BRIEF HISTORY 0F *effective* TIME-reversal in QCD

DSPIN2023 - EFREMOV90

JINR, Dubna, September 04 2023

Oleg Teryaev

JINR, Dubna

Anatoli Vasil'evich Efremov (AV)
26/12/1933 – 01/01/2021

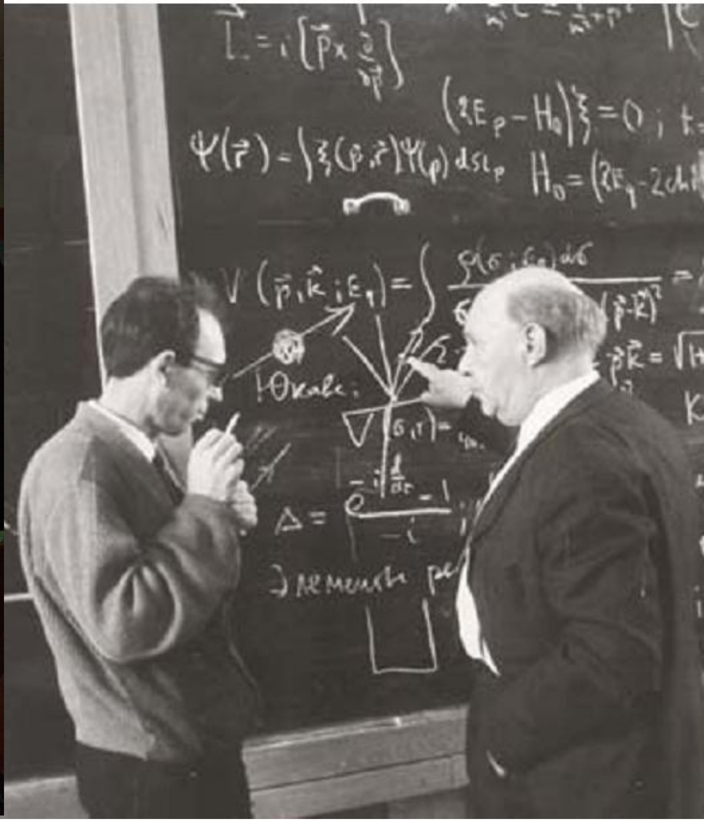
The seas

AV was born on December 26, 1933 in Kerch, Crimea, on the Black Sea, in the family of a naval officer. Since childhood, he retained a love for the sea, was an excellent yachtsman. In particular, he was sailing on Moscow Sea with T. Regge (who, according to AV, denied responsibility for "Reggistics") in 60's.

From MEPhI to JINR

- After graduating from Moscow Engineering and Physics Institute, where his teacher was Isaac Ya. Pomeranchuk (creator of Pomeron), and the advisor of the thesis - Yakov A. Smorodinsky, in 1958, he started to work at Bjgolyubov Laboratory of Theoretical Physics, JINR.

Teachers



- JINR Director was then Dmitri I. Blokhintsev, whom AV has always considered as his teacher, together with Dmitri V. Shirkov, who was an adviser of his Ph.D. thesis which he defended in 1962 at BLTP (topic - the dispersion theory of low-energy scattering of pions).

Asymptotics and factorization

- In 1971, AV defended his Dr.Sc. dissertation (topic - high-energy asymptotics of Feynman diagrams). The papers on which it was based turned out to be extremely timely and immediately found application in his pioneering works on factorization in quantum chromodynamics (QCD). This QCD factorization method is currently the theoretical basis of the entire modern physics of hard hadronic processes.

Exclusive processes

- Particularly famous were the papers of 1979 (together with his student A.V. Radyushkin) on the asymptotics of the pion form factor in QCD, and the evolution equation for exclusive processes which is called the ERBL (Efremov-Radyushkin-Brodsky-Lepage) equation in the literature.

AV Efremov and QCD Spin Physics

- Starting from 1978: polarization in parton model.
- Role of phases (initial/final state interactions), jet spin in parton correlations: road to handedness and T-odd fragmentation functions

SPIN in QCD

- The proof of factorization opened the way for describing in QCD the subtle effects associated with the detection of particle spin, such as parton (twist 3) correlations (transversity entered to the proof as a by-product), which have become known as the “ETQS mechanism” (Efremov-Teryaev-Qiu-Sterman). Later was shown to be related to T-odd Sivers function.

Spin Crisis

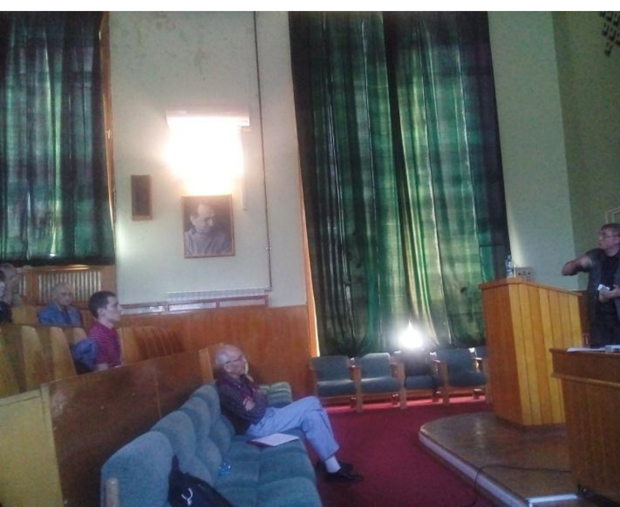
- The role of the axial anomaly and spin of gluons in the spin structure of the nucleon were introduced for the first time.
- These effects served as the theoretical basis for the creation of the polarized particle collider (RHIC, USA) and the COMPASS collaboration at CERN, of which AV was an active member.

