Theory - round table (exclusive DY, GPDs)

Oleg Teryaev
JINR, Dubna

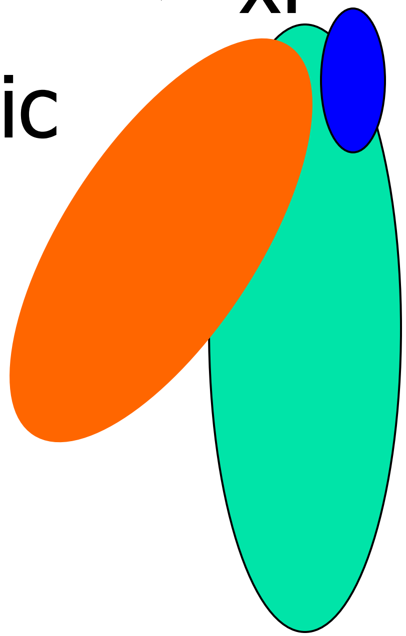
Why exclusive limits of DY are interesting?

- Possibility to study the inclusive-exclusive transition region and duality
- Access to the shape of pion Distribution Amplitude (simplest case of GPDs) – important because of BABAR puzzle and possible violation of (collinear) actorization due to flat DA (Radyushkin, Polyakov)
- Coherence of COMPASS program – study of GPDs in very different processes (crossing and analyticity in QCD)
- Theoretical interplay: TMDs <-> GPDs
- Similarity in theoretical approaches

Exclusive limits for DY

-
- pdf's → (Q)elastic
-
- QT

xF GPD's

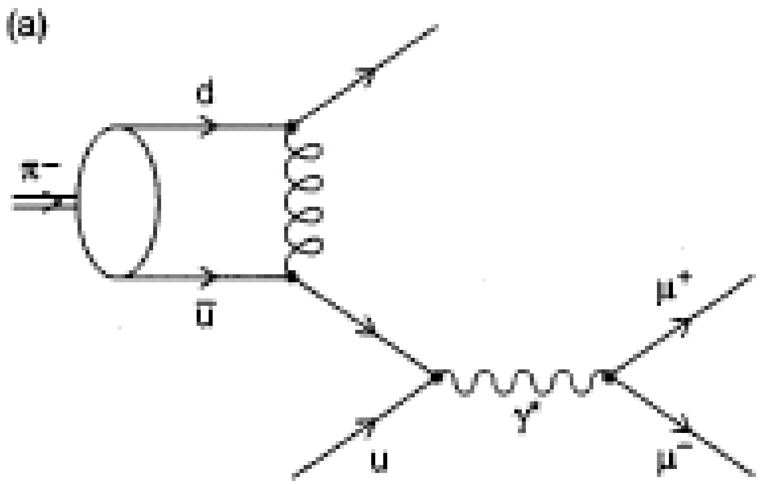


DA

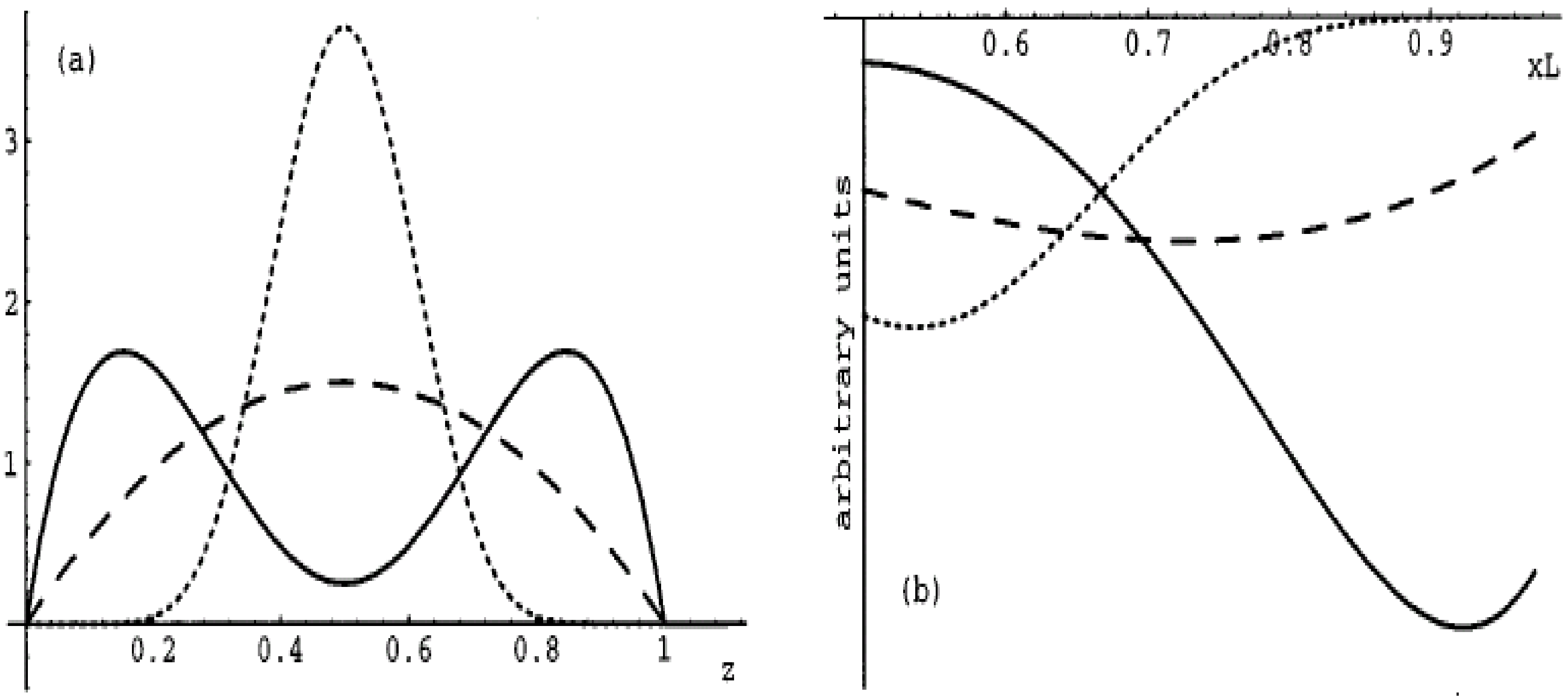
Summed TDAs

- Low invariant mass – various resonances (and continuum) may contribute
- Same coefficient functions -> same scaling - added incoherently
- Similar situation -> in 2 vetor mesons productions at L3 – various GDA’s squared added (Anikin,Pire,OT)

