

Непертурбативная КХД и спиновые асимметрии: теоретический обзор

Non-perturbative QCD and spin asymmetries: theoretical review

Физика частиц при средних и высоких энергиях
НИЦ "Курчатовский институт" – ИФВЭ, Протвино

04.06.2026

О.В. Теряев (ОИЯИ)



Main Topics

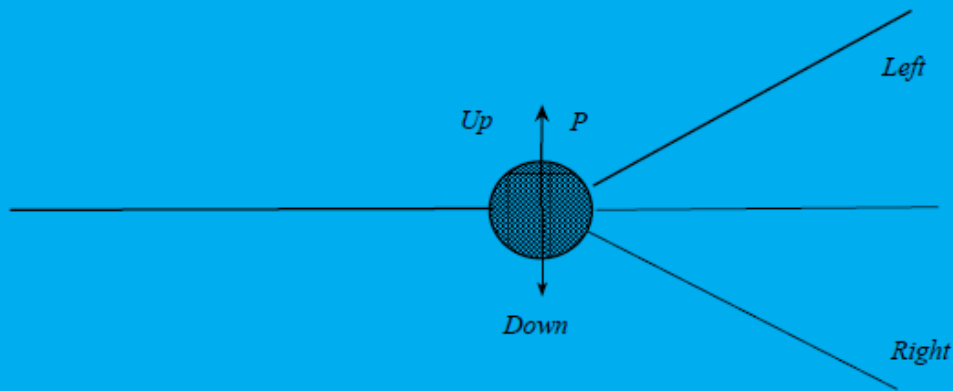
- **Vector Polarization: Single Spin Asymmetries in QCD:** hadrons and heavy ions
- Parity conservation: normal to **some** plane
- **Interference:** twist-3 correlators vs LS coupling
- **T- reversal:** phases vs dissipation

- Fast rotation and acceleration: effective (“equivalent”) gravity
- **Tensor polarization** and spin-gravity coupling

- Conclusions

Single Spin Asymmetries (vector polarization)

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



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

J.D. Bjorken
St. Croix, 1987

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

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

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



SSA

- Parity conservation – normal to scattering plane
- Interference – **LS** coupling: $S(r \times p) \rightarrow S(k \times p) \sim S_n$
- T conservation – absorptive phases



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:

$$\rho = \frac{1}{2}(\hat{p} + m)(1 + \hat{s}\gamma_5)$$

Then: $d\sigma \sim \text{Tr}[\gamma_5 \dots] \sim im\epsilon_{sp_1p_2p_3\dots}$

Imaginary parts (loop amplitudes) are required to produce real observable.

$\epsilon_{abcd} \equiv \epsilon^{\alpha\beta\gamma\delta} a_\alpha b_\beta c_\gamma d_\delta$ each index appears once: P - (compensate S) and T - odd.

However: no real T -violation: interchange $|i\rangle \leftrightarrow |f\rangle$ is the nontrivial operation in the case of nonzero phases of $\langle f|S|i\rangle^* = \langle i|S|f\rangle$.

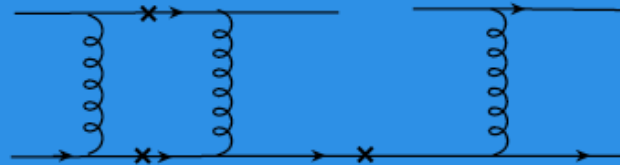
SSA - either T -violation or the phases.

DIS - no phases ($Q^2 < 0$)- real T -violation.

Perturbative PHASES IN QCD

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):

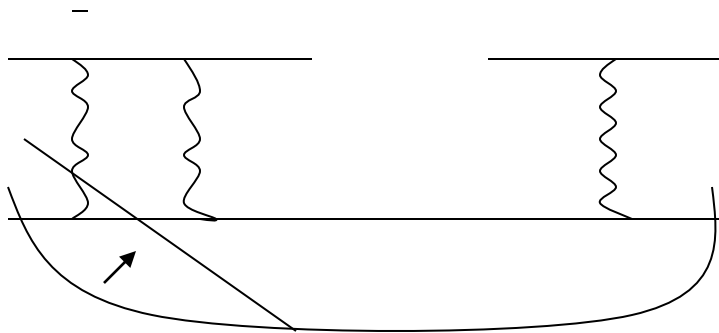


$$A \sim \frac{\alpha_S^{m_{PT}}}{p_T^2 + m^2}$$

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

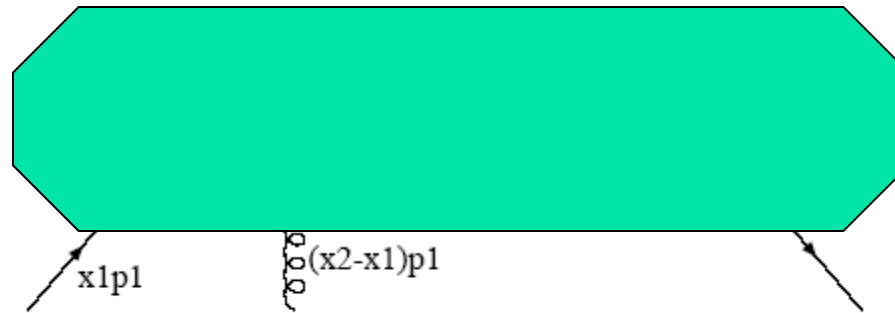
Short+ large overlap– twist 3

- Quarks – **only** from hadrons (NPQCD)
- Various options for factorization – shift of SH separation



