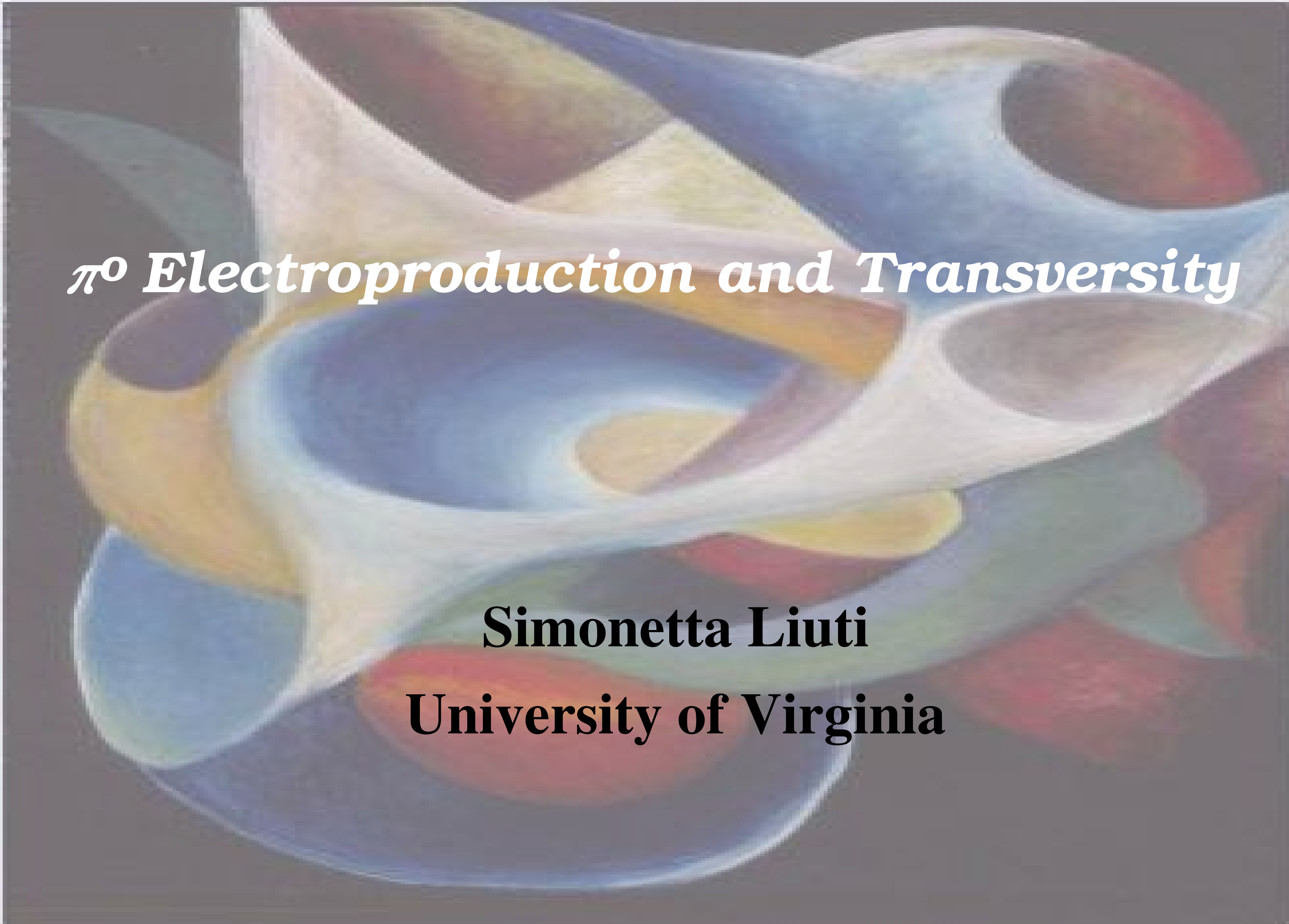


π^o Electroproduction and Transversity

Simonetta Liuti
University of Virginia

Collaborators:

Saeed Ahmad

Gary Goldstein

- AHLT (at the University of Virginia)

(Saeed Ahmad, Heli Honkanen*, S.L. and S.K. Taneja+)

---

* University of Iowa

\+ Stony Brook

Outline

- Main point:

➜ π^0 electroproduction always involves *chiral odd* GPDs

- Will show:

➜ GPDs from proton and neutron data sets $\Rightarrow$

  ★ New results using Jlab data constraints!

➜ Model for Q^2 dependence

➜ Practical method for the extraction of both

tensor charge: δq

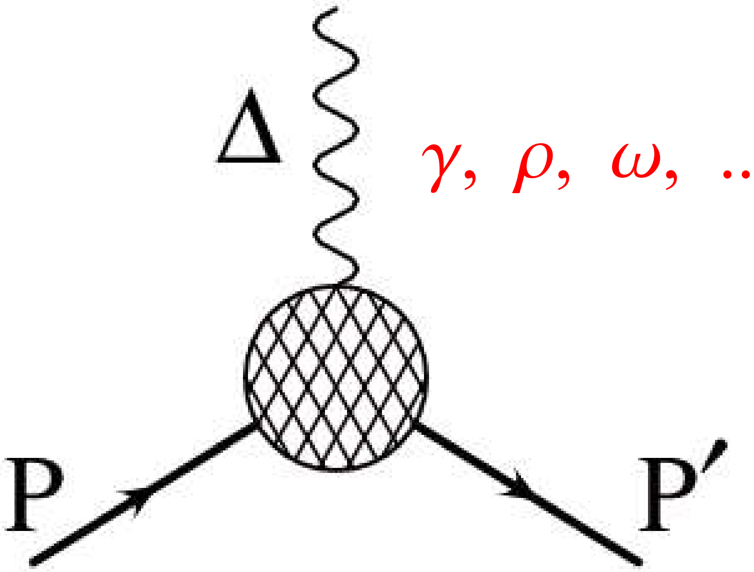
"Burkardt's moment": κ_T^q

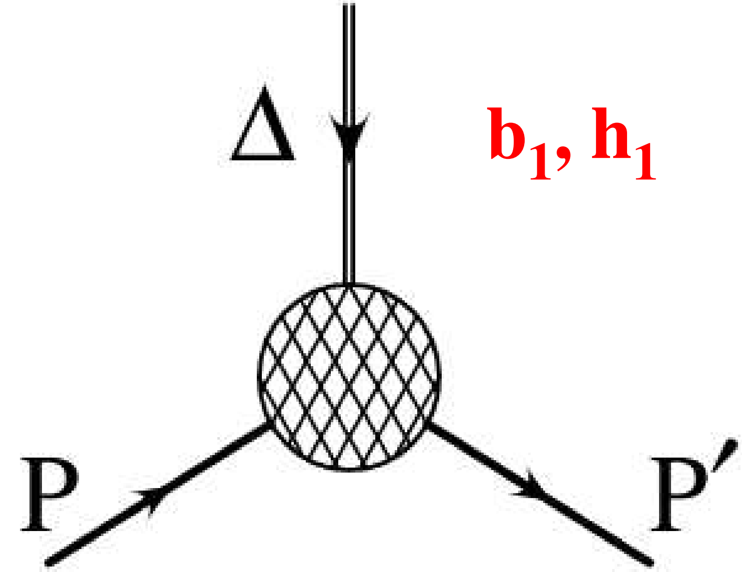
- Conclusions: which experiments, observables, targets for Jlab at 12 GeV?

1. π^o Electroproduction Observables and GPDs*

*Gary Goldstein's talk

π^0 production proceeds via two types <u>only</u> of J^{PC} exchanges:





$J^{PC}=1^{--}$ $\quad\quad$ $J^{PC}=1^{+-}$

$\boxed{i\sigma_{\mu\nu}\gamma_5}$ $\Leftrightarrow J^{PC}=1^{--}, 1^{+-}, \ldots \Leftrightarrow$ H_T, E_T, ...

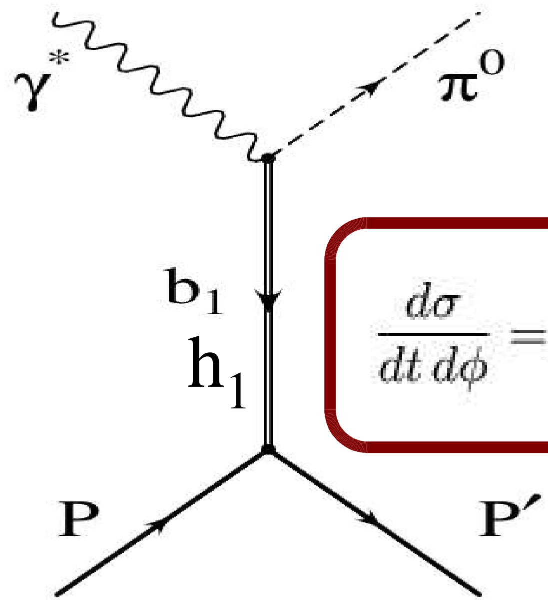
$\boxed{\gamma_5}$ $\Leftrightarrow J^{PC}=1^{++}, \ldots$ (a_1-type exchange) $\Leftrightarrow \tilde{H}, \tilde{E}, \ldots$

Only chiral-odd GPDs!!!

