Relations between TMDs and Chiral Odd GPDs from π^0 and η production

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Outline

1) Relations between TMDs and GPDs: unraveling new multiparton correlations

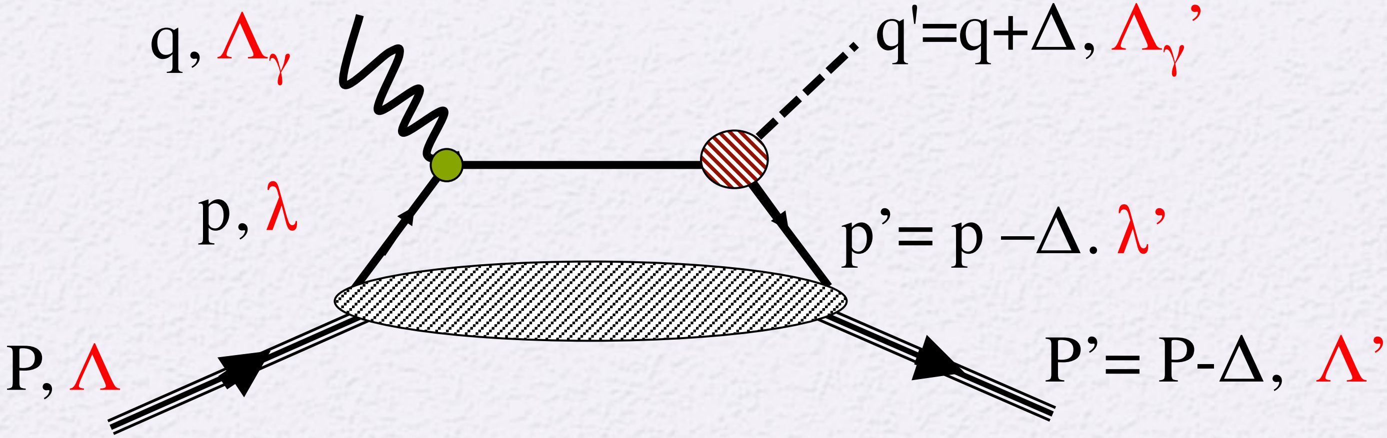
2) How reliably can GPDs be measured? Towards a global fit: models, parameters, theoretical errors, resolution
(GGL, PRD 2011)
Can we understand flavor decomposition of Dirac and Pauli form factors?

3) Exclusive π^o electroproduction ➔ chiral odd sector
(Ahmad et al. PRD 2009, Goldstein et al., hep-ph/1201.6088)

Extraction of GPDs from experimental data

→ Define
"what type of information"

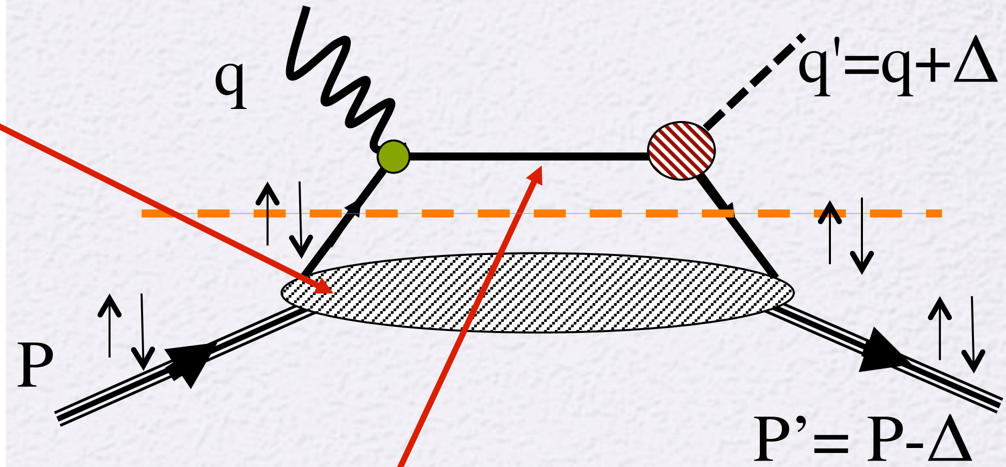
→ Define
"the way to access it"



$$f_{\Lambda_\gamma,\Lambda;\Lambda'_\gamma,\Lambda'} = \epsilon_\mu^{\Lambda_\gamma} T^{\mu\nu}_{\Lambda\Lambda'} \epsilon_\nu^{*\Lambda'_\gamma},$$

Quark-Proton Helicity Amplitudes

$$
\begin{aligned}
f^S_{++} &= f_{++,++} + f_{-+,-+} \\
&= g^S_{++} \otimes \boxed{(A_{++,++} + A_{-+,-+})} \\
f^A_{++} &= f_{++,++} - f_{-+,-+} \\
&= g^A_{++} \otimes (A_{++,++} - A_{-+,-+}) \\
f^S_{+-} &= f_{++,+-} + f_{-+,--} \\
&= g^S_{++} \otimes (A_{-+,++} + A_{++,-+}) \\
f^A_{+-} &= f_{++,+-} - f_{-+,--} \\
&= g^A_{++} \otimes (A_{-+,++} - A_{++,-+})
\end{aligned}
$$



$$
g^{++}_{++} \pm g^{--}_{++} = \sqrt{X(X-\zeta)} \left(\frac{1}{X-\zeta+i\epsilon} \pm \frac{1}{X-i\epsilon} \right)
$$

transversity state

final

initial

$$A^{T}_{\chi\,\Lambda'\lambda',\,\Lambda\lambda}$$

proton

quark

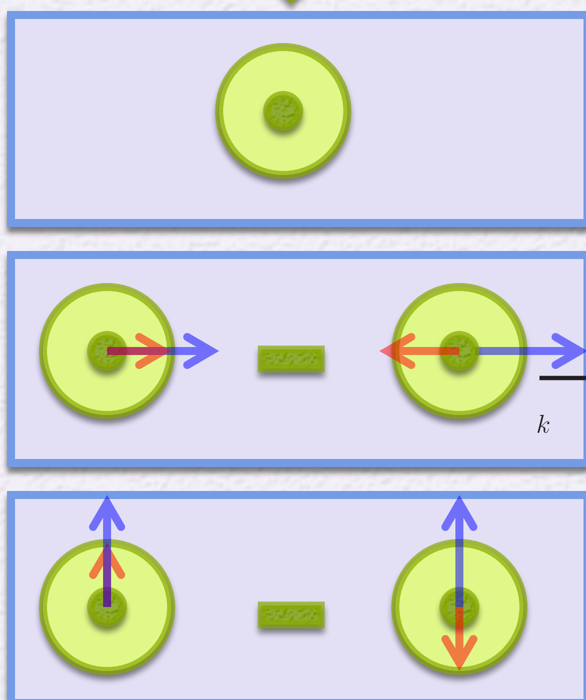
GPDs and TMDs with

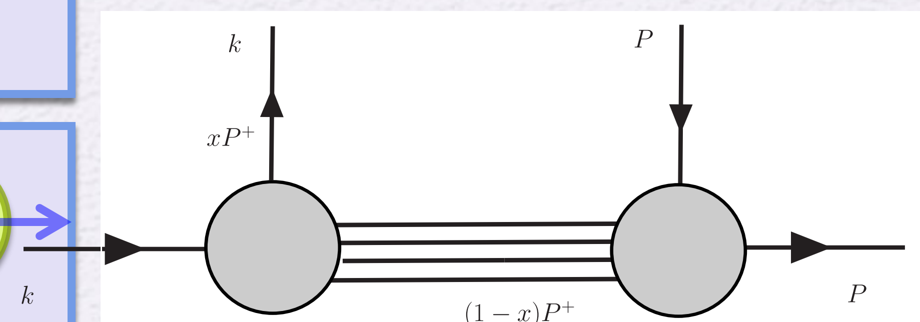
1. same helicity/transversity structure
2. Same parton correlations in a suitably defined forward limit

$$\mathrm{H} \leftrightarrow f_1$$

$$\tilde{\mathrm{H}} \leftrightarrow g_{1L}$$

$$\mathrm{H}_T \leftrightarrow h_1$$





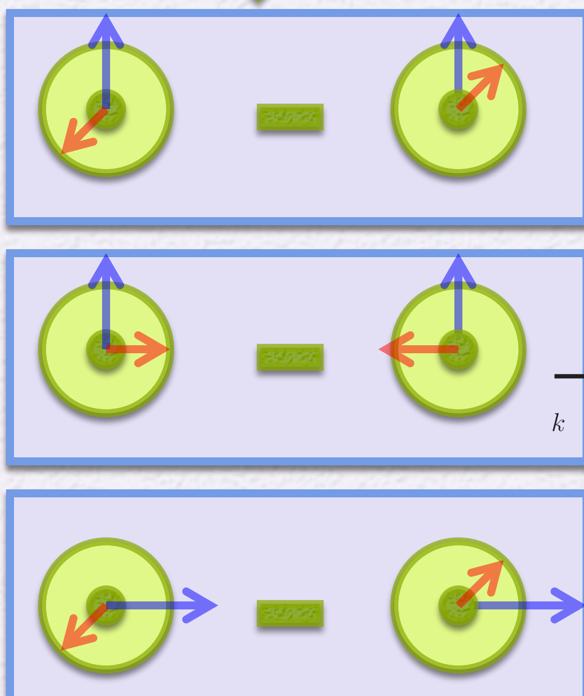
GPDs and TMDs with

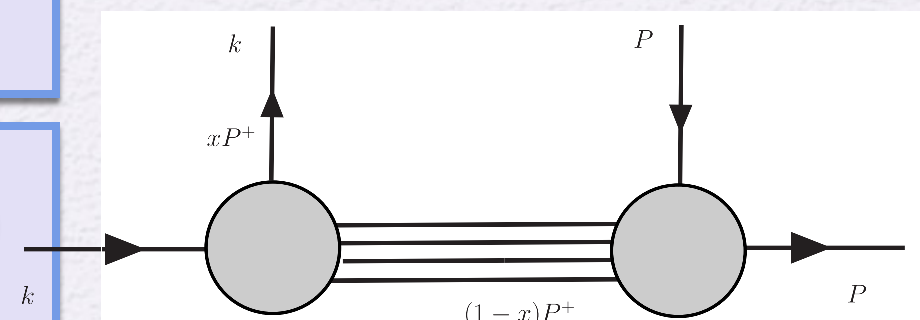
1. same helicity/transversity structure
2. Same parton correlations in a suitably defined forward limit

$\tilde{\mathrm{H}}_T \leftrightarrow h_{1T}^{\perp}$

$\tilde{\mathrm{E}} \leftrightarrow g_{1T}^{\perp}$

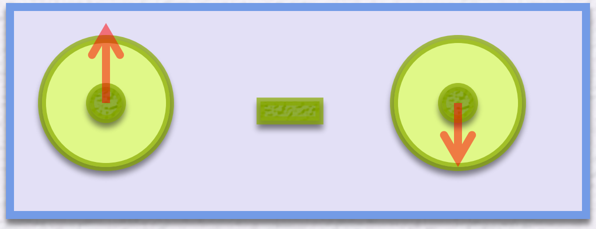
$\tilde{\mathrm{E}}_T \leftrightarrow h_{1L}^{\perp}$



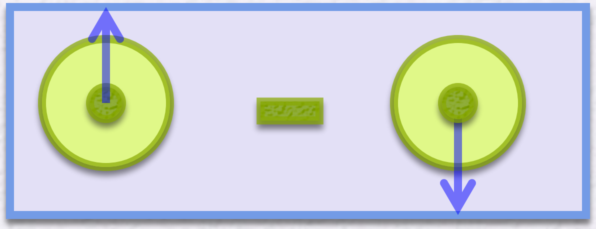


SSA Sector: GPDs and TMDs with same helicity/transversity structure

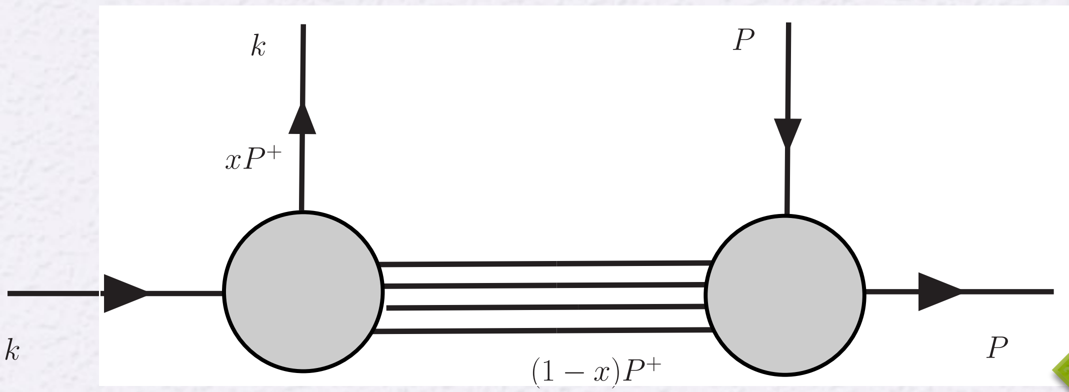
$$2\tilde{\mathrm{H}}_T + \mathrm{E}_T \leftrightarrow h_1^{\perp}$$



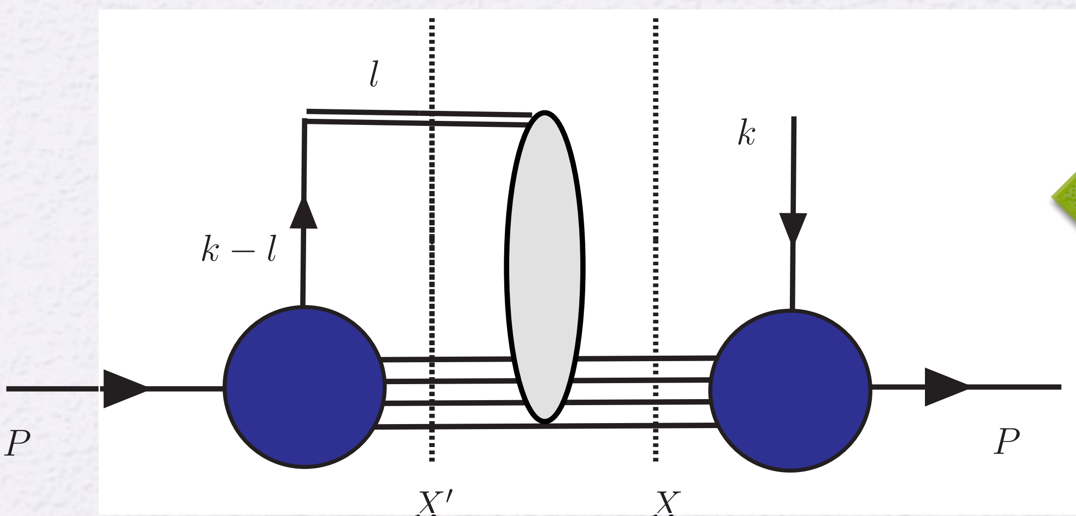
$$\mathrm{E} \leftrightarrow f_{1T}^{\perp}$$



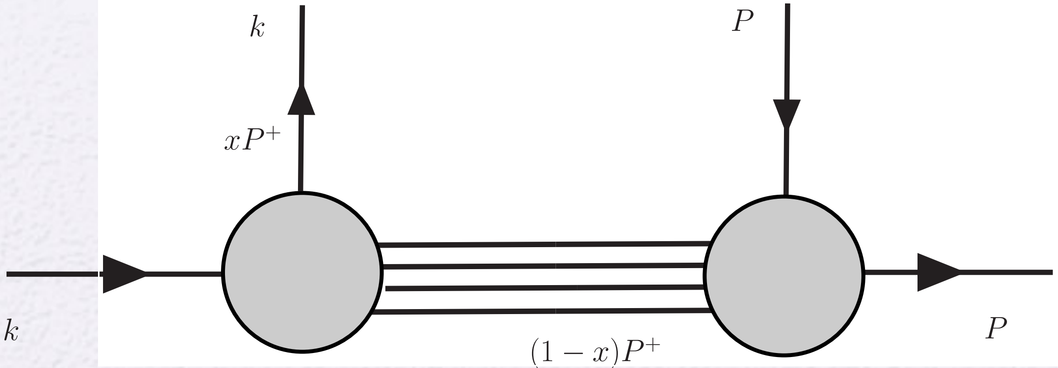
...but different multi-parton correlations in a suitably defined forward limit (aside from spin for a moment...)



$$2\tilde{\mathrm{H}}_T + \mathrm{E}_T, \;\; \mathrm{E}$$



$$h_1^\perp, \; f_{1T}^\perp$$



Momentum Space: diagonal in x non diagonal in k_T

$$E(x,0,t) = \int dz^- \exp^{ixP^+z^-} \langle P' \mid \bar{\psi}(0,z^-,0_T)\,\Gamma\,\psi(0,0,0_T) \mid P\rangle =$$

$$= \sum_X \int dz^- \exp^{i(xP^+ - P'^+ + P_X^+)z^-} \langle P' \mid \bar{\psi}_+(0) \mid X\rangle\langle X \mid \psi_+(0,0,0_T) \mid P\rangle =$$

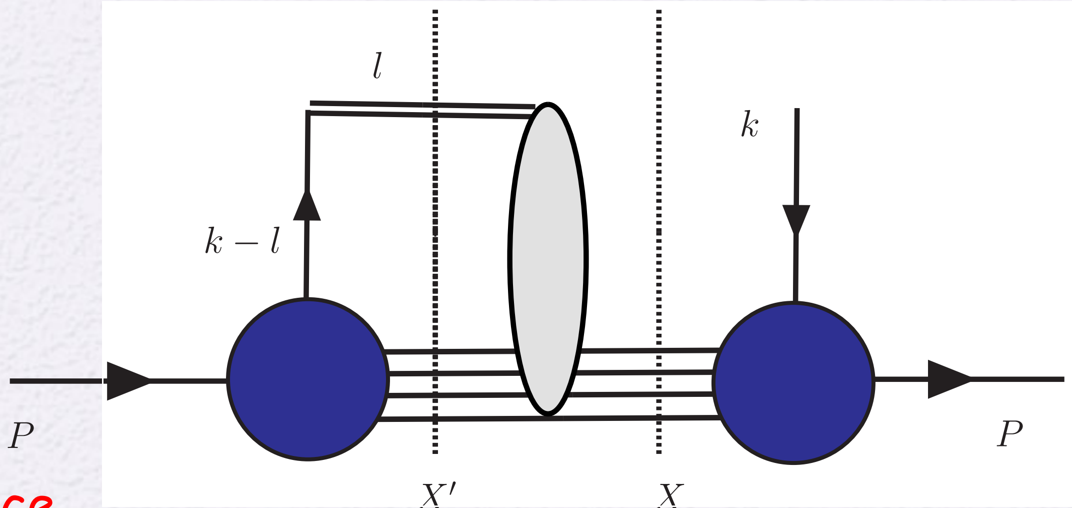
$$= \int d^2k_T \phi^*(x, \underline{k_T - \Delta})\phi(x, \underline{k_T})$$

Coordinate Space: diagonal in b

$$E(x,0,t) = \int d^2b\, e^{ib\cdot\Delta}\, \rho(x, \underline{b})$$

$t=\Delta^2$

GPDs and non SSA TMDs are one particle density distributions!



