T-odd distributions, Formfactors and Duality

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Oleg Teryaev

JINR

Outline

- Duality between quarks and hadrons and between quarks and quarks (= various QCD factorization mechanisms)
- Single Spin Asymmetries in QCD - Sources of (I)FSI
- Non-universality of Sivers function: Colour correlations
- Sivers function and time-like formfactors
- Conclusions

Duality in QCD

- Quark-hadron (soliton ...)
- Various factorization mechanisms ("quark-quark" duality; "matching",...)-also talk of I. Anikin
- Single Spin Asymmetries: Sivers function (cf talk of I. Cherednikov)
- Dual to twist 3 correlations (small large pT)
- Time-like Formfactors – large x - important for lower energies/forward SSA (cf talk of K. Tanida)

Single Spin Asymmetries

Main properties:

– Parity: transverse polarization

– Imaginary phase – can be seen T-invariance or technically - from the imaginary i in the (quark) density matrix

Various mechanisms – various sources of phases

Phases in QCD

- QCD factorization – soft and hard parts-
- Phases form soft, hard and overlap
- Assume (generalized) optical theorem – phase due to on-shell intermediate states – positive kinematic variable (= their invariant mass)
- Hard: Perturbative (a la QED: Barut, Fronsdal

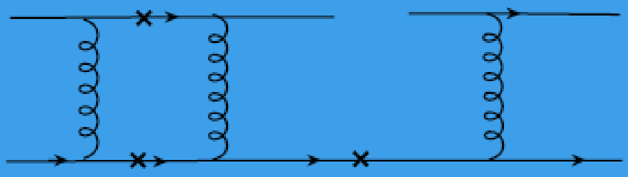
(1960):

Kane, Pumplin, Repko (78) Efremov (78)

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):

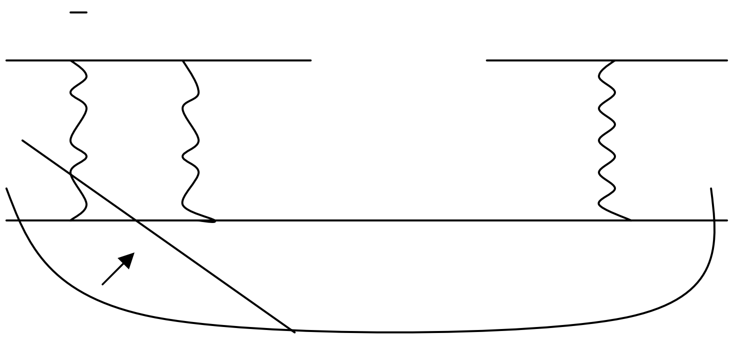


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

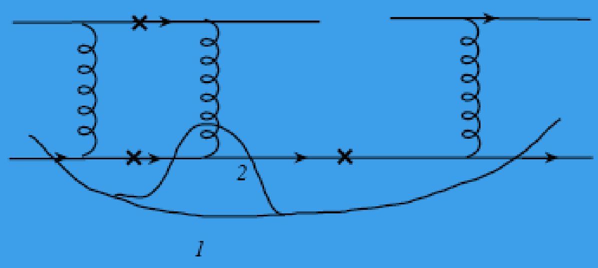
- Quarks – only from hadrons
- Various options for factorization – shift of SH separation (prototype of duality)



- New option for SSA: Instead of 1-loop twist 2 – Born twist 3: Efremov, OT (85, Ferminonc 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 $\rightarrow$ Born diagram
At Large distances - quark distribution $\rightarrow$ 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

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

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

Phases in QCD-Large distances in distributions

- Distributions: Sivers, Boer and Mulders – no positive kinematic variable producing phase
- QCD: Emerge only due to (initial of final state) interaction between hard and soft parts of the process
- Brodsky -Hwang-Schmidt model:the same SH interactions as twist 3 but non-suppressed by Q: Sivers function – leading (twist 2).
- Are they related?