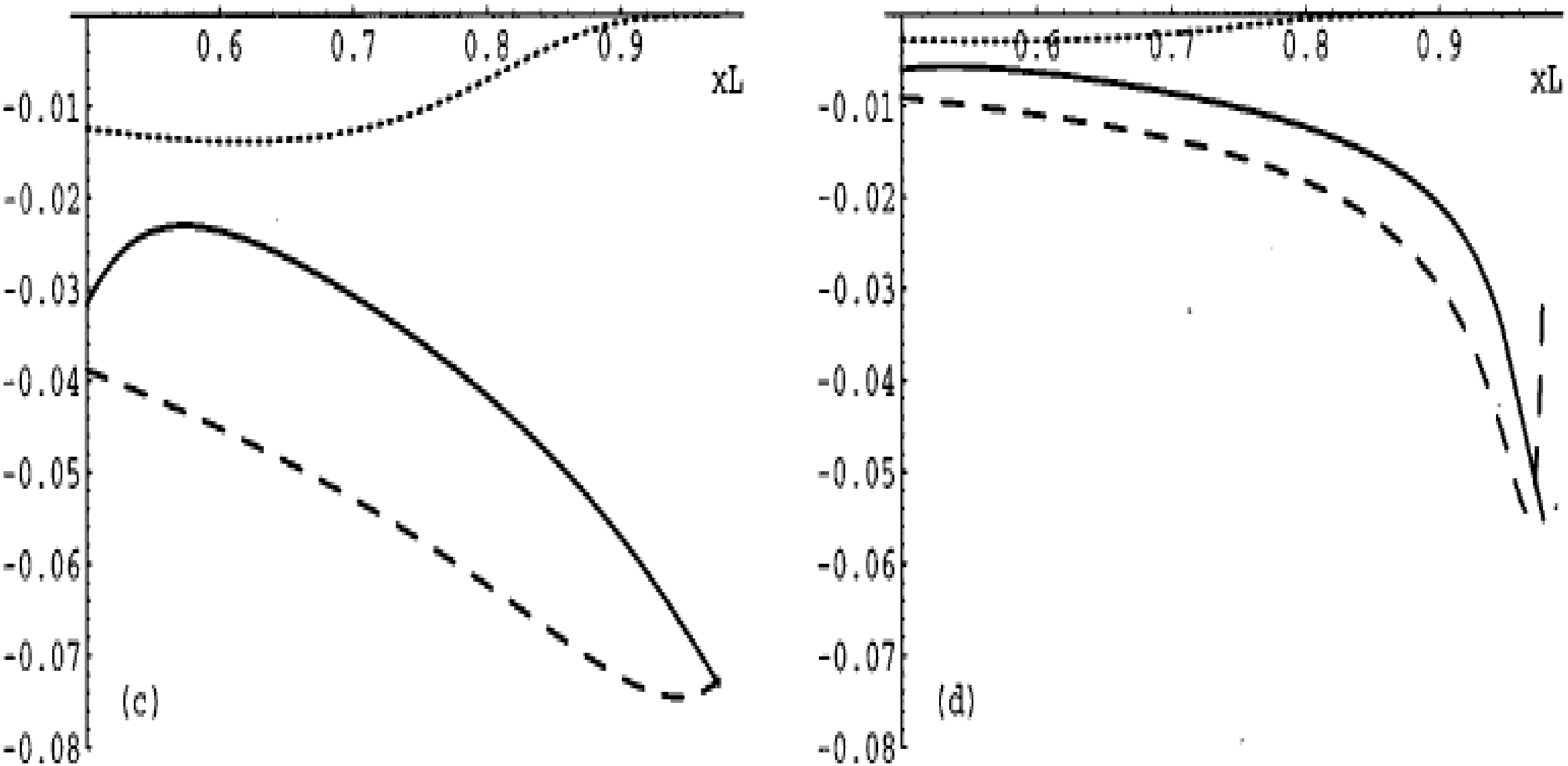
Pion Light-cone Distribution in pion-(q)proton scattering



Models for light-cone distributions and angular-weighted x-sections (Brandenburg, Mueller, OT; Bakulev,Stefanis,OT)



Size of coefficients in angular distributions

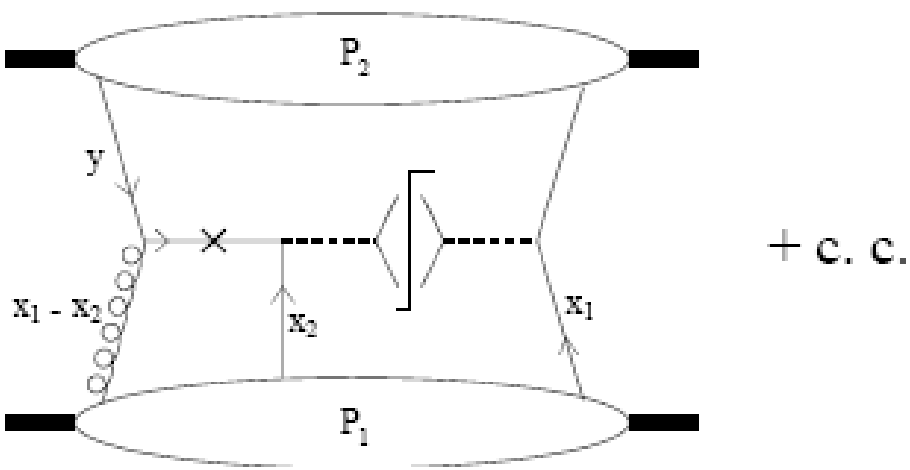


DA@COMPASS?

- Suppression (~QT/Q) of most pure longitudinal (Pire-Ralston) SSA – DA for transverse polarization?
- Transition pdf <-> DA?
- DA in angular distribution for unpolarized target – how flat DA works?
- Pion exclusive electroproduction – flat DA – is similarity with BABAR behaviour observable?!

Duality for SSA in DY

- TM integrated DY with one transverse polarized beam (– unique SSA – gluonic pole (Hammon, Schaefer, OT)

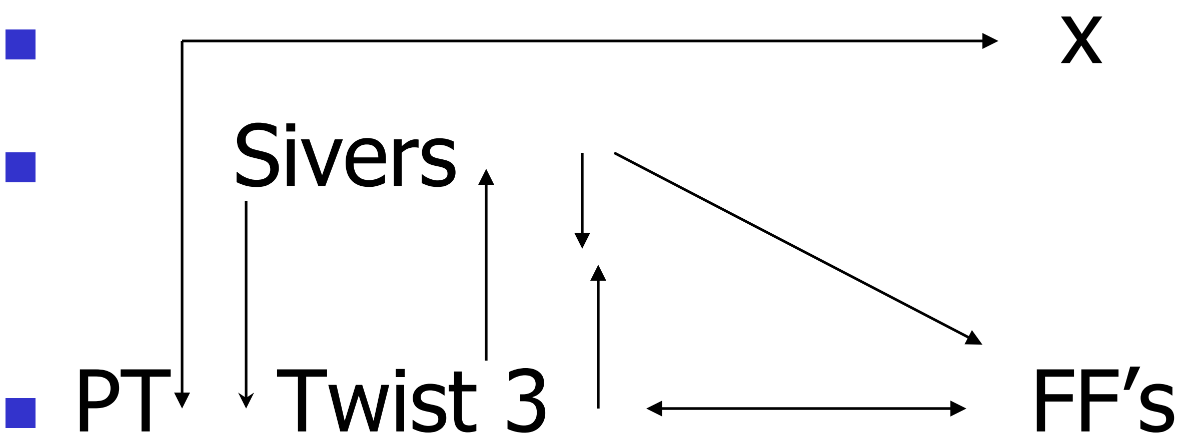


$$A = g\,\frac{\sin 2\theta\ \cos\phi\left[T(x,x) - x\frac{dT(x,x)}{dx}\right]}{M\left[1+\cos^2\theta\right]q(x)}$$

SSA in exclusive limit

- Proton-antiproton – valence annihilation - cross section is described by Dirac FF squared
- The same SSA due to interference of Dirac and Pauli FF's with a phase shift
- Exclusive large energy limit; x -> 1 : T(x,x)/q(x) -> Im F2/F1

Kinematical domains for SSA's



Discussions

- GPDs – Bernard Pire
- Transition to exclusive – Andrea Bianconi

Azimuthal Asymmetries

Sensitive test of QCD – reflect the existence

of natural scattering PLANE

May be T-odd (talks of A.Efremov, A. Prokudin, S, Melis) and T-EVEN

Important case: Drell-Yan process

- Angular distribution (leptons c.m. frame):

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \sim 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi \, .$$

- Lam –Tung relation (sum rule)

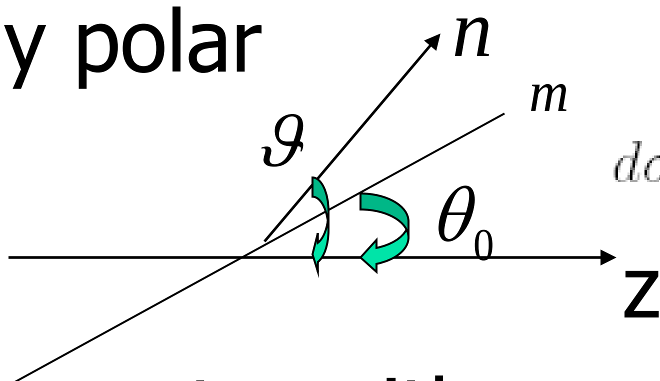
$$1 - \lambda - 2\nu = 0$$

Status of Lam-Tung relation

- Holds at LO and (approximately) at NLO QCD
- violated by
- higher twists (Brodsky et al.),
- correlations of T-odd distributions(Boer),
- entanglement of quarks in QCD vacuum (Nachtmann)
- (and EXPERIMENTALLY).
- Physical origin?!

