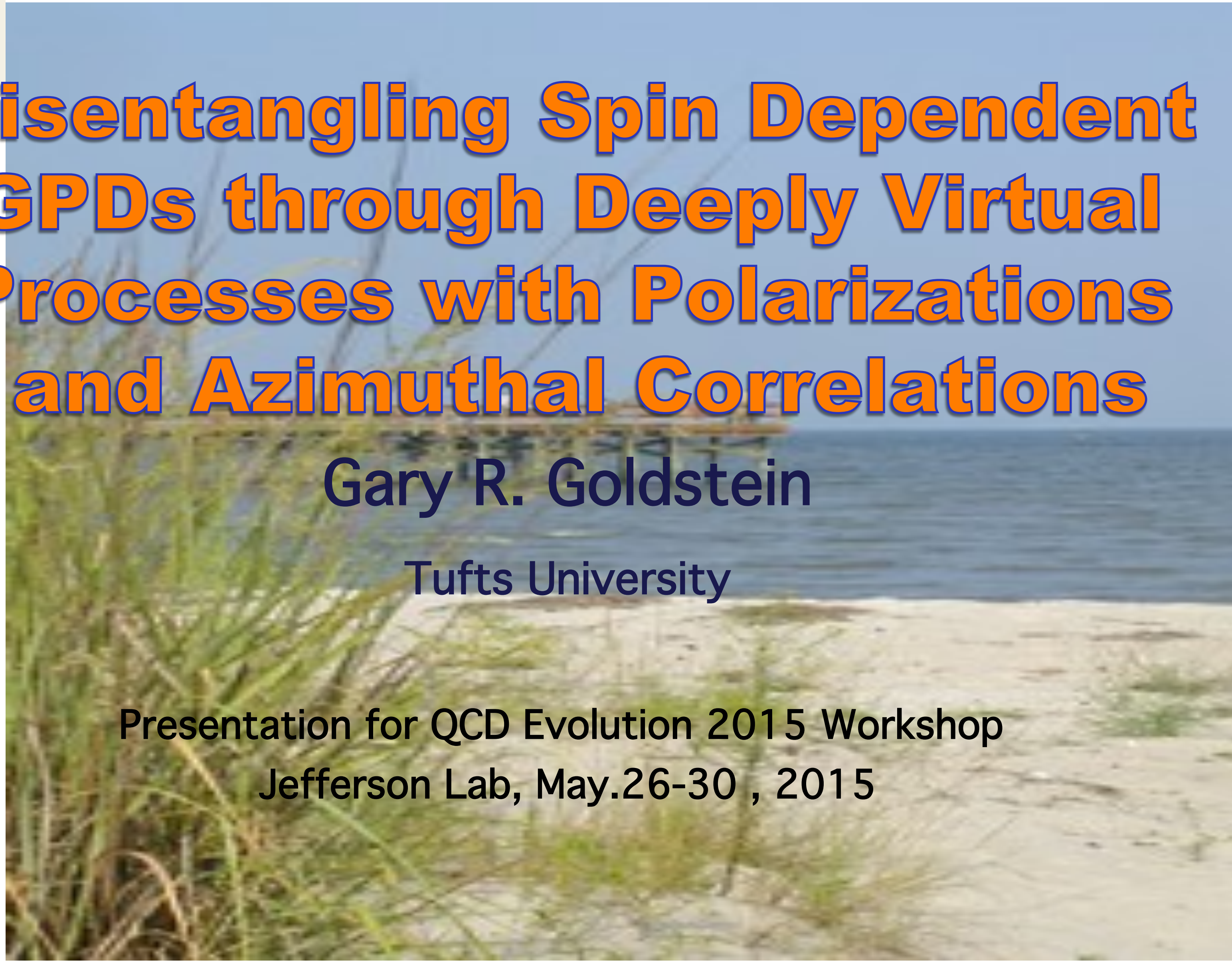


Disentangling Spin Dependent GPDs through Deeply Virtual Processes with Polarizations and Azimuthal Correlations

Gary R. Goldstein

Tufts University

Presentation for QCD Evolution 2015 Workshop

Jefferson Lab, May.26-30 , 2015

These ideas were developed in Jlab, Trento ECT*, INT, DIS2011, SPIN, Frascati INF, Transversity 2011-2013, PANIC, POETIC, QCD2015 & in consultation with many of you

Collaborators

GPDs, Extension to Chiral Odd Sector

S. Liuti, O. Gonzalez Hernandez

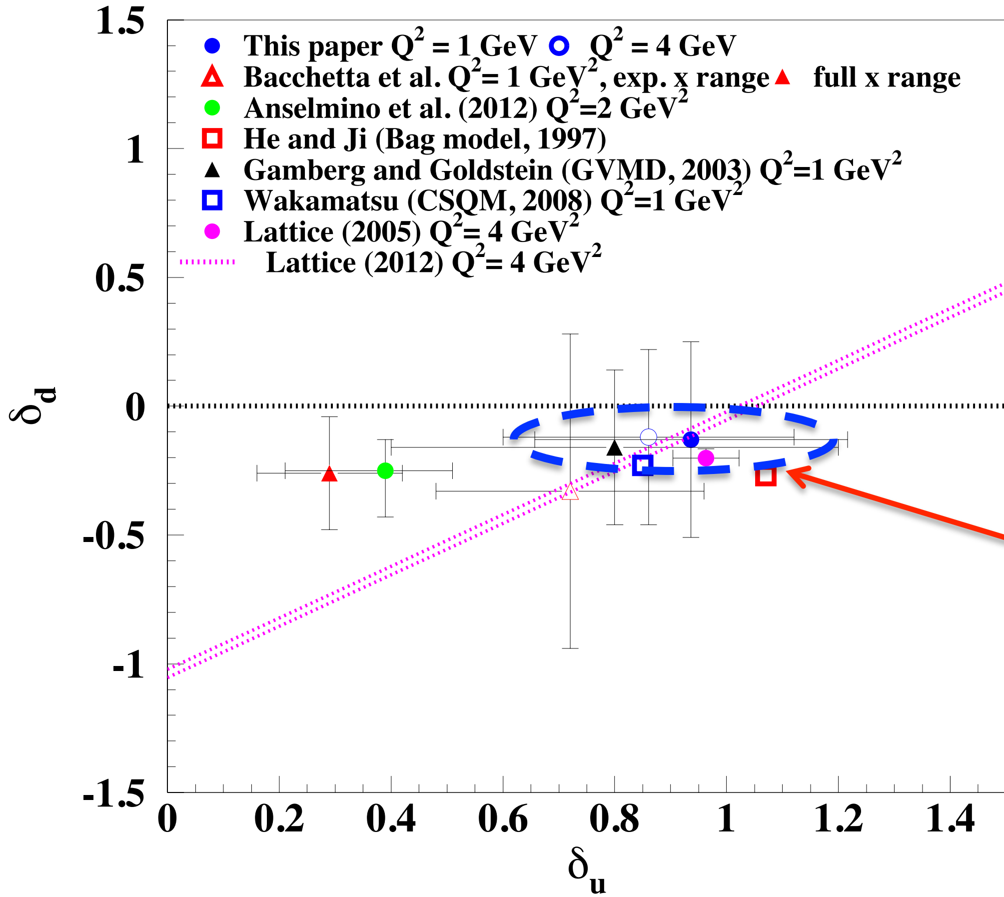
- GRG, O. Gonzalez-Hernandez, S.Liuti, PRD(2015) arXiv: 1311.0483
- GRG, O. Gonzalez-Hernandez, S.Liuti, arXiv:1401.0438
- Ahmad, GRG, Liuti, PRD79, 054014, (2009)
- Gonzalez, GRG, Liuti PRD84, 034007 (2011)
- GRG, Gonzalez Hernandez, Liuti, J. Phys. G: Nucl. Part. Phys. **39** 115001 (2012)
- Gonzalez Hernandez, Liuti, GRG, Kathuria, PRC88, 065206 (2013)

Outline

How to model & measure transversity, tensor charge & Chiral Odd GPDs

- Hadron Spatial Spin Structure from GPDs →
- Our "Flexible" parameterization for Chiral Even GPDs
  - Regge ✖ diquark spectator model: R✖Dq
  - Some results for DVCS (transverse γ^* → transverse γ)
  - EM Form factors
- **Extend to Chiral Odd GPDs** via diquark spin relations
- → Transversity
  - Model relations between Chiral even & odd helicity amps
  - π^0 & η production & flavor separation
  - Tensor charge δ_q
- Observables: Cross sections & Asymmetries
  - Which processes? Exclusive π^0 & η best candidates

Why look for Chiral odd GPDs? → Transversity → tensor charges δ_q



GPD definitions – 8 quark + 8 gluon

Momentum space nucleon matrix elements of quark field correlators

see, e.g. M. Diehl, Eur. Phys. J. C 19, 485 (2001).

$$\frac{1}{2}\int\frac{dz^-}{2\pi}\,e^{ixP^+z^-}\langle p',\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,\gamma^+\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$=\frac{1}{2P^+}\bar u(p',\lambda')\left[H^q\gamma^+ + E^q\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}\right]u(p,\lambda),$$

$$\frac{1}{2}\int\frac{dz^-}{2\pi}\,e^{ixP^+z^-}\langle p',\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,\gamma^+\gamma_5\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$=\frac{1}{2P^+}\bar u(p',\lambda')\left[\tilde H^q\gamma^+\gamma_5 + \tilde E^q\frac{\gamma_5\Delta^+}{2m}\right]u(p,\lambda),$$

Chiral even GPDs
-> Ji sum rule

$$\left\langle J_q^x\right\rangle = \tfrac{1}{2}\int dx\left[H(x,0,0)+E(x,0,0)\right]x$$

$$\frac{1}{2}\int\frac{dz^-}{2\pi}\,e^{ixP^+z^-}\langle p',\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,i\sigma^{+i}\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$=\frac{1}{2P^+}\bar u(p',\lambda')\left[H_T^q\,i\sigma^{+i} + \tilde H_T^q\,\frac{P^+\Delta^i-\Delta^+P^i}{m^2}\right.$$
$$\left. + E_T^q\,\frac{\gamma^+\Delta^i-\Delta^+\gamma^i}{2m} + \tilde E_T^q\,\frac{\gamma^+P^i-P^+\gamma^i}{m}\right]u(p,\lambda$$

Chiral odd GPDs
-> transversity
How to measure
and/or
parameterize them?

quark GPDs

- 8 quark GPDs per flavor (leading twist)
- N→q :: q´→ N´ 8 independent helicity amps
- 2 **questions**: how to model them?
- how to measure them?
- DVCS accesses 4 Chiral Even – $d\sigma/d\Omega$
- linearly via BH X DVCS interference
- DVπ^0S accesses 2 Chiral Even + ***4 Chiral Odd*** See F. Sabatié Jlab/HallA CIPANP talk
- because $d\sigma_T > d\sigma_L$
- bilinearly via $d\sigma/d\Omega$ & polarization asymmetries
- See also - Goloskokov & Kroll EPJA47(2011)112 – Different approach

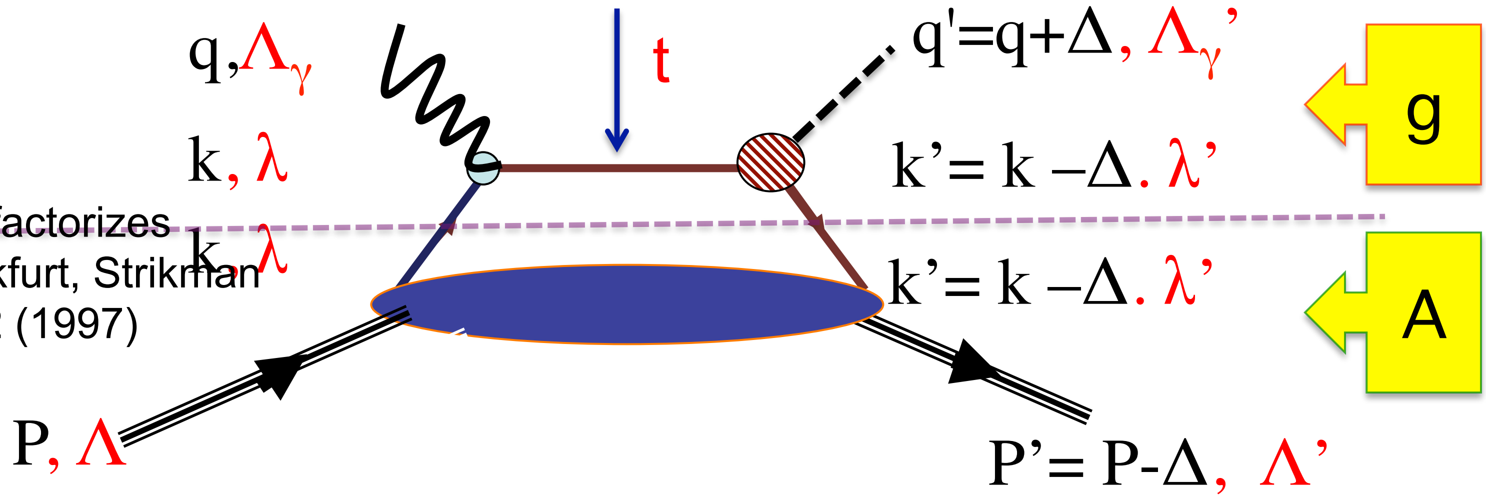
- **Other methods for extracting Chiral Odd**

DV dihadron production - El Beiyad, et al. Phys.Lett. B688 (2010) 154; M.Radici CIPANP talk
- DV longitudinal Vector meson production - Goloskokov & Kroll EPJC74(2014)2725

Factorization in exclusive processes (DVCS, DVMP…)

$$\gamma^* p \rightarrow \gamma(M) p'$$

Longitudinal factorizes
Collins, Frankfurt, Strikman
PRD56, 2982 (1997)



Convolution of "hard part" with quark-proton **Helicity** amplitudes

Regge X diquark model: Chiral Even: Ahmad, Honkanen, Liuti, Taneja PRD75, 094003 (2007); EPJC63, 407 (2009).

$$f_{\Lambda_\gamma,\Lambda;\Lambda'_\gamma,\Lambda'} = \sum_{\lambda,\lambda'} g_{\lambda,\lambda'}^{\Lambda_\gamma,\Lambda'_{\gamma(M)}}(x,k_T,\zeta,t;Q^2) \otimes A_{\Lambda',\lambda';\Lambda,\lambda}(x,k_T,\zeta,t),$$

λ= +(-) λ' chiral even (odd)

see Ahmad, GG, Liuti, PRD79, 054014, (2009)
for first chiral odd GPD parameterization
Gonzalez, GG, Liuti PRD84, 034007 (2011) chiral even GPD

Normalizing GPDs – Chiral even

Form factor, Forward limit

$$\int_0^1 H_q(x,\xi,t)\,dx = F_1^q(t), \quad H_q(x,0,0) = q(x)$$

Integrates to charge

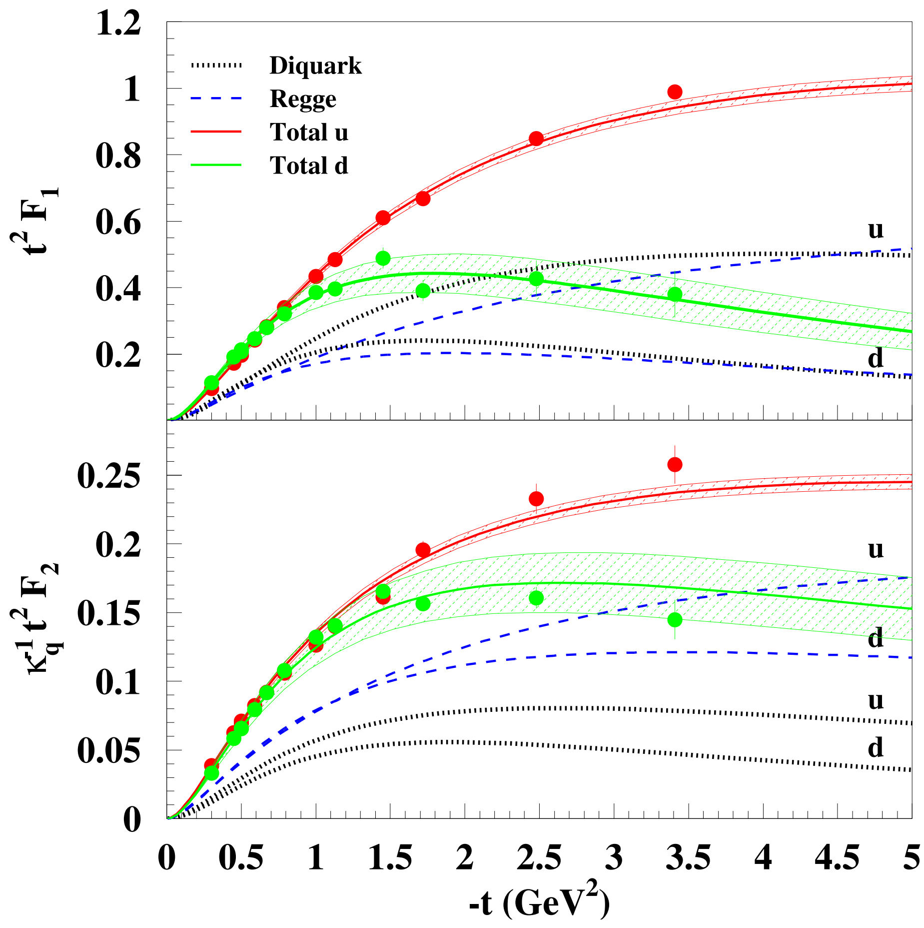
$$\int_0^1 E_q(x,\xi,t)\,dx = F_2^q(t)$$

$$\int_0^1 \tilde{H}_q(x,\xi,t)\,dx = g_A^q(t), \quad \tilde{H}_q(x,0,0) = \Delta q(x) = q_{\Rightarrow}^{\rightarrow}(x) - q_{\Rightarrow}^{\leftarrow}(x)$$

Integrates to axial charge

$$\int_0^1 \tilde{E}_q(x,\xi,t)\,dx = g_P^q(t)$$

EM Form Factors (t dependence)



O.Gonzalez, GRG, S.Liuti, K.Kathuria PRC88, 065206(2013)
data: G.D. Cates, et al. PRL106,252003 (2011).

The question is: how do we normalize chiral-odd GPDs?

