Dispersive approach to axial anomaly and eta meson decays

惠州强子谱仪HHaS合作组年会

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Outline

- QED Axial Anomaly in the IR region and hadron structure
- Anomaly sum rule in the QCD (non-abelian) case : New gluonic off-shell formfactor of photon
- Anomaly sum rule with mixing and eta decays: hunting for new formfactor
- Decays to neutrino-antineutrino pairs via Z emission: background to DM searches
- Check of Arnrllos, Marcianom Parsa paper and account for mixing: consideravle enhancement of branching ratio

Symmetries and conserved currents

- (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)

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

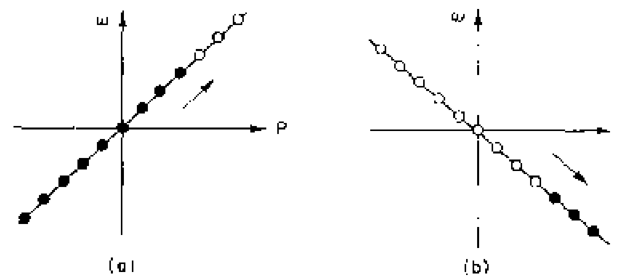
Quantum theory

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

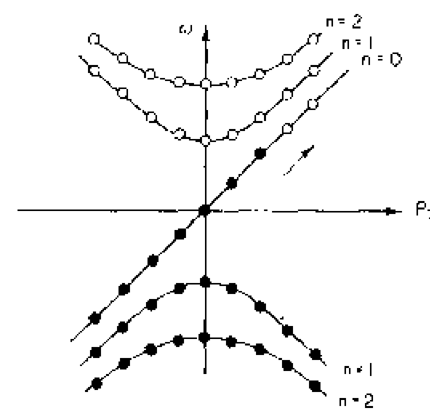
Calculation of anomalies

- 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)



Manifestation of anomalies

- Pion and other pseudoscalars decays (invisible modes: X. Chen, S. Khlebtsov, A. Oganesian, OT, in preparation)
- Nucleon spin problem
- Low energy theorems
- Chiral (and other effective theories) anomalies

Anomaly at low scales

- Often thought that only manifested as UV
- Not true – appears at all scales (continuity of LL flow)
- Natural way – dispersive approach to anomaly (Dolgov, Zakharov'70) - anomaly sum rules
- One real and one virtual photon – Horejsi,OT'95
- Anomaly Sum Rule

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

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

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

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!

$$(q^2 - t)A_3(t) - q^2 A_4(t) = 2mB(t)$$

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

- Anomaly as a finite subtraction

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

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

Properties of anomaly sum rules

- Valid for any Q^2 (and quark mass)
- Model-independent approach
- No perturbative QCD corrections (Adler-Bardeen theorem)
- No non-perturbative QCD corrections (t'Hooft consistency principle: same anomaly for quarks and hadrons)
- Explains massless pion pole for massless quarks: Complementary to NG
- Well suited for mixing description

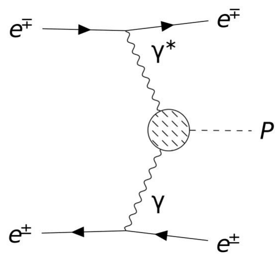
Mesons contributions (Klopot, Oganesian, OT) 1009.1120

- 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 $F_{\pi\gamma\gamma^*}^{\mathrm{asymp}}(Q^2) = \frac{\sqrt{2} f_\pi}{Q^2} + \mathcal{O}(1/Q^4)$
- 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 (cf Hagedorn spectrum)
- For quantitative analysis – quark-hadron duality (s_0 – duality interval)

Mesons contributions within quark hadron duality



- 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")

