Tensor polarization and gluonic shear

Gluon content of proton and deuteron with the Spin Physics Detector at the NICA collider

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Main Topics

- Fundamental gluonic properties in parton distributions
- Gluonic shear in exclusive and inclusive processes

Gluon contribution to

- Mass – most of (light quarks!)
- Momentum (~1/2 for nucleons)
- Other hadrons? – talk of S. Platchkov
- Spin ~ 10% - talk of M. Stolarski
- Pressure, shear
- From exclusive processes (GPDs) – talk of M. Polyakov
- Average shear – from inclusive tensor polarized hard processes

Most general properties described by Energy-Momentum Tensor

Which single book to take to the uninhabited island?

Holy?

Shakespeare/Balzac/Goethe/Tolstoy/…?

Boat construction manual?

Single operator? EMT: probably even more general and universal than EM current

Continuous media

Hydro

Gravity

Gravitational Formfactors (spin ½)

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

- 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

Gravity and hadron structure: (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

EP and hadron structure

"Microscopic" EP (coupling of gravity to EMT)

+

Conservation law

(Momentum SR to get local from LC: $\int dx\, x\, (\Sigma\, q(x) + G(x))=1$)

=

"Macroscopic" EP (universal falling) :

Tested VERY precisely

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

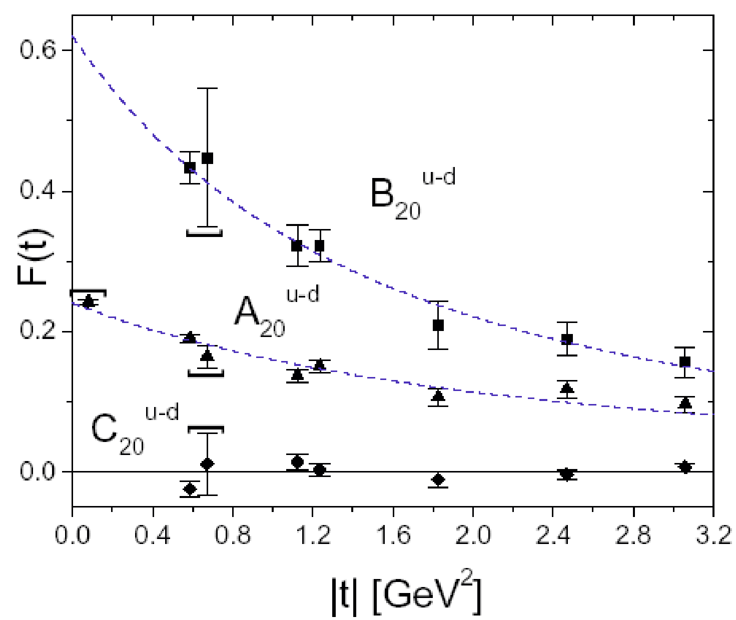
- Newtonian – "Falling elevator" – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on quantum SPIN – known since 1962 (Kobzarev and Okun'; rederived from conservarion laws - Kobzarev and V.I. Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- Dirac eq; also for STRONG fields (Obukhov, Silenko, OT) : More general constraint (cf Lorce, Lowdon)?
- Gravitational analog of Ji's SR $\int dx\, x\ (\Sigma\, E_q+E_G) = 0$!