Only Physical constraints on the various chiral-odd GPDs are

Forward limit

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

Transversity

Integrates to tensor charge δ_q

Form Factors

$$\int H_T^q(x,\xi,t)\,dx = \delta q(t)$$

"Tensor form factor"

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

Integrates to "transverse dipole moment" κ_T^q

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

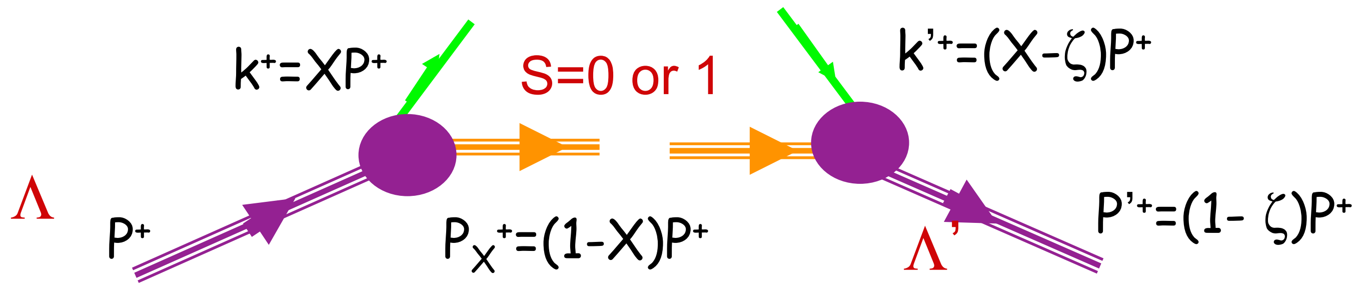
No direct interpretation of E_T

$$\lim_{t\to 0} \frac{t}{4M^2}\tilde{H}_T(x,0,t) = h_1^{\perp}(x)$$

The Model – Reggeized Diquarks

The Model – first for Chiral Even – Reggeized Diquarks

Procedure to construct Chiral Odd GPDs & observables



Product of diquark l.c.w.f.'s $\rightarrow A_{\Lambda\lambda;\Lambda'\lambda'=\lambda}$

↓

$A_{\Lambda\lambda;\Lambda'\lambda} \rightarrow$ chiral even GPDs

↓

$g \otimes A \rightarrow$ exclusive process helicity amps

↓

pdf's, FF's, $d\sigma/d\Omega$ & Asymmetries: parameters & predictions

↓

vertex parity$\rightarrow A_{\Lambda\lambda;-\Lambda'-\lambda'} \rightarrow$ chiral odd GPDs→pdf's, …

Recursive fit

GRG, Gonzalez Hernandez, Liuti, PRD84, 034007 (2011)

Advantage: control over the number of parameters to be fitted at different stages so that it can be optimized

Functional form:

From DIS

$$q(x,Q_o^2) = A_q\, x^{-\alpha_q}(1-x)^{\beta_q} F(x,c_q,d_q,\ldots)$$

to DVCS, DVMP

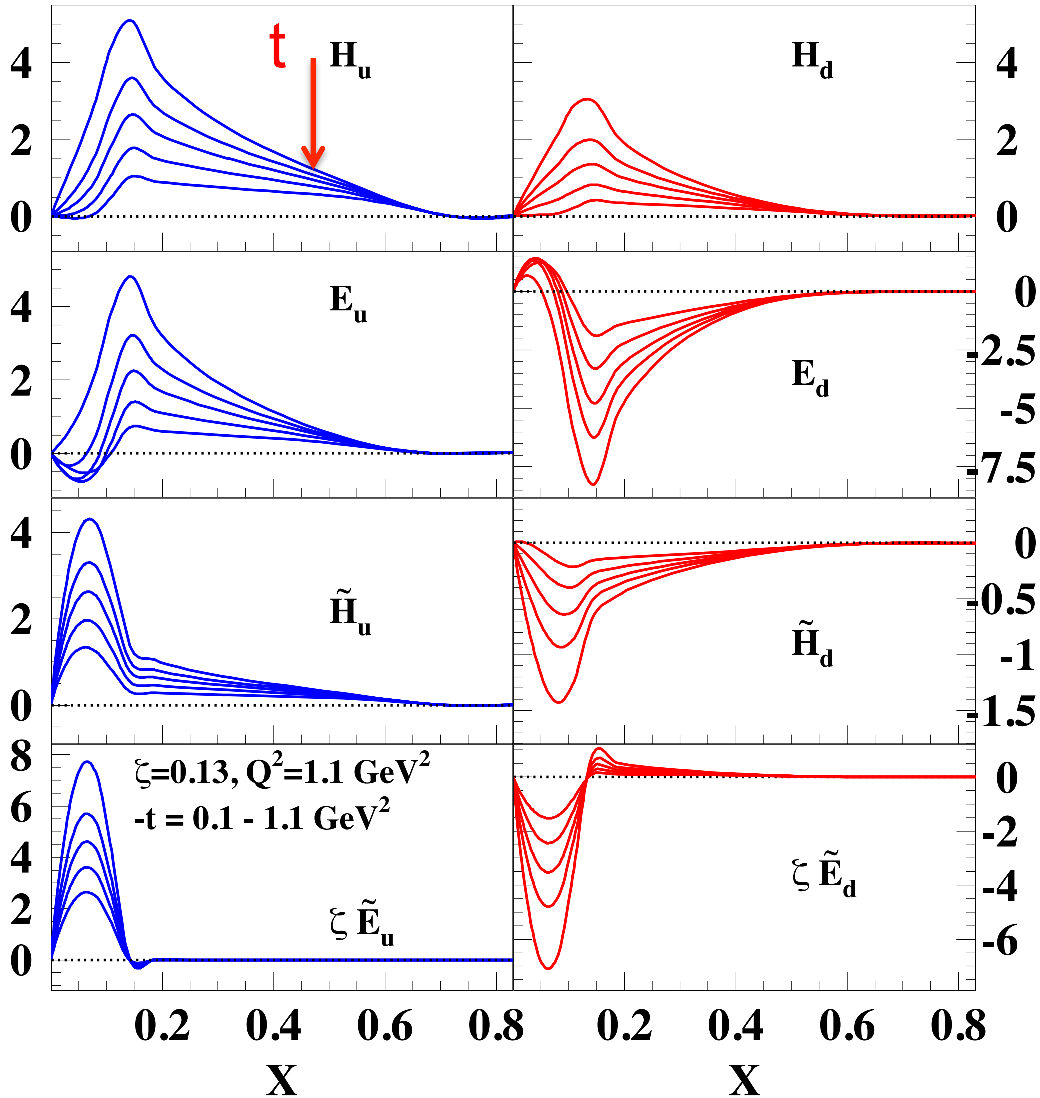
$$H_q(x,\xi,t;Q_o^2) = N_q\, x^{-\left[\alpha_q+\alpha'_q(1-x)^p t\right]} G^{a_1 a_2 a_3 ..}(x,\xi,t)$$

$$a_1 = m_q,\ a_2 = M_X^q,\ a_3 = M_\Lambda^q,\ldots$$

pdf's
Form Factors
$d\sigma / d\Omega$
Asymmetries

"Flexible" parameterization based on the Reggeized quark-diquark model.

Chiral even GPDs



From GPDs with evolution to Compton Form Factors

CFFs to helicity amps

helicity amps to observables

<-> parameters

Observables

Chiral Even

$$A_{\Lambda'\pm,\Lambda\pm} \Leftrightarrow H, E, \tilde{H}, \tilde{E}$$

Chiral Odd

$$A_{\Lambda'\pm,\Lambda\mp} \Leftrightarrow H_T, E_T, \tilde{H}_T, \tilde{E}_T$$

Compton Form Factors

$$\mathcal{H}(\xi,t;Q^2) = \int dx \left[\frac{1}{x-\xi-i\varepsilon} \mp \frac{1}{x+\xi-i\varepsilon} \right] H(x,\xi,t;Q^2)$$

$$\to \left(P.V. \int dx \frac{H(x,\xi,t;Q^2)}{x-\xi} + i\pi H(\xi,\xi,t;Q^2) \right) \mp (symm.term)$$

Re $\mathcal{H}$ Im $\mathcal{H}$

Having fit other data we predicted Hermes data

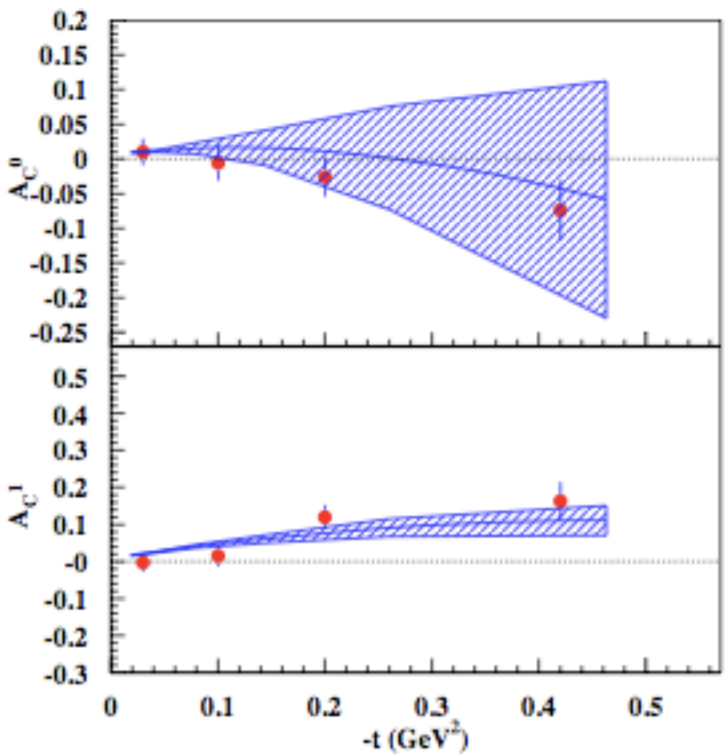


FIG. 20: Coefficients of the beam charge asymmetry, A_C, extracted from experiment [52, 53]. The lower panel is the coefficient for the cos ϕ dependent term in Eq.(82), while the upper panel is the cos ϕ independent term.

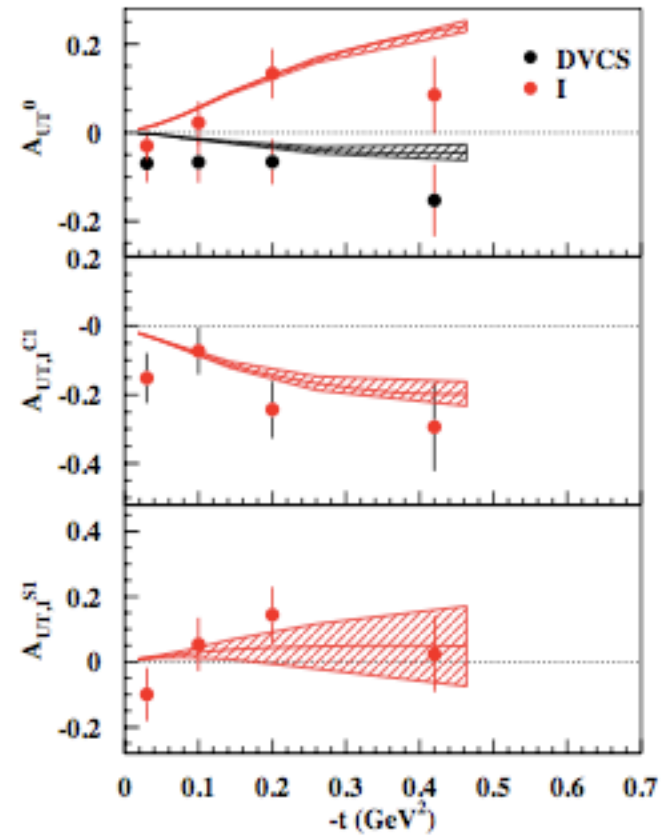
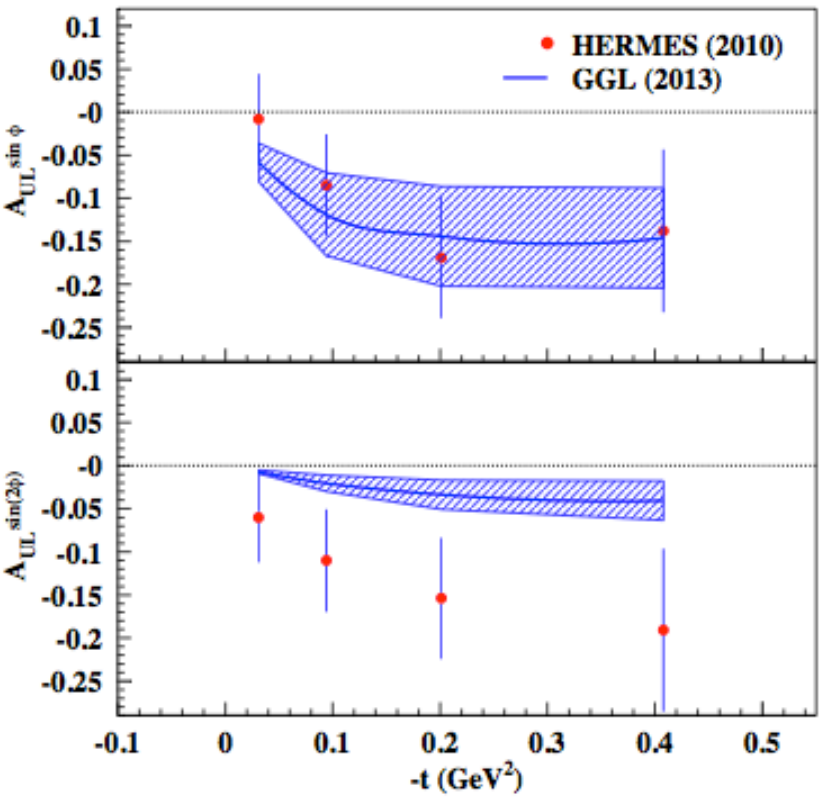


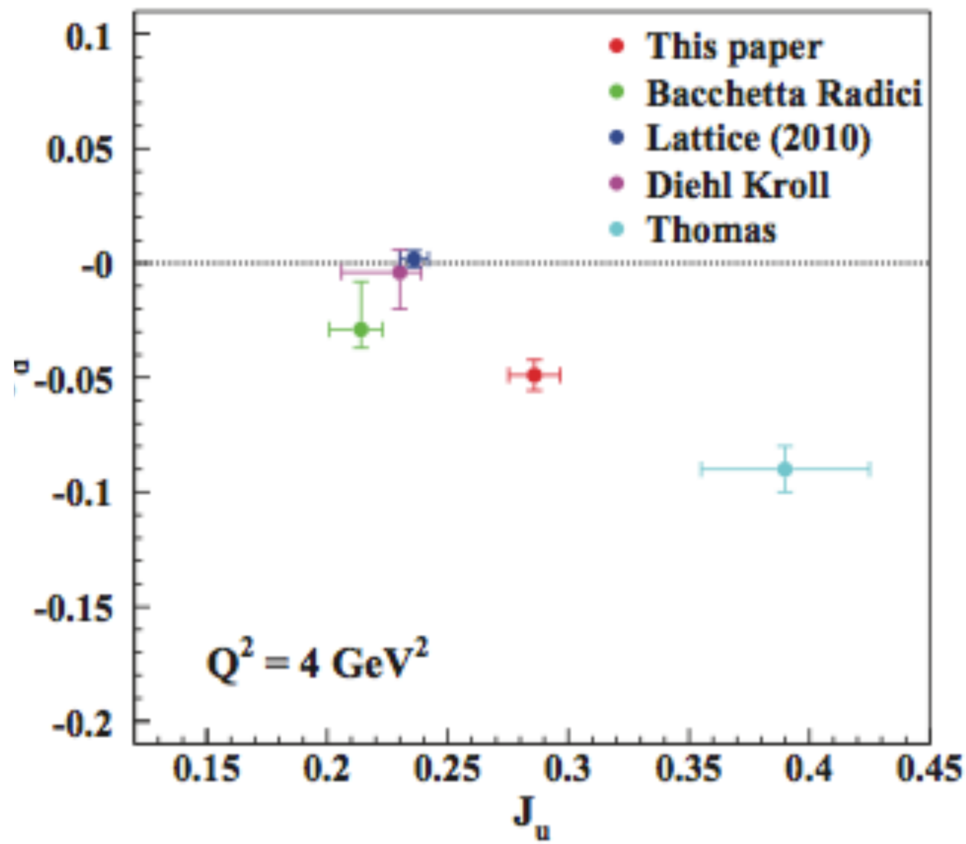
FIG. 21: Coefficients of the b[illegible]etry, A_{UT}, extracted from experiment [5[illegible]anel shows the terms E and F from Eqs.(83) and (84), respectively; the middle panel shows G, and the lower panel H, both in Eq.(84). The curves are predictions obtained extending our quantitative fit of Jefferson lab data to the Hermes set of observables.