Momentum Space

$$\langle k_T^i(x)\rangle_{UT} = \int dz^- \exp^{ixP^+z^-} \langle P \mid \bar\psi(0,-z/2,0_T)\gamma^+ \left[\mathcal{W}(-z/2,z/2)I_q(z/2)\right] \psi(0,z/2,0_T) \mid P\rangle =$$

$$= \sum_{X,X'} \int dz^- \exp^{i(xP^+ - P^+ + P_X^{\prime(+)})z^-} \langle P \mid \bar\psi_+(0) \mid X\rangle\langle X' \mid \psi_+(0) \mid P\rangle\langle X \mid \mathcal{W}(0,0)I_q(0) \mid X'\rangle =$$

$$= \int d^2k_T \int d^2l_T \boxed{\phi^*(x,k_T)\phi(x,k_T-l_T,P)}\boxed{L(x,l_T)}$$

FSI

This has the structure of an unintegrated GPD or GTMD

Coordinate Space

But careful! Although the correlator factorizes into a GTMD and FSI, it describes multiparton correlations which are different from the TMDs

$$\langle k_T^i(x)\rangle_{UT} = \int d^2b_1 d^2b_1' d^2b_2 \; \rho_2[(x,b_1),(0,b_2);(x,b_1'),(0,b_2)] I(b_1 - b_2)$$

semi-diagonal (in b) two-particle density distribution

Once we define observables in terms of multiparton density distributions/ correlations what do we do with this information?

Can we gauge what the extent of these multiparticle correlations effect is?
(Why is this tour into multiparticle correlations useful?)

Intuitively, we interpret the average k_T as measuring:

"the probability of finding a quark correlated with the color field produced by the spectators at a position z^- away from that quark"
M. Burkardt

The multiparticle densities scenario provides a necessary theoretical/formal context/background.

- We understand what makes diquark and quark target models "simple" in this context ➔ they are <u>two component models</u>, therefore all of the "complexity" of multiparton interactions is glossed over, FSI is a simple multiplicative factor.

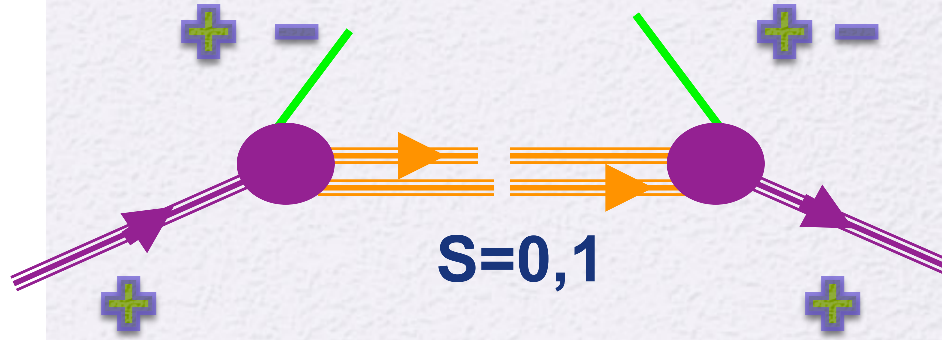
- More realistic diquark type models (with S and D wave spectators, see e.g. Goldstein and Liebl, PL1995; F.Gross and T. Peña, PRD 2011, or taking into account the internal momenta of the spectators, work in progress) could in principle give a very different answer

- Quark models could in principle give a very different answer (see e.g. A. Courtoy and S. Scopetta, PRD 2009)

…on to physically motivated parametrization of data

$A_{\Lambda'\lambda',\Lambda\lambda}$ in Diquark Model

$$
\begin{aligned}
A_{++,++} &= \int d^2k_\perp \phi^*_{++}(k',P')\phi_{++}(k,P) \\
A_{+-,+-} &= \int d^2k_\perp \phi^*_{+-}(k',P')\phi_{+-}(k,P) \\
A_{-+,++} &= \int d^2k_\perp \phi^*_{-+}(k',P')\phi_{++}(k,P) \\
A_{++,-+} &= \int d^2k_\perp \phi^*_{++}(k',P')\phi_{-+}(k,P).
\end{aligned}
$$



$$\phi_{\Lambda,\lambda}(k,P) = \Gamma(k)\frac{\bar{u}(k,\lambda)U(P,\Lambda)}{k^2-m^2}$$

$$\phi^*_{\Lambda'\lambda'}(k',P') = \Gamma(k')\frac{\overline{U}(P',\Lambda')u(k',\lambda')}{k'^2-m^2},$$

$$H = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{\left[(m+MX)\left(m+M\frac{X-\zeta}{1-\zeta}\right)+\mathbf{k}_\perp\cdot\tilde{\mathbf{k}}_\perp\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2}+\frac{\zeta^2}{4(1-\zeta)}E,$$

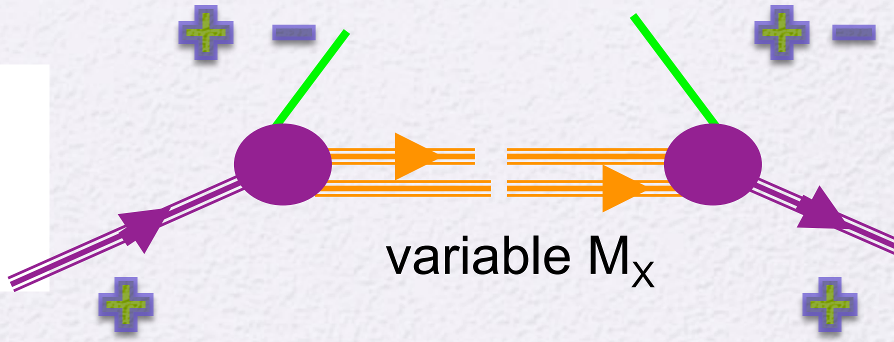
$$E = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{-2M(1-\zeta)\left[(m+MX)\frac{\tilde{k}\cdot\Delta}{\Delta_\perp^2}-\left(m+M\frac{X-\zeta}{1-\zeta}\right)\frac{k_\perp\cdot\Delta}{\Delta_\perp^2}\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2}$$

$$\widetilde{H} = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{\left[(m+MX)\left(m+M\frac{X-\zeta}{1-\zeta}\right)-\mathbf{k}_\perp\cdot\tilde{\mathbf{k}}_\perp\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2}+\frac{\zeta^2}{4(1-\zeta)}\widetilde{E}$$

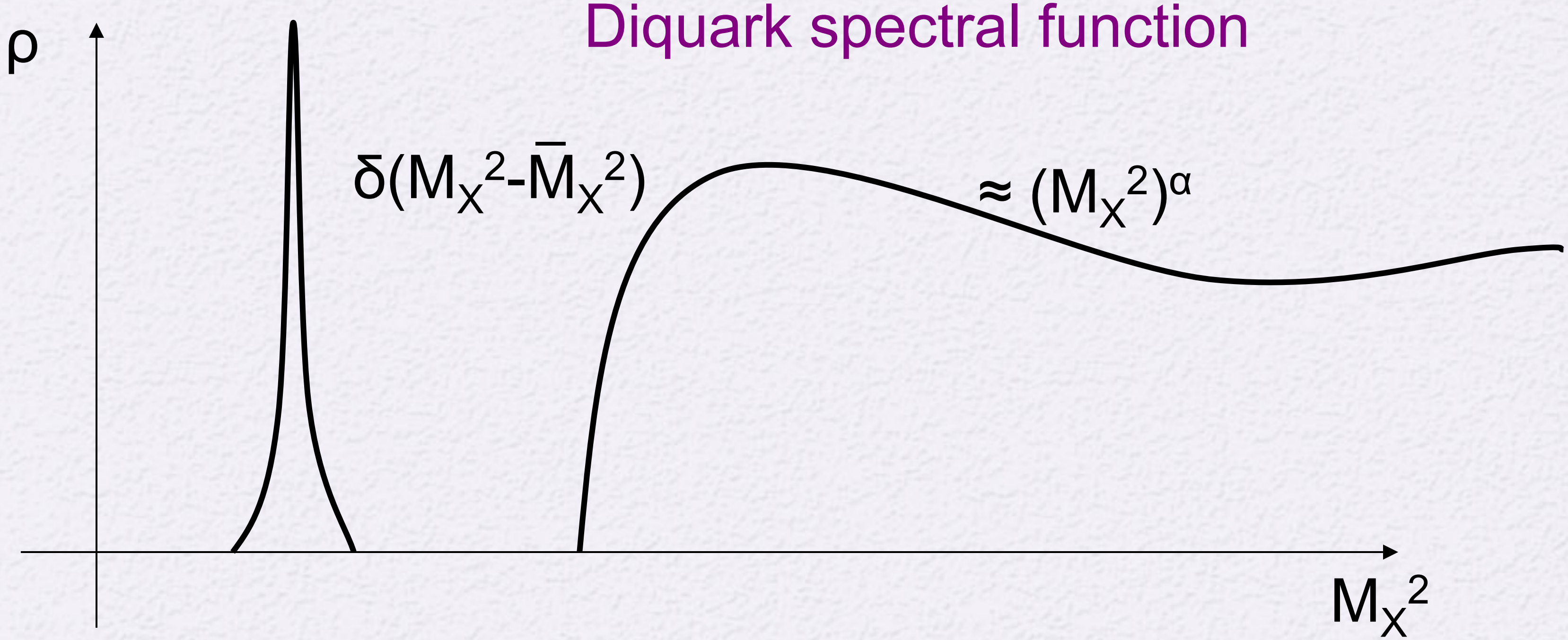
$$\widetilde{E} = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{-\frac{4M(1-\zeta)}{\zeta}\left[(m+MX)\frac{\tilde{k}\cdot\Delta}{\Delta_\perp^2}+\left(m+M\frac{X-\zeta}{1-\zeta}\right)\frac{k_\perp\cdot\Delta}{\Delta_\perp^2}\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2}$$

Reggeization

$$\int_0^\infty dM_X^2 \rho_R(M_X^2) H(X,0,0) \sim X^{-\alpha(0)-1},$$

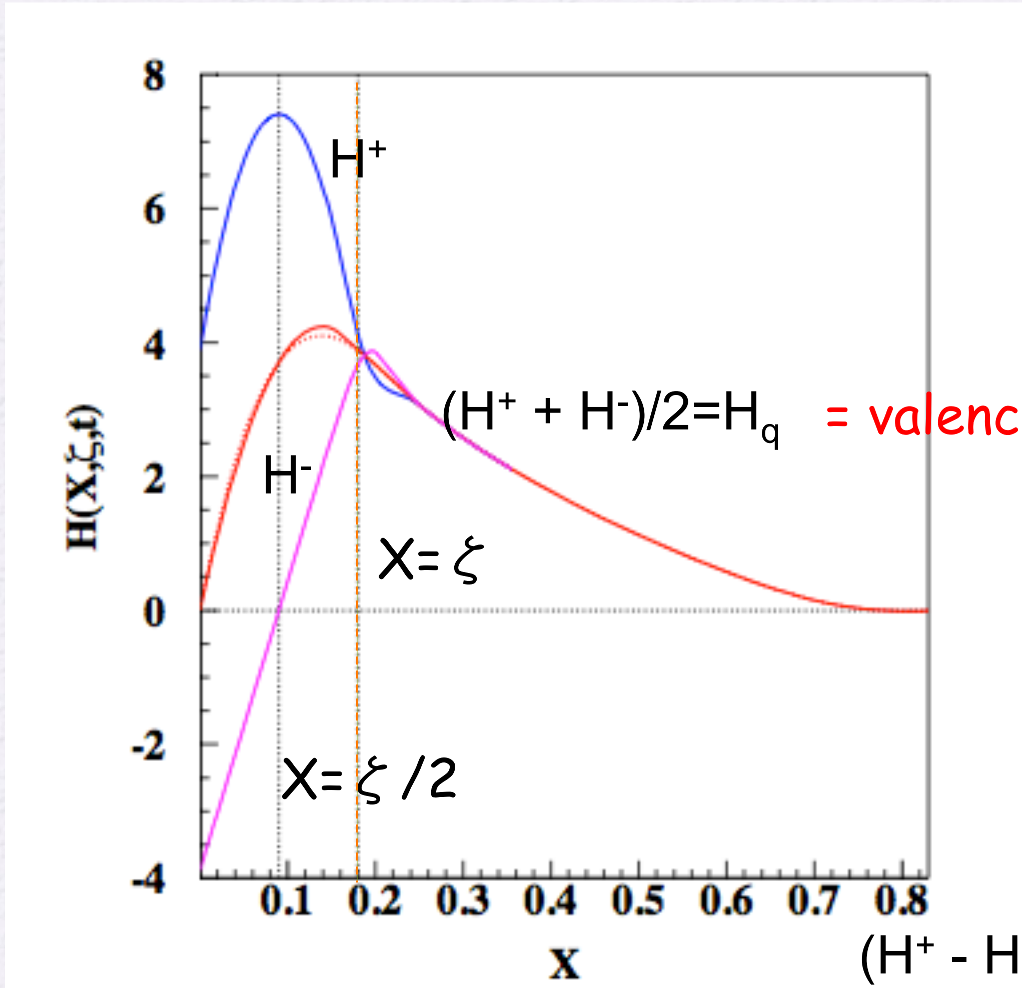


Diquark spectral function



Brodsky, Close, Gunion ➔ DIS ('70s)
Gorshteyn & Szczepaniak (PRD, 2010)
Brodsky, Llanes, Szczepaniak arXiv:0812.0395

Crossing Symmetries



$(H^{+} + H^{-})/2 = H_q$ = valence

$(H^{+} - H^{-})/2 = H_q$ = sea

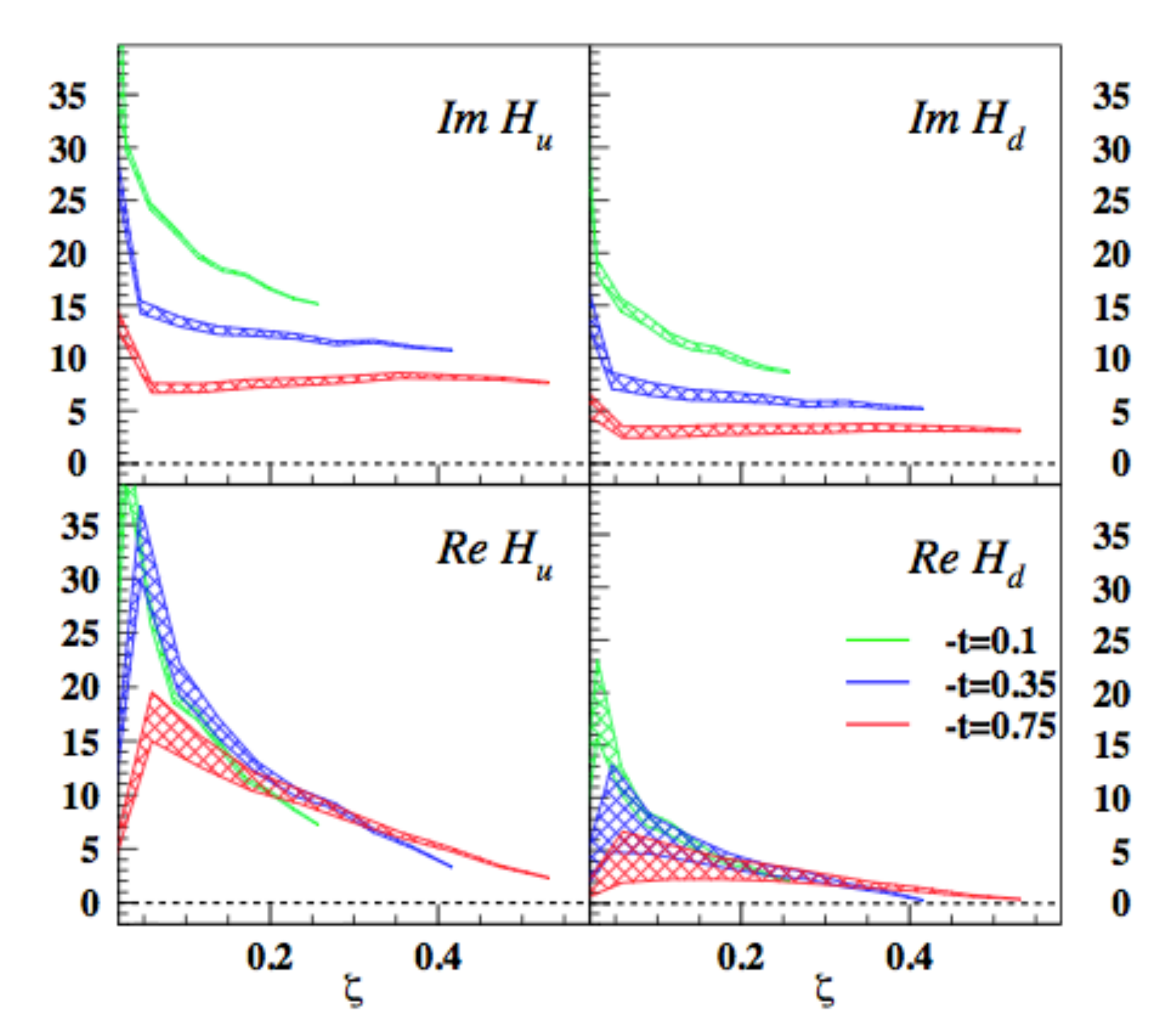
Parametric Form

$$F(X,\zeta,t) = \mathcal{N} G^{M_\Lambda}_{M_X,m}(X,\zeta,t)\, R_p^{\alpha,\alpha'}(X,\zeta,t)$$