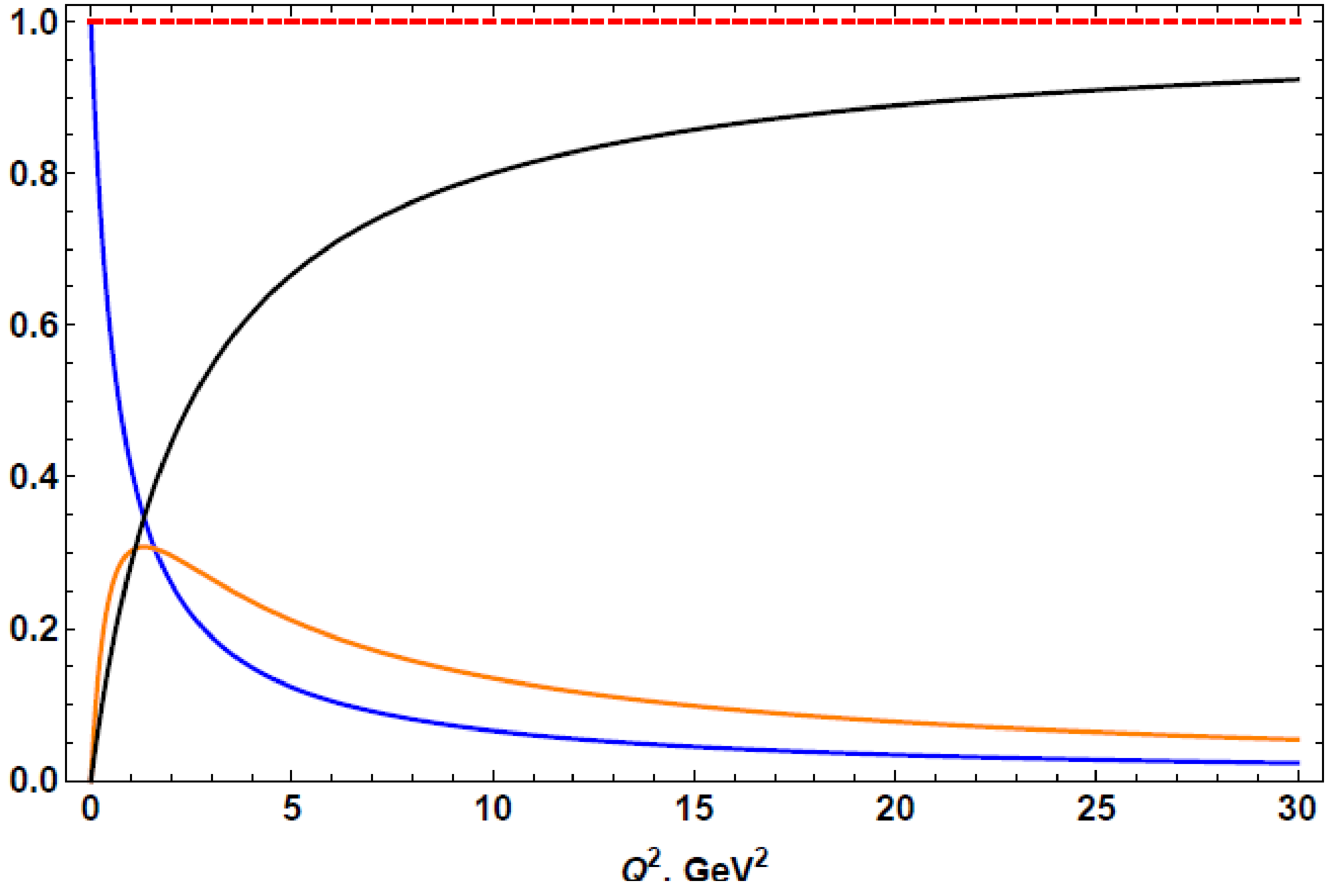
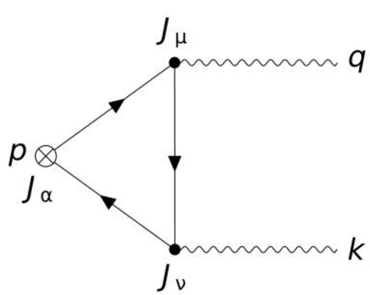
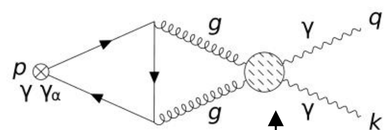


Figure 1: Relative contributions of π (blue line) and a_1 (orange line) mesons, intervals of duality are $s_0 = 0.7\ GeV^2$ and $s_1 - s_0 = 1.8\ GeV^2$ respectively, and continuum (black line), continuum threshold is $s_1 = 2.5\ GeV^2$

Non-abelian anomaly (Khlebtsov, Klopot, Oganesian, OT'19-21)

- Non-perturbative transition of gluons to photon (inverse power of coupling!)
- No massless eta' for massless quarks: cancellation of photon an contributions

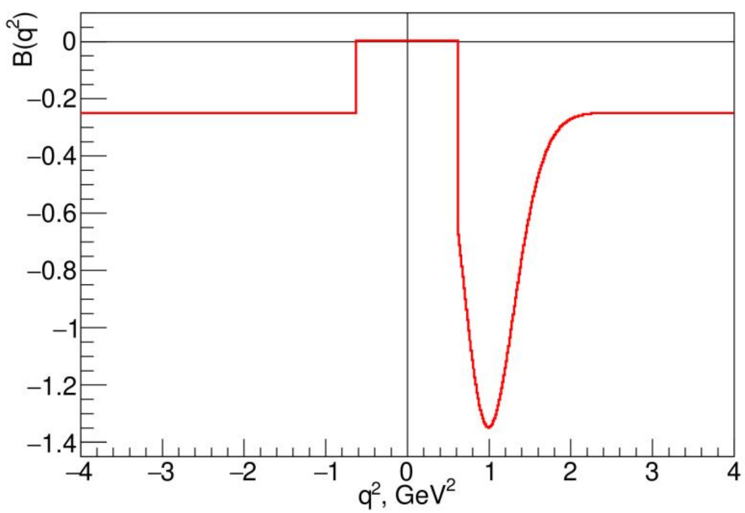




$B(q^2)$

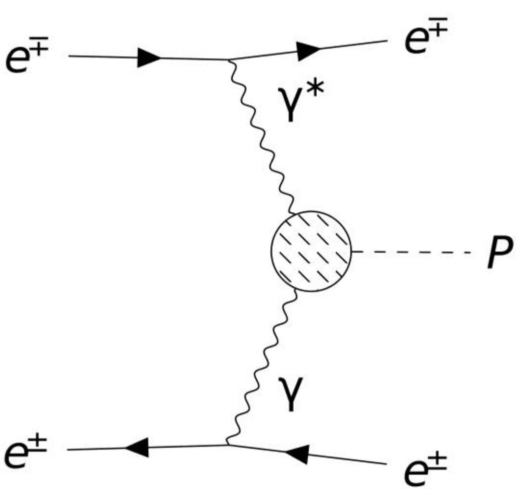
Description of non-perturbative dynamics

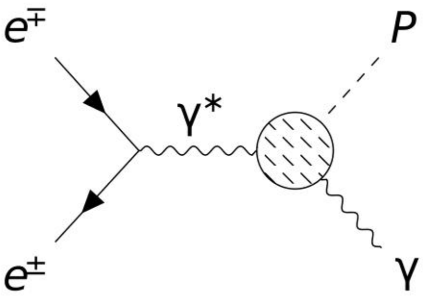
- The non-abelian anomaly implies the new input in dispersive approach: gluons-to-photons NP conversion matrix element (= new off-shell gluon formfactor of photons) $B(q^2)$
- Structure is related to PS glueball: X(2370)?
- Possible manifestation in CME-like effects in HIC