Other chiral even predictions

Gonzalez Hernandez, Liuti, GG, Kathuria

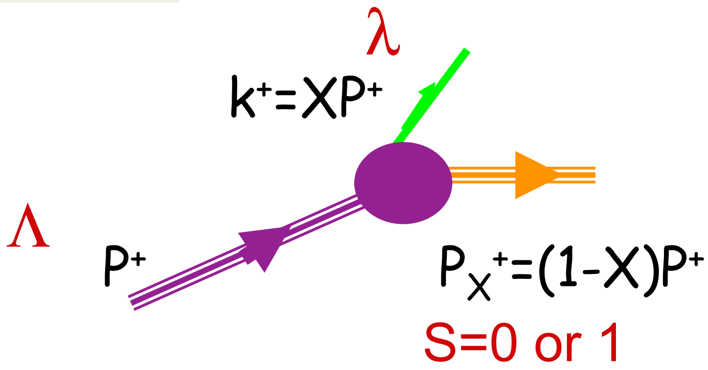
PHYSICAL REVIEW C **88**, 065206 (2013)

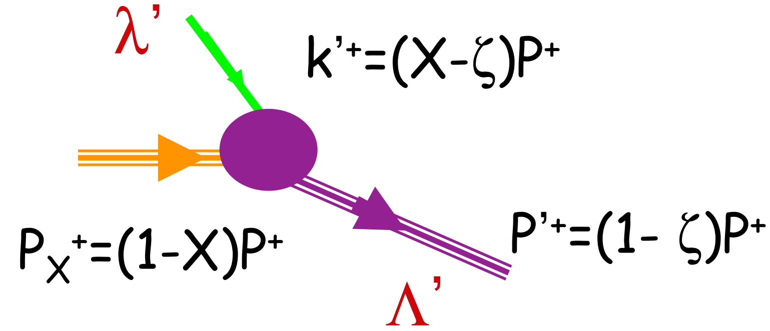




The Model for Chiral Odd – Reggeized Diquarks

Vertex Structures with Diquark Spectator





First focus on S=0 pure spectator - beginning

$$H \Rightarrow \varphi^*_{++}(k',P')\varphi_{++}(k,P) + \varphi^*_{-+}(k',P')\varphi_{-+}(k,P)$$

$$E \Rightarrow \varphi^*_{++}(k',P')\varphi_{+-}(k,P) + \varphi^*_{+-}(k',P')\varphi_{++}(k,P)$$

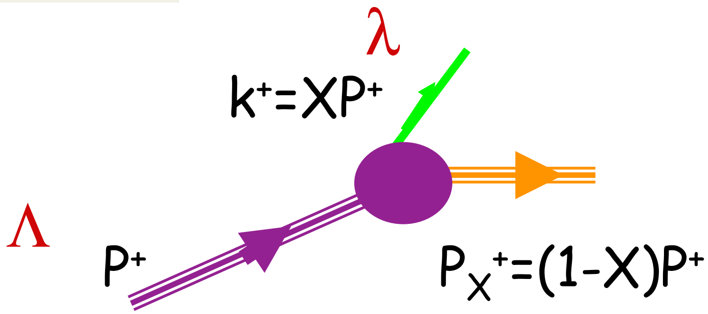
$$\tilde{H} \Rightarrow \varphi^*_{++}(k',P')\varphi_{++}(k,P) - \varphi^*_{-+}(k',P')\varphi_{-+}(k,P)$$

$$\tilde{E} \Rightarrow \varphi^*_{++}(k',P')\varphi_{+-}(k,P) - \varphi^*_{+-}(k',P')\varphi_{++}(k,P)$$

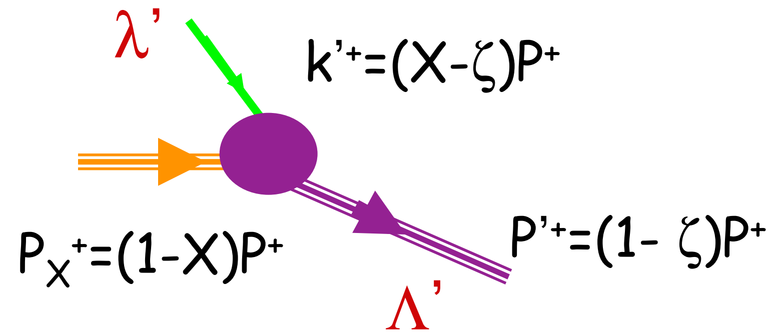
Vertex form factor function

$$\phi(k^2,\lambda) = \frac{k^2 - m^2}{|k^2 - \lambda^2|^2}.$$

Vertex Structures with Diquark Spectator



S=0 or 1



First focus on S=0 pure spectator - beginning

$$H \Rightarrow \varphi^*_{++}(k',P')\varphi_{++}(k,P) + \varphi^*_{-+}(k',P')\varphi_{-+}(k,P)$$

$$E \Rightarrow \varphi^*_{++}(k',P')\varphi_{+-}(k,P) + \varphi^*_{+-}(k',P')\varphi_{++}(k,P)$$

$$\tilde{H} \Rightarrow \varphi^*_{++}(k',P')\varphi_{++}(k,P) - \varphi^*_{-+}(k',P')\varphi_{-+}(k,P)$$

$$\tilde{E} \Rightarrow \varphi^*_{++}(k',P')\varphi_{+-}(k,P) - \varphi^*_{+-}(k',P')\varphi_{++}(k,P)$$

Parity at vertices:

By switching $\lambda \rightarrow -\lambda$ & $\Lambda \rightarrow -\Lambda$ (Parity) will have chiral evens go to ± chiral odds giving relations – <u>before k integrations</u>

$A(\Lambda'\lambda';\Lambda\lambda) \rightarrow \pm A(\Lambda',\lambda';-\Lambda,-\lambda)^*$

Vertex form factor

$$\phi(k^2,\lambda) = \frac{k^2 - m^2}{|k^2 - \lambda^2|^2}.$$

but then $(\Lambda'-\lambda')-(\Lambda-\lambda) \neq (\Lambda'-\lambda')+(\Lambda-\lambda)$ unless $\Lambda=\lambda$

S=0 Chiral even <-> odd helicity amps (+ S=1)

odd <-> even

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

t-channel flip·flip<->nonflip·nonflip
flip·nonflip<->nonflip·flip

Invert both sides to get GPDs – same helicity amp sets

$$\widetilde{H}^0_T = -(1-\zeta)^2 \frac{M(1-x)}{m+Mx'}\left[E^0 - \frac{\zeta}{2}\widetilde{E}^0\right]$$

$$E^0_T = -\frac{(1-\zeta/2)^2}{1-\zeta}\left[2\widetilde{H}^0_T - E^0 + \left(\frac{\zeta/2}{1-\zeta/2}\right)^2 \widetilde{E}^0\right]$$

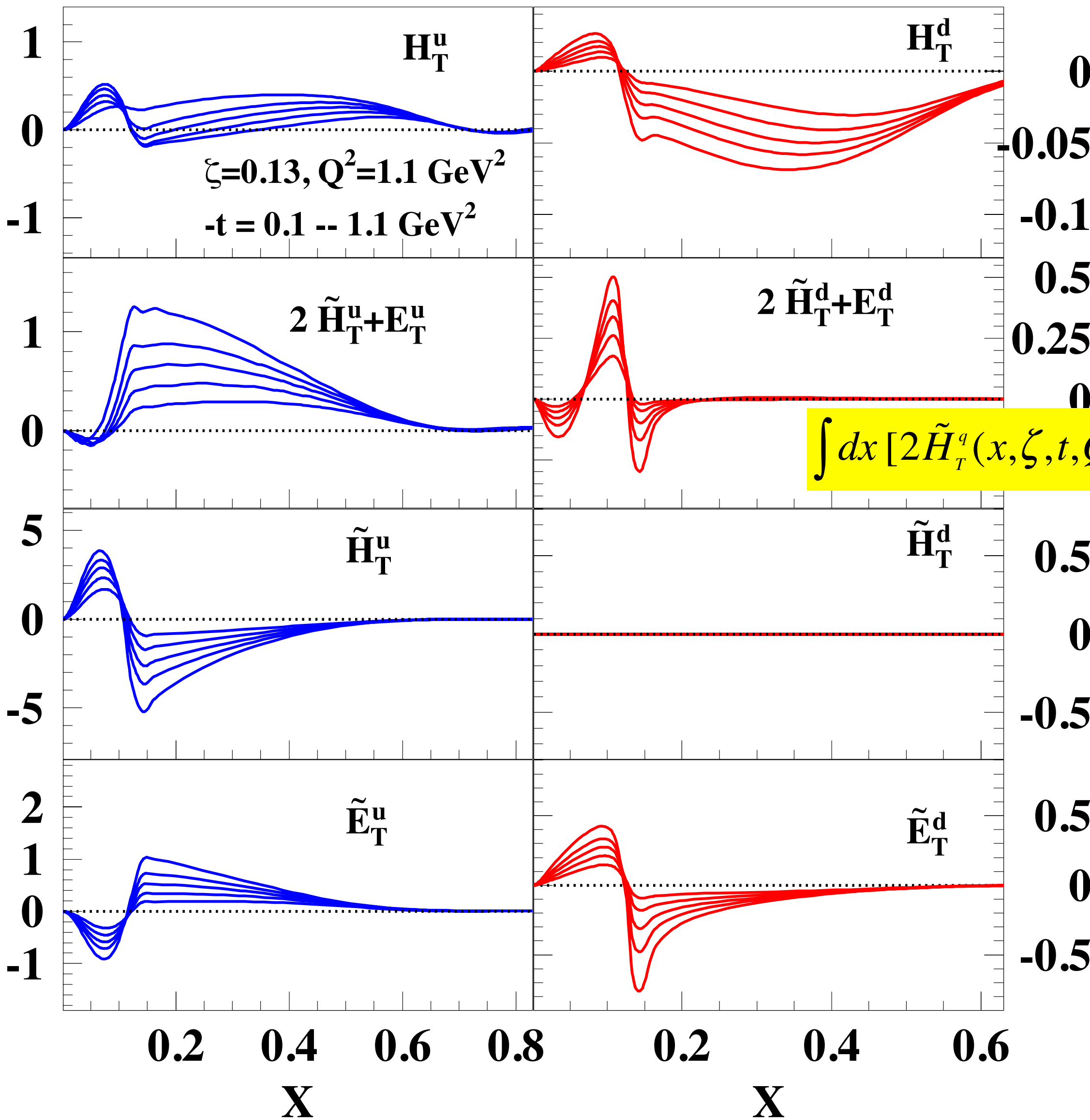
$$\widetilde{E}^0_T = -\frac{\zeta/2(1-\zeta/2)}{1-\zeta}\left[2\widetilde{H}^0_T - E^0 + \widetilde{E}^0\right]$$

$$H^0_T = \frac{H^0+\widetilde{H}^0}{2} - \frac{\zeta^2/4}{1-\zeta}\frac{E^0+\widetilde{\widetilde{E}}^0}{2} - \frac{\zeta^2/4}{(1-\zeta/2)(1-\zeta)}E^0_T + \frac{\zeta/4(1-\zeta/2)}{1-\zeta}\widetilde{E}^0_T + \widetilde{H}^0_T,$$

$S=0$ double helicity flip amplitude was calculated directly from Eq.(16),

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

RESULT: Chiral odd GPDs



$$\int dx\, H_T^q(x,\zeta,t,Q^2) = \delta_q(t,Q^2)$$

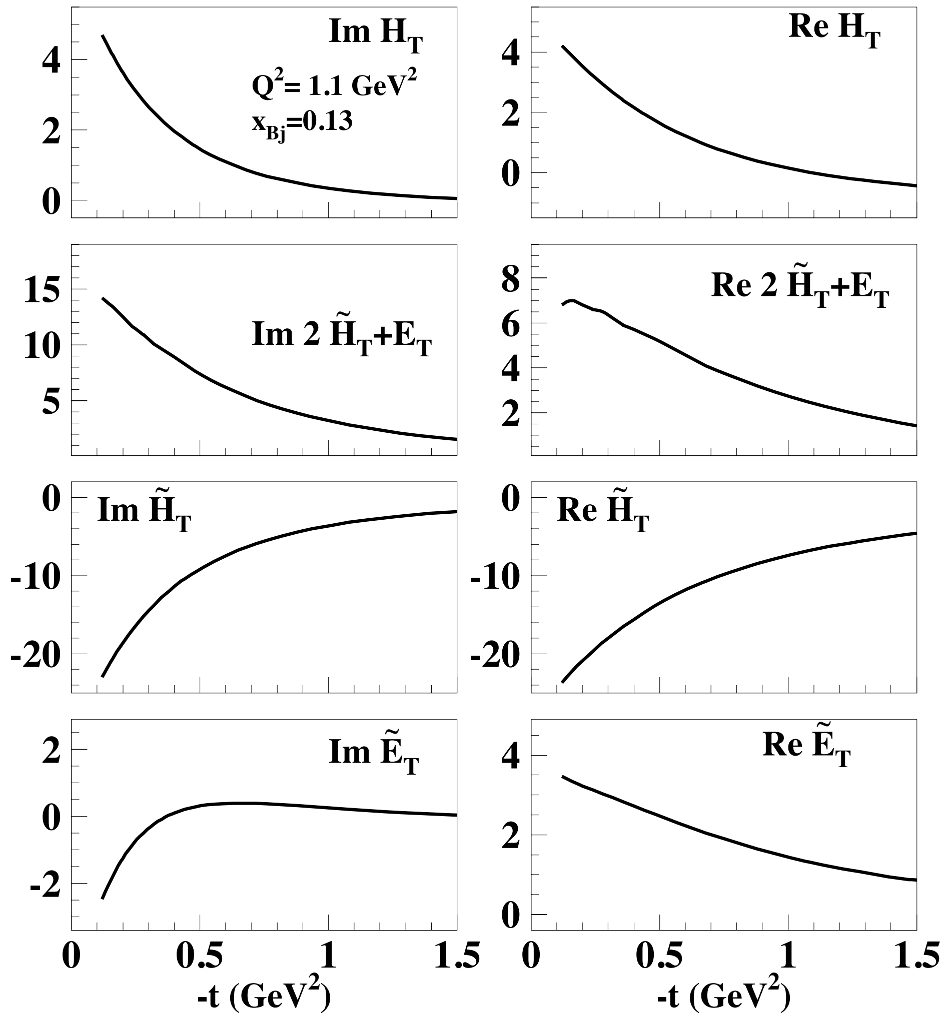
→Tensor charge

$$\int dx\, [2\tilde{H}_T^q(x,\zeta,t,Q^2) + E_T^q(x,\zeta,t,Q^2)] = \kappa_q(t,Q^2)$$

→Transverse dipole moment

→sizeable→f_1-f_4

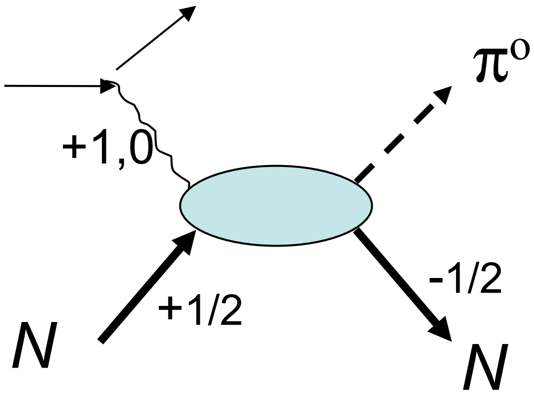
Compton form factors



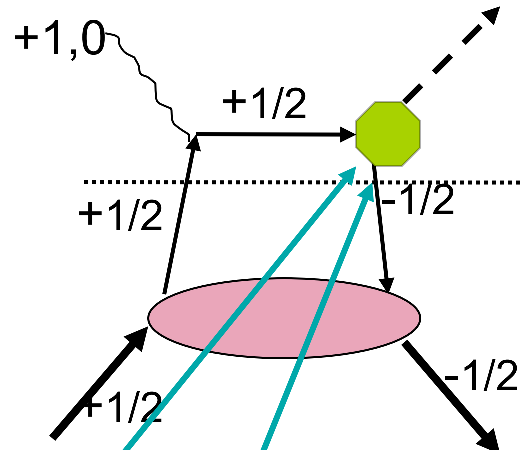
How to single out & measure **chiral odd GPDs**?

Exclusive Lepto-production of π^o or η, η'

to measure **chiral odd GPDs & Transversity**

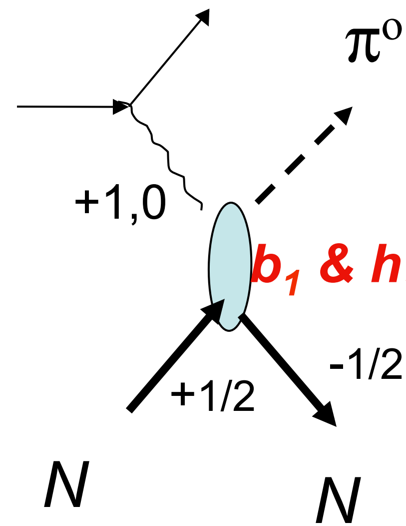


e.g. $f_{+1+,0-}(s,t,Q^2)$



q nos of C-odd
1^{--} exchange
ρ & ω
1^{+-} exchange
b_1 & h_1

$g_{+1+,0-}$ $A_{++,--}$
↓
H_T



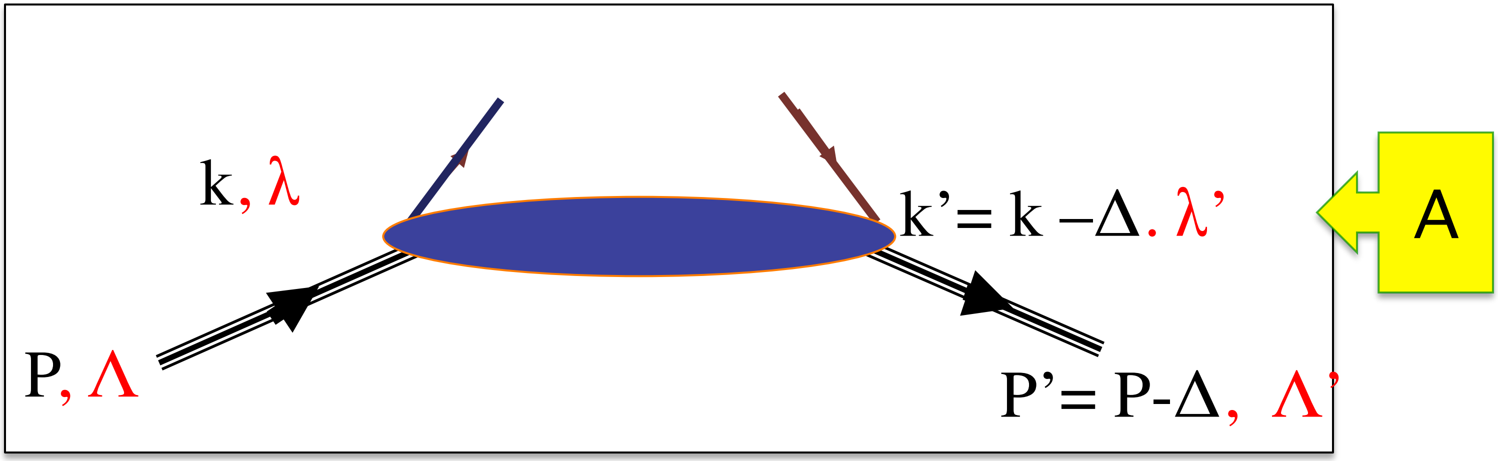
$$\mathcal{P} = K f_\pi \left\{\gamma_5 \not{q}' \phi_\pi(\tau) + \gamma_5 \mu_\pi \phi_\pi^{(3)}(\tau)\right\}$$

twist 2 *twist 3*

t-channel J^{PC} quantum numbers enhance chiral odd

6 independent helicity amps for π^o or η, η' (& K, D_C)