5 ways from Sivers to twist 3

- Twist 3 DY - “Effective” or “non-universal” T-odd quark distribution from GP (Boer, Mulders, OT, 97)
- Moment of SF – GP (Boer, Mulders, Pijlman, 03)
- Explicit calculation of SIDVCS for Q >> P_T (OT, TRANSVERSITY-05) - compensation of 1/Q suppression by GP)
- Matching of perturbative SF and twist 3 for DY, SIDIS +... (Ji,Qiu,Vogelsang,Yuan, 06; Bachetta, Boer, Diehl,Mulders,08)
- SF at large P_T (Ratcliffe, OT, 07)-proof of Torino GPM modified by colour factors
- Follows general line of factorization – all UV to hard part. Also a way to QCD evolution (cf talks of I. Cherednikov, L. Gamberg)?!

What is “Leading” twist?

- Practical Definition - Not suppressed as M/Q
- However – More general definition: Twist 3 may be suppresses

as M/P_T

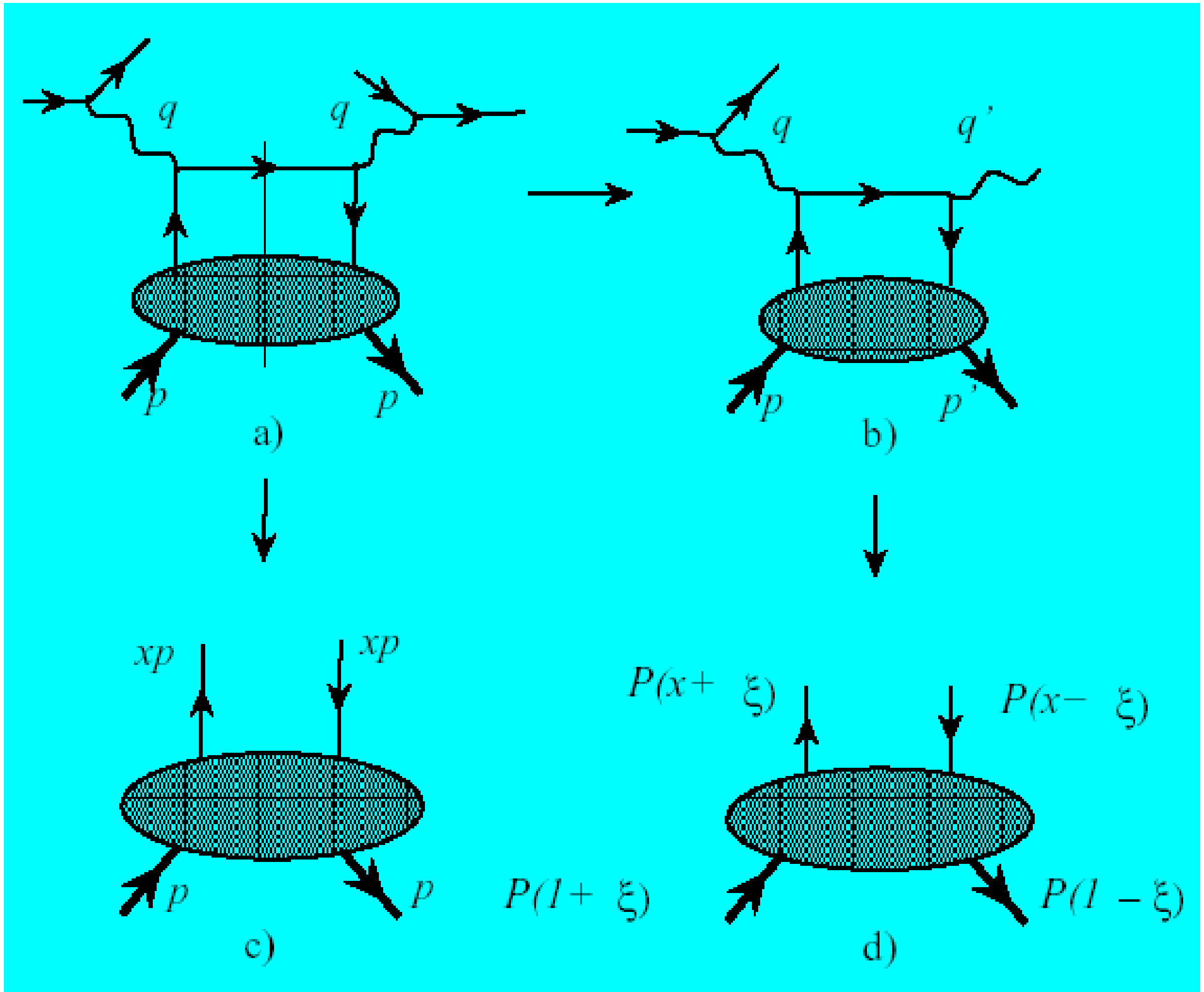
. Twist 3 may contribute at leading order

