Hard Exclusive Reactions as Probes of Hadronic Deep Inelasic Structure

Simonetta Liuti
University of Virginia

INFN, Laboratori Nazionali di Frascati
July 14th, 2008

Collaborators:

Saeed Ahmad

Gary Goldstein

- AHLT (at the University of Virginia)

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

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* University of Iowa

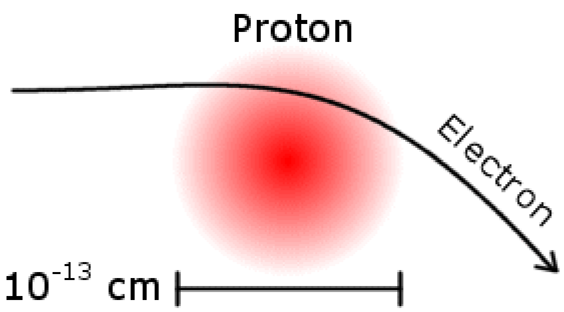
+ Stony Brook

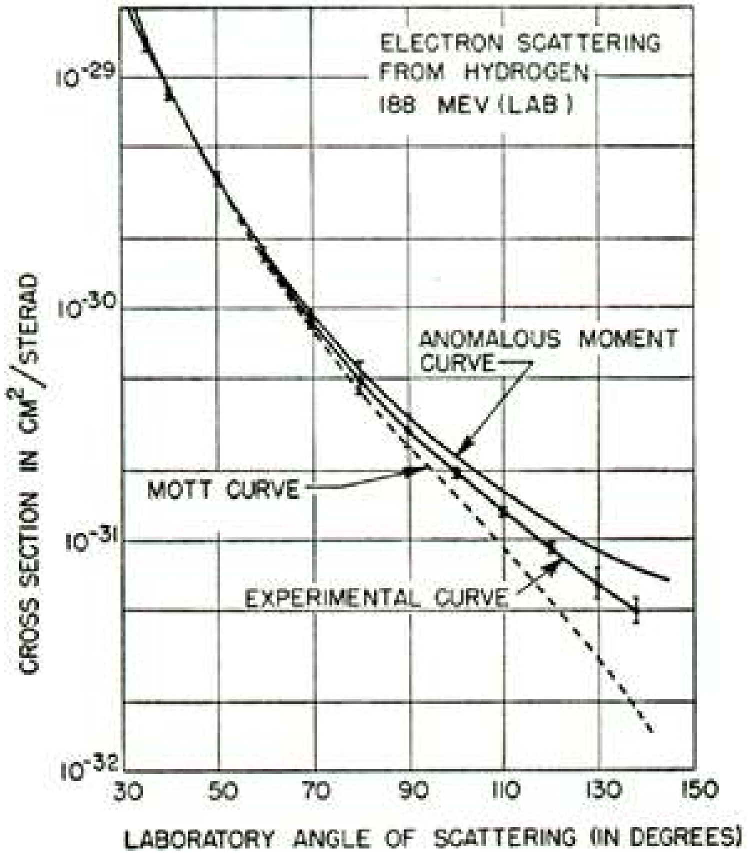
Outline

- An overview of the proton
- Outstanding Questions
- New experimental tools: Deeply virtual exclusive experiments and "femtoimages" (GPDs)
- Phenomenology:
  - DVCS Experiments on nucleons and nuclei
  - Exclusive π^0 Electroproduction
- New computational methods: SelfOrganizing Maps?
- Conclusions

What we know ...

- Charge radius:
  ≈ 0.86 fm



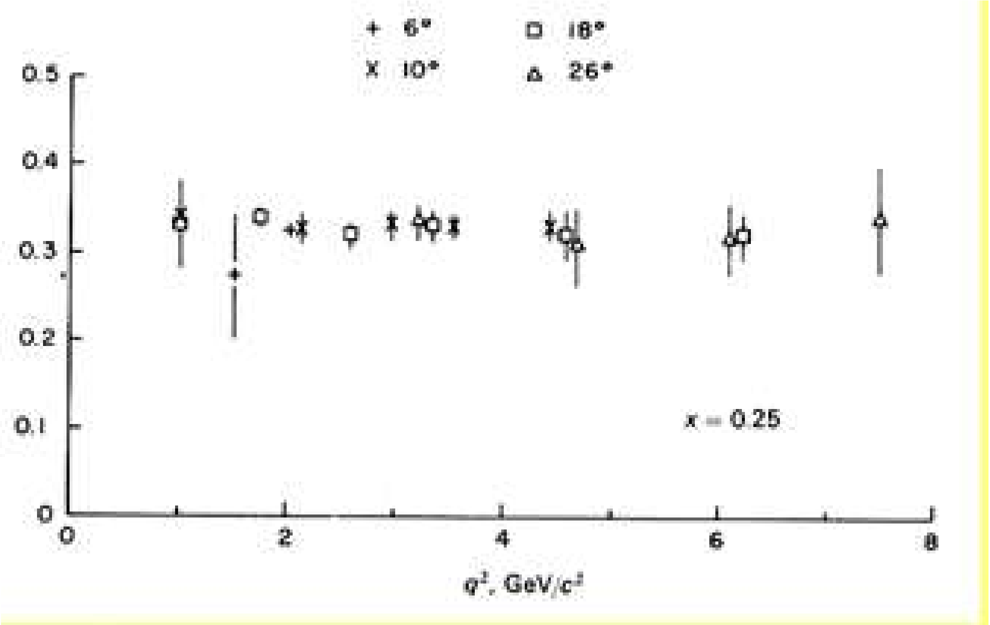


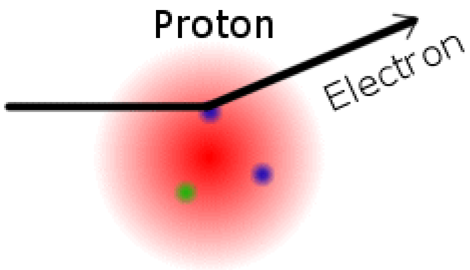
Measured by R. Hofstadter (1955)
Inclusive, elastic ep scattering!