8 Quark-nucleon helicity amps for u,d (& s,c)



odd

$$f_{10}^{++} = g_{10}^{+-} \otimes A_{+-,++}$$
$$f_{10}^{+-} = g_{10}^{+-} \otimes A_{--,++}$$
$$f_{10}^{-+} = g_{10}^{+-} \otimes A_{+-,-+}$$
$$f_{10}^{--} = g_{10}^{+-} \otimes A_{++,+-}$$
$$f_{00}^{+-} = g_{00}^{+-} \otimes (A_{--,++} - A_{+-,-+})$$
$$f_{00}^{++} = g_{00}^{+-} \otimes (A_{++,+-} - A_{+-,++}),$$

$$f_{00}^{+-,\,even} = \frac{\zeta}{\sqrt{1-\zeta}} \frac{1}{1-\zeta/2} \frac{\sqrt{t_o - t}}{2M} \tilde{\mathcal{E}},$$
$$f_{00}^{++,\,even} = \frac{\sqrt{1-\zeta}}{1-\zeta/2} \tilde{\mathcal{H}} + \frac{-\zeta^2/4}{(1-\zeta/2)\sqrt{1-\zeta}} \tilde{\mathcal{E}},$$

even

6 helicity amps for π^0

Compton Form Factors

f_1

$$f_{10}^{++} = g_\pi^{V,odd}(Q)\frac{\sqrt{t_0-t}}{4M}\left[2\tilde{\mathcal{H}}_T + (1+\xi)\left(\mathcal{E}_T + \tilde{\mathcal{E}}_T\right)\right]$$

$$= g_\pi^{V,odd}(Q)\frac{\sqrt{t_0-t}}{2M}\left[\tilde{\mathcal{H}}_T + \frac{1}{2-\zeta}E_T + \frac{1}{2-\zeta}\tilde{\mathcal{E}}_T\right],$$

f_2

$$f_{10}^{+-} = \frac{g_\pi^{V,odd}(Q) + g_\pi^{A,odd}(Q)}{2}\sqrt{1-\xi^2}\left[\mathcal{H}_T + \frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T + \frac{\xi^2}{1-\xi^2}\mathcal{E}_T + \frac{\xi}{1-\xi^2}\tilde{\mathcal{E}}_T\right]$$

$$= \frac{g_\pi^{V,odd}(Q) + g_\pi^{A,odd}(Q)}{2}\frac{\sqrt{1-\zeta}}{1-\zeta/2}\left[\mathcal{H}_T + \frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T + \frac{\zeta^2/4}{1-\zeta}\mathcal{E}_T + \frac{\zeta/2}{1-\zeta}\tilde{E}_T\right]$$

f_3

$$f_{10}^{-+} = -\frac{g_\pi^{A,odd}(Q) - g_\pi^{V,odd}(Q)}{2}\sqrt{1-\xi^2}\,\frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T$$

$$= -\frac{g_\pi^{A,odd}(Q) - g_\pi^{V,odd}(Q)}{2}\frac{\sqrt{1-\zeta}}{1-\zeta/2}\,\frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T$$

f_4

$$f_{10}^{--} = g_\pi^{V,odd}(Q)\frac{\sqrt{t_0-t}}{4M}\left[2\tilde{\mathcal{H}}_T + (1-\xi)\left(\mathcal{E}_T - \tilde{\mathcal{E}}_T\right)\right]$$

$$= g_\pi^{V,odd}(Q)\frac{\sqrt{t_0-t}}{2M}\left[\tilde{\mathcal{H}}_T + \frac{1-\zeta}{2-\zeta}\mathcal{E}_T + \frac{1-\zeta}{2-\zeta}\tilde{\mathcal{E}}_T\right]$$

Also Chiral Even CFFs

f_5

$$f_{00}^{+-} = g_\pi^{A,odd}(Q)\sqrt{1-\xi^2}\left[\mathcal{H}_T + \frac{\xi^2}{1-\xi^2}\mathcal{E}_T + \frac{\xi}{1-\xi^2}\tilde{\mathcal{E}}_T\right]\sqrt{t_0-t}$$

f_6

$$f_{00}^{++} = -g_\pi^{A,odd}(Q)\frac{\sqrt{t_0-t}}{2M}\left[\xi\mathcal{E}_T + \tilde{\mathcal{E}}_T\right]\sqrt{t_0-t}$$

Observables

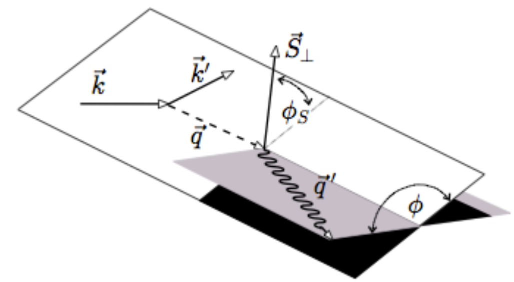
Cross sections

Asymmetries

Cross section with φ modulations & beam/target polarized

$$
\begin{aligned}
\frac{d^4\sigma}{dx_{Bj}dyd\phi dt} = \Gamma\Big\{ & \Big[F_{UU,T}+\epsilon F_{UU,L}+\epsilon\cos 2\phi F_{UU}^{\cos 2\phi}+\sqrt{2\epsilon(\epsilon+1)}\cos\phi F_{UU}^{\cos\phi}+h\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi F_{LU}^{\sin\phi}\Big] \\
& + S_{||}\Big[\sqrt{2\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi}+\epsilon\sin 2\phi F_{UL}^{\sin 2\phi}+h\Big(\sqrt{1-\epsilon^2}\,F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\,\cos\phi F_{LL}^{\cos\phi}\Big)\Big] \\
& + S_{\perp}\Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big)+\epsilon\Big(\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)}+\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\Big) \\
& + \sqrt{2\epsilon(1+\epsilon)}\Big(\sin\phi_S F_{UT}^{\sin\phi_S}+\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big)\Big] \\
& + S_{\perp}h\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\Big(\cos\phi_S F_{LT}^{\cos\phi_S}+\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big)\Big]\Big\}
\end{aligned}
$$

$$A_{LU}=\sqrt{\epsilon(1-\epsilon)}\,\frac{F_{LU}^{\sin\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

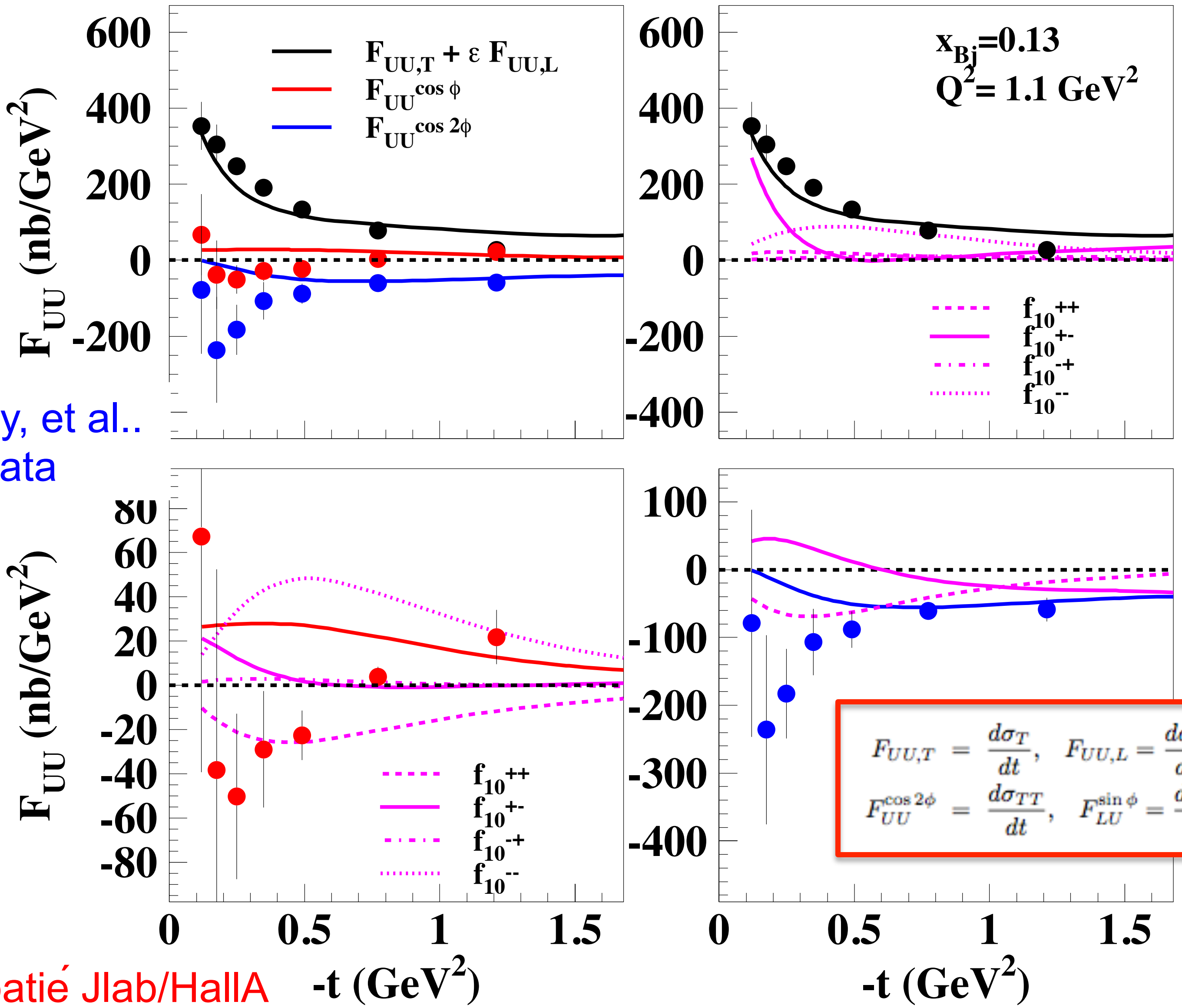


$$A_{UL}=\frac{N_{s_z=+}-N_{s_z=-}}{N_{s_z=+}+N_{s_z=-}}=\frac{\sqrt{\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi}}{F_{UU,T}+\epsilon F_{UU,L}}+\frac{\epsilon\sin 2\phi F_{UL}^{\sin 2\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

$$F_{UU,T}=\frac{d\sigma_T}{dt},\quad F_{UU,L}=\frac{d\sigma_L}{dt},\quad F_{UU}^{\cos\phi}=\frac{d\sigma_{LT}}{dt},$$
$$F_{UU}^{\cos 2\phi}=\frac{d\sigma_{TT}}{dt},\quad F_{LU}^{\sin\phi}=\frac{d\sigma_{LT'}}{dt}$$

$$A_{LL}=\frac{N^{\rightarrow}_{s_z=+}-N^{\rightarrow}_{s_z=-}+N^{\leftarrow}_{s_z=+}-N^{\leftarrow}_{s_z=-}}{N_{s_z=+}+N_{s_z=-}}=\frac{\sqrt{1-\epsilon^2}\;F_{LL}}{F_{UU,T}+\epsilon F_{UU,L}}+\frac{\sqrt{\epsilon(1-\epsilon)}\,\cos\phi\, F_{LL}^{\cos\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

Unpolarized cross sections

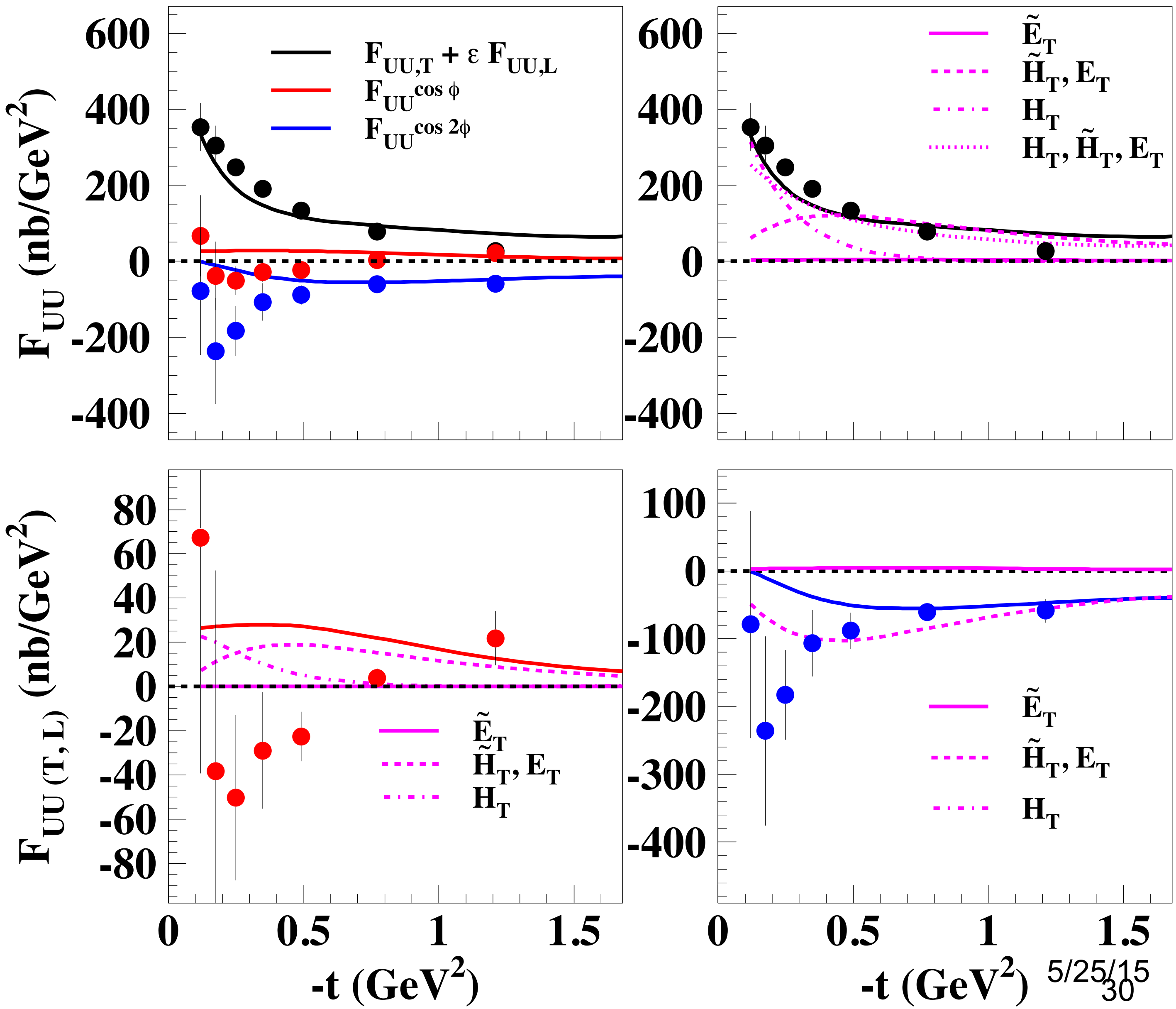


V.Kubarovsky, et al..
Jlab/CLAS data

$$F_{UU,T} = \frac{d\sigma_T}{dt}, \quad F_{UU,L} = \frac{d\sigma_L}{dt}, \quad F_{UU}^{\cos\phi} = \frac{d\sigma_{LT}}{dt},$$
$$F_{UU}^{\cos 2\phi} = \frac{d\sigma_{TT}}{dt}, \quad F_{LU}^{\sin\phi} = \frac{d\sigma_{LT'}}{dt}$$

See F. Sabatié Jlab/HallA CIPANP talk for L & T separation

Same, separating the GPDs contribution



Unpolarized cross section components

$$F_{UU,T} = \frac{d\sigma_T}{dt}, \quad F_{UU,L} = \frac{d\sigma_L}{dt}, \quad F_{UU}^{\cos\phi} = \frac{d\sigma_{LT}}{dt},$$
$$F_{UU}^{\cos 2\phi} = \frac{d\sigma_{TT}}{dt}, \quad F_{LU}^{\sin\phi} = \frac{d\sigma_{LT'}}{dt}$$

$$F_{UU,T} = \mathcal{N}\left[| f_{10}^{++} |^2 + | f_{10}^{+-} |^2 + | f_{10}^{-+} |^2 + | f_{10}^{--} |^2 \right]$$

$|f_{10}^{+-}|$ dominates small t & $>|f_{10}^{\pm\pm}|$

$$F_{UU,L} = \mathcal{N}\left[| f_{00}^{++} |^2 + | f_{00}^{+-} |^2 \right]$$

Jlab/HallA
L & T separation

$$F_{UU}^{\cos 2\phi} = -\mathcal{N}\, 2\Re e\left[(f_{10}^{++})^*(f_{10}^{--}) - (f_{10}^{+-})^*(f_{10}^{-+}) \right]$$

Or form of
$- |f_1+|^2 + |f_1-|^2$

$$F_{UU}^{\cos\phi} = -\mathcal{N}\Re e\left[(f_{00}^{+-})^*(f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} - f_{10}^{--}) \right]$$

Polarized beam $$F_{LU}^{\sin\phi} = \mathcal{N}\Im m\left[(f_{00}^{+-})^*(f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} - f_{10}^{--}) \right]$$

Comparing to other models

- The t-> 0 feature for us is that f_{10}^{+-} dominates & it is driven by H_T. But f_{10}^{++} & f_{10}^{--} also contribute as $\sim\sqrt{(t_0-t)}$, however weaker.
- f_{10}^{++} & f_{10}^{--} are not equal in magnitude, especially vs. ζ or ξ.
- In $A_{LL} \sim |f_{10}^{++}|^2 + |f_{10}^{+-}|^2 - |f_{10}^{-+}|^2 - |f_{10}^{--}|^2$ sensitive to differences

Comparison between models

$$\frac{d\sigma_T}{dt} \propto \left|\mathcal{H}_T\right|^2 + \tau\left|\bar{\mathcal{E}}_T\right|^2$$

Goloskokov and Kroll

$$\tau = \frac{t_o - t}{8M^2}$$

$$\frac{d\sigma_T}{dt} \propto g_\pi^{(1)}\left(Q^2\right)\tau\left|\bar{\mathcal{E}}_T + (1+\xi)\tilde{\mathcal{E}}_T\right|^2 + g_\pi^{(2)}\left(Q^2\right)\tau\left|\bar{\mathcal{E}}_T + (1-\xi)\tilde{\mathcal{E}}_T\right|^2 + g_\pi^{(3)}\left(Q^2\right)\left|\mathcal{H}_T\right|^2$$

Goldstein, Gonzalez, Liuti

$$\frac{d\sigma_{TT}}{dt} \propto \left|\mathcal{E}_T\right|^2$$

Goloskokov and Kroll

$$\frac{d\sigma_{TT}}{dt} \propto \left(\bar{\mathcal{E}}_T + (1+\xi)\tilde{\mathcal{E}}_T\right)^* \left(\bar{\mathcal{E}}_T + (1-\xi)\tilde{\mathcal{E}}_T\right)$$

Goldstein, Gonzalez, Liuti

CLAS π^0: Bedlinskiy, et al. PRL109, 112001 (2012).