Exclusive π^o electroproduction

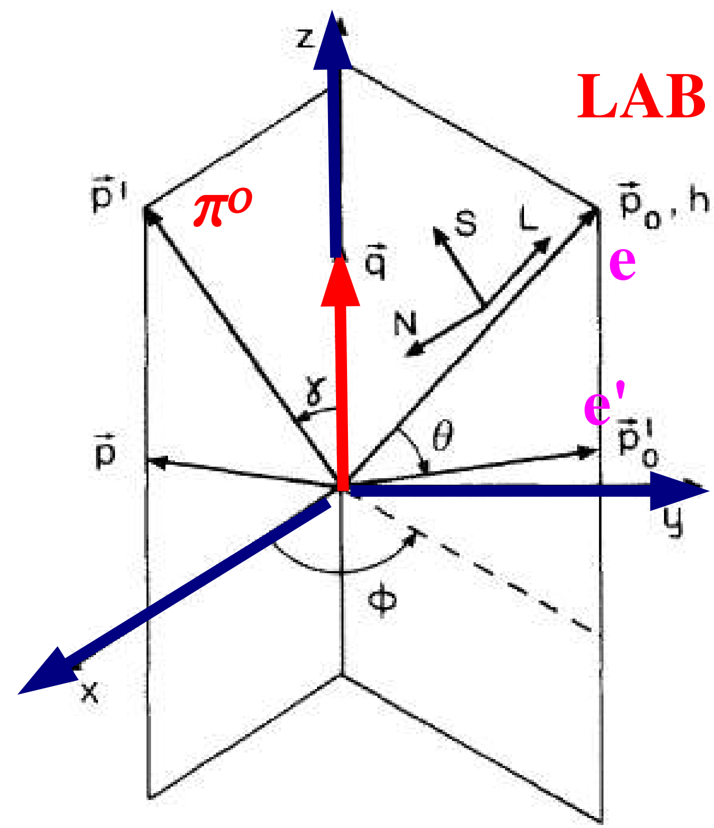
$$ep \to e'p'\pi^o$$

(b)



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

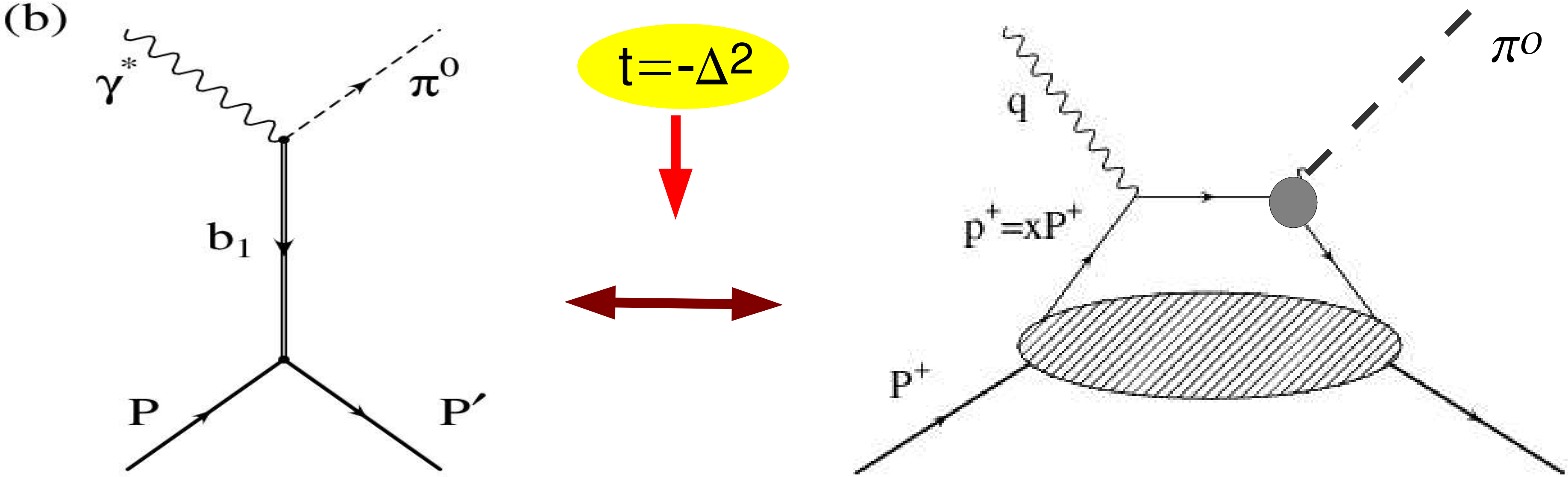
$$d\sigma \propto L_{\mu\nu}^{h=\pi^o} W_{\mu\nu}$$



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

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

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



“quark-hadron” helicity amps.

$$f_{1,\Lambda;0,\Lambda'} = \sum_{\lambda,\lambda'} g_{1,\lambda;0,\lambda'} A_{\Lambda',\lambda';\Lambda,\lambda}$$

“Quark-Hadron” Helicity Amplitudes (Marcus Diehl)

$$\begin{aligned}
f_1 &\equiv f_{1+,0+} \propto A_{++,+-} \\
f_2 &\equiv f_{1+,0-} \propto A_{++,--} \\
f_3 &\equiv f_{1-,0+} \propto A_{+-,-+} \\
f_4 &\equiv f_{1+,0+} \propto A_{++,+-} \\
f_5 &\equiv f_{0+,0-} \propto A_{++,--} \\
f_6 &\equiv f_{0+,0+} = 0
\end{aligned}$$

$$\begin{aligned}
A_{+-,++} &= \frac{1}{2} F^V_{\pi\gamma^*}(Q^2)\, \frac{\sqrt{t_0-t}}{2M} \left[\tilde{\mathcal{H}}_T + \frac{1+\xi}{2}\mathcal{E}_T - \frac{1+\xi}{2}\tilde{\mathcal{E}}_T\right] \\
A_{++,--} &= \frac{F^V_{\pi\gamma^*}(Q^2) + F^A_{\pi\gamma^*}(Q^2)}{2} \sqrt{1-\xi^2} \left[\mathcal{H}_T + \frac{t_0-t}{4M^2}\tilde{\mathcal{H}}_T\right] \\
A_{+-,-+} &= \frac{F^V_{\pi\gamma^*}(Q^2) - F^A_{\pi\gamma^*}(Q^2)}{2} \sqrt{1-\xi^2}\, \frac{t_0-t}{4M^2} \tilde{\mathcal{H}}_T \\
A_{++,+-} &= -\frac{1}{2} F^V_{\pi\gamma^*}(Q^2)\, \frac{\sqrt{t_0-t}}{2M} \left[\tilde{\mathcal{H}}_T + \frac{1-\xi}{2}\mathcal{E}_T + \frac{1-\xi}{2}\tilde{\mathcal{E}}_T\right]
\end{aligned}$$

What goes into the quark-hadron amplitudes?

$$\mathcal{F}(\zeta,t) = -i\pi \sum_q e_q^2 \left[F^q(\zeta,\zeta,t) - F^q(-\zeta,\zeta,t)\right] + \mathcal{P}\int_{1-\zeta}^{1} dX \left(\frac{1}{X-\zeta} + \frac{1}{X}\right) F^q(X,\zeta,t).$$

Generalized Form Factors

$$\mathcal{H}_T, \mathcal{E}_T, \widetilde{\mathcal{H}}_T, \widetilde{\mathcal{E}}_T$$

$H_T(X,0,0) = h_1(X) =$ transversity

$\int h_1(X,Q^2)\; dX = \delta q =$ tensor charge

$$\widetilde{\mathcal{E}}_2 = 2\widetilde{\mathcal{H}}_T + \mathcal{E}_T$$

$\int E_2(X,0,0)\; dX = \kappa_T =$ Burkardt's moment

$\int h_1^{\perp}(X)\; dX\; d^2k_T \sim -\kappa_T$ (A.Metz)

Observables are sensitive to both δq and κ_T!

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

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

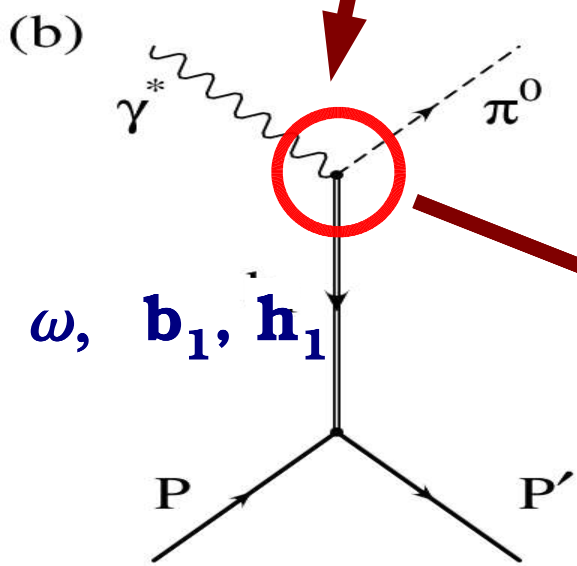
$$\frac{d\sigma_{LT}}{dt} = K\frac{t_0-t}{8M^2}\left[(1-\xi^2)\Re e\left(\widetilde{\mathcal{E}}_2(Q^2)\,\mathcal{H}_T^*(Q^2)\right) + \left(\Re e\,\widetilde{\mathcal{E}}_2(Q^2)\right)^2\right]$$

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

... and more ...!!!

