Exclusive meson leptoproduction and spin dependent generalized parton distributions

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Brunelleschi's Duomo

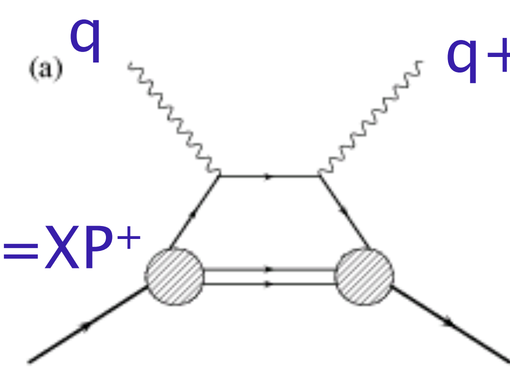
Outline of Discussion

- Exclusive leptoproduction & GPDs
  - 8 quark GPDs: 4 Chiral even + 4 Chiral odd
  - Getting at spin of nucleon's partons
  - Constraints on GPDs
    - theoretical
    - from direct measurements
  - **Spin dependent GPDs, symmetries, crossing & C-parity**
- Model calculations & Spin Relations
  - Some early predictions, Regge poles, Scalar diquark spectator, full parameterization (AHLT)
  - cross sections,
  - asymmetries
  - parameter dependence
- <u>Conclusions</u>

See recent: GRG, Liuti, PRD79, 054014 (2009)
Spin 2008, DIS2009 proceedings

DVCS & DVMP $\gamma^*(Q^2)+P \to (\gamma \text{ or meson})+P'$

partonic picture



Factorized
"handbag"
picture

$\zeta \to 0$
Regge

$X>\zeta$ DGLAP
$X<\zeta$ ERBL

Quark-spectator
quark+diquark

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GPD definitions

Momentum space nucleon matrix elements of quark correlators

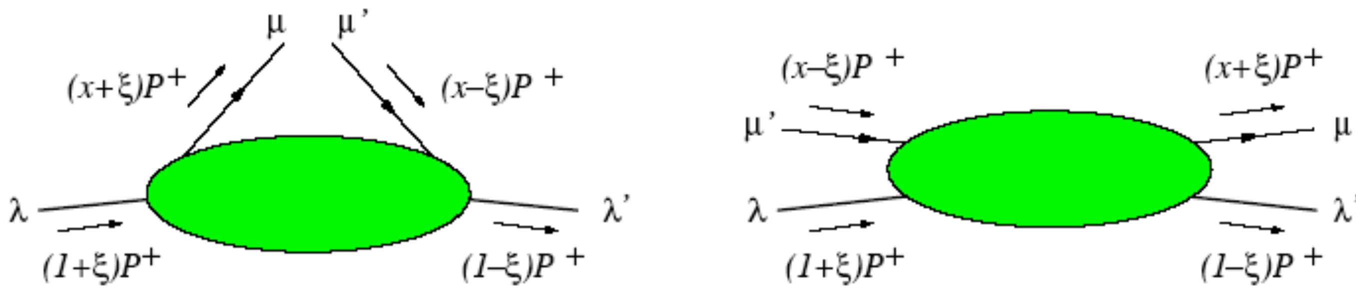
$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\, \bar{\psi}(-\tfrac{1}{2}z)\,\gamma^+\psi(\tfrac{1}{2}z)\,\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[H^q\,\gamma^+ + E^q\,\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}\right]u(p,\lambda),$$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

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

Chiral odd GPDs

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

Eqns connecting GPD & helicity amps - M. Diehl, Eur.Phys.J.C19 (2001) 485;
Boglione & Mulders, Phys.Rev.D 60 (1999) 054007.



(a) (b)

- Exploit these relations to evaluate H_T^q with diquark spectator (scalar & axial vector -> u & d distributions) with constraints from form factors & lattice calculations. (Hägler, Schierholtz, et al. See especially S.Liuti, et al. DIS 2008.)

Spin complications

<u>8 independent GPDs</u>

4 Chiral even $\lambda=\lambda'$

non-flip

$H(X,\zeta,t)$, E, H~, E~

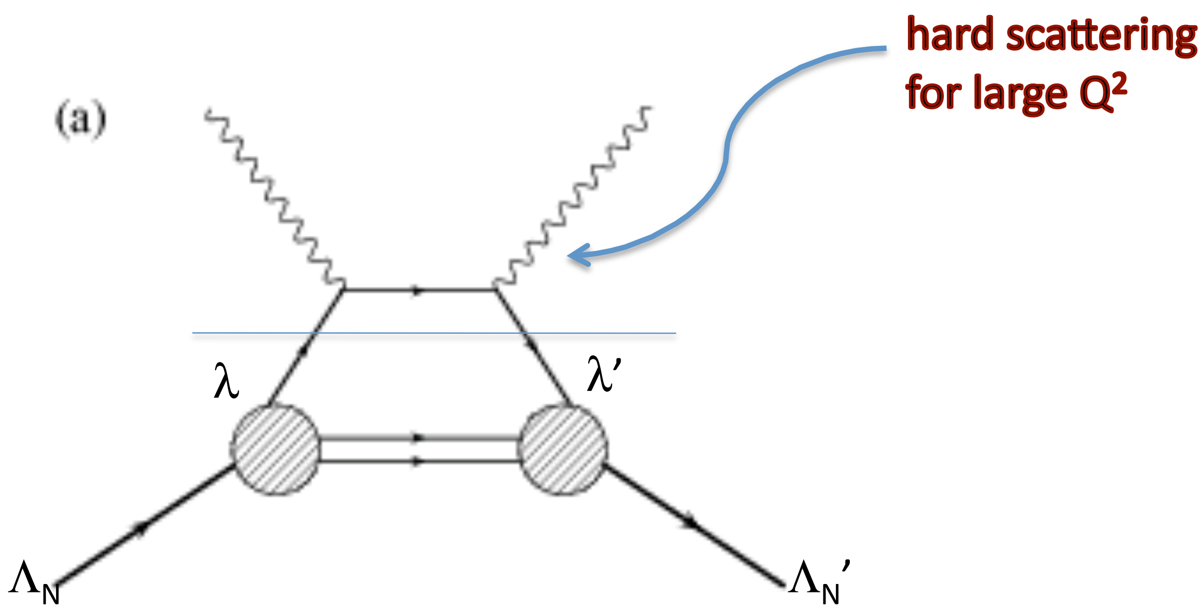
4 Chiral odd $\lambda= -\lambda'$

helicity flip

H_T, E_T, $H^{\sim}_T$, $E^{\sim}_T$

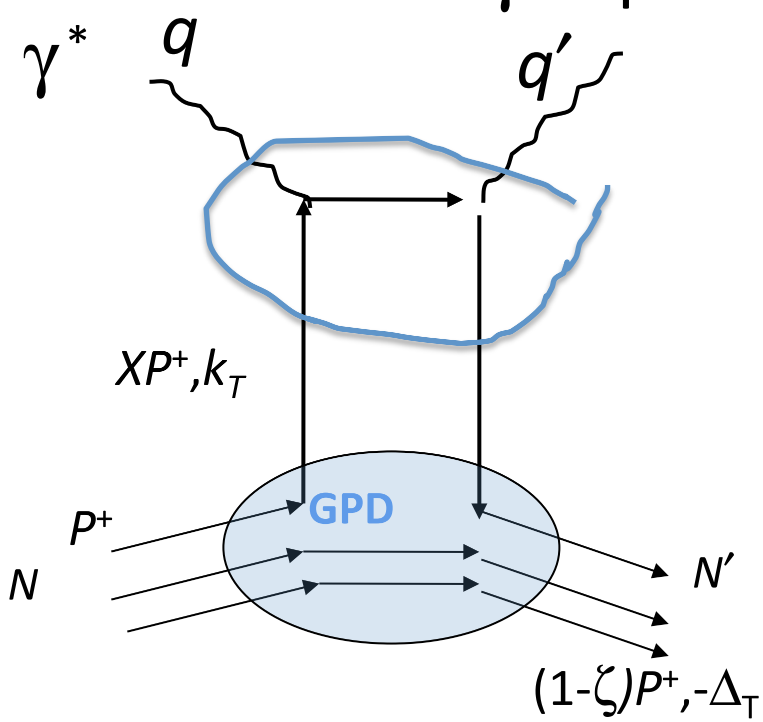
$H_T(x,0,0)=h_1(x)$

transversity



- What are theoretical expectations?
- What kinds of processes & observables access different spin GPDs?
  - DVCS with Bethe-Heitler interference probes **<u>Chiral evens</u>**, H & E. (Transverse γ^*->Transverse γ)
  - DVMP ρ,ω,ϕ spin-density matrices (longitudinal γ^*->longitudinal ρ,ω,ϕ)
  - &/or Polarized beams, targets can get E~,H~ separated from E,H

How to measure Chiral odds? t-channel view: What J^{PC} ?



- $\gamma^* + \pi^0 \rightarrow$ q+anti-q
  $\rightarrow$ N+anti−N

for $t \geq 0$ need to

- Conserve J, P, C , (Isospin)

$\gamma^* + \pi^0$ is C-parity odd

- Must couple to C-parity odd
- q+anti-q & N+antiN

- Field Theory perspective

$$\overline{\psi}(z)\ \Gamma\ \psi(0)$$

bilocal operator. Expand via O.P.E.

J^{PC} quantum numbers & GPDs

$$N\overline{N}: \text{ spin S} = 0\text{ , J = L, P} = (\text{-}1)^{\text{L+1}}\text{, C} = (\text{-}1)^{\text{L+S}}$$

$$\text{J}^{\text{PC}}: \text{ L} = 0 \Rightarrow 0^{-+}$$

$$\text{L} = 1 \Rightarrow 1^{+-}$$

$$\text{L} = 2 \Rightarrow 2^{-+} \quad \ldots \text{ L}^{(\text{-}1)^{\text{L+1}} \; (\text{-}1)^{\text{L}}}$$

$$\text{spin S} = 1, \quad \text{J}^{\text{PC}}: \text{ L} = 0 \Rightarrow 1^{--}$$

$$\text{L} = 1 \Rightarrow 0^{++}, 1^{++}, 2^{++}$$

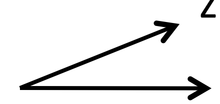
$$\text{L} = 2 \Rightarrow 1^{--}, \; 2^{--}, 3^{--} \; \ldots . (\text{L -1, L, L +1})^{(\text{-}1)^{\text{L+1}} \; (\text{-}1)^{\text{L+1}}}$$

These must match the q+anti-q states' quantum numbers (quarkonium states – actually local quark field operators from OPE).

q+anti-q ↔ N+antiN although the S_z totals need not match for $\theta_t \neq 0$.

