Sources of time reversal odd spin asymmetries in QCD

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Generation of T-odd single spin asymmetries (SSA) by the various ingredients of QCD factorization is discussed. The possible use of SSA in studies of Generalized Parton Distribution (GPD) at HERA with the polarized lepton beam is suggested. The role of GPD in the investigation of orbital angular momenta of partons is discussed. The generalization of Equivalence principle, leading to the equipartition of momenta and total angular momentum, violated in perturbation theory, but possibly restored due to confinement and chiral symmetry breaking, is proposed. The T-odd fragmentation and fracture function are considered. The T-odd distribution (Sivers) function may be only effective, due to the imaginary cuts in the SIDIS and Drell-Yan process, while the existence of such universal functions should lead, after the integration over transverse momentum, to the strong T violation in polarized DIS.

Key words: single spin asymmetry, distribution, fragmentation

1 Introduction

The single transverse spin asymmetries are most easily studied experimentally, as they require only one polarized particle (usually, the polarized target). At the same time, they are known to be one of the most subtle effects in QCD. They should be proportional to mass scale, and the only scale in "naive" perturbative QCD is that of the current quark mass.

The additional suppression comes from the fact, that single asymmetries are related to the antisymmetric part of the density matrix. Due to its hermiticity, the imaginary part of scattering amplitude is relevant. As a result, the spin-dependent contribution to the hard scattering cross section starts at the one-loop level only. More exactly, it is due to the interference of the one-loop spin-flip amplitude and Born non-flip one. At the same time, the Born graphs provide a leading approximation to the spin-averaged cross section and the asymmetry is proportional to $\alpha_s$.

These spin effects are T-odd but not related to the CP-violation. They are generated by the term in the cross-section proportional to the polarization of one of the spin-1/2 particles. If parity is conserved, such term should contain Levi-Civita tensor which changes sign when the direction of time axis is changed, that’s why the effect is called T-odd. Sometimes such a transformation is called "naive" T-reflection. At the same time, the "full" time reflection T contains also the interchange of the initial and final states, so if this later operation is non-trivial (which is guaranteed by the existence of the non-trivial phases in the S-matrix elements), the T-odd effects may emerge in the T-invariant theory. If, for some reason, phases cannot emerge, the real T(CP) violation is required, and the role of phases is taken
by the complex couplings. The appearance of phases is, in turn, related through the
generalized optical theorem to the existence of the cuts in some kinematical variables. The analysis of such cuts in the different ingredients of QCD factorization
can be the main tool of the unraveling of T-odd effect in QCD.

2 Generalized Parton Distributions

Generalized Parton Distributions (GPD) encode the information about the
hadron structure relevant for hard exclusive processes in the most complete way
and has been the subject of extensive theoretical investigations for a few years.
The Deeply Virtual Compton Scattering (DVCS) [1, 2] is the probably the cleanest
among these hard process. The SSA currently plays a major role in its investigation[3].
The imaginary phase emerges in the handbag parton subprocess, while the interfer-
ence is that of DVCS and BH amplitudes. As the latter is substantially larger at
JLAB and HERMES kinematics, SSA provides the most sensitive test for GPD, as
it depends on the ratio $r = \left| M_{DVCS} \right| / \left| M_{BH} \right|$ linearly, rather than quadratically. At
the same time, SSA may be also studied at HERA in the collider more as well, pro-
vided the polarized lepton beam is used at the forthcoming stages of experiments
(see [4]). As BH process contribution is much smaller, the BH-DVCS asymmetry is
of the order $1/r$, and the interference between various DVCS amplitudes becomes
important. In particular, the twist-3 contributions to DVCS [5] and exclusive vector
meson production [6] may be studied in such a way.