Teacher

- AV continued to develop concrete manifestations of his fundamental ideas throughout his life, becoming a teacher and leader of many physicists both at JINR and in other countries. The last work with his participation was accepted for publication just a few days after he passed away. His students successfully work at JINR, Russian institutes (PNPI, Southern Federal University) and other countries of the world (USA, France, Germany).

Spin Physics: JINR&Worldwide

- Since 1991, AV has been the initiator and permanent chairman of the organizing committee of the Dubna International Workshops on High Energy Spin Physics (1993,… 2017, 2019) in each of which more than one hundred experimenters and theorists participate. He was a long-term and authoritative member of the International Committee on Spin Physics, which coordinates work in this area.



DSPIN2023: EFREMOV-90

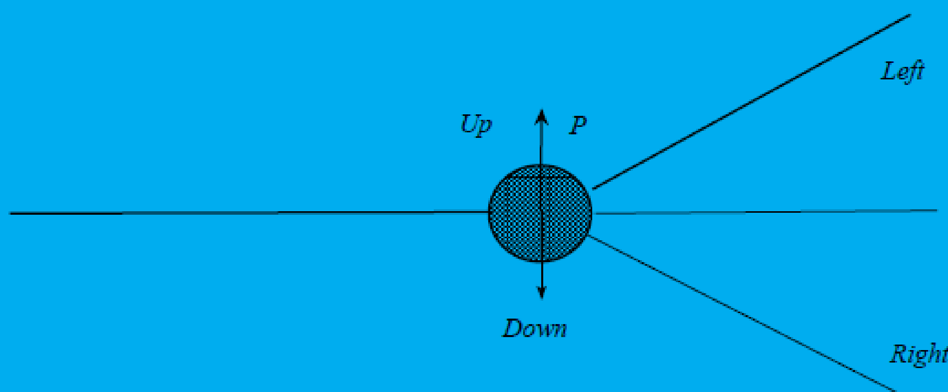
- NICA:
- SPD (Monday, Thursday)
- Spin@MPD (Wednesday, Thursday)
- Axions, EDM (Tuesday, Wednesday)
- SPASCHARM (Friday)
- Spintronics (Friday)

Effective T-oddness

- Physics of SSA. Role of T-symmetry
- SSA in QCD: twist 3 vs Sivers function
- SSA in HIC: classical/quantum, dissipation
- Handedness

Single Spin Asymmetries

Simplest example - (non-relativistic) elastic pion-nucleon scattering $\pi\vec{N} \to \pi N$



$M = a + ib(\vec{\sigma}\vec{n})$ $\vec{n}$ is the normal to the scattering plane.

Density matrix: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,

Differential cross-section: $d\sigma \sim 1 + A(\vec{P}\vec{n})$, $A = \frac{2Im(ab^*)}{|a|^2+|b|^2}$

Properties of SSA

The same for the case of initial or final state polarization.

Various possibilities to measure the effects: change sign of $\vec{n}$ or $\vec{P}$: left-right or up-down asymmetry.

Qualitative features of the asymmetry

Transverse momentum required (to have $\vec{n}$)

Transverse polarization (to maximize $(\vec{P}\vec{n})$)

Interference of amplitudes

IMAGINARY phase between amplitudes - absent in Born approximation

Phases and T-oddness

Clearly seen in relativistic approach:
$\rho = \frac{1}{2}(\hat{p} + m)(1 + \hat{s}\gamma_5)$
Than: $d\sigma \sim Tr[\gamma_5 ....] \sim im\varepsilon_{sp_1p_2p_3}...$
Imaginary parts (loop amplitudes) are required to produce real observable.
$\varepsilon_{abcd} \equiv \varepsilon^{\alpha\beta\gamma\delta} a_\alpha b_\beta c_\gamma d_\delta$ each index appears once: $P-$ (compensate S) and $T-$ odd.
However: no real $T-$violation: interchange $|i> \leftrightarrow |f>$ is the nontrivial operation in the case of nonzero phases of $< f|S|i>^* = < i|S|f>$.
SSA - either T-violation or the phases.
DIS - no phases ($Q^2 < 0$)- real T-violation.

AV and SSA: 1978 (also ERBL!)= (1933+2023)/2

FOUNDATIONS OF PERTURBATIVE QCD

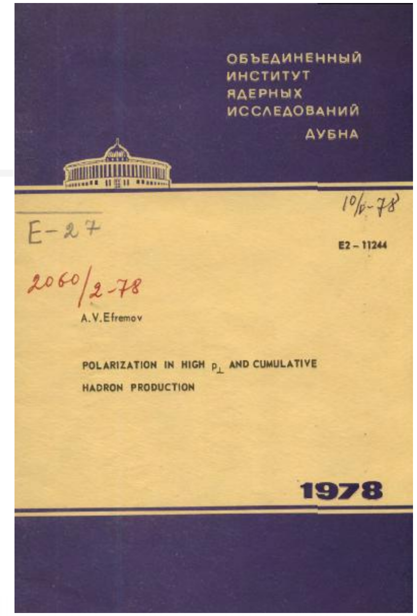
JOHN COLLINS

Penn State University

Eden R. J., *et al.* (1966). *The Analytic S-matrix*. Cambridge: Cambridge University Press.

Efremov A. V. (1978). Polarization in high P_T and cumulative hadron production. *Sov. J. Nucl. Phys.* **28**, 83.

Einhorn M. B. (1976). Confinement, form factors, and deep-inelastic scattering in two-dimensional quantum chromodynamics. *Phys. Rev.* **D14**, 3451–3471.