Kinematic azimuthal asymmetry from polar one

Only polar



$$d\sigma \propto 1+\lambda_0(\vec{n}\vec{m})^2 = 1+\lambda_0\cos^2\theta_{nm}^2$$

asymmetry with respect to m!

$$\cos\theta_{nm} = \cos\theta\cos\theta_0 + \sin\theta\sin\theta_0\cos\phi$$ - azimuthal

angle appears with new

$$\lambda = \lambda_0\frac{2-3\sin^2\theta_0}{2+\lambda_0\sin^2\theta_0}$$

$$\nu = \lambda_0\frac{2sin^2\theta_0}{2+\lambda_0\sin^2\theta_0}$$

Generalized Lam-Tung relation

- Relation between coefficients (high school math sufficient!)

$$\lambda_0 = \frac{\lambda + \frac{3}{2}\nu}{1 - \frac{1}{2}\nu}$$

- Reduced to standard LT relation for transverse polarization (λ_0 =1)
- LT - contains two very different inputs: kinematical asymmetry+transverse polarization

How realistic is "m-model"?- averaging procedure

- Theorem for averages

$$\frac{\int d\vec{x}\Delta\sigma(\vec{x})}{\int d\vec{x}\sigma(\vec{x})} = \frac{\Delta\sigma(\vec{x}_0)}{\sigma(\vec{x}_0)}$$

- Convenient tool for asymmetries analysis (e.g. Collins suppression with respect to Sivers – talks of A. Prokudin, S. Melis)
- For N-dimesinsional integration – N-1-dimensional "orbits"

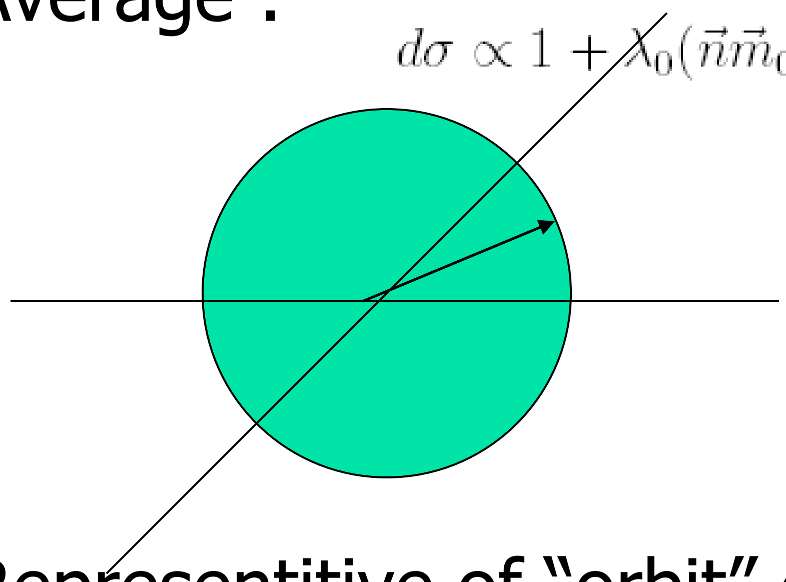
Application for average in semi-inclusive Drell-Yan

- Choose

$$d\sigma = \sigma \lambda_0 (\vec{n}\vec{m})^2$$

- Average :