Another important relation of GPD to nucleon spin structure is provided by
relations of their moments to the particular matrix elements of Belinfante energy-
momentum tensors, and in, turn, to the total angular momenta of partons,

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

(1)

where $P^\mu = (p^\mu + p'^\mu)/2$, $\Delta^\mu = p'^\mu - p^{\mu}$, and $u(p)$ is the nucleon spinor. We dropped
here the irrelevant terms of higher order in $\Delta$, as well as containing $g^{\mu\nu}$, which will
be discussed later. The parton momenta and total angular momenta are:

$$P_{q,g} = A_{q,g}(0),$$
$$J_{q,g} = \frac{1}{2} [A_{q,g}(0) + B_{q,g}(0)].$$

(2)

Taking into account the conservation of momentum and angular momentum

$$\sum_{i=q,g} \int_0^1 dx x H_i(x, \xi, Q^2) = A_q(0) + A_g(0) = 1$$

(3)

$$\sum_{i=q,g} \int_0^1 dx (H + E_i(x, \xi, Q^2) = A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1,$$

(4)

where we recalled the relation of formfactors to the moments of GPD $H, E$, one
can see that the difference between partition of the momentum and orbital angular momentum entirely comes from "anomalous" formfactors $B_q(0) = -B_g(0) = \ldots$
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\[ \sum_{x} \int_{0}^{1} dx x E_{i}(x, \xi, Q^{2}). \]  

It may look surprising that the smallness of such a contribution may be related to some generalization of famous Equivalence principle (which, as it is known, was developed by Einstein just in Prague). Indeed, matrix element of energy momentum tensor determines the nucleon behaviour in the external gravity field.

Let us start with a more common case of the interaction with electromagnetic field described by the matrix element of electromagnetic current,

\[ M = \langle P'| J^\mu_q | P \rangle A_\mu(q). \]  

This matrix element at a zero momentum transfer is fixed by the fact that the interaction is due to the local U(1) symmetry, whose global counterpart produces the conserved charge (and, of course depends on the normalization of eigenvectors \( \langle P | P' \rangle = (2\pi)^3 2E \delta(\vec{P} - \vec{P}') \)).

\[ \langle P | J^\mu_q | P \rangle = 2e_q \mathcal{P}^\mu, \]  

so that in the rest frame the interaction is completely defined by the scalar potential:

\[ M_0 = \langle P | J^\mu_q | P \rangle A_\mu = 2e_q M \phi(q) \]  

At the same time, the interaction with a weak classical gravitational field is:

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

where \( h \) is a deviation of the metric tensor from its Minkowski value. The relative factor 1/2, which will play a crucial role, comes from the fact that the variation of the action with respect to the metric produces an energy-momentum tensor with the coefficient 1/2, (while, say, the variation with respect to classical source \( \mathcal{A}^\mu \) produces the current without such a coefficient). It is this coefficient that guarantees the correct value for the Newtonian limit fixed by the global translational invariance

\[ \sum_{q,G} \langle P | T_{q,G}^{\mu\nu} | P \rangle = 2P^\mu P^\nu, \]  

which, together with the approximation for \( h \) (with factor of 2 having the geometrical origin) \[9\]

\[ h_{00} = 2\phi(x) \]  

results in the rest frame expression:

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

where we used the same notation for gravitational and scalar electromagnetic potentials, and identified normalization factor 2M in order to make the similarity...
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between (7) and (11) obvious. One can see that the interaction with gravitational field is described by the charge, equal to the particle mass, which is just the equivalence principle. It is appearing here as a low energy theorem, rather than postulate. The similarity with electromagnetic case allows to clarify the origin of such a theorem, suggesting, that the interaction with gravity is due to the local counterpart of global symmetry, although it may be proved starting just from the Lorentz invariance of the soft graviton approximation [10].

The situation with the terms linear in $\Delta$ is different for electromagnetism and gravity. While such a term is defined by the specific dynamics in the electromagnetic case, producing the anomalous magnetic moment, the similar contribution in the gravitational case is entirely fixed by the angular momentum conservation [11], which was known in the context of gravity for more than 35 years [11, 12, 13]. It means, in terms of the gravitational interaction, that Anomalous Gravitomagnetic Moment (AGM) of any particle is identically equal to zero.

As soon as the formfactors in spin-1/2 case differ from the ones for the matrix element of vector current $J_\mu$ by the common factor $P^\nu$, one may define gyrogravitomagnetic ratio in the same way as common gyromagnetic ratio, and it should have Dirac value $g = 2$ for particle of any spin $J$:

$$\mu_G = J$$

which coincide with the standard Dirac magnetic moment, up to the interchange $e \leftrightarrow M$, making the Bohr magneton equal to 1/2.