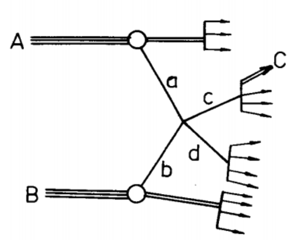


Fig. 3

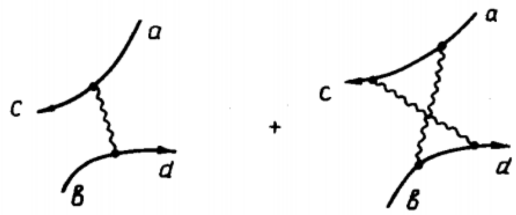


Fig.5.

$$P_{\lambda\lambda'} \frac{d\sigma}{dt'} = a(s',t') + b(s',t')\sin\varphi\,(\vec{\sigma}\vec{n})$$

I. Introduction

One of the problems of inclusive high $p_\perp$ processes is the polarization of Λ-particles [1,2]. Experiments [3] in the 300 GeV proton beam show that Λ-particles produced at Be target

i) Are polarized perpendicularly to the scattering plane.

ii) The polarization weakly depends on x in the interval 0.3 – 0.7.

iii) The polarization linearly rises with $p_\perp$ up to 28% at $p_\perp \geq 1.5$ (Fig.1).

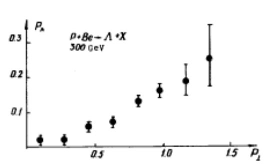


Fig. 1

$$a = \sum_{ij}\left[\left(\frac{t'}{s'}\right)^2 C^{(1)}_{ij} + \left(\frac{u'}{s'}\right)^2 C^{(1)}_{ji} + \frac{u't'}{s'^2} C^{(2)}_{ij}\right] \mathrm{Re}\left(A_i(s',t')A^*_j(s',u')\right)$$

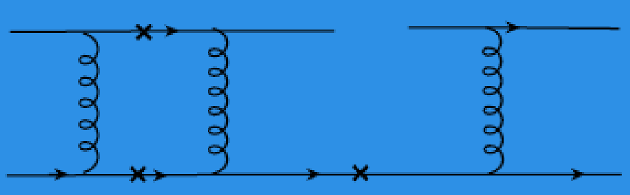
$$b = \sum_{ij} \frac{u't'}{s'^2} C^{(3)}_{ij}\, \mathrm{Im}\left(A_i(s',t')A^*_j(s',u')\right), \qquad (3)$$

φ is the angle between $\vec{a}$ and $\vec{b}$ and $\vec{n} = \frac{\vec{a}\times\vec{b}}{|\vec{a}\times\vec{b}|}$

Perturbative PHASES IN QCD: Kane&Pumplin&Repko'78

QCD factorization: where to borrow imaginary parts?

Simplest way: from short distances - loops in partonic subprocess. Quarks elastic scattering (like $q - e$ scattering in DIS):

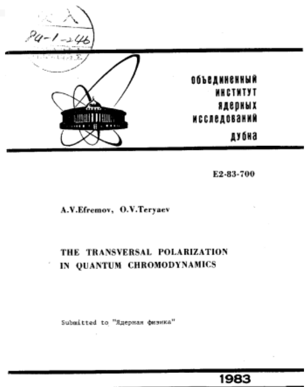


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

Large SSA "...contradict QCD or its applicability"

AV+OT: quark mass -> twist 3

- Twist 4(EFP)->twist 3(ET)


объединенный
институт
ядерных
исследований
дубна

E2-83-700

A.V.Efremov, O.V.Teryaev

THE TRANSVERSAL POLARIZATION IN QUANTUM CHROMODYNAMICS

Submitted to "Ядерная физика"

1983

The T -invariance, which is convenient to take into account just now, provides further simplifications. Note that in T - invariant theories the phase of hadron-parton amplitudes is fully determined by the Born approximation, because the coupling constant is real (and the cuts providing the imaginary part are absent after taking the discontinuity in M_x^2). By this reason, B^A is real and B^V is pure imaginary. (This fact also provides the absence of single asymmetries in Born approximation /15/). On the other hand, making use of translational in-

15. Christ A., Lee T. Phys.Rev., 1966, 143, p.1316.

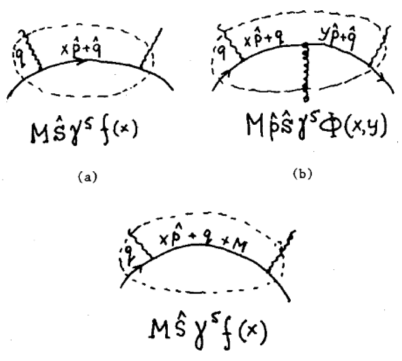


Fig.1

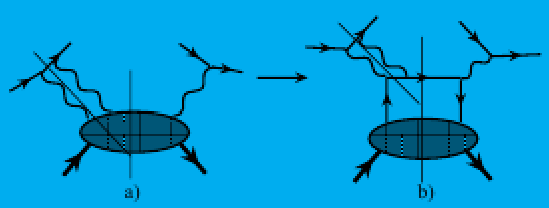
- DVCS: Anikin, Pire, OT'2000

S_T<-> Δ_T/M

T-odd effects: Low and high energies

Unpolarized leptons scattering on the transverse polarized nucleon. Completely analogous to the asymmetry in the scattering of transverse polarized neutrons on tensor polarized deuterons - modern low energy test of $T-$violation.