We asked the question: "What is the minimal number of parameters necessary to fit X and t ?" Can be addressed with Recursive Fit

Parameters	H	E	$\widetilde{H}$	$\widetilde{E}$
m_u (GeV)	0.420	0.420	2.624	2.624
M_X^u (GeV)	0.604	0.604	0.474	0.474
M_Λ^u (GeV)	1.018	1.018	0.971	0.971
α_u	0.210	0.210	0.219	0.219
α'_u	2.448 ± 0.0885	2.811 ± 0.765	1.543 ± 0.296	5.130 ± 0.101
p_u	0.620 ± 0.0725	0.863 ± 0.482	0.346 ± 0.248	3.507 ± 0.054
$\mathcal{N}_u$	2.043	1.803	0.0504	1.074
χ^2	0.773	0.664	0.116	1.98
m_d (GeV)	0.275	0.275	2.603	2.603
M_X^d (GeV)	0.913	0.913	0.704	0.704
M_Λ^d (GeV)	0.860	0.860	0.878	0.878
α_d	0.0317	0.0317	0.0348	0.0348
α'_d	2.209 ± 0.156	1.362 ± 0.585	1.298 ± 0.245	3.385 ± 0.145
p_d	0.658 ± 0.257	1.115 ± 1.150	0.974 ± 0.358	2.326 ± 0.137
$\mathcal{N}_d$	1.570	-2.800	-0.0262	-0.966
χ^2	0.822	0.688	0.110	1.00

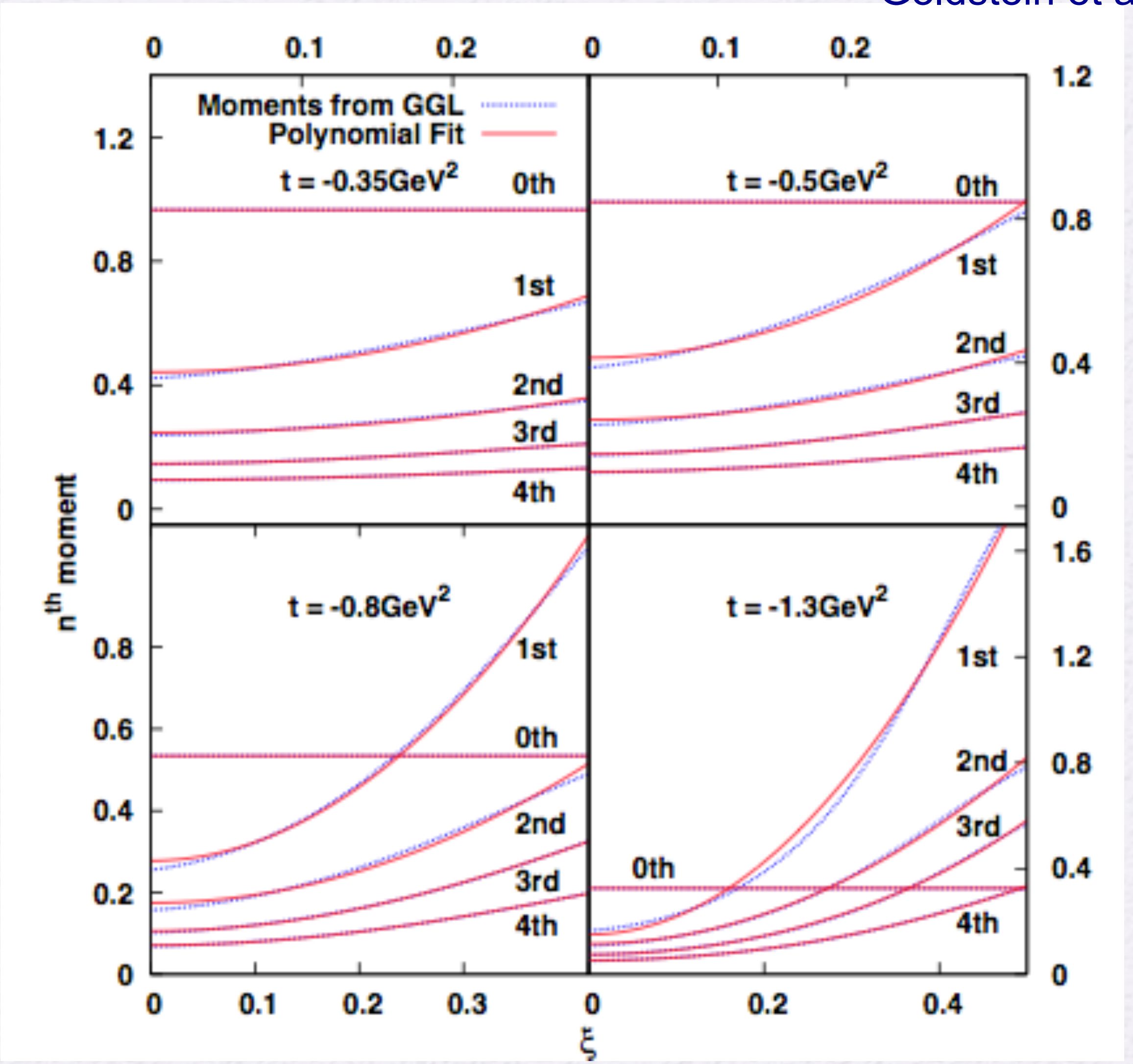
Compton Form factors vs. ζ



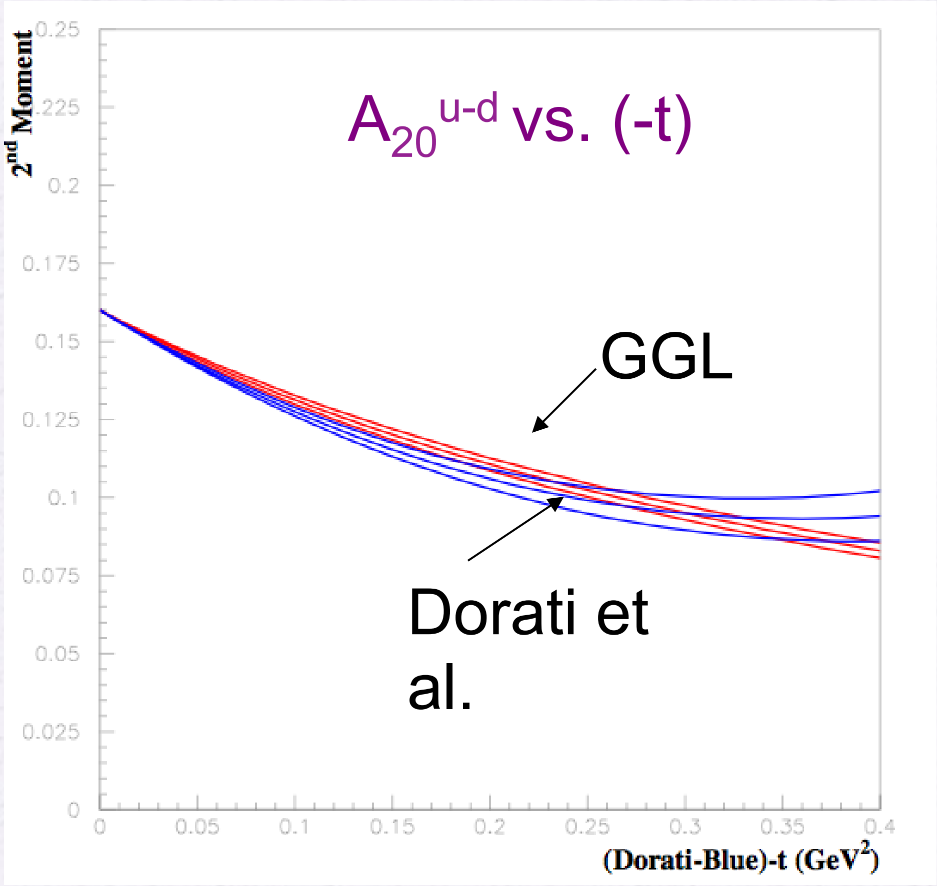
Q^2=2 GeV^2

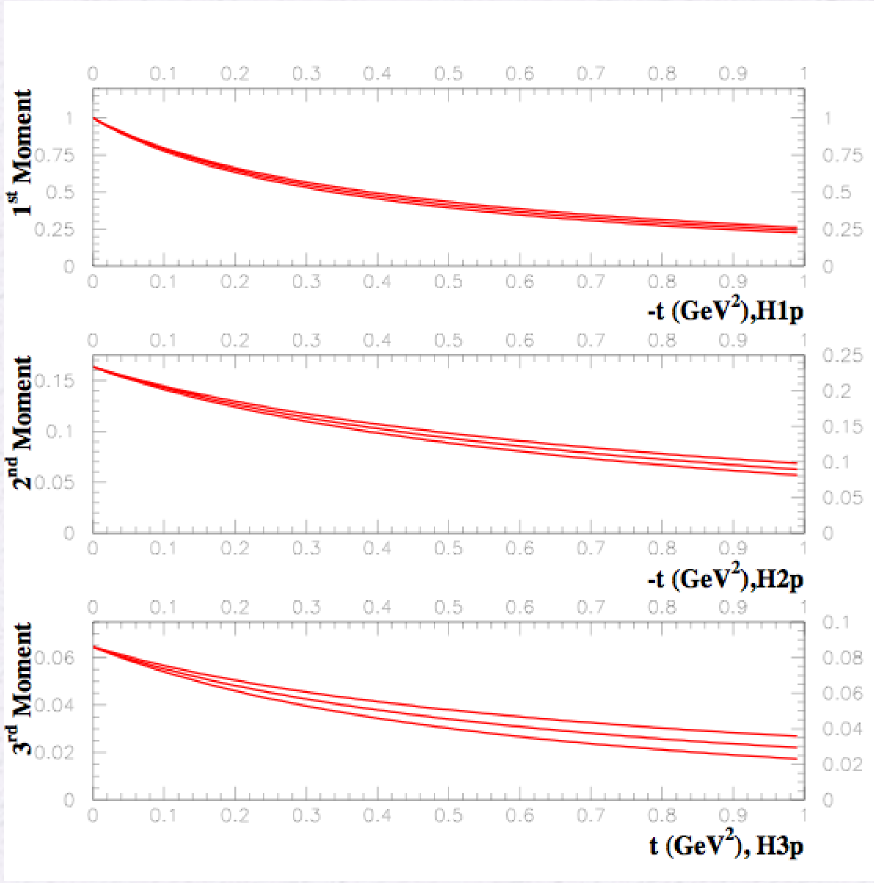
Polynomiality!