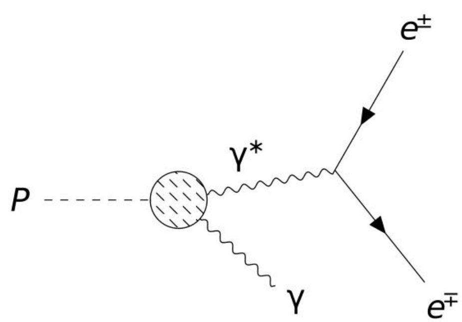


Processes with eta(')a

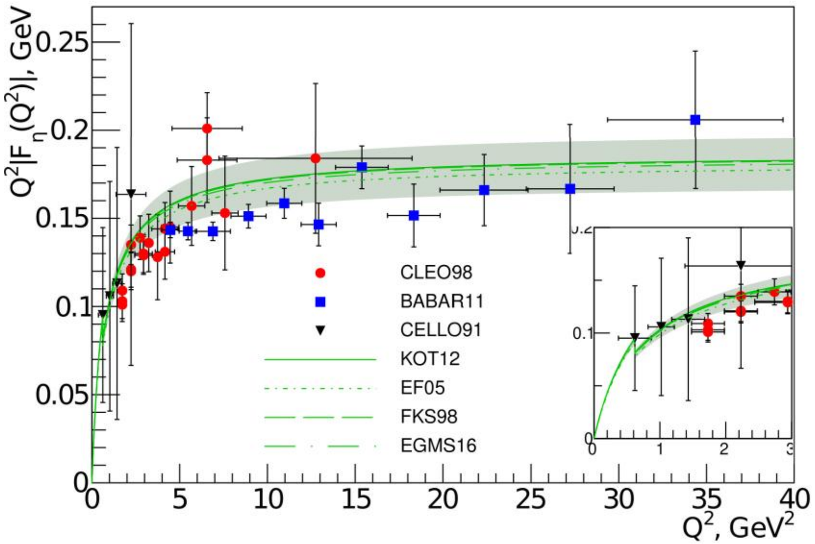
- Production and decays with real and virtual photons



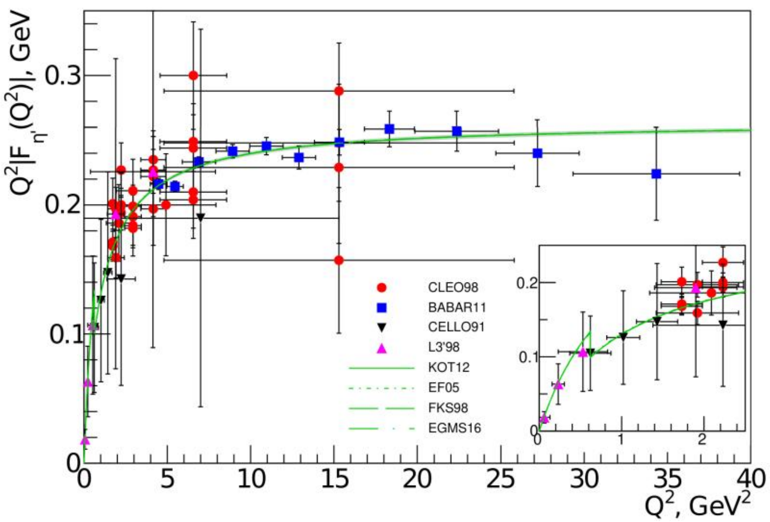




Eta(`)s TFF



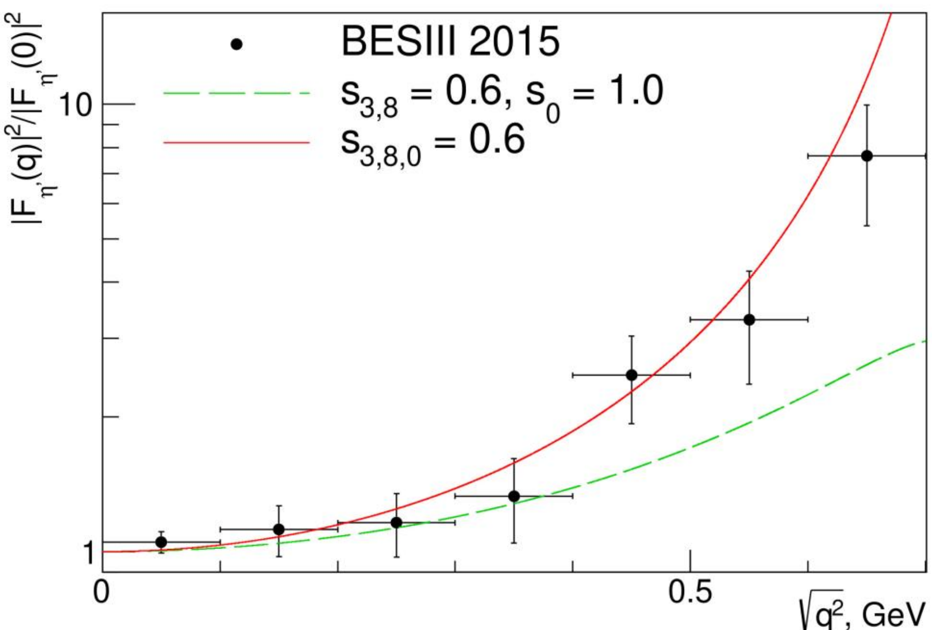
$Q^2|F_\eta(Q^2)|$, GeV
Q^2, GeV^2
CLEO98
BABAR11
CELLO91
KOT12
EF05
FKS98
EGMS16