GGL vs. G&K

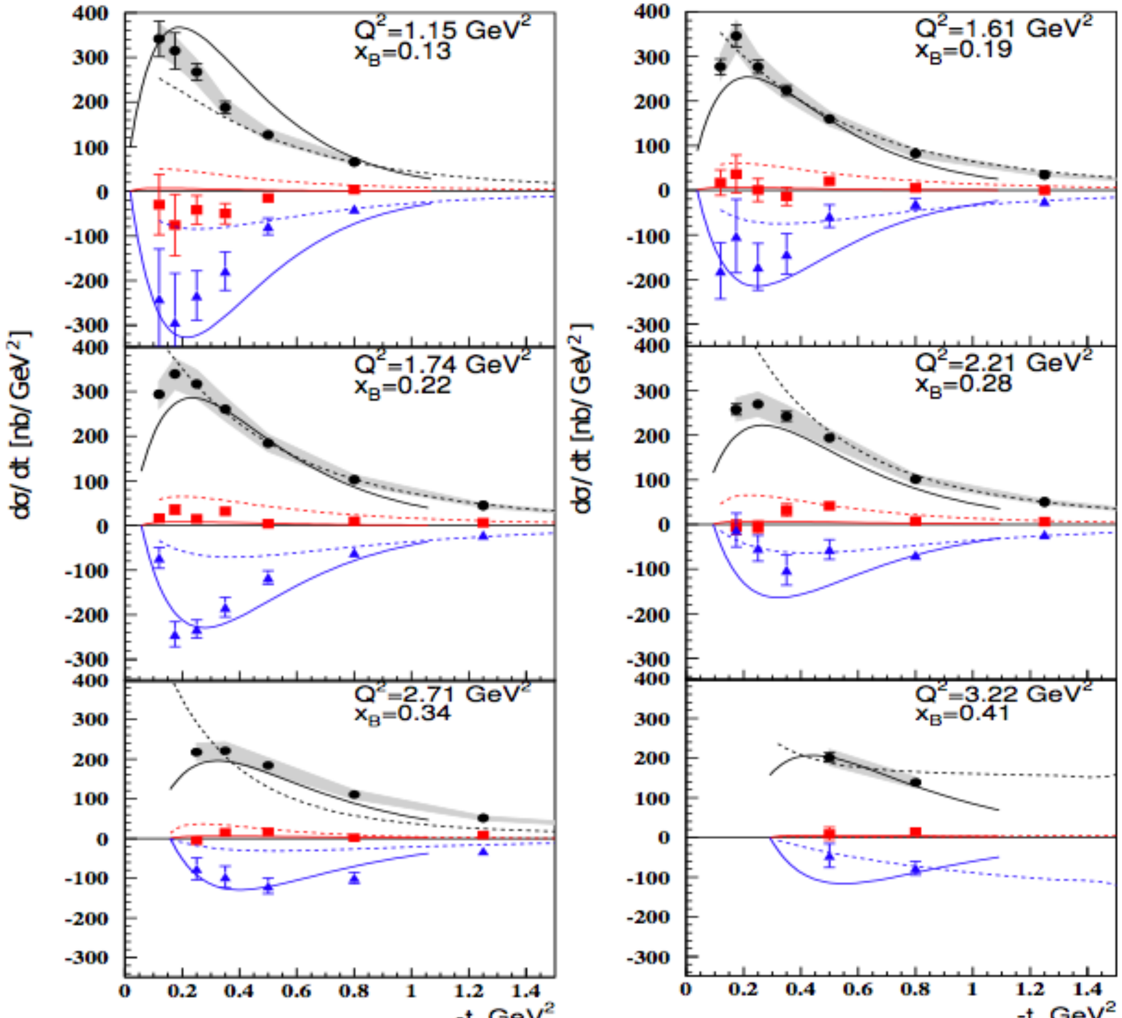


FIG. 2: The extracted structure functions vs. t for the bins with the best kinematic coverage and for which there are theoretical calculations. The data and curves are as follows: black-$\sigma_U(=\sigma_T+\epsilon\sigma_L)$, blue-$\sigma_{TT}$, and red-σ_{LT}. The shaded bands reflect the experimental systematic uncertainties.The curves are theoretical predictions produced with the models of Refs. [14] (solid) and [15] (dashed).

Important combinations of overall helicity amps

$$f_{10}^{++} + f_{10}^{--} \propto \frac{\sqrt{t_0 - t}}{4M}\left[2\widetilde{\mathcal{H}}_T + \left(\mathcal{E}_T - \xi\widetilde{\mathcal{E}}_T\right)\right]$$ "natural"

$$f_{10}^{++} - f_{10}^{--} \propto \frac{\sqrt{t_0 - t}}{4M}\left[\xi\mathcal{E}_T - \widetilde{\mathcal{E}}_T\right]$$ "unnatural"

→ 0 for $\xi \to 0$

Quite sizable effect for $\xi > 0$

Goloskokov&Kroll take ***only*** H_T and ($2\,\tilde{H}_T + E_T$) non-zero
EPJA47, (2011) 112 for π^0 and EPJC74 (2014)2725 for V_0 .

What observables reveal this? $A_{LU}^{\sin\varphi}$, . . .

Asymmetries:
Longitudinal polarizations
Sensitive to f_{10}^{++} - f_{10}^{--}

$$F_{UL}^{\sin\phi} = \frac{1}{\sqrt{2}}\mathcal{N}\Im m\left[(f_{00}^{+-})^*(f_{10}^{+-} - f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} + f_{10}^{--})\right]$$

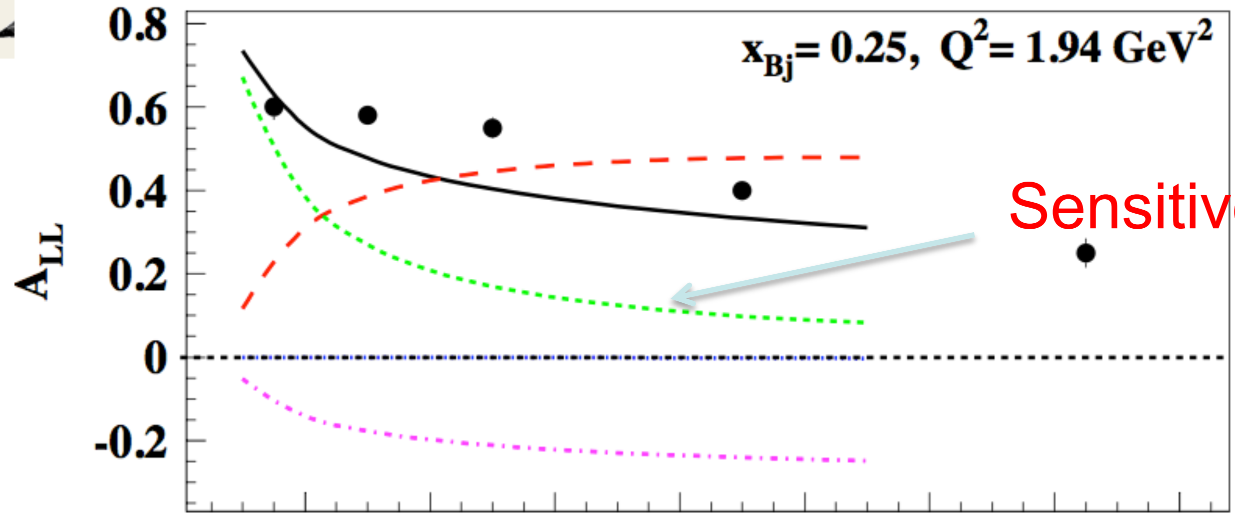
$$F_{UL}^{\sin 2\phi} = -\mathcal{N}\Im m\left[(f_{10}^{++})^*(f_{10}^{--}) - (f_{10}^{+-})^*(f_{10}^{-+})\right]$$

$$F_{LL}^{\cos\phi} = \frac{1}{\sqrt{2}}\mathcal{N}\Re e\left[(f_{00}^{+-})^*(f_{10}^{+-} - f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} + f_{10}^{--})\right]$$

$$F_{LL} = \frac{1}{2}\mathcal{N}\left[\mid f_{10}^{++}\mid^2 + \mid f_{10}^{+-}\mid^2 - \mid f_{10}^{-+}\mid^2 - \mid f_{10}^{--}\mid^2\right]$$

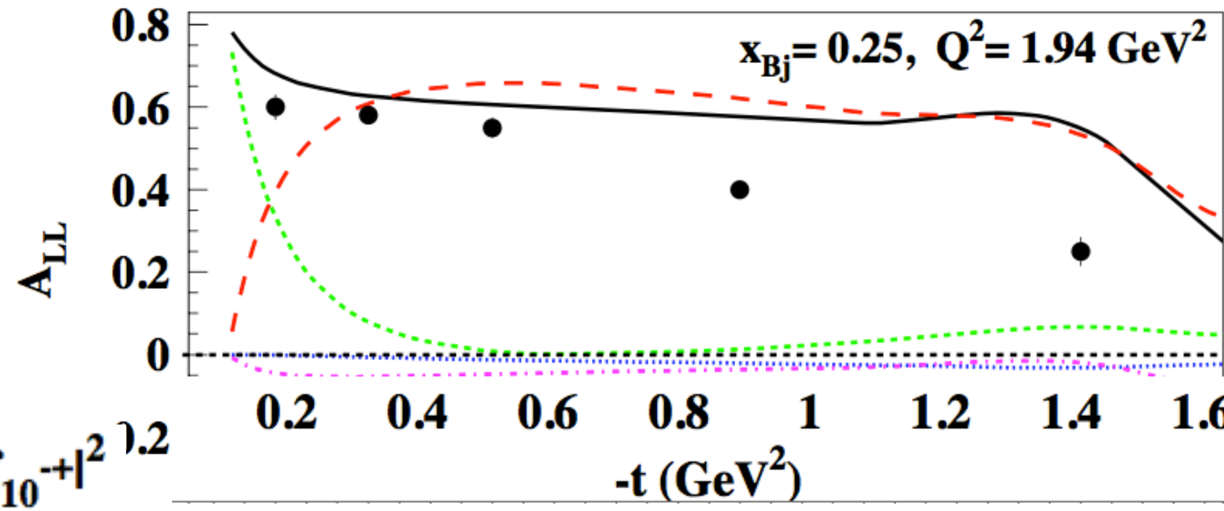
$$A_{LL} = \frac{\sqrt{1-\epsilon^2}\,F_{LL} + \sqrt{2\epsilon_L(\epsilon-1)}\,\cos\phi\,F_{LL}^{\cos\phi}}{F_{UU,T} + \epsilon_L F_{UU,L}}$$

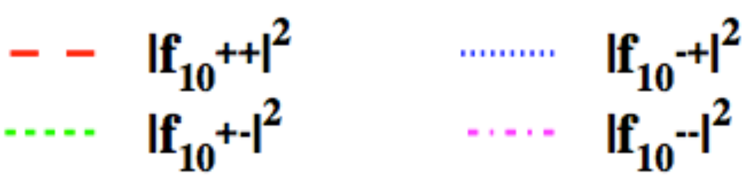
Andrey Kim, Harut Avakian et al., Jefferson Lab CLAS Collaboration



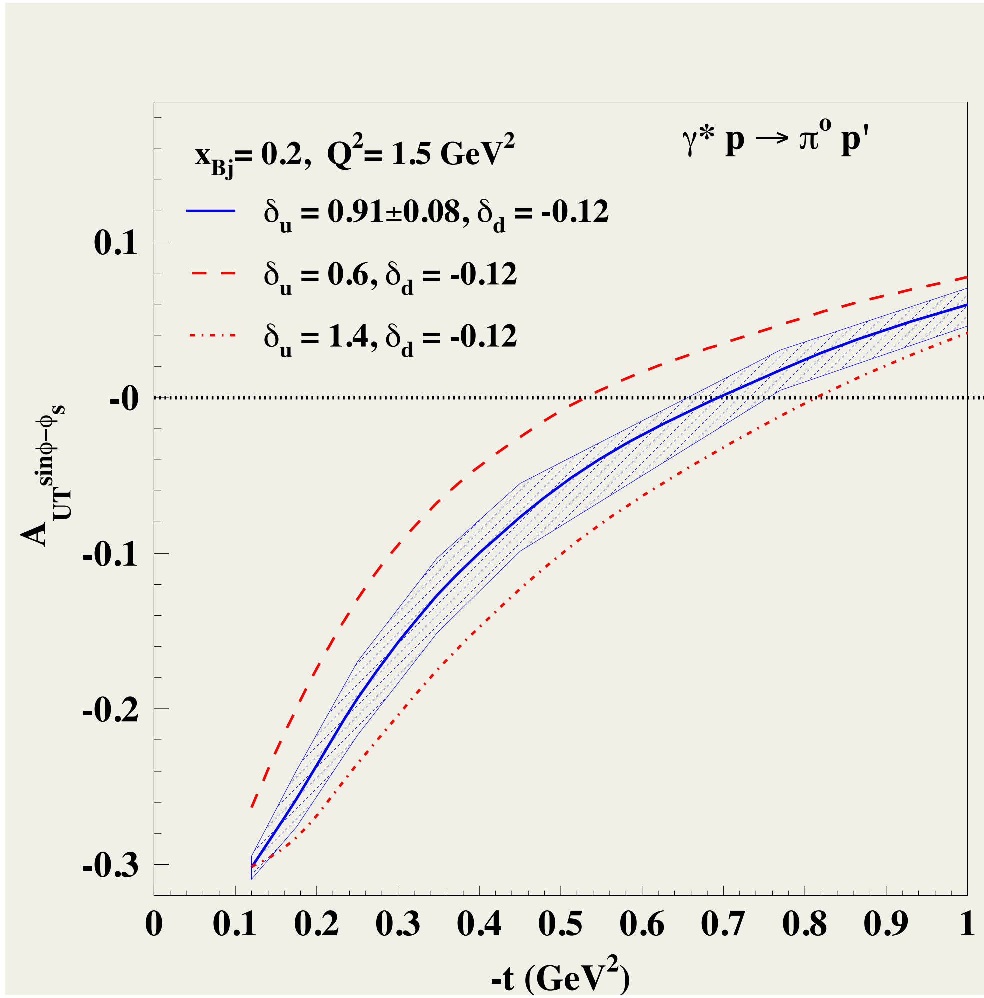
Sensitive to tensor charge

Role of parameters





Asymmetry sensitive to tensor charge



Chiral odd GPD's & helicity/transversity interpretation?

$$
\begin{aligned}
\tau\left[2\widetilde{H}_T(X,0,t)+E_T(X,0,t)\right] &= A_{++,+-}+A_{-+,--} \\
&= A^{T_Y}_{++,++}-A^{T_Y}_{+-,+-}+A^{T_Y}_{-+,-+}-A^{T_Y}_{--,--} \\
H_T(X,0,t) &= A_{++,--}+A_{-+,+-} \\
&= A^{T_X}_{++,++}-A^{T_X}_{+-,+-}-A^{T_X}_{-+,-+}+A^{T_X}_{--,--} \\
\tau^2\widetilde{H}_T(X,0,t) &= -A_{-+,+-} \\
&= A^{T_Y}_{++,++}-A^{T_Y}_{+-,+-}-A^{T_X}_{-+,-+}+A^{T_X}_{--,--} \\
\widetilde{E}_T(X,0,t) &= A_{++,+-}-A_{-+,--}=0
\end{aligned}
$$

From T invariance for ξ =0

Chiral odd GPDs & TMDs ? Transversity transfer; Boer-Mulders; pretzelosity; worm gears

$$H_T(X,0,0) \;=\; h_1(X),$$ *Transversity pdf*

Model dependent relations

with the Boer-Mulders, $h_1^\perp(X)$, and $h_{1T}^\perp(X)$ functions,

Pretzelosity

$$\lim_{t\to 0}\frac{t}{4M^2}\widetilde{H}_T(X,0,t) \;=\; h_{1T}^\perp(X) = \int d^2k_T\, h_{1T}^\perp(X,k_T)$$

B-M

$$2\widetilde{H}_T(X,0,t) + E_T(X,0,t) \;=\; h_1^\perp(X) = \int d^2k_T\, h_1^\perp(X,k_T),$$

y the integration to form factors at $t=0$, giving the tensor charge,

$$\delta_q = \int_0^1 dx H_T(X,0,0)$$

$$\widetilde{E}_T(X,\xi,t) \;=\; A_{++,+-} - A_{-+,--}$$

$h_{1L}{}^{T}$ worm-gear

***Tensor charge can be related to BSM couplings*

A.~Courtoy, S.~Baessler, M.~Gonzalez-Alonso and S.~Liuti, arXiv:1503.06814.

Connecting tensor charge to BSM:
Courtoy, Baessler, Gonzalez-Alonso and Liuti, arXiv:1503.06814.