Goldstein et al. arXiv:1012.3776



Comparison with lattice

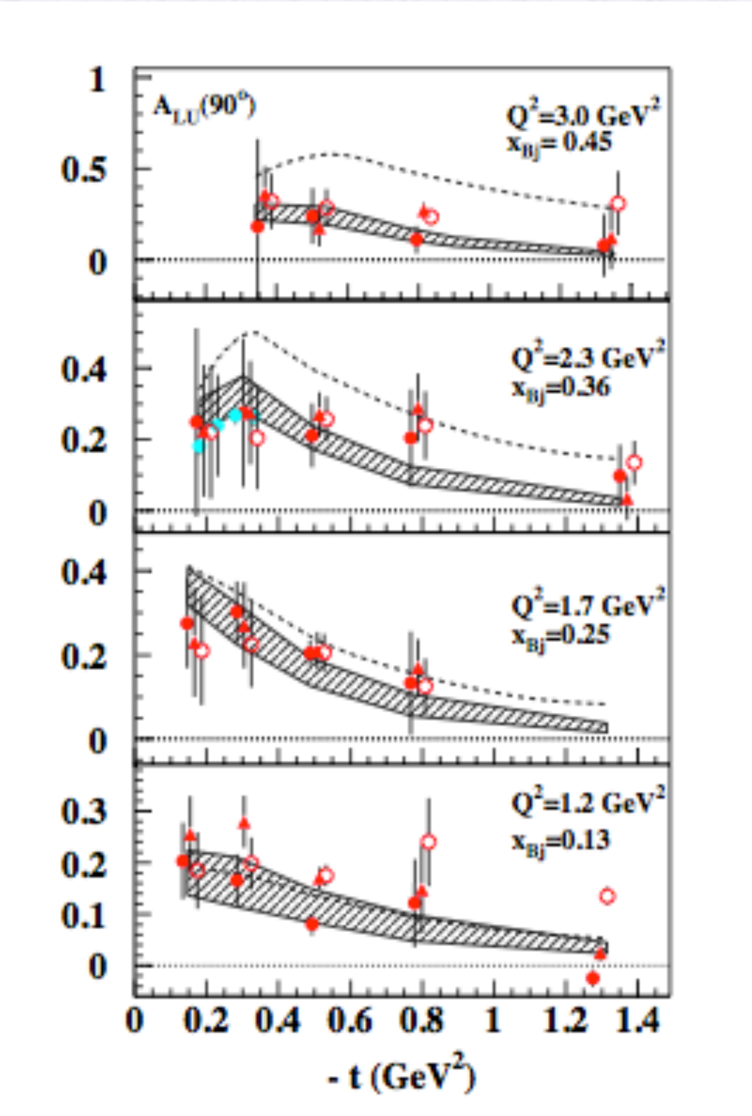




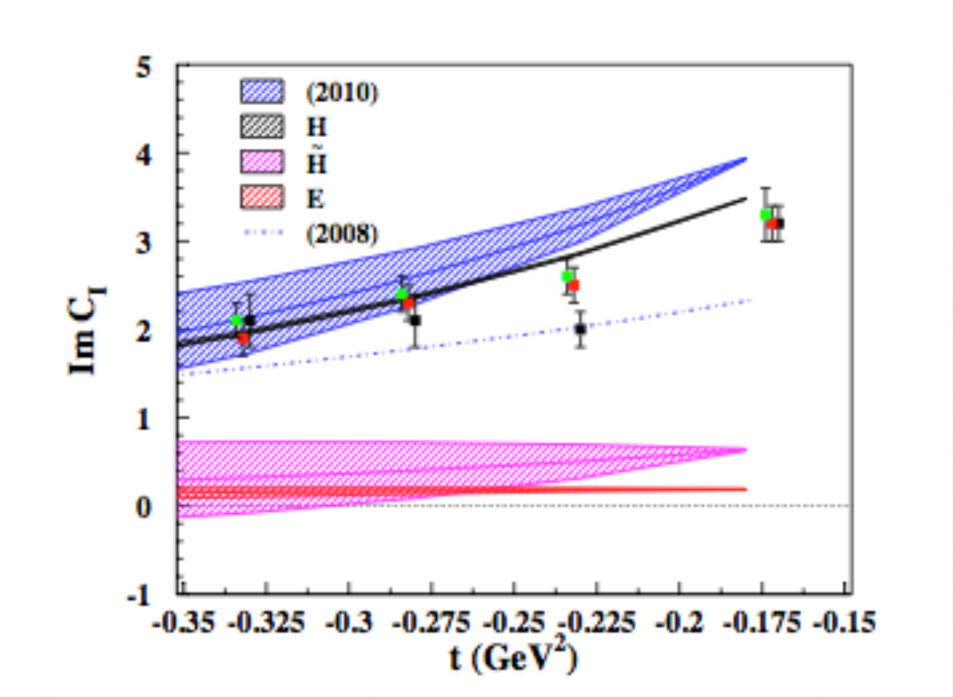
Implementing DVCS data…

$$R = X^{-[\alpha+\alpha'(X)t+\beta(\zeta)t]},$$

extra term



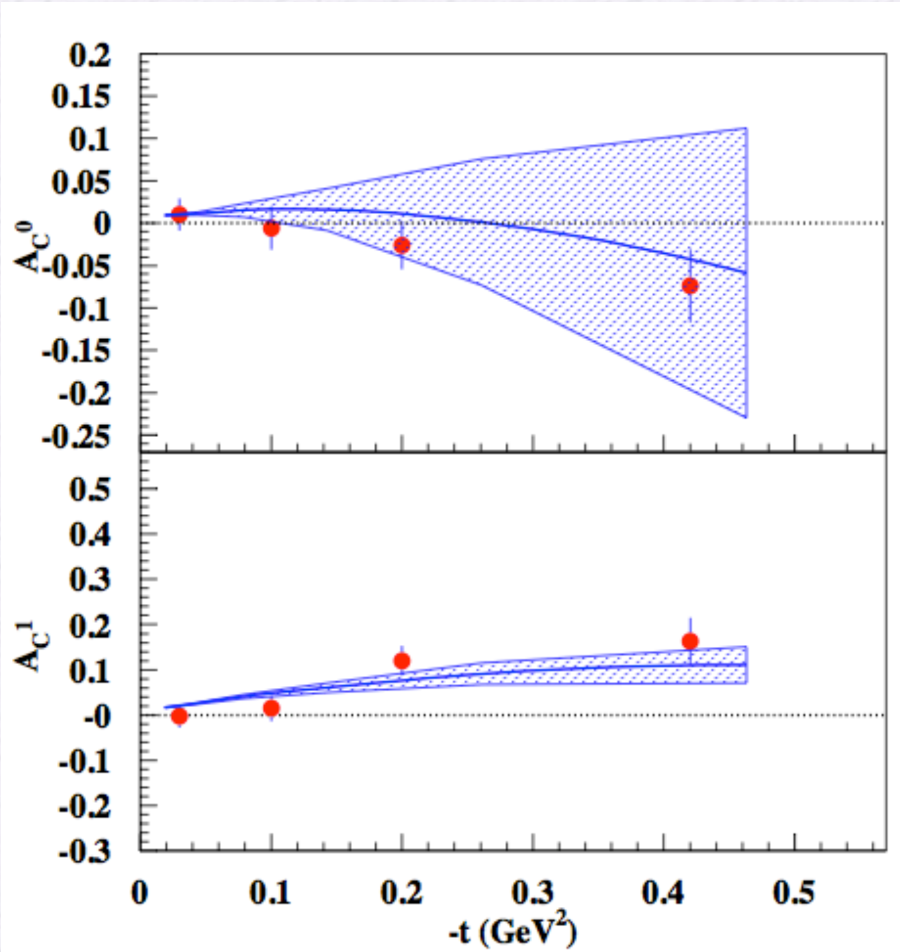
Girod et a., Hall B

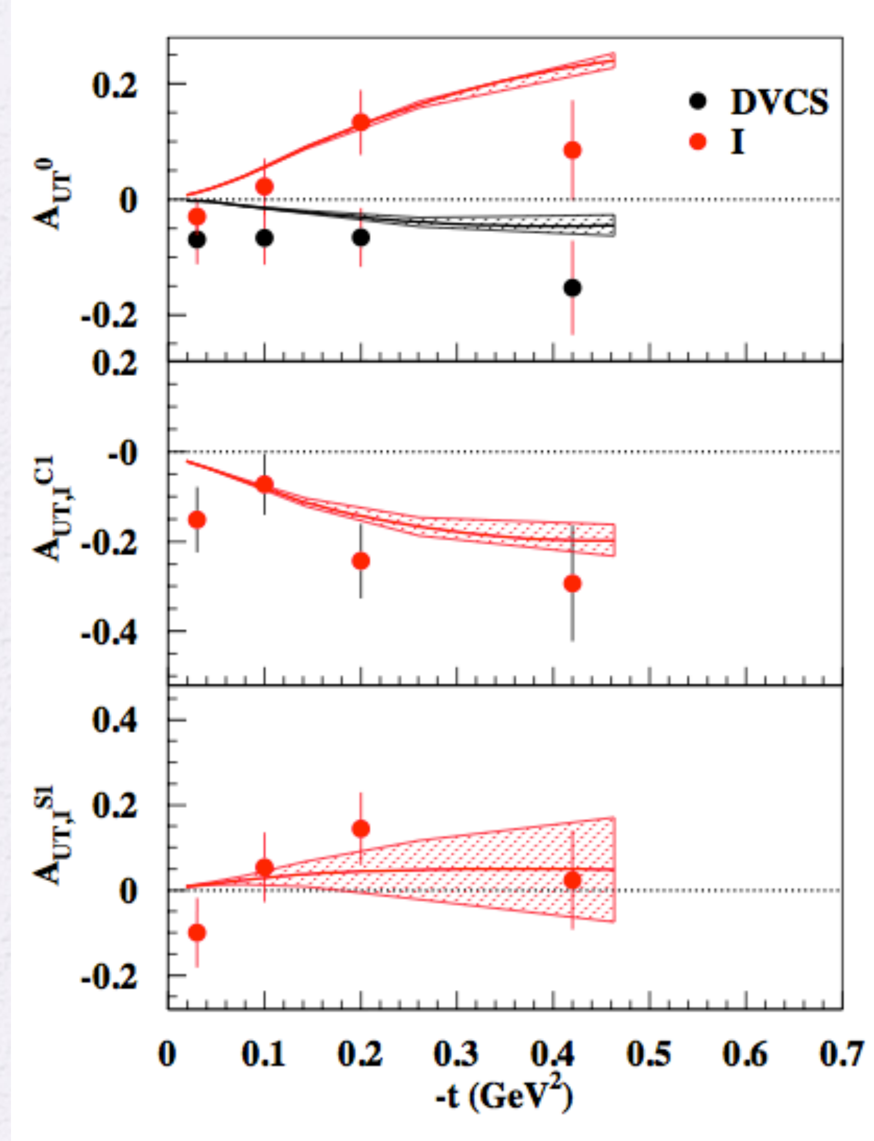

(2010)
H
H̃
E
(2008)
Im C_I
t (GeV^2)
5
4
3
2
1
0
-1
-0.35 -0.325 -0.3 -0.275 -0.25 -0.225 -0.2 -0.175 -0.15

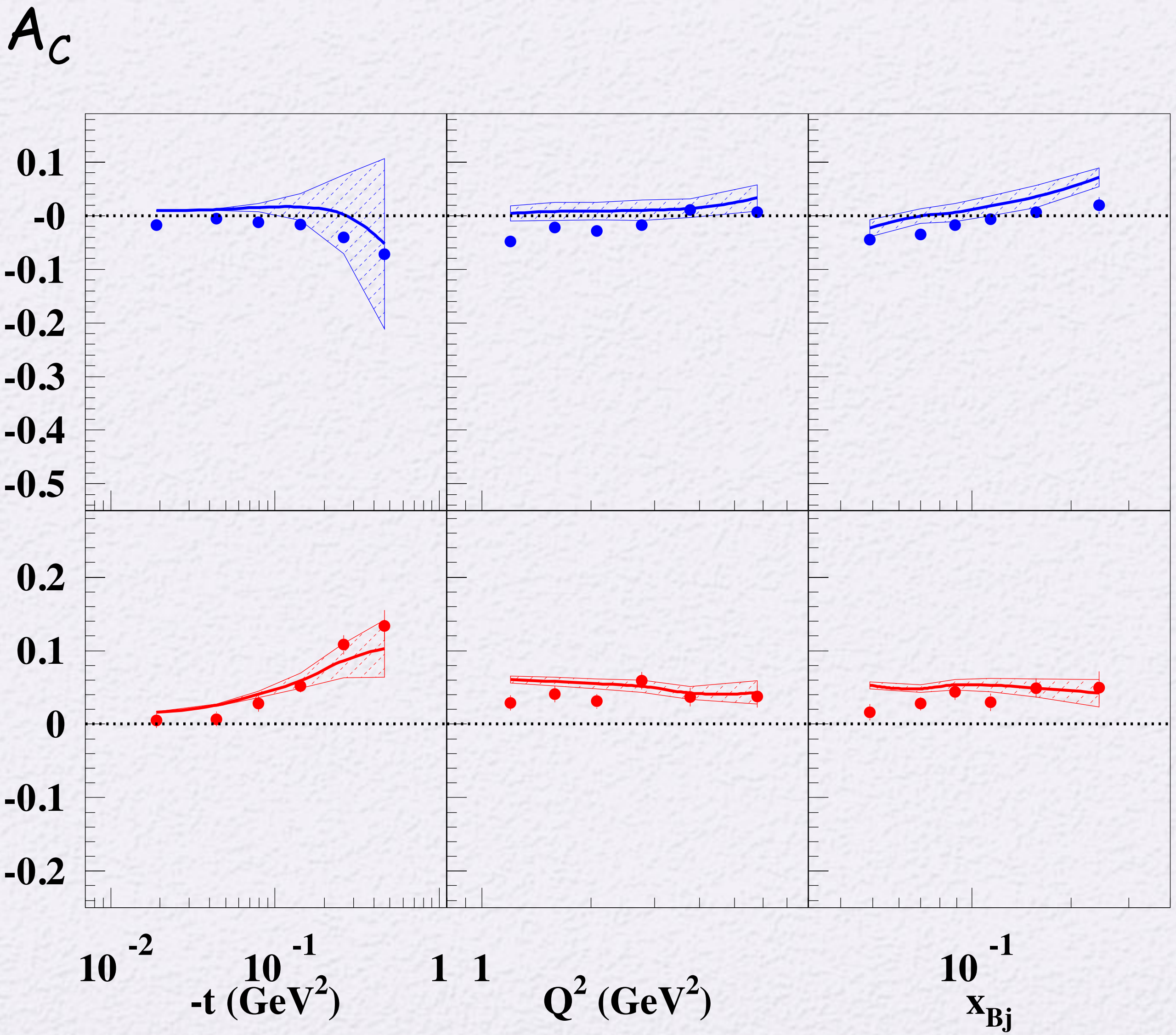
Hall A

Having fitted Jlab data, we predict Hermes

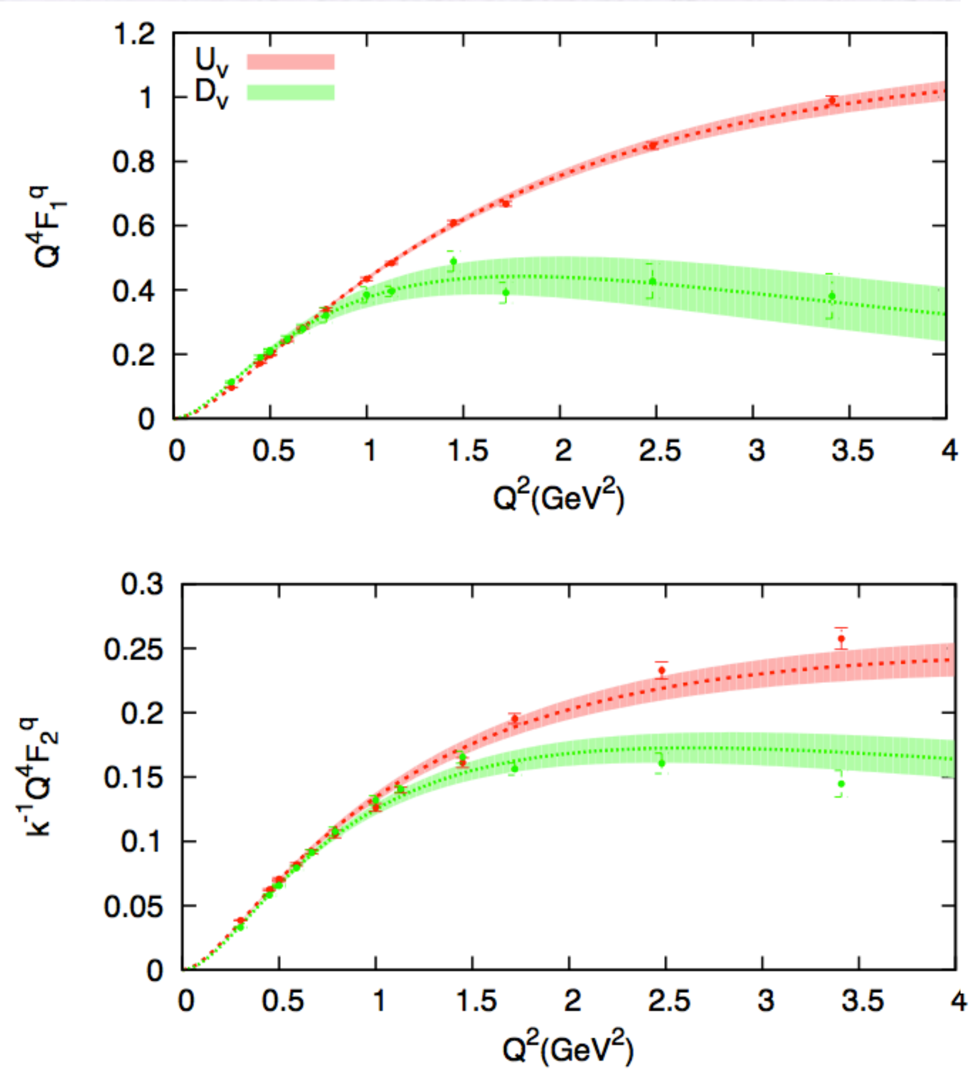
Goldstein et al. arXiv:1012.3776



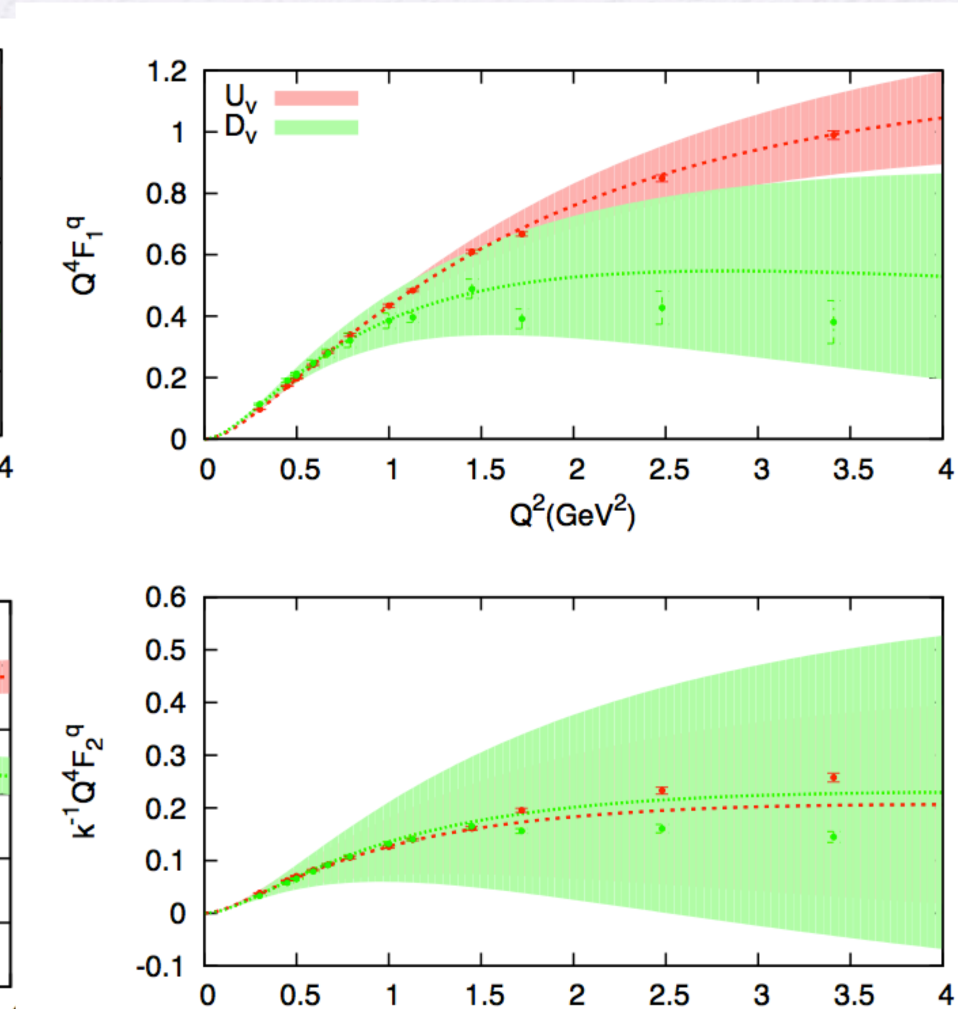



A_C
0.1
-0
-0.1
-0.2
-0.3
-0.4
-0.5
0.2
0.1
0
-0.1
-0.2
10^-2
10^-1
1
1
-t (GeV^2)
Q^2 (GeV^2)
10^-1
x_Bj

New flavor separated data on form factors (G.Cates et al., PRL 2011)



After



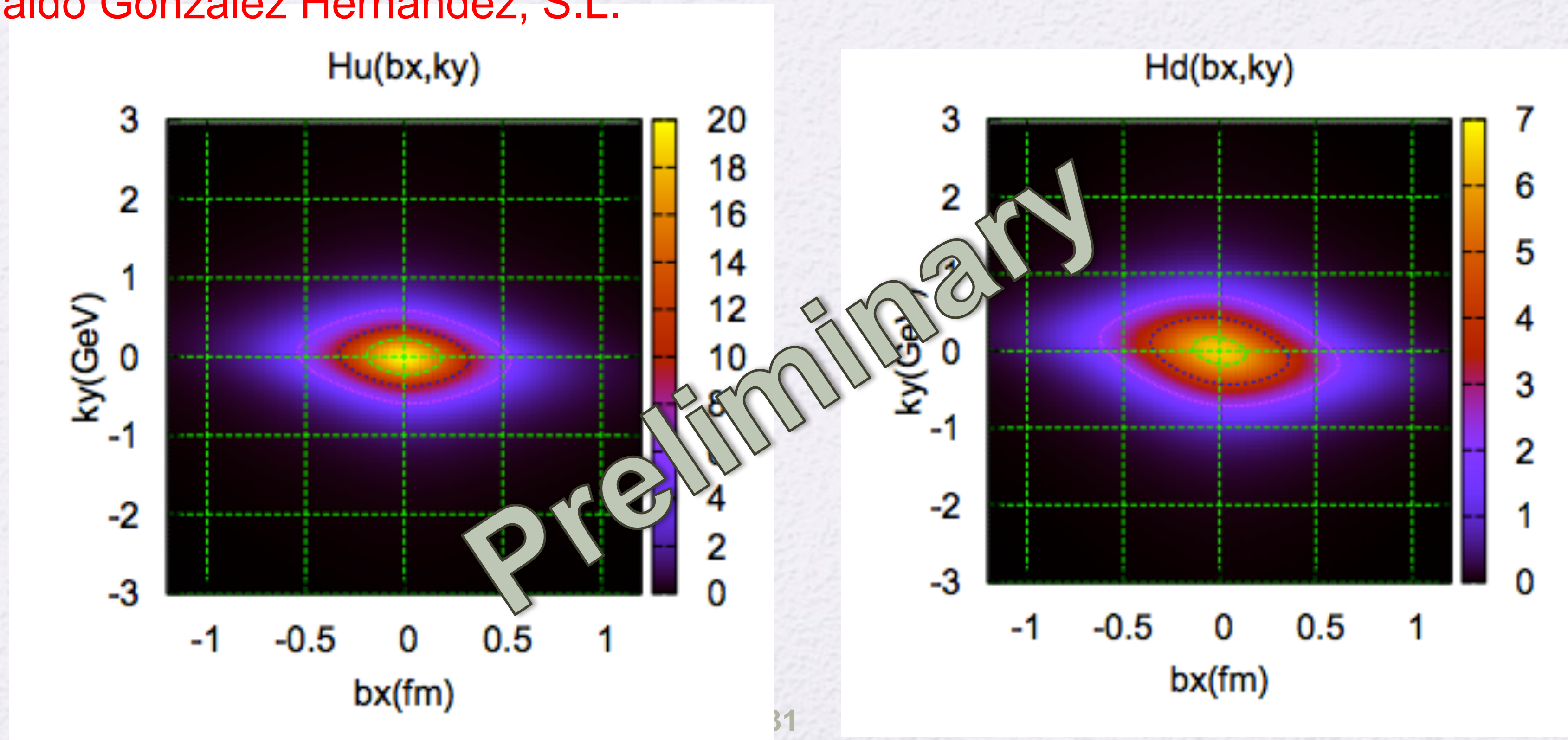
…Before

Interpretation?