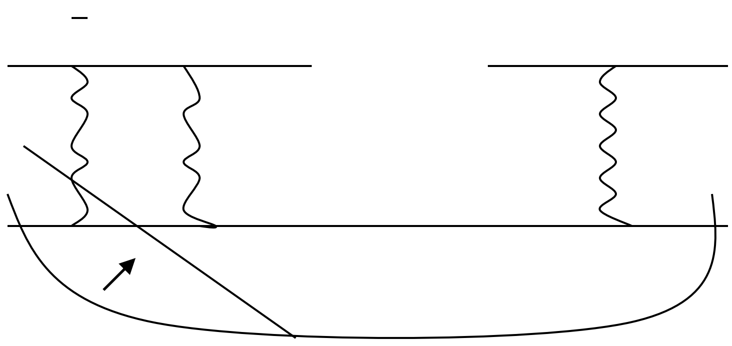
However, 2-photon exchange between lepton and nucleon - imaginary phase (due to QED -$\sim \alpha$).



What are QCD sources?

Phases from twist 3

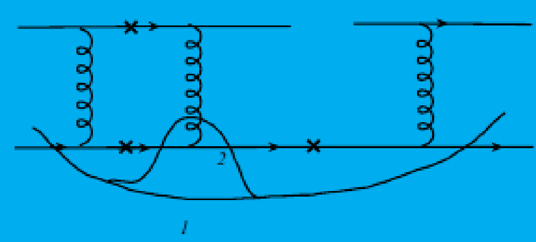
- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



- New option for SSA: Instead of 1-loop twist 2 – Born twist 3: Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, GLUONIC poles)

Twist 3 correlators

Escape: QCD factorization - possibility to shift the borderline between large and short distances



At short distances - Loop → Born diagram
At Large distances - quark distribution → quark-gluon correlator.
Physically - process proceeds in the external gluon field of the hadron.
Leads to the shift of α_S to non-perturbative domain AND
"Renormalization" of quark mass in the external field up to an order of hadron's one

$$\frac{\alpha_S m p_T}{p_T^2 + m^2} \to \frac{M b(x_1, x_2) p_T}{p_T^2 + M^2}$$

Further shift of phases completely to large distances - T-odd fragmentation functions. Leading twist transversity distribution - no hadron mass suppression.

Sivers function

- D. Sivers: Hadron spin/quark transverse momentum correlation
- J. Collins: violates T-invariance!
- In JINR (A. Efremov, OT – understood that and did not try to introduce)
- S. Brodsky, D.-S. Hwang, I. Schmidt, J. Collins ’02 – FSI (Wilson lines)
- ~ Gluonic poles (twist 3 suppression compensated by pole)!

Λ-polarisation

- *Self-analyzing (spin-momentum couplins) in weak decay*
- *Directly related to s-quarks polarization: complementary probe of strangeness*
- *Hadronic processes (AV-1987)*
- *Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: '87): Randomization – smearing – of the scattering plane*

Global polarization

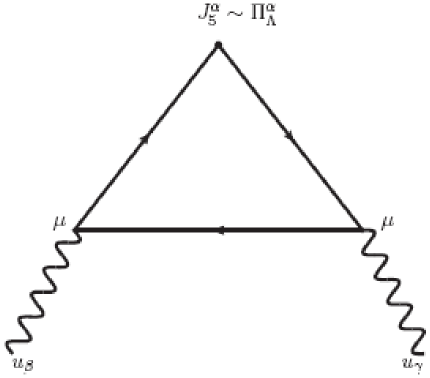
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Due to locality of LS coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?

Anomalous mechanism – polarization similar to C(A)VE (talks of V. Zakharov, G. Prokhorov). LS-> classical/quantum Phases -> dissipation

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al): $\mu\, \varrho = \mu\, J_0\, V^0 \;\text{->}\; \mu\, J_\gamma\, V^\gamma$

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

- Triangle anomaly leads to polarization of quarks and hyperons (Rogachevsky, Sorin, OT '10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov,OT'88)
- 4-velocity instead of gluon field!



“Anomalous” mechanism

O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

- Prediction of decrease with energy (due to chemical potential)

One would expect that polarization is proportional to the anomalously induced axial current [7]

$$j_A^\mu \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \qquad (6)$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

- Prediction of P~1%

BAZNAT, GUDIMA, SORIN, AND TERYAEV

PHYSICAL REVIEW C **88**, 061901(R) (2013)

$$\langle P_\Lambda \rangle \sim \frac{\langle \mu^2 \rangle N_c H}{2\pi^2 \langle N_\Lambda \rangle}.$$

For numerical estimate at NICA energies, we take (see Fig. 3) $H = 30\ \mathrm{fm}^2 (c = 1)$ and, as typical values, $\langle \mu^2 \rangle = 900\ \mathrm{MeV}^2$, $\langle N_\Lambda \rangle = 15$ to get $\langle P_\Lambda \rangle \sim 0.8\%$. This value is

- Postdiction of larger polarization of antilambdas

ALEXANDER SORIN AND OLEG TERYAEV

PHYSICAL REVIEW C **95**, 011902(R) (2017)

The proportionality of the polarization to the square of the chemical potential related to C-even parity of axial current leads to the same sign of polarization of Λ and $\bar{\Lambda}$ hyperons. The smaller number of the latter should result in a larger fraction of the axial charge, corresponding to each antihyperon and to a larger absolute value of polarization. Detailed numerical sim-

Handedness: directly observable P-odd momentum correlations: also AV-1978! Phases in T-odd fragmentation funcions (Collins,…)