However, the situation changes if one define the gyrogravitomagnetic moment as a response to the external gravitomagnetic field. The $\epsilon$ tensor in the coordinate space produces the curl, and the gravitomagnetic field, acting on the particle spin, is equal to

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

where factor 1/2 is just the mentioned normalization factor in (5). The relevant off-diagonal components of the metric tensor may be generated by the rotation of massive gravity source [9].

There is also another effect, induced by this field: the straightforward analog of Lorentz force [9], produced by the spin-independent term in (9). In that case the gravitomagnetic field, for the low velocity of the particle (such a restriction is actually inessential, as we can always perform the Lorentz boost, making the particle velocity small enough) is:

$$\vec{H}_L = \text{rot} \vec{g} = 2\vec{H}_G,$$

Consider now the motion of the particle in the gravitomagnetic field. The effect of Lorentz force is reduced, due to the Larmor theorem [14], (which is also valid for

1) The reason is that the structure of Poincare group is more reach than that of $U(1)$ group.
small velocity) to the rotation with the Larmor frequency

$$\omega_L = \frac{H_L}{2}. \quad (15)$$

This is also the frequency of the \textit{macroscopic} gyroscope dragging. At the same time, the \textit{microscopic} particle dragging frequency is

$$\omega_J = \frac{\mu G J H_J}{\mu J} = \frac{H_L}{2} = \omega_L. \quad (16)$$

The common frequency for microscopic and macroscopic gyroscopes is just the Larmor frequency, so that the gravitomagnetic field is equivalent to the frame rotation. This should be considered as a Post-Newtonian manifestation of the equivalence principle.

Let us make here a brief comparison with the literature. The low energy theorem discussed here is the necessary ingredient for validity of gravitational Larmor theorem \cite{14}, which otherwise require an arbitrary assumption about the "classical" gyroggravitomagnetic ratio, say, for electron \cite{15}. At the same time, the equality of the "classical" and "quantum" frequencies was found long ago \cite{13} by comparison of the quantum spin-orbit interaction with the classical one calculated earlier \cite{16}. Our approach clarify the origin of this equality, as a cancellation of "geometrical" factor $1/2$ in \cite{5} and "quantum" value 2 of gyroggravitomagnetic ratio. Note that for free particle the latter coincides with the usual gyromagnetic ratio, and such a cancellation provides an interesting connection between geometry, equivalence principle and special renormalization properties (cancellation of strongest divergencies) for particles with $g = 2$ (c.f. \cite{17}).

The crucial factor $1/2$ makes the evolution of the particle helicity in magnetic and gravitomagnetic fields rather different. The spin of the (Dirac) particle in the magnetic field is dragging with the cyclotron frequency, being twice larger than Larmor one. It coincides with the frequency of the velocity precession so that helicity is conserved. At the same time, the gravitomagnetic field is making the velocity dragging twice faster than spin, changing the helicity. This factor of 2, however, is precisely the one required by the possibility to reduce all the effect of gravitomagnetic field to the frame rotation. While spin vector is the same in the rotating frame and is dragging only due to the rotation of the coordinate axis, the velocity one is transformed and getting the additional contribution, providing factor 2 to Coriolis acceleration.

Note that all the consideration is essentially based on the smallness of the particle velocity, achieved by the mentioned Lorentz boost, and therefore do not leading to the loss of generality. There is no doubt about the possibility to construct the invariant proof, which should result in the Fermi-Walker transport equation $D_\alpha s^\mu = 0$.

Let us consider massive particle scattered by rotating astrophysical object. The effect of the gravitomagnetic field is reduced to the rotation of the local comoving frame, which is becoming inertial at large distances before and after scattering.
Consequently, the helicity is not changed by gravitomagnetic field, which is confirmed by the explicit calculation of the Born helicity-flip matrix element in the case of massive neutrino [18].

