Deeply Virtual Neutrino Production of π^0 from Nucleon & Nuclear Targets: Part II

Spin Dependence, Cross Sections and Asymmetries

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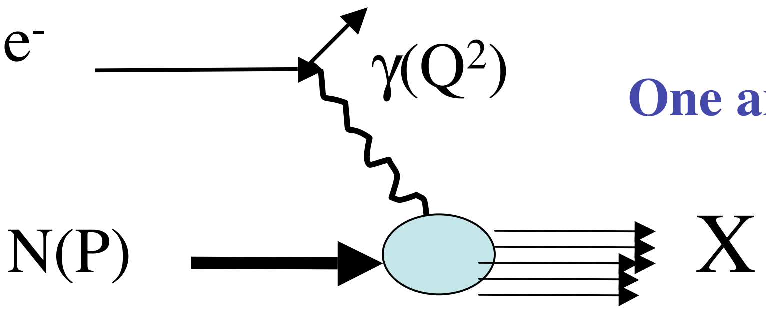
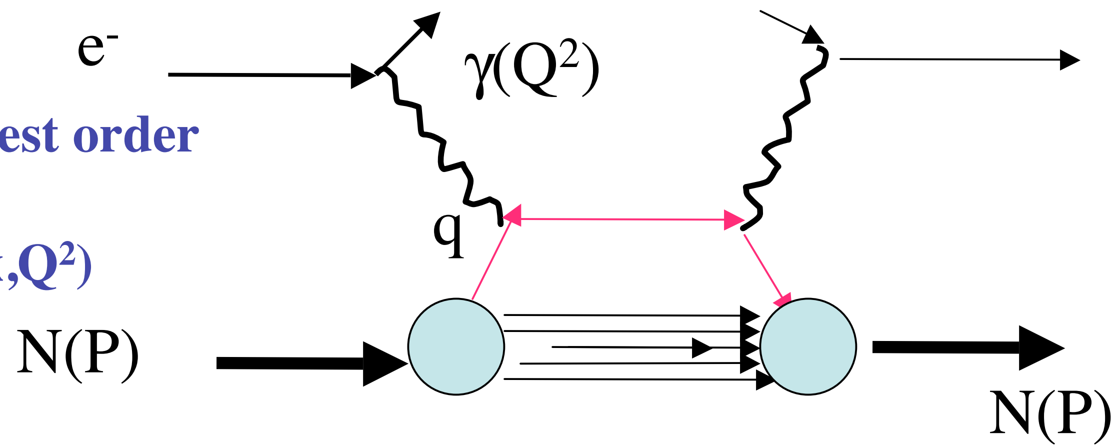
Generalized Parton Distributions (GPDs) spin & transversity distributions

See Ahmad, Goldstein, Liuti
PRD 49, 054014 (2009)

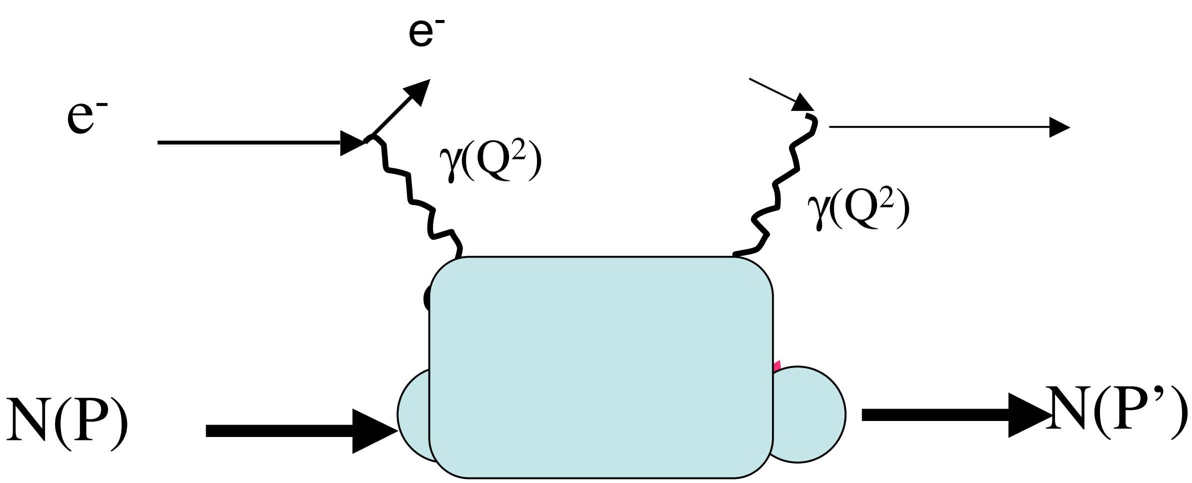


One amp for Deep *InElastic* Scattering via X

$\sigma(x,Q^2)$ for DIS from squaring amp
& summing over X's
$\propto \mathrm{Im}(f(\gamma N \rightarrow \gamma N))_{t=0}$
"Handbag" model is lowest order
Perturbative QCD
$\rightarrow$ Structure functions (x,Q^2)

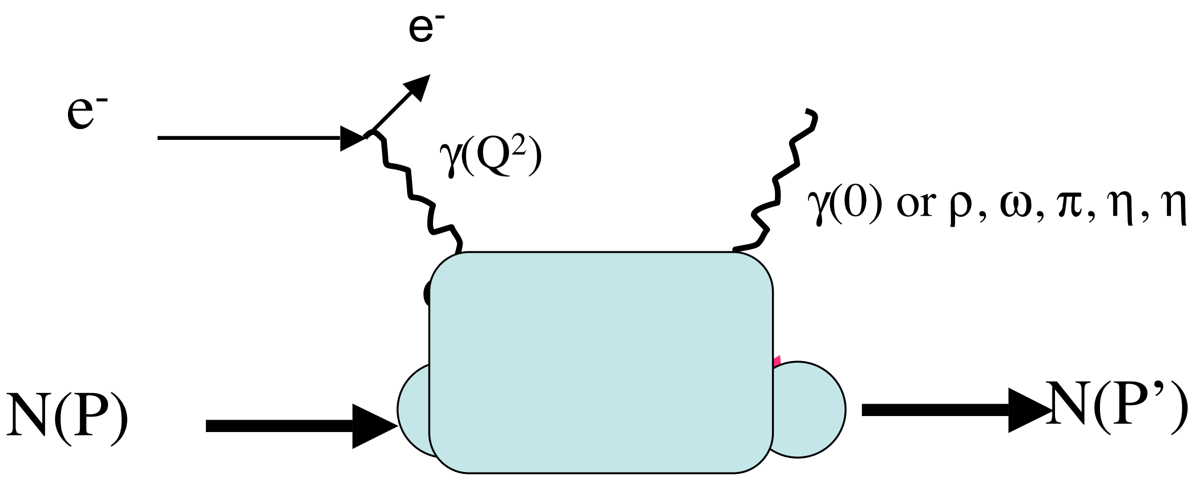


From DIS to exclusive electroproduction



$$T_{EM}^{\mu\nu} = i \int d^4x \int d^4y \, e^{-iq_1 \cdot x + iq_2 \cdot y} \langle N(p_2, s_2) | T \{ J_{EM}^{\mu}(y) J_{EM}^{\nu}(x) \} | N(p_1, s_1) \rangle$$