$$d\sigma \propto 1 + \lambda_0 (\vec{n}\vec{m}_0)^2$$

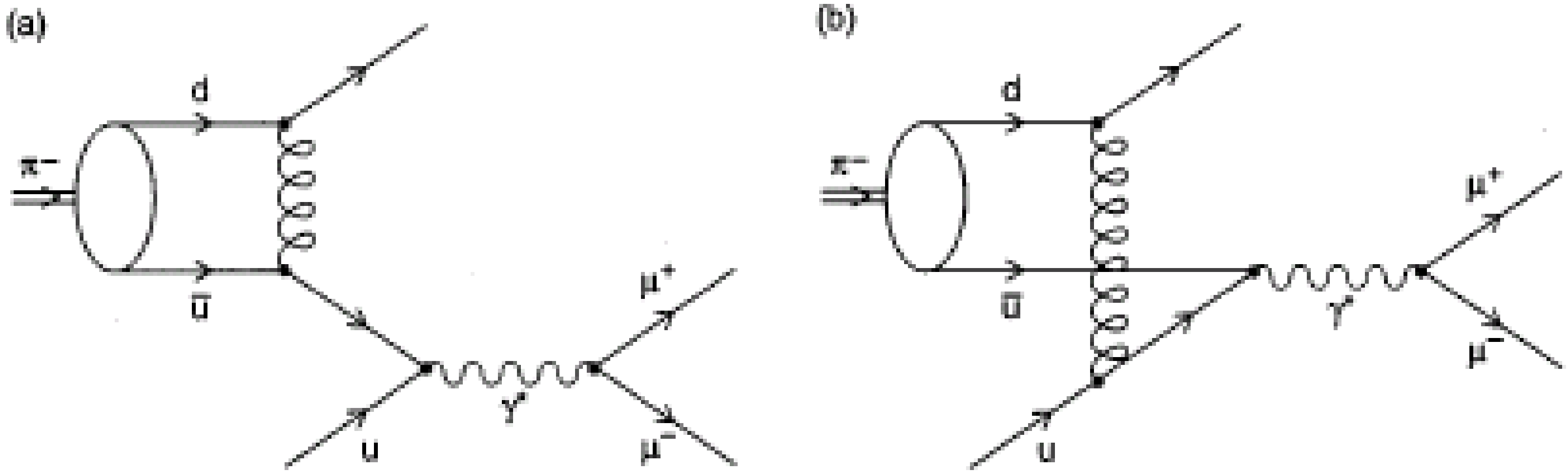


- Representitive of “orbit” crossing scattering plane – cannot depend on n

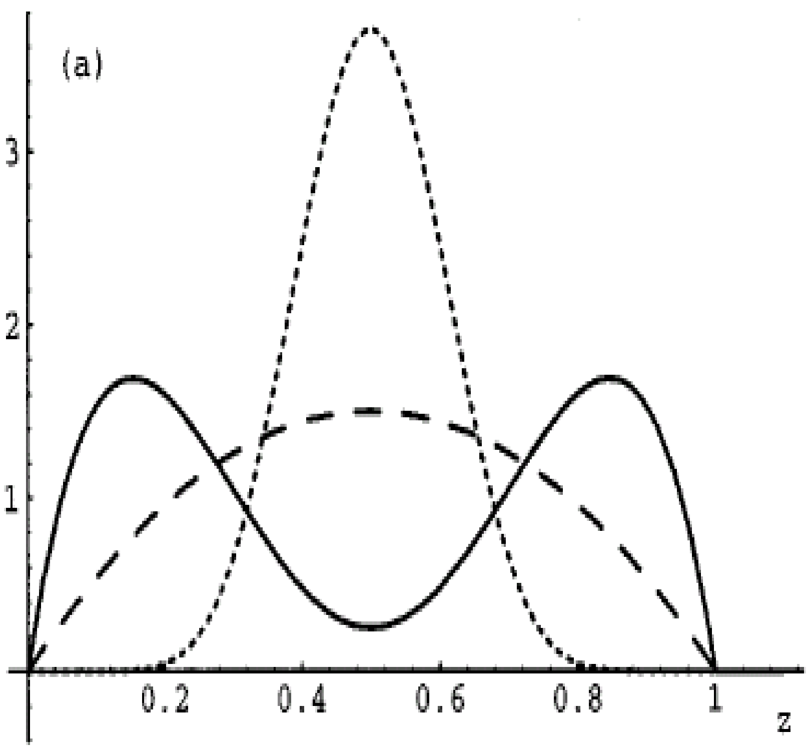
GLT relation -applicability

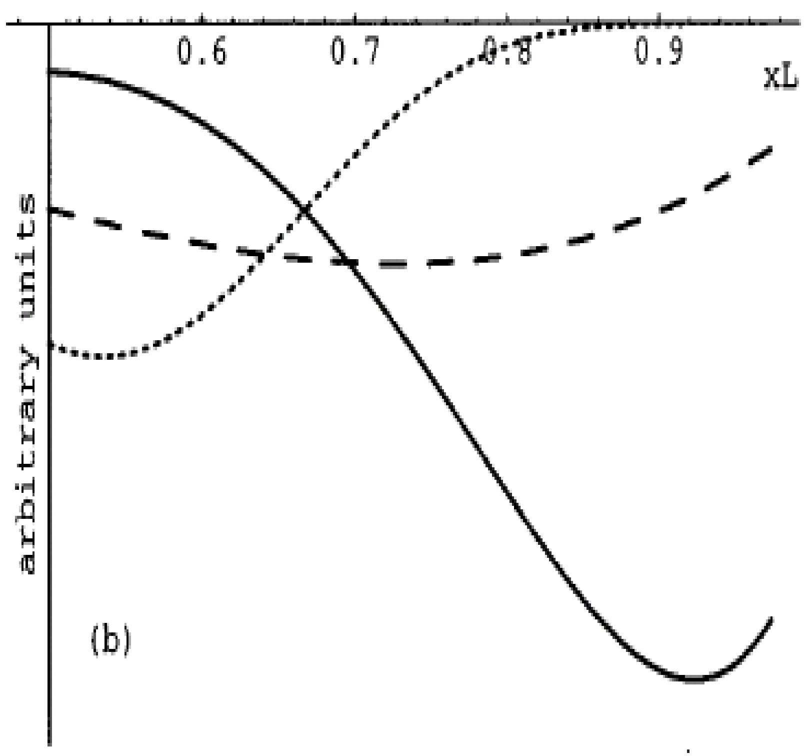
- Appears for KINEMATICAL asymmetry in semi-inclusive process (only one physical plane exists)
- Violated if there is azimuthal asymmetry already in the subprocess (with respect to m) – NLOQCD, HT.

Pion Light-cone Distribution in pion-(q)proton scattering



Models for light-cone distributions and angular-weighted x-sections





Further studies

- Various energy dependnece of various sources of LT violation – DY at COMPASS, LHC (CMS)
- HT-updated pion distribution (Bakulev, Stefanis, OT)
- Simultaneous analysis with spin-dependent azimuthal asymmetries
- Heavy-ion collisions

CONCLUSIONS

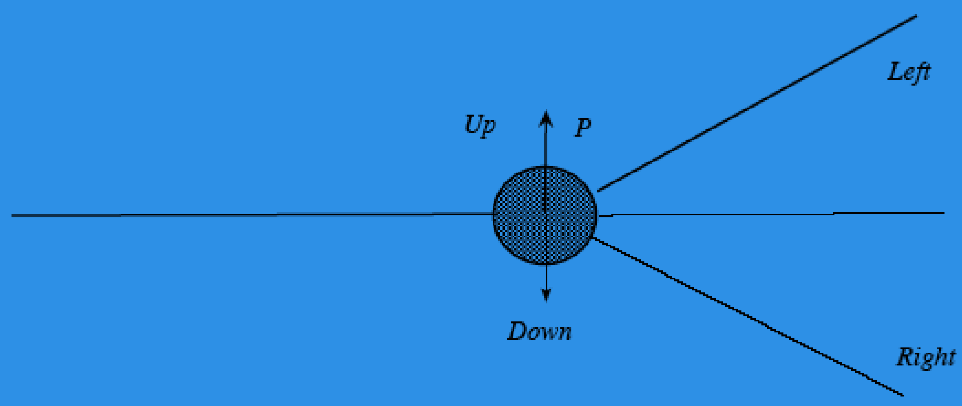
Lam – Tung relation – different inputs

Separating of their role – generalization

DY at very different energy scale,
Heavy-Ion collisions

Non-relativistic Example

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

Phases in QCD-I

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

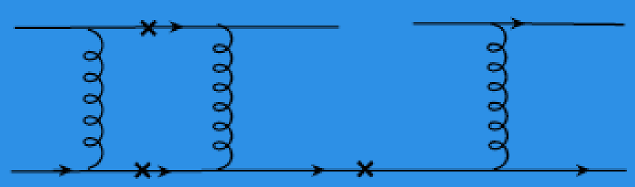
(1960), found at JLAB recently):

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):

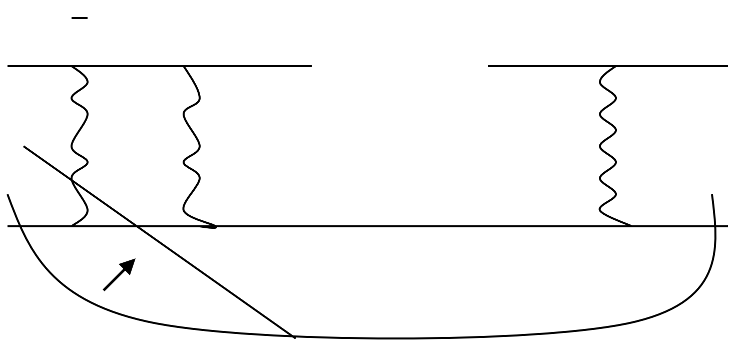


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

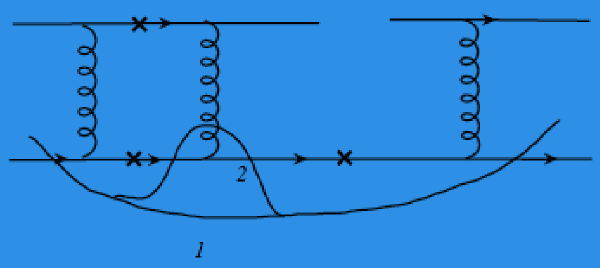
- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



- 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 fragmentation

- Non-perturbative - positive variable
- Jet mass-Fragmentation function: Collins(92);Efremov,Mankiewicz, Tornqvist (92),
- Correlated fragmentation: Fracture function: Collins (95), O.T. (98).

Phases in QCD-Large distances in distributions

- Distribution :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: “Effective” or “non-universal” SH interactions by physical gluons – Twist-3 (Boer, Mulders, OT, 97)
- Brodsky (talk) -Hwang-Schmidt(talk) model:the same SH interactions as twist 3 but non-suppressed by Q: Sivers function – leading (twist 2).

What is "Leading" twist?