- New option for SSA: Instead of 1-loop twist 2 – Born twist 3 (quark-gluon correlator): Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, GLUONIC poles -> Sivers function)
- Further shift to large distances – T-odd fragmentation and (effective) distribution functions (Collins, Sivers)

Quark-gluon correlators



- *Non-perturbative NUCLEON structure – physically mean the quark scattering in external gluon field of the HADRON.*
- *Depend on TWO parton momentum fractions*
- *For small transverse momenta – quark momentum fractions are close to each other- gluonic pole; probed if :*

$$Q \gg P_T \gg M$$

$$x_2 - x_1 = \delta = \frac{P_T^2 x_B}{Q^2 z}$$



Zoo of T-odd functions

- Twist-3,4... correlators (chiral-even and odd)
- Fragmentation (interference, polarizing...)
- Collinear factorization: either large or integrated **T**ransverse **M**omentum; low **TM** Dependence - **TMD**
- May be related to **GPDs** (**Wigner functions**)

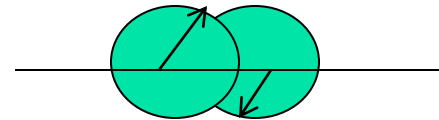


Λ -polarisation

- Self-analyzing in weak decay
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: '87): Randomization – smearing – no direction normal to the **scattering** plane
- **But is the randomization complete (smoothly from hadrons to ions)?!**

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!
- Maybe due to locality of **LS** coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?





Inclusive vs Global polarization

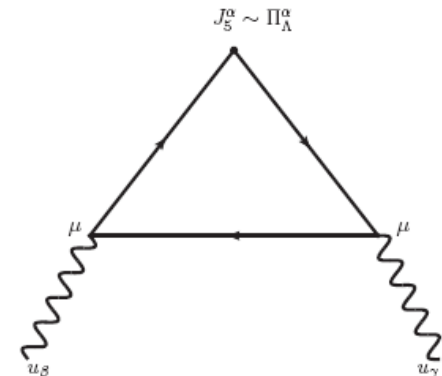
- May it contribute to global polarization?
- Yes, due to directed flow
- $d\sigma(\phi) \sim 1 + (P_d P_i) = 1 + P_d P_i \cos \phi$ (wrt scattering plane)
- $\langle d\sigma(\phi) \rangle = \langle (1 + P_d P_i \cos \phi) (1 + 2 v_1 \cos \phi) \rangle$
- $= 1 + P_d P_i v_1$
- $P_{gl} = P_i v_1$
- Collectivity of global polarization – shifted to flow!
- Importance of elementary processes for HIC: also for polarization (SPASCHARM, talks of V. Abramov, A. Vasiliev, V. Mochalov today)

Anomalous mechanism – polarization similar to CM(V)E

- 4-Velocity is also a **GAUGE FIELD (V.I. Zakharov et al, talk of G. Prokhorov)**

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

- 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!**





Anomaly for polarization

- Induced axial charge

$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Neglect axial chemical potential
- T-dependent term- related to gravitational anomaly
- Lattice simulation: suppressed due to collective effects



Energy dependence

- Coupling -> chemical potential

$$Q_5^s = \frac{N_c}{2\pi^2} \int d^3x \mu_s^2(x) \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Field -> velocity; (Color) magnetic field strength -> vorticity;
- Axial charge <-> hydrodynamic helicity
- **Chemical potential: Rapid decrease with energy**
- Largest chemical potential: NICA/**U-70** energies
- Heavy -> Light -> protons: Small Systems