What we know ...

- Proton is made of pointlike constituents:

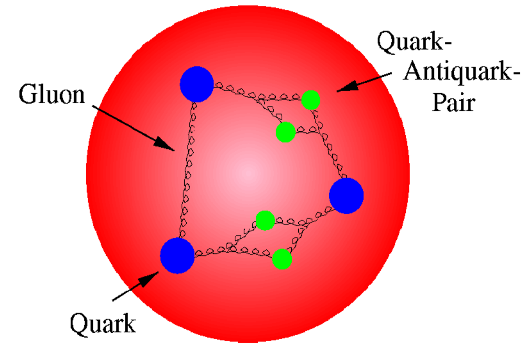
  → *"partons"*





Direct evidence observed by Friedman, Kendall and Taylor (1969): Inclusive, deep inelastic ep scattering!

Proton Dynamics: QCD

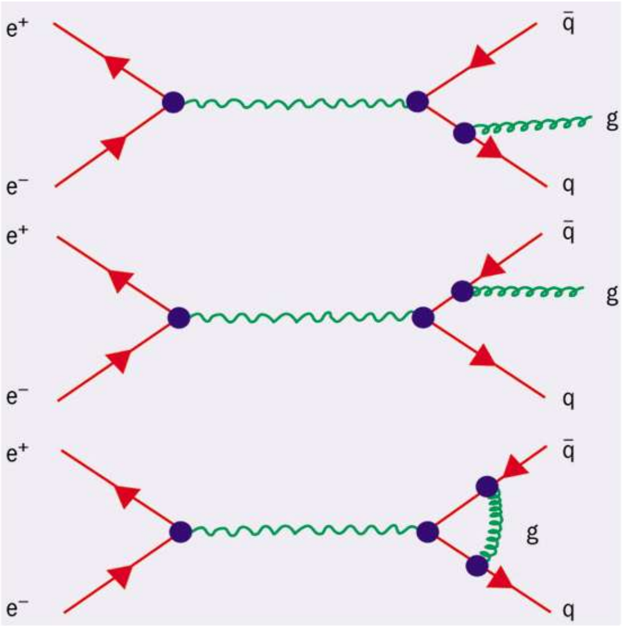


Quarks:

u,d,s,c,...; 3 colors; spin 1/2; $m_{u,d..} \ll m_p$

Gluons:

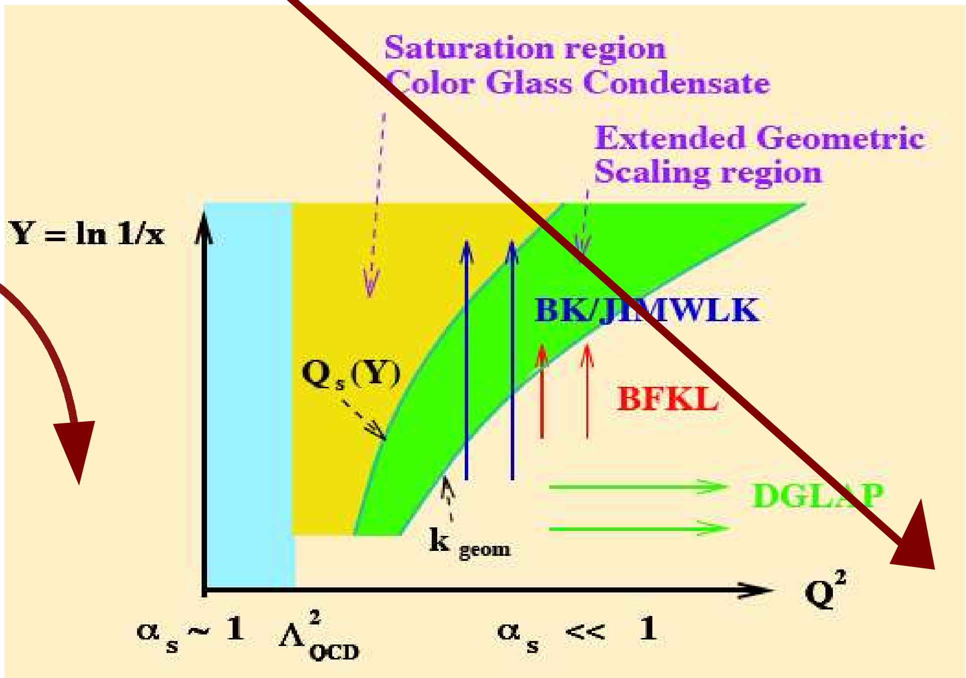
no charge; 8 “color types”; spin 1; $m_g = 0$



G. Wolf, P. Söding, S.L. Wu, B. Wiik (1979)

QCD: Asymptotic Freedom

- High energy/momentum transfer ⬌ Probe small distances
  "strong" coupling is "weak": perturbative QCD (DGLAP)
- Low momentum transfer ⬌ Low spatial resolution
  Relativistic, strongly coupled, many-body problem



How does one proceed? "A Flow Chart"

Theoretical tools:

- ⇒ Lattice QCD
- ⇒ EFT (Large N_c, χPT,..)
- ⇒ AdS/CFT

↓

Phenomenology

Devise observables and experimental probes

↓

Experiments: measure and compare with theory

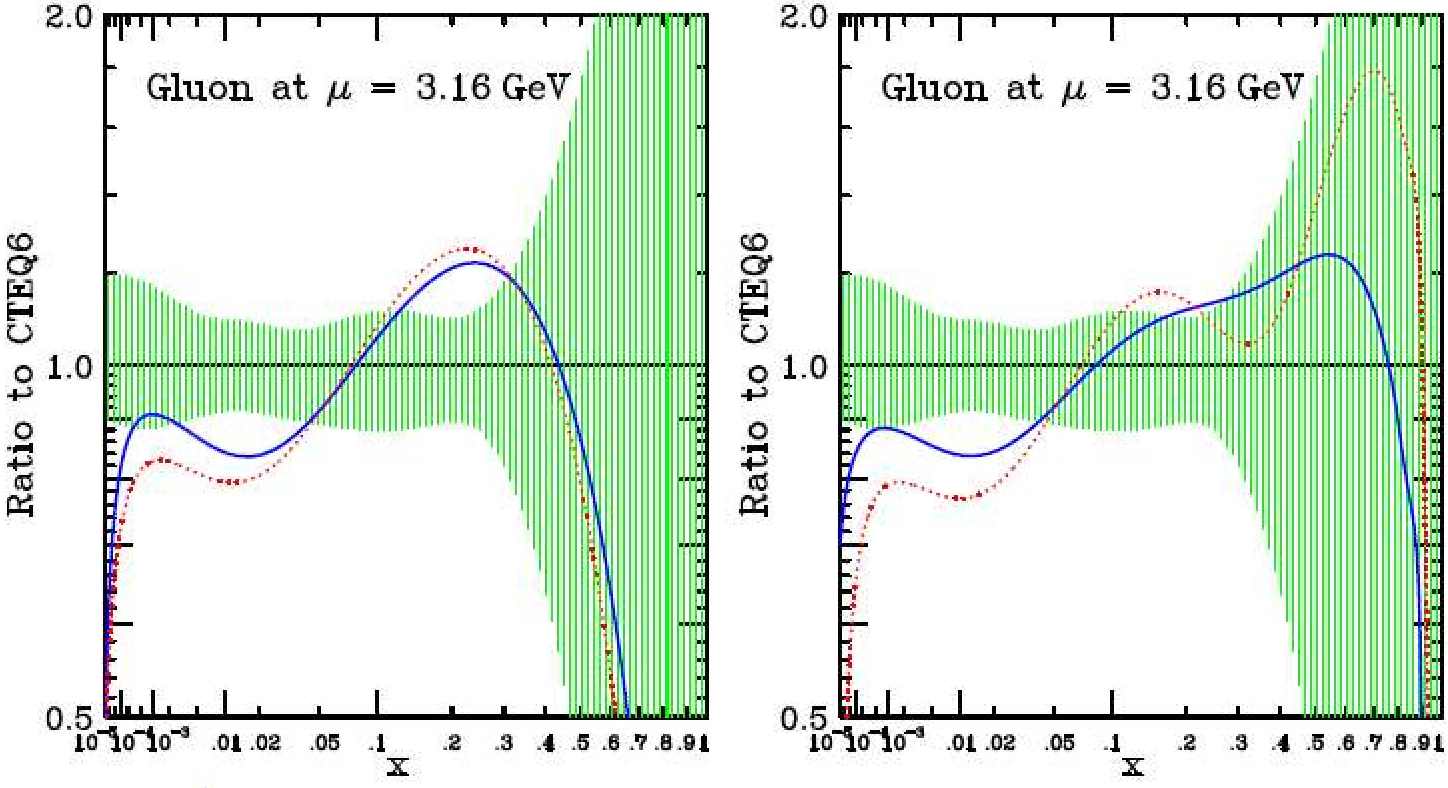
Validation

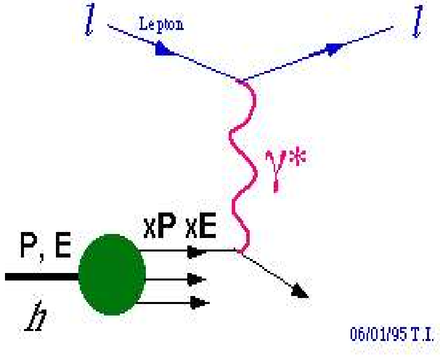
2. Outstanding Questions

Outstanding Questions arise through Validation

- What are the momentum distributions of quarks, anti-quarks and gluons ?
- How is the flavor symmetry broken ? $\overline{u} \neq \overline{d}, \quad s \neq \overline{s}$
- How do partons carry spin ½ of proton ?
- Longitudinal vs. transverse spin difference?
- Spatial distribution of quarks?
- Transition from partonic to hadronic d.o.f.: how are quarks and gluons correlated?
- How do protons and neutrons form atomic nuclei ?

Example 1: momentum distributions





Fundamental input for the LHC !