in 1/Q !

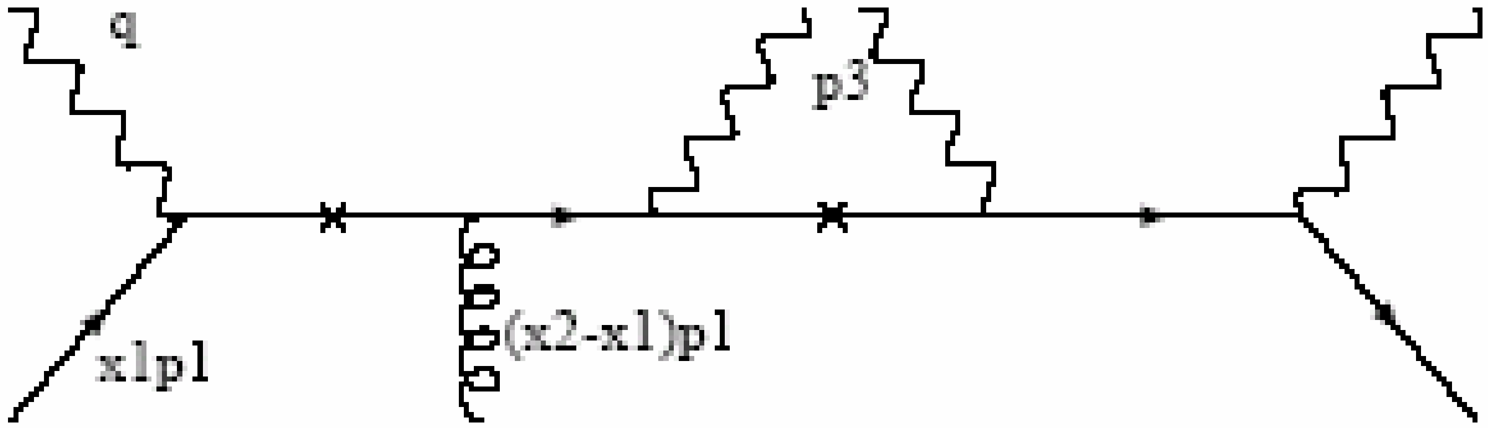
Does this happen indeed?? – Explicit calculation

for the case when $Q >> P_T$

Final Pion -> Photon: SIDIS -> SIDVCS (clean, easier than exclusive) - analog of DVCS



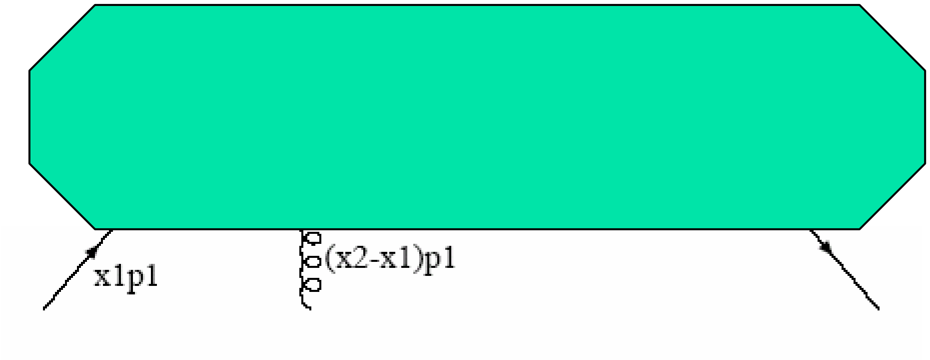
Twist 3 partonic subprocesses for SIDVCS