One might compare the prediction below with the right panel figures

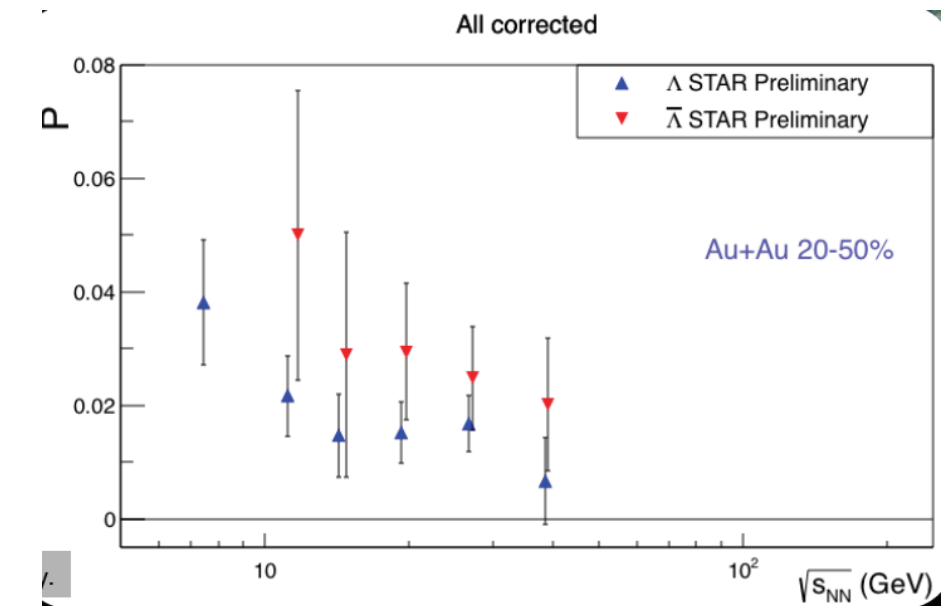
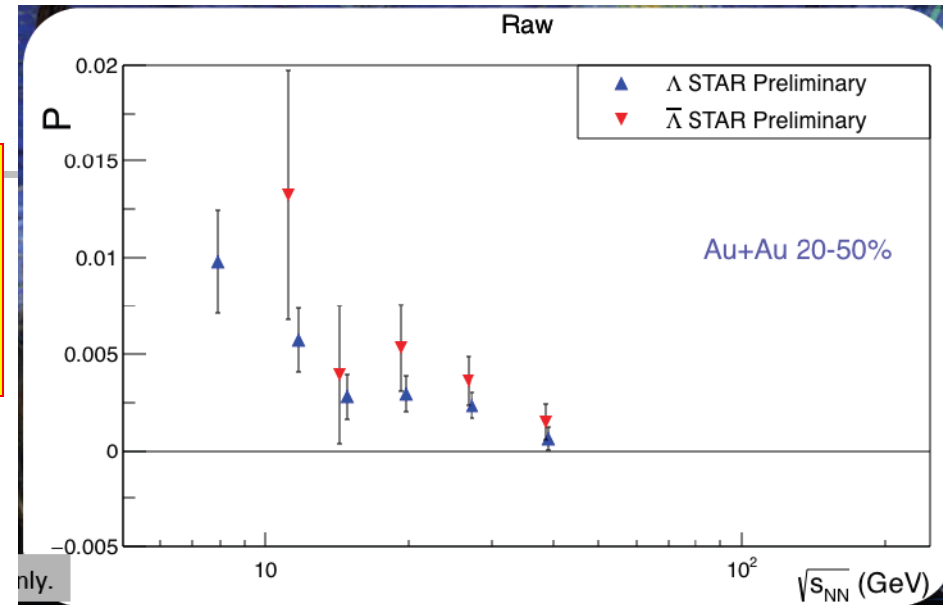
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortical effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

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

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

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.



"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]

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

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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 $P \sim 1\%$

BAZNAT, GUDIMA, SORIN, AND TERYAEV

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

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

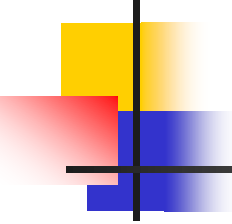
PHYSICAL REVIEW C 88, 061901(R) (2013)