Example 2: Proton's Spin Structure

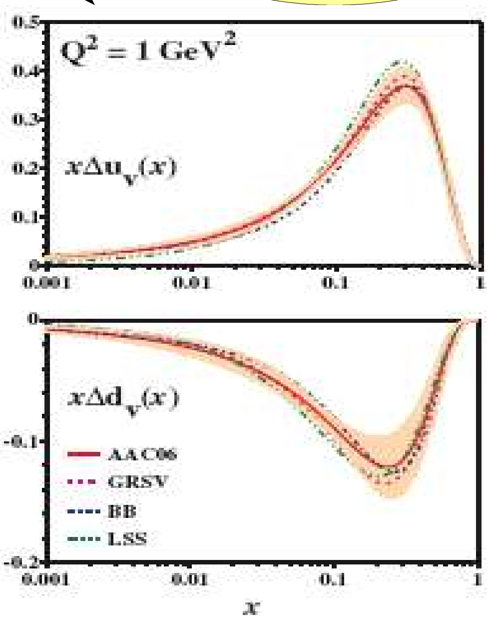
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

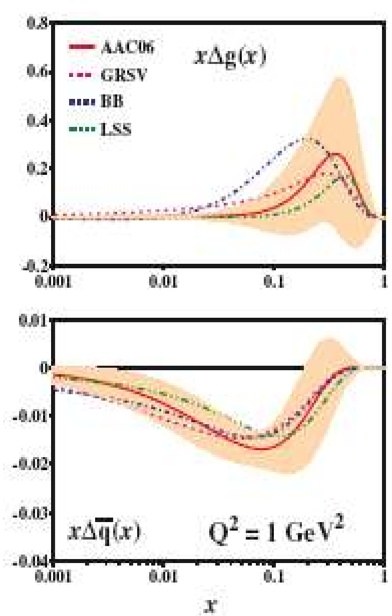
30 %

QUARKS SPIN

GLUONS SPIN

Q & G
ORBITAL ANGULAR MOM.





$\Delta g \approx 0$

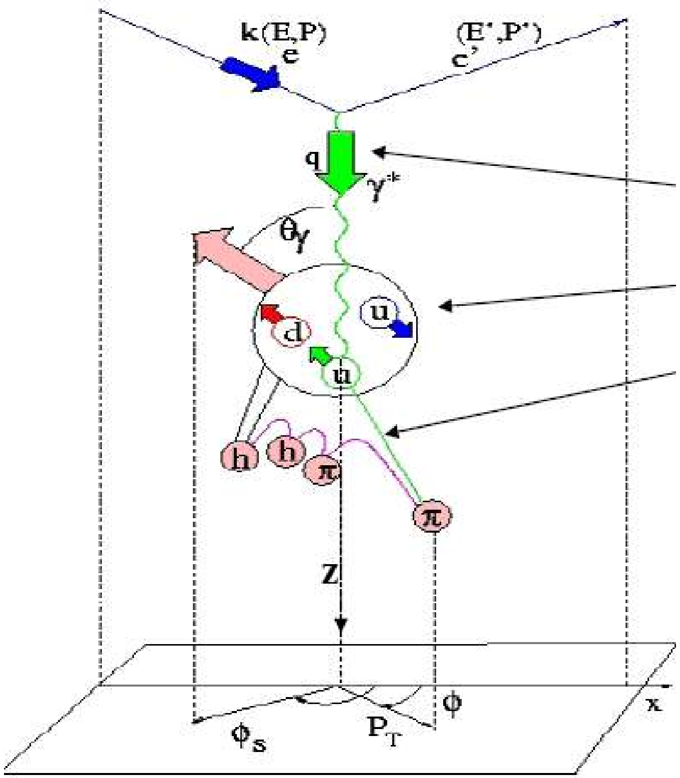
?

Hirai, Kumano, Saito, PRD 74(2006)

Proton Spin Crisis fostered searches for "different" observables

- Transversity (Goldstein & Moravscik, Jaffe, Ji, …)
- Orbital angular momentum (Ji, …)

"New type" of experiments: from inclusive to semi-inclusive …



Semi-inclusive DIS: Transversity

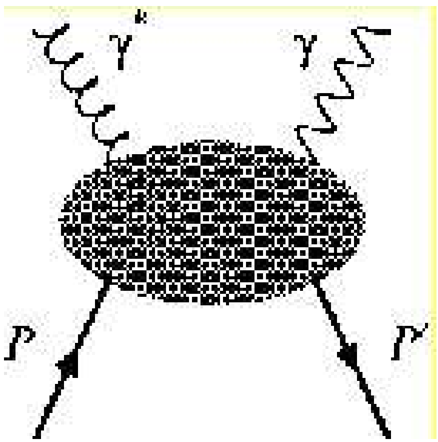
$$ep^{\uparrow} \rightarrow e'\pi X$$

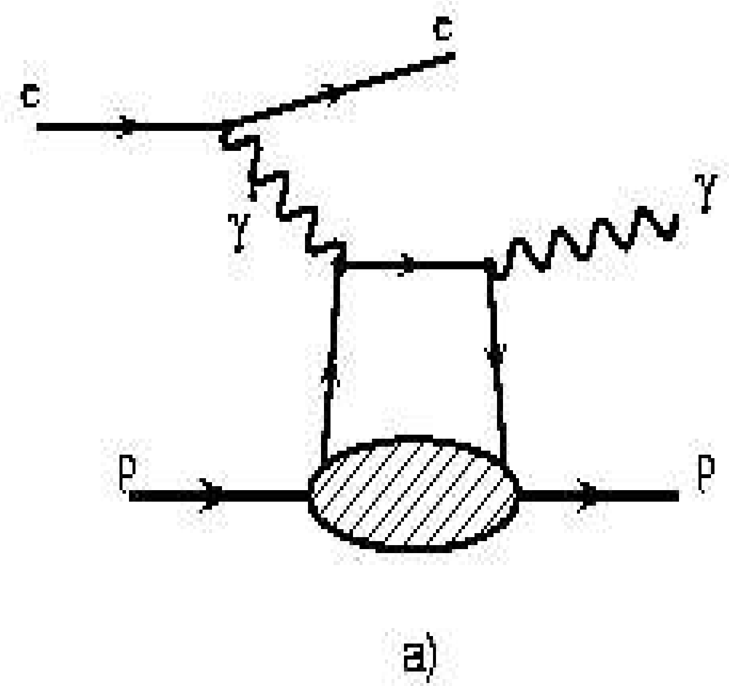
$$ep^{\uparrow} \rightarrow e'\Lambda' X$$

$$ep^{\uparrow} \rightarrow e'\pi\pi X$$

Observable = azymuthal dist. of pions

... and from semi-inclusive to exclusive ...