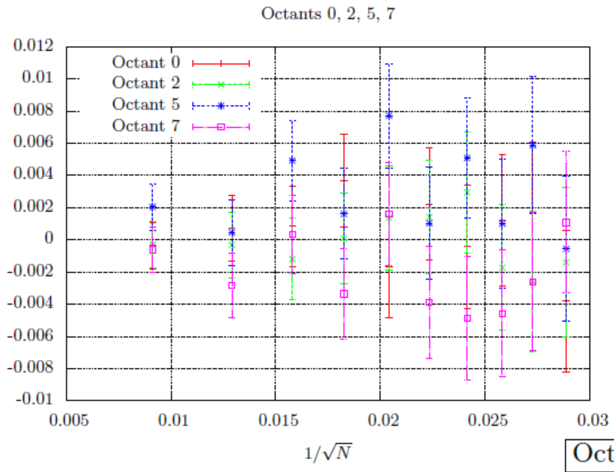
- Found in jets in e^+e^- annihilation (LEP, BELLE) with AV participation
- First attempt in HIC: OT, Usubov, arXiv:1406.4451 (PRC92 (2015) 1, 014906)
- Average =0: Phase space – 8 octants

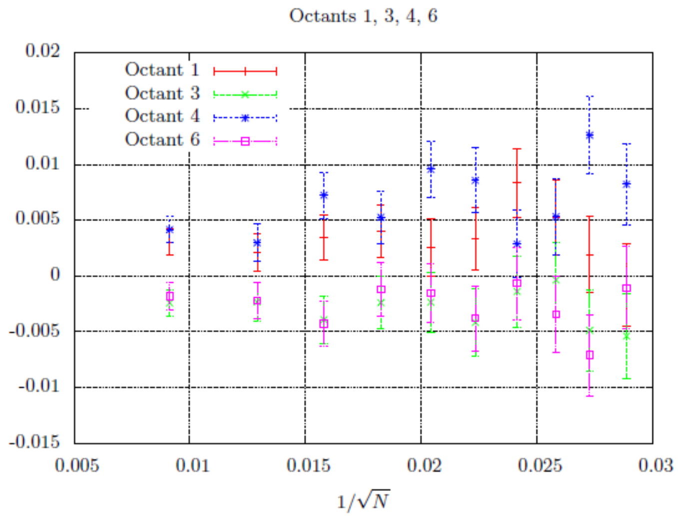
Octant	Momentum
0	$p_x > 0, p_y > 0, p_z > 0$
1	$p_x > 0, p_y > 0, p_z \leq 0$
2	$p_x > 0, p_y \leq 0, p_z > 0$
3	$p_x > 0, p_y \leq 0, p_z \leq 0$
4	$p_x \leq 0, p_y > 0, p_z > 0$
5	$p_x \leq 0, p_y > 0, p_z \leq 0$
6	$p_x \leq 0, p_y \leq 0, p_z > 0$
7	$p_x \leq 0, p_y \leq 0, p_z \leq 0$

$$\eta = \frac{\sum(\vec{p_3}, \vec{p_2}, \vec{p_1})}{\sum |(\vec{p_3}, \vec{p_2}, \vec{p_1})|}$$

Handedness separation

- Indication for small separation effect in some of the octants





Octant	Momentum
0	$p_x > 0, p_y > 0, p_z > 0$
1	$p_x > 0, p_y > 0, p_z \leq 0$
2	$p_x > 0, p_y \leq 0, p_z > 0$
3	$p_x > 0, p_y \leq 0, p_z \leq 0$
4	$p_x \leq 0, p_y > 0, p_z > 0$
5	$p_x \leq 0, p_y > 0, p_z \leq 0$
6	$p_x \leq 0, p_y \leq 0, p_z > 0$
7	$p_x \leq 0, p_y \leq 0, p_z \leq 0$

How to add SSAs?

- NOT just sum (P<1!)
- Similar to velocities in special relativity (OT, 2204.08796 and PRC)

$$\vec{P}_0 = \vec{n}\frac{2\Im(ab^*)}{|a|^2+|b|^2} \quad P_f = \frac{(|a|^2+|b|^2)P + 2\Im(ab^*)}{|a|^2+|b|^2+2P\Im(ab^*)} = \frac{P+P_0}{1+PP_0} \qquad \hbar \leftrightarrow c. \qquad P_f^2 = \frac{(\vec{P}+\vec{P}_0)^2 - [\vec{P}\vec{P}_0]^2}{(1+(\vec{P}\vec{P}_0))^2}$$

- Transition from “macro” to micro” d.o.f.
- Dominance of FSI (Polarizing FF) or ISI (Sivers) corresponds to Galilean (c->∞) and Carroll (c->0) limits (in preparartion)

CONCLUSIONS

- SSA in QCD – phases: stem from AV-1978
- To be studied at EIC, SPD,…
- HIC: QFT/Statistics/gravity

phases<-> dissipation?

Quantum<-> classical?

- “Macro” <-> “Micro” ?
- Relation to LS in Condenced matter?

Spin-gravity interactions

- How to describe hadron spin/gravity(inertia) couplings?
- Matrix elements of Energy- Momentum Tensor
- May be studied in non-gravitational experiments/theory
- Simple interpretation in comparison to EM field case

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!?)

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

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

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

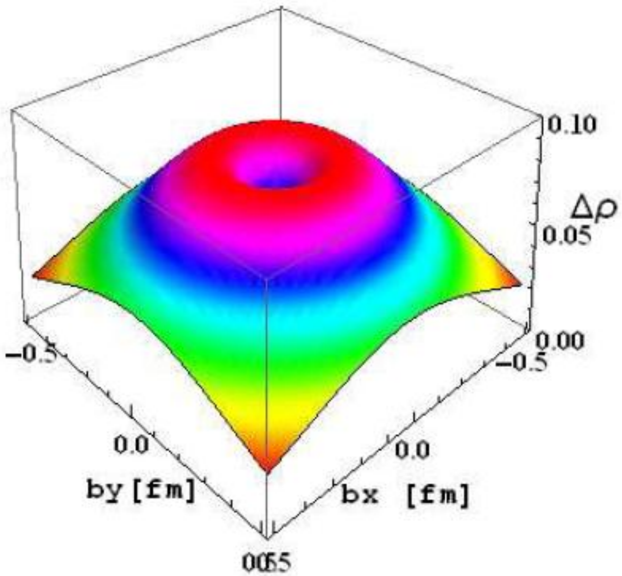


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)