For z-axis quantization,

$$\langle \lambda\lambda' | \rightarrow S_{Z'} = \lambda - \lambda' \text{ for } \vec{z}' \text{ along } \vec{k} \text{ similarly for } |\Lambda\Lambda'\rangle$$



$$\text{forward limit } f_1(x) + g_1(x) \sim |\Lambda = + \rightarrow \lambda = +|^2 \quad \sim \langle + + | T | + + \rangle$$

$$f_1(x) - g_1(x) \sim |\Lambda = + \rightarrow \lambda = -|^2 \quad \sim \langle - - | T | + + \rangle$$

linear combinations for S_Z=0, S=0 or 1 in t-channel amps

to GPD J^{PC}

$$f_1(x) = H(x,0,0) \sim \left(\langle + + | T | + + \rangle + \langle - - | T | + + \rangle \right)$$

$$g_1(x) = \tilde{H}(x,0,0) \sim \left(\langle + + | T | + + \rangle - \langle - - | T | + + \rangle \right)$$

There are 6 more GPDs. How are they related to pdf’s, Form Factors, helicity amps, Transversity?

to GPD J^{PC}

$$f_1(x) = H(x,0,0) \sim \left(\langle + + | T | + + \rangle + \langle - - | T | + + \rangle\right)$$

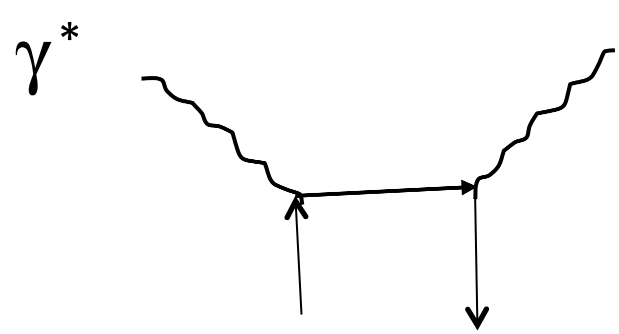
$$g_1(x) = \tilde{H}(x,0,0) \sim \left(\langle + + | T | + + \rangle - \langle - - | T | + + \rangle\right)$$

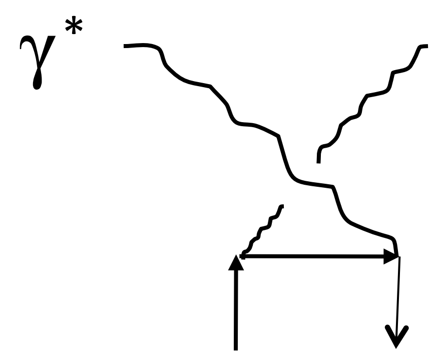
$$h_1(x) = H_T(x,0,0) \sim \langle - + | T | - + \rangle$$

One more input into J^{PC} assignments for all GPDs

C - parity involves symmetry under $q \leftrightarrow \bar{q}$ & $N \leftrightarrow \bar{N}$

Crossing operation exchanges $x \leftrightarrow -x$





Additional connections for Chiral odd

$$A_{++,+-} = \epsilon \frac{\sqrt{t_0 - t}}{2m} \left(\tilde{H}_T^q + (1-\xi) \frac{E_T^q + \tilde{E}_T^q}{2} \right),$$

$$A_{-+,--} = \epsilon \frac{\sqrt{t_0 - t}}{2m} \left(\tilde{H}_T^q + (1+\xi) \frac{E_T^q - \tilde{E}_T^q}{2} \right),$$

} no nucleon flip

$$A_{++,--} = \sqrt{1-\xi^2} \left(H_T^q + \frac{t_0 - t}{4m^2} \tilde{H}_T^q - \frac{\xi^2}{1-\xi^2} E_T^q + \frac{\xi}{1-\xi^2} \tilde{E}_T^q \right)$$

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

} nucleon flip

$$\int_{\zeta-1}^{1} dX \, [E(X,\zeta,t)]_{\zeta=t=0} = \kappa^q \qquad \int_{\zeta-1}^{1} dX \left[2\tilde{H}_T^q(X,\zeta,t) + E_T^q(X,\zeta,t) \right]_{\zeta=t=0} \overset{\sim}{=} \kappa_T^q$$

See M.Burkardt

$$\int d^2k_T \, dX \, f_{1T}^{\perp q}(X,k_T) = \kappa^q \qquad -\int d^2k_T \, dX \, h_1^{\perp q}(X,k_T) = \kappa_T^q$$

$$\int d^2k_T dX \, h_1^{\perp q}(X,k_T) = -\kappa_T^q$$

J^{PC} for chiral even GPDs

distribution	J^{PC}	
$H^q(x,\xi,t) - H^q(-x,\xi,t)$	$0^{++}, 2^{++}, \ldots$	} S=1 crossing even
$E^q(x,\xi,t) - E^q(-x,\xi,t)$	$0^{++}, 2^{++}, \ldots$	
$\widetilde{H}^q(x,\xi,t) + \widetilde{H}^q(-x,\xi,t)$	$1^{++}, 3^{++}, \ldots$	← S=1 crossing odd
$\widetilde{E}^q(x,\xi,t) + \widetilde{E}^q(-x,\xi,t)$	$0^{-+}, 1^{++}, 2^{-+}, 3^{++}, \ldots$	S=0 crossing even & S=1 crossing odd
$H^q(x,\xi,t) + H^q(-x,\xi,t)$	$1^{--}, 3^{--}, \ldots$	} S=1 crossing odd
$E^q(x,\xi,t) + E^q(-x,\xi,t)$	$1^{--}, 3^{--}, \ldots$	
$\widetilde{H}^q(x,\xi,t) - \widetilde{H}^q(-x,\xi,t)$	$2^{--}, 4^{--}, \ldots$	S=1 crossing even
$\widetilde{E}^q(x,\xi,t) - \widetilde{E}^q(-x,\xi,t)$	$1^{+-}, 2^{--}, 3^{+-}, 4^{--}, \ldots$	S=0 crossing odd & S=1 crossing even

Hence only *E~* will enter in π^0 but will be suppressed by $\Delta\xi$ or ξ^2.

Tables: See Lebed & Ji, PRD63,076005 (2001); Diehl & Ivanov, Eur. Phys. Jour. C52, 919 (2007)

J^{PC} for chiral odd GPDs

- 2 series for each GPD, space-space or time-space tensor from $\sigma^{\mu\nu}$. μ-> + in light cone.
- Indices become (+,1) or (+,2), so mixtures.
- see P. Haegler, PLB 594 (2004) 164–170; Z.Chen & X.Ji, PRD 71, 016003 (2005)

$n\backslash J$	1	2	3	4	$\cdots$
0	$1^{--}_{0,2}$				
1	1^{-+}	$2^{++}_{1,3}$			
2	$1^{--}_{0,2}$	2^{+-}	$3^{--}_{2,4}$		
3	1^{-+}	$2^{++}_{1,3}$	3^{-+}	$4^{++}_{3,5}$	
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$

$n\backslash J$	1	2	3	4	$\cdots$
0	1^{+-}_{1}				
1	1^{++}_{1}	2^{-+}_{2}			
2	1^{+-}_{1}	2^{--}_{2}	3^{+-}_{3}		
3	1^{++}_{1}	2^{-+}_{2}	3^{++}_{3}	4^{-+}_{4}	
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$

$H_T, E_T, \tilde{H}_T$

$\tilde{E}_T$

lowest J values have lowest L for N-Nbar states & are nearest meson singularities

Weak form factors

$$\left\langle N(p')\Lambda' \middle| J_A^{\nu} \middle| N(p)\Lambda \right\rangle = \overline{U}^{(\Lambda')}(p') \left[g_A(t)\gamma^{\nu}\gamma^5 + \frac{g_P(t)}{m_\mu}\Delta^{\nu}\gamma^5 \right] U^{(\Lambda)}(p)$$

- $g_A(0)=1.267$ & t dependence $\propto 1/(t-M_A^2)^n$
- PCAC relates divergence to pion pole (Dispersion Relation) Goldberger-Trieman relation $g_A(0) \propto g_{\pi NN}$
- Pion pole approximation yields relation

$$g_P(t) = \frac{2m_\mu M}{m_\pi^2 - t} g_A(0)$$

Weak form factors

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- $g_A(0)$=1.267 & t dependence ∝ $1/(t-M_A^2)^n$
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$$g_P(t) = \frac{2m_\mu M}{m_\pi^2 - t} g_A(0)$$

How does this contribute to π^0 production?

No π^0 pole for this (γ^* does not $\rightarrow \pi^0\pi^0$)

What is left of $g_P(t)$ then? Data show $g_P(-0.88m_\mu^2) = 10 \pm 2$

vs. PCAC value of 8.2

Gorringe & Fearing, Rev.Mod.Phys.76 (2004)

$\tilde{E}$ norm will be small for π^0

dσ with factor t (like E) & vanishes for ξ (skewness) →0.