Real and virtual photons - most clean tests of QCD

- Both initial and final – real :Efremov, O.T. (85)
- Initial – quark/gluon, final - real : Efremov, OT (86, fermionic poles); Qui, Sterman (91, GLUONIC poles)
- Initial - real, final-virtual (or quark/gluon) – Korotkiian, O.T. (94)
- Initial –virtual, final-real: O.T., Srednyak (05; smooth transition from fermionic via hard to GLUONIC poles).

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 >> P_T>> M

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

Cross-sections at low transverse momenta:

$$d\sigma_{total} = f(x_{Bj}) 8Q^2 \frac{x_{Bj}^2(1+(1-y)^2)(1+(1-z)^2)}{y^2 z\delta} \quad (12)$$

$$d\sigma_{ax1x2} = b_A(x_{Bj}, x_2) 8M p_T \frac{x_{Bj}(1+(1-y)^2)(2-z)}{y^2(1-z)\delta} s_T sin(\phi_s^h) \quad (13)$$

$$d\sigma_{vx1x2} = b_V(x_{Bj}, x_2) 8M p_T \frac{x_{Bj}(1+(1-y)^2)(1+(1-z)^2)}{y^2 z(1-z)\delta} s_T sin(\phi_s^h) \quad (14)$$

$$d\sigma_{a0x2} = -b_A(0, x_2) 8M p_T \frac{x_{Bj}^2(2(1-y)(1-2z)+y^2(1-z))}{y^2 z^2 \delta} s_T sin(\phi_s^h)$$

(14) - non-suppressed for large Q if Gluonic pole exists=effective Sivers function; spin-dependent looks like unpolarized (soft gluon)

$$A \propto \frac{2M\, p_T \varphi_V(x_B)}{m_T^2 x_B q(x_B)} s_T \sin\phi_h^s$$

Other way - NP Sivers and gluonic poles at large PT (P.G. Ratcliffe, OT, **hep-ph/0703293**)

- Sivers factorized (general!) expression

$$d\Delta\sigma = \int d^2k_T dx\, f_S(x,k_T)\ \mathrm{Tr}[\gamma^\rho H(x,k_T)]\frac{\epsilon^{\rho s P k_T}}{M}$$

- Expand in kT = twist 3 part of Sivers

$$d\Delta\sigma = \int dx\, f_S(x,k_T)\ \mathrm{Tr}\left[\gamma^\rho \frac{\partial H(x,k_T=0)}{\partial k_T^\alpha} k_T^\alpha\right] \epsilon^{\rho s P k_T}$$

From Sivers to twist 3 - II

- Angular average : $\langle k_T^\mu k_T^\nu \rangle = -\frac{g_T^{\mu\nu}}{2} \langle k_T^2 \rangle$

$$g_T^{\mu\nu} = g^{\mu\nu} - P^\mu n^\nu - n^\mu P^\nu$$

- As a result $d\Delta\sigma = -M \int dx\, f_S^{(1)}(x)\, \mathrm{Tr}\left[\gamma^\rho \frac{\partial H(x, k_T = 0)}{\partial k_T^\alpha}\right]$

$$f_S^{(1)}(x) = \int d^2k_T\, f_S(x, k_T)\, \frac{k_T^2}{2M^2}.$$

$$(\epsilon^{\rho s P \alpha} - P^\alpha \epsilon^{\rho s P n})$$

- M in numerator - sign of twist 3. Higher moments – higher twists. KT dependent function – resummation of higher twists

From Sivers to gluonic poles - III

- Final step – kinematical identity

$$\epsilon^{\rho s P \alpha} = P^{\alpha} \epsilon^{\rho s P n} - P^{\rho} \epsilon^{\alpha s P n}$$