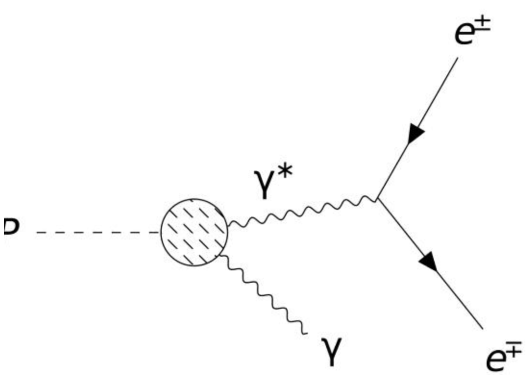


$Q^2|F_{\eta'}(Q^2)|$, GeV
Q^2, GeV^2
CLEO98
BABAR11
CELLO91
L3'98
KOT12
EF05
FKS98
EGMS16

Dalits decays

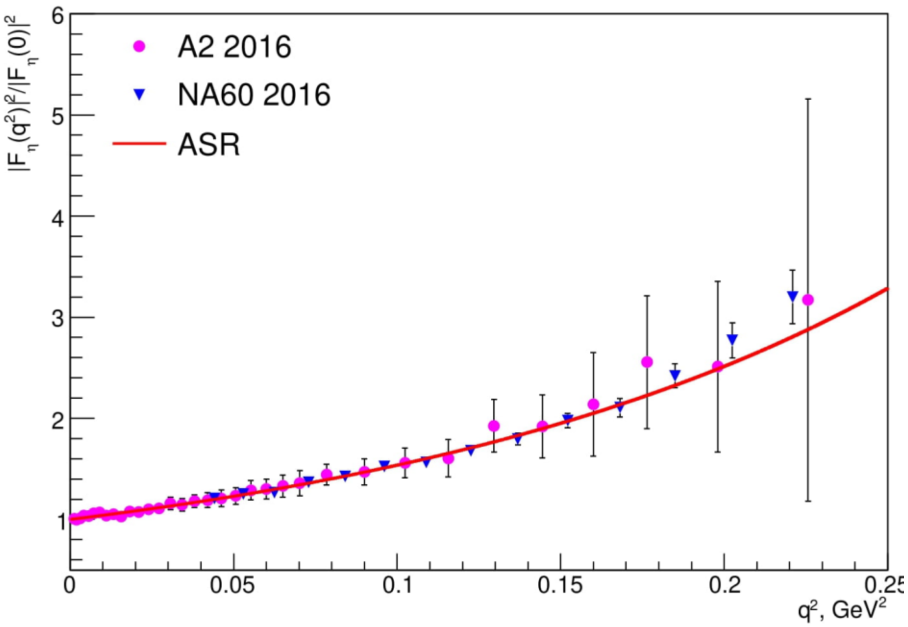
- Sensitive probes of duality intervals
- Models of $B(q^2)$
- To be studied at HHaS (talk of XiaoLin Kang)

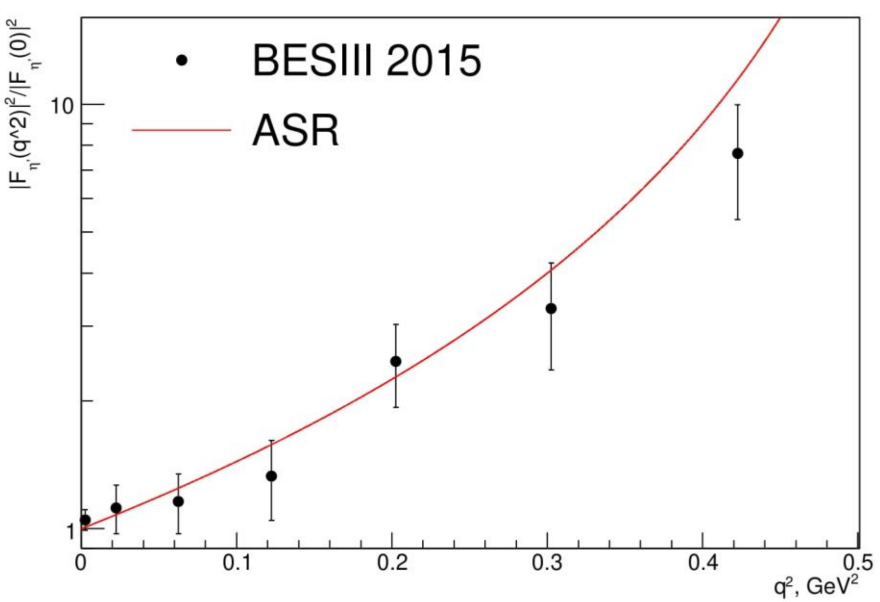




Dalitz decays in non-Abelian ASR (Chen, Khlebtsov, Oganesian, OT, in preparation)

- Eta and Eta’





Invisible modes

- Decay $\eta \to \gamma + (Z^0)\ 2\nu$
- Background for decay to dark matter
- May be studied at HIAF η factory
- Pioneering calculation for pion: L. Arnellos, W. J. Marciano and Z. Parsa, Nucl. Phys. B 196 (1982) 365
- New approach (X. Chen, S. Khlebtsov, A Oganesian, OT, in preparation) reproduces the old result when mixing is neglected but provides orders of magnitude enhancement for eta when mixing is accounted for
- Still remains low enough to provide substantial background for DM searches