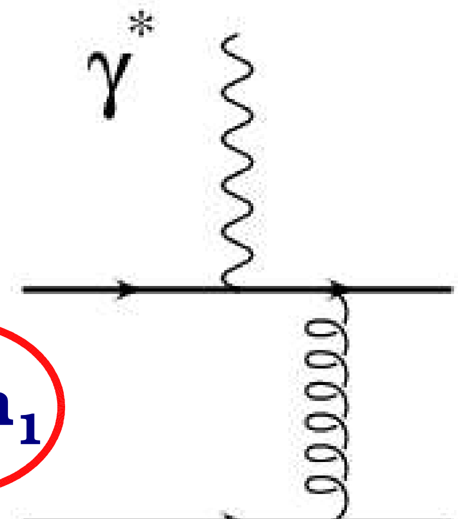
2. Q^2 dependence

t-channel exchange vertex



ρ, ω, $\mathbf{b_1}$, $\mathbf{h_1}$

modeled as $F_{\pi\gamma^*}$ (pseudoscalar-meson transition form factor)



π^0

$J^{PC}=0^{+-}$

ρ, ω, $\mathbf{b_1}$, $\mathbf{h_1}$

$J^{PC}=1^{--}$ $({}^3S_1)$

$J^{PC}=1^{+-}({}^1P_1)$

quark content: $\frac{1}{\sqrt{2}}\left(u\bar{u} \pm d\bar{d}\right)$

Distinction between ρ, ω and b_1, h_1 exchanges

$J^{PC}=1^{--}$ ⟶ π^0: qqbar from (S=1 L=0) ⇒ (S=0 L=0) ⇒ $\Delta L = 0$

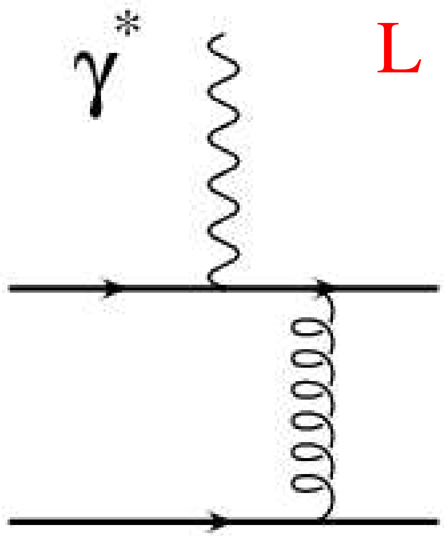
$J^{PC}=1^{+-}$ ⟶ π^0: qqbar from (S=0 L=1) ⇒ (S=0 L=0) ⇒ $\Delta L = 1$

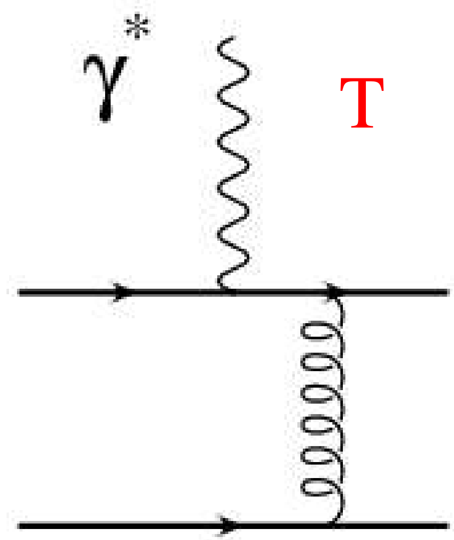
"Vector" exchanges ⇒ no change in OAM

"Axial-vector" exchanges ⇒ change 1 unit of OAM!

Reminiscent of PQCD analysis of Nucleon's Pauli Form Factor

(Belitsky, Ji, Yuan, 2003)



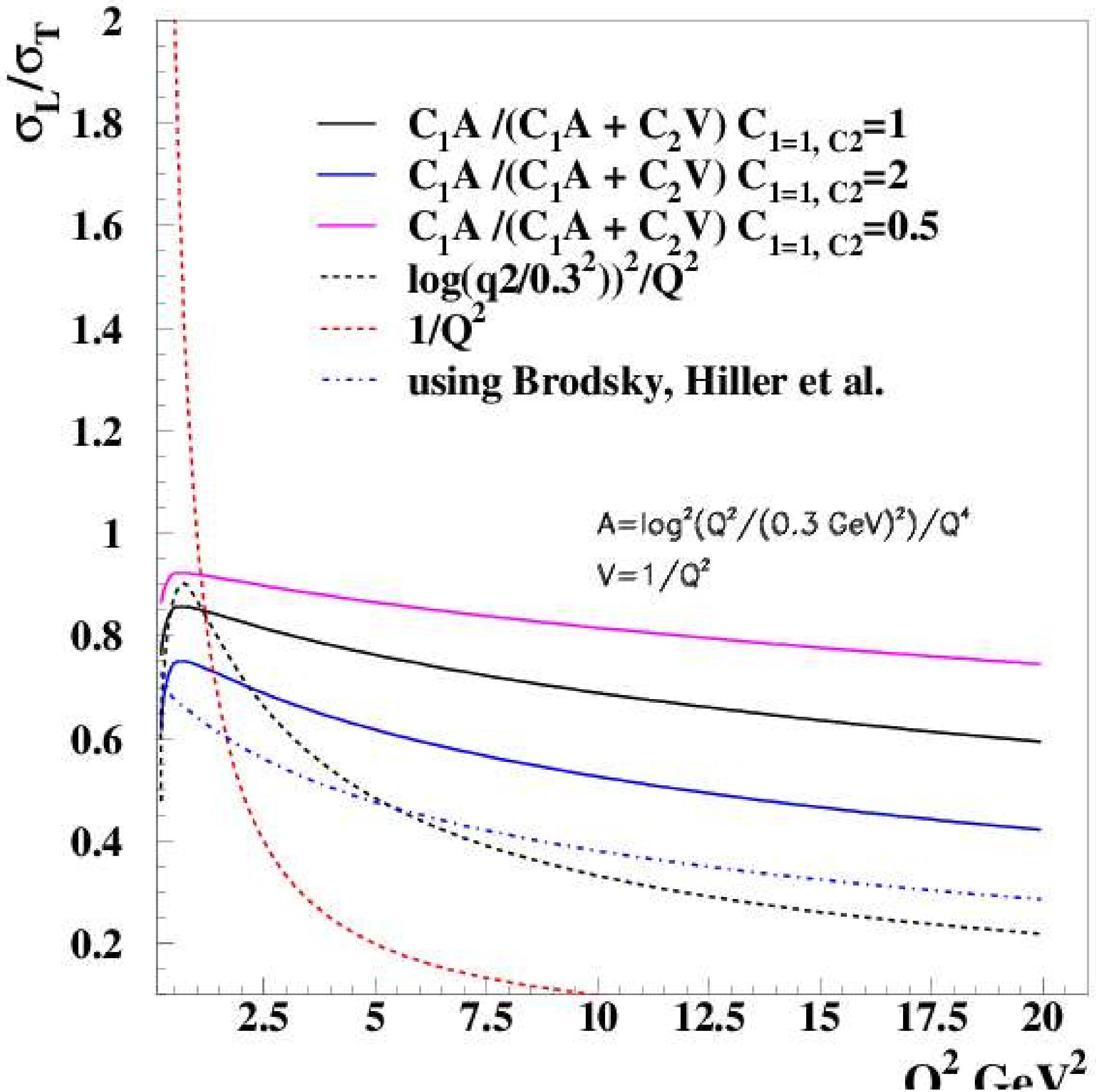


$\Delta L = 1 \Rightarrow A \propto \log^2(Q^2/)/Q^4\ V$

$\Delta L = 0 \Rightarrow V \propto 1/Q^2$
and $\Delta L = 1$

$\Delta L = 1$ further suppressed by
Sudakov form factor

Preliminary!



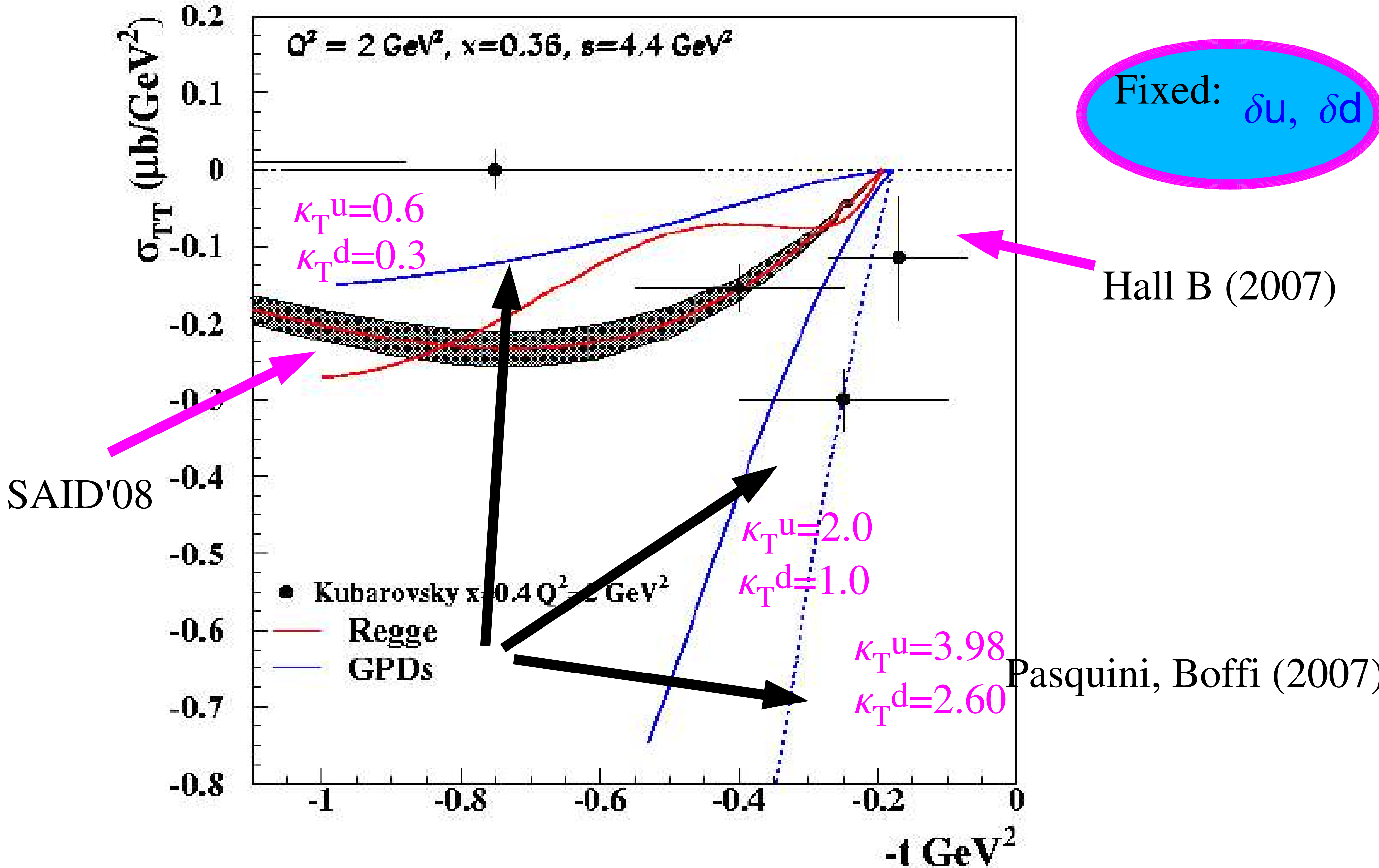
3. Extraction from data needs a reliable GPD model