- 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-

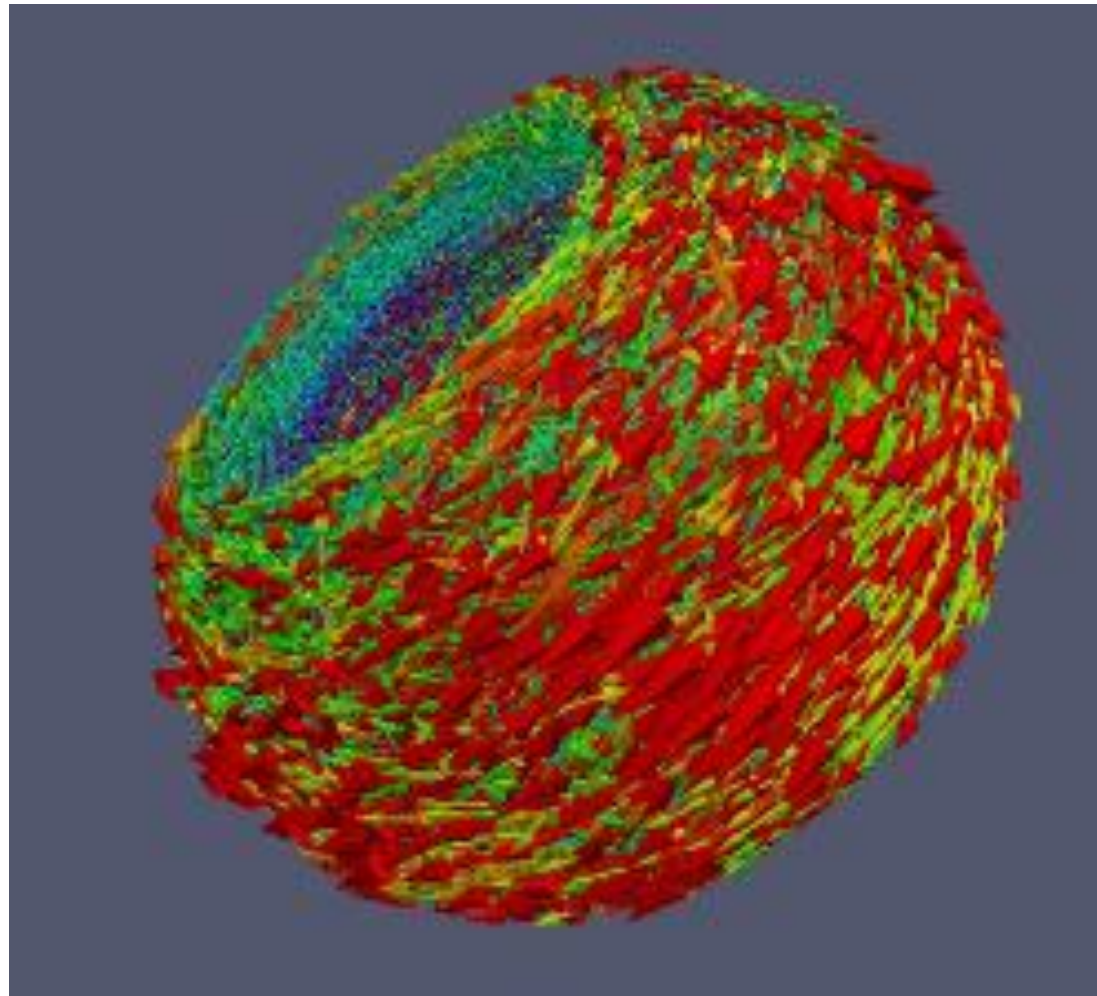


Microworld: where is the fastest possible rotation?

- Non-central heavy ion collisions (Angular velocity $\sim c/\text{Compton wavelength}$)
- ~ 27 orders of magnitude faster than Earth's rotation
- Differential rotation – vorticity

- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes):
Baznat, Gudima, Sorin, OT, PRC'13,16,18

Vortex sheets (talks of Yu. Ivanov, Alexei Zinchenko)



From axial charge to polarization (and from quarks to confined hadrons) – Sorin, OT'16

- Analogy of matrix elements and classical averages

$$\langle p_n | j^0(0) | p_n \rangle = 2p_n^0 Q_n \quad \langle Q \rangle \equiv \frac{\sum_{n=1}^N Q_n}{N} = \frac{\int d^3x j_{class}^0(x)}{N}$$

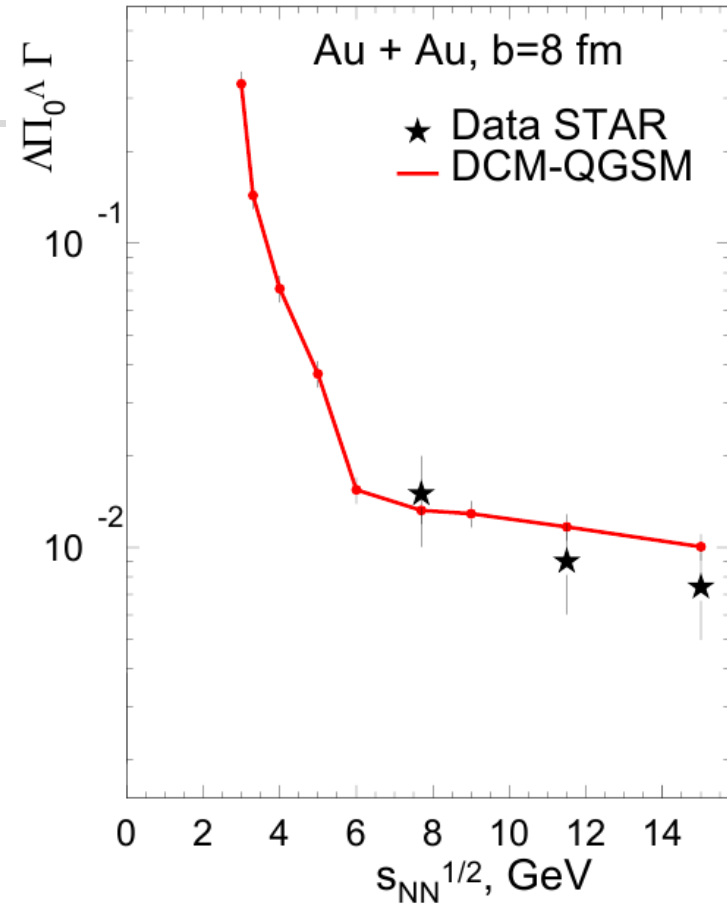
- Lorentz boost: compensate the sign of helicity

$$\Pi^{\Lambda, lab} = (\Pi_0^{\Lambda, lab}, \Pi_x^{\Lambda, lab}, \Pi_y^{\Lambda, lab}, \Pi_z^{\Lambda, lab}) = \frac{\Pi_0^\Lambda}{m_\Lambda} (p_y, 0, p_0, 0)$$