Virtual Compton Scattering

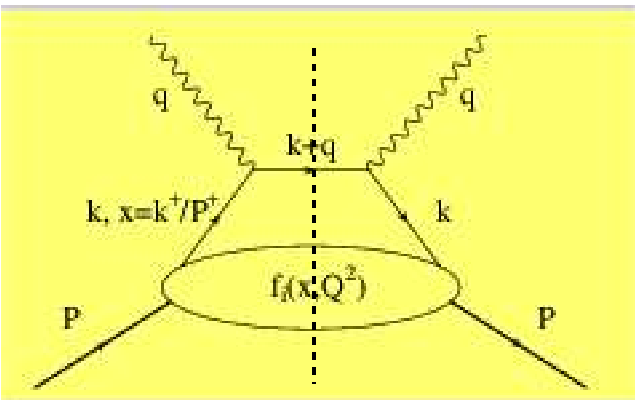
Deeply Virtual Compton Scattering

Bjorken limit

3. DVCS: new dimensions in proton studies

DVCS and Generalized Parton Distributions 1

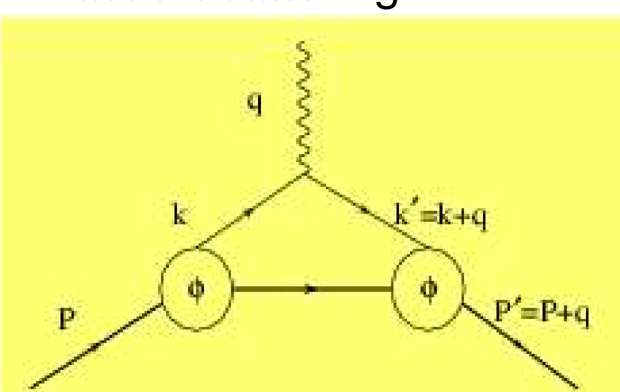
Deep inelastic Scattering



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

Extract Parton Distribution

Elastic Scattering



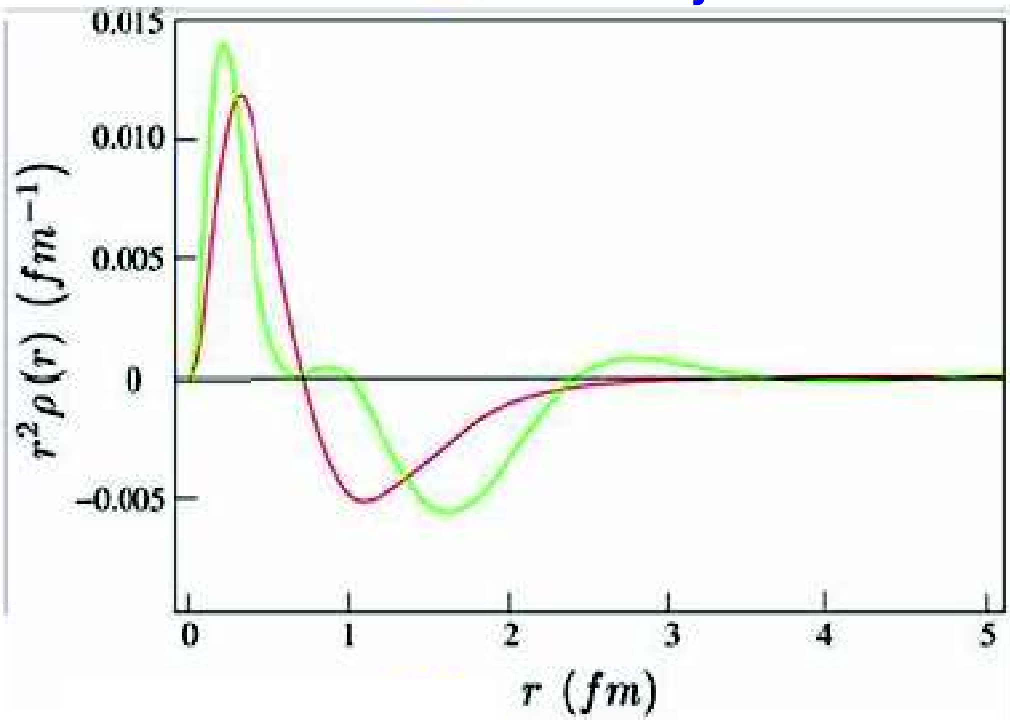
Extract Form Factors

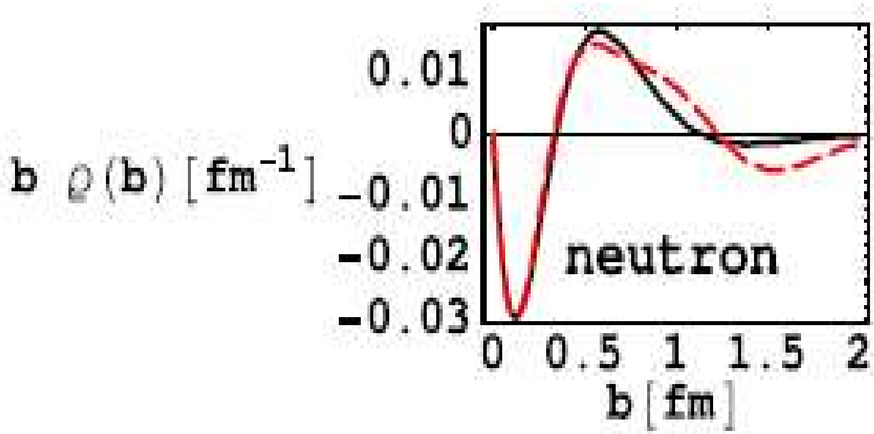
$$\langle P',S' \mid \psi(0)\gamma^+\psi(0) \mid P,S\rangle = \bar{u}(P',S')\left[\gamma^+ F_1(Q^2) + \frac{i\sigma^{+\nu}q_\nu}{2M}F_2(Q^2)\right]u(P,S)$$