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

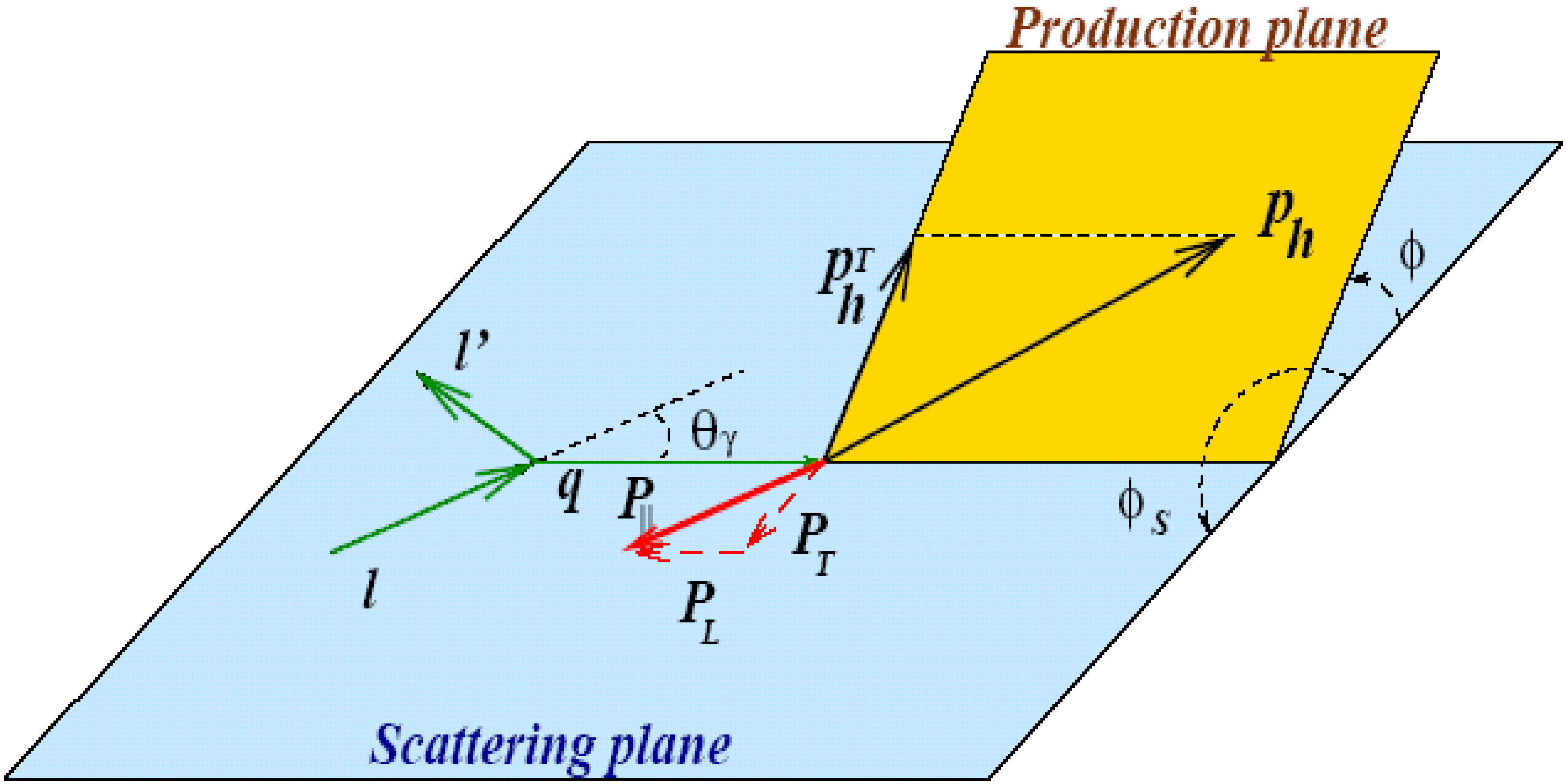
as M/P_T

. Twist 3 may contribute at leading order in 1/Q !

Does this happen indeed?? – Explicit calculation for the case when $Q >> P_T$

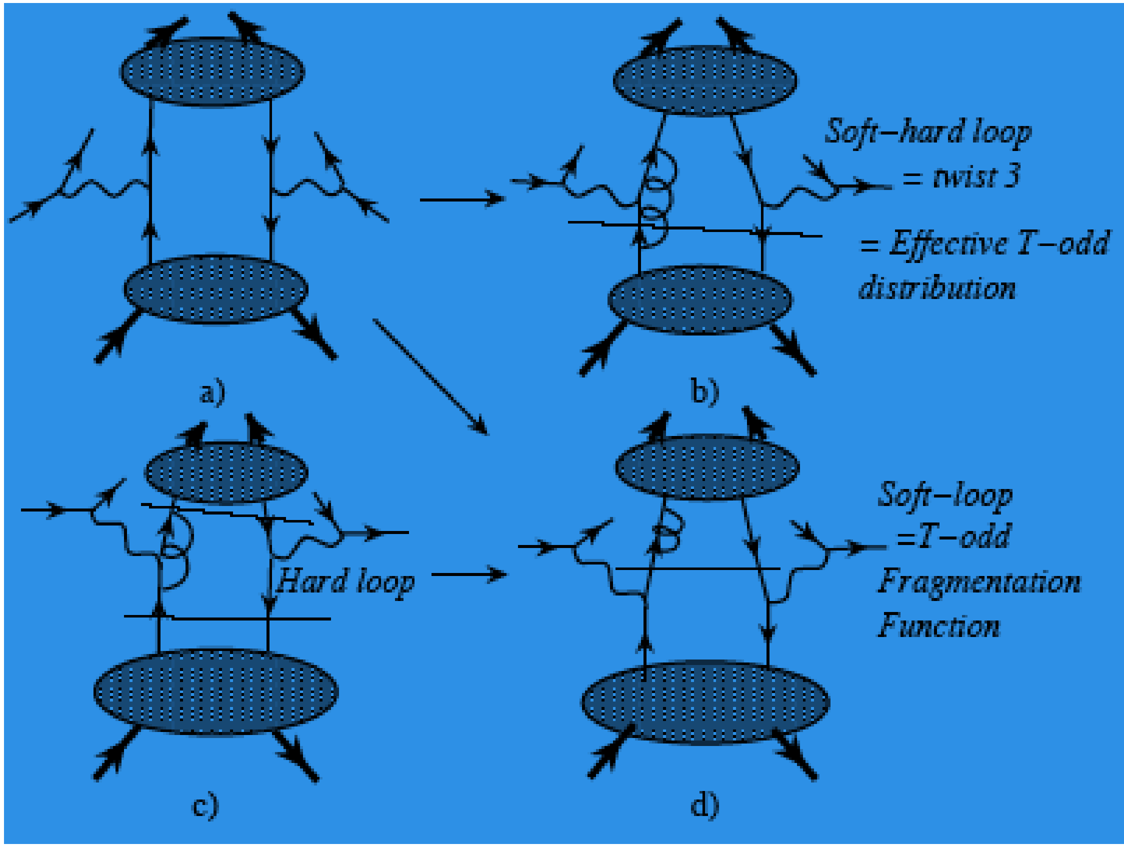
May be interesting for experimental studies