BSM couplings $1, \gamma_5, (\gamma_\mu + \gamma_\mu \gamma_5), i\sigma^{j+}\gamma_5$

$$C_T = \frac{G_F}{\sqrt{2}} V_{ud} g_T \varepsilon_T$$

$$b = \frac{2}{1+3\lambda^2}\left[g_S \epsilon_S - 12 g_T \epsilon_T \lambda\right]$$

$$b_\nu = \frac{2}{1+3\lambda^2}\left[g_S \epsilon_S \lambda - 4 g_T \epsilon_T (1+2\lambda)\right],$$

The observable is always the product of the fundamental coupling times a hadronic matrix element!

g_T and g_S are the flavor- non-singlet/isovector hadronic matrix elements

$$\langle p'_p, S_p | \bar{u}u - \bar{d}d | p_p, S_p \rangle = g_S(-t)\, \overline{U}(p'_p, S_p) U(p_p, S_p) \quad ,$$

$$\langle p'_p, S_p | \bar{u}\sigma_{\mu\nu}u - \bar{d}\sigma_{\mu\nu}d | p_p, S_p \rangle = g_T(-t)\, \overline{U}(p'_p, S_p)\sigma_{\mu\nu} U(p_p, S_p),$$

... or by using isospin symmetry:

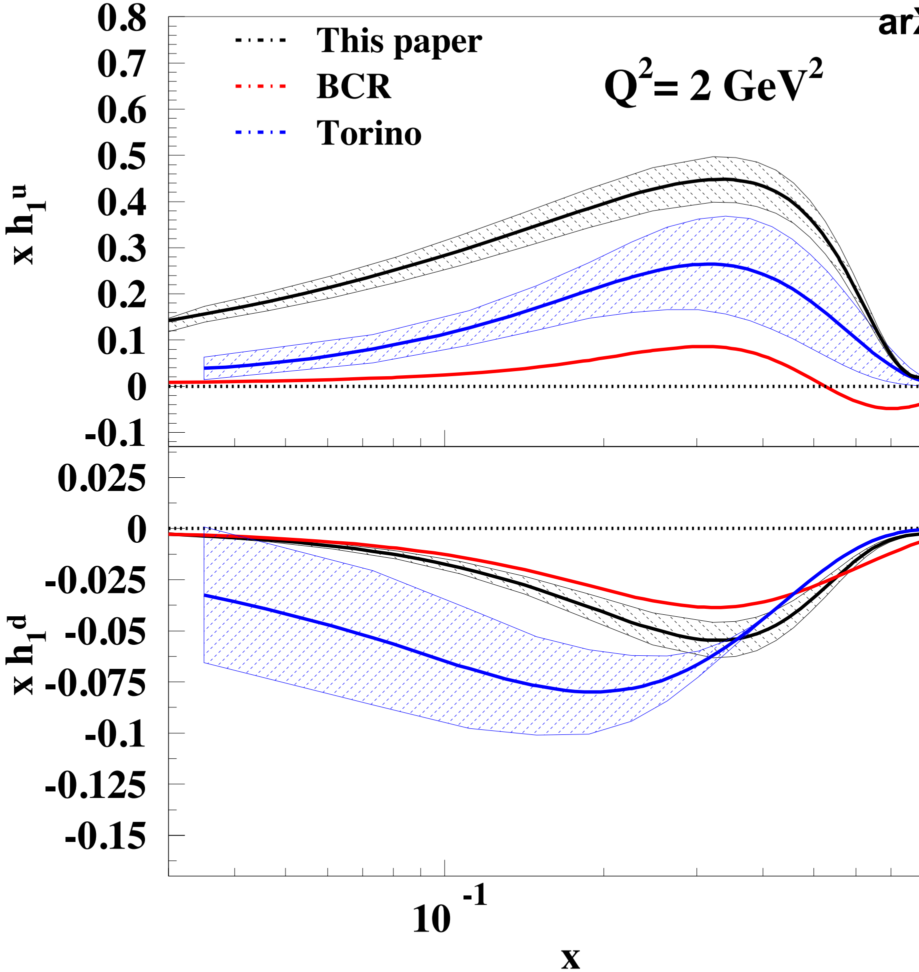
$$\langle p_p, S_p | \bar{u}d | p_n, S_n \rangle = g_S(-t)\, \overline{U}(p_p, S_p) U(p_n, S_n) \quad ,$$

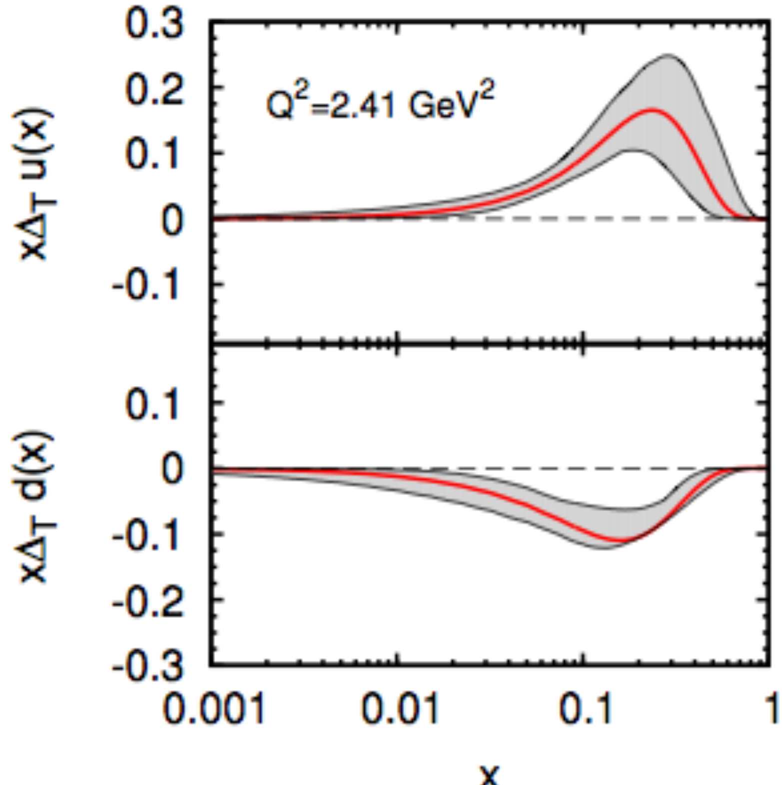
$$\langle p_p, S_p | \bar{u}\sigma_{\mu\nu}d | p_n, S_n \rangle = g_T(-t)\, \overline{U}(p_p, S_p)\sigma_{\mu\nu} U(p_n, S_n),$$

The precision with which ε_T can be measured depends on the uncertainty on g_T

Extraction of transversity after using DVCS data via chiral even←→odd **Transversity** → pdf's: $h_1^q(x,Q^2)$

GG, Gonzalez, Liuti, arXiv:1311.0483 PRD

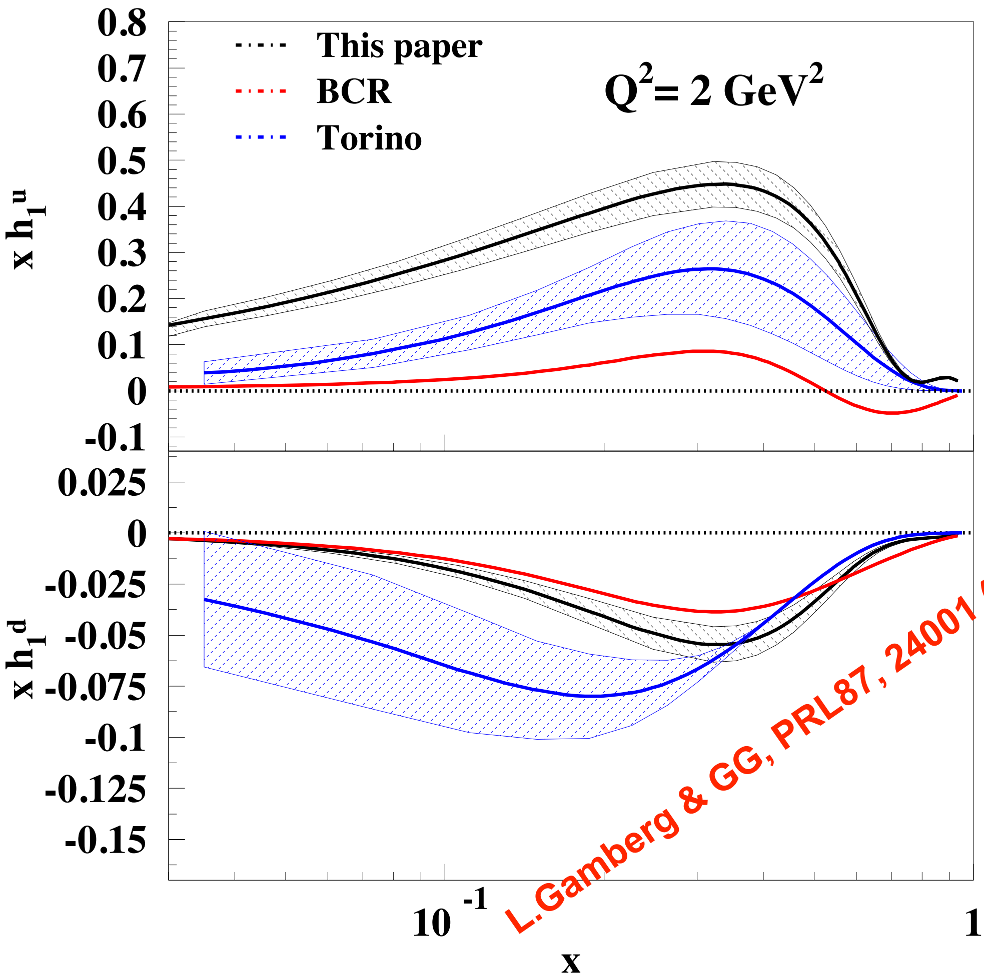


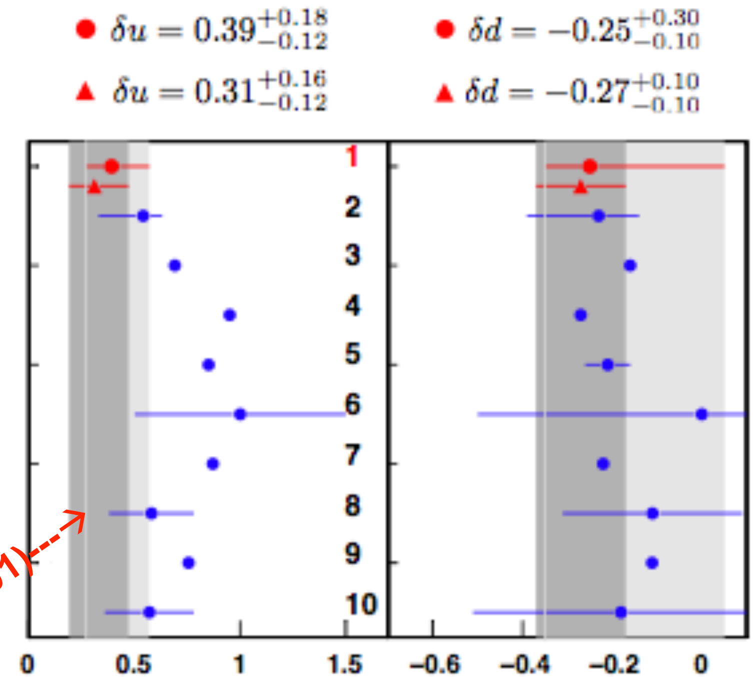


BCR=Bacchetta, Conte, Radici

Anselmino, Boglione, et al., Phys.Rev. D87 (2013) 094019
$\delta u = 0.31_{-0.12}^{+0.16}$ $\delta d=-0.27_{-0.10}^{+0.10}$

Extraction of tensor charge

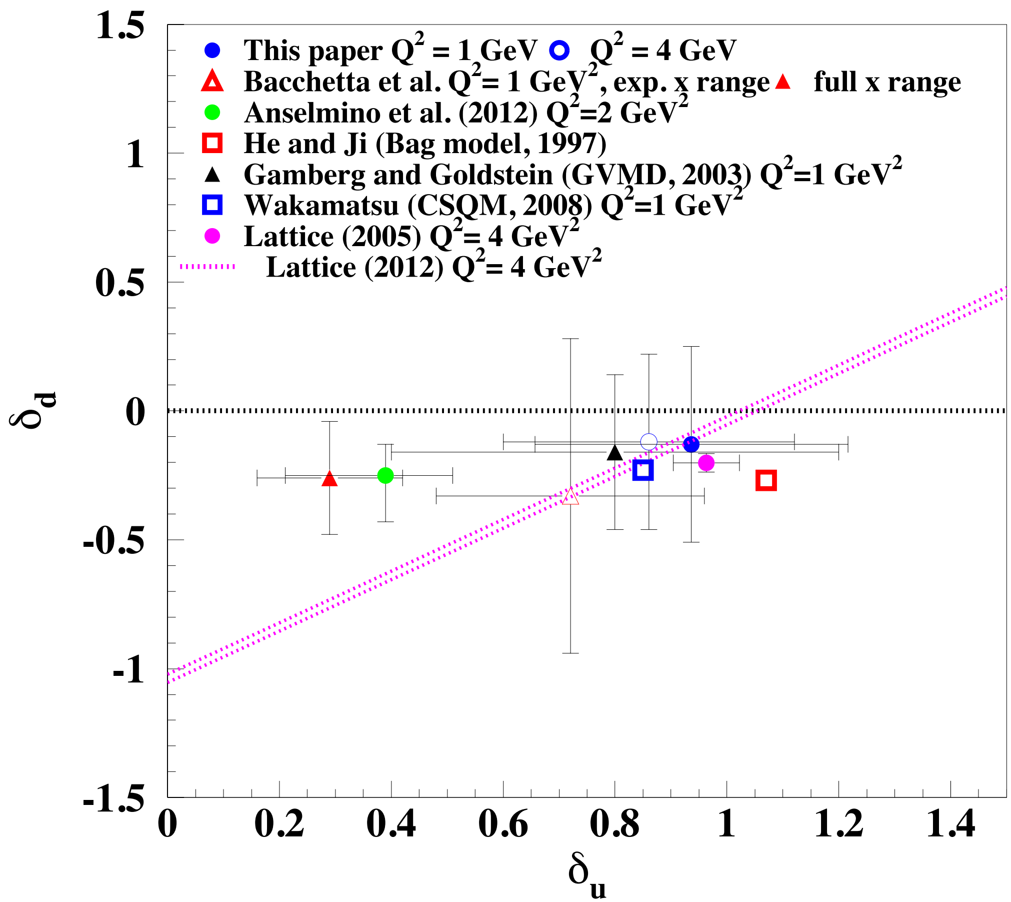




Anselmino, Boglione, et al., Phys.Rev. D87 (2013) 094019
$\delta u = 0.31_{-0.12}^{+0.16}$ $\delta d = -0.27_{-0.10}^{+0.10}$

From our Reggeized form
$\delta u \approx 1.2$ $\delta d \approx -0.08$
Closer to QCD sum rule values

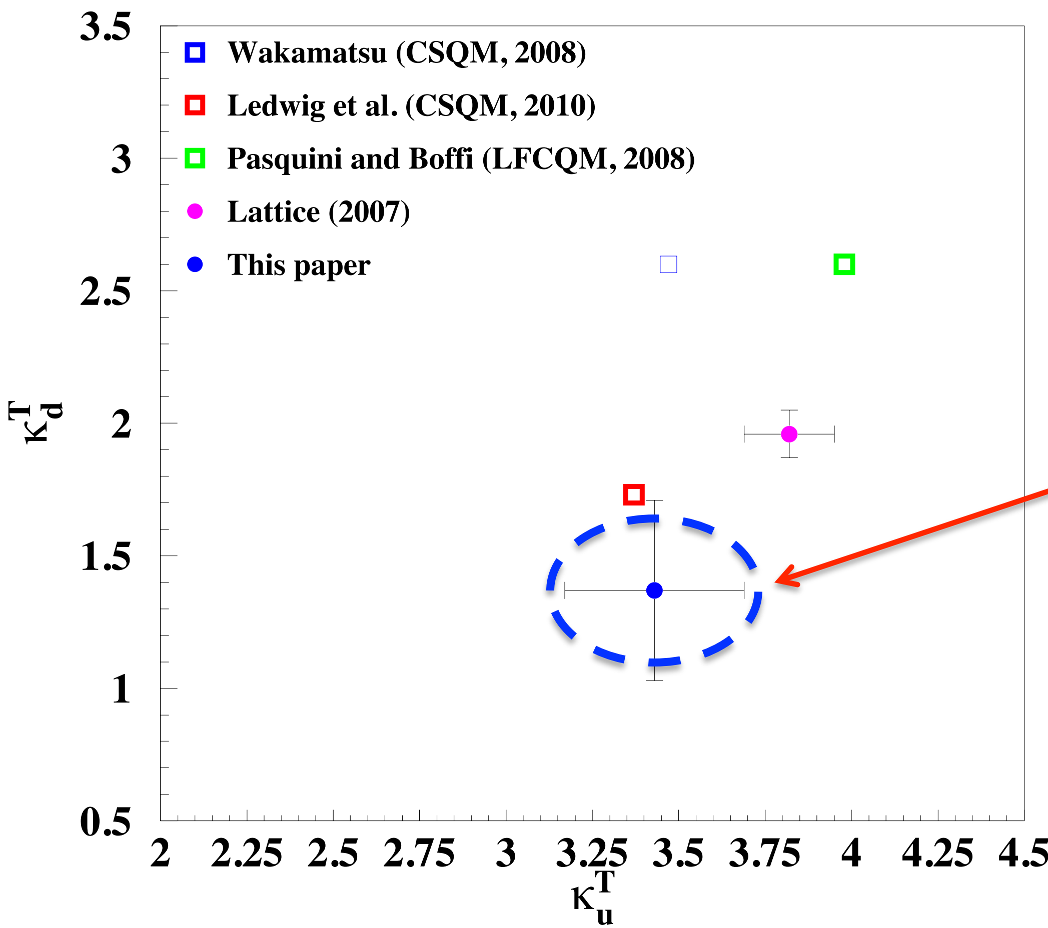
Chiral odd GPDs → Transversity → tensor charges δ_q



GG, Gonzalez, Liuti, arXiv:1401.0438 PRD

Chiral odd GPDs → transverse spin-flavor **"dipole moments"** κ_T^q

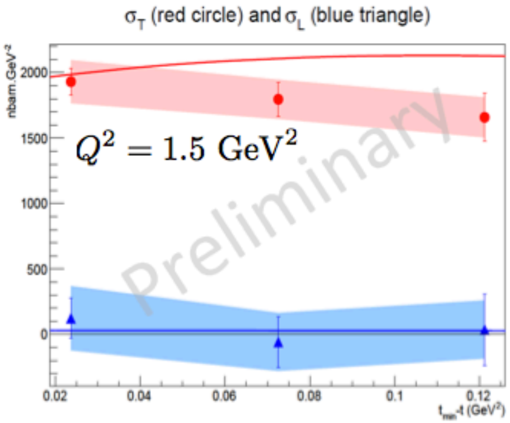
defined by M. Burkardt, PRD72,094020(2005)