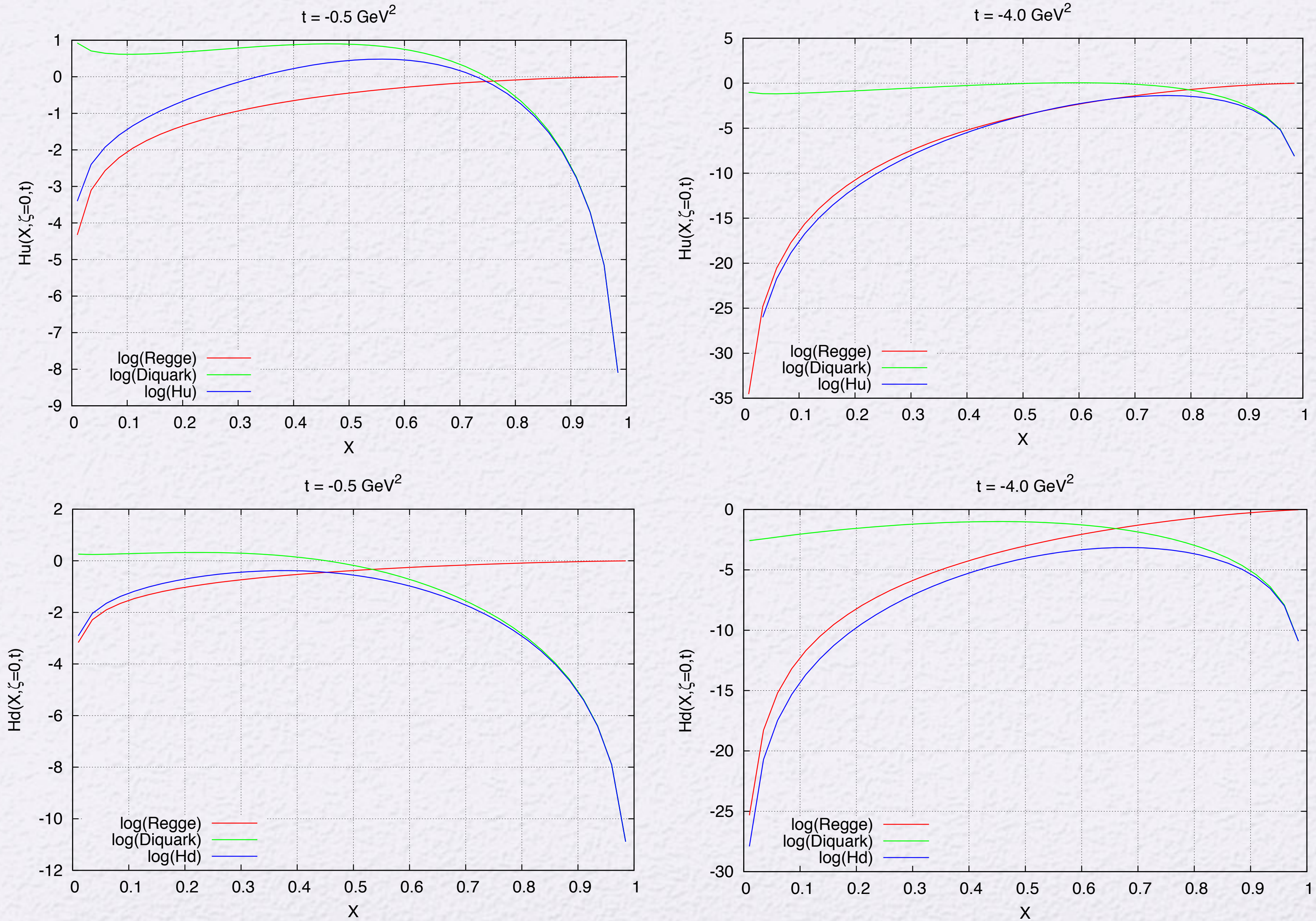
We believe it is not a simple model (pointlike diquark excluded), but closer to hypothesis of u-quark keeping at larger distances from remnants, than d-quark (Z.E. Meziani)

What determines the interquark distances? Wigner distribution studies

Osvaldo Gonzalez Hernandez, S.L.



The partonic configurations radii are determined by an interplay of the Regge and diquark terms



Pseudoscalar Mesons Electroproduction

π^0 and η production probing the GPD chiral-odd sector

Goldstein et al., arXiv:hep-ph/1201.6088

Issue in a nutshell:

"Collinear factorization approach" for chiral-even process

$$g_{0,+;0,+} \approx \frac{1}{Q}\int d\tau \frac{\phi_\pi(\tau)}{\tau} C^+ \Rightarrow \boxed{\frac{d\sigma_L^{even}}{dt} \propto \frac{1}{Q^6}}$$

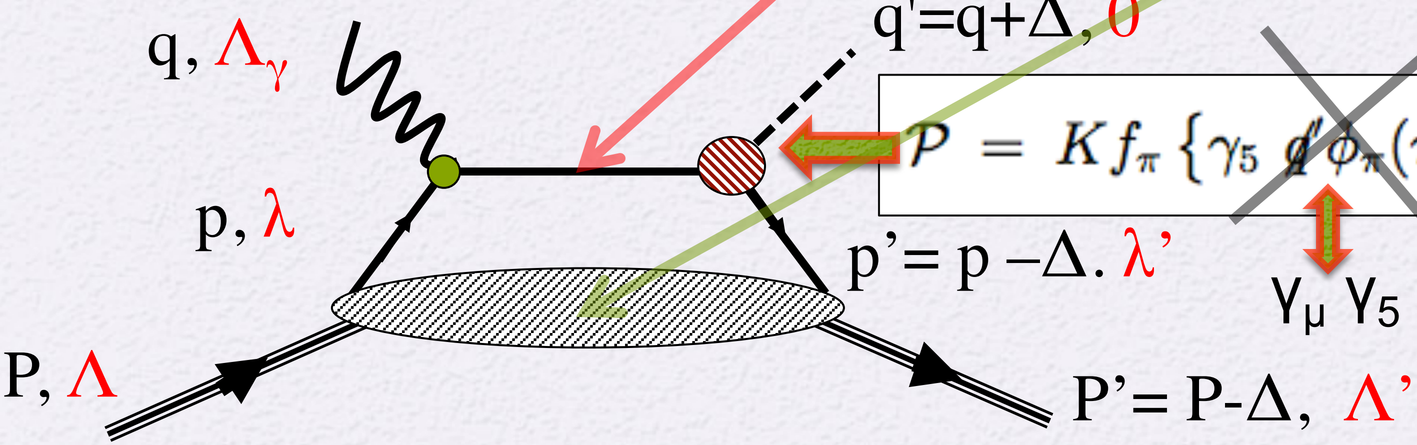
$$g_{1,+;0,+} \approx \frac{1}{Q^2}\int d\tau \frac{\phi_\pi(\tau)}{\tau} C^+ \Rightarrow \boxed{\frac{d\sigma_T^{even}}{dt} \propto \frac{1}{Q^8}}.$$

"Collinear factorization approach" for chiral-odd process

$$g_{0+,0-} \approx \boxed{\frac{d\sigma_L^{odd}}{dt} \propto \frac{1}{Q^{10}}} \quad g_{1+,0-} \approx \boxed{\frac{d\sigma_T^{odd}}{dt} \propto \frac{1}{Q^8}}.$$

Transverse component seems to be larger than naively expected

$$f_{\Lambda_\gamma,\Lambda;0,\Lambda'}(\xi,t) = \sum_{\lambda,\lambda'} \int dx\, d^2k_\perp \, g_{\Lambda_\gamma,\lambda;0,\lambda'}(x,k_\perp,\xi,t) \, A_{\Lambda',\lambda';\Lambda,\lambda}(x,k_\perp,\xi,t)$$



$$\mathcal{P} = K f_\pi \left\{\gamma_5 \cancel{\not{q}\, \phi_\pi(\tau)} + \gamma_5 \mu_\pi \phi_\pi^{(3)}(\tau)\right\}$$

$\gamma_\mu \gamma_5$ γ_5

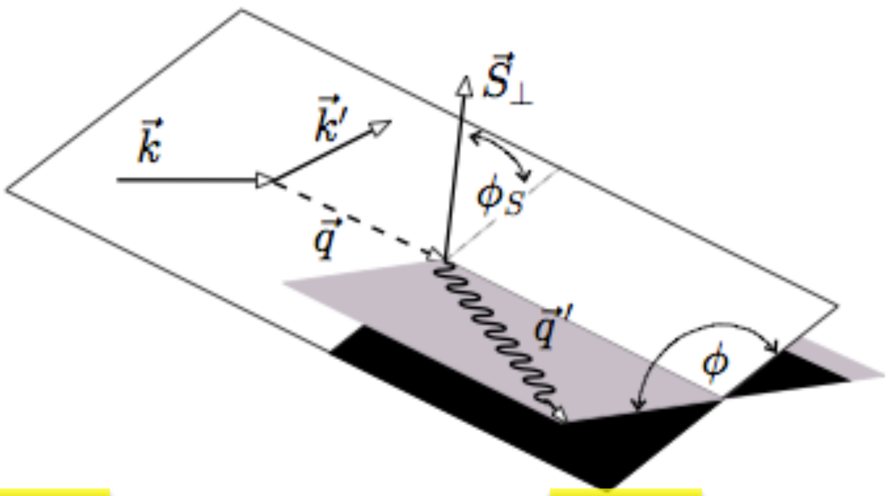
T
$$g_T = g_\pi^{odd}(Q) \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] = g_\pi^{odd}(Q)\, C^+$$

L
$$g_L = g_\pi^{odd}(Q) \sqrt{\frac{t_o - t}{Q^2}} \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] = g_\pi^{odd}(Q) \sqrt{\frac{t_o - t}{Q^2}}\, C^+,$$

T
$$\begin{aligned}
f_1 = f_{1+,0+} &= g_{1+,0-} \otimes A_{+-,++} \\
f_2 = f_{1+,0-} &= g_{1+,0-} \otimes A_{--,++} \\
f_3 = f_{1-,0+} &= g_{1+,0-} \otimes A_{+-,-+} \\
f_4 = f_{1-,0-} &= g_{1+,0-} \otimes A_{--,-+},
\end{aligned}$$

L
$$\begin{aligned}
f_5 = f_{0+,0-} &= g_{0+,0-} \otimes A_{--,++} \\
f_6 = f_{0+,0+} &= g_{0+,0-} \otimes A_{+-,++},
\end{aligned}$$

Cross Section



$$\frac{d^4\sigma}{d\Omega d\epsilon_2 d\phi dt} = \Gamma \left\{ \boxed{\frac{d\sigma_T}{dt} + \epsilon_L \frac{d\sigma_L}{dt}} + \epsilon \cos 2\phi \boxed{\frac{d\sigma_{TT}}{dt}} + \sqrt{2\epsilon_L(\epsilon+1)} \cos\phi \boxed{\frac{d\sigma_{LT}}{dt}} \right.$$
$$\left. + \; h\sqrt{2\epsilon_L(\epsilon-1)} \boxed{\frac{d\sigma_{L'T}}{dt}} \sin\phi \right\},$$

$$\frac{d\sigma_T}{dt} = \mathcal{N}\left(|f_1|^2 + |f_2|^2 + |f_3|^2 + |f_4|^2\right)$$

$$\frac{d\sigma_L}{dt} = \mathcal{N}\left(|f_5|^2 + |f_6|^2\right),$$

$$\frac{d\sigma_{TT}}{dt} = 2\mathcal{N}\,\Re e\left(f_1^* f_4 - f_2^* f_3\right).$$

$$\frac{d\sigma_{LT}}{dt} = 2\mathcal{N}\,\Re e\left[f_5^*(f_2+f_3) + f_6^*(f_1-f_4)\right].$$

$$\frac{d\sigma_{LT'}}{dt} = 2\mathcal{N}\,\Im m\left[f_5^*(f_2+f_3) + f_6^*(f_1-f_4)\right]$$

In terms of GPDs

$$\epsilon_T^{\mu} T_{\mu}^{\Lambda\Lambda'} = e_q \int_{-1}^{1} dx \, \frac{g_T}{2\overline{P}^+} \, \overline{U}(P',\Lambda') \left[i\sigma^{+i} H_T^q(x,\xi,t) + \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2M} E_T^q(x,\xi,t) \right.$$
$$\left. \frac{\overline{P}^+\Delta^i - \Delta^+\overline{P}^i}{M^2} \widetilde{H}_T^q(x,\xi,t) + \frac{\gamma^+\overline{P}^i - \overline{P}^+\gamma^i}{2M} \widetilde{E}_T^q(x,\xi,t) \right] U(P,\Lambda),$$

M. Diehl, 2001

$$\mathcal{H}_T,\ \mathcal{E}_T,\ \tilde{\mathcal{E}}_T,\ \bar{\mathcal{E}}_T$$

$$\frac{d\sigma_T}{dt} \approx \mathcal{N}^2 [g_\pi^{odd}(Q)]^2 \frac{1}{(1+\xi)^4} \left[|\mathcal{H}_T|^2 + \tau \left(|\bar{\mathcal{E}}_T|^2 + |\tilde{\mathcal{E}}_T|^2 \right) \right] \quad (1$$

$$\frac{d\sigma_L}{dt} \approx \mathcal{N}^2 [g_\pi^{odd}(Q)]^2 \frac{1}{(1+\xi)^4} \frac{2M^2 \tau}{Q^2} |\mathcal{H}_T|^2 \quad (1$$

$$\frac{d\sigma_{TT}}{dt} \approx \mathcal{N}^2 [g_\pi^{odd}(Q)]^2 \frac{1}{(1+\xi)^4} \tau \left[|\bar{\mathcal{E}}_T|^2 - |\tilde{\mathcal{E}}_T|^2 + \Re e \mathcal{H}_T \frac{\Re e(\bar{\mathcal{E}}_T - \mathcal{E}_T)}{2} + \Im m \mathcal{H}_T \frac{\Im m(\bar{\mathcal{E}}_T - \mathcal{E}_T)}{2} \right. \quad (1$$

$$\frac{d\sigma_{LT}}{dt} \approx \mathcal{N}^2 [g_\pi^{odd}(Q)]^2 \frac{1}{(1+\xi)^4}\, 2 \sqrt{\frac{2M^2 \tau}{Q^2}}\, |\mathcal{H}_T|^2 \quad (1$$

$$\frac{d\sigma_{L'T}}{dt} \approx \mathcal{N}^2 [g_\pi^{odd}(Q)]^2 \frac{1}{(1+\xi)^4} \tau \sqrt{\frac{2M^2 \tau}{Q^2}} \left[\Re e \mathcal{H}_T \frac{\Im m(\bar{\mathcal{E}}_T - \mathcal{E}_T)}{2} - \Im m \mathcal{H}_T \frac{\Re e(\bar{\mathcal{E}}_T - \mathcal{E}_T)}{2} \right] \quad (1$$

$\tau = (t_0 - t)/2M^2$

The question is: how do we normalize the GPDs?

Only Physical constraints on the various chiral-odd GPDs are

Forward limit

$$H_T(x,0,0) = q_{\Uparrow}^{\uparrow}(x) - q_{\Uparrow}^{\downarrow}(x) = h_1(x)$$

Form Factors

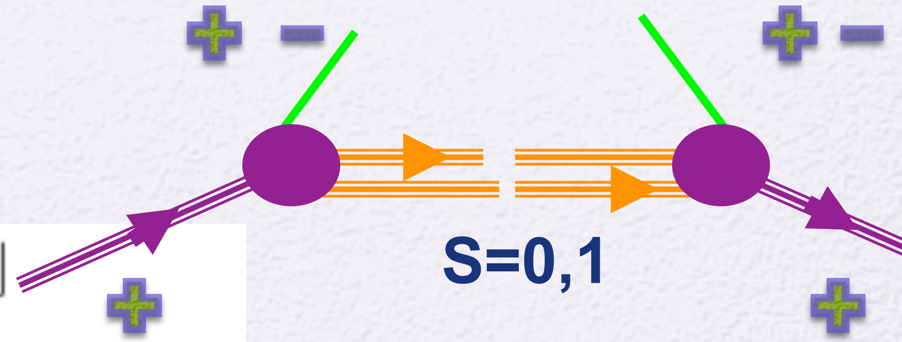
$$\int H_T(x,\xi,t)\,dx = \delta_T(t)$$

$$\int \overline{E}_T(x,\xi,t)\,dx = \int\left(2\tilde{H}_T + E_T\right)dx = \kappa_T(t)$$

$$\int \tilde{E}_T(x,\xi,t)\,dx = 0$$

No direct interpretation of E_T

In the diquark model the GPDs are related through Parity



$S=0$	$S=1$
$\phi^*_{\Lambda'\lambda'}\phi_{\Lambda\lambda}$	$\phi^\mu_{\Lambda'\lambda'}\left(\sum_{\lambda''}\epsilon^{*\lambda''}_\mu\epsilon^{\lambda''}_\nu\right)\phi^\nu_{\Lambda\lambda}$

In order to explain the working of Parity transformations, we write the LHS and RHS of Fig. 1

	RHS	LHS
$S=0$	$\phi^*_{\Lambda'\lambda'}$	$\phi_{\Lambda\lambda}$
$S=1$	$\phi^\mu_{\Lambda'\lambda'}\epsilon^{*\lambda''}_\mu$	$\epsilon^{\lambda''}_\nu\phi^\nu_{\Lambda\lambda}$

S=1

Odd Even

$$A^{(1)}_{++,--} = -\frac{X+X'}{1+XX'}\,A^{(1)}_{++,++}$$

$$A^{(1)}_{+-,-+} = 0$$

$$A^{(1)}_{++,+-} = -\sqrt{\frac{\langle\tilde{k}_\perp^2\rangle}{X'^2+\langle\tilde{k}_\perp^2\rangle/P^{+2}}}\,A^{(1)}_{++,-+}$$

$$A^{(1)}_{+-,++} = -\sqrt{\frac{\langle k_\perp^2\rangle}{X^2+\langle k_\perp^2\rangle/P^{+2}}}\,A^{(1)}_{-+,++},$$