Reaching a more advanced phase of extracting GPDs from data

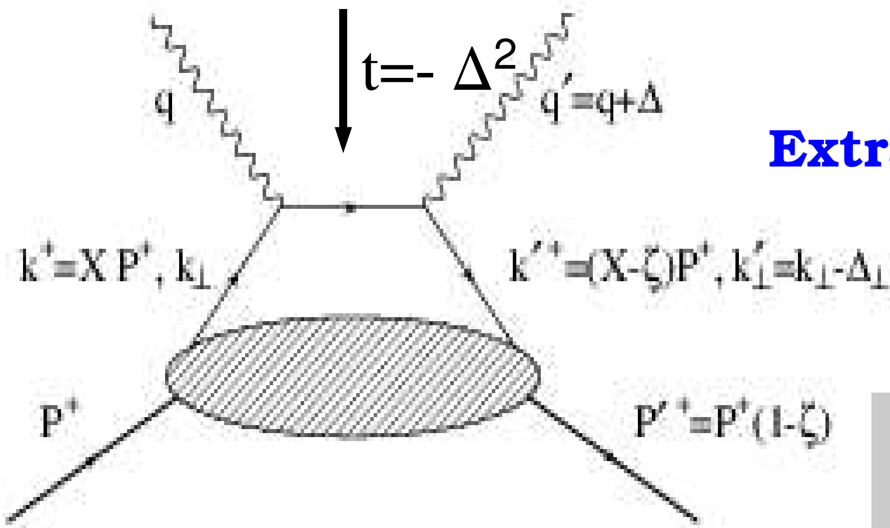
- No longer simple models (agree with Dieter Muller)
- Incorporate Q2 dependence
- Incorporate all constraints from data “non DVCS, DVMP type” data
- Incorporate new data as they become available
- Lattice + Chiral Extrapolations (see also Philip Hagler)
- Connect various experiments, separate valence from sea, flavors, ...

The observables we singled out are sensitive to δu, δd, $\kappa_T^u \kappa_T^d$

Measure interplay of four quantities!



DVCS and Generalized Parton Distributions



Extract "Generalized Parton Distributions"

$$\bar{P}^+ \int \frac{d\xi^-}{2\pi} e^{ixP^+\xi^-} \langle P', S' \,|\, \psi\left(-\frac{\xi^-}{2}\right) \gamma^+ \psi\left(\frac{\xi^-}{2}\right) |\, P, S\rangle =$$

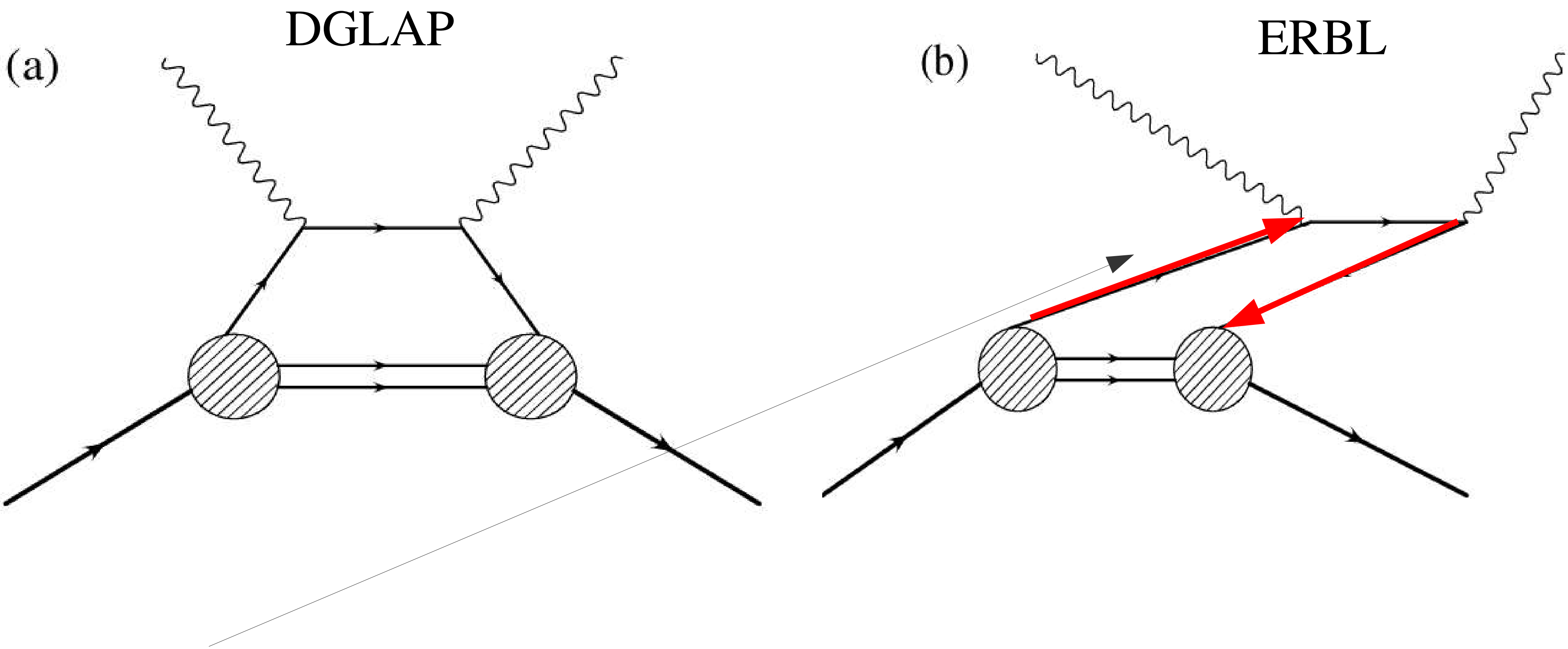
$$\bar{u}(P', S') \left[\gamma^+ H(x, \xi, -\Delta^2) + \frac{i\sigma^{+\nu} q_\nu}{2M} E(x, \xi, -\Delta^2)\right] u(P, S)$$

- **GPDs are hybrids of PDFs and FFs: describe simultaneously x and t-dependences !**
- **GPDs give access to spatial d.o.f. of partons !**
- **GPDs give access to orbital angular momentum of partons!**

$$\int dx\,x\,[H_q(x, \zeta, t = 0) + E_q(x, \zeta, t = 0)] = 2J_q$$

X. Ji

Two different time orderings/pole structure!



Quark anti-quark pair describes similar physics (dual to) Regge t-channel exchange!!

What goes into a theoretically motivated parametrization...?

The name of the game: Devise a form combining essential dynamical elements with a flexible model that allows for a fully quantitative analysis constrained by the data

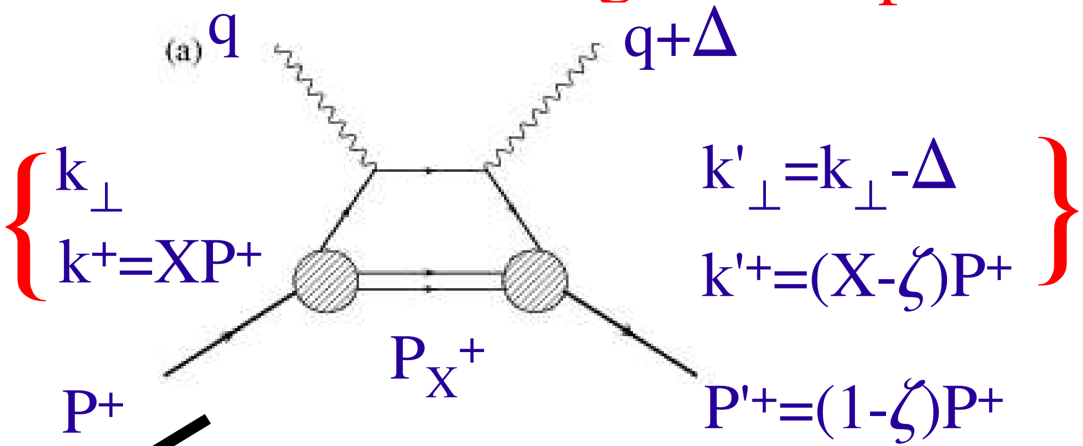
$$H_q(X,t) = R(X,t)\, G(X,t)$$

"Regge"

Quark-Diquark

Q^2 Evolution is an essential element!!