DVCS and Generalized Parton Distributions 2

Breit Frame interpretation of the form factor (Sachs):

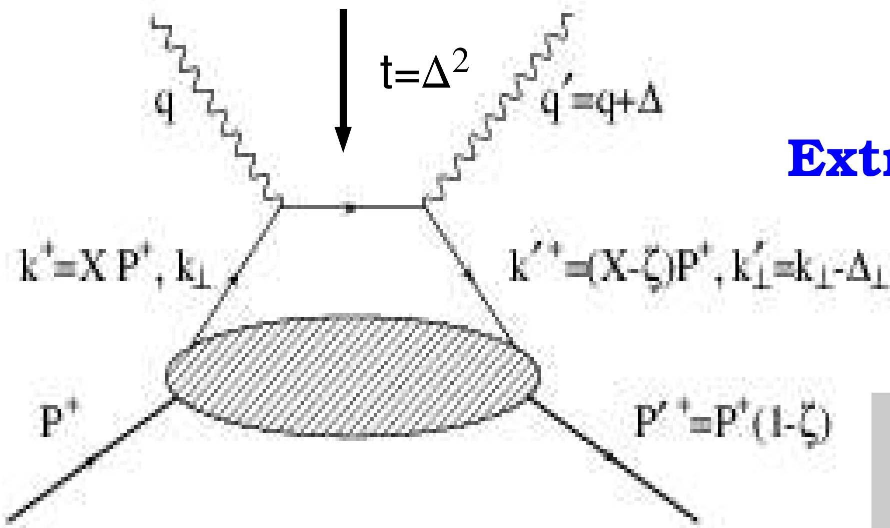
neutron density dist.





G. Miller, nucl-th, 0705.2409

DVCS and Generalized Parton Distributions 3



Extract "Generalized Parton Distributions"

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

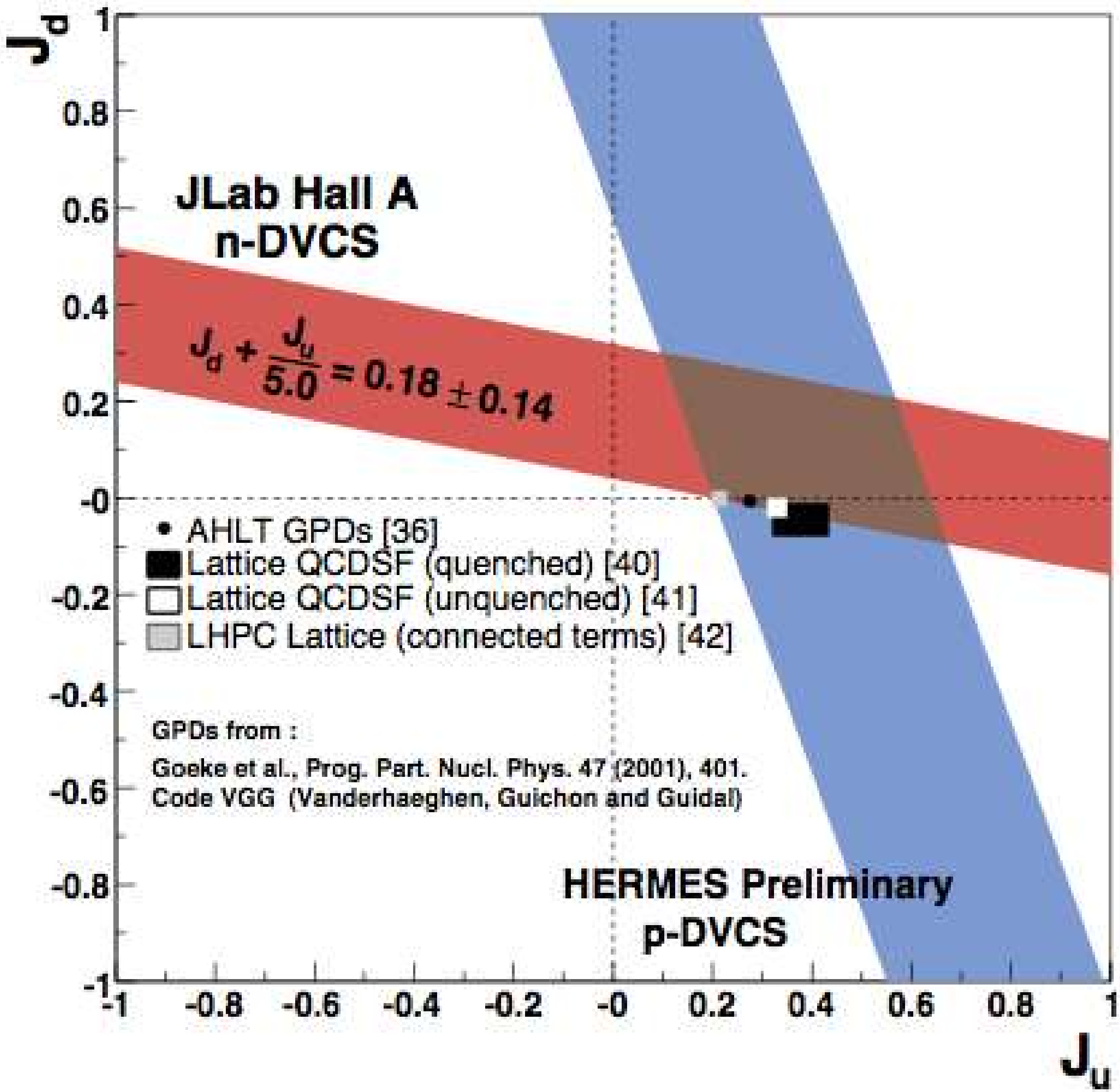
$$\bar{u}(P',S') \left[\gamma^+ H(x,\xi,-\Delta^2) + \frac{i\sigma^{+\nu}q_\nu}{2M} E(x,\xi,-\Delta^2) \right] u(P,S)$$