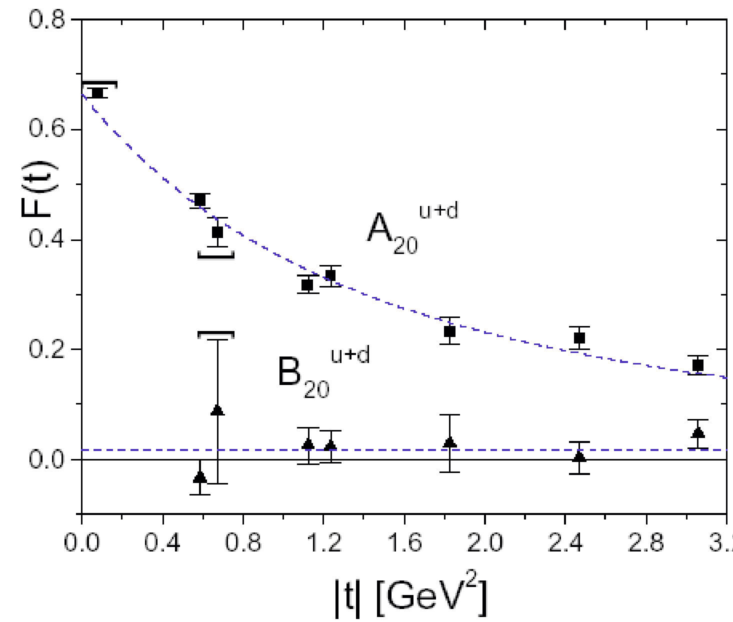
Quantim measurement and EP

- If spin is just a (pseudo) vector : EP due to Earth rotation is trivial
- Crucial if measured by a device in rotating frame
- Quantum measurement problem becomes practical
- Cf Unruh effect in HIC (Prokhorov, OT, Zakharov'19)

Generalization of Equivalence principle

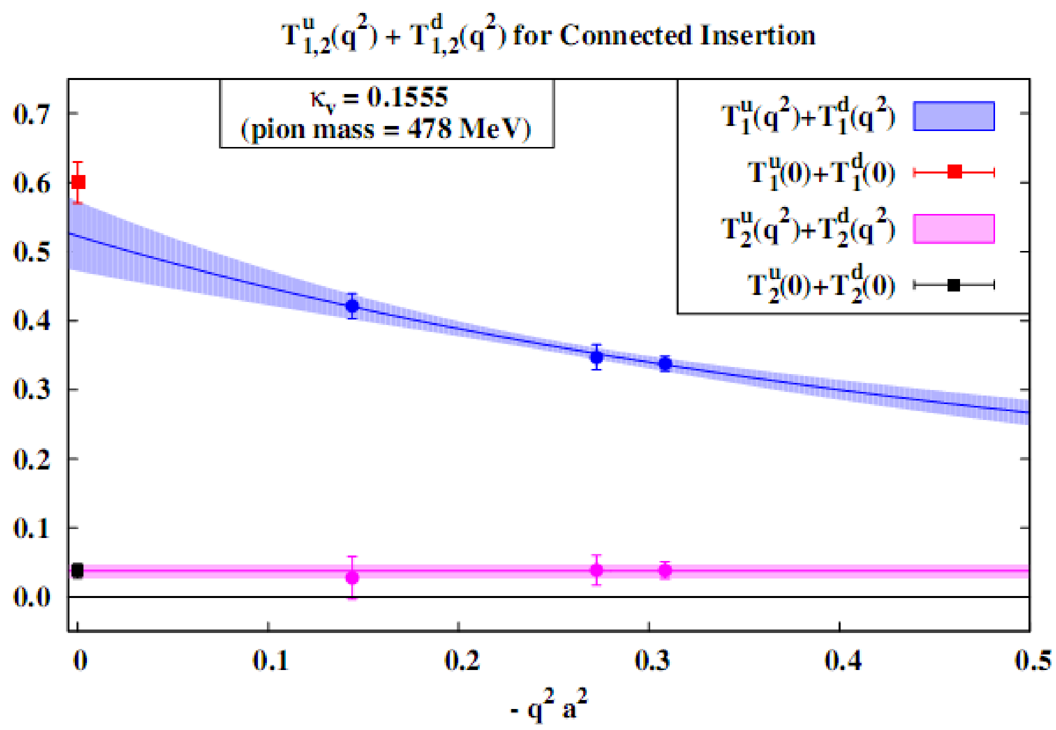
- Various arguments: AGM ≈0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





Recent lattice study (M. Deka et al. Phys.Rev. D91 (2015) no.1, 014505) – also talk of K.-F. Liu

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



Extended Equivalence Principle=Exact EquiPartition

- In QED, pQCD – violated (Brodsky et al)
- 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?
- Support by recent observation of smalness of (nucleon "cosmological constant") Cbar

Spin 1 EMT and inclusive processes

- Forward matrix element ->density matrix
- Contains P-even term: tensor polarization $S^{\alpha\beta}$
- Symmetric and traceless: correspond to (average) shear forces
- For spin ½: P-odd vector polarization requires another vector (q) to form vector product

SUM RULEs

- Efremov,OT’81 : zero sum rules:
- 1st moment: also in parton model by Close and Kumano (90)
- 2nd moment (forward analog of Ji’s SR)
- Average shear force (compensated between quarks and gluons)
- Gravity and (Ex)EP (zero average shear separately for quarks and gluons) – OT’09