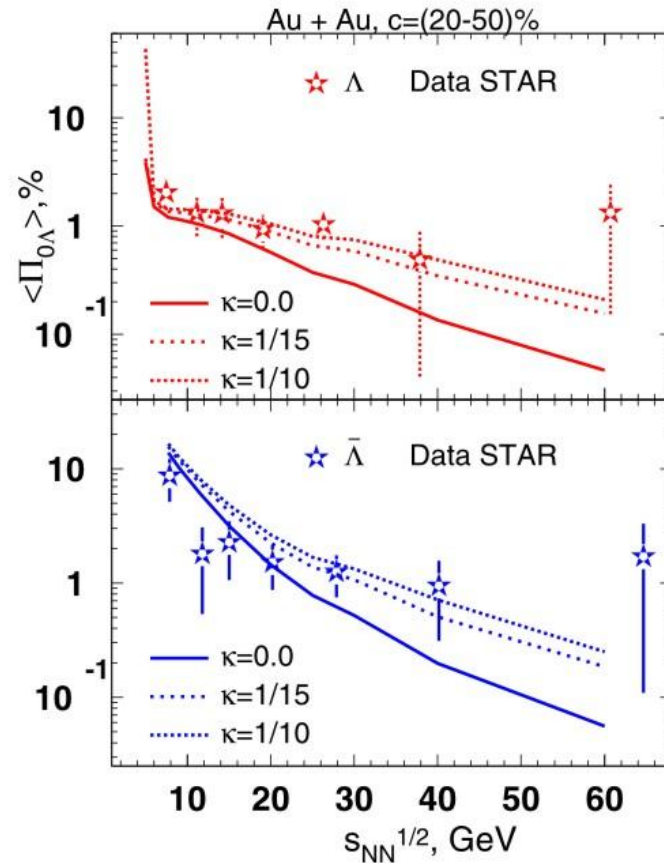
$$\langle \Pi_0^\Lambda \rangle = \frac{m_\Lambda \Pi_0^{\Lambda, lab}}{p_y} = \langle \frac{m_\Lambda}{N_\Lambda p_y} \rangle Q_5^s \equiv \langle \frac{m_\Lambda}{N_\Lambda p_y} \rangle \frac{N_c}{2\pi^2} \int d^3x \mu_s^2(x) \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

Energy dependence

- Growth at low energy
- Close to STAR data



Λ vs Anti Λ : *same* axial charge is distributed between *lower* number of hadrons (*also* for Ω^- ?!)



Where is phase?! Other approach to baryons in confined phase: vortices in pionic superfluid (V.I. Zakharov, OT'17)

- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin, Sadofyev, Zakharov'12)

$$\frac{\pi_0}{f_\pi} = \mu \cdot t + \varphi(x_i) \quad \partial_i \varphi = \mu v_i \quad \oint \partial_i \varphi dx_i = 2\pi n$$

$$T_{0i} \sim \mu_5 \partial_i \tilde{\varphi}, \quad \lim_{q_i \rightarrow 0, \omega \equiv 0} \langle T_{0i}, T_{0k} \rangle \sim \mu_5^2 \frac{q_i q_k}{q_i^2}$$

$$j_5^\mu = \frac{1}{4\pi^2 f_\pi^2} \epsilon^{\mu\nu\rho\sigma} (\partial_\nu \pi^0) (\partial_\rho \partial_\sigma \pi^0)$$

- Suggestion: core of the vortex- baryonic degrees of freedom- polarization

Anomaly vs TD (talk of G. Prokhorov)

- Wigner function, Zubarev d.m. – induced axial current

$$\langle : j_\mu^5 : \rangle = \left(\frac{1}{6} \left[T^2 + \frac{a^2 - \omega^2}{4\pi^2} \right] + \frac{\mu^2}{2\pi^2} \right) \omega_\mu + \frac{1}{12\pi^2} (\omega \cdot a) a_\mu$$

$$\alpha_\mu = \frac{1}{T} u^\nu \partial_\nu u_\mu = \frac{a_\mu}{T}, \quad w_\mu = \frac{1}{2T} \epsilon_{\mu\nu\alpha\beta} u^\nu \partial^\alpha u^\beta = \frac{\omega_\mu}{T}$$

$$\langle : j_\mu^5 : \rangle = 2\pi \operatorname{Im} \left[\left(\frac{1}{6} (T^2 + \varphi^2) + \frac{\mu^2}{2\pi^2} \right) \varphi_\mu \right]$$

$$\varphi_\mu = \frac{a_\mu}{2\pi} + \frac{i\omega_\mu}{2\pi}$$

- $H + iE \leftrightarrow \omega + ia$ (“imaginary acceleration”)
- Largest ever angular velocity and acceleration – effective **gravity**, Unruh radiation

Another manifestation of spin-gravity interactions in QCD: Gravitational Formfactors

$$\langle p' | T_{q,g}^{\mu\nu} | p \rangle = \bar{u}(p') \left[A_{q,g}(\Delta^2) \gamma^{(\mu} p^{\nu)} + B_{q,g}(\Delta^2) P^{(\mu} i \sigma^{\nu)\alpha} \Delta_\alpha / 2M \right] u(p)$$