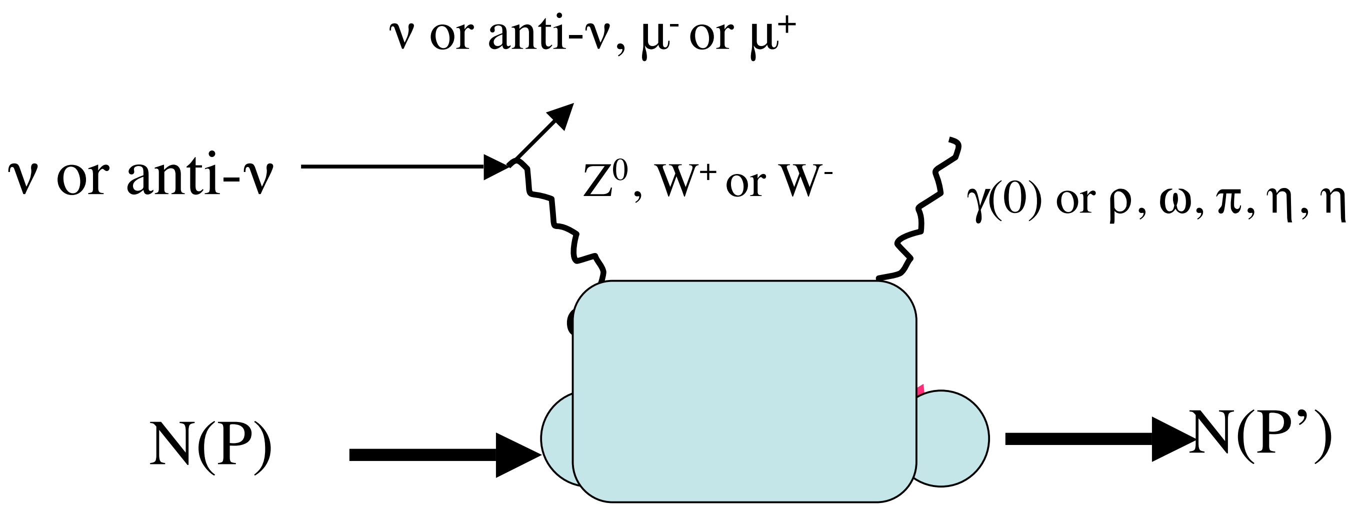
From DIS to exclusive electroproduction of γ or mesons



$$T_{EM}^{\mu\nu} = i \int d^4x \int d^4y \, e^{-iq_1 \cdot x + iq_2 \cdot y} \langle N(p_2, s_2) | T \{ J_{EM}^{\mu}(y) J_{EM}^{\nu}(x) \} | N(p_1, s_1) \rangle$$

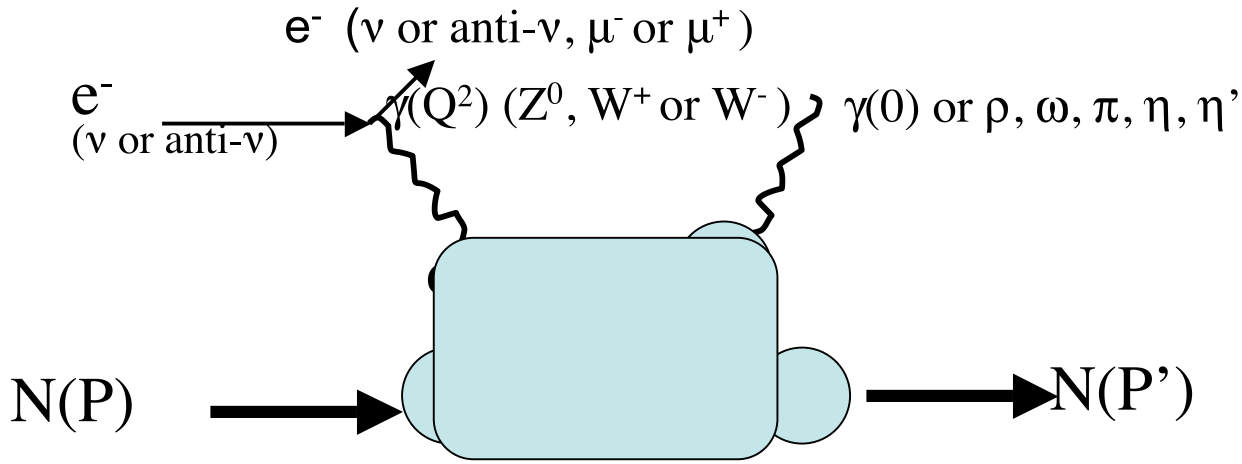
Deeply Virtual Compton Scattering or
Deeply Virtual Meson Production

From exclusive electroproduction to neutrino-production



$$T^{\mu\nu}_{EM} = i \int d^4x \int d^4y \, e^{-iq_1\cdot x + iq_2\cdot y} \langle N(p_2, s_2) | T\{J^{\mu}_{EM}(y) J^{\nu}_{EM}(x)\} | N(p_1, s_1)\rangle$$

From exclusive electroproduction to neutrino-production



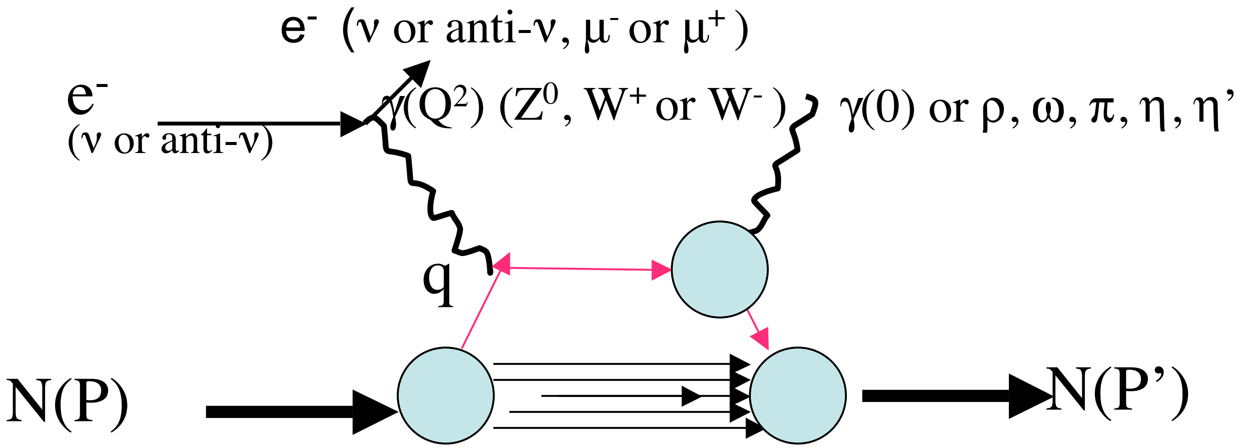
$$T^{\mu\nu}_{EM} = i\int d^4x \int d^4y\, e^{-iq_1\cdot x + iq_2\cdot y} \langle N(p_2,s_2)| T\{J^{\mu}_{EM}(y)\, J^{\nu}_{EM}(x)\} |N(p_1,s_1)\rangle$$

Replace EM current entering with Weak current.