Test ground for SSA : Semi-Inclusive DIS - kinematics

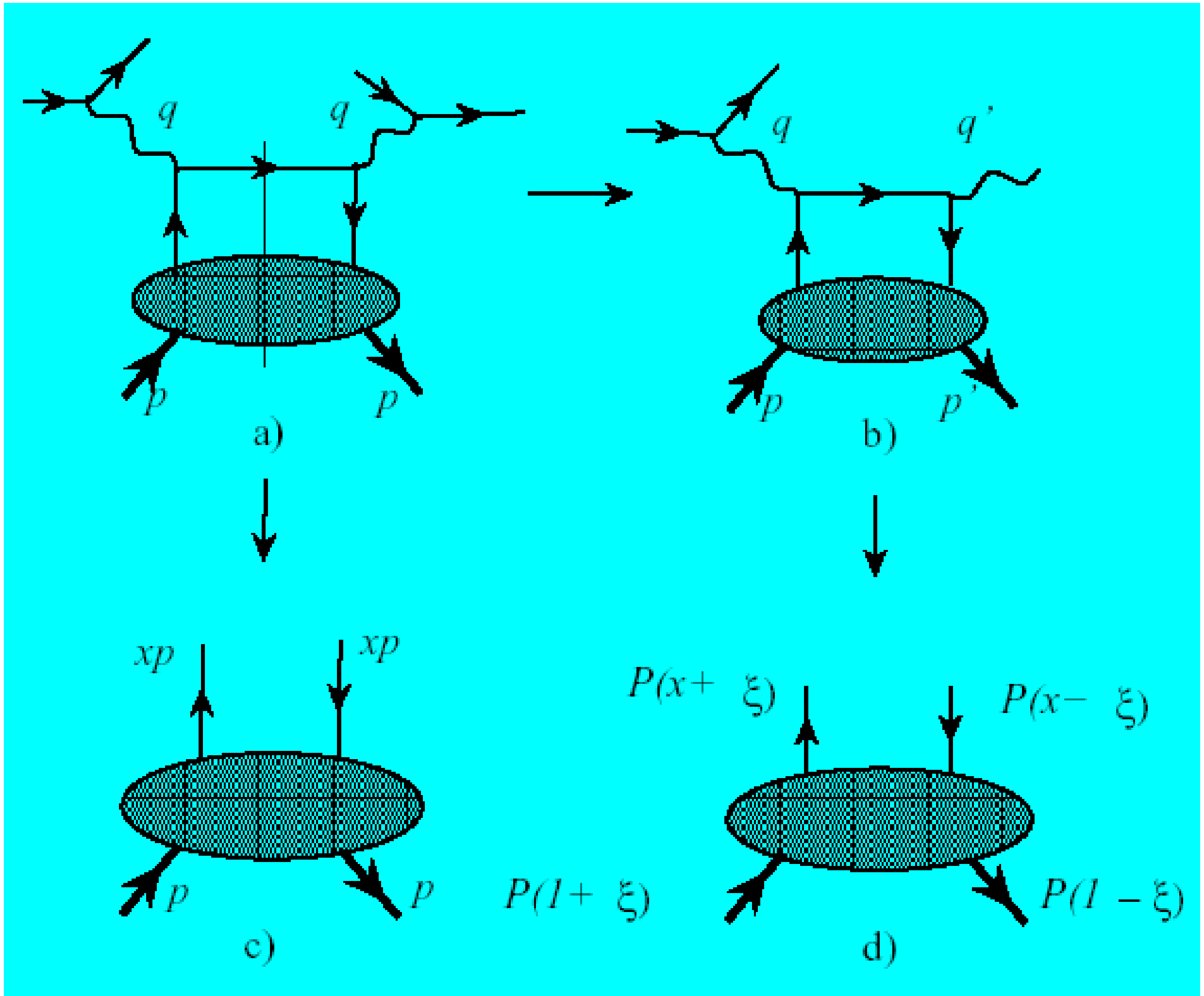


Sources of Phases in SIDIS

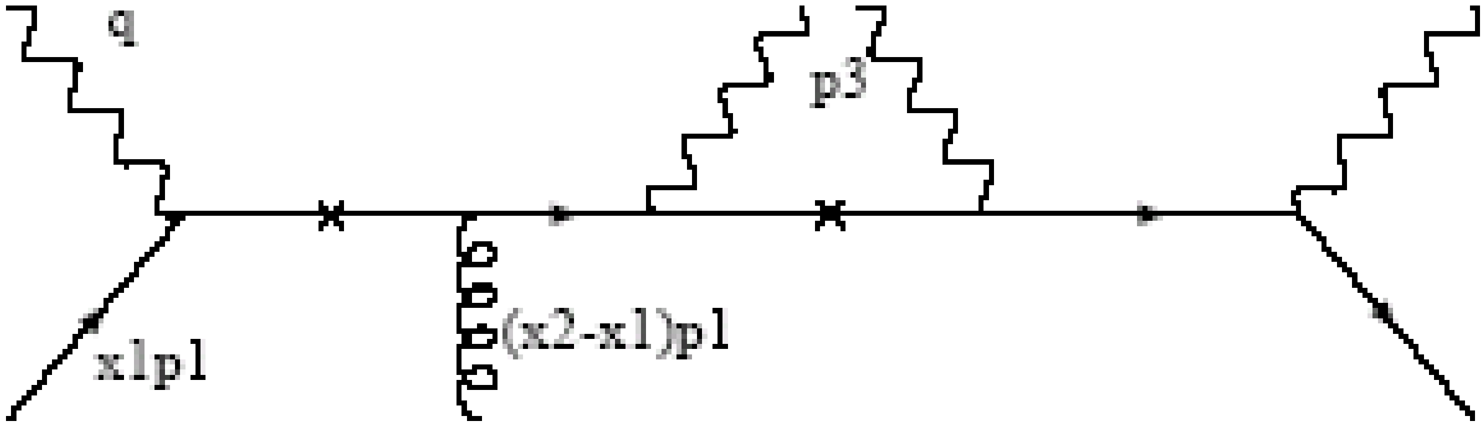
- a) Born - no SSA
- b) -Sivers (can be only effective)
- c) Perturbative
- d) Collins



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



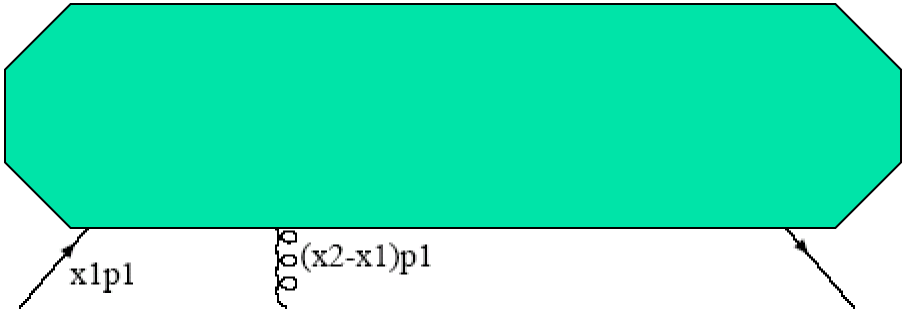
Twist 3 partonic subprocesses for SIDVCS



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, in preparation; smooth transition from fermionic 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:

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

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

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

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

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

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

Effective Sivers function

- Needs (soft) talk of large and short distances
- Complementary to gluonic exponential, when longitudinal (unsuppressed by Q, unphysical) gluons get the physical part due to transverse link (Belitsky, Ji, Yuan)
- We started instead with physical (suppressed as 1/Q) gluons, and eliminated the suppression for gluonic pole.
- Advantage: use of standard twist-3 factorization, describing also T-EVEN DOUBLE Asymmetries – key for relating single and double asymmetries

Twist 3 factorization (Efremov, OT '84, Ratcliffe,Qiu,Sterman)

- Convolution of soft (S) and hard (T) parts

$$d\sigma_s = \int dx_1 dx_2 \frac{1}{4} Sp[S_\mu(x_1,x_2)T_\mu(x_1,x_2)]$$

- Vector and axial correlators: define hard process for both double (g_2) and single asymmetries

$$T_\mu(x_1,x_2) = \frac{M}{2\pi}(\hat{p}_1\gamma^5 s_\mu b_A(x_1,x_2) - i\gamma_\rho\epsilon^{\rho\mu s p_1} b_V(x_1,x_2))$$

Twist 3 factorization -II

- Non-local operators for quark-gluon correlators

$$b_A(x_1,x_2) = \frac{1}{M}\int \frac{d\lambda_1 d\lambda_2}{2\pi} e^{i\lambda_1(x_1-x_2)+i\lambda_2 x_2} \langle p_1, s|\bar{\psi}(0)\hat{n}\gamma^5(D(\lambda_1)s)\psi(\lambda_2)|p_1, s\rangle,$$

$$b_V(x_1,x_2) = \frac{i}{M}\int \frac{d\lambda_1 d\lambda_2}{2\pi} e^{i\lambda_1(x_1-x_2)+i\lambda_2 x_2} \epsilon^{\mu s p_1 n} \langle p_1, s|\bar{\psi}(0)\hat{n}D_\mu(\lambda_1)\psi(\lambda_2)|p_1, s\rangle$$

- Symmetry properties (from T-invariance)

$$b_A(x_1,x_2) = b_A(x_2,x_1),\ \ b_V(x_1,x_2) = -b_V(x_2,x_1)$$

Twist-3 factorization -III

- Singularities

$$b_A(x_1,x_2) = \varphi_A(x_1)\delta(x_1-x_2) + b^r_A(x_2,x_1).$$

$$b_V(x_1,x_2) = \frac{\varphi_V(x_1)}{x_1-x_2} + b^r_V(x_1,x_2)$$

- Very different: for axial – Wandzura-Wilczek term due to intrinsic transverse momentum
- For vector-GLUONIC POLE (Qiu, Sterman '91) – large distance background

Sum rules

- EOM + n-independence (GI+rotational invariance) –relation to (genuine twist 3) DIS structure functions

$$\int_0^1 x^n \bar{g}_2(x)dx = \int_0^1 x^n(\frac{n}{n+1}g_1(x) + g_2(x))dx =$$

$$-\frac{1}{\pi(n+1)}\int_{|x_1,x_2,x_1-x_2|\leq 1} dx_1 dx_2 \sum_f e_f^2[\frac{n}{2}b_V(x_1,x_2)(x_1^{n-1} - x_2^{n-1}) +$$

$$b_A^r(x_1,x_2)\phi_n(x_1,x_2)], \quad \phi_n(x,y) = \frac{x^n - y^n}{x-y} - \frac{n}{2}(x^{n-1} - y^{n-1}), \quad n = 0, 2...$$