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

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

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

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons **and** interaction with both classical and TeV **external (its weakness does not enter)** gravity
- Special interest: quadrupole FF is related to **pressure** (talk of P. Sznajder) – **another link** between hadrons and QCD matter

Counterpart of Ji's SR: Equivalence Principle (OT'99)

- Interaction – field vs metric deviation

$$M = \langle P' | J_q^\mu | P \rangle A_\mu(q)$$

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

- Static limit

$$\langle P | J_q^\mu | P \rangle = 2e_q P^\mu$$

$$\sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle = 2P^\mu P^\nu$$
$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P | J_q^\mu | P \rangle A_\mu = 2e_q M \phi(q)$$

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

- Mass as charge – equivalence principle



Gravitomagnetism

- Gravitomagnetic field (weak, except in gravity waves) – action on spin from $M = \frac{1}{2} \sum_{q,G} \langle P' | T_{q,G}^{\mu\nu} | P \rangle h_{\mu\nu}(q)$

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

spin dragging twice
smaller than EM

- Lorentz force – similar to EM case: factor $1/2$ cancelled with 2 from frequency same as EM $h_{00} = 2\phi(x)$ Larmor

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

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

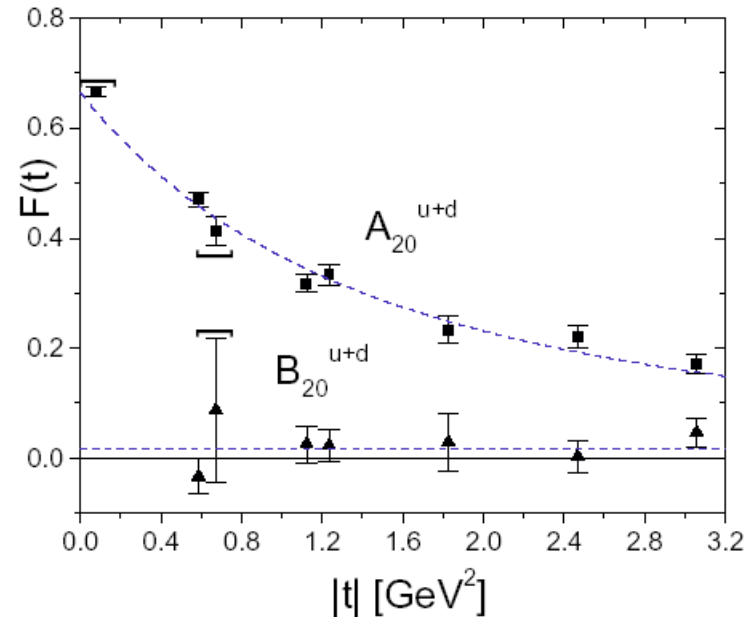
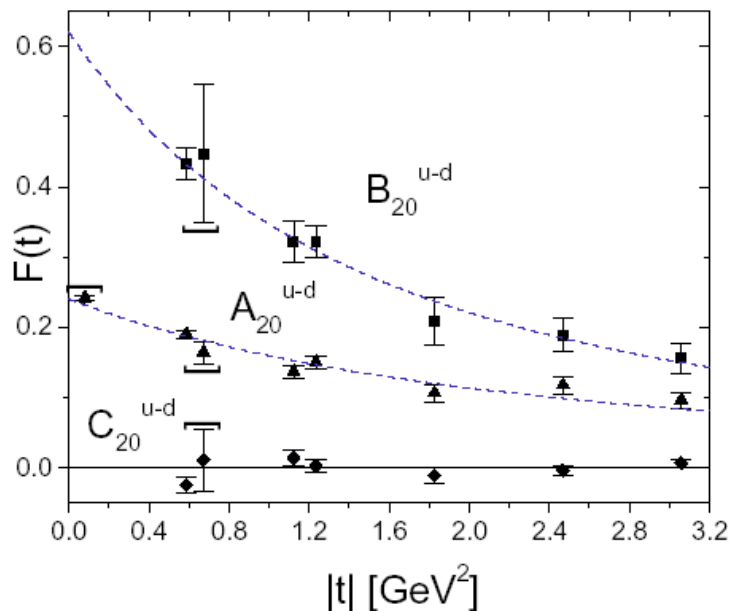


Equivalence principle

- Newtonian – “Falling elevator” – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’; rederived from conservation laws - Kobzarev and V.I. Zakharov)
- Anomalous gravitomagnetic (and electric-CP-odd) moment is ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- Gravitational analog of Ji’s SR $\int dx \times (\sum E_q + E_G) = 0!$