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

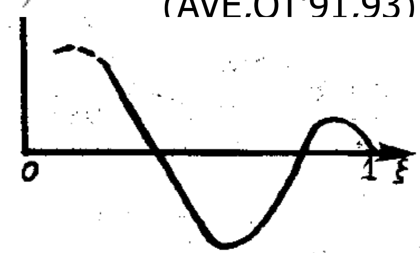
- Tensor polarization - coupling of EMT to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

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

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

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

(AVE,OT'91,93)



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

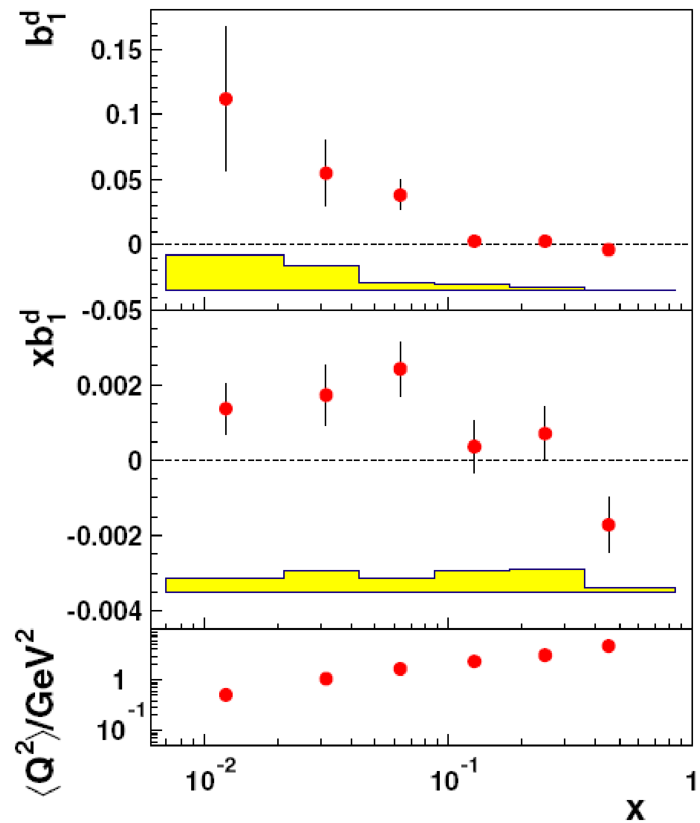
$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^\mu P^\nu \delta(\mu^2) - 2M^2 S^{\mu\nu}\delta_1(\mu^2)$$

$$\sum_q \int_0^1 C_i^T(x)xdx = \delta_1(\mu^2)$$ =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 (Ex)EP
- Second moments – compatible to zero better than the first one (collective glue << sea)



Where else to test?

- COMPASS
- EIC
- DY@J-PARC: (talk of S. Kumano)
- However: ET'81-any hard process ("multi-messenger")
- Possibility: hadronic tensor SSA@NICA

Tensor polarized beams

- Opportunity: NICA@JINR with polarized hadronic beams
- Polarized deuterons is easier to accelerate: no depolarizing resonances
- SPD: J/Ψ + hadronic SSA

Vector vs Tensor SSA

- Vector: A = (σ(+)-σ(-))/(σ(+)+σ(-))

  Tensor:

  A_T =

  (σ(+)+σ(-)-2σ(0))/(σ(+)+σ(-)+σ(0))

$$A_T = \frac{d\sigma(+) + d\sigma(-) - 2d\sigma(0)}{d\sigma(+) + d\sigma(-) + d\sigma(0)} \sim \frac{\sum_{i=q,\bar{q},g} \int d\hat{\sigma}_i \delta_{Ti}(x)}{\sum_{i=q,\bar{q},g} \int d\hat{\sigma}_i f_i(x)}$$

- Inclusive hadron (pion,kaon…) production: (T-odd) vector SSA may be also excluded by summing σ(L)+ σ(R)

Polarization directions

NICA – transverse is easier

Lonfitudinal: enhanced like longitudinal vector polarization

For tensor polarization: diagonal components are not independent (also property of shear)

$$\sum_i \rho^i_{00} = 1; \quad \sum_i S_{ii} = 0.$$

Transverse polarization generates also dominant LL components

Shear: viscosity?!