Replace outgoing photon with meson e.g. π^0.

$$T^{\nu}_{W} = i\int d^4x \int d^4y\, e^{-iq_1\cdot x + iq_2\cdot y} \langle N'(p_2,s_2)| T\{J_{\pi^0}(y)\, J^{\nu}_{W}(x)\} |N(p_1,s_1)\rangle$$

From hadrons to partons



$$T^{\mu\nu}_{EM} = i \int d^4x \int d^4y \, e^{-iq_1\cdot x + iq_2\cdot y} \langle N(p_2, s_2) | T\{J^{\mu}_{EM}(y) J^{\nu}_{EM}(x)\} | N(p_1, s_1)\rangle$$

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Replace outgoing photon with meson e.g. π^0.

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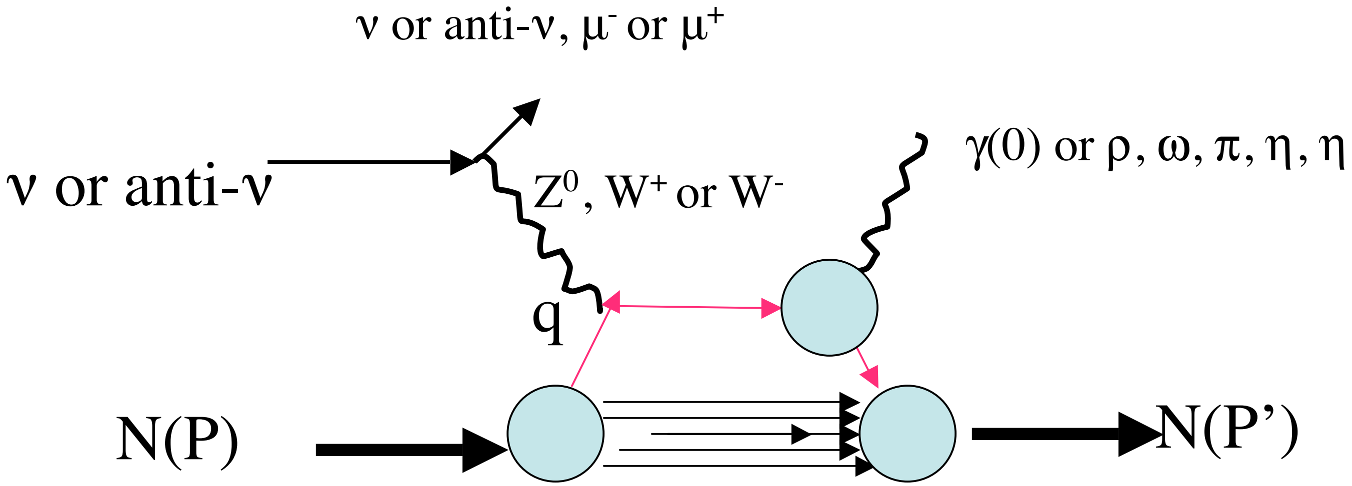
From hadrons to partons



$$T_W^{\nu} = i \int d^4x \int d^4y \, e^{-iq_1 \cdot x + iq_2 \cdot y} \langle N'(p_2, s_2) | T\{J_{\pi^0}(y) J_W^{\nu}(x)\} | N(p_1, s_1) \rangle$$

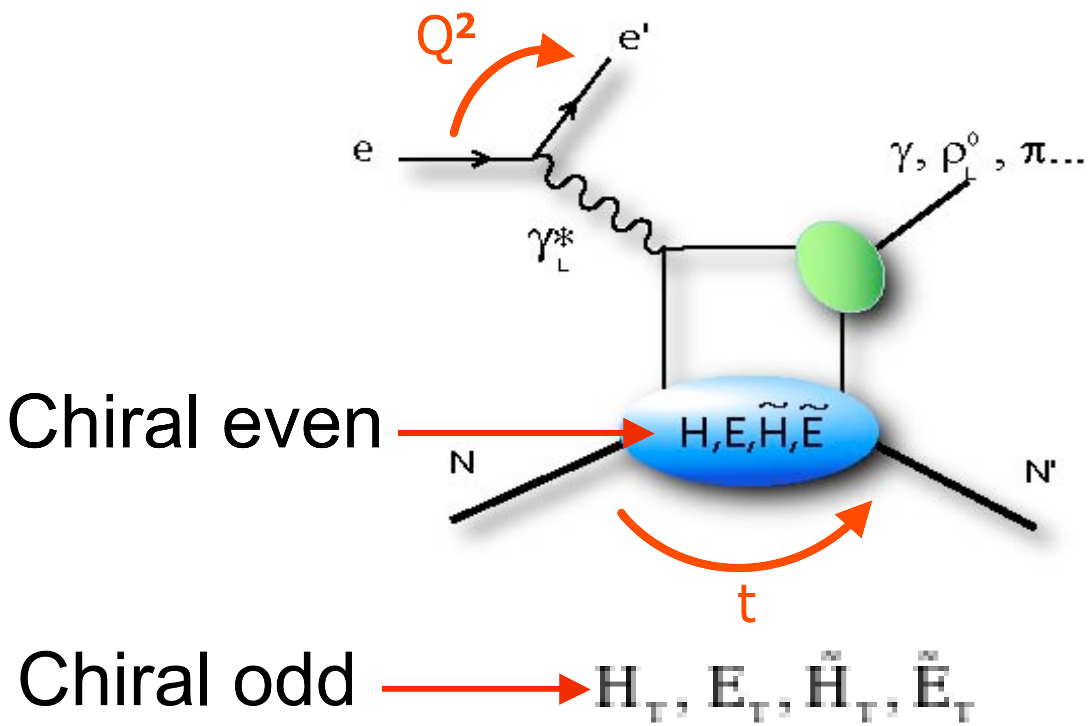
Product of current operators has decomposition into quark field operators (OPE)

Leading twist involves free quark spinors. Now consider π production (outgoing $\gamma \to \pi$)

$$iT\{J_{\pi^0}(z/2) J^{\nu}_{WN}(-z/2)\} = i \sum_f \Big[\bar{\psi}_f(z/2) \gamma^5 i \, \not{S}(z) \gamma^{\nu} \frac{1}{2} \left(c_V^f - \gamma_5 c_A^f\right) \psi_f(-z/2)$$

$$+ \bar{\psi}_f(-z/2) \gamma^{\nu} \frac{1}{2} \left(c_V^f - \gamma_5 c_A^f\right) i \, \not{S}(-z) \gamma^5 \psi_f(z/2) \Big]$$

Spin dependent GPDs upon insertion of T product into nucleon matrix elements



Spin dependence relates H,E to E.M.: $F_1(t)$, $F_2(t)$ & $f_1(x,Q^2)$, $g_1(x,Q^2)$
H_T to $h_1(x,Q^2)$

Parity violating V-A coupling doubles the number of helicty amps from 6 to 12.