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

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=0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background

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

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

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)
- Arbitrary fields – Obukhov, Silenko, OT ’09,’11,’13

Gravity vs accelerated frame for spin and helicity

- Spin precession – well known factor 3 (Probe B; spin at satellite – probe of PNEP!) – smallness of relativistic correction ($\sim\mathbf{P}^2$) is compensated by $1/\mathbf{P}^2$ in the momentum direction precession frequency
- Helicity flip – the same!
- No helicity flip in gravitomagnetic field – another formulation of PNEP (OT'99)

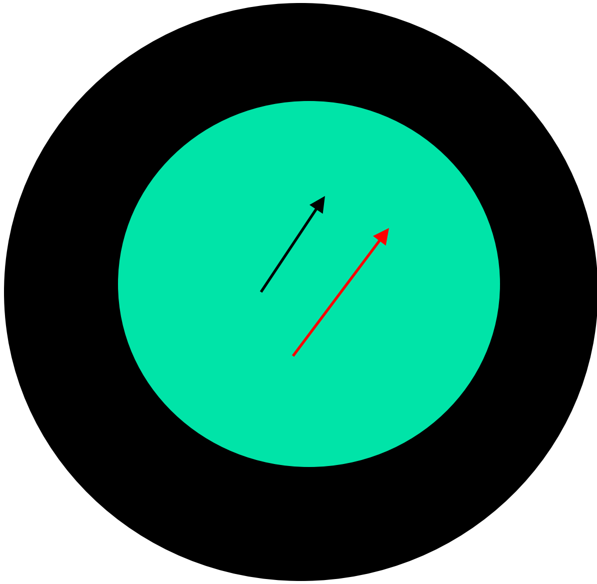
Gyromagnetic and Gravigyromagnetic ratios

- Free particles – coincide
- $<P+q|T^{mn}|P-q> = P^{\{m}<P+q|J^{n\}}|P-q>/e$ up to the terms linear in q
- Special role of g=2 for any spin (asymptotic freedom for vector bosons)

- Should Einstein know about PNEP, the outcome of his and de Haas experiment would not be so surprising
- Recall also g=2 for Black Holes. Indication of "quantum" nature?!

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 ?!



Torsion – acts only on spin (violates EP)

Dirac eq+FW transformation-Obukhov,Silenko,OT, **arXiv:1410.6197**

- Hermitian Dirac Hamiltonian

$$e_i^{\widehat{0}} = V\,\delta_i^0, \qquad e_i^{\widehat{a}} = W^{\widehat{a}}{}_b\,(\delta_i^b - cK^b\,\delta_i^0)$$

$$ds^2 = V^2c^2dt^2 - \delta_{\widehat{a}\widehat{b}}W^{\widehat{a}}{}_cW^{\widehat{b}}{}_d\,(dx^c - K^c cdt)\,(dx^d - K^d cdt)$$

$$\mathcal{H} = \beta mc^2V + q\Phi + \frac{c}{2}\left(\pi_b\,\mathcal{F}^b{}_a\alpha^a + \alpha^a\mathcal{F}^b{}_a\pi_b\right) + \frac{c}{2}\left(\boldsymbol{K}\cdot\boldsymbol{\pi} + \boldsymbol{\pi}\cdot\boldsymbol{K}\right) + \frac{\hbar c}{4}\left(\boldsymbol{\Xi}\cdot\boldsymbol{\Sigma} - \Upsilon\gamma_5\right),$$

$$\mathcal{F}^b{}_a = VW^b{}_{\widehat{a}}, \qquad \Upsilon = V\epsilon^{\widehat{a}\widehat{b}\widehat{c}}\Gamma_{\widehat{a}\widehat{b}\widehat{c}}, \qquad \Xi^a = \frac{V}{c}\,\epsilon^{\widehat{a}\widehat{b}\widehat{c}}\left(\Gamma_{\widehat{0}\widehat{b}\widehat{c}} + \Gamma_{\widehat{b}\widehat{c}\widehat{0}} + \Gamma_{\widehat{c}\widehat{0}\widehat{b}}\right)$$

- Spin-torsion coupling

$$-\frac{\hbar cV}{4}\left(\boldsymbol{\Sigma}\cdot\check{\boldsymbol{T}} + c\gamma_5\check{T}^{\hat{0}}\right)$$

$$\check{T}^{\alpha} = -\frac{1}{2}\,\eta^{\alpha\mu\nu\lambda}T_{\mu\nu\lambda}$$

- FW – semiclassical limit - precession

$$\Omega^{(T)} = -\frac{c}{2}\check{\boldsymbol{T}} + \beta\frac{c^3}{8}\left\{\frac{1}{\epsilon'},\left\{\boldsymbol{p},\check{T}^{\hat{0}}\right\}\right\} + \frac{c}{8}\left\{\frac{c^2}{\epsilon'(\epsilon'+mc^2)},\left(\{\boldsymbol{p}^2,\check{\boldsymbol{T}}\} - \{\boldsymbol{p},(\boldsymbol{p}\cdot\check{\boldsymbol{T}})\}\right)\right\}$$

Experimental bounds for torsion

- Magnetic field+rotation+torsion

$$H = -g_N \frac{\mu_N}{\hbar} \boldsymbol{B} \cdot \boldsymbol{s} - \boldsymbol{\omega} \cdot \boldsymbol{s} - \frac{c}{2} \check{\boldsymbol{T}} \cdot \boldsymbol{s}$$

