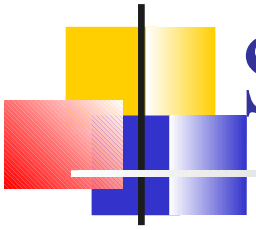
Estimate of viscosity

$(e+p)\, v_\mu v^\lambda \sim A\, P_\mu P^\lambda$

- $\eta\, dv_\mu/d\, x_T{}^\lambda \sim E_\eta\, p\, [\mu\, \Delta^\lambda]$
- TD: e+p -> Ts
- η/s (> $1/(4\pi)$)~ $E_\eta T /AM$ (smallness due to ExEP and small coupling to exotics)
- Correct dependence on Planck constant recovered via Δ^λ ->- $i\hbar\, d /d\, x_T{}^\lambda$
- Song,OT,Yoshida,2503.11316 &PLB : relation in QCD factorization to structure of pseudoscalar mesons: $\eta/s \sim 0.05$ (cf Holographic KSS bound $1/4\pi$)

Shear for deuterons: Spin 1 EMT and inclusive processes

- Forward matrix element -> density matrix
- Contains P-even term: tensor polarization $S^{\alpha\beta}$ New EMT FF
- $< P|T^{\alpha\beta}|P> = A\, P^{\alpha} P^{\beta} + T\, S^{\alpha\beta}$
- Symmetric and traceless: correspond to (average) shear forces
- Cf with spin ½ and spin 1 vector polarization : P-odd vector polarization requires another vector (q) to form vector product



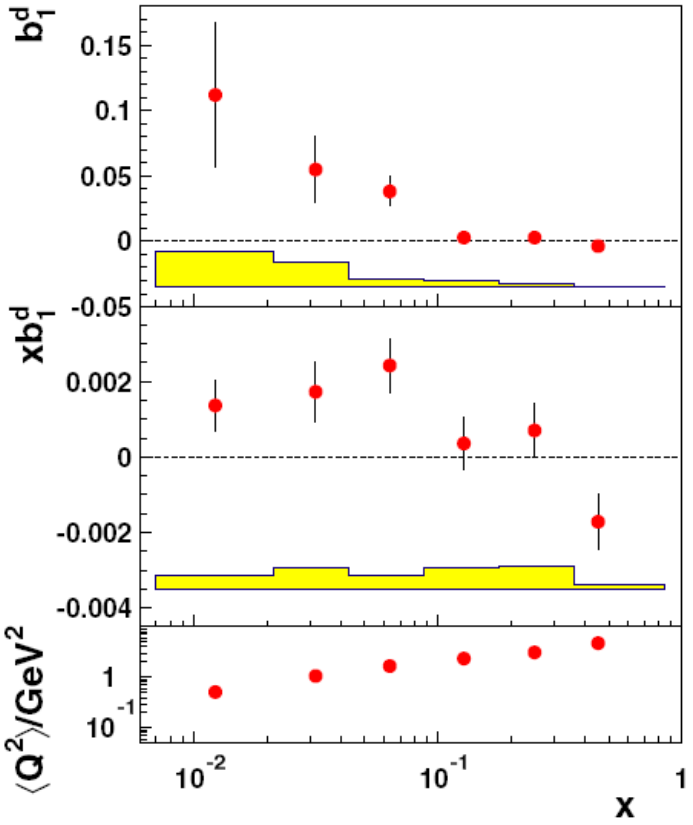
SUM RULEs

- Efremov,OT'82 : zero sum rules in QCD factorization:
- Current conservation: 1st moment: also in parton model by Close and Kumano (90)
- EMT conservation: 2nd moment (forward analog of Ji's SR: $\sum$ B=0 <=> $\sum$ T=0)
- Average shear force (compensated between quarks and gluons)
- Gravity and (Ex)EP (zero average shear separately for quarks and gluons) – OT'09

HERMES – data on tensor spin structure function

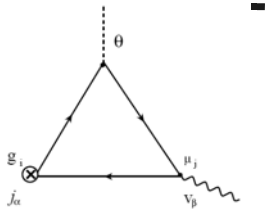
PRL **95,** 242001 (2005)

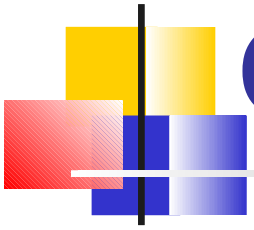
- Isoscalar target – proportional to the sum of u and d quarks – combination required by (Ex)EP
- Second moments – compatible to zero better than the first one (collective tensor polarized glue << sea
- Further studies: SPD?