Procedure: GPDs to $d\sigma^n/d\Omega_{lepton}d\Omega_{meson}dt$ & asymmetries, especially φ for $\rightarrow\gamma$ or $\rho,\omega,\pi,\eta,,K$

1. Exclusive spin dependent e or ν amps
2. Factorized into handbag with quarks (2 scales)
3. PQCD for Virtual boson+quark $\rightarrow\gamma$ (or ρ,ω,π,η,K)+quark'
4. Soft quark/nucleon amp$\rightarrow$GPD
5. 4 chiral even + 4 chiral odd GPDs
Connected to 8 helicity amps
6. Combine soft & hard. Integrate over p_{quark} $\rightarrow$ T-matrix for each helicity combination $\rightarrow$ form $d\sigma/d\Omega dt$…
7. Models: diquark or exchanges $\rightarrow$ predictions

Defining GPDs via quark correlation on light cone

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, \gamma^+ q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z^+=0,\, \mathbf{z}=0}$$

$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\,\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\,\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right]$$

$$\tilde{F}^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, \gamma^+\gamma_5\, q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z^+=0,\, \mathbf{z}=0}$$

$$= \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\,\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\,\bar{u}(p')\frac{\gamma_5\Delta^+}{2m}u(p)\right]$$

These are chiral even – no quark helicity flip

4 other chiral odd GPDs with $\gamma^5\,\sigma^{+j}$

Collinear factorization applied (k_T quark momenta integrated over)

GPD is Real function of *x* (unobservable longitudinal momentum of parton),
ξ or ζ (fraction of long. Mom. lost by target), *t*, Q[2] .
>Observables cannot depend on ξ or ζ.
>Integrated GPD is like a Compton Form Factor - complex
>phases enable interferences & asymmetries

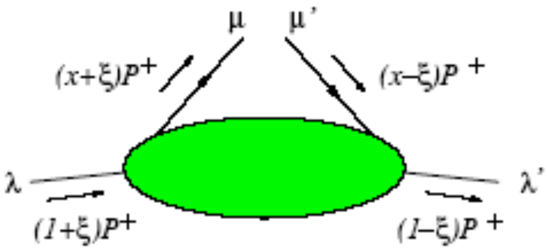
$$T^{\mu\nu}(\nu,Q^2,t) = \frac{1}{2} g^{\mu\nu} \overline{u}(p')\hat{n}u(p) \sum_{flavors} e_f^2 \mathcal{H}_f(\xi,t)$$

$$\mathcal{H}_f(\xi,t) = \int_{-1}^{+1} dx \frac{H_f(x,\xi,t)}{x-\xi+i\varepsilon}$$

$$\mathrm{Im}\,\mathcal{H}_f(\xi,t) = H_f(\xi,\xi,t) \qquad \mathrm{Re}\,\mathcal{H}_f(\xi,t) = \frac{1}{\pi} PV \int_{-1}^{+1} dx \frac{H_f(x,\xi,t)}{x-\xi}$$

$$\text{Dispersion Relation: } \mathrm{Re}\,\mathcal{H}_f(\xi,t) = \frac{1}{\pi} PV \int_{-1}^{\xi(Max)?} dx \frac{H_f(x,x,t)}{x-\xi}$$

GPDs & helicity



Functions of *x*, ξ, Δ

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

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

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

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

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

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

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

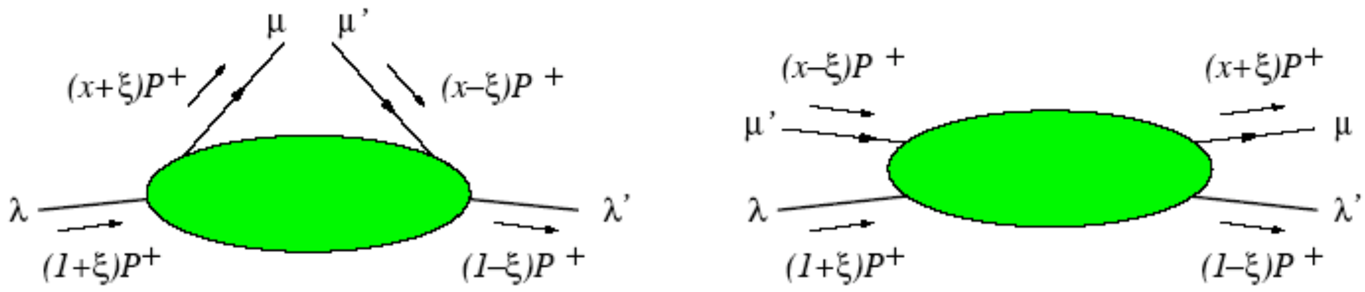
$H(x,0,0)=f_1(x)$
& $H^{\sim q}(x,0,0)=g_1(x)$

M. Diehl; Boglione & Mulders

Chiral odd GPDs

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

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

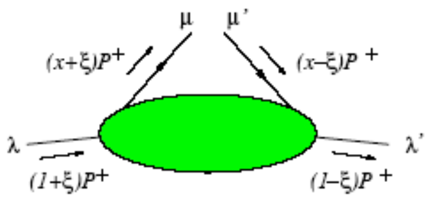


(a) (b)

- 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 tomorrow.)

How does transversity enter?

- Quark helicity flip amps $\Rightarrow$quark transversity



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

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

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

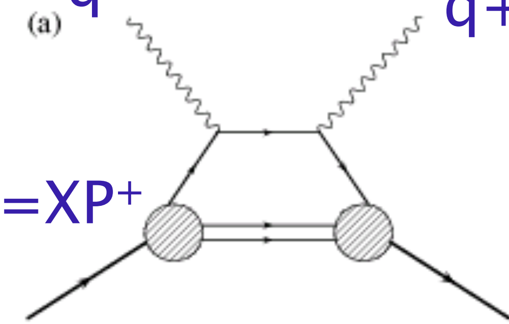
$$A_{-+,+-} = -\sqrt{1-\xi^2} \frac{t_0 - t}{4m^2} \tilde{H}_T^q$$

$H_T^q(x,t=0,\xi=0)$
$=h_1(x)$ 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