Models of $\tilde{E}$

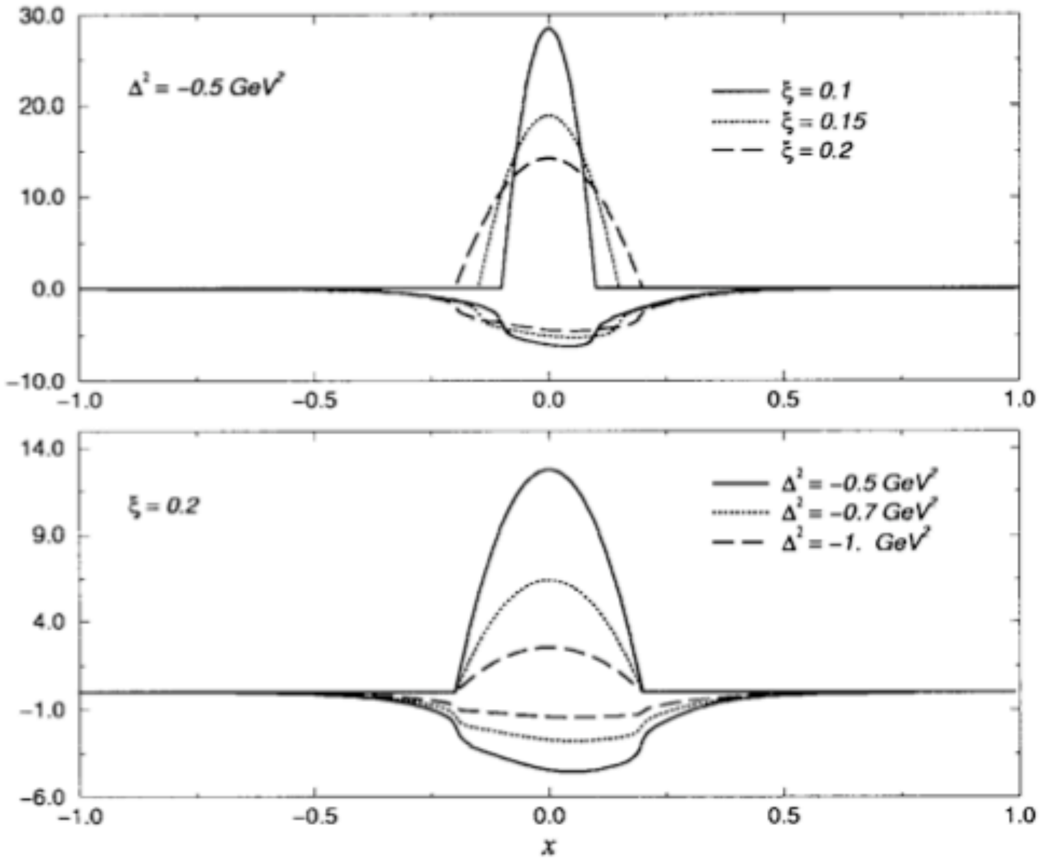
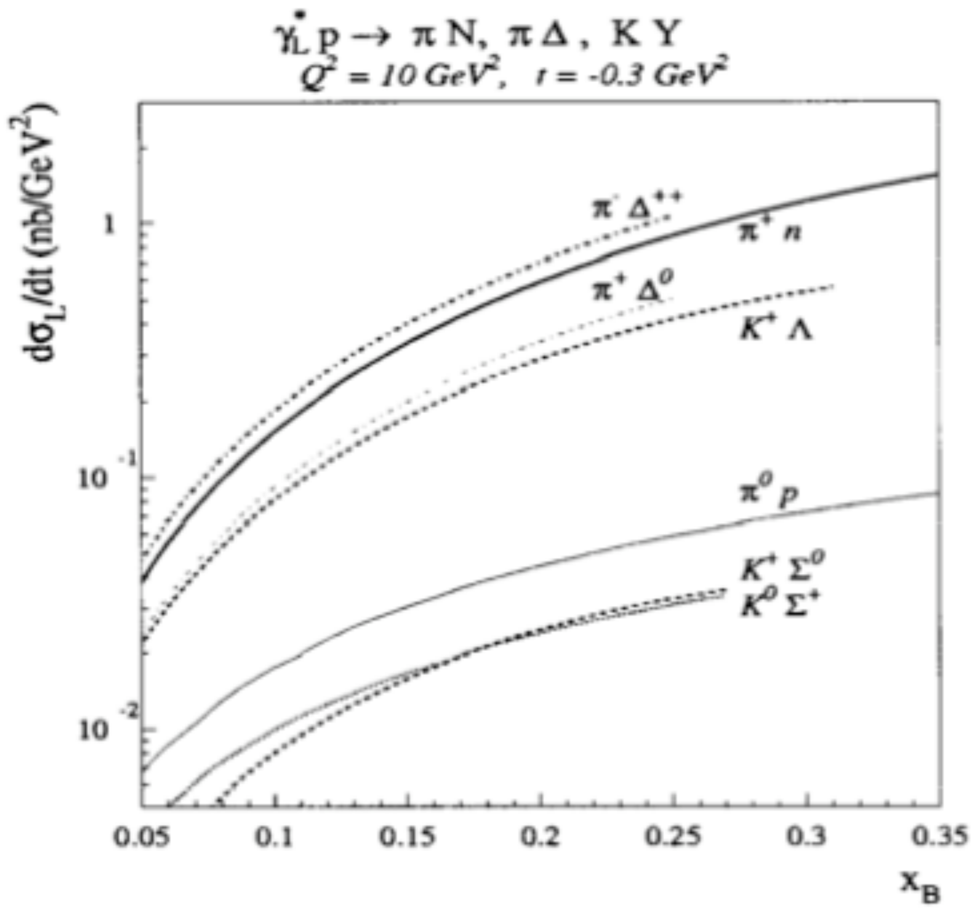


Figure 10: Comparison of pion pole contribution and non-pole part of the isovector GPD $\widetilde{E}$ at various values of t and ξ. The positive curves correspond to pion pole contributions.

Goeke, Polyakov, Vanderhaeghen, Prog.Nuc.Phys.47, 401 (2001)

Model calculations of π^0 production



π^+ pole in $\tilde{E}$

No π^0 pole in $\tilde{E}$ for π^0 production

contribution supressed

Goeke, Polyakov,
Vanderhaeghen, Prog.Nuc.Phys.47, 401 (2001)

only longitudinal photons

How to determine GPDs? Constraints on GPDs

<u>Constraints from Form Factors</u>

$$\int_0^1 dx H(x,\xi,t) = F_1(t)$$ Dirac

$$\int_0^1 dx E(x,\xi,t) = F_2(t)$$ Pauli, etc.

<u>How can these be independent of ξ?</u>

<u>Constraints from Polynomiality</u>

Result of Lorentz invariance & causality.
Not necessarily built in to models

$$\int_{-1}^{+1} dx\, x^n H(x,\xi,t) = \sum_{k=0,2,..}^{n} A_{n,k}(t)\xi^k + \frac{1-(-1)^n}{2} C_n(t)\xi^{n+1}$$

$$\int_{-1}^{1} dx\, x^n E(x,\xi,t) = \sum_{k=0,2,...}^{n} B_{n,k}(t)\xi^k - \frac{1-(-1)^n}{2} C_n(t)\xi^{n+1}$$

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Other chiral even GPDs

$$\int_{-1}^{+1} dx x^n \tilde{H}(x,\xi,t) = \sum_{k=0,2...}^{n} \tilde{A}_{n,k}(t)\xi^k$$

$$\int_{-1}^{+1} dx x^n \tilde{E}(x,\xi,t) = \sum_{k=0,2...}^{n} \tilde{B}_{n,k}(t)\xi^k$$

Chiral odd decompositions

$$\int_{-1}^{+1} dx x^n H_T(x,\xi,t) = \sum_{k=0,2...}^{n} A_{Tn,k}(t)\xi^k$$

$$\int_{-1}^{+1} dx x^n E_T(x,\xi,t) = \sum_{k=0,2...}^{n} B_{Tn,k}(t)\xi^k$$

$$\int_{-1}^{+1} dx x^n \tilde{H}_T(x,\xi,t) = \sum_{k=0,2...}^{n} \tilde{A}_{Tn,k}(t)\xi^k$$

$$\int_{-1}^{+1} dx x^n \tilde{E}_T(x,\xi,t) = \sum_{k=1,3...ODD}^{n} \tilde{B}_{Tn,k}(t)\xi^k$$

First three: n=0 1^{--}, 1^{+-} fourth enters at n=1 with no C= -

How to determine GPDs?
Constraints on GPDs

Constraints from Form Factors

$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t),$$

Dirac EM Form Factor
norm 1

$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t),$$

Pauli EM Form Factor
norm κ^q

$$\int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t),$$

Weak axial vector Form Factor
norm g_A axial charge

$$\int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = g_P^q(t).$$

Weak "induced" pseudoscalar
Form Factor – norm? enters dσ
with factor t (like *E*).

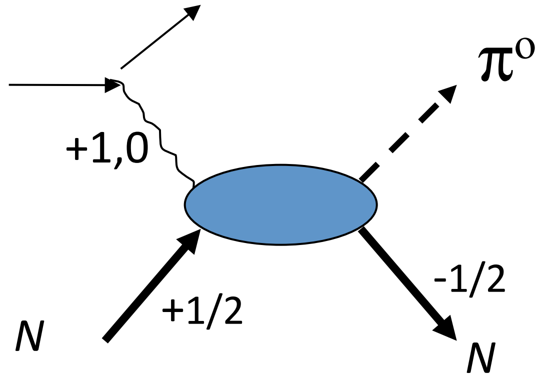
Spectator model

- scalar diquark:

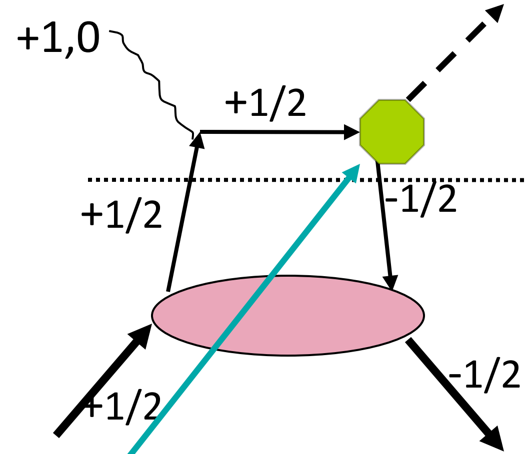
  $H \leftrightarrow H_T$ and same for other 3 pairs