Sum rules -II

- To simplify – low moments

$$\int_0^1 x^2 \hat{g}_2(x)dx =$$
$$-\frac{1}{3\pi}\int_{|x_1,x_2,x_1-x_2|\le 1} dx_1 dx_2 \sum_f e_f^2 b_V(x_1,x_2)(x_1-x_2)$$

- Especially simple – if only gluonic pole kept:

$$\int_0^1 x^2 \bar{g}_2(x)dx = -\frac{1}{3\pi}\int_{|x_1,x_2,x_1-x_2|\le 1} dx_1 dx_2 \sum_f e_f^2 \varphi_V(x_1)$$
$$= -\frac{1}{3\pi}\int_{-1}^1 dx_1 \sum_f e_f^2 \varphi_V(x_1)(2-|x_1|)$$

Gluonic poles and Sivers function

- Gluonic poles – effective Sivers functions-Hard and Soft parts talk, but SOFTLY
- Supports earlier observations: Boer, Mulders, O.T. (1997); Boer, Mulders, Pijlman (2003).
- Implies the sum rule for effective Sivers function (soft=gluonic pole dominance assumed in the whole allowed x's region of quark-gluon correlator)

$$x f_T(x) = \frac{1}{2M} T(x,x) = \frac{1}{4} \phi_v(x)$$

$$\int_0^1 dx x^2 \bar{g}_2(x) = \frac{4}{3\pi} \int_0^1 dx x f_T(x)(2-x)$$

Compatibility of single and double asymmetries

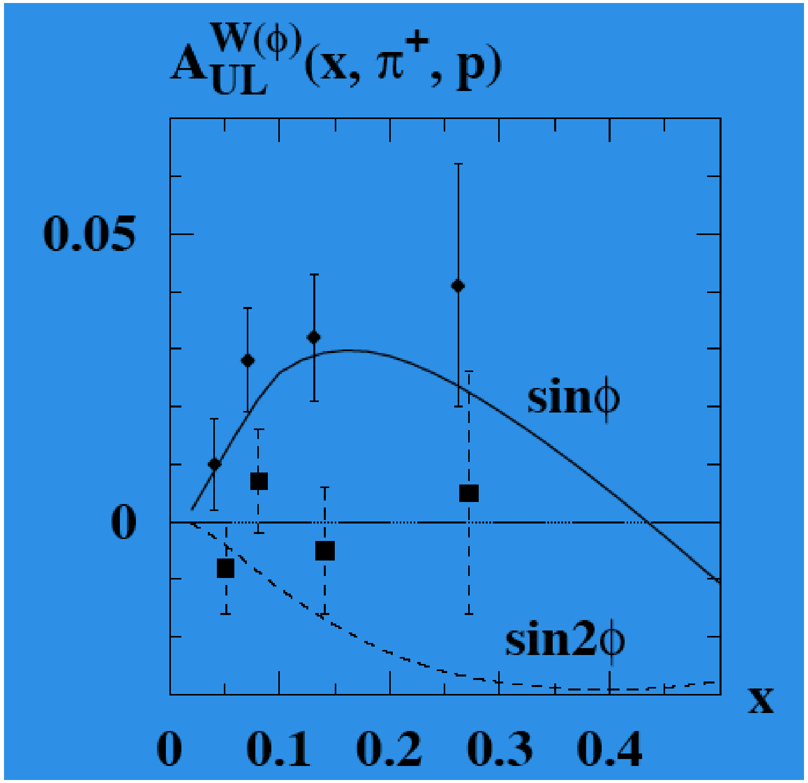
- Recent extractions of Sivers function:Efemov(talk), Goeke, Menzel, Metz,Schweitzer(talk); Anselmino(talk), Boglione, D'Alesio, Kotzinian, Murgia, Prokudin(talks) – "mirror" u and d
- First moment of EGMMS = 0.0072 (0.0042 – 0.014) – courtesy P.Schweitzer
- Twist -3 g_2 (talk of J.P. Chen) - larger for neutron(0.0025 vs 0.0001) and of the same sign – nothing like mirror picture seen.
- Current status: Scale of Sivers function – seems to be reasonable, but flavor dependence seems to differ qualitatively.
- More work is needed: NLO corrections (happen to mix Collins and Sivers asymmetries! – work in progress), regular (beyond gluonic poles) twist 3 contribution,...
- Inclusion of pp data, global analysis including gluonic (=Sivers) and fermionic poles

CONCLUSIONS

- Relations of single and double asymmetries: phase should be known
- Semi-inclusive DVCS - new interesting hard process
- Low transverse momenta - effective twist 3 (but not suppressed as 1/Q) Sivers function (bounded by g_2) – soft talk of large and short distances –supports earlier findings
- Rigorous QCD relations between single and double asymmetries: Sivers function – not independent! Double count (say, in PP at RHIC) should be avoided!
- Reasonable magnitude, but problems with flavor dependence. More experimental and theoretical studies on both sides required.

Typical observable SSA in SIDIS

- Theory - Efremov, Goeke, Schweitzer
- Phase - from Collins function - extracted earlier from jets spin correlations qt LEP
- Spin of proton - transversity - from chiral soliton model



Spin-dependent cross-section

$$d\sigma^{\rightarrow} - d\sigma^{\leftarrow} =$$
$$M\, p_T b_A(0, x_2)(M_{A0} sin(\phi_s) + N_{A0} sin(\phi_s^h)) s_T +$$
$$M\, p_T b_A(x_1, x_2)(M_{A1} sin(\phi_s) + N_{A1} sin(\phi_s^h)) s_T +$$
$$M\, p_T b_V(0, x_2)(M_{V0} sin(\phi_s) + N_{V0} sin(\phi_s^h)) s_T +$$
$$M\, p_T b_V(x_1, x_2)(M_{V1} sin(\phi_s) + N_{V1} sin(\phi_s^h)) s_T$$

STRAIGHTFORWARD APPLICATION OF

TWIST 3 FACTORIZATION

Properties of spin-dependent cross-section

- Complicated expressions
- Sivers (but not Collins) angle naturally appears
- Not suppressed as 1/Q provided gluonic pole exist
- Proportional to correlators with arguments fixed by external kinematics-

  twist-3 “partonometer”

Experimental options for SIDVCS

Natural extension of DVCS studies: selection of elastic final state – UNNECESSARY

BUT : Necessity of BH contribution also - interference may produce SSA

Theoretical Implications

- Twist - 3 SSA survive in Bjorken region provided gluonic poles exist
- The form of SSA - similar to the one provided by Sivers function
- Twist-3 (but non-suppressed as 1/Q) effective Sivers function is found
- Rigorously related to twist 3 part of structure function g_2 - problems seen!
- New connection between different spin experiments

Pion from real photons –simple expression for asymmetry A=

$$\frac{b_A(0,x) - b_V(0,x)}{f(x)} \times$$

$$\times \frac{(1-x_F)(C_F x_F - (x_F+1)C_A/2)}{C_F(1+x_F^2)} \frac{2Mp_T}{m_T^2}$$

Properties of pion SSA by real photons

- Does not sensitive to gluonic poles
- Probe the specific (chiral) combinations of quark-gluon correlators
- Require (moderately) large P_T - may be advantageous with respect to DIS due to the specific acceptance.