- Two terms are combined to one

$$d\Delta\sigma = M \int dx\, f_S^{(1)}(x)\ \mathrm{Tr}\left[\gamma \cdot P \frac{\partial H(x, k_T = 0)}{\partial k_T^{\alpha}}\right] \epsilon^{\alpha s P n}$$

- Key observation – exactly the form of Master Formula for gluonic poles (Koike et al, 2007)

Effective Sivers function

- Follows the expression similar to BMP

$$x f_S^{(1)}(x) = \sum C_i \frac{1}{2M} T_j(x,x),$$

- Up to Colour Factors !
- Defined by colour correlation between partons in hadron participating in (I)FSI
- SIDIS = +1; DY= -1: Collins sign rule
- Generally more complicated
- Factorization in terms of twist 3 but NOT SF

Colour correlations

- SIDIS at large pT : -1/6 for mesons from quark, 3/2 from gluon fragmentation (kaons?)
- DY at large pT: 1/6 in quark antiquark annihilation, - 3/2 in gluon Compton subprocess – Collins sign rule more elaborate – involve crossing of distributions and fragmentations - special role of PION DY (COMPASS).
- **Direct inclusive photons in pp   = – 3 / 2**
- Hadronic pion production – more complicated – studied for P-exponentials by Amsterdam group + VW
- IF cancellation – small EFFECTIVE SF
- Vary for different diagrams – modification of hard part
- FSI for pions from quark fragmentation

-1/6 x (non-Abelian Compton) +1/8 x (Abelian Compton)

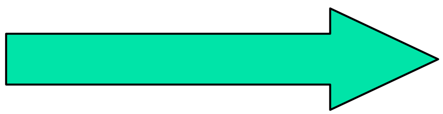
How to pass from high to low PT

- Hard poles in correlators (become soft at small PT – c.f. SIDVCS)
- Low pT – cannot distinguish fragmentation from quarks and gluons: 3/2-1/6 = 4/3 (Abelian)
- Strong transverse momentum dependence, very different for mesons from quark and gluon fragmentation

Colour flow

- Quark at large PT:-1/6

- Gluon at large PT : 3/2



- Low PT – combination of quark and gluon: 4/3 (absorbed to definition of Sivers function)

- Similarity to colour transparency phenomenon

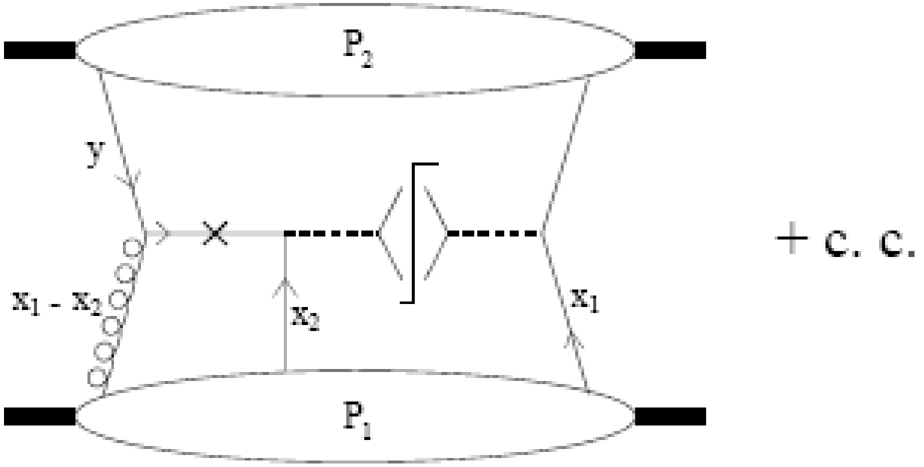
Sivers function and formfactors

- Relation between Sivers and AMM known on the level of matrix elements (Brodsky, Schmidt, Burkardt)
- Phase?
- Duality for observables?
- Solution: SSA in DY