- Same '92 EDM experiment

$$\frac{\hbar c}{4} |\check{T}| \cdot |\cos\Theta| < 2.2 \times 10^{-21}\,\mathrm{eV}, \qquad |\check{T}| \cdot |\cos\Theta| < 4.3 \times 10^{-14}\,\mathrm{m}^{-1}$$

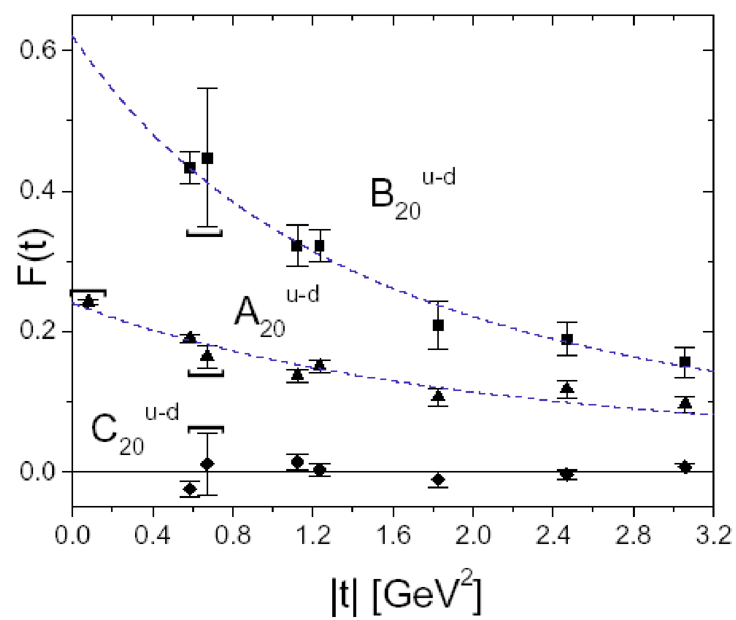
- New(based on Gemmel et al '10)

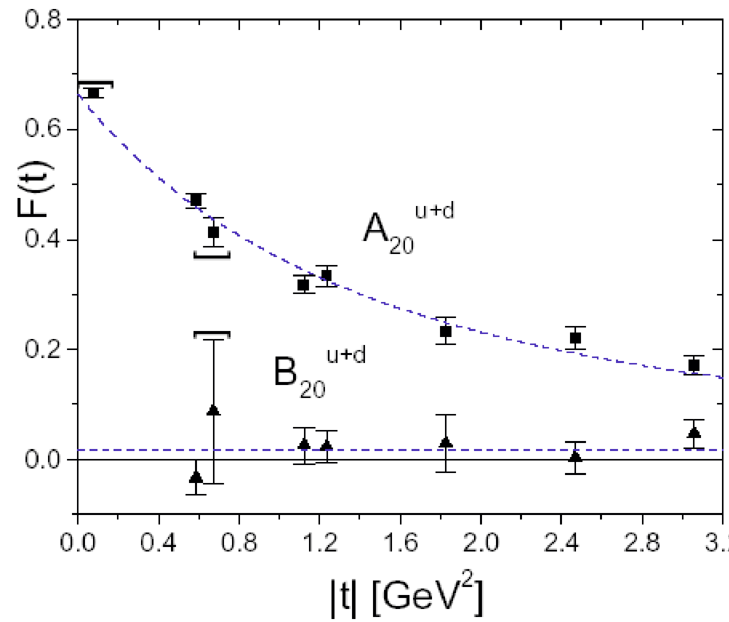
$$\frac{\hbar c}{2} |\check{T}| \cdot |(1-\mathcal{G})\cos\Theta| < 4.1 \times 10^{-22}\,\mathrm{eV}, \qquad |\check{T}| \cdot |\cos\Theta| < 2.4 \times 10^{-15}\,\mathrm{m}^{-1}$$

$$\mathcal{G} = g_{He}/g_{Xe}$$

Generalization of Equivalence principle

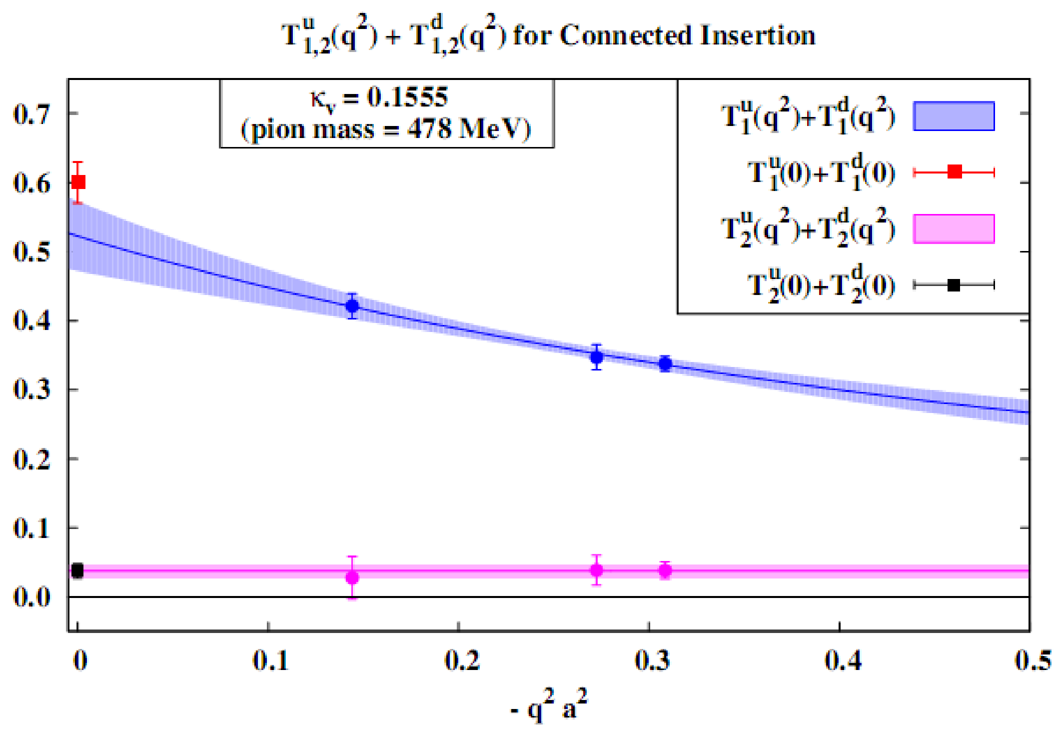
- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