For ζ= 0 and in the DGLAP region $\Rightarrow$ partonic picture



$$R^I_{1(2)} = X^{-\alpha^I - \beta^I_{1(2)}(1-X)^{p^I_{1(2)}} t}$$

$$G^\lambda_{M_X}(X,t) = \mathcal{N}\frac{X}{1-X}\int d^2\mathbf{k}_\perp \frac{\phi(k^2,\lambda)}{D(X,\mathbf{k}_\perp)}\frac{\phi(k'^2,\lambda)}{D(X,\mathbf{k}_\perp+(1-X)\mathbf{\Delta}_\perp)}$$

Summary of Constraints

Constraints from Form Factors

$$\int_0^1 dX\, H^q(X,t) = F_1^q(t)$$ Dirac

$$\int_0^1 dX\, E^q(X,t) = F_2^q(t),$$ Pauli

$$F^p_{1(2)}(t) = \frac{2}{3}F^u_{1(2)}(t) - \frac{1}{3}F^d_{1(2)}(t) + \frac{1}{3}F^s_{1(2)}(t)$$ Dirac(Pauli) proton

$$F^n_{1(2)}(t) = -\frac{1}{3}F^u_{1(2)}(t) + \frac{2}{3}F^d_{1(2)}(t) + \frac{1}{3}F^s_{1(2)}(t),$$ Dirac(Pauli) neutron

Constraints from PDFs

$$q(x) = H_q(x,0,0)$$

GPDs from available data 2

Parton Distribution Functions

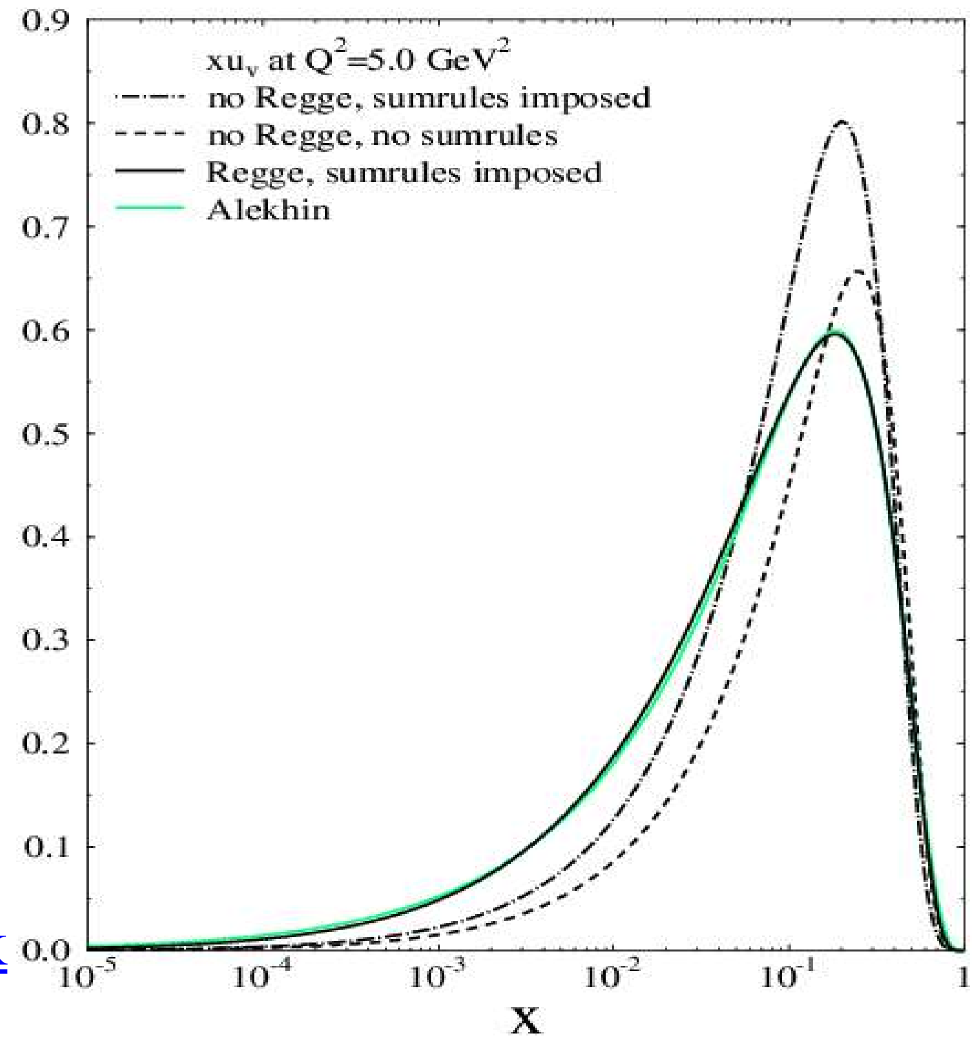
Notice! GPD parametric form is given at $Q^2=\mu^2$ and evolved to Q^2 of data.

Notice! We provide a parametrization for GPDs that simultaneously fits the PDFs:

$$H_q(X,t) = R(X,t)\, G(X,t)$$

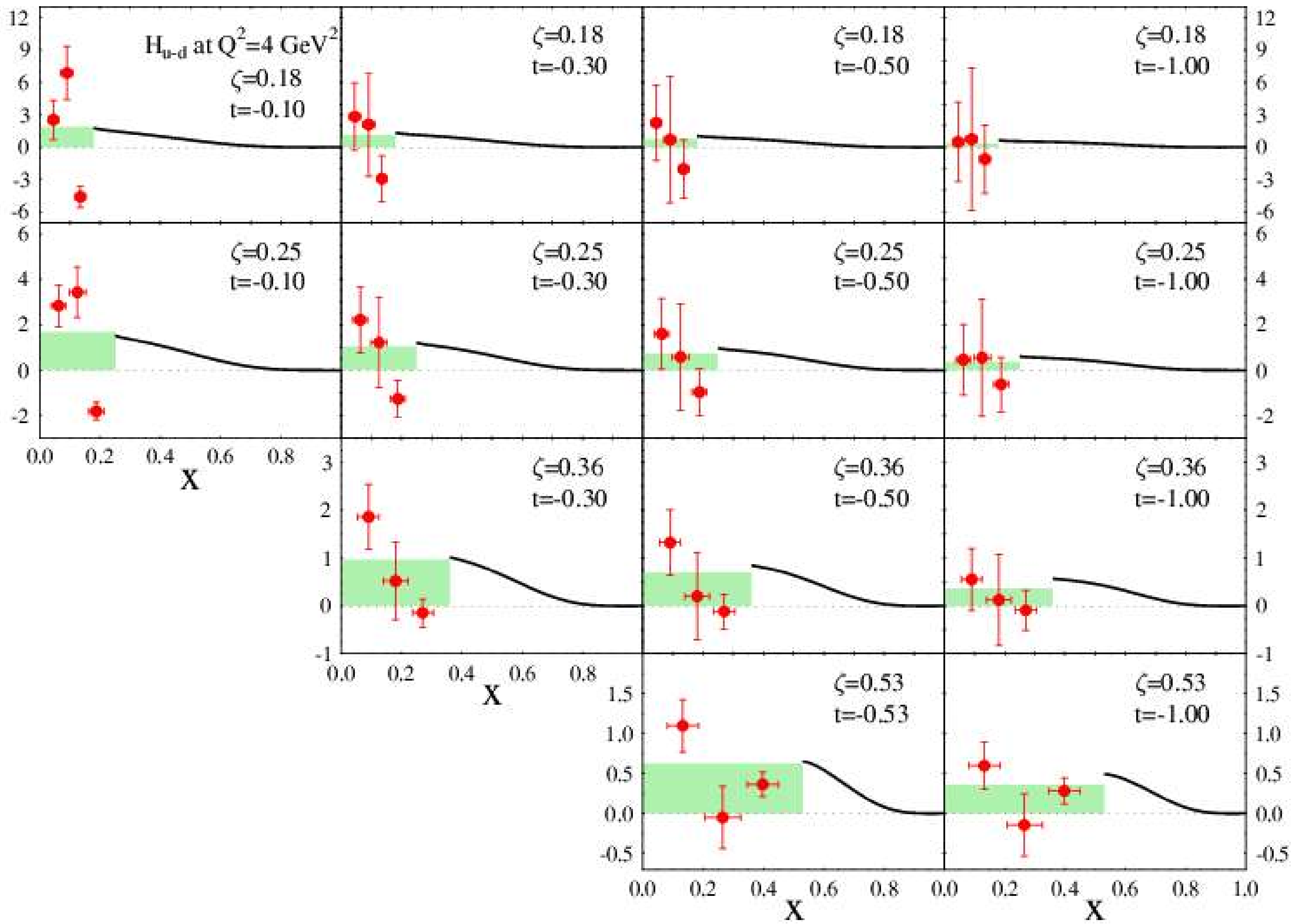
Regge

Quark-Diquark



ERBL Region

AHLT arXiv:0708.0268



First "model independent" extraction of GPDs!!!

GPDs from Bernstein moments

$$\overline{H}(X,\zeta,t) = \frac{(n+1)!}{k!}\sum_{l=0}^{n-k}\frac{(-1)^l}{l!(n-k-l)!}M_{l+k}$$

Mellin moments

$$\overline{H}_{02}(X_{02}) = 3A_{10} - 6A_{20} + 3\left[A_{30} + \left(\frac{2\zeta}{2-\zeta}\right)^2 A_{32}\right],$$