SSA in DY

- TM integrated DY with one transverse polarized beam (cf talk of S. Melis)– unique SSA – gluonic pole (Hammon, Schaefer, OT)

$$A = g\,\frac{\sin 2\theta\ \cos\phi\left[T(x,x) - x\frac{dT(x,x)}{dx}\right]}{M\left[1+\cos^2\theta\right]q(x)}$$



SSA in exclusive limit

- Proton-antiproton – valence annihilation - cross section is described by Dirac FF squared

$$D = |G_M|^2\left(1+\cos^2\theta\right) + \frac{1}{\tau}|G_E|^2\sin^2\theta$$

$$G_M = F_1 + F_2\,,\qquad G_E = F_1 + \tau F_2\,.$$

$$\tau \equiv q^2/4m_B^2 > 1$$

- New kind of duality in time-like region –similar to Drell-Levy-Yan and Bloom-Gilman for DIS
- The same SSA due to interference of Dirac and Pauli FF's with a phase shift

$$\mathcal{P}_y = \frac{\sin 2\theta\,\mathrm{Im}G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau-1)\sin 2\theta\,\mathrm{Im}F_2^* F_1}{D\sqrt{\tau}}$$

- Exclusive : large Q^2 ~ 1/(1-x) limit; x -> 1 : T(x,x)/q(x) -> Im F2/F1 (cf talk of V. Punjabi)
- Sivers/unpolarized ~ $(1-x)^n$ n=1-2

CONCLUSIONS

- Dual mechanisms of SSA’s
- Effective SF – small in pp - factorization in terms of twist 3 only
- Large x – relation between SF, GP and time-like FF’s
- What do we test? – complementarity (in Bohr/Feynman sense) of various ways of description/degrees of freedom

Outlook (high energies)

- TMD vs UGPD
- T-odd UGPD?
- T-odd (P/O) diffractive distribiutions
- (analogs - also at small energies)
- Quark-hadron duality: description of gluon coupling to exotic objects – diffractive production

Relation of Sivers function to GPDs

- Qualitatively similar to Anomalous Magnetic Moment (Brodsky et al)
- Quantification : weighted TM moment of Sivers PROPORTIONAL to GPD E (**hep-ph/0612205**): $x f_T(x) \propto xE(x)$
- Burkardt SR for Sivers functions is now related to Ji SR for E and, in turn, to Equivalence Principle

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

How gravity is coupled to nucleons?

- Current or constituent quark masses ?– neither!
- Energy momentum tensor - like electromagnertic current describes the coupling to photons

Equivalence principle

- Newtonian – “Falling elevator” – well known and checked
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’) – not yet checked
- Anomalous gravitomagnetic moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way

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 – similar t-dependence to EM FF

Electromagnetism vs Gravity

- 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

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

$$\sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle = 2 P^\mu P^\nu$$

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

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

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

- Mass as charge – equivalence principle

Gravitomagnetism

- Gravitomagnetic field – action on spin – ½ from $M = \frac{1}{2}\sum_{q,G} \langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$