Some numbers for branching

- AMP branching for pions: 2×10^{-18}
- Our result without mixing: AMP confirmed up to factor 3 due to 3 neutrino flavors
- Mixing (especially with η′ due to relative enhancement by $\sin\theta_W$): 2.18×10^{-17} for pions, 7.94×10^{-14} for η
- Still well below current accuracy of DM searches

Conclusions

- HHaS can play the crucial role in investigation of new off-shell gluon formfactor of photons
- Dalitz decays are the sensitive probe of this formfactor
- Decay to neutrino is strongly enhanced by mixing but is well below the accuracy of DM searches

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

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

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

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

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

- 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

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

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

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

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

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

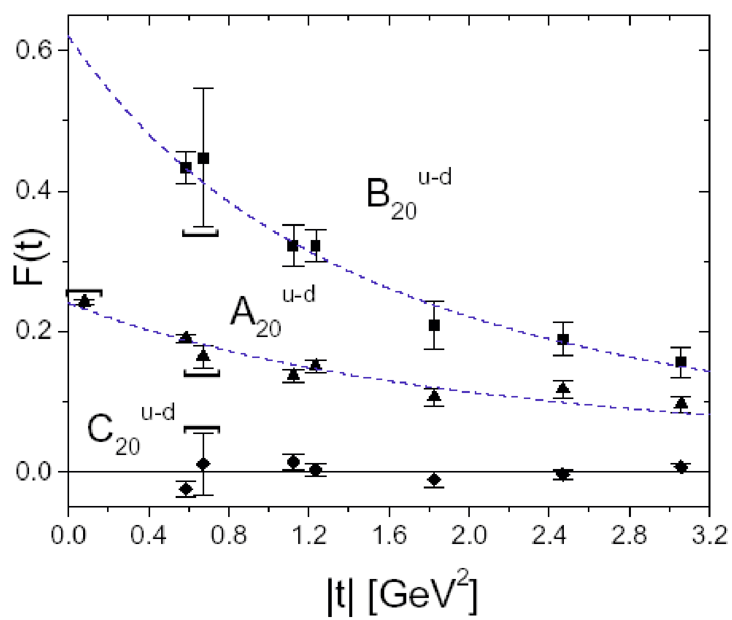
- Gravitational test of Ji's SR (for Hg)!
- New high precision EDM experiments: gravity is essential (NN Nikolaev,Vergeles,Obukhov, Silenko,OT, 2204.00427 and UFN)

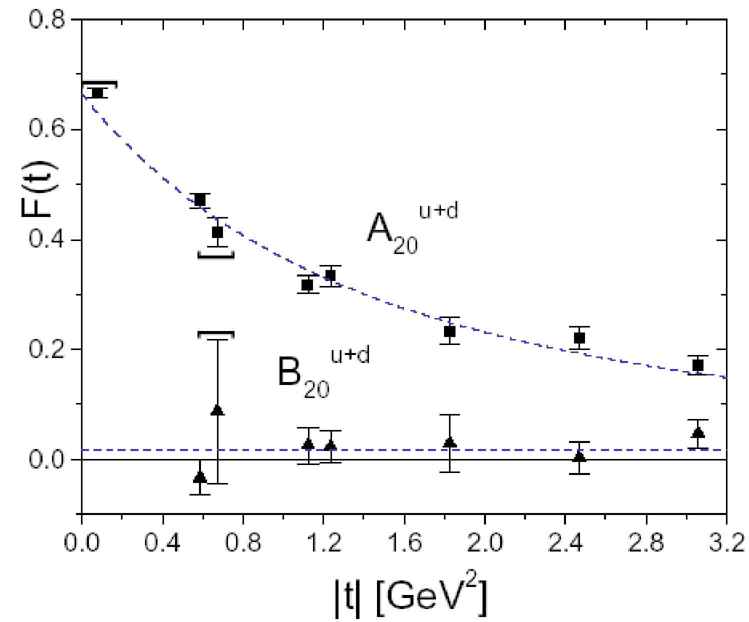
EP and quantum measurement

- 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 (talk of G. Prokhorov): measurement in accelerated frame is crusial, medium as an (active) detector

Extension of Equivalence principle

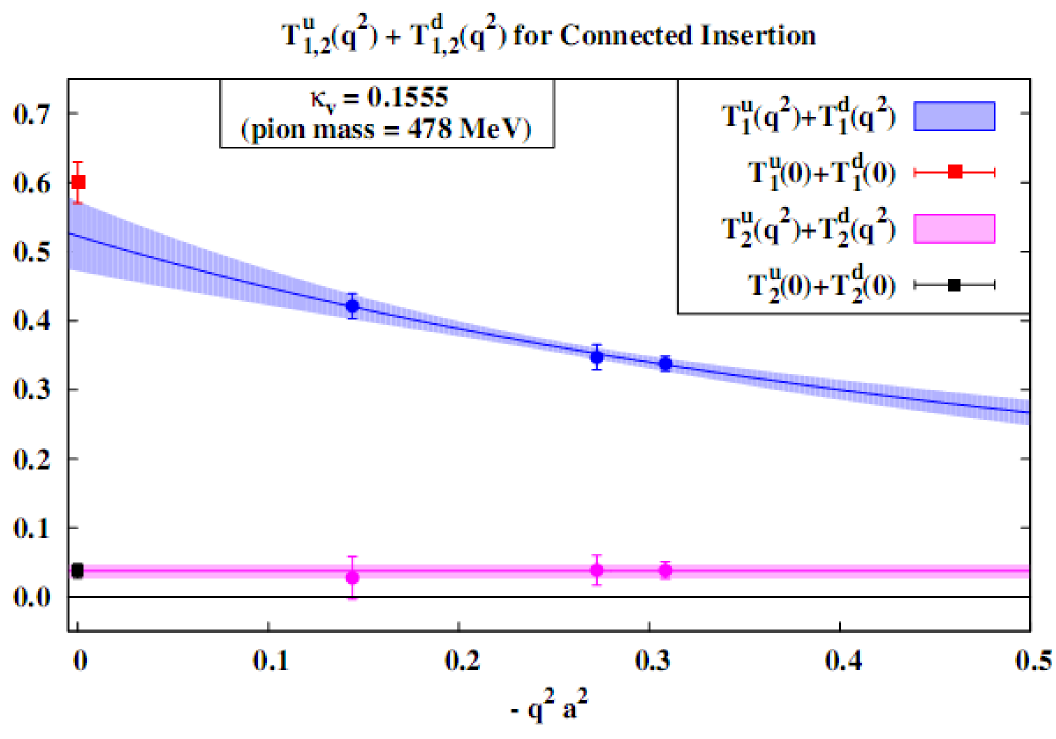
- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