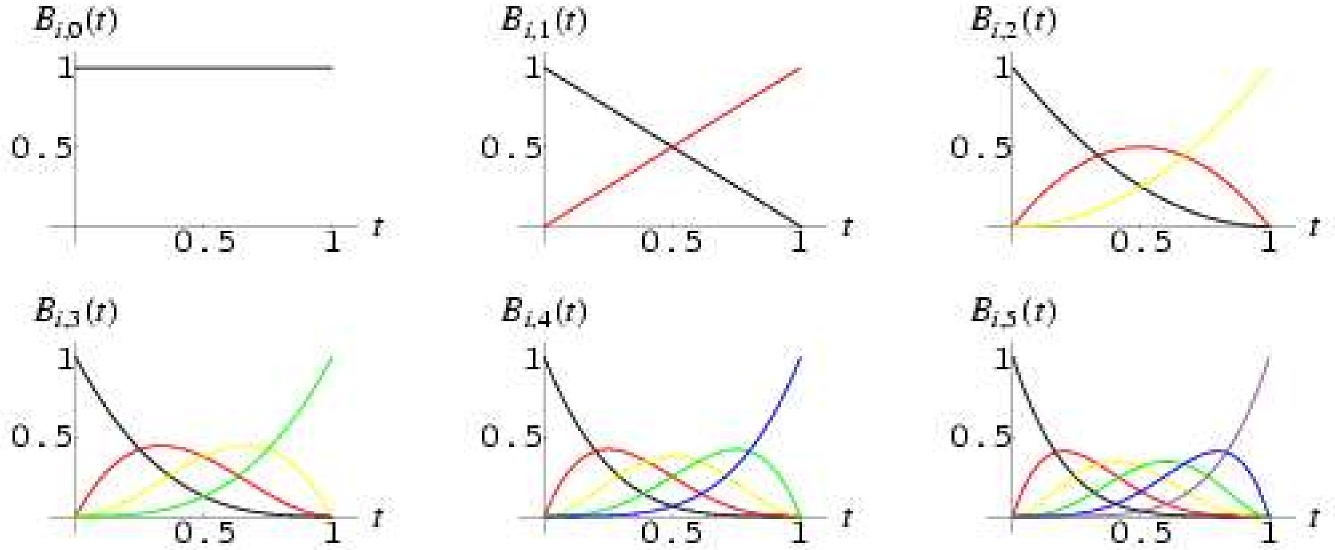
$$\overline{H}_{12}(X_{12}) = 6A_{20} - 6\left[A_{30} + \left(\frac{2\zeta}{2-\zeta}\right)^2 A_{32}\right],$$

$$\overline{H}_{22}(X_{22}) = 3A_{30} + \left[\left(\frac{2\zeta}{2-\zeta}\right)^2 A_{32}\right].$$

Weighted Average ⇒ $$\overline{H}(X,\zeta,t) = \int_0^1 H(X,\zeta,t) b_{k,n}(X) dX \quad k = 1,...n,$$

X-bin ⇒ $$\overline{X}_{k,n} = \int_0^1 X b_{k,n}(X) dX = \frac{k+1}{n+1},$$

Dispersion ⇒ $$\Delta_{k,n} = \left(\overline{X^2}_{k,n} - \overline{X}^2_{k,n}\right)^{1/2}$$

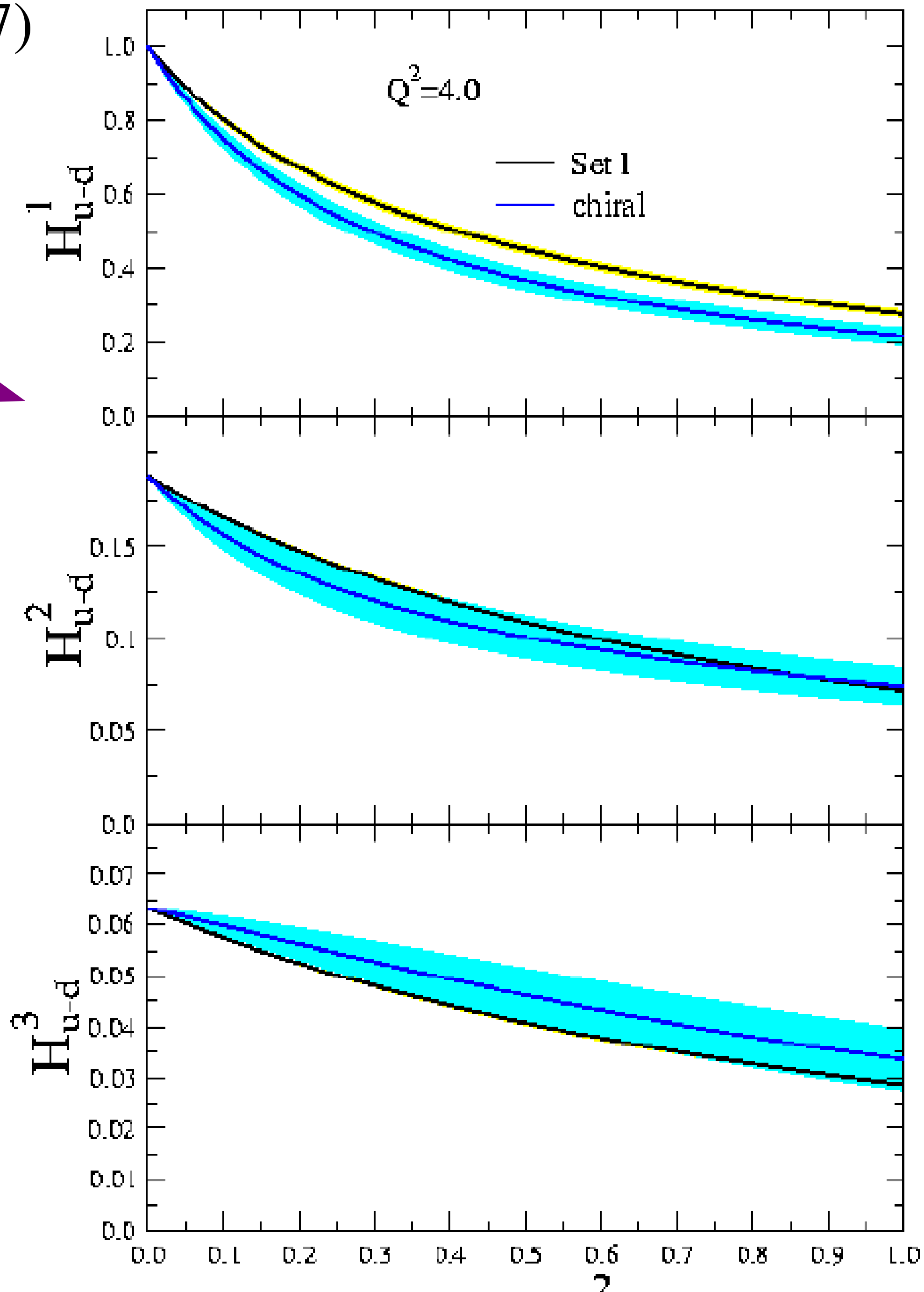


Chiral Extrapolations

Dorati, Gail and Hemmert (2007)

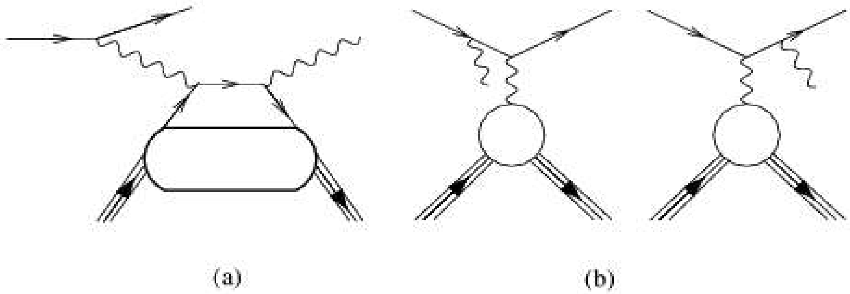
Wang and Thomas (2008)

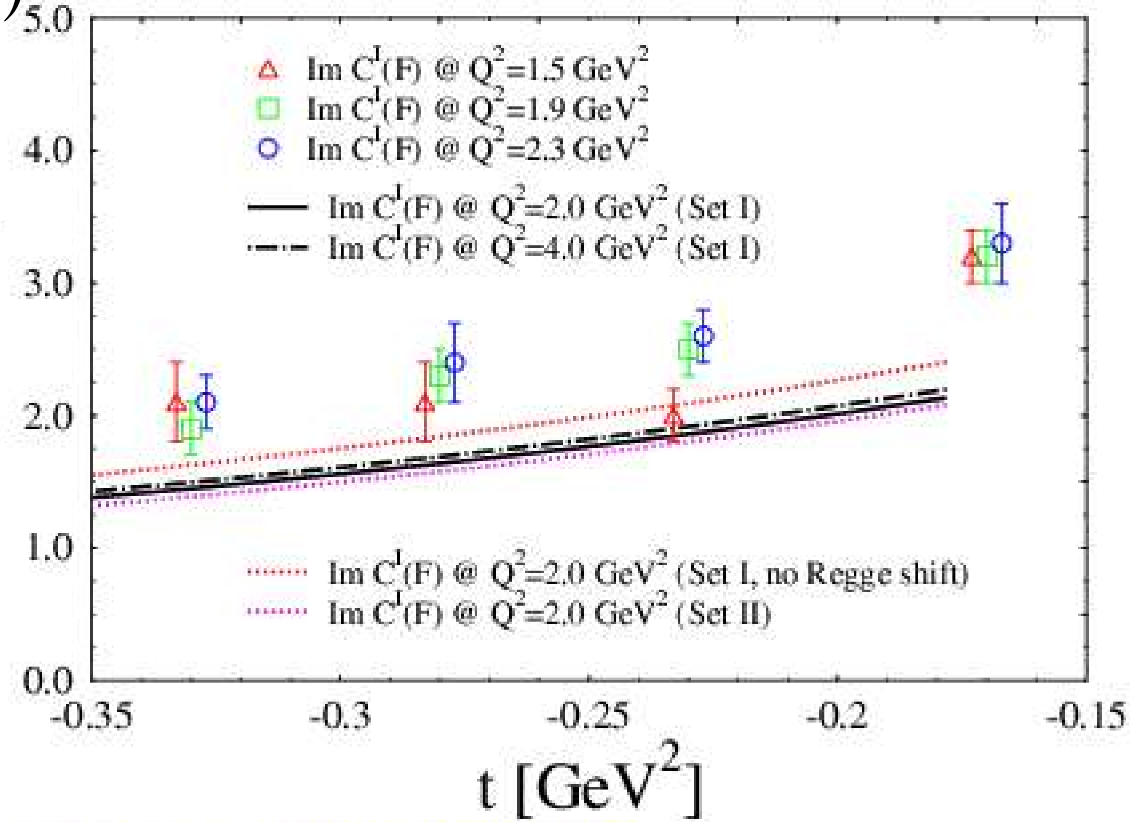
⇒Ashley et al. (2003)



Comparison with Jlab Hall A data (proton)

Munoz Camacho et al., (2006)