DVCS $\gamma^* + P \rightarrow (\gamma \text{ or meson}) + P'$

partonic picture



q

$q+\Delta$

k_T

$k^+ = XP^+$

$k'_T = k_T - \Delta$

$k'^+ = (X - \zeta)P^+$

$X > \zeta$ DGLAP

$X < \zeta$ ERBL

P^+

$P'^+ = (1-\zeta)P^+$

$P'_T = -\Delta$

Factorized "handbag" picture

$\zeta \rightarrow 0$

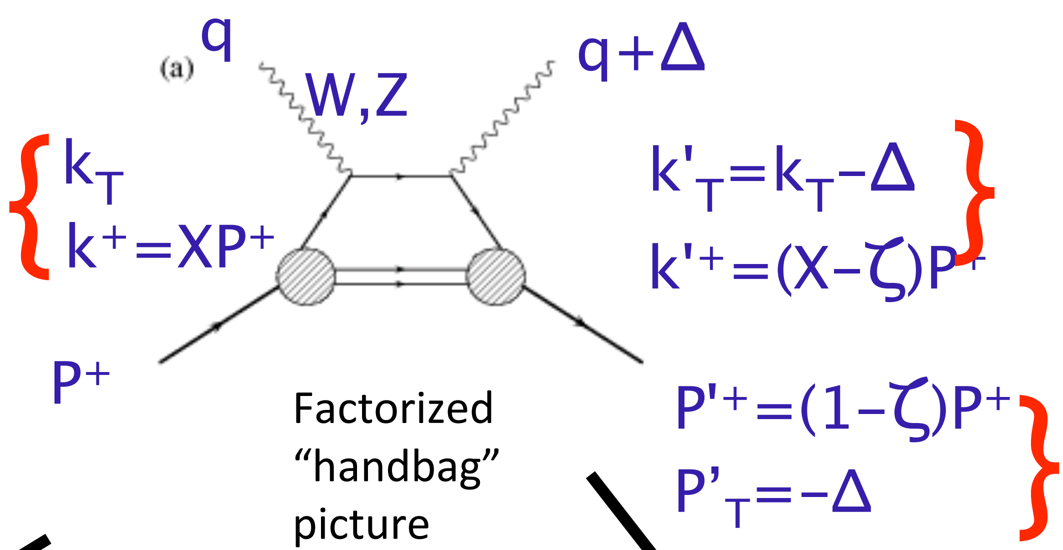
High E

Quark-spectator

quark+diquark

DVCS $\gamma^* + P \rightarrow (\gamma \text{ or meson}) + P'$

partonic picture



X>ζ DGLAP

X<ζ ERBL

$$f_{\Lambda_\gamma,\Lambda;0,\Lambda'} = \sum_{\lambda,\lambda'} g_{\Lambda_\gamma,\lambda;0,\lambda'}(X,\zeta,t,Q^2) \otimes A_{\Lambda',\lambda';\Lambda,\lambda}(X,\zeta,t)$$

12 *g* amps in V and A combinations

For νDVCS get 4 chiral even GPDs (see Psakar, et al., PRD 75,054001 (2007))

For νDVπ get 4 chiral odd GPDs **Pion selects chiral odd, C-parity odd in electro**

$$i\int\frac{d^4l}{(2\pi)^4}\,e^{-il\cdot z}\frac{l_\mu}{l^2+i0}\cdot\sum_f\left[g^{\mu\nu}\left(c_V^f\mathcal{O}_5^+-c_A^f\mathcal{O}_I^-\right)+ic_A^f\mathcal{O}_{\mu\nu}^+-ic_V^f\mathcal{O}_{5\mu\nu}^-\right]. \tag{13}$$

$$\langle N_2\left|\mathcal{O}_\Gamma\right|N_1\rangle=\bar{u}_2\left|\sum_A(\text{Dirac}\times\text{external kinematic factors})_A\int_{-1}^{+1}dxe^{ixp\cdot z}GPD_A(x,\xi,t)\right|u_1. \tag{14}$$

Insert this into Eqn. 4 and use the integral over l of the propagator, Eqn. 5, to obtain for each $\mathcal{O}_\Gamma$

$$-\frac{1}{2}\int_{-1}^{+1}dx\int\frac{d^4l}{(2\pi)^4}\int d^4ze^{+i(xp+q-l)\cdot z}\frac{l_\mu}{l^2+i0}\,\bar{u}_2\left[\sum_A(\text{Dirac}\times\text{kinematic})_A^{\mu\nu}GPD_A(x,\xi,t)\right]u_1 \tag{15}$$

$$=-\frac{1}{2}\int_{-1}^{+1}dx\frac{l_\mu}{l^2+i0}\,\bar{u}_2\left[\sum_A(\text{Dirac}\times\text{kinematic})_A^{\mu\nu}GPD_A(x,\xi,t)\right]u_1|_{l=xp+q} \tag{16}$$

For $\mathcal{O}_{\mu\nu}^+$ we have

$$-\frac{i}{2}\int_{-1}^{+1}dx\frac{l_\mu}{l^2+i0}\,\bar{u}_2\left[H_T^+\,i\sigma^{\mu\,\nu}+\widetilde{H}_T^+\frac{P^\mu\Delta^\nu-\Delta^\mu P^\nu}{M^2}+E_T^+\frac{\gamma^\mu\Delta^\nu-\Delta^\mu\gamma^\nu}{2M}+\widetilde{E}_T^+\frac{\gamma^\mu P^\nu-P^\mu\gamma^\nu}{M}\right]u_1|_{l=xp+q}. \tag{19}$$

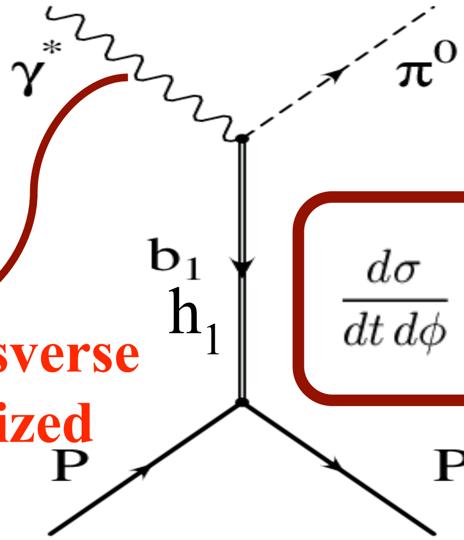
For $\mathcal{O}_{5\mu\nu}^-$ we have

$$-\frac{1}{2}\int_{-1}^{+1}dx\frac{l_\mu}{l^2+i0}\,\bar{u}_2\left[H_T^-\,\gamma^5\sigma^{\mu\,\nu}+\widetilde{H}_T^-\frac{\epsilon^{\mu\nu\rho\sigma}\Delta_\rho P_\sigma}{M^2}+E_T^-\frac{\epsilon^{\mu\nu\rho\sigma}\Delta_\rho\gamma_\sigma}{M^2}+\widetilde{E}_T^-\frac{\epsilon^{\mu\nu\rho\sigma}P_\rho\gamma_\sigma}{M^2}\right]u_1|_{l=xp+q}. \tag{20}$$

(b)

Exclusive π^o electroproduction

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



Transverse polarized

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

Sensitive to tensor charge!

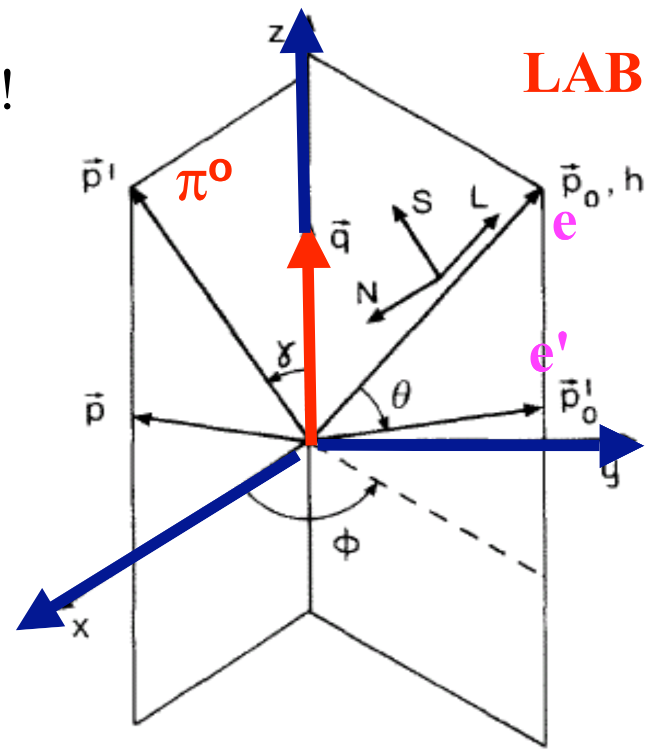
$$d\sigma \propto L_{\mu\nu}^{h=\pi^o} W_{\mu\nu}$$