S=0

Odd Even

$$A^{(0)}_{++,--} = A^{(0)}_{++,++}$$

$$A^{(0)}_{++,+-} = -A^{(0)}_{++,-+}$$

$$A^{(0)}_{+-,++} = -A^{(0)}_{-+,++},$$

$$A^{(0)}_{+-,-+} = \frac{t_0-t}{4M}\frac{1}{\sqrt{1-\zeta}}\frac{1}{(1-\zeta/2)}\frac{\tilde{X}}{m+MX'}\left[E-(\zeta/2)\tilde{E}\right]$$

$$H_T^u = \frac{3}{2}H_T^{S=0} - \frac{1}{6}H_T^{S=1}$$

$$H_T^d = -\frac{1}{3}H_T^{S=1}$$

In terms of GPDs

$S = 0$

$$\tilde{H}_T^{(0)} = -\frac{M(1-x)}{m+Mx} E^{(0)} \tag{27a}$$

$$E_T^{(0)} = 2\left(1 + \frac{M(1-x)}{m+Mx}\right) E^{(0)} \tag{27b}$$

$$\tilde{E}_T^{(0)} = 0 \tag{27c}$$

$$H_T^{(0)} = \frac{H^{(0)} + \tilde{H}^{(0)}}{2} - \frac{t_0 - t}{4M^2} \frac{M(1-x)}{m+Mx} E^{(0)} \tag{27d}$$

$S = 1$

$$\tilde{H}_T^{(1)} = 0 \tag{28a}$$

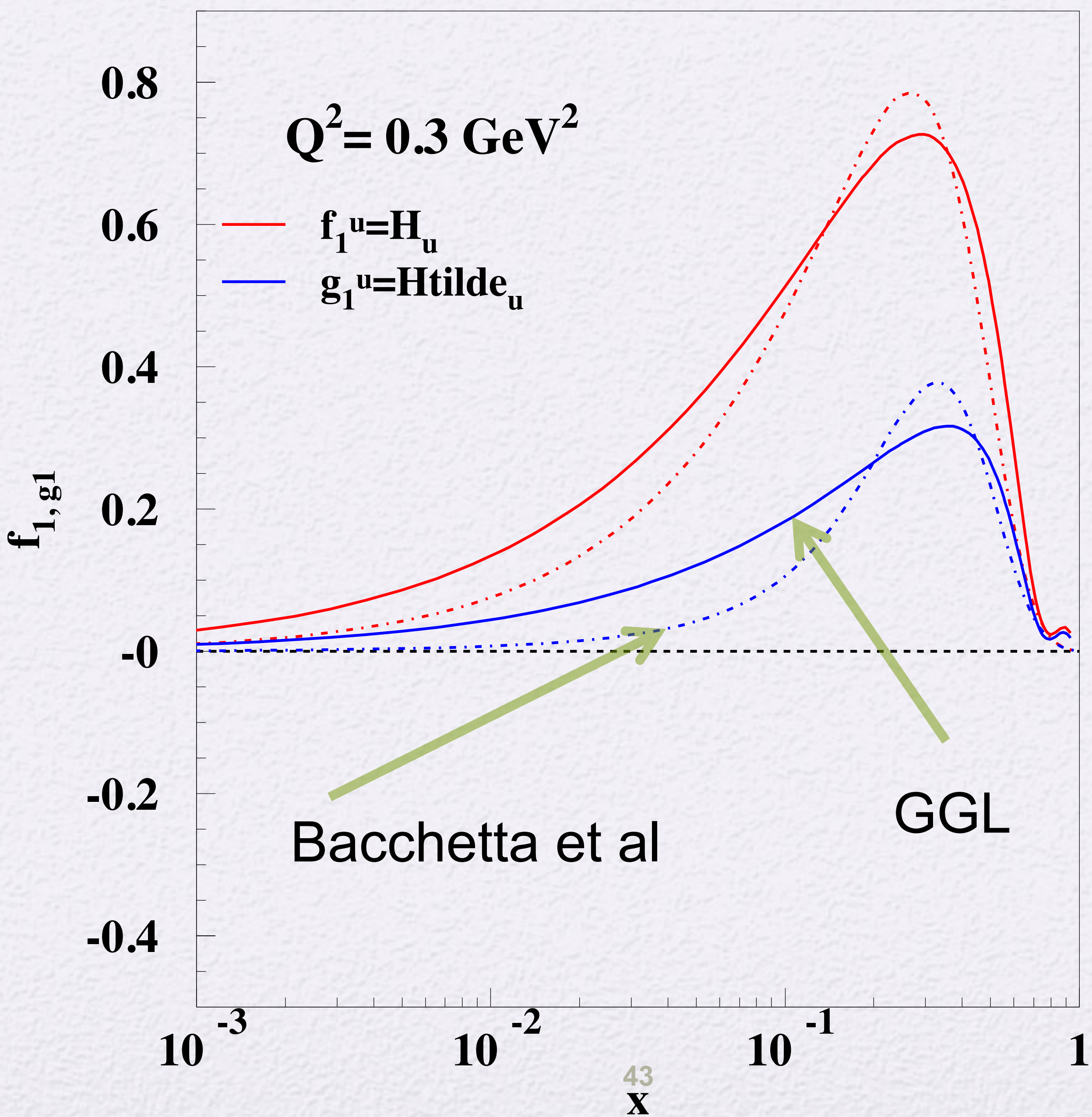
$$E_T^{(1)} = 2E^{(1)} \tag{28b}$$

$$\tilde{E}_T^{(1)} = 0 \tag{28c}$$

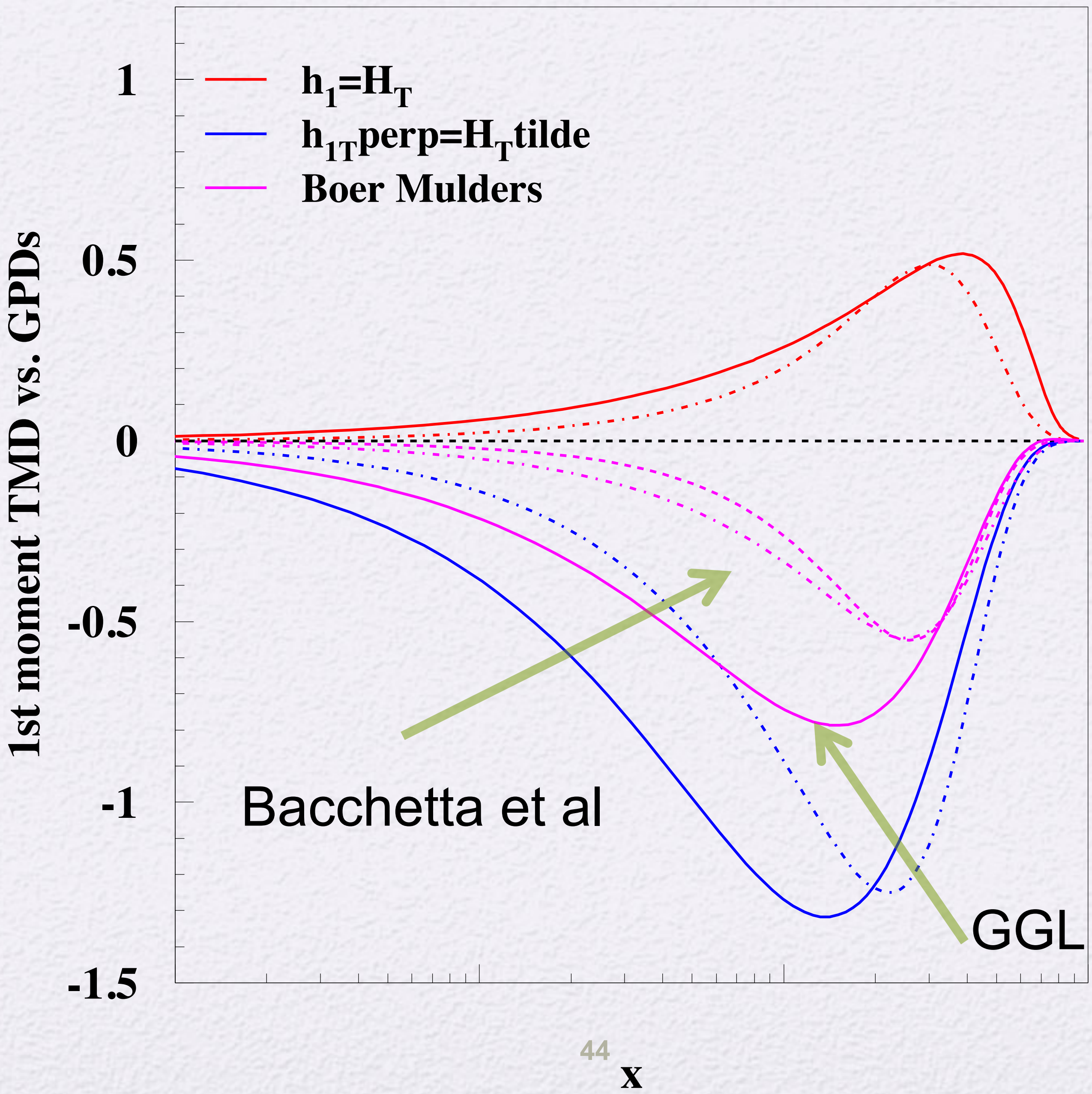
$$H_T^{(1)} = -\frac{2x}{1+x^2} \frac{H^{(1)} + \tilde{H}^{(1)}}{2} \tag{28d}$$

Odd

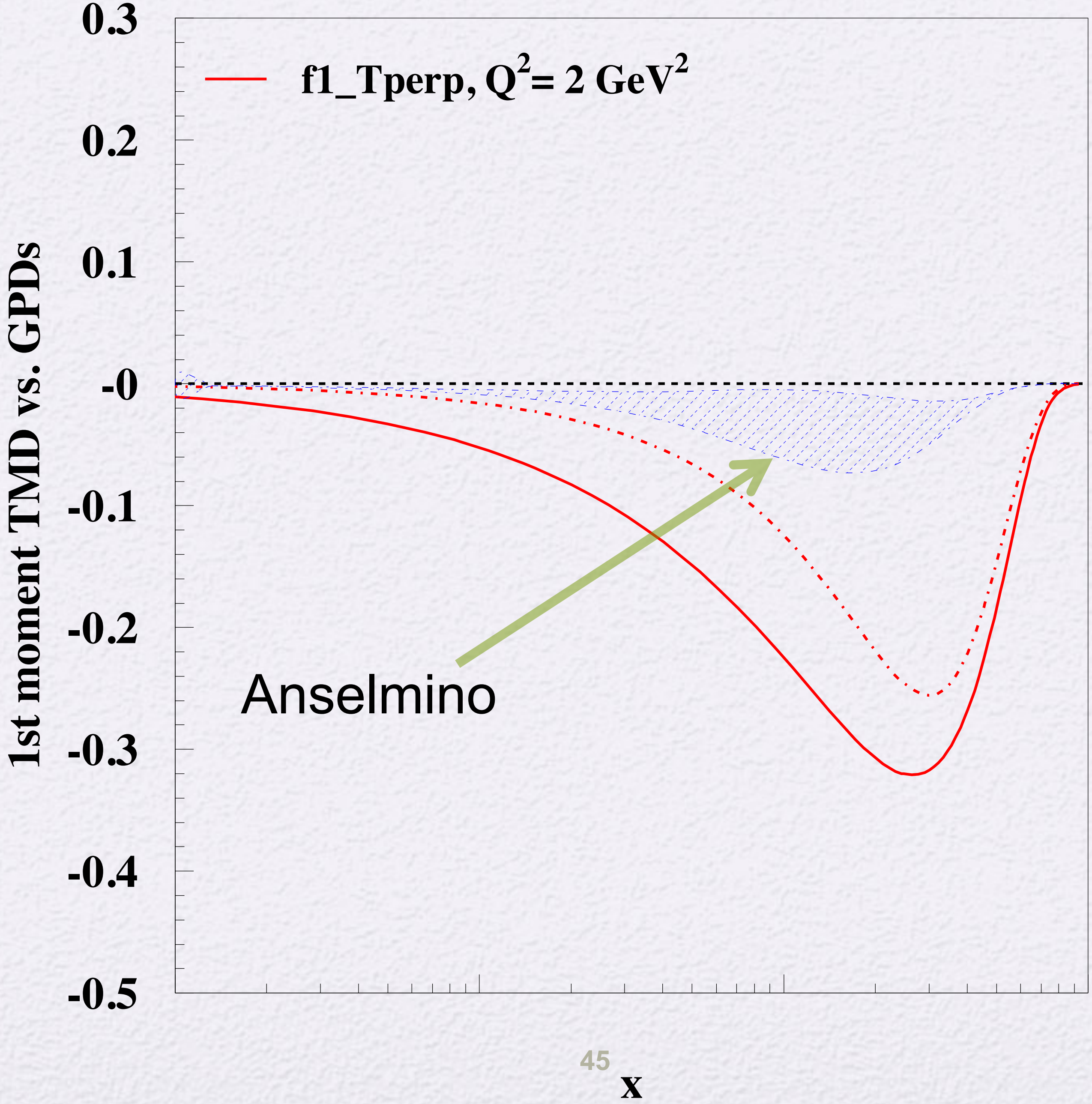
Even



0.8
0.6
0.4
0.2
-0
-0.2
-0.4
Q^2= 0.3 GeV^2
f_1^u=H_u
g_1^u=Htilde$_u$
$f_{1,g1}$
Bacchetta et al
GGL
10^{-3}
10^{-2}
10^{-1}
1
x

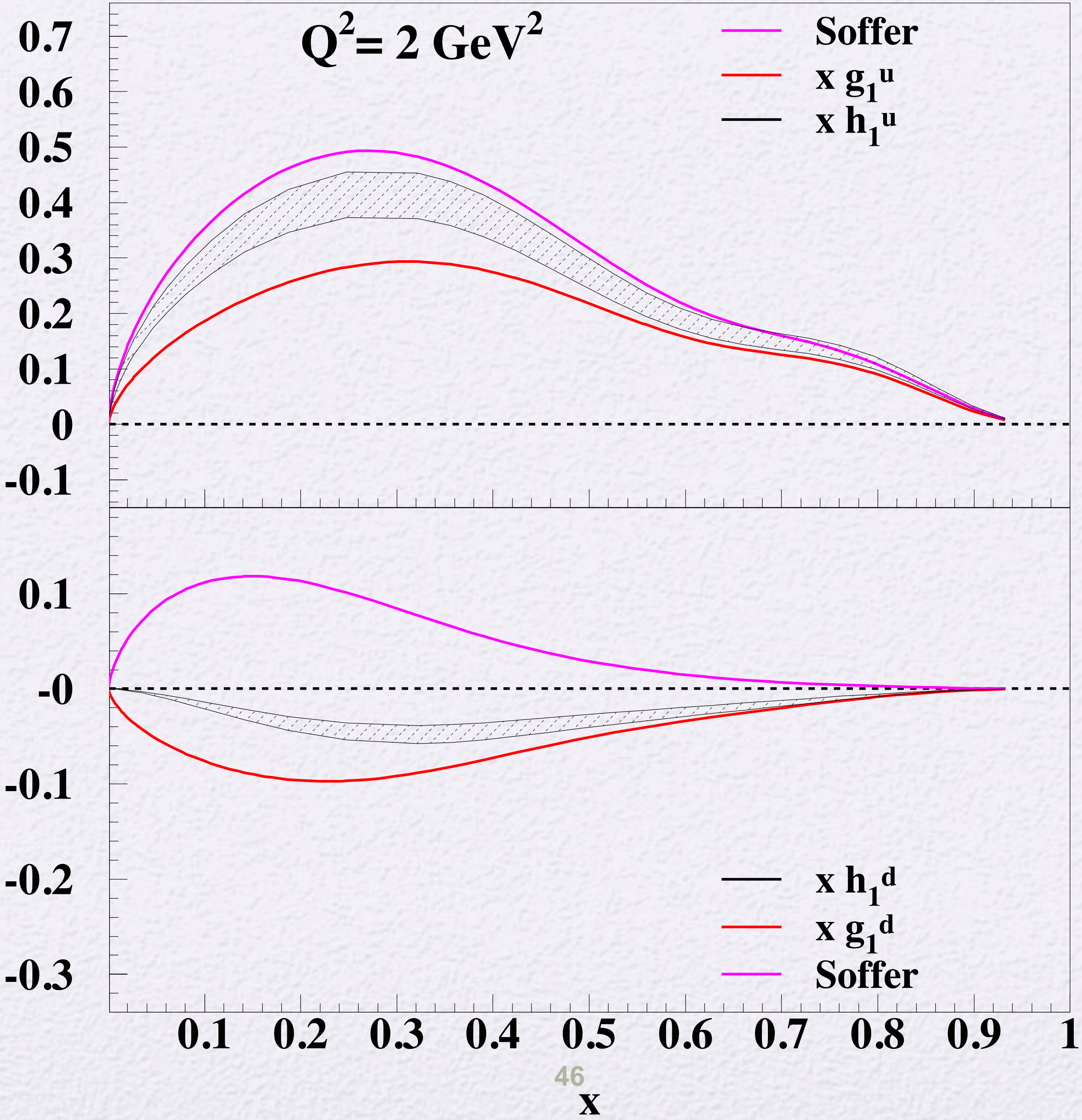


1
0.5
0
-0.5
-1
-1.5
1st moment TMD vs. GPDs
x
h1=HT
h1Tperp=HTtilde
Boer Mulders
Bacchetta et al
GGL