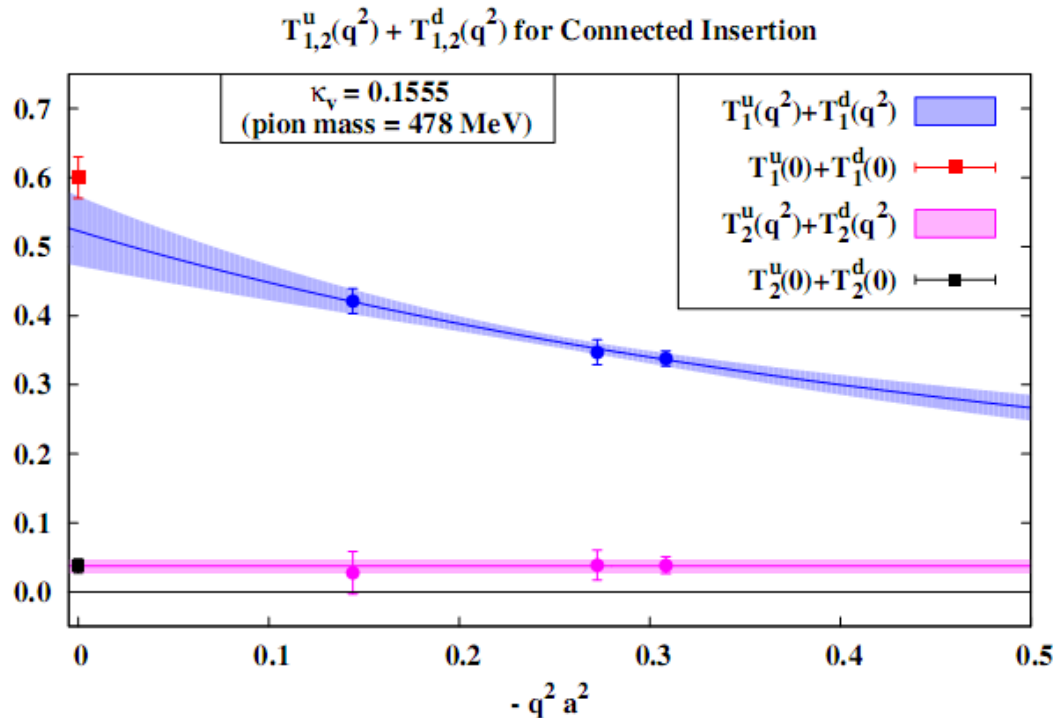
Generalization of Equivalence principle

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



Recent lattice study (M. Deka 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 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
- Gravityproof confinement? Nucleons do not break even by black holes?
- Where else to observe: **Spin1 coupling to gravity**



Tensor polarization

- Vector: $(\sigma(+)-\sigma(-))/(\sigma(+)+\sigma(-))$

Tensor:

$$(\sigma(+)+\sigma(-)-2\sigma(0))/(\sigma(+)+\sigma(-)+\sigma(0))$$

Simplest way : meson from

Polarized (anti) quarks (small quadratic effect)

BUT: correlation is enough!

Alignment from correlations (Efremov, OT'82)

$$\rho = \frac{1}{4} (\mathbf{I} \otimes \mathbf{I} + a_i \sigma_i \otimes \mathbf{I} + b_j \mathbf{I} \otimes \sigma_j + c_{ij} \sigma_i \otimes \sigma_j)$$

$$\rho_{00} = \frac{1 - c_{zz} + c_{xx} + c_{yy}}{3 + c_{zz} + c_{xx} + c_{yy}} \equiv \frac{1 - \text{Sp}_{\parallel} \mathbf{c} + \text{Sp}_{\perp} \mathbf{c}}{3 + \text{Sp} \mathbf{c}}$$

$$\sum_i \rho_{ii}^i = 1; \quad \sum_i S_{ii} = 0.$$



Spin 1 in QCD

- Tensor polarization in QCD: Frankfurt, Strikman (81), Efremov, OT (81)
- Spin $\frac{1}{2}$: kinematically enhanced longitudinal polarization; transverse-twist 3
- Spin 1: LL/TT related by tracelessness



SUM RULEs

- BLTP JINR (A.V. Efremov, OT'81): zero sum rules:
- Vector Current: 1st moment: also in parton model by Close and Kumano (90)
- EMT: 2nd moment (forward analog of Ji's SR)
- Spin-Gravity coupling for tensor polarization; also for inclusive processes
- Gravity and (Ex)EP: zero average shear (tracesees part of EMT) separately for quarks and gluons) – OT'09

Manifestation of post-Newtonian (Ex)EP for spin 1 hadrons

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

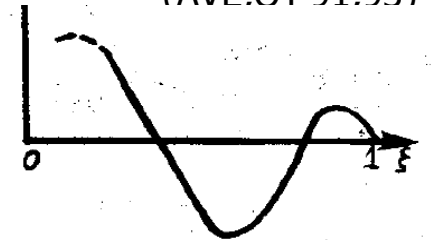
$$A_T = \frac{\sigma_+ + \sigma_- - 2\sigma_0}{3\bar{\sigma}}$$

$$\int_0^1 C_i^T(x) dx = 0$$

$$\langle P, S | \bar{\psi}(0) \gamma^\nu D^{\nu_1} \dots D^{\nu_n} \psi(0) | P, S \rangle_{\mu^2} = i^{-n} M^2 S^{\nu\nu_1} P^{\nu_2} \dots P^{\nu_n} \int_0^1 C_q^T(x) x^n dx \quad (\text{AVE.OT'91.93})$$