- axial diquark: more complex linear relations

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



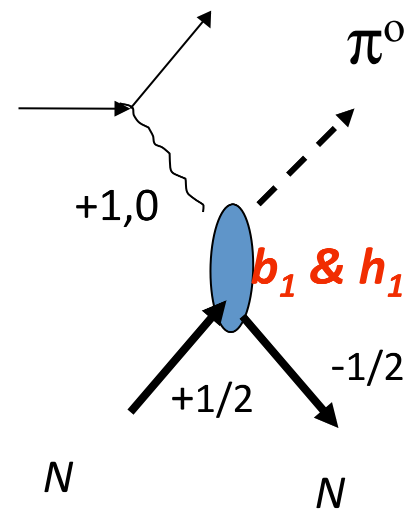
e.g. $f_{+1+,0-}(s,t,Q^2)$



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

$g_{+1+,0-}$ $A_{++,--}$

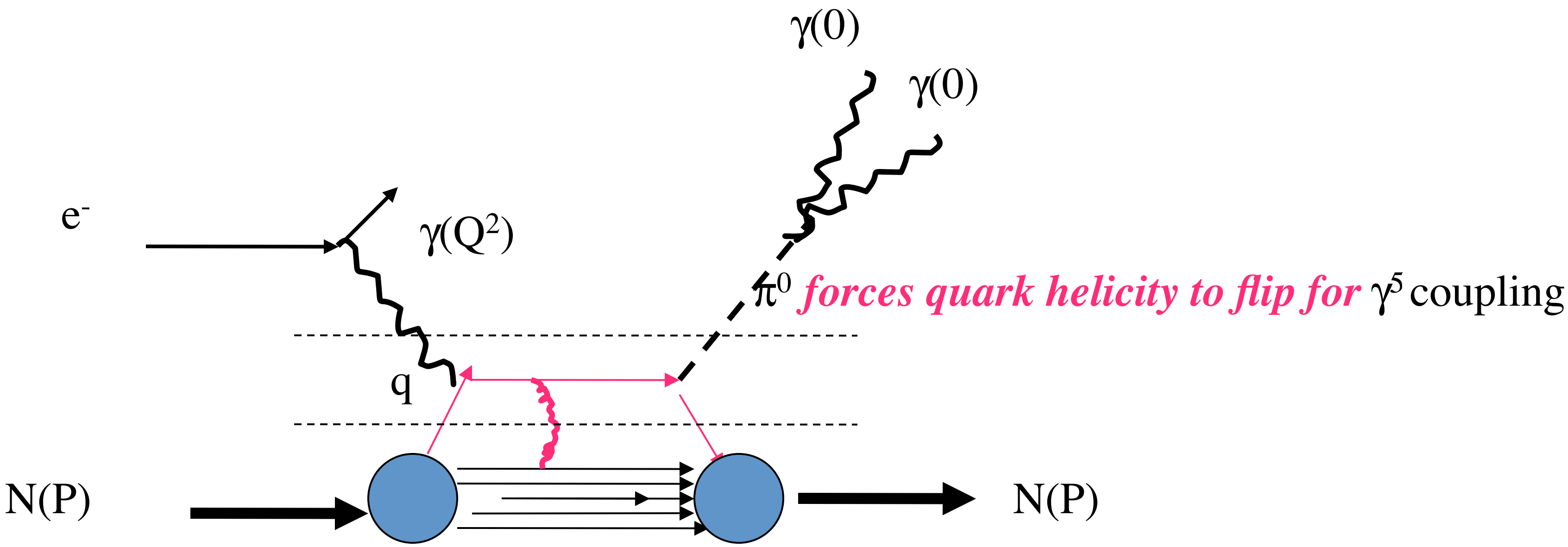
H_T



What about coupling of π to $q \to q'$? Assumed γ^5 vertex
Then for $m_{quark}=0$ has to flip helicity
for $q \to \pi + q'$ and $\mathbf{q \cdot q' \neq 0}$. ***Naïve twist 3*** $\bar{\psi} \gamma^5 \psi$

Rather than $\gamma^\mu \gamma^5$ – does not flip ***twist 2.*** But $q' \bullet \gamma \gamma^5$ will not contribute to transverse γ. Differs from t-channel approach to Regge factorization:

π^0 electroproduction



For virtual photoproduction of π^0 quark helicity must flip at π vertex

Questions: Amps for γ_L shown to factorize in DVCS. Do amps for γ_T factorize for π^0 as $1/Q^2 \rightarrow 0$? What to do about moderate Q^2?

Where does b_1 exchange approximate t dependence of GPD?

How is x dependence modeled? Small x -> large s. Regge! Many recent resurrections - Laget, et al., Sczepaniak, et al., VGG, Liuti, et al., Goloskokov & Kroll, ...

Important ingredients for relating transversity to exclusive π^0 electroproduction

- Tensor charge couples via $\sigma^{\mu\nu}\gamma_5$ to nucleons
- Coupled quantum numbers 1^{+-} correspond to b_1 & h_1 couplings ($\gamma^\mu\,\gamma_5$ is opposite Chirality does not contribute)
- $\gamma^* + \pi^0$ is C-parity eigenstate coupling to
  - 1^{+-} q+anti-q states (S=0, L=1…) $\Rightarrow b_1^0$ & h_1
  - 1^{--} q+anti-q states (S=1, L=1…) $\Rightarrow \rho^0$ & ω
- $\gamma^*_L + \pi^0$ does not couple to ρ^0 & ω but does to b_1^0 & h_1
- $\gamma^*_T + \pi^0$ couples to <u>both</u> sets
- Factorization proofs: QCD $\rightarrow \gamma_L$. Applicable to γ_T & GPDs?
- Different transition form factors $\rho^0 \rightarrow \pi^0$ & $b_1^0 \rightarrow \pi^0$
- Which picture - Regge or partons? Both connected…

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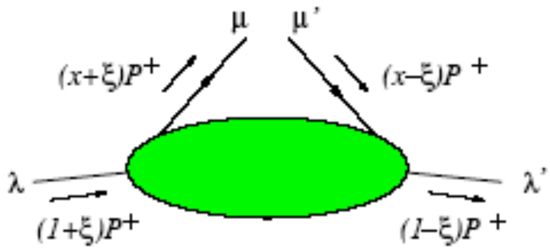
GPDs & helicity



$\tilde{E}$ always enters with ξ powers and $\sqrt{t_0 - t}$

$$A_{\lambda'\mu',\lambda\mu} = \int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda' |\, \mathcal{O}_{\mu',\mu}(z)\, | p,\lambda\rangle \Big|_{z^+=0,\, \mathbf{z}_T=0}$$

$$= \int \frac{d^2k_T}{(2\pi)^3} \left[\int dz^-\, d^2z_T\, e^{ik\cdot z} \langle p',\lambda' |\, \mathcal{O}_{\mu',\mu}(z)\, | p,\lambda\rangle \right]_{z^+=0,\, k^+=xP^+}$$

Quarks
do **not**
flip helicity
for these
amps
⇒ **not** quark
transversity

$$A_{++,++} = \sqrt{1-\xi^2}\left(\frac{H^q+\tilde{H}^q}{2} - \frac{\xi^2}{1-\xi^2}\,\frac{E^q+\tilde{E}^q}{2}\right),$$

$$A_{-+,-+} = \sqrt{1-\xi^2}\left(\frac{H^q-\tilde{H}^q}{2} - \frac{\xi^2}{1-\xi^2}\,\frac{E^q-\tilde{E}^q}{2}\right),$$

$$A_{++,-+} = -\epsilon\,\frac{\sqrt{t_0-t}}{2m}\,\frac{E^q-\xi\tilde{E}^q}{2},$$

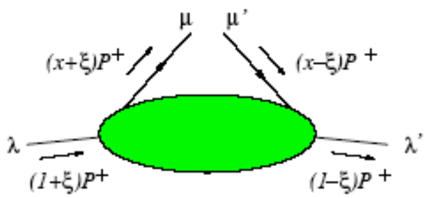
$$A_{-+,++} = \epsilon\,\frac{\sqrt{t_0-t}}{2m}\,\frac{E^q+\xi\tilde{E}^q}{2},$$

M. Diehl; Boglione & Mulders

How does transversity enter?

- Quark helicity flip amps

$\Rightarrow$quark transversity



$$A_{++,+-} = \epsilon \frac{\sqrt{t_0 - t}}{2m} \left(\tilde{H}_T^q + (1-\xi) \frac{E_T^q + \tilde{E}_T^q}{2} \right),$$

$$A_{-+,--} = \epsilon \frac{\sqrt{t_0 - t}}{2m} \left(\tilde{H}_T^q + (1+\xi) \frac{E_T^q - \tilde{E}_T^q}{2} \right),$$

$$A_{++,--} = \sqrt{1-\xi^2} \left(H_T^q + \frac{t_0 - t}{4m^2} \tilde{H}_T^q - \frac{\xi^2}{1-\xi^2} E_T^q + \frac{\xi}{1-\xi^2} \tilde{E}_T^q \right)$$

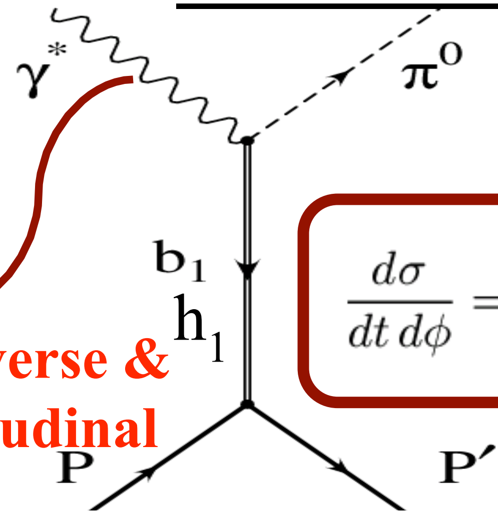
$$A_{-+,+-} = -\sqrt{1-\xi^2} \frac{t_0 - t}{4m^2} \tilde{H}_T^q$$

$H_T^q(x,t=0,\xi=0)$
$=h_1(x)$ Norm δq
Also $H(x,0,0)=f_1(x)$
& $H^{\sim q}(x,0,0)=g_1(x)$ Norm Δq

M. Diehl; Boglione & Mulders

Exclusive π^o electroproduction

$$ep \rightarrow e'p'\pi^o$$



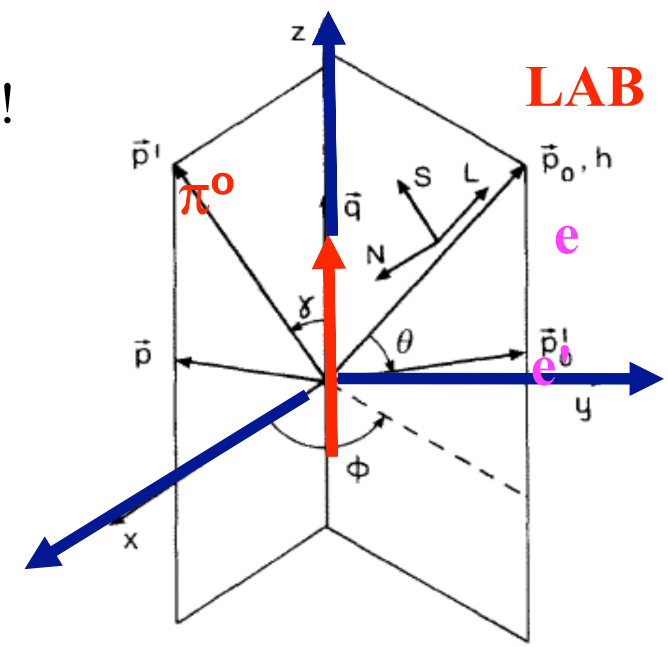
Transverse & Longitudinal

$$\frac{d\sigma}{dt\,d\phi} = \left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi$$

$$d\sigma \propto L_{\mu\nu}^{h=\pi^o} W_{\mu\nu}$$

Sensitive to tensor charge!