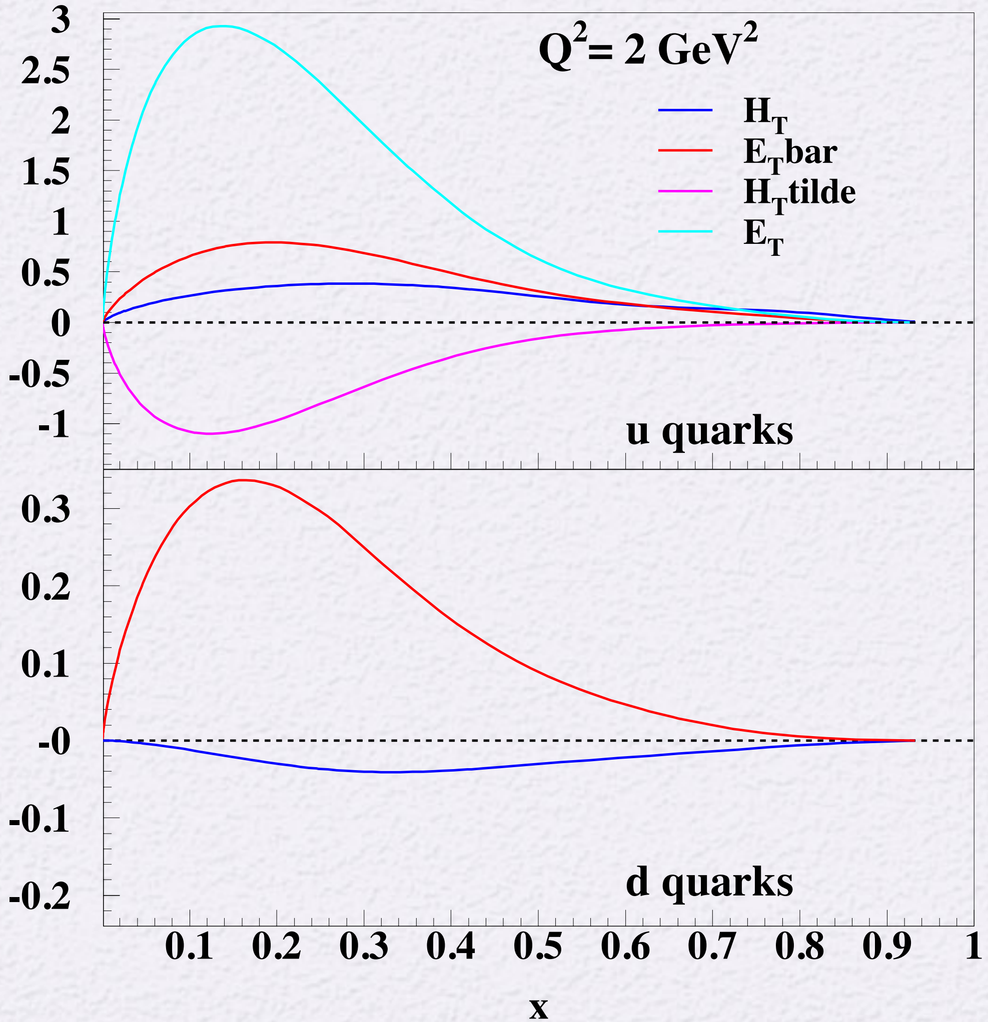


f1_Tperp, Q^2= 2 GeV^2
0.3
0.2
0.1
-0
-0.1
-0.2
-0.3
-0.4
-0.5
1st moment TMD vs. GPDs
Anselmino
x

h_1, g_1



Q²= 2 GeV²
Soffer
x g₁ᵘ
x h₁ᵘ
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0.1
-0
-0.1
-0.2
-0.3
x h₁ᵈ
x g₁ᵈ
Soffer
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
x



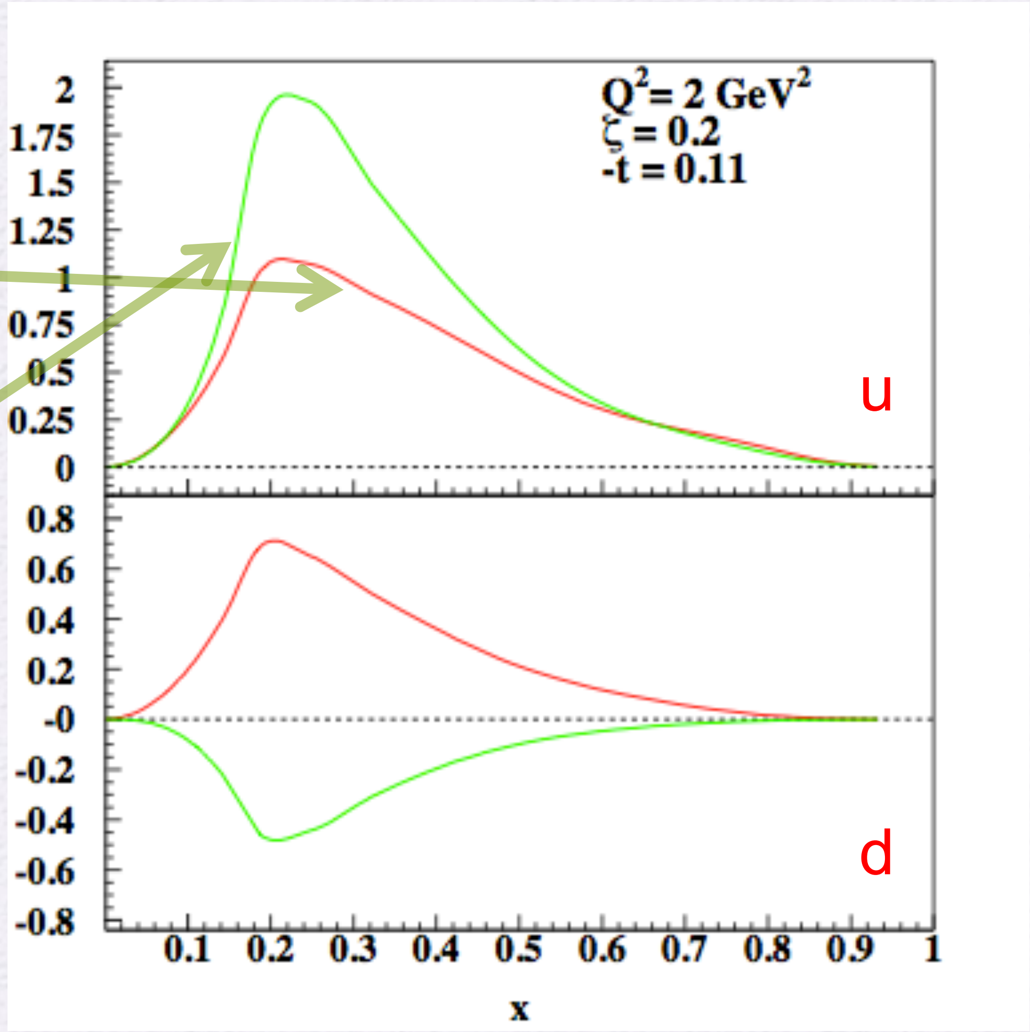
$Q^2 = 2\ GeV^2$
H_T
$E_T$bar
$H_T$tilde
E_T
u quarks
d quarks
x

$$\sum_\Lambda \Im m\, F_{\Lambda+,\Lambda-} \propto h_1^\perp(x,k_T^2) \qquad \Longleftrightarrow \qquad A_{++,+-} - A_{+-,++} \propto 2\tilde{H}_T + E_T$$

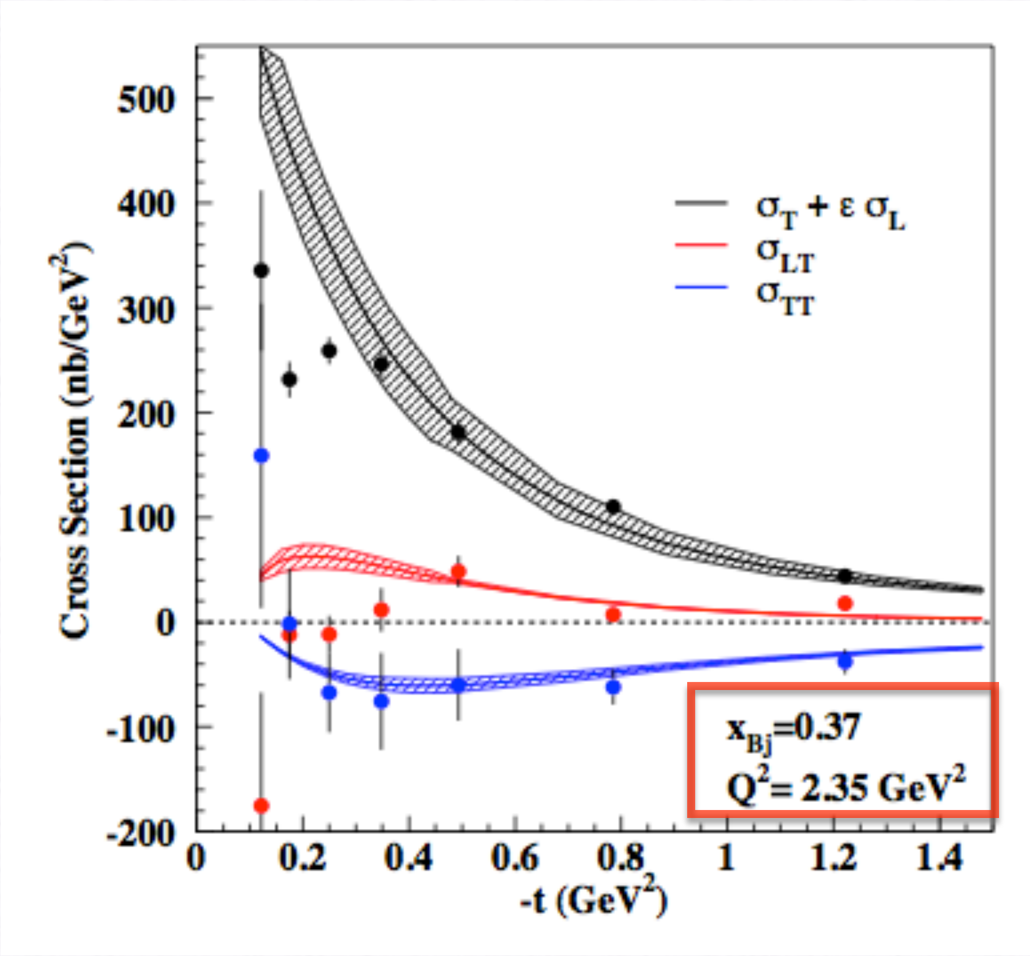
$$\sum_\lambda \Im m\, F_{+\lambda,-\lambda} \propto f_{1T}^\perp(x,k_T^2) \qquad \qquad A_{++,-+} - A_{-+,++} \propto E$$

(h_1^T) $2\tilde{H}_T + E_T$

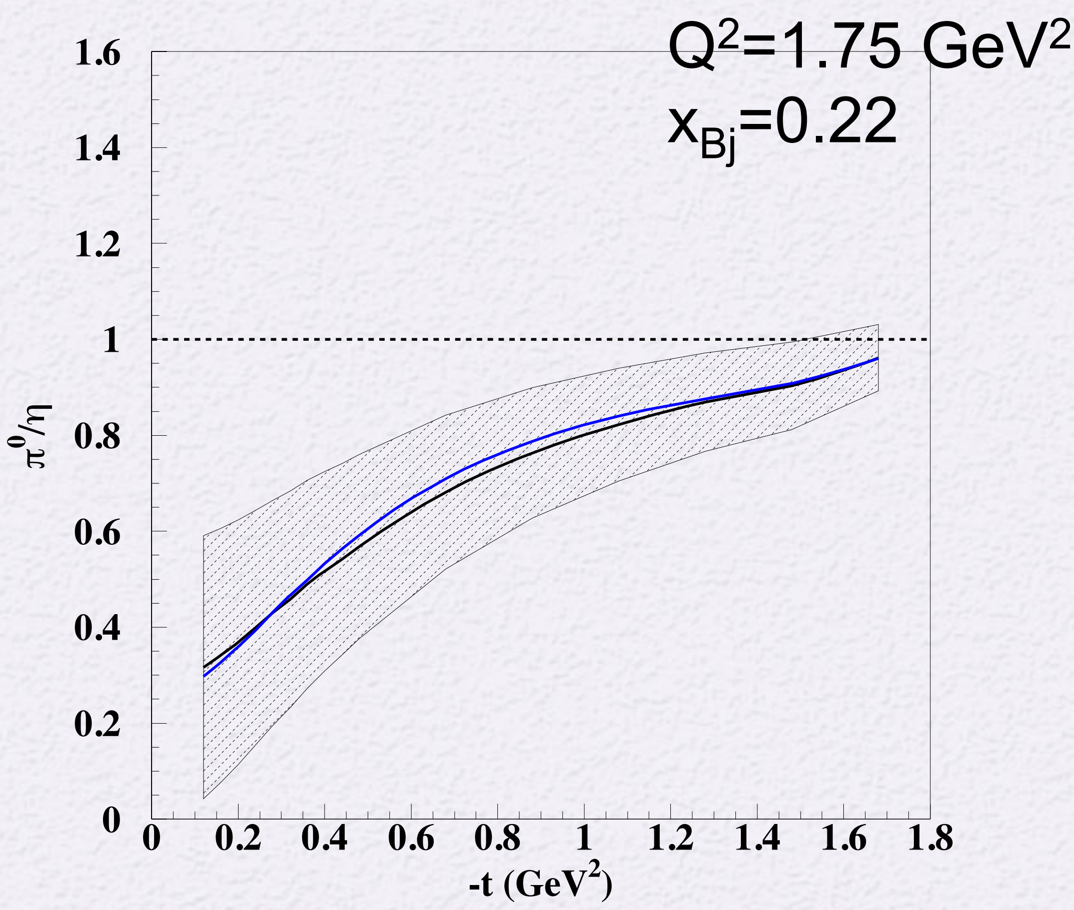
$\tilde{E}_T$



How well do the parameters fixed with DVCS data reproduce π^o electroproduction data?



Hall B data, Kubarovsky& Stoler, PoS ICHEP 2010


Q2=1.75 GeV2
xBj=0.22
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
π0/η
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
-t (GeV2)

Vary tensor charge as a parameter to see sensitivity of data

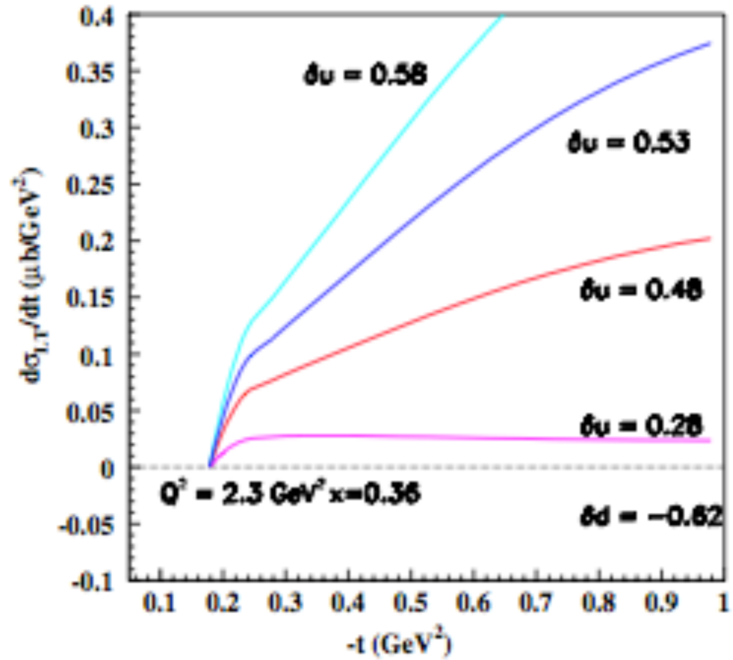


FIG. 9 (color online). (color online) Longitudinal/transverse interference term, $d\sigma_{LT}/dt$, Eq. (15), plotted vs $-t$ at $Q^2 = 2.3\ \mathrm{GeV}^2$, $x_{Bj} = 0.36$, for different values of the u quarks tensor charge, δu, used as a freely varying parameter in the GPD approach. The d quark component, δd was taken as $\delta d = -0.62$, i.e. equal to the central value extracted in the global fit of Ref. [44].

Q^2 dependence ➔obviously not predicted by collinear factorization

✓ Presence of a large transverse component

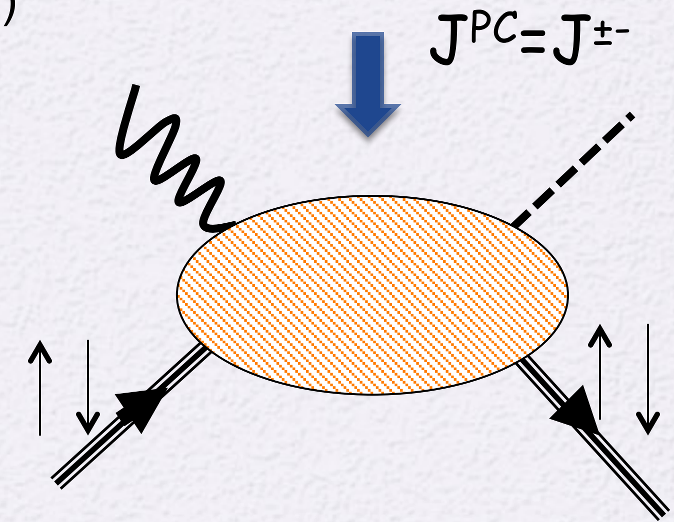
✓ "Anomalous" Pion Vertex behavior

Back up

Explain large T component

M.Diehl, Phys.Rep.(2003)

Chiral Even GPD	J^{PC}	
$H(x,\xi,t) - H(-x,\xi,t)$	$0^{++}, 2^{++}, \ldots$	$(S=1)$
$E(x,\xi,t) - E(-x,\xi,t)$	$0^{++}, 2^{++}, \ldots$	$(S=1)$
$\widetilde{H}(x,\xi,t) + \widetilde{H}(-x,\xi,t)$	$1^{++}, 3^{++}, \ldots$	$(S=1)$
$\widetilde{E}(x,\xi,t) + \widetilde{E}(-x,\xi,t)$	$0^{-+}, 1^{++}, 2^{-+}, 3^{++}, \ldots$	$(S=0,1)$
$H(x,\xi,t) + H(-x,\xi,t)$	$1^{--}, 3^{--}, \ldots$	$(S=1)$
$E(x,\xi,t) + E(-x,\xi,t)$	$1^{--}, 3^{--}, \ldots$	$(S=1)$
$\widetilde{H}(x,\xi,t) - \widetilde{H}(-x,\xi,t)$	$2^{--}, 4^{--}, \ldots$	$(S=1)$
$\widetilde{E}(x,\xi,t) - \widetilde{E}(-x,\xi,t)$	$1^{+-}, 2^{--}, 3^{+-}, 4^{--}, \ldots$	$(S=0,1)$