Recent lattice study (M. Deka et al. arXiv:1312.4816)

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



Extended Equivalence Principle=Exact EquiPartition

- In pQCD – violated
- Reason – in the case of ExEP- no smooth transition for zero fermion mass limit (Milton, 73)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Gravity-proof confinement (should the hadrons survive enetering Black Hole?)?!

Conclusionss

- Rotation in heavy-ion collisions – essentially non-inertial frame
- Related P-odd effects are not numerically large (smearing) but may be observable

- BACKUP SLIDES

Sum rules for EMT (and OAM)

- First (seminal) example: X. Ji’s sum rule (’96). Gravity counterpart – OT’99
- Burkardt sum rule – looks similar: can it be derived from EMT?
- Yes, if provide correct prescription to gluonic pole (OT’14)

Pole prescription and Burkardt SR

- Pole prescription (dynamics!) provides ("T-odd") symmetric part!
  $$\sum \int \int dx_1 dx_2 \frac{T(x_1, x_2)}{x_1 - x_2 + i\varepsilon} = 0$$
- SR: $\sum \int dx T(x,x) = 0$ (but relation of gluon Sivers to twist 3 still not founs – prediction!)
- Can it be valid separately for each quark flavour: nodes (related to "sign problem")?
- Valid if structures forbidden for TOTAL EMT do not appear for each flavour
- Structure contains besides S gauge vector n: If GI separation of EMT – forbidden: SR valid separately!

Another manifestation of post-Newtonian (E)EP for spin 1 hadrons

- Tensor polarization - coupling of gravity to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

$$\langle P,S|\bar{\psi}(0)\gamma^{\nu}D^{\nu_1}...D^{\nu_n}\psi(0)|P,S\rangle_{\mu^2} = i^{-n}M^2S^{\nu\nu_1}P^{\nu_2}...P\nu_n\int_0^1 C_q^T(x)x^n dx$$

$$\sum_q \langle P,S|T_i^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}(1-\delta(\mu^2)) + 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

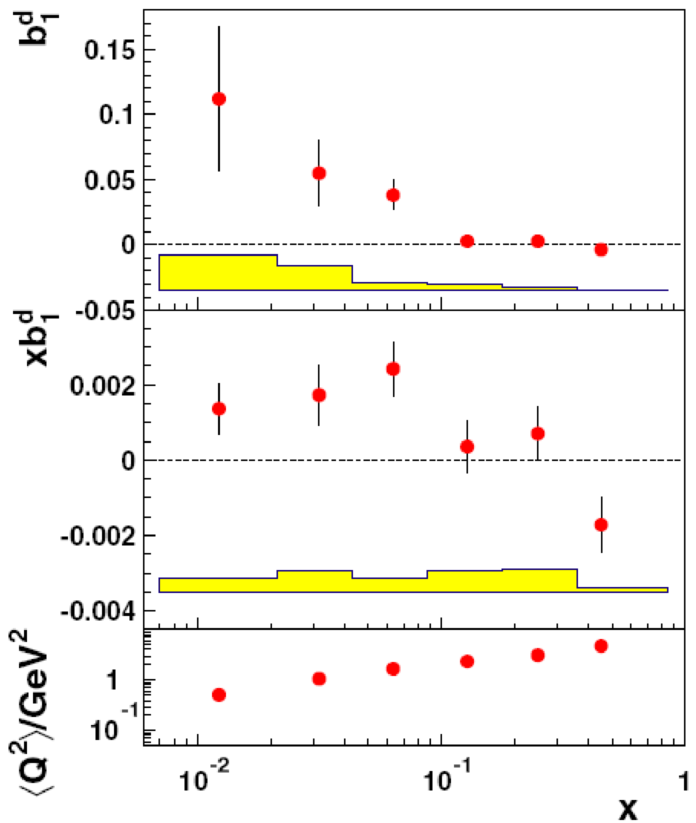
$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}\delta(\mu^2) - 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

$$\sum_q \int_0^1 C_i^T(x)x dx = \delta_1(\mu^2)$$ =0 for ExEP

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 EEP
- Second moments – compatible to zero better than the first one (collective glue << sea) – for valence: $\int_0^1 C_i^T(x)dx = 0$



Are more accurate data possible?

- HERMES – unlikely

- JLab may provide information about collective sea and glue in deuteron and indirect new test of Equivalence Principle

CONCLUSIONS

- Spin-gravity interactions may be probed directly in gravitational (inertial) experiments and indirectly – studing EMT matrix element
- Torsion and EP are tested in EDM experiments
- SR's for deuteron tensor polarization-indirectly probe EP and its extension separately for quarks and gluons

EEP and AdS/QCD

- Recent development – calculation of Rho formfactors in Holographic QCD (Grigoryan, Radyushkin)
- Provides g=2 identically!
- Experimental test at time –like region possible