It may seem, that the equivalence principle should exclude the possibility of helicity flip in the scattering by gravity source at all. This is, however, not the case, if usual Newtonian-type ”gravitoelectric” force is considered [7]. Its action is also reduced to the local acceleration of the comoving frame, in which the helicity of the particle is not altered. However, the comoving frame after scattering differs from the initial one by the respective velocity \( \delta \vec{v} = \int \vec{a} dt \). The corresponding boost to the original frame is, generally speaking, changing the helicity of the massive particle (the similar effect for the gravitomagnetic field is just the rotation for the solid angle \( \delta \vec{\Omega} = \int \vec{\omega} dt \) and does not affect the helicity). The same boost may be considered as a source of the famous deflection of particle momentum \( \delta \phi \approx |\delta \vec{v}|/|\vec{v}| \). The average helicity of the completely polarized beam after such a scattering may be estimated in the semiclassical approximation as \(< P > \approx \cos \phi \approx 1 - \frac{\phi^2}{2} \). Due to the correspondence principle, this quantity may be expressed as

\[
<P> = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} \approx 1 - 2 \frac{d\sigma_{+-}}{d\sigma_{++}},
\]

(17)

where \( d\sigma_{+-} \ll d\sigma_{++} \) - the helicity-flip and non-flip cross-sections, respectively. Comparing ”classical” and ”quantum” expression for \(< P >\), one get

\[
\frac{d\sigma_{+-}}{d\sigma_{++}} \approx \frac{\phi^2}{4}.
\]

(18)

To check this simple approach, one may perform the calculation of this ratio for the Dirac particle scattered by the gravitational source. In the Born approximation, the result is easy to find:

\[
\frac{d\sigma_{+-}}{d\sigma_{++}} = \frac{tg^2(\frac{\phi}{2})}{(2\gamma - \gamma^{-1})^2}.
\]

(19)

This expression is coinciding with the estimate [18], as soon as the deflection angle is small and the particle is slow \((\gamma = E/m \to 1)\), while for the fast particles

\[
\frac{d\sigma_{+-}}{d\sigma_{++}} \approx \frac{\phi^2}{16\gamma^2}.
\]

(20)

Such an effect should, in particular, lead to the helicity flip of any massive neutrino. It is very small, when the scattering by the single object is considered, but may be enhanced while neutrino is propagating in Universe. Should the propagation time be large enough, the effect would result in unpolarized beam of the initially polarized neutrino, effectively reducing its intensity by the factor of 2.

The manifestation of post-Newtonian equivalence principle is especially interesting, when ”gravitoelectric” component is absent. Contrary to electromagnetic
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case, one cannot realize this situation through cancellation of contributions of positive and negative charges. At the same time, one may consider instead the interior of the rotating shell (Lense-Thirring effect). Especially interesting is the case of the shell constituting the model of Universe, whose mass and radius are of the same order, when the dragging frequency may be equal to the shell rotation frequency, which is just the Mach’s principle [19]. One should note, that the low energy theorem, guaranteeing the unique precession frequency for all quantum and classical rotators, is the necessary counterpart of the Mach’s principle.

Up to this moment, we considered the gravitational interaction of the particle, being the eigenstate of the momentum and spin projection and described by the conserved energy-momentum tensor. Any assumptions on the particle locality except the locality of energy-momentum tensor were unnecessary.

We are now ready to postulate the following straightforward generalization [7] of this principle:

**Contributions of quarks and gluons to the Anomalous Gravitomagnetic Moment of nucleon are zero**

\[
\langle P' | T^{\mu\nu}_{i} | P \rangle = N_{i} [2(P^{\mu} P^{\nu} - g^{\mu\nu} M^{2}) + \frac{i}{M} P^{(\mu} \epsilon^{\nu)\sigma} P^{\rho} S^{\sigma} \Delta^{\alpha} ] + O(g^{\mu\nu}, \Delta^{2}).
\] (21)

To test this suggestion let us first turn to perturbative QED analysis. The matrix elements of energy momentum tensors of electrons and photons acquire the logarithmically divergent contributions, cancelled in their sum. This problem, at leading order(LO), is similar to the calculation of QED corrections to gravity coupling [20]. It is sufficient to consider the matrix elements of either electron or photon energy momentum tensor switched between free electron states, and the latter case is more simple, being described by the single diagram. It is enough to consider the terms of zero and first order in \(\Delta\). The divergent contribution to the former is appearing [20] in the traceless part and may be identified with the second moment of spin-independent DGLAP kernel \(\int_{0}^{1} dx x G_{q}(x)\). The linear term is known from the orbital angular momentum calculations [21, 22, 23] and is also equal to that quantity, so that AGM is really zero.