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

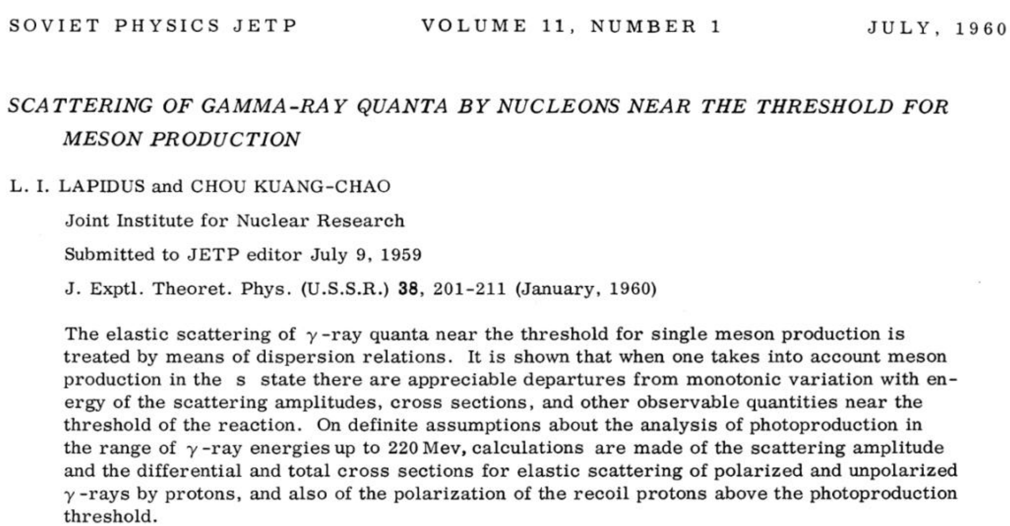


Extended Equivalence Principle=Exact EquiPartition

- 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 (cf talk of A. Kotikov)

- 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

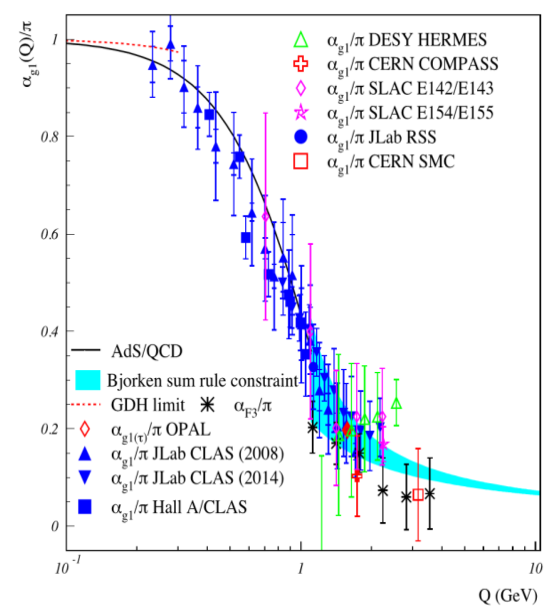
Joint Institute for Nuclear Research

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

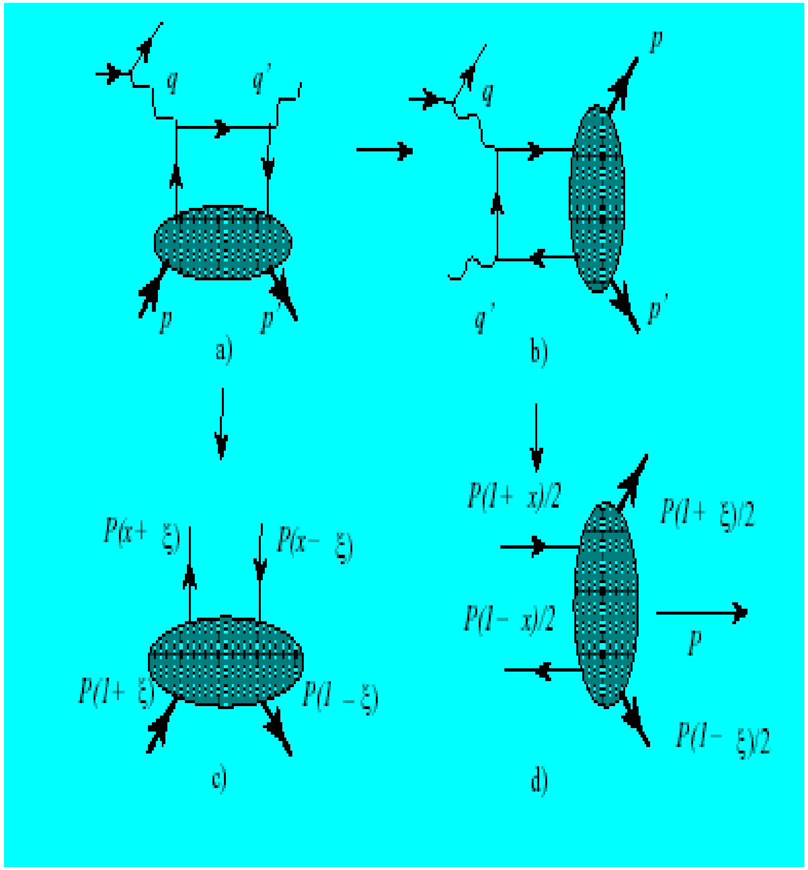
- Closeness of AMMs of proton (1.79) and neutron (-1.91) squared