Anomaly in medium – new external lines in VVA graph

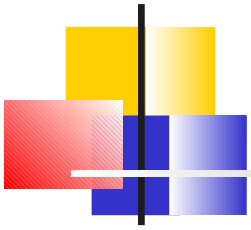
- Gauge field -> velocity
- Strength ->vorticity
- Gauge and gravitational anomalies
- Relation to global polarization of baryons in HIC (decrease woth energy and scale predicted)
- EP & SPD: Tensor polarization





CONCLUSIONS

- Anomalies and low energy theorems are essential to hadron structure
- QCD anomaly is applied to eta factory physics
- Gravitational low energy theorems (various manifestations of Equivalence Principle) defines hadron structure detailes
- ExEP valid separately for quarks and gluons remains a puzzle (gravityproof confinement?)



- Thank you very much!

- Welcome to DSPIN-2026

September 7-11

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

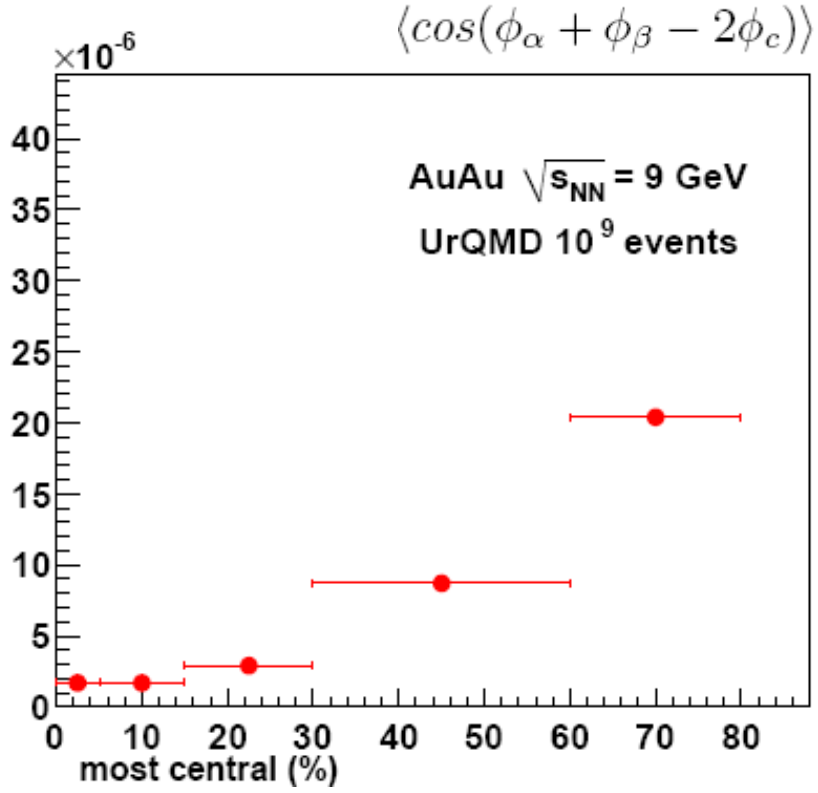
- Orbital Angular Momentum and magnetic moment are proportional – Larmor theorem
- Vorticity for uniform rotation – proportional to OAM
- Same scale as magnetic field
- Tests are required

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!