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:

$V^{\mu} = (P^{\mu} + a(t)\, k_T^{\ \mu}) / (M^2 + a^2(t)\, k_T^{\ 2})^{1/2}$

Viscosity: $\sim \eta\ p^{[\mu} \Delta^{\lambda]}$
Naïve T-oddness: phases

Viscosity in GDA channel

- Possibility to study gravitational FFs in time-like region (Kumano, Song,OT'18)
- Viscosity (new!):will correspond to Exotic $J^{PC}=1^{-+}$ meson (already studied: Anikin, Pire, Szymanowski,OT, Wallon'06)
- $\pi\eta$ pairs observation instead of $\pi\,\pi$ required
- Smallness of viscosity: related to smallness of T-odd GPDs and exotic GDAs ?!

Conclusions

- Tensor polarization: way to test of gravitational coupling of quarks and gluons in inclusive processes: shear

- Tests in J/Ψ and hadronic TSSA at NICA are possible
- Shear viscosity: relation to exotic hybrid mesons?!

BACKUP

Another appearance of T-oddness in EMT: Burkardt SR

T-invariance : antisymmetry of twist 3 gluonic pole matrix element nullifies its contribution to EMT

BUT Pole prescription (dynamics!) provides ("T-odd") symmetric part (OT'14)!

SR:

$$\sum \int \int dx_1 dx_2 \frac{T(x_1, x_2)}{x_1 - x_2 + i\varepsilon} = 0$$

$$\sum \int dx T(x, x) = 0$$

Also EP!

ExEP: approximate validity separately for quarks and gluons: smallness of deuteron Sivers function

D-term interpretation: Inflation and annihilation

- Quadrupole gravitational FF

$$\langle P+q/2|T^{\mu\nu}|P-q/2\rangle = C(q^2)(g^{\mu\nu}q^2 - q^\mu q^\nu) + \ldots$$

- Moment of D-term – positive
- Vacuum – Cosmological Constant $\langle 0|T^{\mu\nu}|0\rangle = \Lambda g^{\mu\nu}$

- 2D effective CC – negative in scattering, positive in annihilation

$$\Lambda = C(q^2)q^2$$

- Similarity of inflation and Schwinger pair production – Starobisnky, Zel'dovich
- Was OUR Big Bang resulting from one graviton annihilation at extra dimensions??! Version of "ekpyrotic" ("pyrotechnic") universe

C vs Cbar

- Cancellations of Cbars – negative pressure (cf Chaplygin gas)

- Cancellation in vacuum; Pauli (divergent), Zel'dovich (finite)

- Flavour structure of pressure: DVMP!

Unphysical regions

- DIS : Analytical function – polynomial in $1/x_B$ if $1 \leq |x_B|$

$$H(x_B) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x) \frac{x^n}{x_B^{n+1}}$$

- DVCS – additional problem of analytical continuation of $H(x,\xi)$
- Solved by using of Double Distributions Radon transform

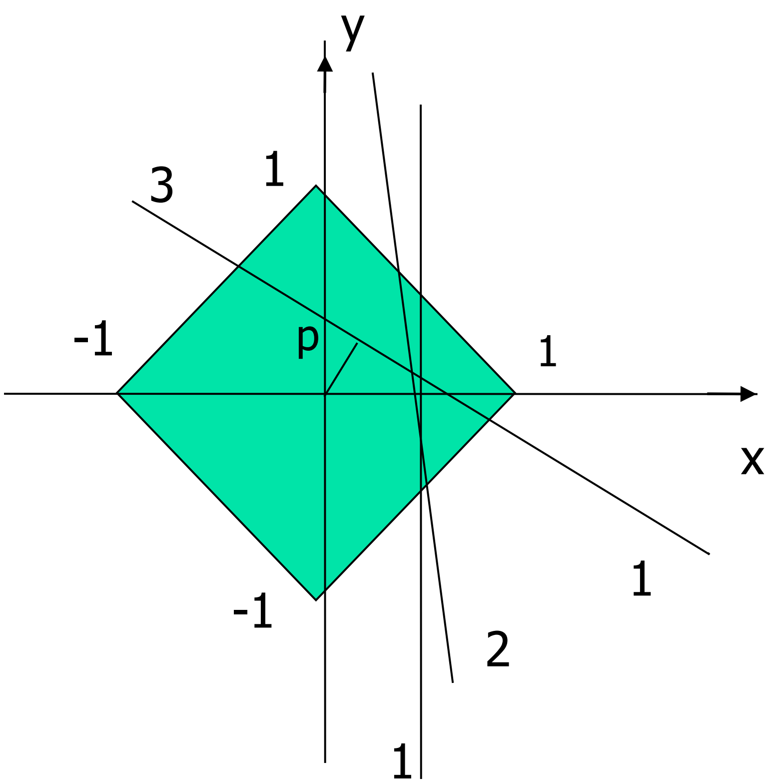
$$H(z,\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy (F(x,y) + \xi G(x,y)) \delta(z - x - \xi y)$$