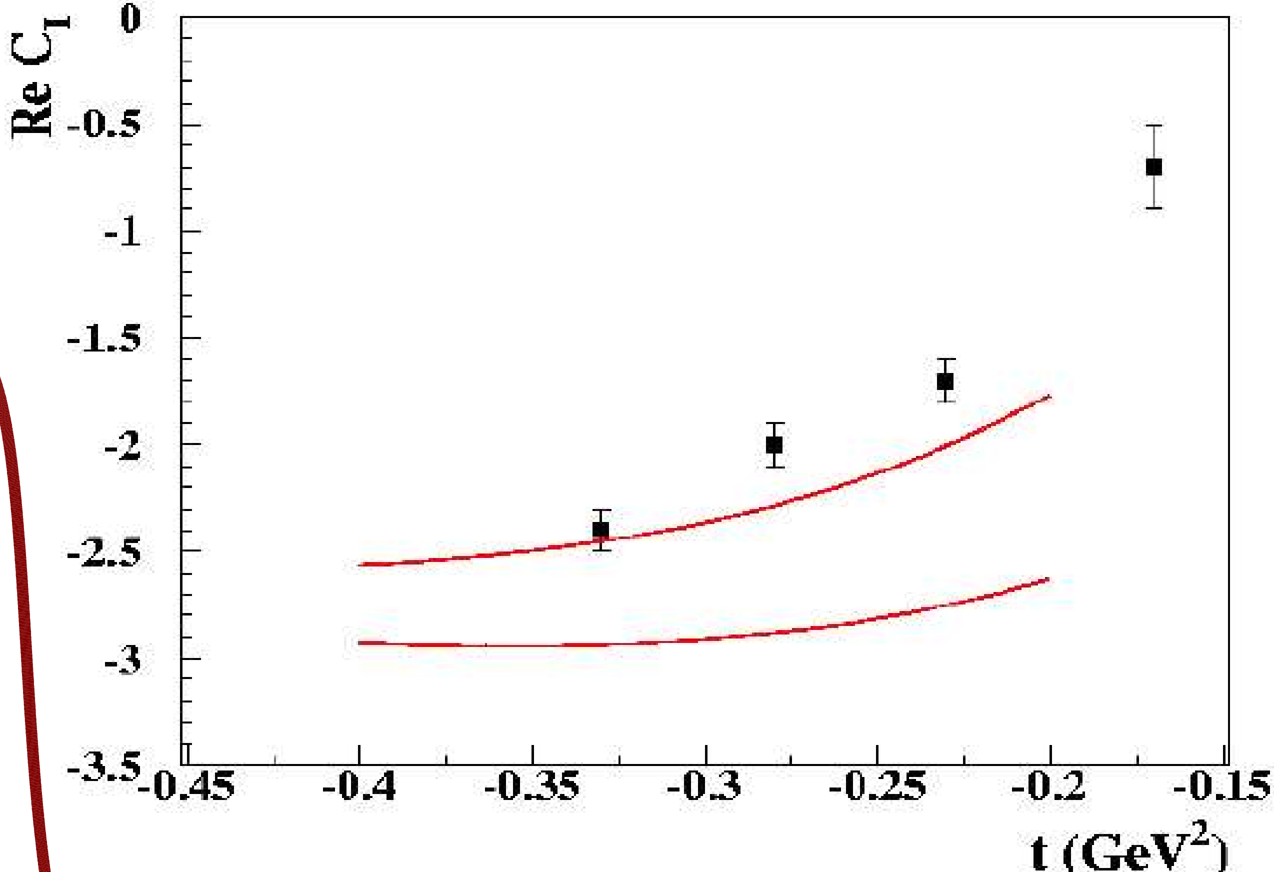


- Observable given by Interference Term between DVCS (a) and BH(b):

$$d\sigma^{\rightarrow} - d\sigma^{\leftarrow} \propto sin\phi \left[F_1(\Delta^2)\mathcal{H} + \frac{x}{2-x}(F_1 + F_2)\widetilde{\mathcal{H}} + \frac{\Delta^2}{M^2} F_2(\Delta^2)\mathcal{E} \right]$$

$$\mathcal{H} = \sum_q e_q^2 (H(\xi, \xi, \Delta^2) - H(-\xi, \xi, \Delta^2))$$

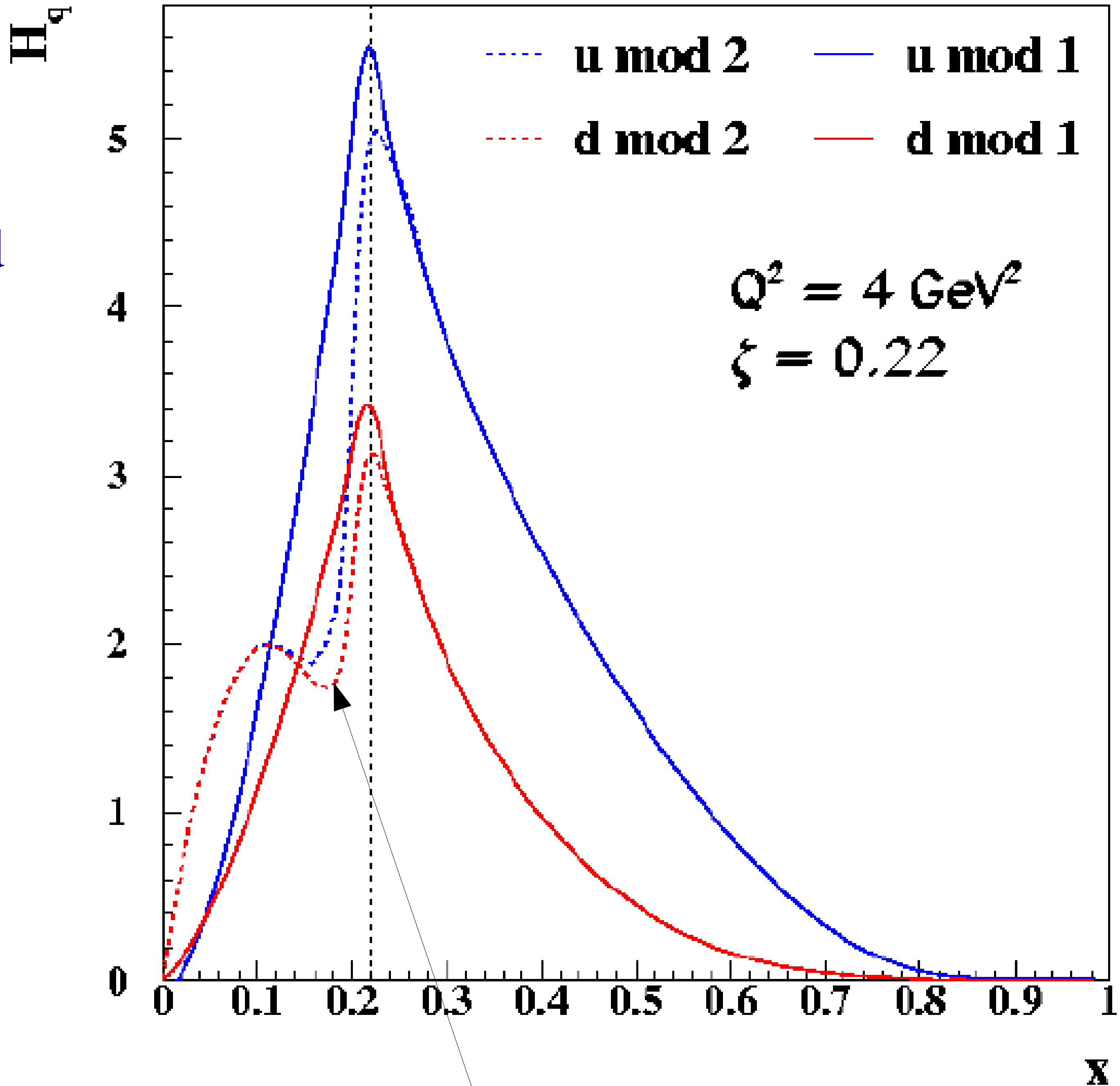
Real Part



$$\mathcal{F}(\zeta,t) = -i\pi \sum_q e_q^2 \left[F^q(\zeta,\zeta,t) - F^q(-\zeta,\zeta,t)\right] +$$