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

- 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 1711.10086

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

- Gravitational FFs are related to twist-2 GDAs

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

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

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

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

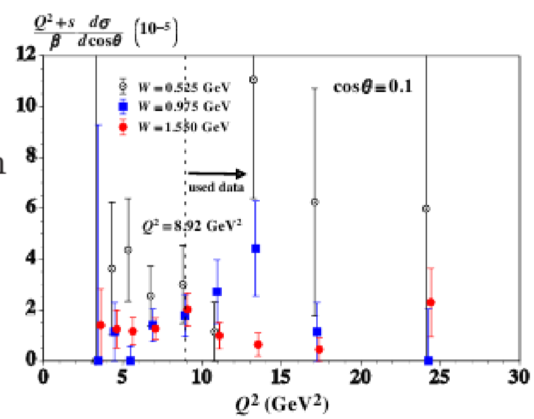
$$P = p_1 + p_2\ ,\ \Delta = p_1 - p_2$$

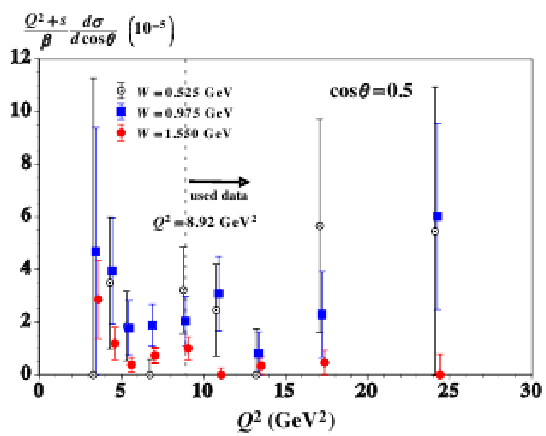
M. Masuda et al. [Belle Collaboration], PRD 93 (2016), 032003

- Belle data and scaling : W=0.525,0.975, 1.55 GeV

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

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





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 (0^{th} 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 $\Delta^\lambda \to -i\hbar\, d/d\, x_T{}^\lambda$
- 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

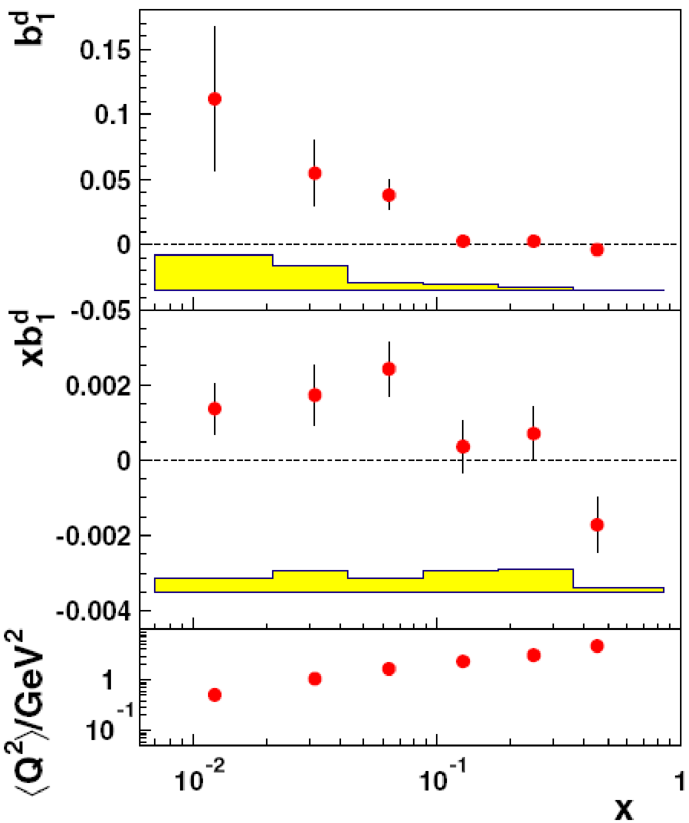
SUM RULEs

- 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: $\sum B=0 \Leftrightarrow \sum T=0$)
- 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

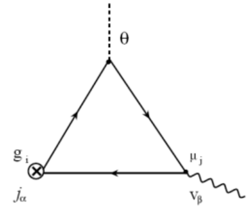
PRL **95**, 242001 (2005)

- 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)
- Extensive work (talk of Georgy Prokhorov tomorrow afternoon)