The next important step is to consider the respective finite terms, constituting the AGM of electron. It was calculated in QED [21, 25], resulting in the check of the low-energy theorems [4]. To consider the separate AGM of photons and gluons in photon, one should perform the respective decomposition of the total result, and get the non-zero answer, confirmed recently by S. Brodsky and collaborators [26].

The general reason for this value was also founded [24] as emerging due to use the unsubtracted dispersion relations for the relevant formfactors, while performing the subtraction, resulting in the zero AGM, leads to the absence of the smooth transition \(m_{e} \rightarrow 0\).

Note, however, that these subtraction play the prominent role in the enforcing gravitational gauge invariance. While in QED the appearance of gauge invariant
field strength $F^{\mu\nu}$ corresponds to the subtractions in the relevant amplitudes, the
same should be true for the gravity, where the corresponding gauge-invariant quantity
is the curvature $R^{\mu\nu}$. As it is quadratic in coordinates (rather than linear, as in
in QED), the subtraction should make the moments, linear in $\Delta$, equal to zero.

Performing these subtraction for the separate contributions of various fields
while imposing Extended Equivalence Principle (EEP) means, that such a gauge
invariance is postulated for each field separately. The QED example shows, that due
to fields interactions the simplest form of such assumption is not valid. However,
we will now present some arguments in favor of the hypothesis [8], that in full QCD
manifesting such phenomena as confinement and chiral symmetry breaking, sepa-
rate gauge invariance of quarks and gluons (and, therefore, EEP and equipartition)
may be restored.

Note that due to field interactions the scattering of electron in the external
gravitational field is accompanied by the emission of soft photons. Let us therefore
suggest, that EEP should include this emitted photons, and the zero AGM should
correspond to the ”coherent state” of ”bare” electron (which is the QED analog
of quark contribution to the nucleon AGM) and emitted photon. In QCD, due to
confinement phenomenon, the emission of soft gluons is forbidden and zero AGM of
quarks themselves should appear. Note that only the singlet combination of quarks
could manifest zero AGM, which is seen already from the perturbative evolution
[23]: only the total contribution of all quarks, appearing as virtual in QCD beta-
function, can preserve equipartition at various $Q^2$. The equipartition therefore holds
at leading order both in QED and QCD. At NLO order it is violated in QED, and,
according to our hypothesis, this corresponds to the modification of EEP by
including the soft emitted photons. In QCD equipartition is, in the same line of
reasoning, restored due to confinement, so that same phenomenon is manifested at
LO and beyond the perturbation theory.

The confinement phenomenon is accompanied by chiral symmetry restoration,
which, according to present understanding [27], is deeply related to confinement
and, in particular, happens at the same temperature in the lattice simulations.
This makes the mentioned above argument [24] against the subtraction, providing
the equipartition, unapplicable to full QCD. Indeed, the term $1/m_q$ provided by
this subtraction in perturbation theory should be replaced by hadronic scale \(^3\)
when chiral symmetry breaking is taken into account.

## 3 Higher twist correlations, fragmentation and fracture functions

Twist 3 quark-gluon correlations (CGC) provide another (and, in QCD, probably
the earliest found [28]) source of T-odd asymmetries. The transverse gluon field
provides both the mass scale and phase shift. These effects are in fact quite similar
to GPD: in both cases the momenta of participating quarks are different: for GPD
this difference emerges because of different hadron momoenta, while for CGC because
of extra gluon. This leads, in particular, to the similarity between transverse spin

\(^3\) More specifically, by the ratio of gluon and quark condensates, determined by trace anomaly
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in QGC and transverse momentum of symmetry properties emerging due to T-invariance, found for QGC and GPD.

While SSA emerged due to high twist correlations involve contributions from both large and short distances, their pure non-perturbative sources include T-odd distribution, fragmentation and fracture functions.