LAB



$$L_{\mu\nu}^{h=\pi^o} \approx \gamma^* \text{ polarization density matrix}$$

$$W_{\mu\nu} = \sum_f J_\mu J_\nu^* \delta(E_i - E_f) = \text{hadronic tensor}$$

$$\frac{d\sigma_{TT}}{dt} = W_{yy} - W_{xx} \equiv 2\Re e(J_1 J_{-1}*)$$

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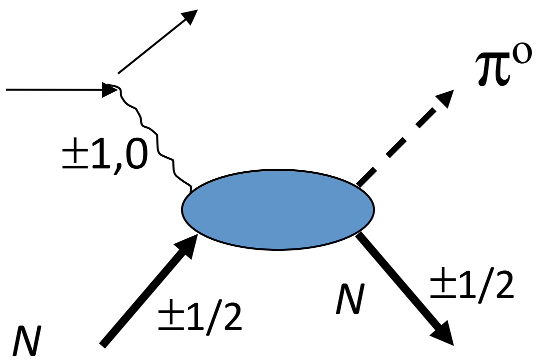
Exclusive π^o electroproduction and Transversity

$$\frac{d\sigma_{TT}}{dt} = W_{yy} - W_{xx} \equiv 2\Re e(J_1 J_{-1}*)$$

$$2\,Re(f^*_{+1+,0+} f_{+1-,0,-} - f^*_{+1+,0-} f_{+1-,0,+})$$

only $f_{+1+,0-}(s,t,Q^2) = f_2$ survives at $t \to 0$

Connect to helicity amps- make spin behavior explicit
Relate exchange picture to GPDs



Target asymmetry for γ_T ($\cos\theta_\gamma$ term)

$$A_{UT} \propto 2Im(f^*_{+1+,0+} f_{+1-,0,+} - f^*_{+1-,0-} f_{+1+,0,-})$$

$$d\sigma_T \propto |f_{+1+,0+}|^2 + |f_{+1+,0-}|^2 + |f_{+1-,0+}|^2 + |f_{+1-,0-}|^2$$

Observables are sensitive to both δq and κ_T!

$$\frac{d\sigma_T}{dt} = K\left[\frac{t_0-t}{8M^2}\,|\,\widetilde{\mathcal{E}}_2(Q^2)\,|^2 + (1-\xi^2)|\,\mathcal{H}_T(Q^2)\,|^2 + (1-\xi^2)\frac{t_0-t}{8M^2}\,|\,\widetilde{\mathcal{H}}_T(Q^2)\,|^2\right]$$

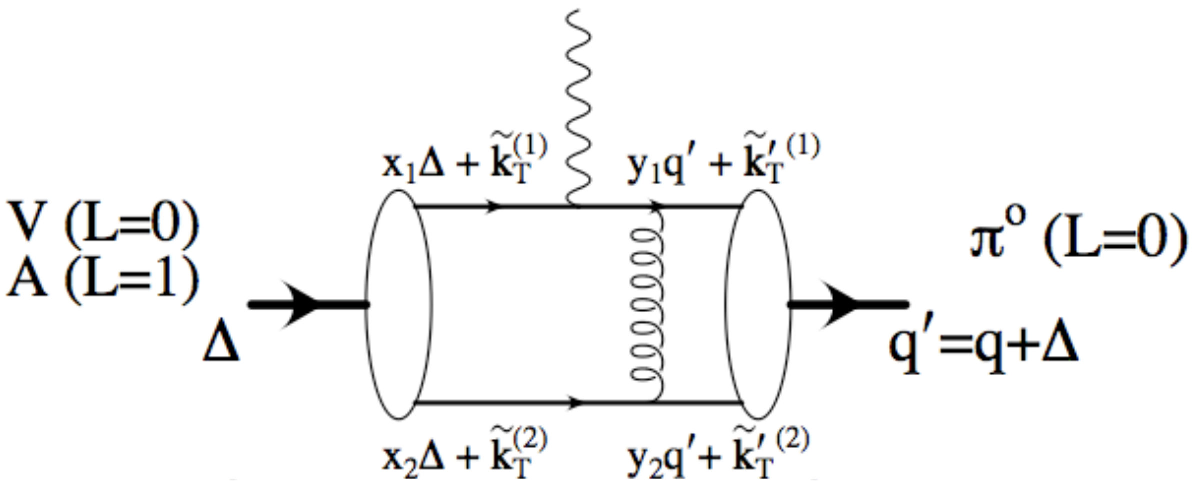
$$\frac{d\sigma_{TT}}{dt} = K\frac{t_0-t}{8M^2}\left[(1-\xi^2)\Re e\left(\widetilde{\mathcal{E}}_2(Q^2)\,\mathcal{H}_T^*(Q^2)\right) + \left(\Re e\,\widetilde{\mathcal{E}}_2(Q^2)\right)^2 + \left(\Im m\,\widetilde{\mathcal{E}}_2(Q^2)\right)^2\right]$$

$$\frac{d\sigma_{LT}}{dt} = K\frac{t_0-t}{8M^2}\left[(1-\xi^2)\Re e\left(\widetilde{\mathcal{E}}_2(Q^2)\,\mathcal{H}_T^*(Q^2)\right) + \left(\Re e\,\widetilde{\mathcal{E}}_2(Q^2)\right)^2\right]$$

$$A_{UT} = K\frac{t_0-t}{8M^2}\left[\frac{\sqrt{t_0-t}}{2M}\Im m\left(\widetilde{\mathcal{E}}_2^*(Q^2)\,\widetilde{\mathcal{H}}_T(Q^2)\right) - \sqrt{1-\xi^2}\,\Im m\left(\mathcal{H}_T^*(Q^2)\widetilde{\mathcal{E}}_2(Q^2)\right)\right]$$

... and more ...!!!

Q^2 dependent form factors t-channel view



$$F_{\gamma^* A \pi^o} = \int dx_1 dy_1 \int d^2\mathbf{b}\, \psi_A^{(1)}(y_1, b) \mathcal{C} K_o(\sqrt{x_1(1-x_1)Q^2}b) \times \psi_{\pi^o}(x_1, b) \exp(-S), \quad (50)$$

where now

$$\psi_A^{(1)}(y_1, b) = \int d^2 k_T J_1(y_1 b) \psi(y_1, k_T), \quad (51)$$

Helicity amps with Compton Form Factors

$$f_1 = f_4 = \frac{g_2}{\mathcal{C}_q} F_V(Q^2) \frac{\sqrt{t_0 - t}}{2M} \left[\tilde{\mathcal{H}}_T + \frac{1-\xi}{2} \mathcal{E}_T + \frac{1-\xi}{2} \tilde{\mathcal{E}}_T \right],$$

$$f_2 = \frac{g_2}{\mathcal{C}_q} [F_V(Q^2) + F_A(Q^2)] \sqrt{1-\xi^2} \left[\mathcal{H}_T + \frac{t_0 - t}{4M^2} \tilde{\mathcal{H}}_T - \frac{\xi^2}{1-\xi^2} \mathcal{E}_T + \frac{\xi}{1-\xi^2} \tilde{\mathcal{E}}_T \right],$$

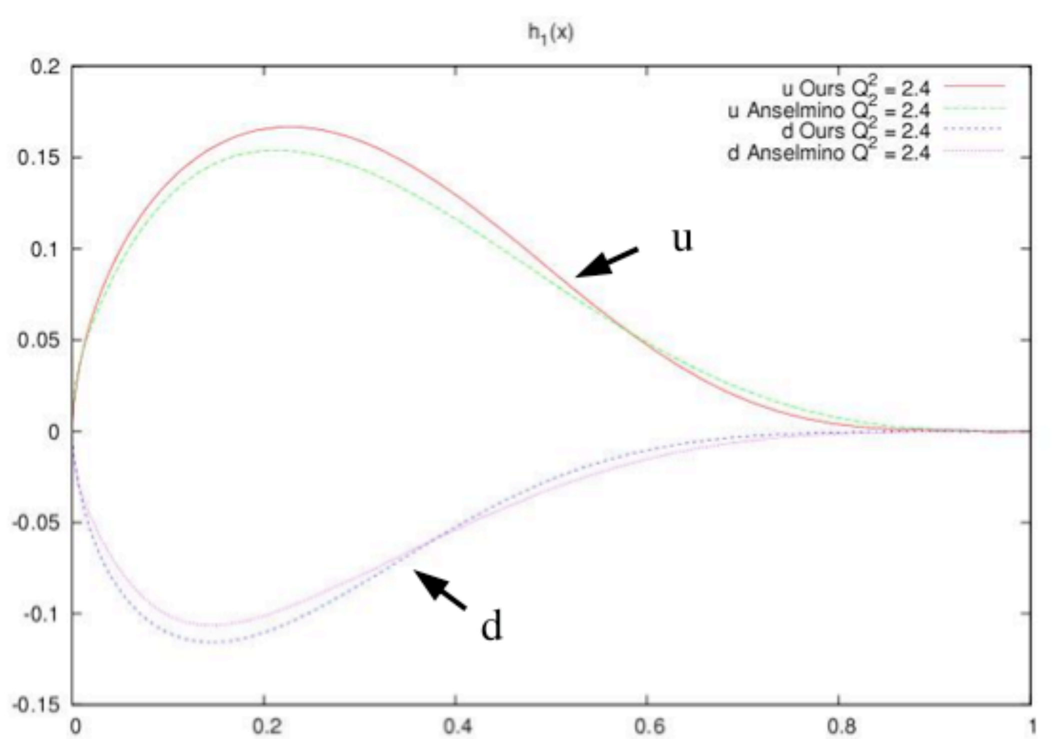
$$f_3 = \frac{g_2}{\mathcal{C}_q} [F_V(Q^2) - F_A(Q^2)] \sqrt{1-\xi^2} \frac{t_0 - t}{4M^2} \tilde{\mathcal{H}}_T,$$

$$f_5 = \frac{g_5}{\mathcal{C}_q} F_A(Q^2) \sqrt{1-\xi^2} \left[\mathcal{H}_T + \frac{t_0 - t}{4M^2} \tilde{\mathcal{H}}_T - \frac{\xi^2}{1-\xi^2} \mathcal{E}_T + \frac{\xi}{1-\xi^2} \tilde{\mathcal{E}}_T \right].$$

Modeling Spin-dependent GPDs

Build on spin-independent analysis of AHLT, based on data & lattice calculations of moments.