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

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

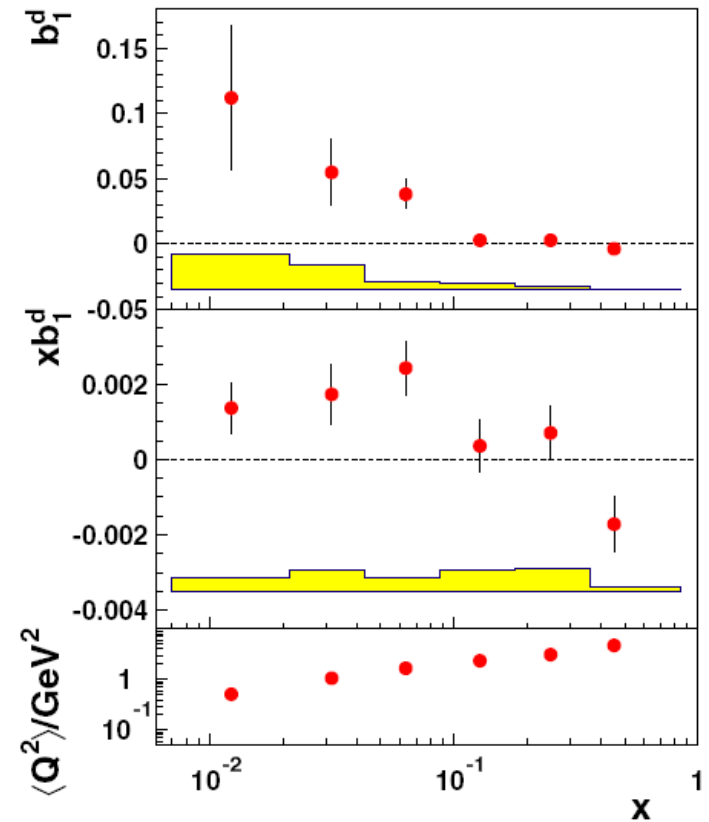


$$\sum_q \int_0^1 C_i^T(x) x dx = \delta_1(\mu^2) = 0 \quad \text{for ExEP}$$

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 (Ex)EP
- Second moments – compatible to zero better than the first one (collective glue \ll sea)





Where else to test?

- EIC?
- DY@J-PARC:
(Song, Kumano: 1902.04712)
- ET'81-**any** hard process

- $f_{AI} \sim b_1$

$$\frac{P_{xx} - 2P_{yy} - 2P_{zz}}{3 \int_0^1 d\xi f(\xi) \text{Sp}[\hat{P}E(\xi, P)]} = \frac{2 \int_0^1 d\xi f_{AI}(\xi) \text{Sp}[\hat{P}E(\xi, P)]^2}{3F(x_1, x_2)}$$

- Suggestion: **hadronic** tensor SSA(OT'19)



Vector vs Tensor SSA

- Vector: $A = (\sigma(+)-\sigma(-))/(\sigma(+)+\sigma(-))$
- Phase is required
- Tensor:
 $A = (\sigma(+)+\sigma(-))/(\sigma(+)+\sigma(-)+\sigma(0))$
- **No need for phase!**
- Inclusive pion production: (T-odd) vector SSA may be also excluded by summing $\sigma(L)+\sigma(R)$



Tensor polarized beams

- Opportunity: SPD@NICA with polarized **hadronic** beams (talk of I. Denisenko today)
- Polarized deuterons is easier to accelerate: no depolarizing resonances
- J/ψ (+**hadronic** SSA)
- **Tensor fragmentation functions: vector mesons at U-70 (talks of A. Vasiliev and V. Mochalov today)**




Conclusions/Outlook

- Same ingredients in hadrons and heavy ions – in different ways!
- Scattering -> Reaction plane
- Interference -> LS via anomaly
- Phases -> dissipation in core of vortices in pionic superfluid

- Strongest ever inertial effects (rotation and acceleration): role of gravity
- Gravitational Ffs of hadrons – pressure and **shear**
- **Effective (Equivalent) gravity studies in hadronic and heavy-ion collisions!**
- May be studied at NICA/SPASCHARM with tensor polarized beams/targets

Thank you for your attention and Welcome to DSPIN-2026 (7-11.09) <https://indico.jinr.ru/event/6047/>



DSPIN-26

XX Workshop on High Energy Spin Physics

JINR, Dubna, Russia, 7 – 11 September 2026

Topics and scopes:




- Recent experimental data on spin physics
- Nucleon spin structure, TMDs and GPD's
- Spin physics and QCD
- Spin physics in the Standard Model
- Fundamental symmetries beyond the Standard Model
- Polarization and heavy ion physics
- Spin in gravity and astrophysics
- Spin physics at NICA
- Polarimeters for high energy polarized beams
- Acceleration and storage of polarized beams
- New polarization technologies

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