Pion beam + polarized target

- Allows to study various ingredients of pion structure – rather different from nucleon
- Most fundamental one – pion-light cone

distribution – manifested in SSA in DY:

Brandenburg, Muller, O.T. (95)

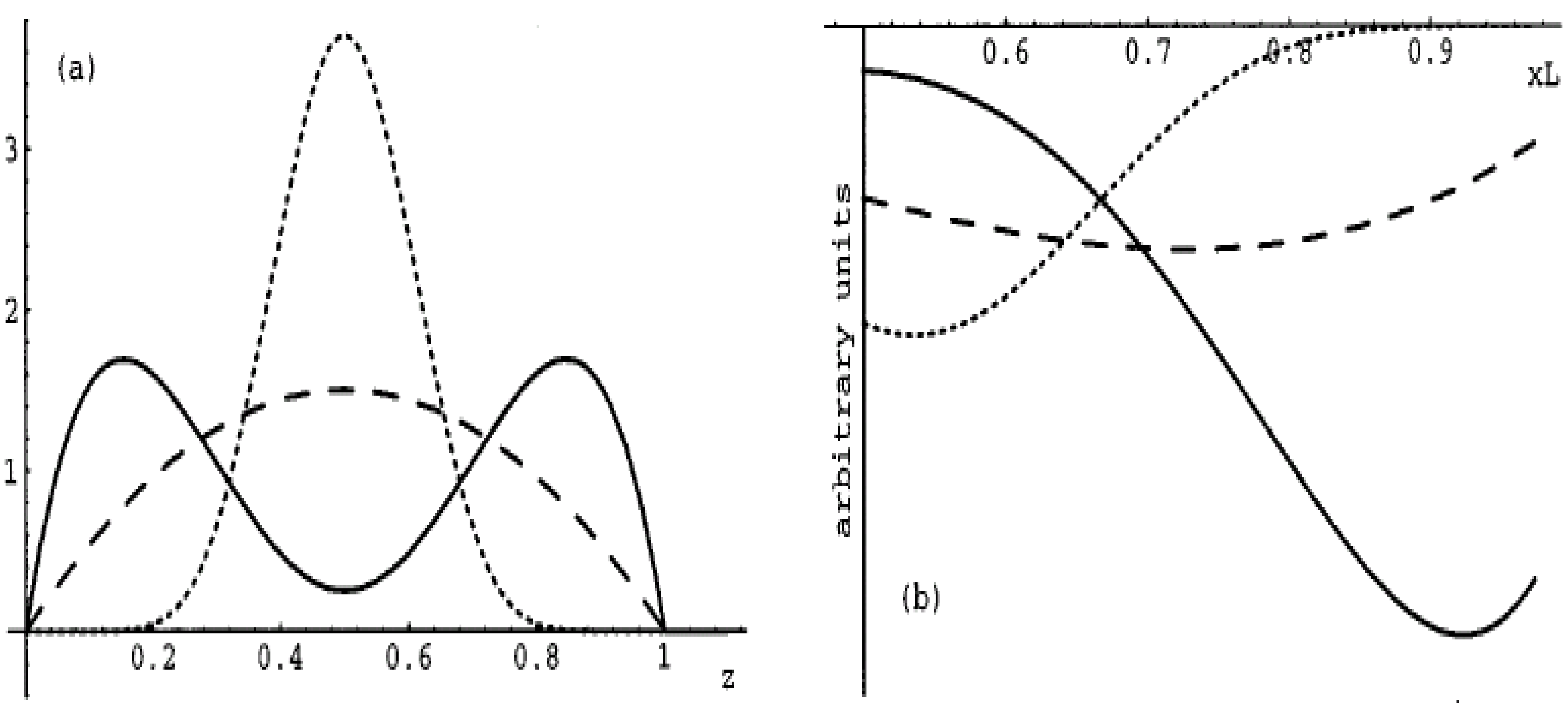
Where to measure?! COMPASS(Torino)?!!

Simplest case-longitudinal polarization- "partonometer"

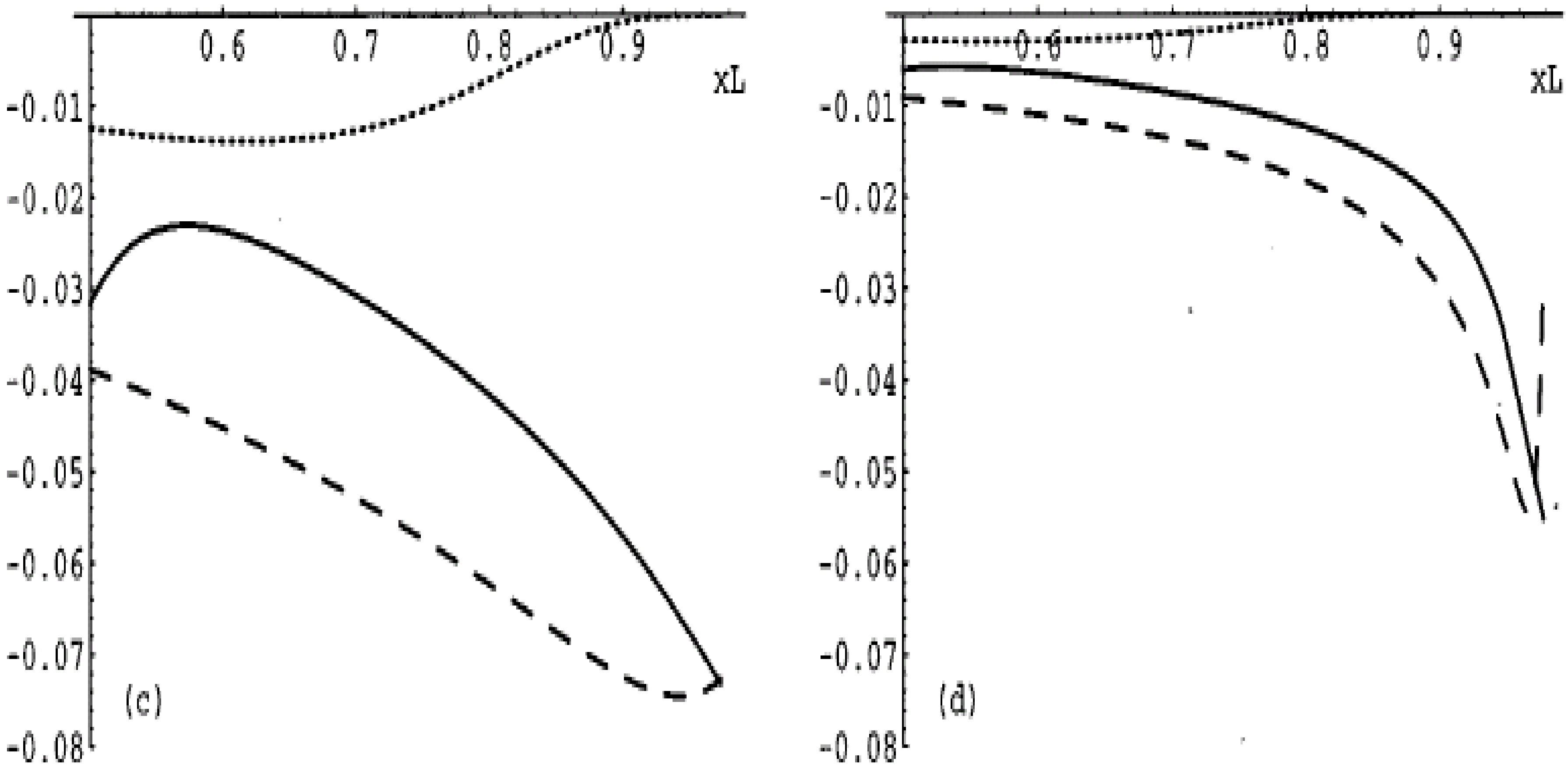
- Two extra terms in angular distribution, proportional to longitudinal polarization

$$\overline{\mu}\sin 2\theta \, \sin\phi + \frac{\nu}{2}\sin^2\theta \, \sin 2\phi$$

Models for light-cone distributions and angular-weighted x-sections



Size of coefficients in angular distributions



Transverse polarization

- Much more complicated – many contributions
- Probe of transversity (X Boer T-odd effective distribution), Sivers function, twist-3 correlations, pion chiral-odd distributions)

CONCLUSIONS-I

- (Moderately) high Pions SSA by real photons – access to quark gluon correlators
- Real photons SSA: direct probe

  of gluonic poles, may be included to DVCS studies

CONCLUSIONS-II

- Pion beam scattering on polarized target – access to pion structure
- Longitudinal polarization – sensitive to pion distrbution
- Transverse polarization – more reach and difficult