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

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

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

LAB



Neutrino analog

Electroproduction differential cross section

$$\frac{d^4\sigma}{d\Omega d\varepsilon_2 d\phi dt} = \Gamma\left\{\frac{d\sigma_T}{dt} + \varepsilon_L \frac{d\sigma_L}{dt} + \varepsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon_L(\varepsilon+1)}\cos\phi \frac{d\sigma_{LT}}{dt}\right\}$$

where subscript *T* = transversely polarized virtual γ

L=longitudinal γ , *TT*= $\perp$- || to hadron scattering plane,

LT=long.$\times$transverse interference

Neutrino (antineutrino) cross section

$$\frac{d^4\sigma}{d\Omega d\varepsilon_2 d\phi dt} = \Gamma\left\{\frac{d\sigma_T}{dt} + \varepsilon_L \frac{d\sigma_L}{dt} + \varepsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon_L(\varepsilon+1)}\cos\phi \frac{d\sigma_{LT}}{dt}\right\}$$

$$\pm(\varepsilon \text{ factor}) \sin\phi \frac{d\sigma_{L'T}}{dt} + (\varepsilon \text{ factor}) \sin 2\phi \frac{d\sigma_{T'T}}{dt}\}$$

Neutrino (antineutrino) cross section

$$\frac{d^4\sigma}{d\Omega d\varepsilon_2 d\phi dt} = \Gamma\left\{\frac{d\sigma_T}{dt} + \varepsilon_L \frac{d\sigma_L}{dt} + \varepsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon_L(\varepsilon+1)}\cos\phi \frac{d\sigma_{LT}}{dt}\right.$$

$$\left. \pm(\varepsilon \text{ factor}) \sin\phi \frac{d\sigma_{L'T}}{dt} + (\varepsilon \text{ factor}) \sin 2\phi \frac{d\sigma_{T'T}}{dt}\right\}$$

- Extra terms from parity violation - V and A interference -

- **sinϕ** term would be obtained from polarized electron beam spin asymmetry
- Neutrino beam is 100% polarized left ⇒ separates parity
  odd & even combinations of helicity amps ⇒ spin dependent GPDs

•**sin2ϕ** term is tranverse in-plane V interference (Im) with transverse perp-plane A
•Would have no phases w/o rescattering- GPDs involve removing quark from target at origin of light front & returning quark further up the light front.

- How to see ϕ dependence? CC like $\nu N \rightarrow \mu^- \pi^+ N$ allows 2 planes to be seen

•What to expect? From $eN \rightarrow e\ \pi^0\ N$ see $d\sigma_L/dt$, showing importance of long. Photon.

Procedure: GPDs to $d\sigma^n/d\Omega_{lepton}d\Omega_{meson}dt$ & asymmetries, especially φ for $\rightarrow\gamma$ or $\rho,\omega,\pi,\eta,,K$

Exclusive spin dependent e or ν amps

↓

Factorized into handbag with quarks (2 scales)

↓

PQCD for Virtual boson+quark $\rightarrow\gamma$ (or ρ,ω,π,η,K)+quark'

↓

Soft quark/nucleon amp$\rightarrow$GPD

↓

4 chiral even + 4 chiral odd GPDs
Connected to 8 helicity amps

↓

Combine soft & hard. Integrate over p_{quark} $\rightarrow$ T-matrix for each helicity combination $\rightarrow$ form $d\sigma/d\Omega dt$…

↓

Models: diquark or exchanges $\rightarrow$ predictions

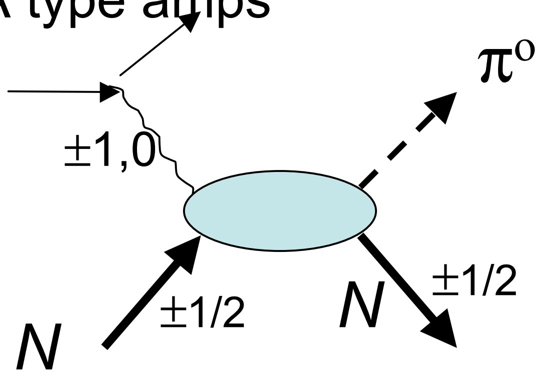
Exclusive π^o electroproduction and Transversity

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

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

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

Connect to helicity amps- make spin behavior explicit
In each observable there will be both V and A type amps



Target asymmetry for γ_T

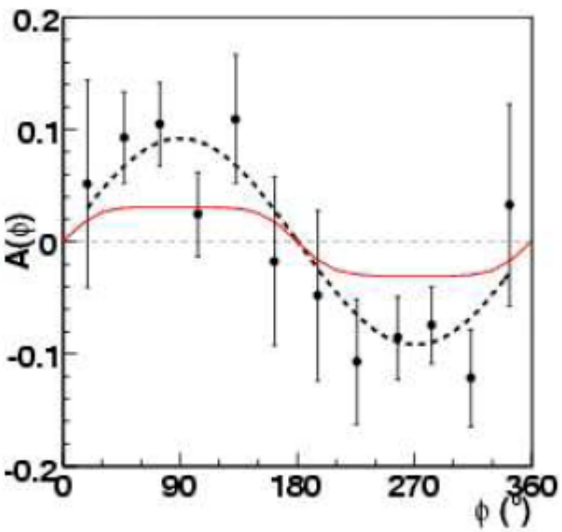
$$A_{UT} \propto 2Im(f^*_{+1+,0+}\, f_{+1-,0,+} - f^*_{+1-,0-}\, f_{+1+,0,-})$$