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

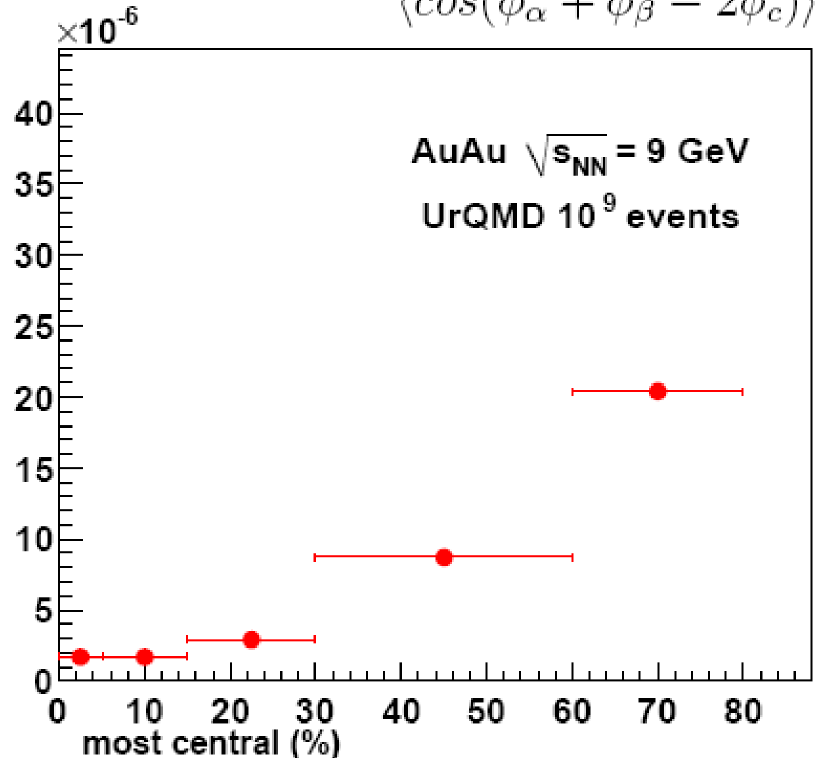
Observation of GCVE

- 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)

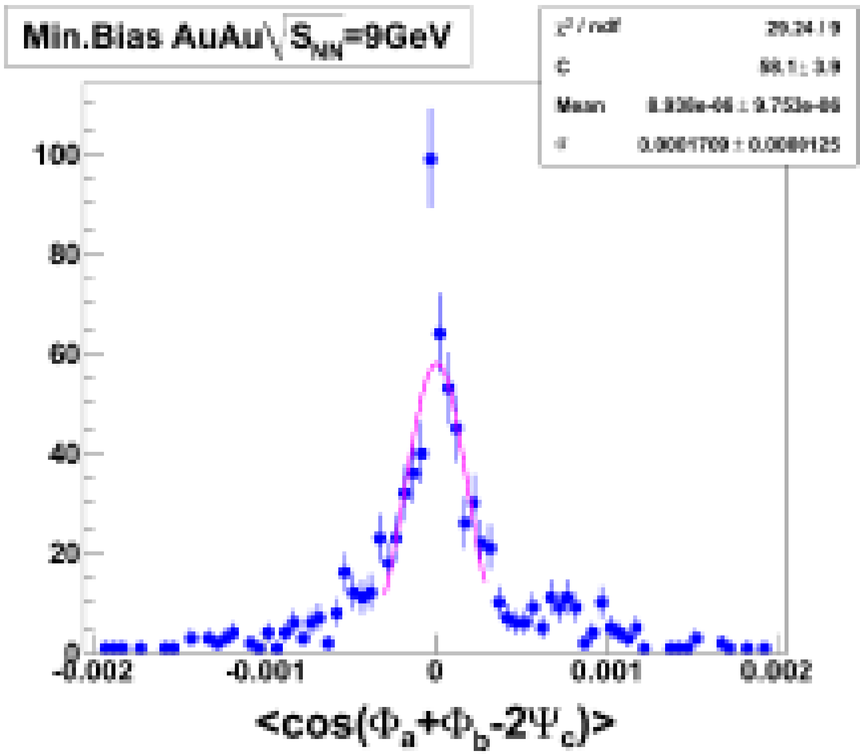
- UrQMD model : $Au + Au$ at $\sqrt{s_{NN}} = 9$ GeV
- 2-particles -> 3-particles correlations
  no necessity to fix the event plane
- 2 neutrons from mid-rapidity $(|\eta| < 1)$
- +1 from ZDC $(|\eta| > 3)$

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



Background effects

- Can correlations be simulated by UrQMD generator?



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

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

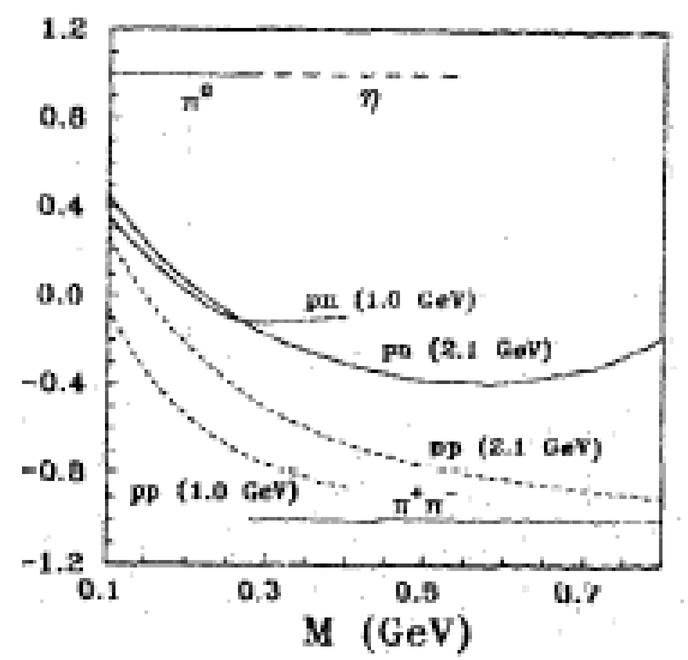
- Structures –similar to DIS F1, F2 (p ->v)

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 !

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

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



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

- zz-component of conductivity (~hadronic) tensor dominates
- 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 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