The most widely known objects are parton distributions, describing the fragmentation of hadrons to partons and related to the forward matrix elements \[ \langle X|A|P \rangle = \langle X|A(x)|P \rangle \] of renormalized non-local light-cone quark and gluon operators. As they do not contain any variable, providing the cut and corresponding imaginary phase (to put it in the dramatic manner, the proton is stable), the T-odd distribution functions can not appear in the framework of the standard factorization scheme. At the same time, they may appear effectively, when the imaginary phase is provided by the cut from the hard process, but may be formally attributed to the distribution. Another way of treating the final state interaction, found in the explicit model calculations, as it was recently stressed by J.C. Collins, is provided by the path-ordered gluonic exponential. However, in all cases, the T-odd distribution cannot be universal, as the imaginary phase appearance depends on the subprocess it is convoluted with. To prove the non-universality of T-odd distribution \( H(x) \), it is sufficient to consider its contribution the quark jet asymmetry in semi-inclusive DIS, where the hadronic tensor is proportional to

\[ W_{\mu\nu} \sim Tr[\gamma^\alpha \gamma^\mu (x\hat{P} + \hat{k}_T)\gamma^\nu]H(x)\epsilon^{\alpha\beta k_T}, \] (22)

and average it over and \( k_T \), assuming that \( < k_T^2 > = 0, < k_T^4 > = 0 \), where transverse direction \( T \) is defined with respect to the light cone vectors \( P \) and \( xP + q \):

\[ W_{\mu\nu} \sim \frac{< k_T^2 >}{Pq} H(x)[P^\mu \epsilon^{\nu P S q} + P^\nu \epsilon^{\mu P S q}]. \] (23)

The appearance of such a symmetric spin-dependent hadronic tensor is violating the real T-invariance. It is interesting that such observable is quite similar to the one suggested for the search of T-violation and discussed at this conference. In both cases one is dealing with correlations of transverse polarization of target nucleon and tensor polarization of the beam (deuteron in neutron experiment and virtual photon in our case) in the total cross-section. Note also that (23) is not manifestly electromagnetically gauge invariant, which is of course true for original expression (22). Although gauge dependence disappears after contraction with the leptonic tensor, this signals about necessity to take into account another higher twist effects.

At the same time, the similar effects for the crossing related process of semi-inclusive annihilation correspond to the distributions substituted by fragmentation functions, describing the fragmentation of partons to hadrons and constructed from the time-like cutvertices of the similar operators \[ \sum_X < 0|A(0)|P, X > < P, X|A(x)|0 > \]. As the latter may contain the imaginary cuts, simulating the T-violation, the performed calculation is starting to be more related with physics.
Namely, it describes the production of transverse polarized baryon (one should typically think about Λ, whose polarization is easily revealed in its weak decay) in the annihilation of the unpolarized leptons \[37\].

The FRACTURE function (FF) \[38\], whose particular example is represented by the diffractive distribution (DD) \[39\], is related to the object \(\sum X < P_1 | A(0) | P_2, X > < P_2, X | A(x) | P_1 >\), combining the properties of FRAgmentation and struCTURE functions. They describe the correlated fragmentation of hadrons to partons and vice versa. Originally this term was applied to describe the quantities integrated over the variable \(t = (P_1 - P_2)^2\), while the fixed \(t\) case is described by the so-called extended fracture functions \[40\]. They may be also extended \[41\] to describe SSA in such processes. Namely, such functions can easily get the imaginary phase from the cut produced by the variable \((P_1 + k)^2\). Due to the extra momentum of produced hadron \(P_2\), the number of the possible \(P\)-odd combinations increases. Therefore, they may naturally allow for the \(T\)-odd counterparts. The \(T\)-odd fracture function may describe a number of SSA at HERMES and, especially, NOMAD \[42\].

4 Conclusion

As we see, the \(T\)-odd spin asymmetries play a major role in studies of various QCD non-perturbative inputs. For GPD, the beam asymmetry in DVCS was the main instruments for the experimental check of QCD factorization at JLAB and HERMES. The studies of SSA at H1 and ZEUS with the polarized lepton may give access to twist 3 effects.

The important spin-related aspect of GPD is represented by their connection to the angular momenta of partons. This problem is also related to the post-Newtonian Equivalence principle. Its generalization for the separate contributions of quarks and gluons which is violated in perturbation theory, but may be restored in full QCD due to the confinement and spontaneous chiral symmetry breaking, would lead to the equipartition of momentum and angular momentum between quarks and gluons.

The \(T\)-odd distributions may be only effective, as the imaginary phase may be associated only with the cut, depending on the subprocess. The assumption about the universality of Sivers function leads, after integration over \(k_T\) to the real \(T\)-violation. At the same time, the \(T\)-odd fragmentation and fracture functions are related to the process-independent cuts at large distances and are therefore universal.

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