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

Beam asymmetry measures L-T interference

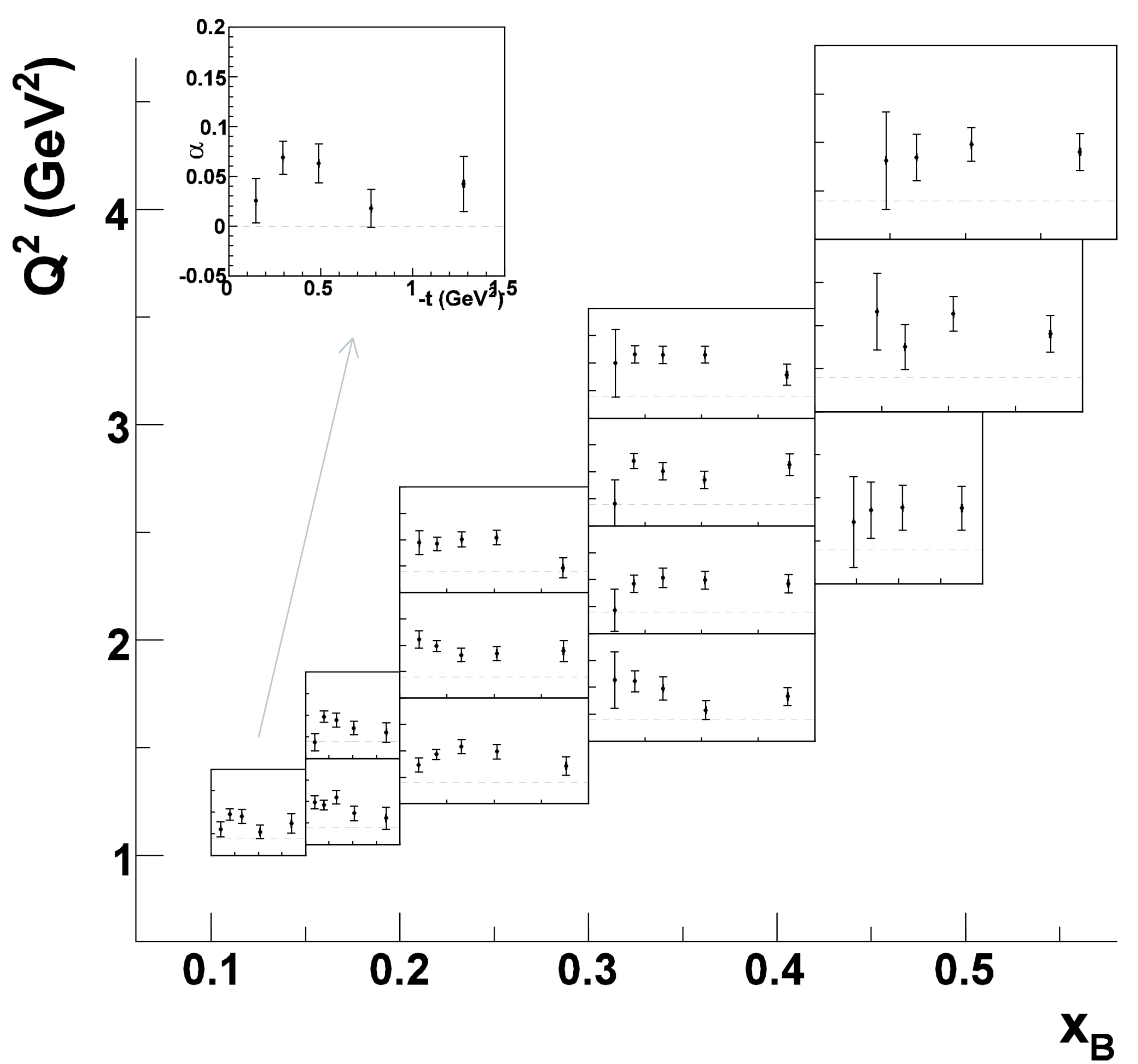
α vs t Preliminary Hall B data

[redacted]