Transversity



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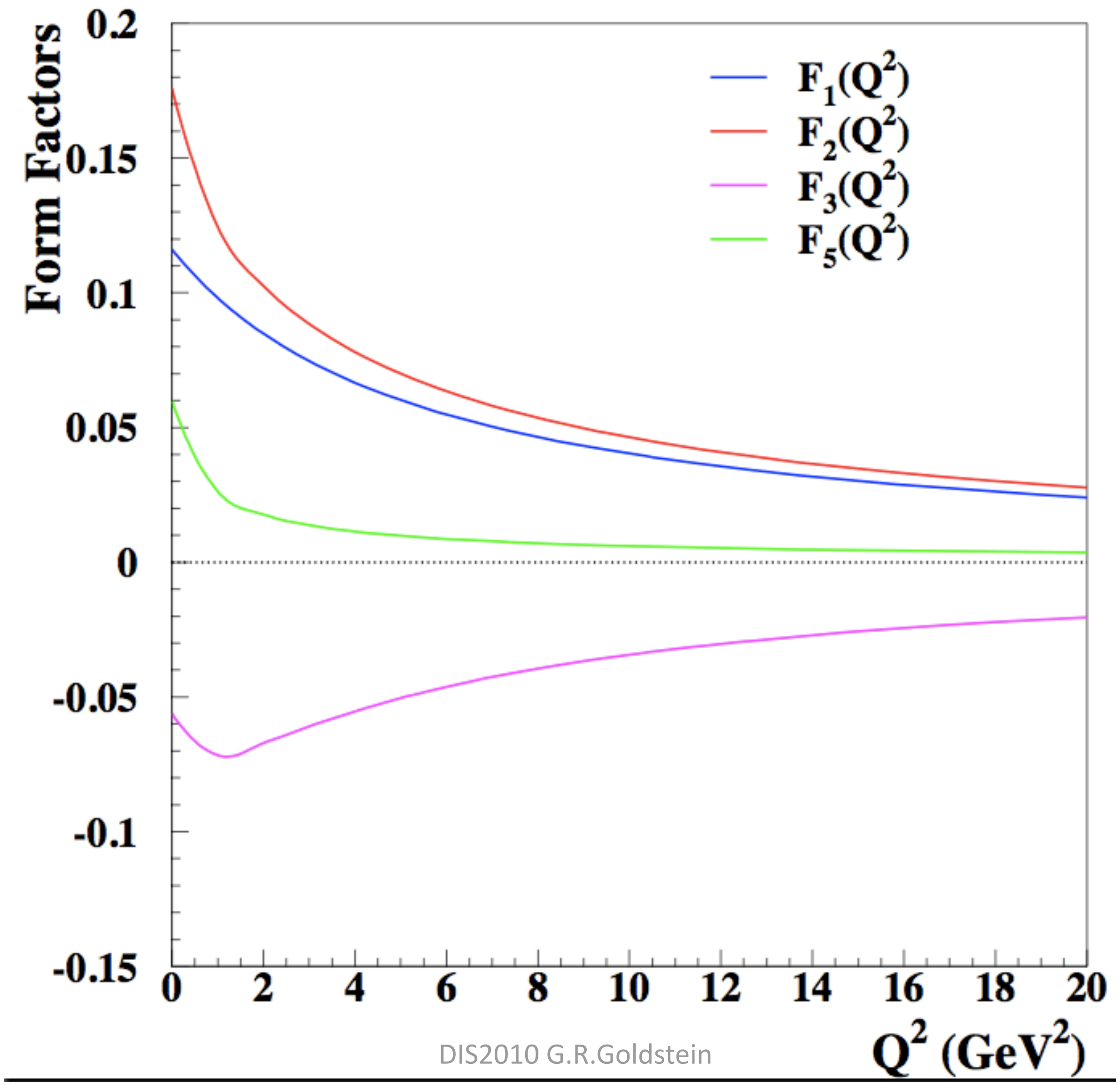
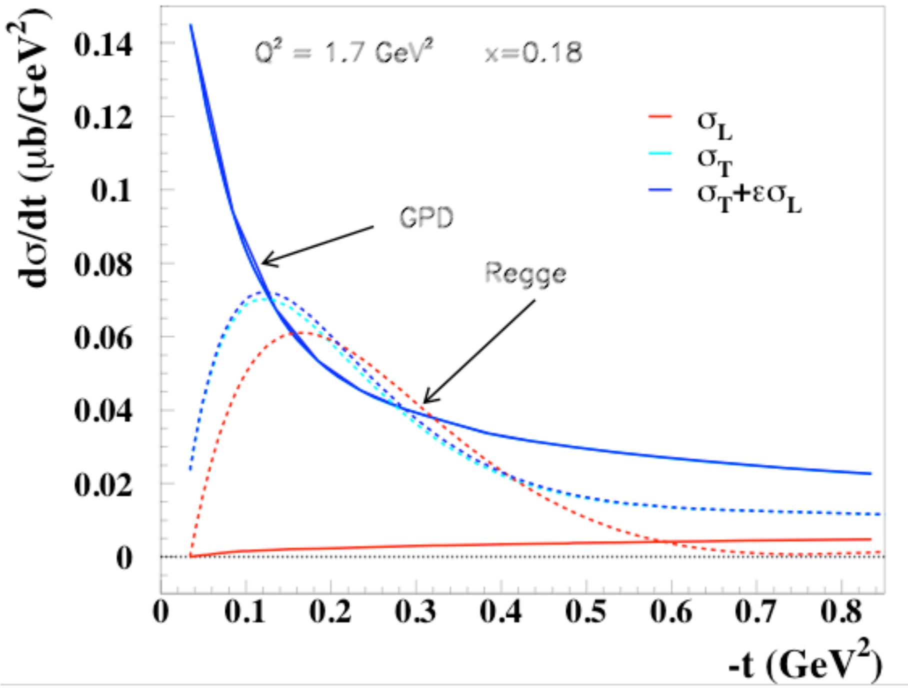
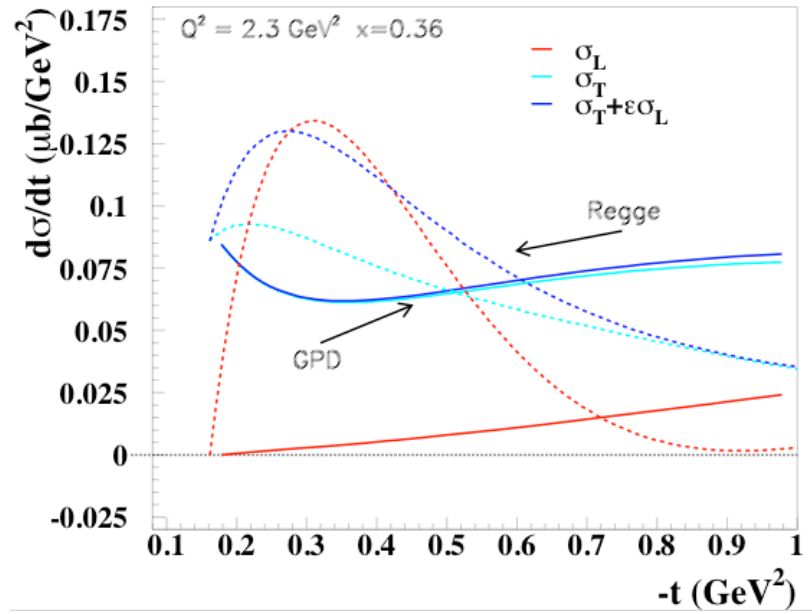
transition form factors







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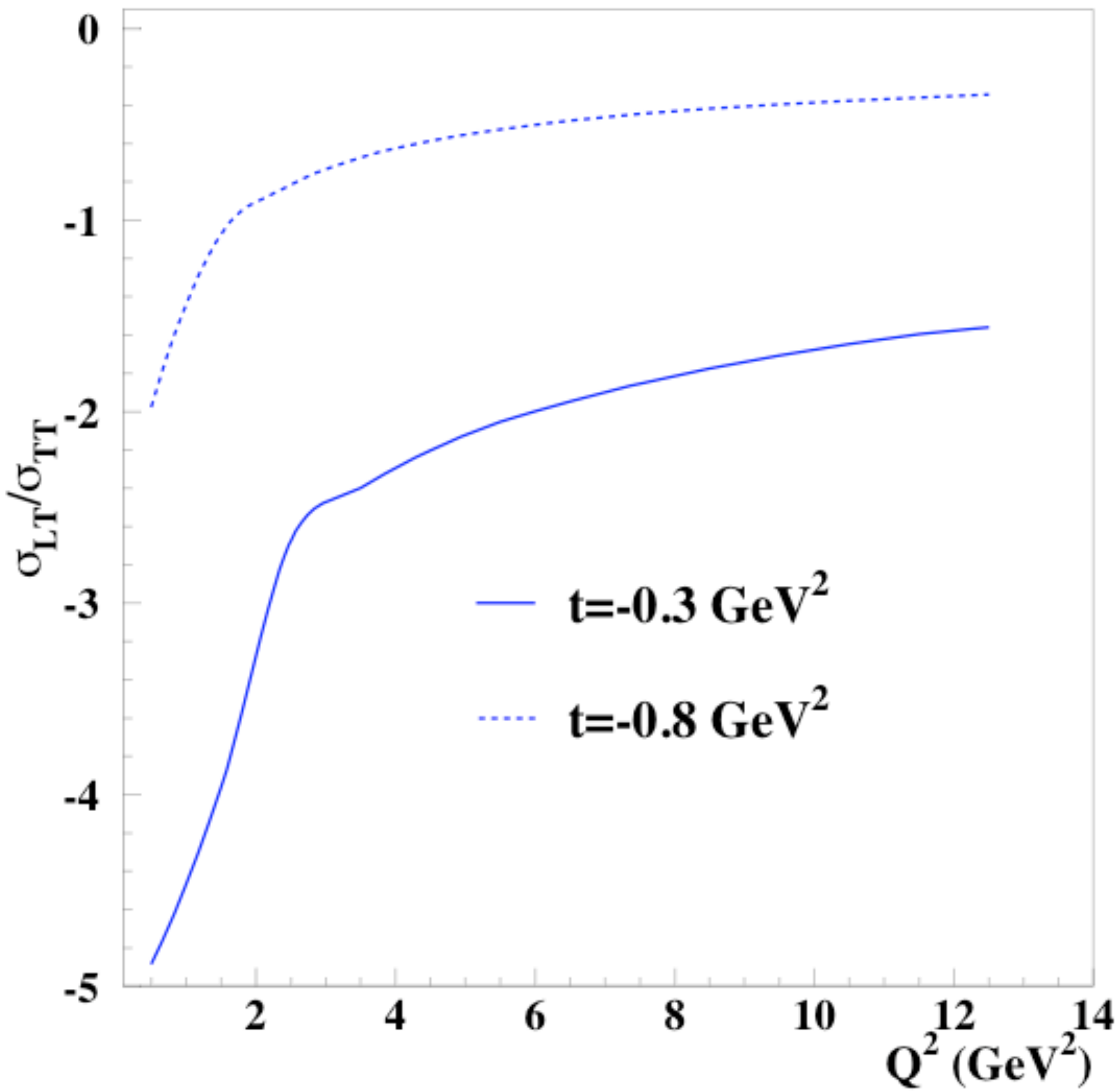
GPDs with
vector &
axial vector
Form Factors