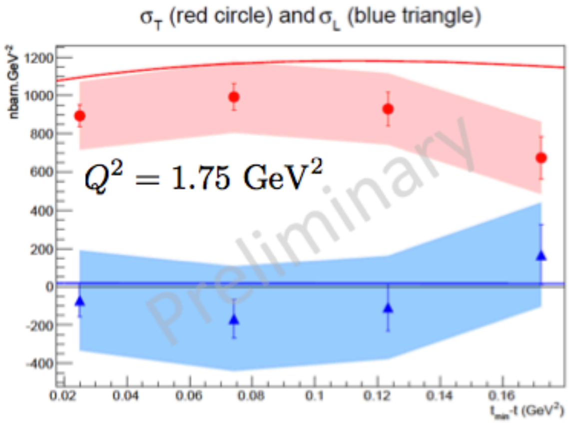


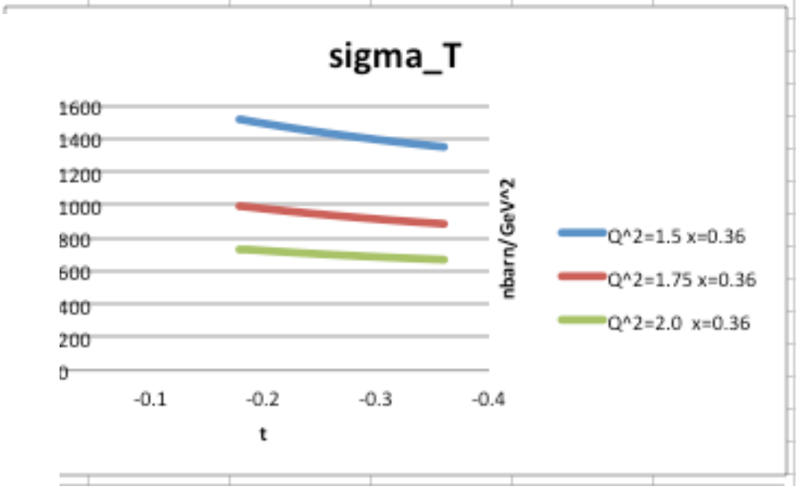
GG, Gonzalez, Liuti, arXiv:1401.0438

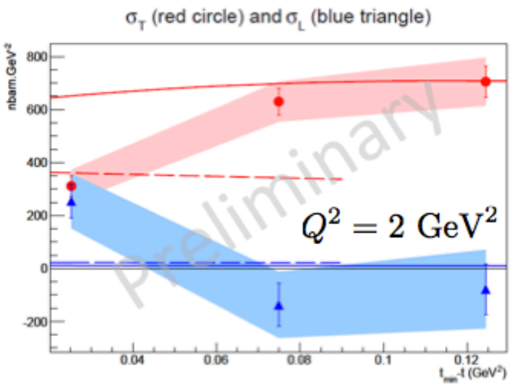
Comparing with new data from Hall A

courtesy F. Sabatie, CIPANP





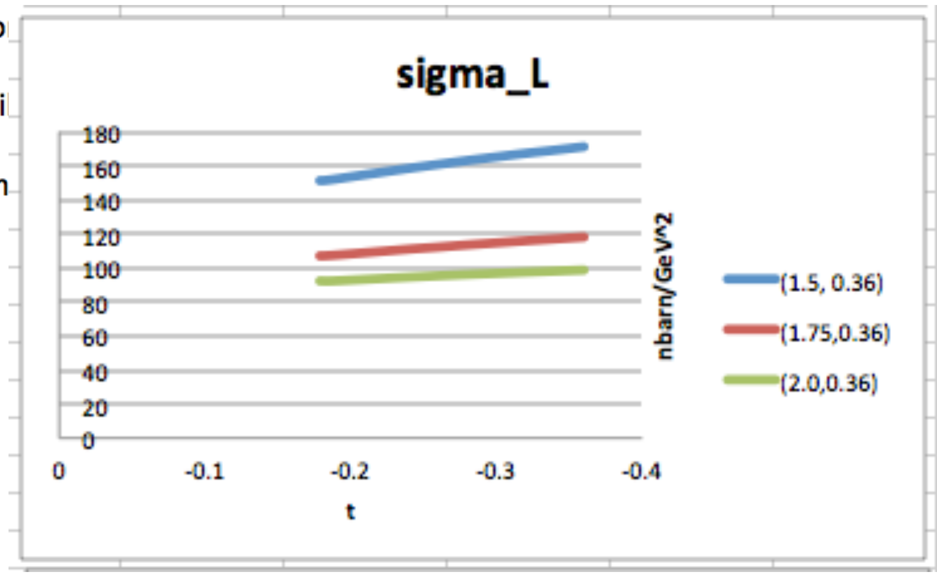




Shaded area: 2% normalizatio

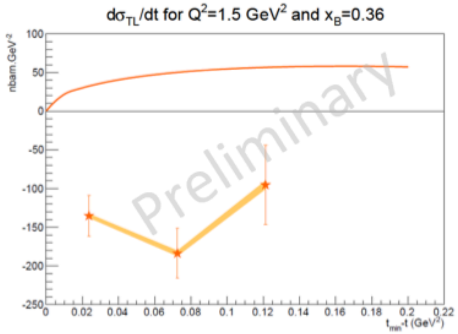
Solid line: GK11 model (descri

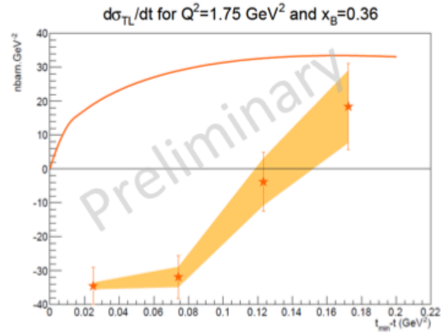
Dashed line: Goldstein-Liuti m
(waiting for updated values)

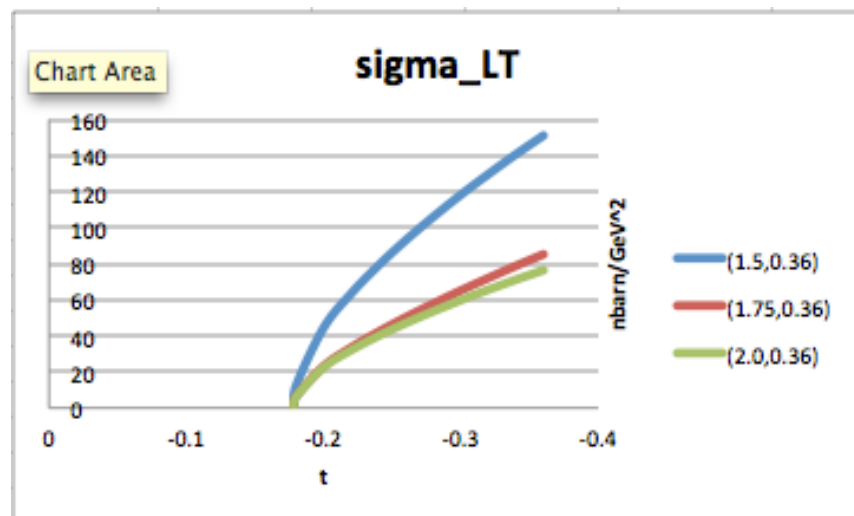


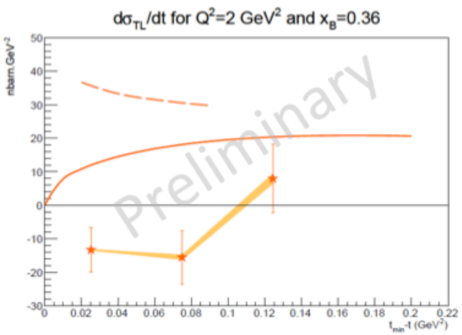
Comparing with new data from Hall A

courtesy F. Sabatie, CIPANP









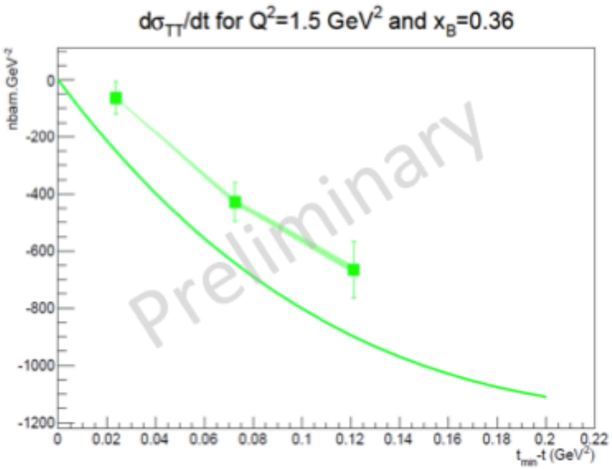
Shaded area: 2% normalization uncertainty

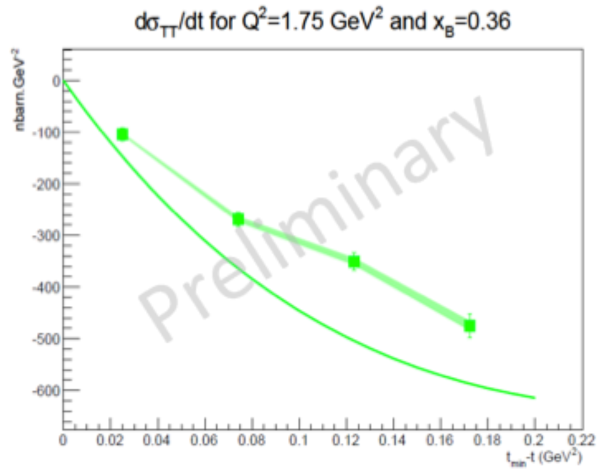
Solid line: GK11 model (described earlier)

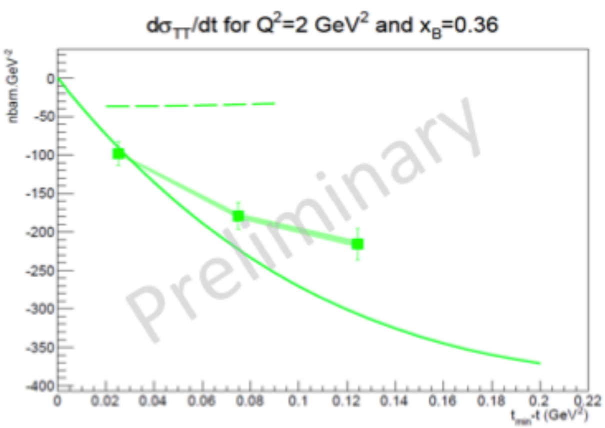
Dashed line: Goldstein-Liuti model
(waiting for updated values)

Comparing with new data from Hall A

courtesy F. Sabatie, CIPANP



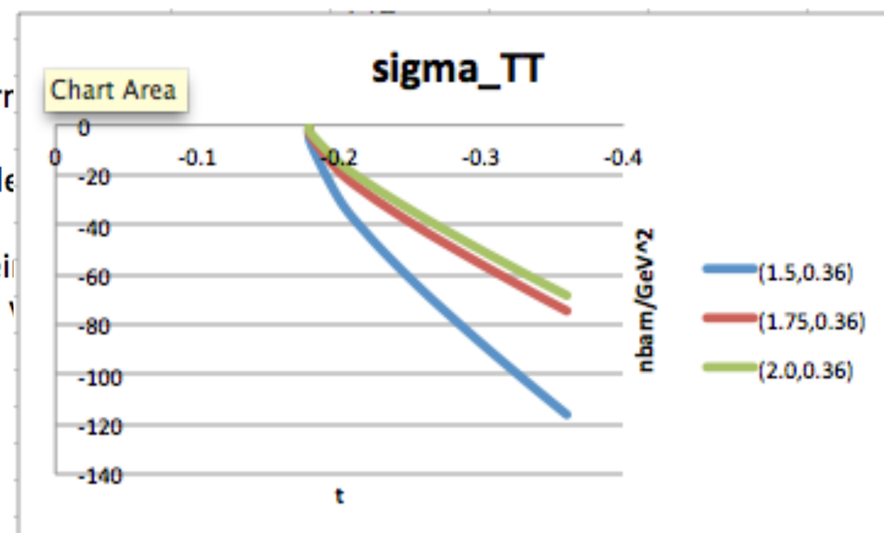




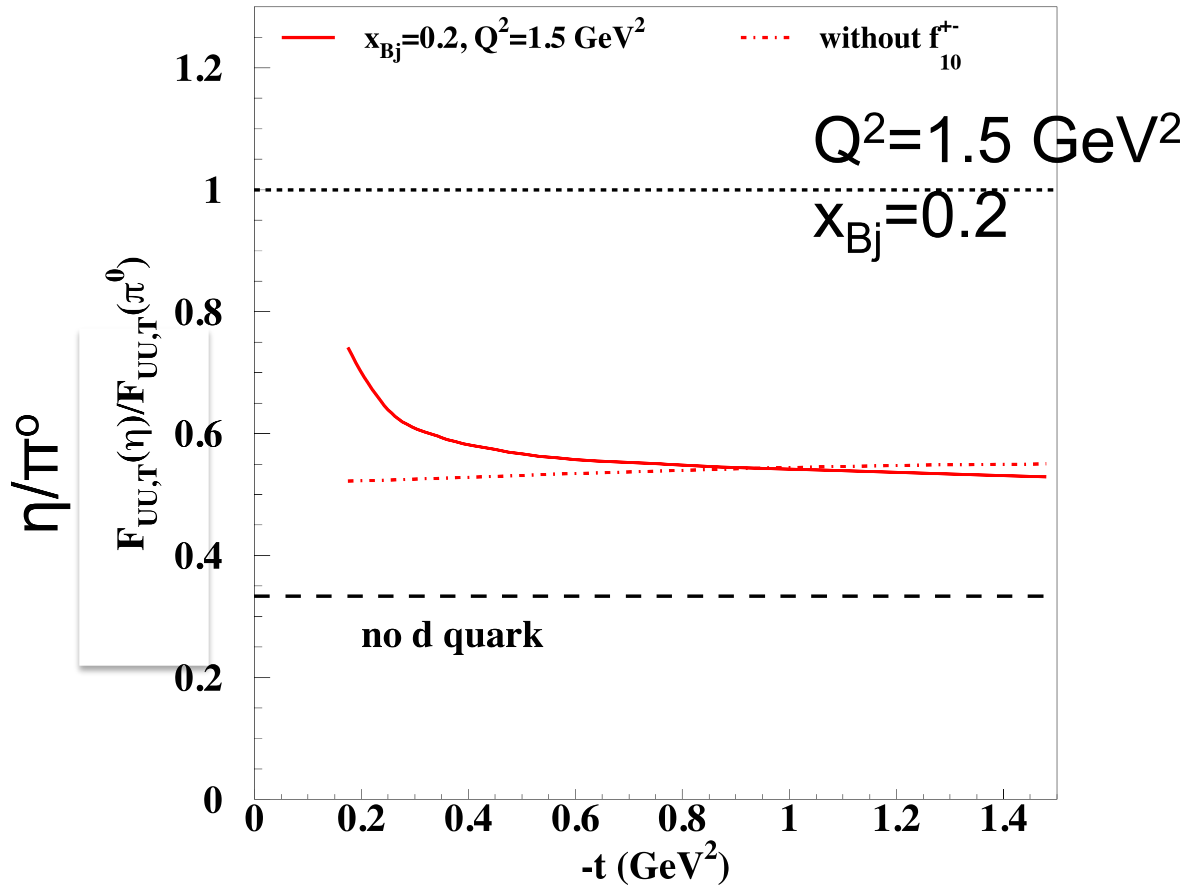
Shaded area: 2% norr

Solid line: GK11 mode

Dashed line: Goldstei
(waiting for updated v



Ratio of unpolarized η / π^0

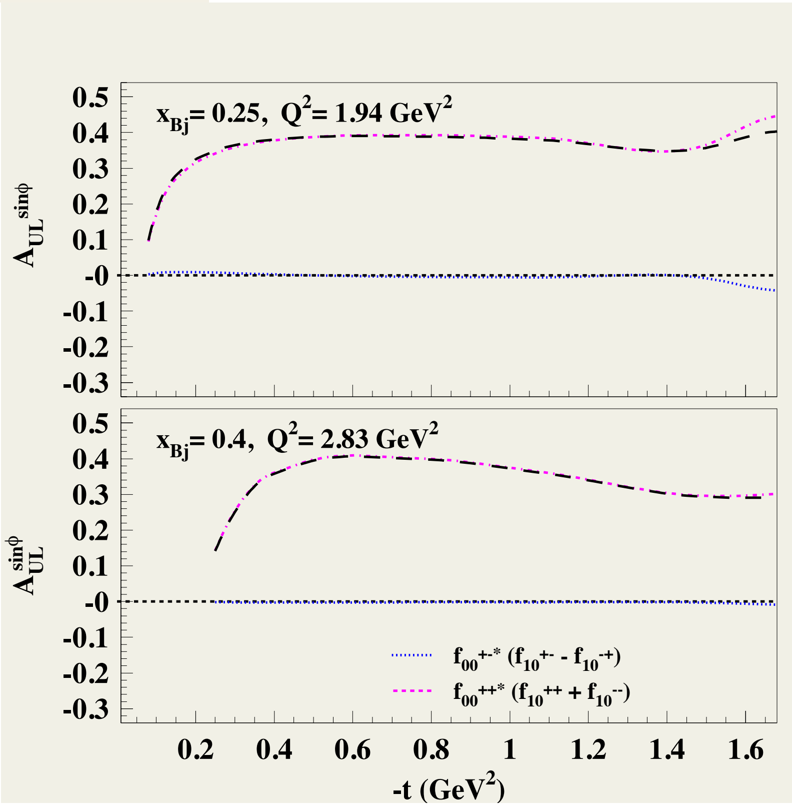


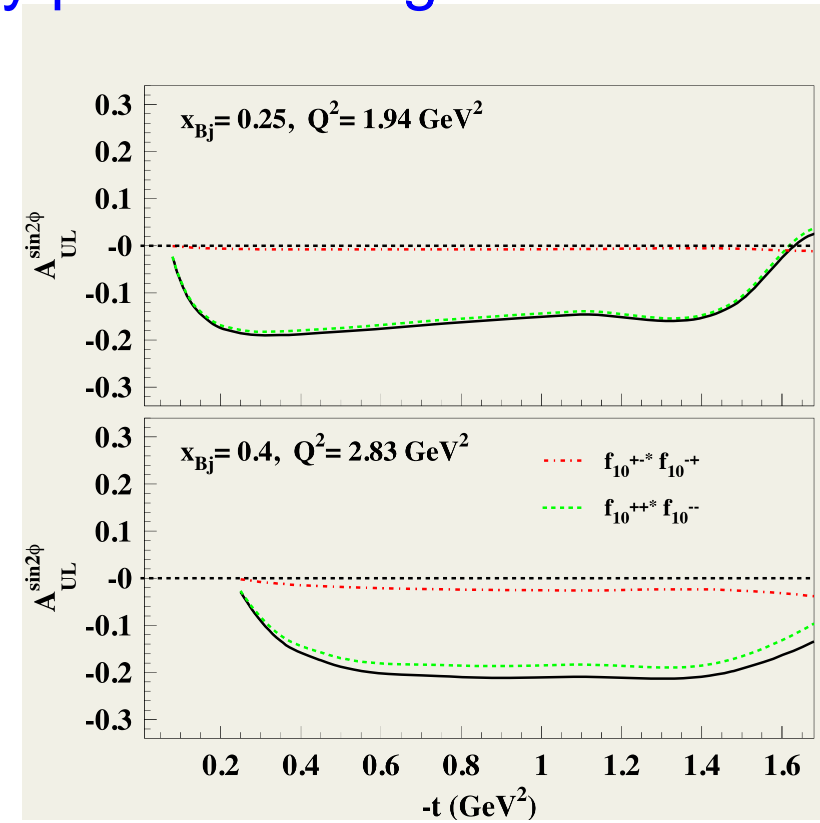
Summary

- Flexible parameterization for chiral even from form factors, pdfs & DVCS **R✖Dq**
- Extended **R✖Dq** to chiral odd sector
- DVMP – π^0 many dσ 's & Asymmetries measure ***Transversity***