- - - - $A = \alpha \sin\phi$

→ any non-zero BSA indicates L-T interference

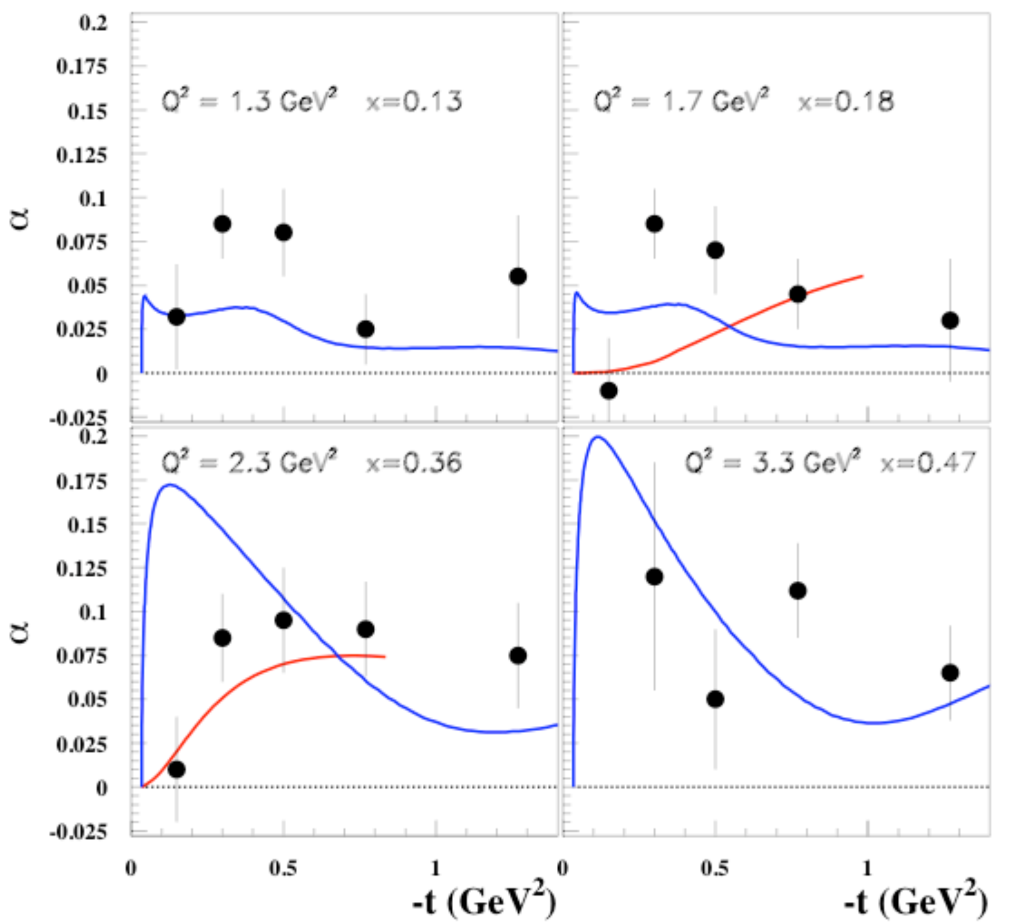


Models Beam-spin asymmetry α

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

Regge-cut predictions - comparisons involve ε_L, ε

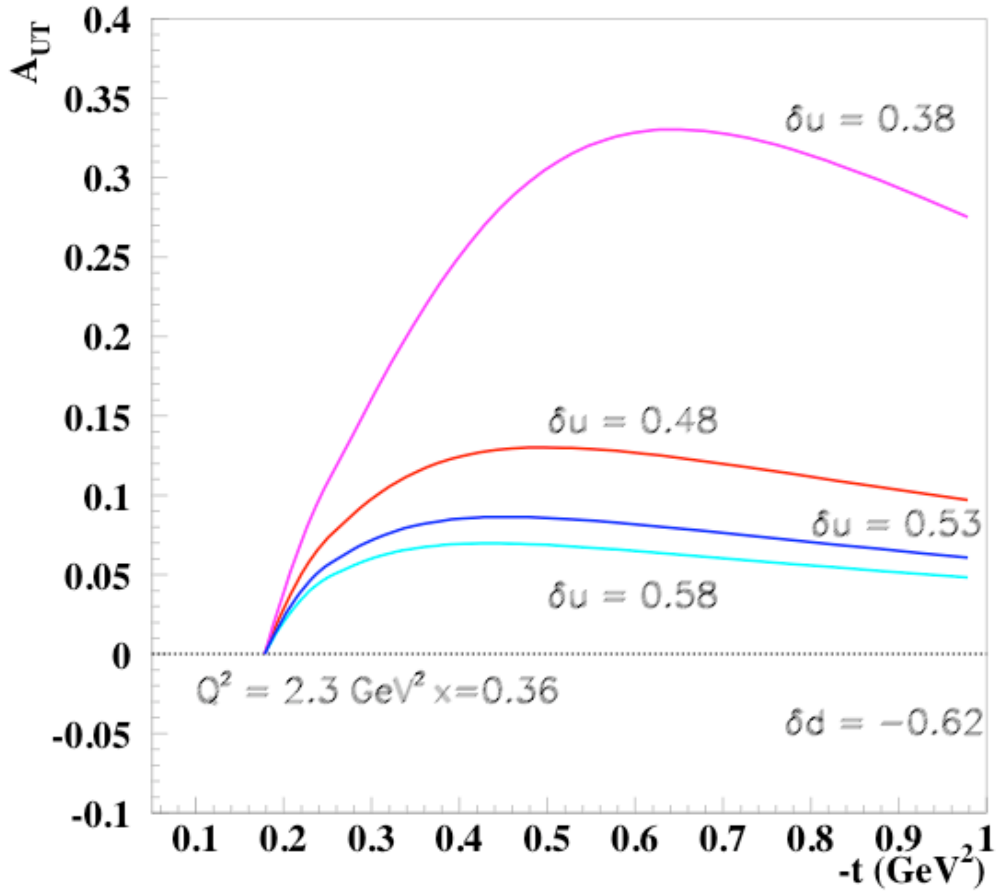
Ahmad, GRG, Liuti, PRD79,054014 (2009) blue



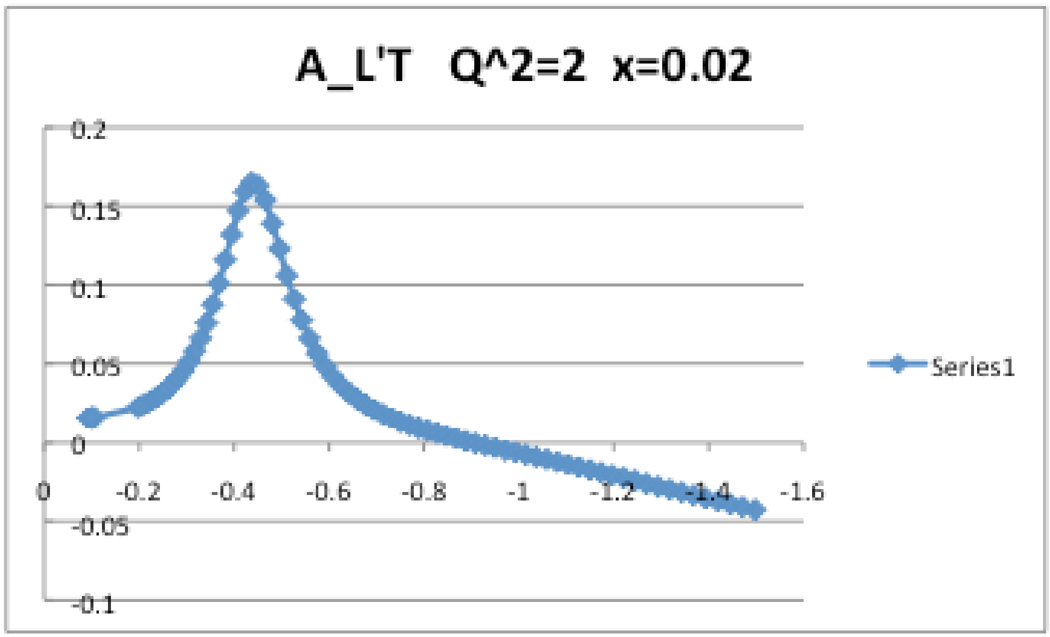
GPD predictions (preliminary) red

Variation of asymmetries with tensor charge
All GPDs

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



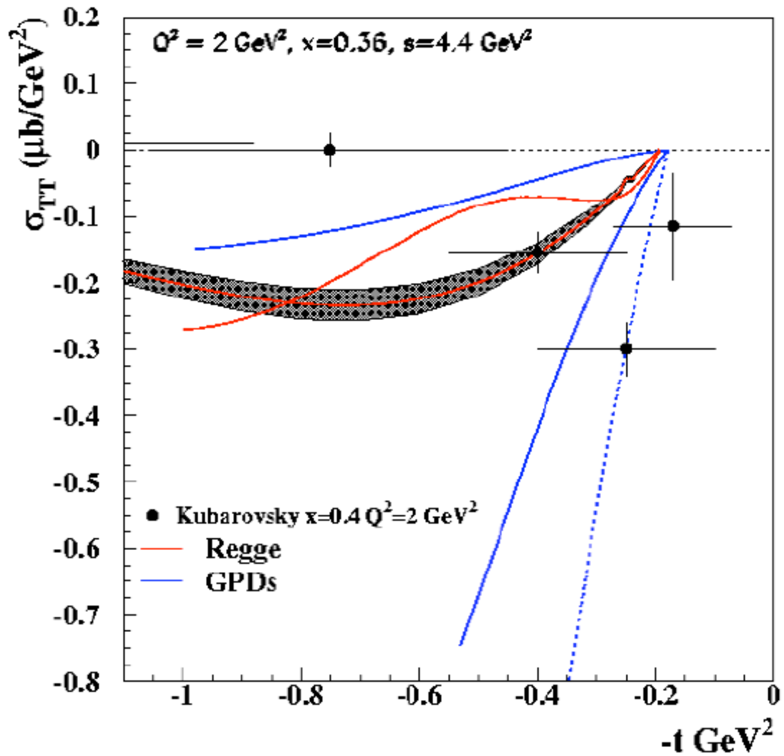
sinϕ term $\Rightarrow$ parity violating Longitudinal x Transverse Interference $\Rightarrow$ V & A phase difference
example from exchange model



How to compare σ_{TT} with data for $Q^2>0$?

Different choices of $\kappa_T{}^q$ from small to large u&d

SAID curve



Conclusions

☯ electroproduction of γ or ρ, ω, π, η at $Q^2 \approx 2$ to5, $W \approx 6$ GeV is described by GPDs

• Coherent neutrino-production of γ or ρ, ω, π, η in similar energy regime should be amenable to similar description of dynamics

• Exclusive π^0 electroproduction observables depend on p(π) & *azimuthal* orientation of hadron vs. lepton plane

• $d\sigma_T/dt$, $d\sigma_{TT}/dt$, A_{UT}, beam asymmetry, beam-target correlations, $d\sigma_L/dt$, $d\sigma_{LT}/dt$ contribute to full $d\sigma^5/$ dtd. . . along with parity-violating observables $d\sigma_{L' T}/dt$ and $d\sigma_{T' T}/dt$

☯ Charge Current interactions $\Rightarrow$ azimuthal asymmetry measurements & T-odd being related to GPD loop integral

☯ electroproduction, GPDs in overlapping kinematic region can bring enlightenment to neutrino scattering & transversity of nucleon within nucleus.