Ahmad, GRG, Liuti
PRD79, 054014 (2009)



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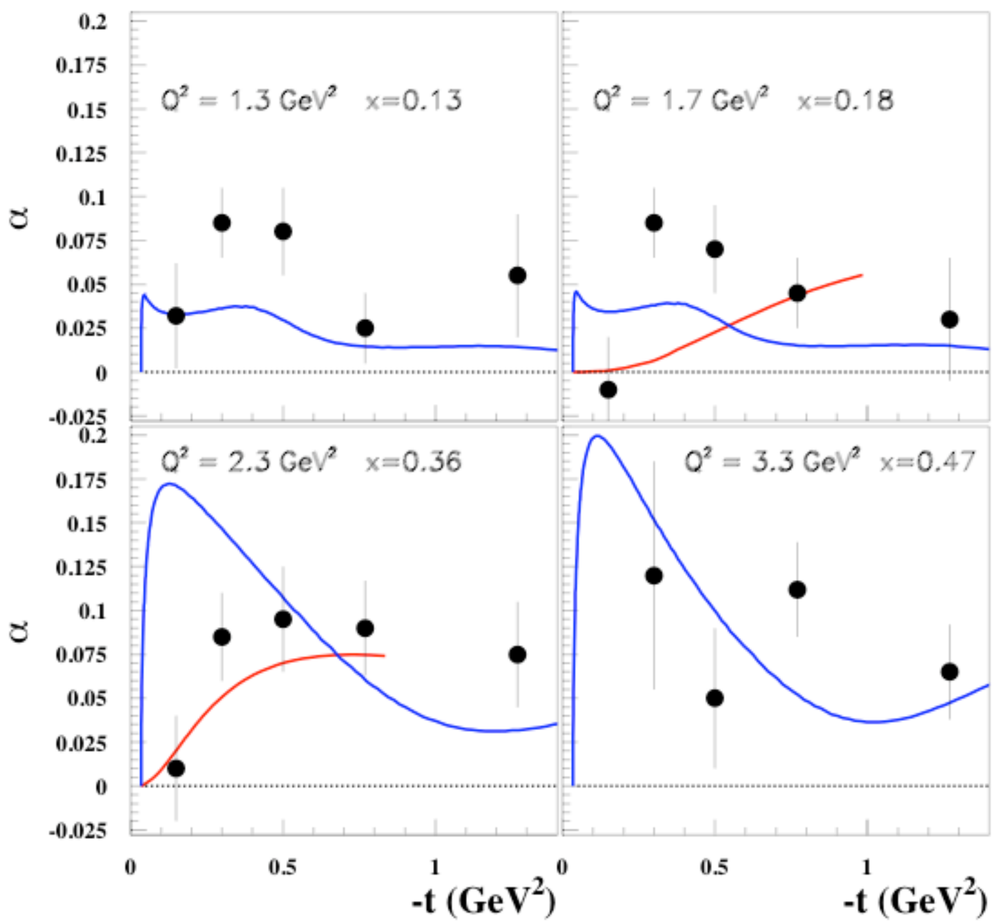
Regge-cut model Beam-spin asymmetry α

data R. De Masi et al.,Phys.Rev.C77, 042201 (2008).

Regge-cut predictions - comparisons involve ε_L, ε

Ahmad, GRG, Liuti, PRD79, 054014 (2009) blue

GPD predictions (preliminary) red



$$A_{UT} = \frac{2\Im m(f_1^* f_3 - f_4^* f_2)}{\frac{d\sigma_T}{dt}}$$

and the beam spin asymmetry

$$A \approx \alpha \sin\phi,$$

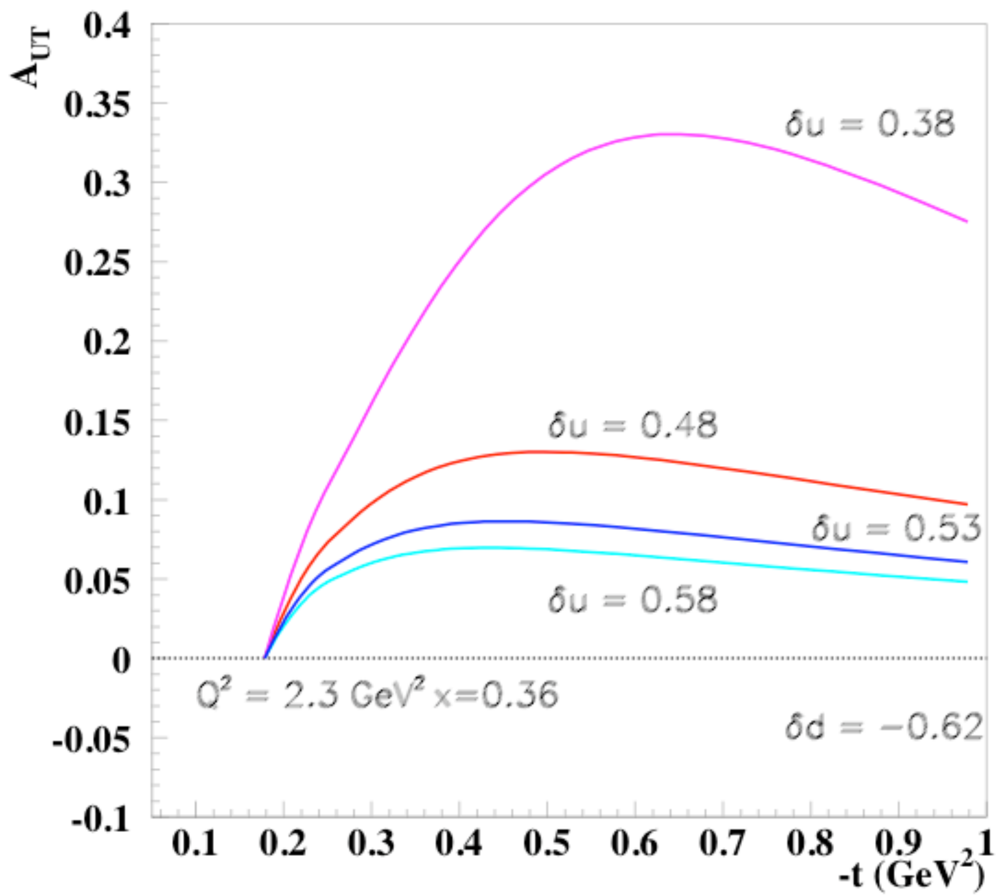
where

$$\alpha = \frac{\sqrt{2\epsilon_L(1-\epsilon)}\,\frac{d\sigma_{LT'}}{dt}}{\frac{d\sigma_T}{dt} + \epsilon_L \frac{d\sigma_L}{dt}}$$

$$\sigma_{LT'} \sim Im\,[f_5^*(f_2+f_3) + f_6^*(f_1-f_4)]$$

Variation of asymmetries with tensor charge
All GPDs

Ahmad, GRG, Liuti PRD79, 054014 (2009)



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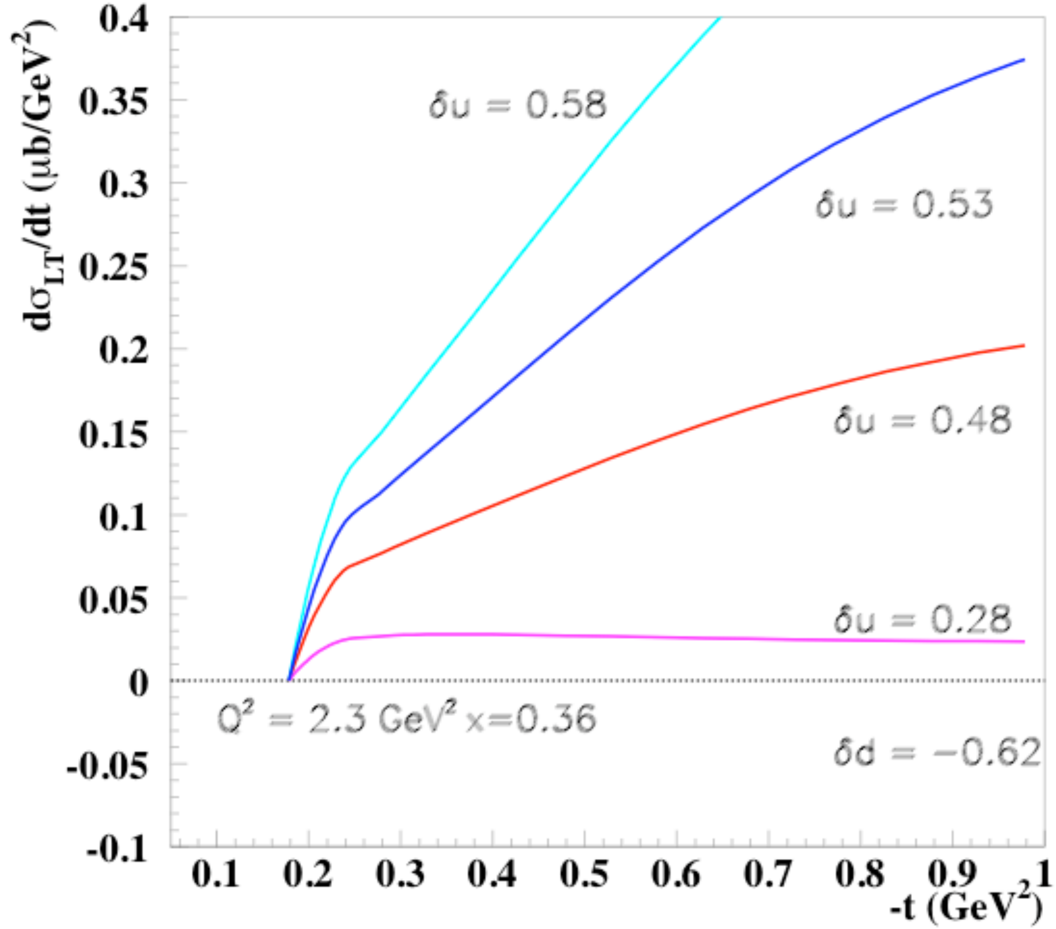

All GPDs

Ahmad, GRG, Liuti, PRD79, 054014 (2009)