Backup slides

Longitudinally polarized target

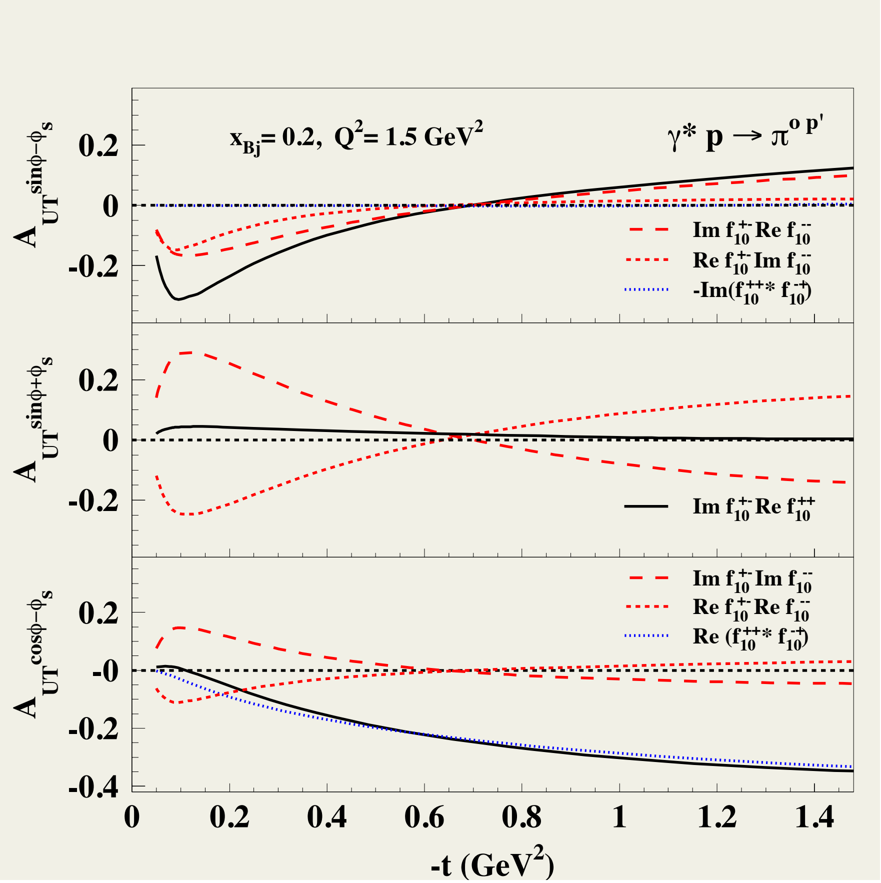


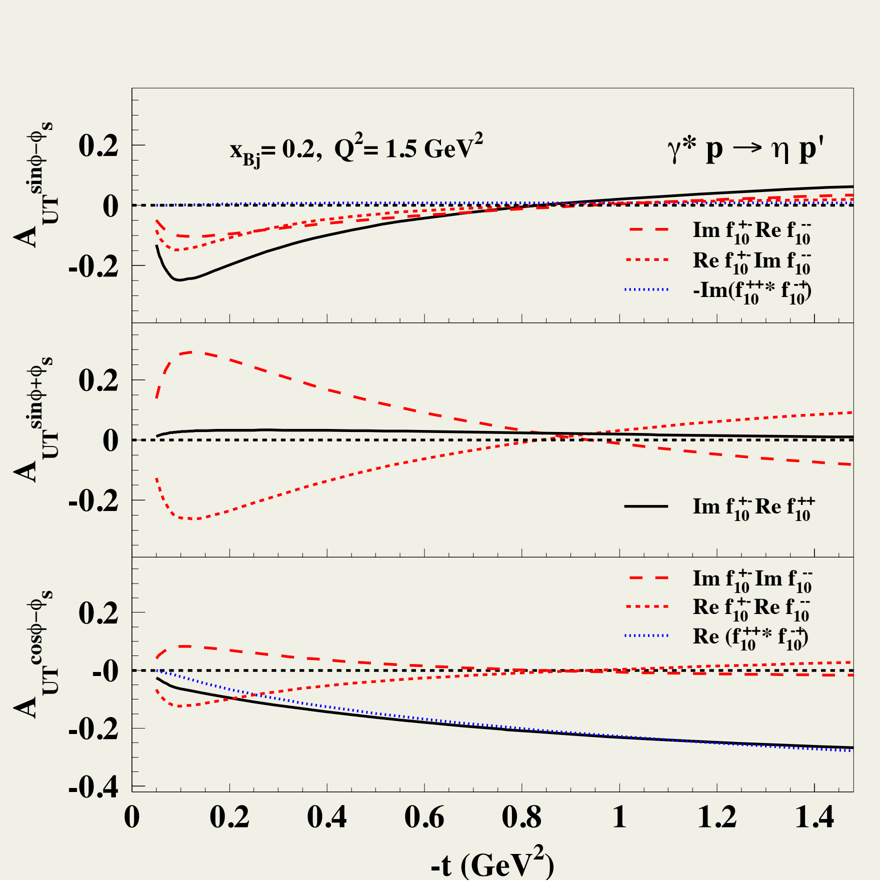


Look for tensor charge in f_{10}^{+-}

Transverse dipole moment in f_{10}^{++},f_{10}^{--}

Transverse target





Look for tensor charge in f_{10}^{+-}

Transverse dipole moment in f_{10}^{++}, f_{10}^{--}

Reggeization via spectator diquark mass formulation
Where does the Regge behavior come from?

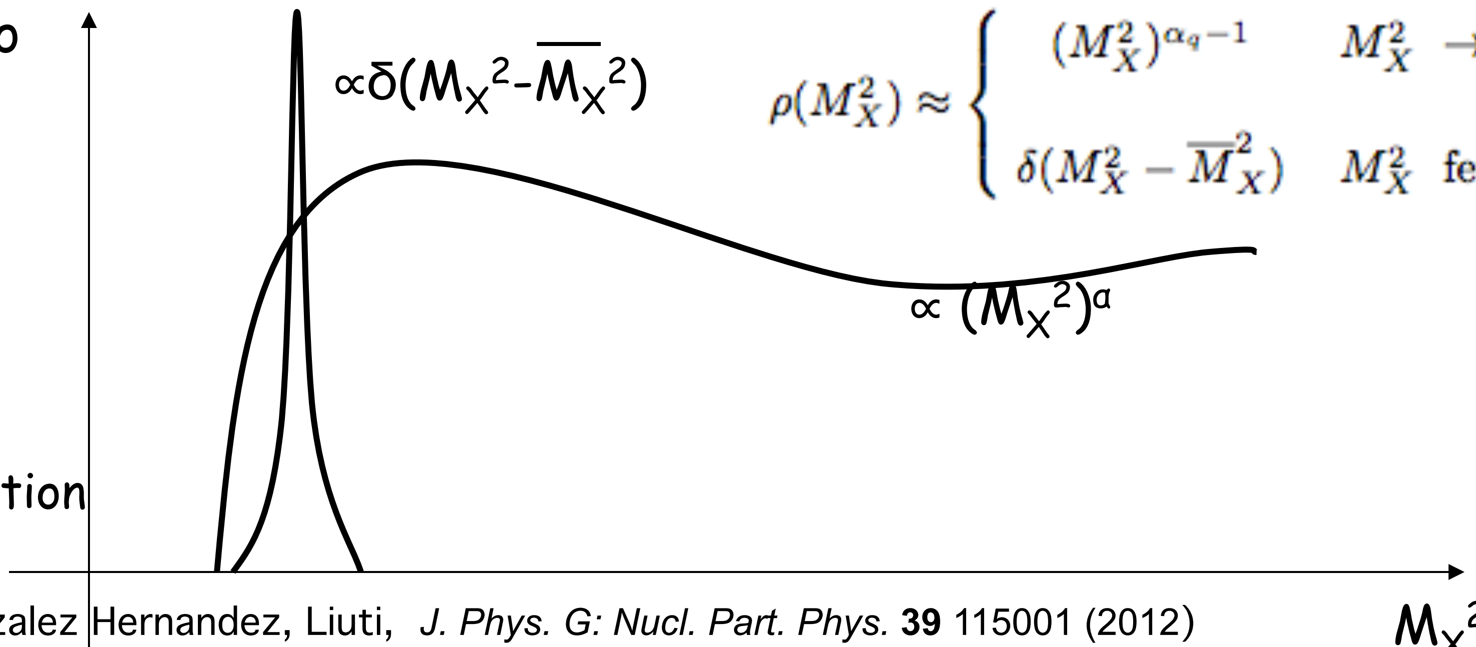
$$F_T^q(X,\zeta,t) = \mathcal{N}_q \int_0^\infty dM_X^2 \rho(M_X^2) F_T^{(m_q,M_\Lambda^q)}(X,\zeta,t;M_X),$$

Diquark spectral function

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

"Regge"

$$\rho(M_X^2) \approx \begin{cases} (M_X^2)^{\alpha_q - 1} & M_X^2 \to \infty \\ \delta(M_X^2 - \overline{M}_X^2) & M_X^2 \text{ few GeV}^2 \end{cases}$$

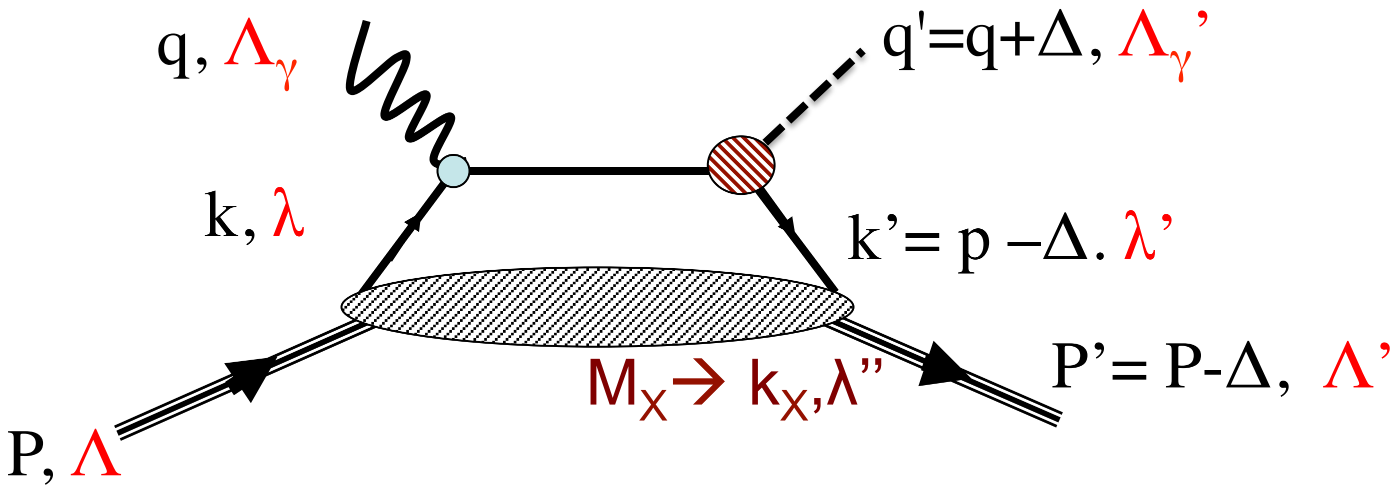


+ Q^2 Evolution

GRG, Gonzalez Hernandez, Liuti, *J. Phys. G: Nucl. Part. Phys.* **39** 115001 (2012)

Following DIS work by Brodsky, Close, Gunion (1973)

Reggeization



$$A = \mathcal{N} \int \frac{dk_X^2 dk^2}{(k^2 - m^2 - i\epsilon)(k'^2 - m^2 - i\epsilon)} \frac{\rho(k_X^2, k^2) \times (spin\ structure)}{(k_X^2 - M_X^2 - i\epsilon)}$$

Landshoff, Polkinghorn, Short '71
Brodsky, Close, Gunion '71 Regge behavior required for Compton
Ahmad, Honkanen,Liuti,Taneja '07, '09
Gorshteyn & Szczepaniak (PRD, 2010)
Brodsky, Llanes-Estrada '07
Brodsky, Llanes, Szczepaniak '08

GRG, Gonzalez Hernandez, Liuti, *J. Phys. G: Nucl. Part. Phys.* **39** 115001 (2012)

Helicity amps (q'+N->q+N') are linear combinations of GPDs

$$A_{+,+;+,+} = \sqrt{1-\xi^2}\left[\frac{H+\tilde{H}}{2} - \frac{\xi^2}{1-\xi^2}\frac{E+\tilde{E}}{2}\right]$$

$$A_{-,+;-,+} = \sqrt{1-\xi^2}\left[\frac{H-\tilde{H}}{2} - \frac{\xi^2}{1-\xi^2}\frac{E-\tilde{E}}{2}\right]$$

$$A_{+,+;-,+} = -\frac{\sqrt{t_0-t}}{4M}(E-\xi\tilde{E})$$

$$A_{-,+;+,+} = \frac{\sqrt{t_0-t}}{4M}(E+\xi\tilde{E})$$

for chiral even GPDs and

$$A_{+-,++} = -\frac{\sqrt{t_0-t}}{2M}\left[\widetilde{H}_T + \frac{1+\xi}{2}E_T - \frac{1+\xi}{2}\widetilde{E}_T\right]$$

$$A_{++,--} = \sqrt{1-\xi^2}\left[H_T + \frac{t_0-t}{4M^2}\widetilde{H}_T - \frac{\xi^2}{1-\xi^2}E_T + \frac{\xi}{1-\xi^2}\widetilde{E}_T\right]$$

$$A_{+-,-+} = -\sqrt{1-\xi^2}\,\frac{t_0-t}{4M^2}\,\widetilde{H}_T$$

$$A_{++,+-} = \frac{\sqrt{t_0-t}}{2M}\left[\widetilde{H}_T + \frac{1-\xi}{2}E_T + \frac{1-\xi}{2}\widetilde{E}_T\right],$$

for chiral odd GPDs, where for consistency with previous literature we have

T-reversal at $\xi = 0$

In diquark spectator models $A_{++;++}$, etc. are calculated directly. Inverted -> GPDs

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Invert to obtain model parameterization for GPDs

S=0 diquark
Spectator model

$A_{++,-+} = - A_{++,+-}^*$
$A_{-+,++} = - A_{+-,++}^*$
$A_{++,++} = A_{++,--}$

$$H(x,\xi,t) = \frac{1}{\sqrt{1-\xi^2}}(A_{+,+;+,+} + A_{-,+;-,+}) - \frac{2M\xi^2}{\Delta(1-\xi^2)}(A_{+,+;-,+} - A_{-,+;+,+})$$
$$E(x,\xi,t) = -\frac{2M}{\Delta}(A_{+,+,-,+} - A_{-,+;+,+})$$
$$\tilde{H}(x,\xi,t) = \frac{1}{\sqrt{1-\xi^2}}(A_{+,+;+,+} - A_{-,+;-,+}) + \frac{2M\xi}{\Delta(1-\xi^2)}(A_{+,+,-,+} + A_{-,+;+,+})$$
$$\tilde{E}(x,\xi,t) = \frac{2M}{\Delta\xi}(A_{+,+,-,+} + A_{-,+;+,+})$$

for chiral even GPDs and

$$H_T(x,\xi,t) = \frac{1}{\sqrt{1-\xi^2}}(A_{+,+;-,-} + A_{-,+;+,-}) + \frac{2M\xi}{\Delta(1-\xi^2)}(A_{+,+;+,-} - A_{-,+;-,-})$$
$$\xi E_T(x,\xi,t) - \tilde{E}_T(x,\xi,t) = \frac{2M}{\Delta}(A_{+,+;+,-} - A_{-,+;-,-})$$
$$E_T(x,\xi,t) + \tilde{E}_T(x,\xi,t) = \frac{\Delta}{2M(1-\xi)}[2A_{+,+;+,-} + \frac{4M}{\Delta\sqrt{1-\xi^2}}A_{-,+;+,-}]$$

double flip

$$\tilde{H}_T(x,\xi,t) = \frac{4M^2}{\Delta^2\sqrt{1-\xi^2}}A_{-,+;+,-}$$

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Unpolarized Helicity Amplitudes