Double distributions and their integration

- Slope of the integration line-skewness
- Kinematics of DIS: $\xi = 0$

  ("forward") - vertical line (1)
- Kinematics of DVCS: $\xi < 1$

  - line 2
- Line 3: $\xi > 1$ unphysical region - required to restore DD by inverse Radon transform: tomography

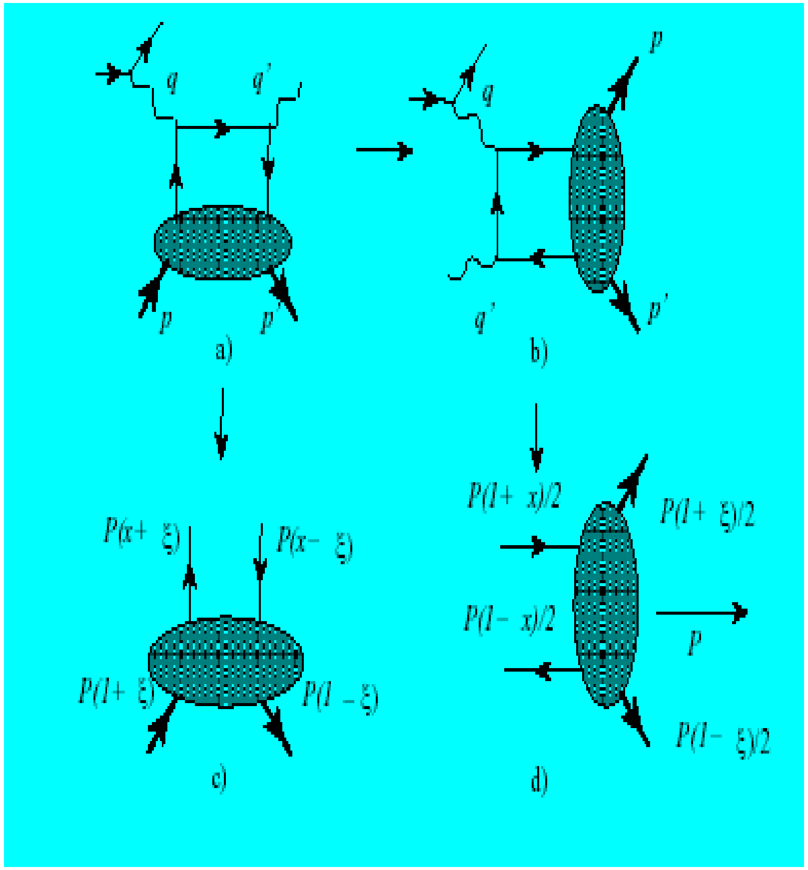


$$f(x,y) = -\frac{1}{2\pi^2}\int_0^\infty \frac{dp}{p^2}\int_0^{2\pi} d\phi |cos\phi| (H(p/cos\phi + x + ytg\phi, tg\phi) - H(x + ytg\phi, tg\phi)) =$$

$$= -\frac{1}{2\pi^2}\int_{-\infty}^\infty \frac{dz}{z^2}\int_{-\infty}^\infty d\xi (H(z + x + y\xi, \xi) - H(x + y\xi, \xi))$$

Crossing for DVCS and GPD

- DVCS -> hadron pair production in the collisions of real and virtual photons
- GPD -> Generalized Distribution Amplitudes
- Duality between s and t channels (Polyakov,Shuvaev, Guzey, Vanderhaeghen)



GDA -> back to unphysical regions for DIS and DVCS

- Recall DIS

$$H(x_B) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x) \frac{x^n}{x_B^{n+1}}$$

- Non-positive powers of x_B

- DVCS

$$H(\xi) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x,\xi) \frac{x^n}{\xi^{n+1}}$$