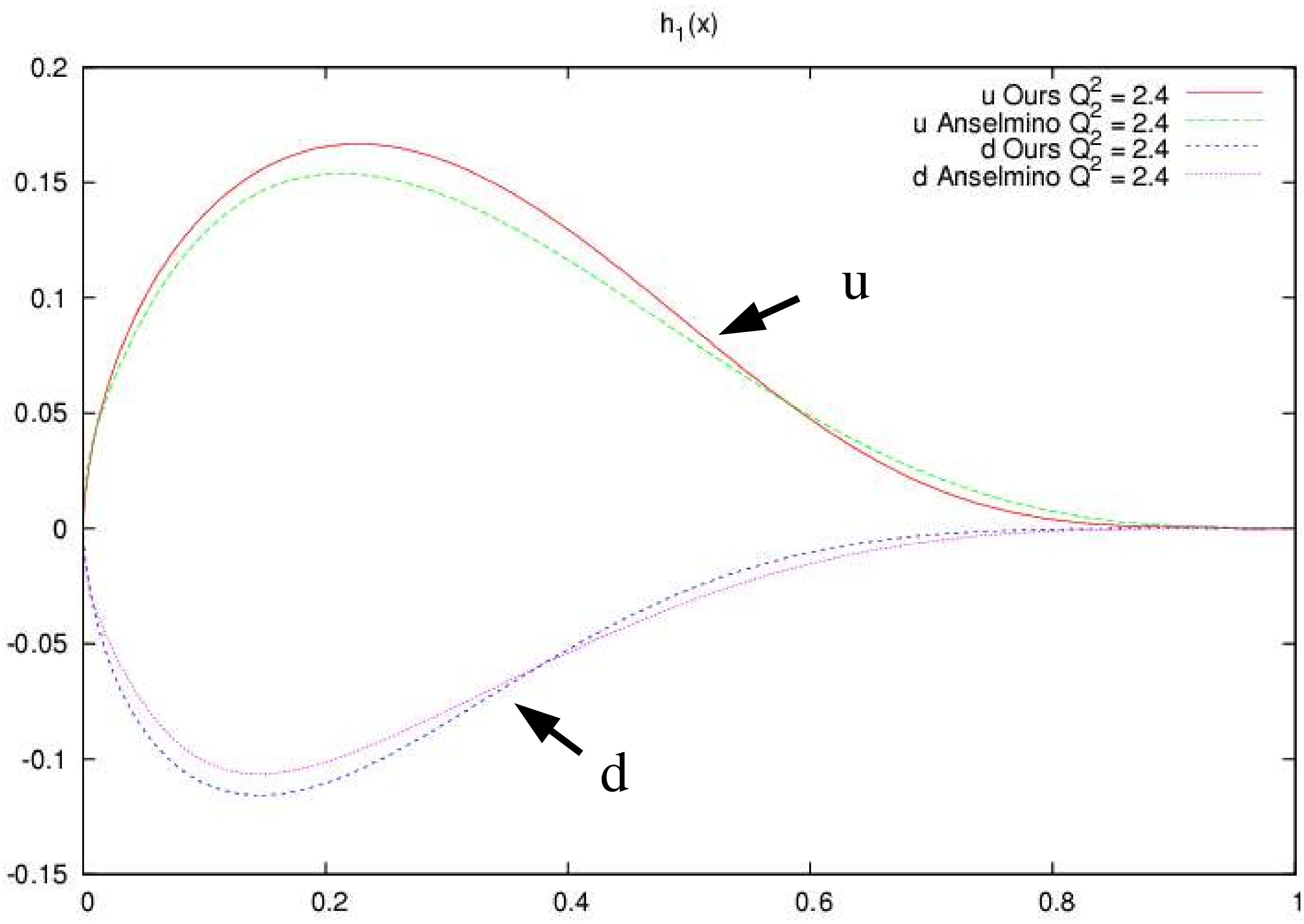
$$\mathcal{P}\int_{1-\zeta}^{1} dX \left(\frac{1}{X-\zeta} + \frac{1}{X}\right) F^q(X,\zeta,t).$$

S. Ahmad



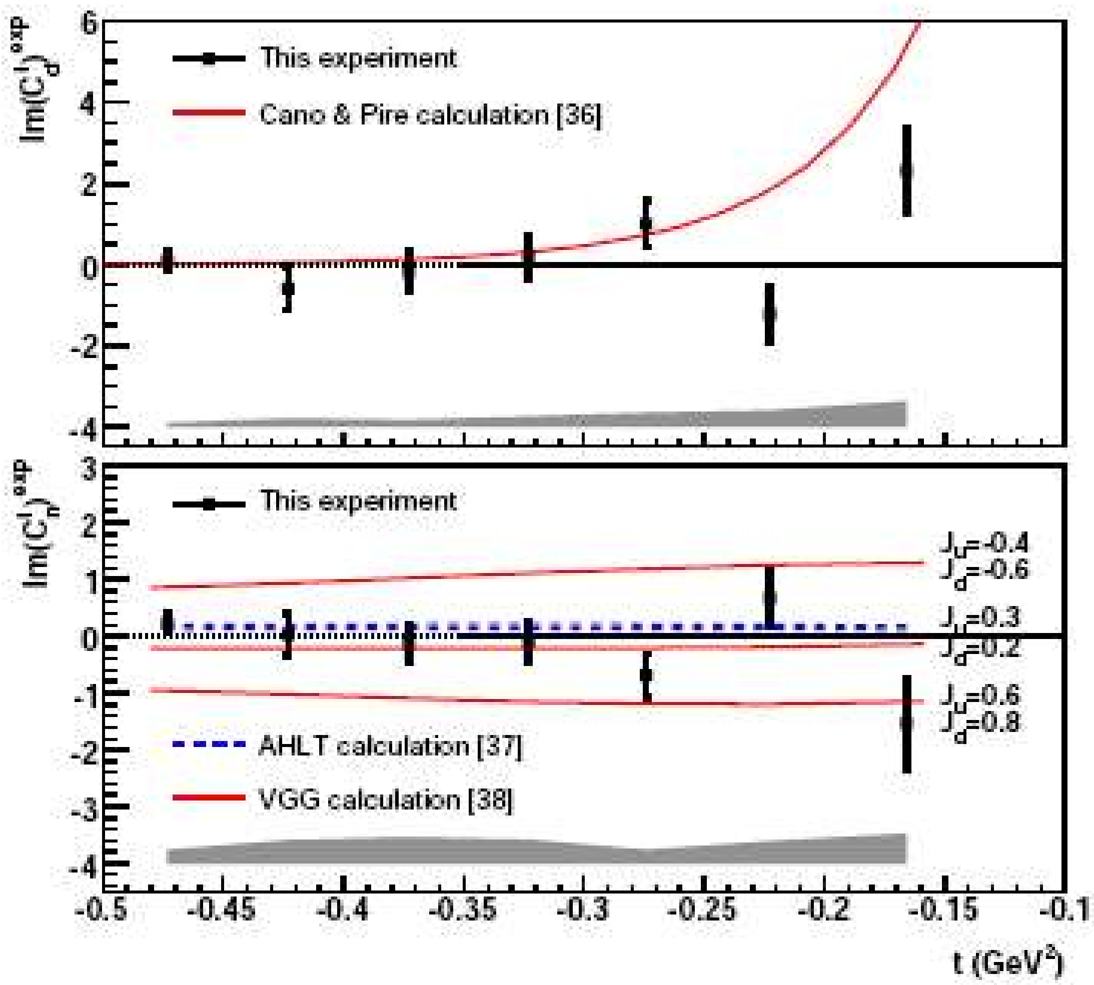
Behavior determined by Jlab data on Real Part and Q^2 dependence

Transversity



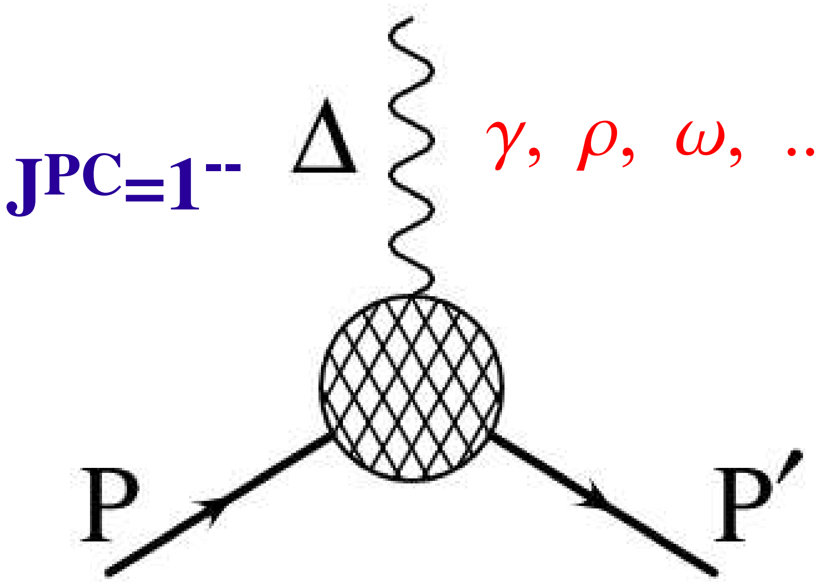
Comparison with Jlab Hall A data (neutron)

Mazouzet al., (2007)

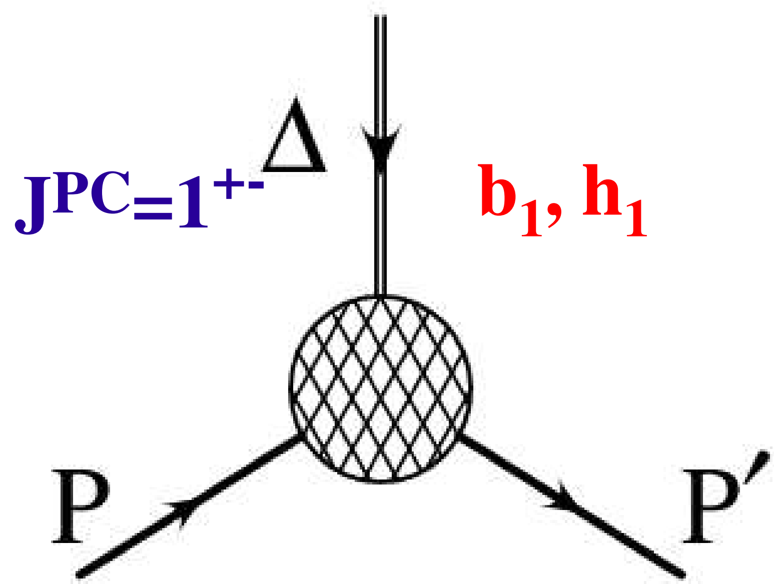


Conclusions and Outlook

- We presented a NEW method to extract transversity observables from <u>experimental data</u> on exclusive electroproduction experiments.
- We learn a number of interesting things along the way: physical interpretation of GPDs... (Partons $\Leftrightarrow$ Regge)!
  - GPDs other than what claimed so far appear in pion production (chiral-odd GPDs)
  - Factorization can apply in transverse case as well
  - Paper to be posted shortly, stay tuned..
- νA scattering at Minerva involves GPDs (Spin 0 nuclei!)
- Big part of the program for Jlab at 12 GeV!
- Crossed channels?



$J^{PC}=1^{--}$
Δ
γ, ρ, ω, ..
P
P′



$J^{PC}=1^{+-}$
Δ
b_1, h_1
P
P′