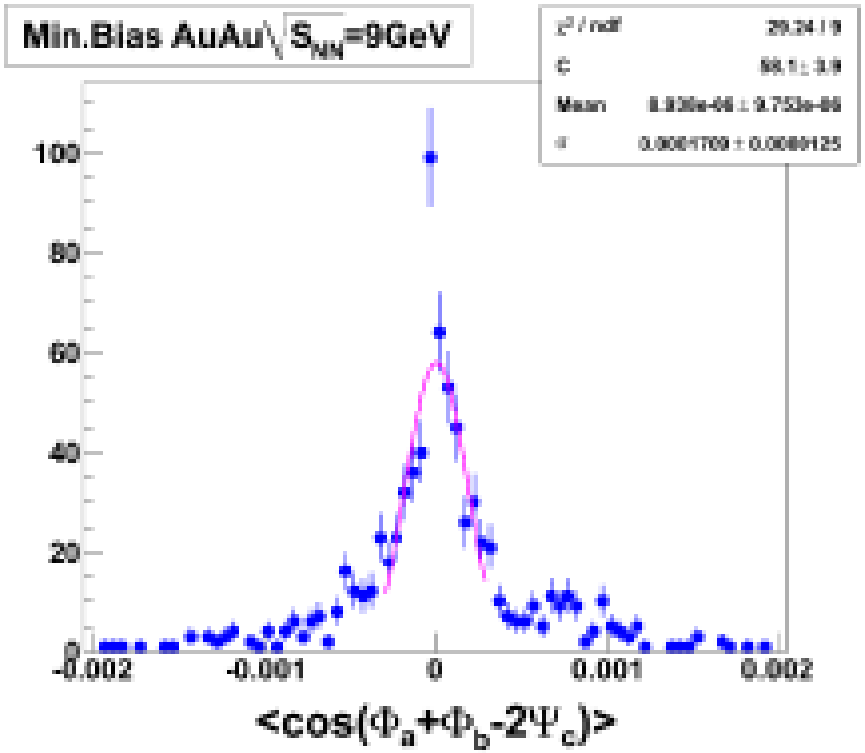
Estimates of statistical accuracy at NICA MPD (months of running)

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

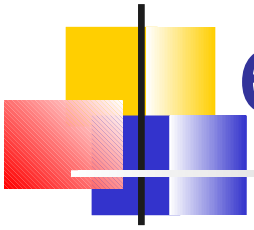


Background effects

- Can correlations be simulated by UrQMD generator?



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

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

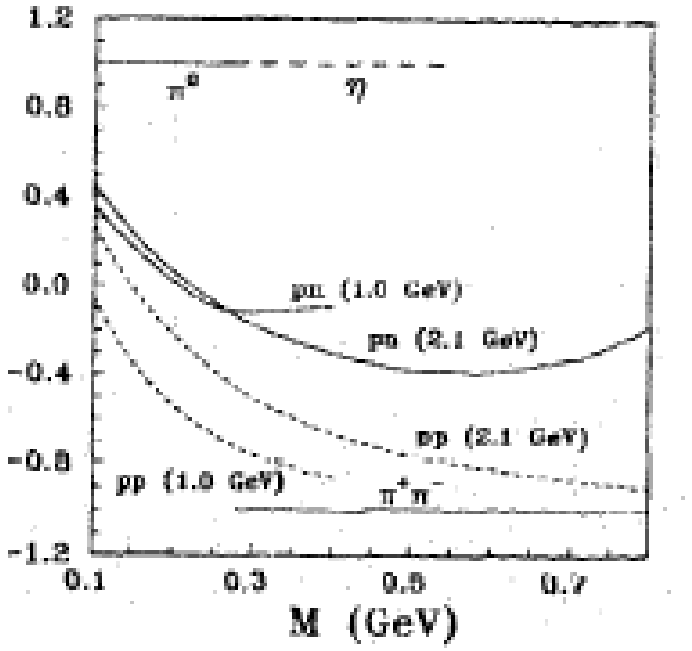
- Structures –similar to DIS F1, F2 (p ->v)

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 - recently performed by HADES in Ar+KCl at 1.75 A GeV !

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

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



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)

$$\begin{pmatrix} \frac{1-\lambda}{2} & \mu & \rho \\ \mu & \frac{1+\lambda+\nu}{2} & \sigma \\ \rho & \sigma & \frac{1+\lambda-\nu}{2} \end{pmatrix} \quad M > 0$$

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

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

- 1st line – Lam&Tung by SF method

Magnetic field conductivity and asymmetries

- zz-component of conductivity (~hadronic) tensor dominates
- $\lambda = -1$
- 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 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
- Two-current effects – dilepton tensor polarization
- New source of hyperon polarization in heavy ions collisions

What do we test (question of A.M. Baldin)?

- Fundamental field-theoretical property of anomaly manifested in the new effects:
- - Non-perturbative exact sum rule controlling the meson spectrum as a whole
- - Medium velocity and vorticity as an effective fields coupled to anomaly