- Polynomiality (general property of Radon transforms): moments - integrals in x weighted with x^n - are polynomials in $1/\xi$ of power n+1
- As a result, analyticity is preserved: only non-positive powers of ξ appear

Holographic property - II

- Directly follows from double distributions

$$H(z,\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy (F(x,y) + \xi G(x,y))\delta(z - x - \xi y)$$

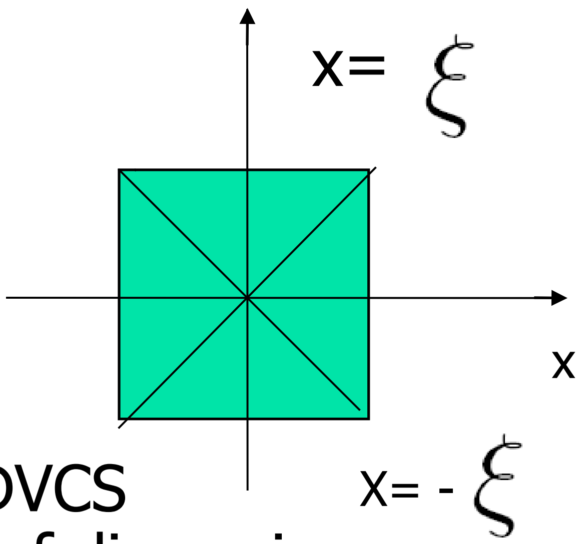
- Constant is the SUBTRACTION one - due to the (generalized) Polyakov-Weiss term G(x,y)

$$\Delta\mathcal{H}(\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy \frac{G(x,y)}{1-y}$$

$$= \int_{-\xi}^{\xi} dx \frac{D(x/\xi)}{x - \xi + i\epsilon} = \int_{-1}^{1} dz \frac{D(z)}{z-1} = const$$

Holographic property - III

- 2-dimensional space -> 1-dimensional section!
- Momentum space: any relation to holography in coordinate space ?!



- Strategy (now adopted) of GPD's
  studies: start at diagonals
  (through SSA due to imaginary part of DVCS amplitude) and restore by making use of dispersion relations + subtraction constants

Pressure in hadron pairs production

- Back to GDA region
- -> moments of H(x,x) - define the coefficients of powers of cosine!– 1/
- Higher powers of cosine ξ in t-channel – threshold in s -channel
- Larger for pion than for nucleon pairs because of less fast decrease at x ->1
- Stability defines the sign of GDA and (via soft pion theorem) DA: work in progress

$$\mathscr{H}(\xi) = -\int_{-1/\xi}^{1/\xi} dx \sum_{n=0}^{\infty} H(x,\xi) \frac{x^n}{\xi^{n+1}}$$

$$= -\int_{-1/\xi}^{1/\xi} dx \sum_{n=0}^{\infty} H(x,x) \frac{x^n}{\xi^{n+1}} + \Delta\mathscr{H}.$$

Analyticity of Compton amplitudes in energy plane (Anikin,OT'07)

- Finite subtraction implied

$$\mathrm{Re}\mathcal{A}(\nu, Q^2) = \frac{\nu^2}{\pi}\mathcal{P}\int_{\nu_0}^{\infty}\frac{d\nu'^2}{\nu'^2}\frac{\mathrm{Im}\mathcal{A}(\nu', Q^2)}{(\nu'^2-\nu^2)} + \Delta \qquad \Delta = 2\int_{-1}^{1} d\beta \frac{D(\beta)}{\beta - 1}$$

$$\Delta^p_{\mathrm{CQM}}(2) = \Delta^n_{\mathrm{CQM}}(2) \approx 4.4, \qquad \Delta^p_{\mathrm{latt}} \approx \Delta^n_{\mathrm{latt}} \approx 1.1$$

- Numerically close to Thomson term for real proton (but NOT neutron) Compton Scattering!

- Duality (sum of squares vs square of sum; proton: 4/9+4/9+1/9=1)?!

Loss of stability?

- D=0 -> extra node required (cf tensor distribution - Efremov,OT- mechanical analogy – c.m. and c.i.)
- Smooth decrease – two extra nodes
- ++++------------------
- +++++++-------+++++--------------
- J=2 (Talk of Barbara Pasquini, comment by Maxim – zeros of Bessel functs?!)

BACKUP

Is D-term independent?