- **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!**

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

X. Ji

Orbital Angular Momentum (Camacho et al., PRL(2007))



AHLT includes only valence contribution!

$$J_q = (\kappa_q + 1) A_{20}(0)$$

DVCS and Generalized Parton Distributions 4: Optics

Question #1: How do we interpret the spatial d.o.f. of partons?

Theoretical Ideas:

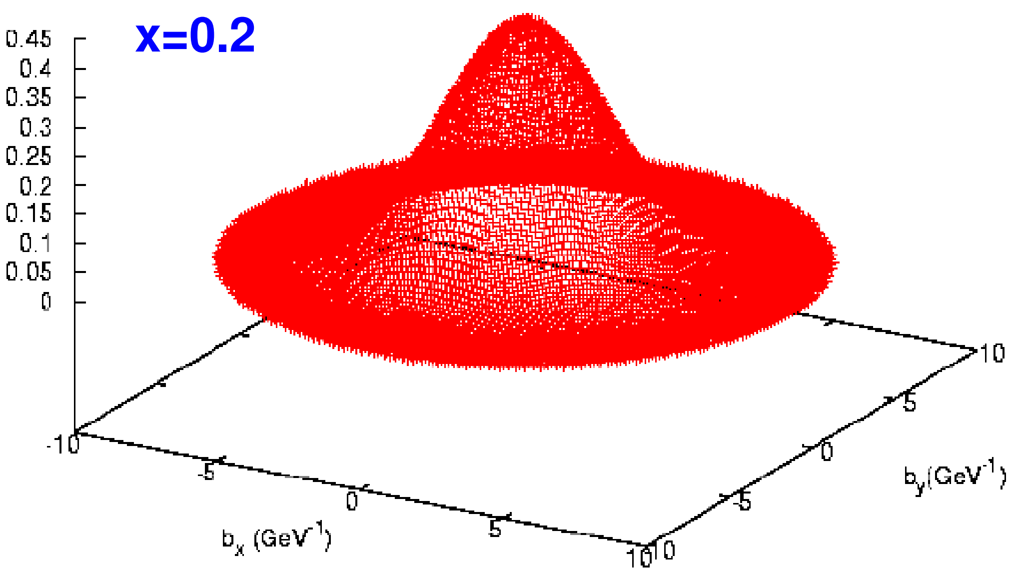
- Impact parameter dependent PDFs (M. Burkardt, 2000 ↔ D. Soper, 1977)
- Holography (Ralston and Pire, 2000)
- Interference patterns (Brodsky et al., 2006)
- Wigner Distributions (Belitsky, Ji, Yuan, 2004)

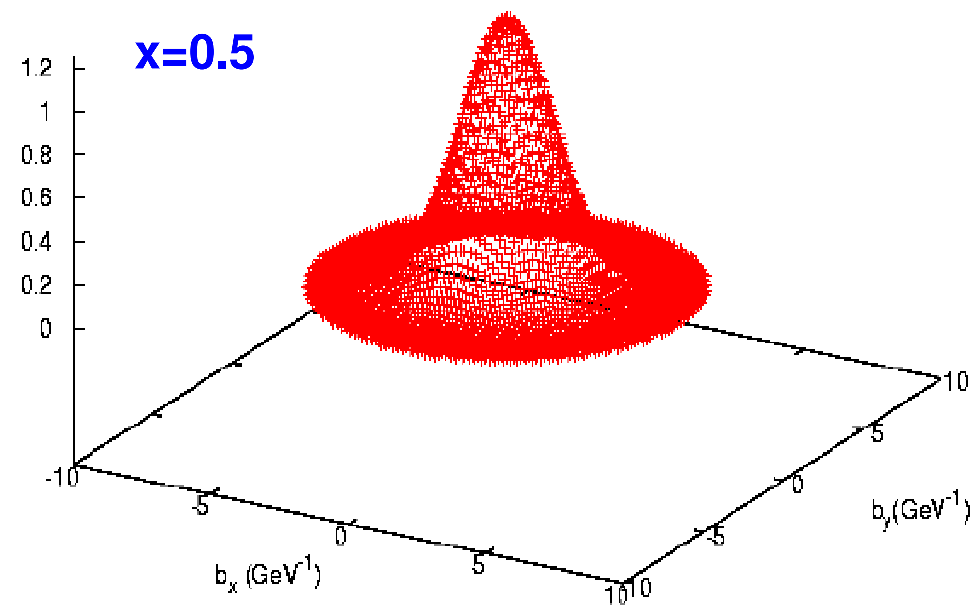
DVCS and Generalized Parton Distributions 5: IPPDFs