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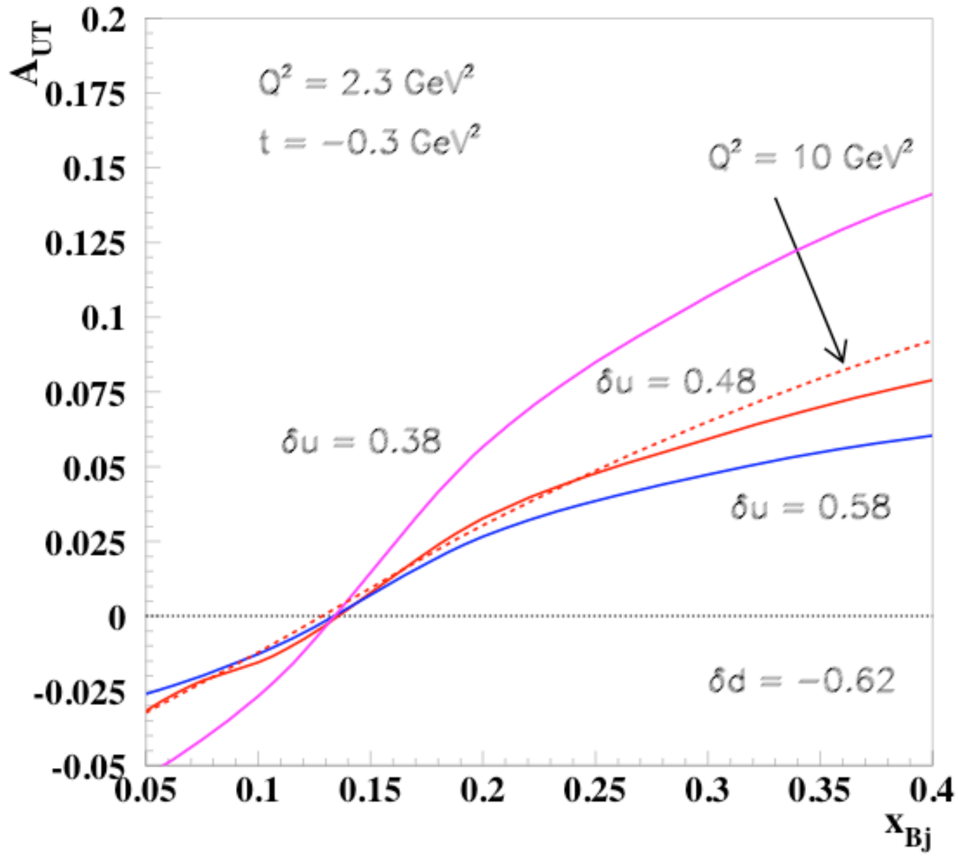

All GPDs

Ahmad, GRG, Liuti, PRD79, 054014 (2009)

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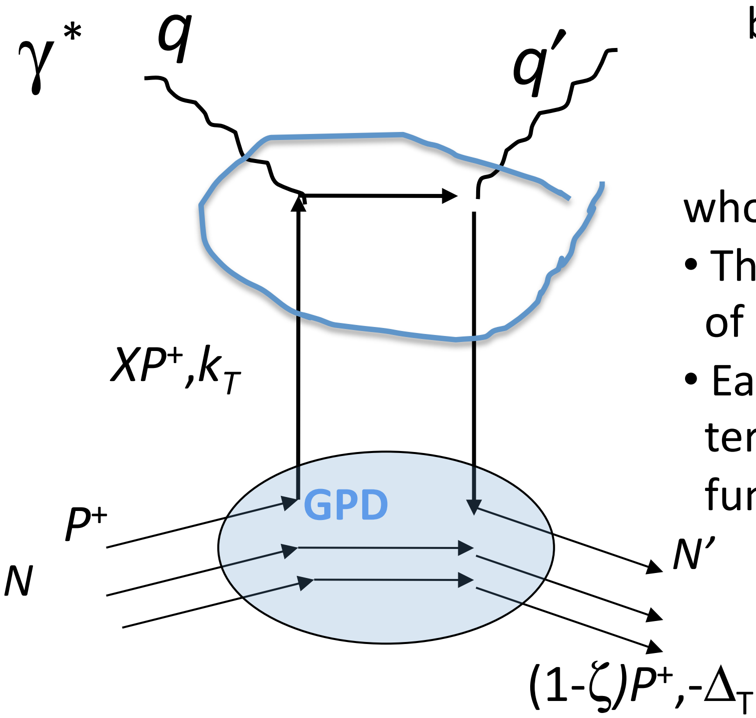
Conclusions

- Symmetries – J, P & C play important role in constraining GPDs
- Two kinds of π^0 couplings to quarks → very different GPDs
- C-parity odd & chiral odd combinations select Transversity
- C-parity odd & chiral even emphasizes E-tilde which is small for π^0 –no pole
  - and enters $d\sigma_L/dt$ with supression factors of Δ and ξ
- Exclusive π^0 electroproduction (plentiful background to DVCS at JLab) observables depend on axial vector exchange quantum numbers
- Pseudoscalar form factor without π^0 limits axial vector coupling for π^0
- Model GPDs (AHLT) → phenomenology
- GPD H_T yield values of δu & δd also κ_T^u & κ_T^d .
- $d\sigma_T/dt$, $d\sigma_{TT}/dt$, A_{UT}, beam asymmetry, beam-target correlations, $d\sigma_L/dt$, $d\sigma_{LT}/dt$
- DVCS & plenty of π^0 production can bring much enlightenment to basic parameters of SM, transversity & hadronic spin.

EXTRA SLIDES

field theory -> J^{PC}



$$\bar{\psi}(z)\ \Gamma\ \psi(0)$$

bilocal operator. Expand via O.P.E. Insert into

$$\langle P'\Lambda'|\bar{\psi}(z)\ \Gamma\ \psi(0)\,|P\Lambda\rangle$$

whose Fourier transform is combination of GPDs.

- The x-moments of GPDs are then matrix elements of local operators.
- Each moment order has a decomposition in terms of polynomials in ξ with coefficient functions that are t-dependent form factors.

$$\bar{\psi}(0)\ \Gamma iD^{\mu 1} iD^{\mu 2} \ldots iD^{\mu n}\psi(0)$$

symmetrized in indices and traceless

$\Gamma = \gamma^{\mu}, \gamma^{\mu}\gamma^{5}, i\sigma^{\mu\nu}$ corresponds to (*H&E, H~ & E~*, Chiral-odds)

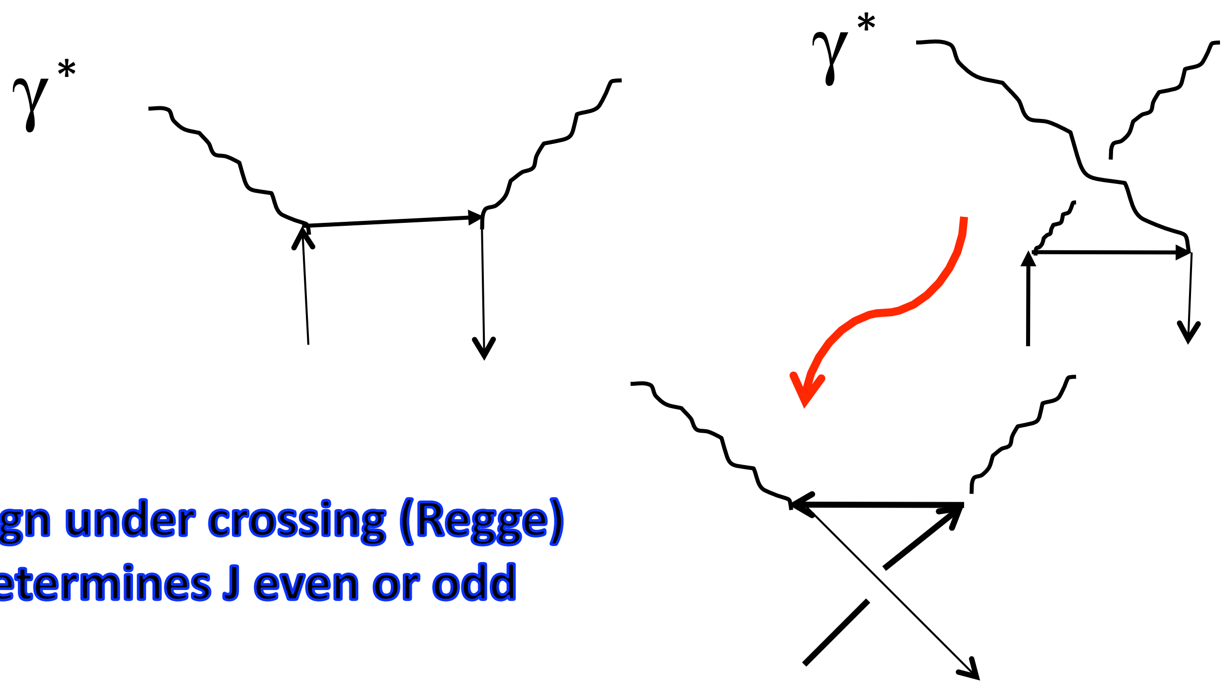
- The local operators transform as representation of Lorentz Group.
- They have definite t-channel J^{PC} series of values.
- These have to match $N\bar{N}$ states

to GPD J^{PC}

One more input into J^{PC} assignments for all GPDs

$$\text{C - parity involves symmetry under } q \leftrightarrow \bar{q} \ \ \& \ \ N \leftrightarrow \bar{N}$$

$$\text{Crossing operation exchanges } x \leftrightarrow -x$$



Sign under crossing (Regge) determines J even or odd

Contributions to π^0 production?

- Conventional view – Mankiewicz, et al., Goeke, et al., Collins, et al., etc. $\pi^{0,\pm}$ is produced via leading twist "factorized" form
- $\pi^{0,\pm}$ produced via π- q+anti-q distribution amplitude that conserve quark helicity ($\gamma_\mu\gamma^5$) coupling (Twist 2 operator)
- so in light cone limit ~$\Psi\gamma_\mu\gamma^5\Psi$ correlator & no Transverse contribution
- amps determine H~ and E~ AND Longitudinal photons dominate *at leading twist*
- Experiment (preliminary) shows Transverse photons are as important at Jlab intermediate Q^2. HERMES $A_{UT}^{\sin\phi S}$ shows sizable L*T interference.
- Alternative view: Leading *t*-channel J^{PC} quantum numbers dominate – flip quark helicity
- $\gamma_\mu\gamma_\nu\gamma^5$ enters correlator $\Psi\gamma_\mu\gamma_\nu\gamma^5\Psi$
- so Chiral odd GPDs H_T, $E_{T,}$ etc. are probed
- q+anti-q J^{PC} transitions to π^0

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