- Fast enough decrease at large energy ->

$$\mathrm{Re}\,\mathcal{A}(\nu) = \frac{\mathcal{P}}{\pi}\int_{\nu_0}^{\infty} d\nu'^2 \frac{\mathrm{Im}\,\mathcal{A}(\nu')}{\nu'^2 - \nu^2} + \mathrm{C}_0$$

$$\mathrm{C}_0 = \Delta - \frac{\mathcal{P}}{\pi}\int_{\nu_0}^{\infty} d\nu'^2 \frac{\mathrm{Im}\,\mathcal{A}(\nu')}{\nu'^2}$$

$$= \Delta + \mathcal{P}\int_{-1}^{1} dx \frac{H^{(+)}(x,x)}{x}.$$

- FORWARD limit of Holographic equation

$$\Delta = \mathcal{P}\int_{-1}^{1} dx \frac{H^{(+)}(x,0) - H^{(+)}(x,x)}{x}$$

$$= 2\mathcal{P}\int_{-1}^{1} dx \frac{H(x,0) - H(x,x)}{x},$$

$$\mathrm{C}_0(t) = 2\mathcal{P}\int_{-1}^{1} dx \frac{H(x,0,t)}{x}$$

“D – term” 30 years before…

- Cf Brodsky, Close, Gunion’72 (seagull ~ pressure) – but NOT DVMP
- D-term – a sort of renormalization constant
- May be calculated in effective theory if we know fundamental one
- OR
- Recover through special regularization procedure (D. Mueller)?

Vector mesons and EEP

- J=1/2 -> J=1. QCD SR calculation of Rho's AMM gives g close to 2.

- Maybe because of similarity of moments
- $g-2=\langle E(x)\rangle$; $B=\langle xE(x)\rangle$
- Directly for charged Rho (combinations like p+n for nucleons unnecessary!). Not reduced to non-extended EP:

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

EEP and Sivers function

- Sivers function – process dependent (effective) one
- T-odd effect in T-conserving theory- phase
- FSI – Brodsky-Hwang-Schmidt model
- Unsuppressed by M/Q twist 3
- Process dependence- colour factors
- After Extraction of phase – relation to universal (T-even) matrix elements

EEP and Sivers function -II

- Qualitatively similar to OAM and Anomalous Magnetic Moment (talk of S. Brodsky)
- Quantification : weighted TM moment of Sivers PROPORTIONAL to GPD E (OT'07, **hep-ph/0612205**):

$$x f_T(x) : xE(x)$$

- Burkardt SR for Sivers functions is then related to Ji's SR for E and, in turn, to Equivalence Principle

$$\sum_{q,G} \int dx\, x f_T(x) = \sum_{q,G} \int dx\, x E(x) = 0$$

EEP and Sivers function for deuteron

- EEP - smallness of deuteron Sivers function
- Cancellation of Sivers functions – separately for quarks (before inclusion gluons)
- Equipartition + small gluon spin – large longitudinal orbital momenta (BUT small transverse ones –Brodsky, Gardner)

Another relation of Gravitational FF and NP QCD (first reported at 1992: **hep-ph/9303228**)

- BELINFANTE (relocalization) invariance :

decreasing in coordinate –

$$M^{\mu,\nu\rho} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} J^5_{S\sigma} + x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu}$$

smoothness in momentum space

$$M^{\mu,\nu\rho} = x^\nu T^{\mu\rho}_B - x^\rho T^{\mu\nu}_B$$

- Leads to absence of massless pole in singlet channel – U_A(1)

$$\epsilon_{\mu\nu\rho\alpha} M^{\mu,\nu\rho} = 0.$$

- Delicate effect of NP QCD

$$(g_{\rho\nu} g_{\alpha\mu} - g_{\rho\mu} g_{\alpha\nu})\partial^\rho (J^\alpha_{5S} x^\nu) = 0$$

- Equipartition – deeply related to relocalization invariance by QCD evolution

$$q^2 \frac{\partial}{\partial q^\alpha} \langle P|J^\alpha_{5S}|P+q\rangle = (q^\beta \frac{\partial}{\partial q^\beta} - 1) q_\gamma \langle P|J^\gamma_{5S}|P+q\rangle$$

$$\langle P,S|J^5_\mu(0)|P+q,S\rangle = 2MS_\mu G_1 + q_\mu (Sq) G_2,$$

$$q^2 G_2|_0 = 0$$