GGL, arXiv:hep-ph 1201.6088

Chiral Odd GPD	J^{-C}		J^{+C}	
$H_T(x,\xi,t) - H_T(-x,\xi,t)$	$2^{-+}, 4^{-+}, \ldots$	$(S=0)$	$1^{++}, 3^{++} \ldots$	$(S=1)$
$E_T(x,\xi,t) - E_T(-x,\xi,t)$	$2^{-+}, 4^{-+}, \ldots$	$(S=0)$	$1^{++}, 3^{++} \ldots$	$(S=1)$
$\widetilde{H}_T(x,\xi,t) - \widetilde{H}_T(-x,\xi,t)$			$1^{++}, 3^{++}, \ldots$	$(S=1)$
$\widetilde{E}_T(x,\xi,t) - \widetilde{E}_T(-x,\xi,t)$	$2^{-+}, 4^{-+}, \ldots$	$(S=0)$	$3^{++}, 5^{++} \ldots$	$(S=1)$
$H_T(x,\xi,t) + H_T(-x,\xi,t)$	$1^{--}, 2^{--}, 3^{--} \ldots$	$(S=1)$	$1^{+-}, 3^{+-} \ldots$	(S=0)
$E_T(x,\xi,t) + E_T(-x,\xi,t)$	$1^{--}, 2^{--}, 3^{--} \ldots$	$(S=1)$	$1^{+-}, 3^{+-} \ldots$	(S=0)
$\widetilde{H}_T(x,\xi,t) + \widetilde{H}_T(-x,\xi,t)$	$1^{--}, 2^{--}, 3^{--} \ldots$	$(S=1)$		
$\widetilde{E}_T(x,\xi,t) + \widetilde{E}_T(-x,\xi,t)$	$2^{--}, 3^{--}, 4^{--} \ldots$	$(S=1)$	$3^{+-}, 5^{+-} \ldots$	(S=0)

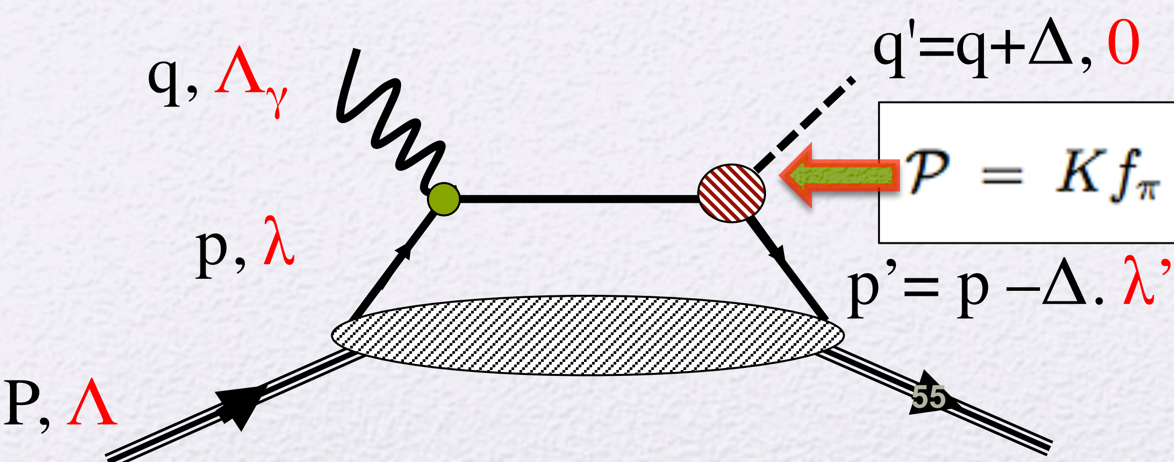
$\widetilde{H}(x,\xi,t)-\widetilde{H}(-x,\xi,t)$	$2^{--}, 4^{--}, \ldots$	$(S=1)$
$\widetilde{E}(x,\xi,t)-\widetilde{E}(-x,\xi,t)$	$1^{+-}, 2^{--}, 3^{+-}, 4^{--}, \ldots$	$(S=0,1)$

Polarized antiquarks

No!

All these combinations are possible, therefore…

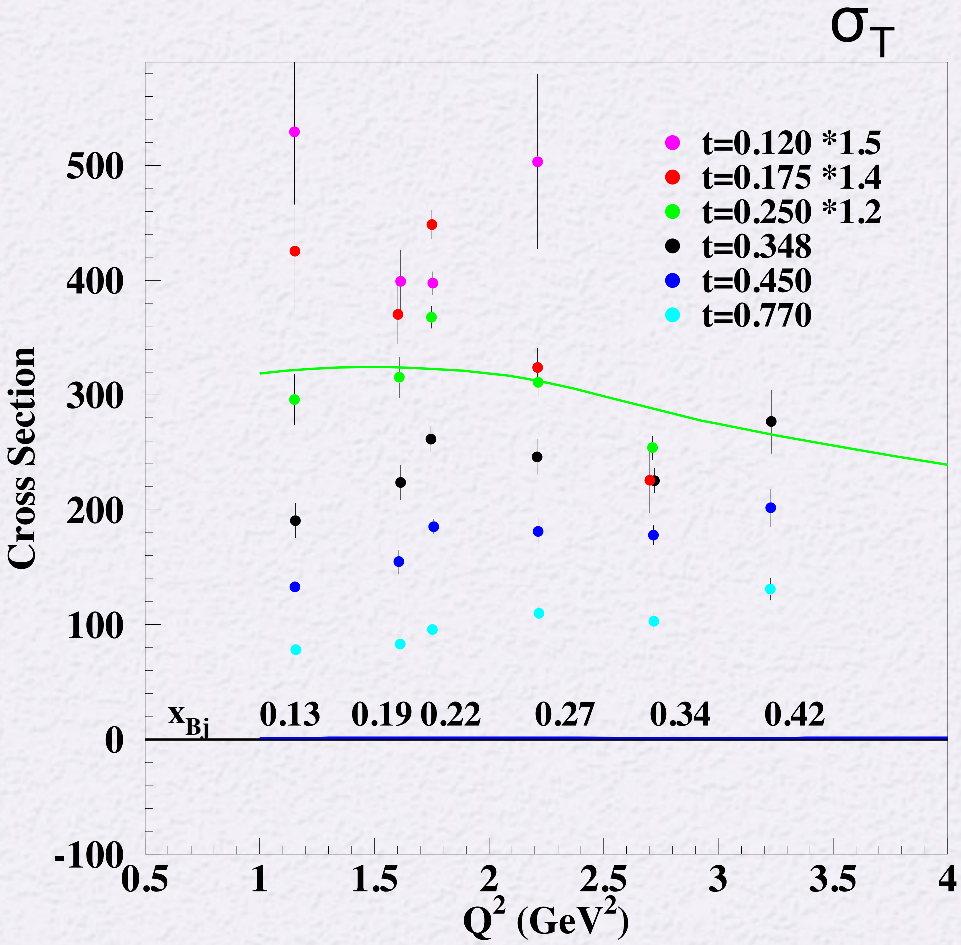
$H_T(x,\xi,t)+H_T(-x,\xi,t)$	$1^{--}, 2^{--}, 3^{--} \ldots$	$(S=1)$	$1^{+-}, 3^{+-} \ldots$	(S=0)
$E_T(x,\xi,t)+E_T(-x,\xi,t)$	$1^{--}, 2^{--}, 3^{--} \ldots$	$(S=1)$	$1^{+-}, 3^{+-} \ldots$	(S=0)
$\widetilde{H}_T(x,\xi,t)+\widetilde{H}_T(-x,\xi,t)$	$1^{--}, 2^{--}, 3^{--} \ldots$	$(S=1)$		
$\widetilde{E}_T(x,\xi,t)+\widetilde{E}_T(-x,\xi,t)$	$2^{--}, 3^{--}, 4^{--} \ldots$	$(S=1)$	$3^{+-}, 5^{+-} \ldots$	(S=0)

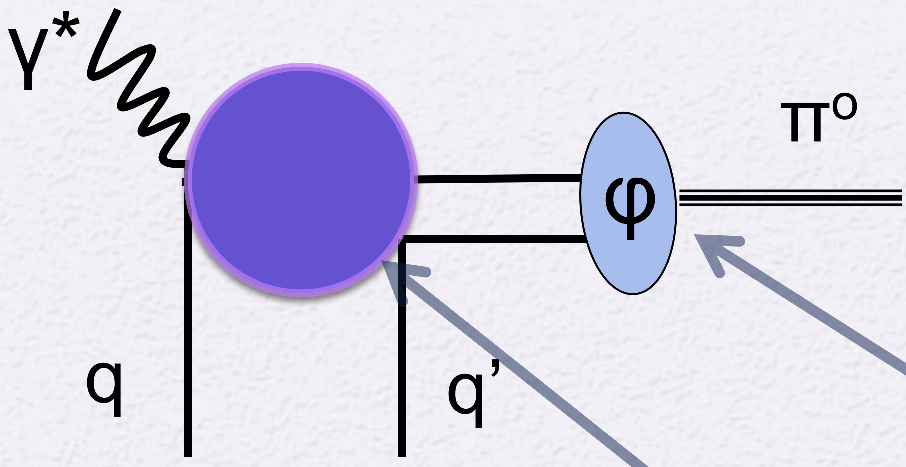


$$\boxed{\mathcal{P} = K f_\pi \left\{\cancel{\gamma_5 \not{q}' \phi_\pi(\tau)} + \gamma_5 \mu_\pi \phi_\pi^{(3)}(\tau)\right\}}$$

$\gamma_\mu \gamma_5$ γ_5

Now that we have allowed for a large T component, explain the Q^2 dependence….



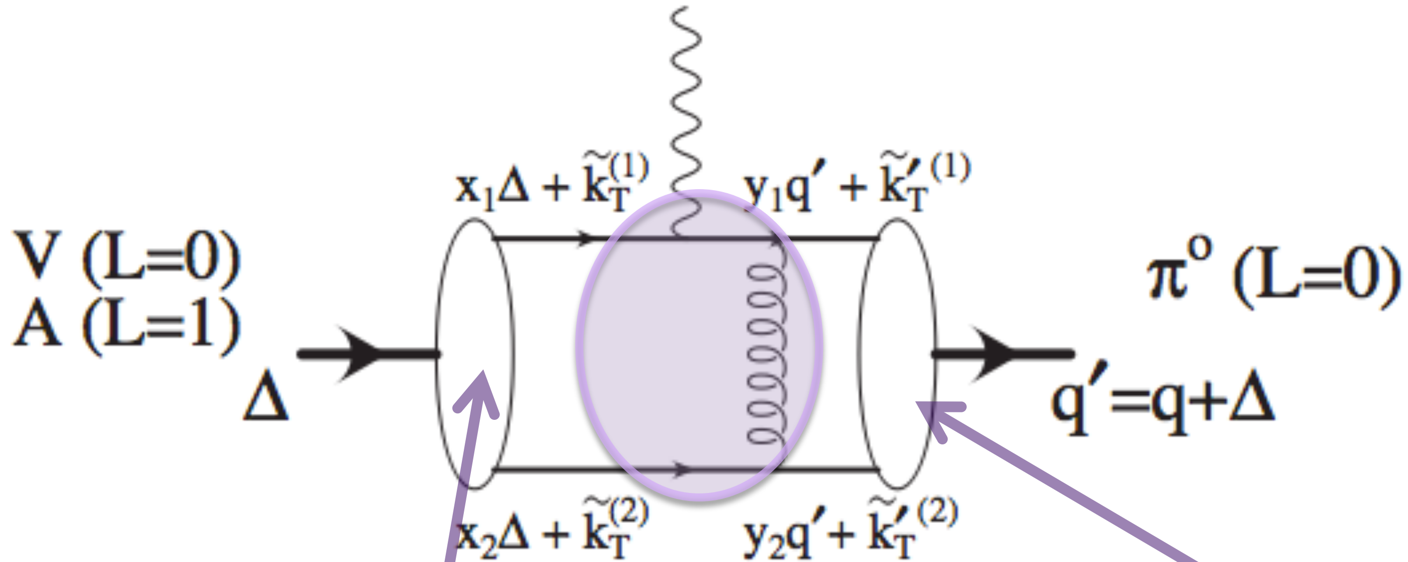


Take e.g. the modified perturbative approach

$$g_{\Lambda_{\gamma^*},\lambda;0,\lambda'} = \int d\tau \int d^2b \, \boxed{\hat{\mathcal{F}}_{\Lambda_{\gamma^*},\lambda;0,\lambda'}(Q^2,\tau,b)\alpha_S(\mu_R)} \, \boxed{\exp[-S]\hat{\phi}_\pi(\tau,b)}$$

Spin plays a role

LIUTI Ahmad et al., PHYSICAL REVIEW D 79, 054014 (2009



twist 3

"size matters"

$$g^V_{\Lambda_{\gamma^*},\lambda;0,\lambda'} = \int dx_1 dy_1 \int d^2b \, \boxed{\hat{\psi}_V(y_1,b)} \, \hat{F}_{\Lambda_{\gamma^*},\lambda;0,\lambda'}(Q^2,x_1,x_2,b)\alpha_S(\mu_R)\exp[-S] \, \boxed{\hat{\phi}_{\pi^o}(x_1,b)}$$

$$g^A_{\Lambda_{\gamma^*},\lambda;0,\lambda'} = \int dx_1 dy_1 \int d^2b \, \boxed{\hat{\psi}_A(y_1,b)} \, \hat{F}_{\Lambda_{\gamma^*},\lambda;0,\lambda'}(Q^2,x_1,x_2,b)\alpha_S(\mu_R)\exp[-S] \, \boxed{\hat{\phi}_{\pi^o}(x_1,b)}$$

V=1^{--}, 2^{--}, 3^{--}, … A=1^{+-}, 3^{+-}, …

Size of qqbar pair

We obtain a mixture of configurations of different "radii" (and different Q2 dependence)

✓ V ➔ π^o ➔ No change of OAM, $\Delta L=0$

✓ A ➔ π^o ➔ One unit change of OAM, $\Delta L=1$

Axial vector transition involves Bessel J_1

$$\psi_A^{(1)}(y_1, b) = \int d^2 k_T J_1(y_1 b) \psi(y_1, k_T),$$ qqbar pair are more separated!

Summary of Q^2 dependence

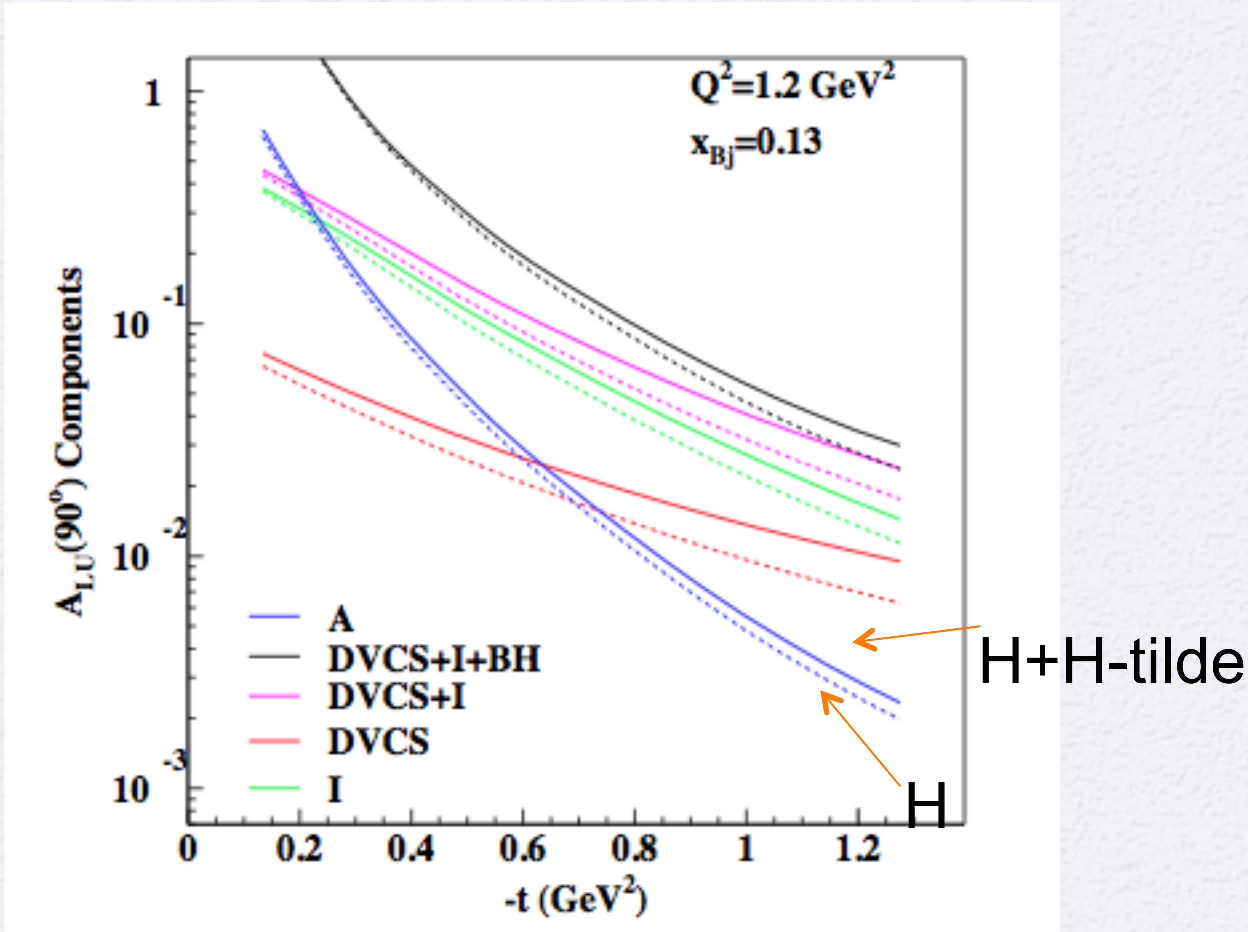
✓ Twist 3 DA has a steeper dependence in the longitudinal variable "x" yields larger contribution

✓ This can compensate for the fall off in Q^2

✓ Spin plays a role

(A connection is possible with A. Radyushkin's et al. interpretation of Babar data more channels including rho production need to be explored)

Role of BSA components: H and H-tilde



Goldstein et al. arXiv:1012.3776

Preliminary Results (PDFs)

(D. Perry, DIS 2010 and MS Thesis 2010, K. Holcomb, Exclusive Processes Workshop, Jlab 2010)

$Q^2 = 7.5\ GeV^2$