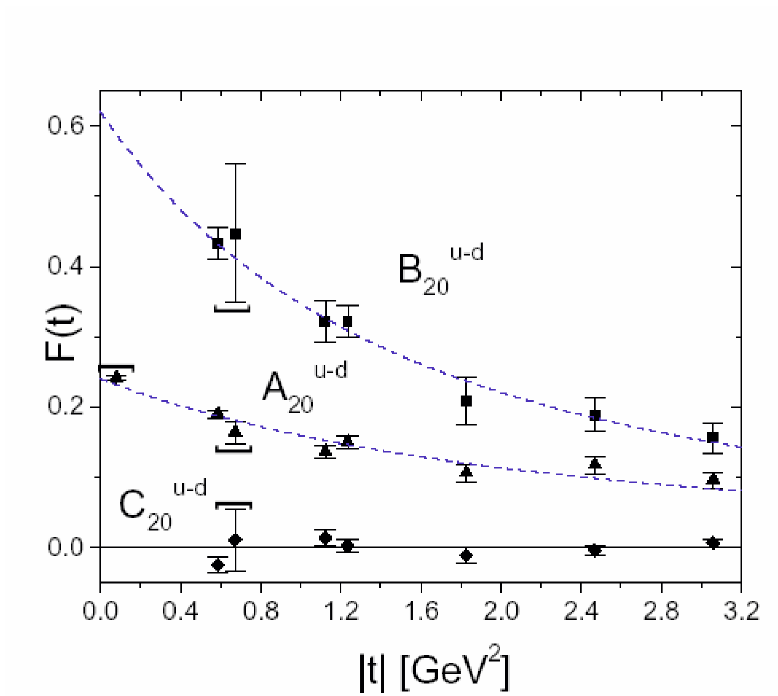
  $\vec{H}_J = \frac{1}{2} rot \vec{g};\ \vec{g}_i \equiv g_{0i}$ spin dragging twice smaller than EM
- Lorentz force – similar to EM case: factor ½ cancelled with 2 from $h_{00} = 2\phi(x)$
  Larmor frequency same as EM $\vec{H}_L = rot \vec{g}$
- Orbital and Spin momenta dragging – the same - Equivalence principle $\omega_J = \frac{\mu_G}{J} H_J = \frac{H_L}{2} = \omega_L$

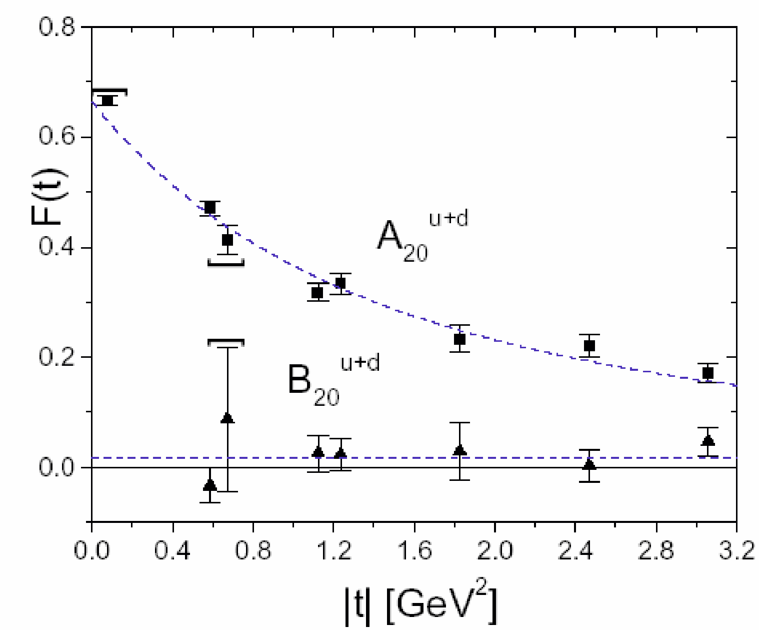
Sivers function and Extended Equivalence principle

- Second moment of E – zero SEPARATELY for quarks and gluons –only in QCD beyond PT (OT, 2001) - supported by lattice simulations etc.. ->
- Gluon Sivers function is small! (COMPASS, STAR, Brodsky&Gardner)
- BUT: gluon orbital momentum is NOT small: total – about 1/2, if small spin – large (longitudinal) orbital momentum
- Gluon Sivers function should result from twist 3 correlator of 3 gluons: remains to be proved!

Generalization of Equivalence principle

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





CONCLUSIONS

- Sivers and other TMD functions contain infinite tower of twists starting from 3 – special role of moments
- Colour charge of initial/final partons crucial – NO factorization in naive sense

$\sum \int dx \qquad \bar{g}_2$

- Transverse momentum dependence of Sivers SSA in SIDIS and DY (PAX) is a new sensitive test of QCD
- Relation of Sivers function to twist 3 in DIS: Reasonable magnitude, but problems with flavor dependence.Bochum results with suppressed singlet twist 3 supported!
- Relation of Sivers to GPD's – link to Nucleon Spin and Equivalence Principle
- Problems: evolution (no WW for Sivers) and SR from twist 3.