$\zeta = 0$

$$q(x,\mathbf{b}) = \int \frac{d^2\mathbf{\Delta}}{(2\pi)^2} e^{-i\mathbf{b}\cdot\mathbf{\Delta}} H_q(x,0,-\mathbf{\Delta}^2)$$

$$\langle \mathbf{b}^2(x) \rangle = \mathcal{N}_b \int d^2\mathbf{b}\, q(x,\mathbf{b})\, \mathbf{b}^2$$





H_q (x,t) from Ahmad, Honkanen, S.L., Taneja (2006)

DVCS and GPDs 6: Wigner Distributions

$\zeta \neq 0$

"Quantum Phase-Space" distributions (Wigner, 1932): f(**p**,**r**)

Not positive-definite because of uncertainty principle

Become positive in classical limit

Vast literature – observable (!) in atomic systems

How do we generalize to relativistic systems/physics on the light-cone?

Belitsky, Ji, Yuan: **Breit Frame**

$$\rho_+(\vec{r},x) = \int \frac{d^3\vec{q}}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} [H(x,\xi,t) - \tau E(x,\xi,t)]$$

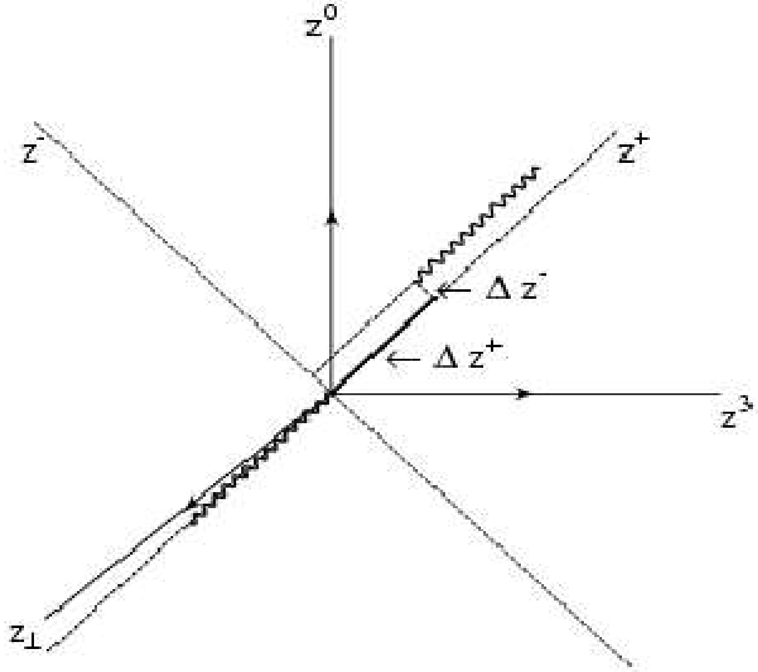
Phase-space Charge Density

$$j_+^z(\vec{r},x) = \int \frac{d^3\vec{q}}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} i[\vec{s}\times\vec{q}]^z \frac{1}{2M_N} [H(x,\xi,t) + E(x,\xi,t)]$$

Phase-space Convection Current

But: … "Ioffe time"

Deeply Virtual Compton Scattering in Coordinate Space



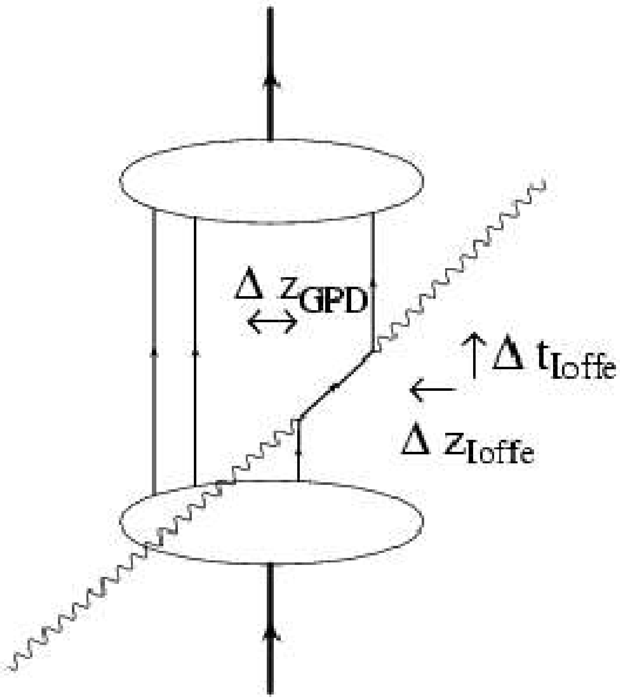
- Probe is local in $\perp$ direction:

  $$\Delta z_\perp \approx 1/\sqrt{Q^2}$$

- *Non-local* in $||$ direction:

  $$\Delta z^+ \approx 1/M_N x_{Bj}$$

Longitudinal variables



quark's *mobility* *(P. Hoyer)*

$$(\Delta z + \Delta t)_{\rm Ioffe} \equiv \Delta z^+$$

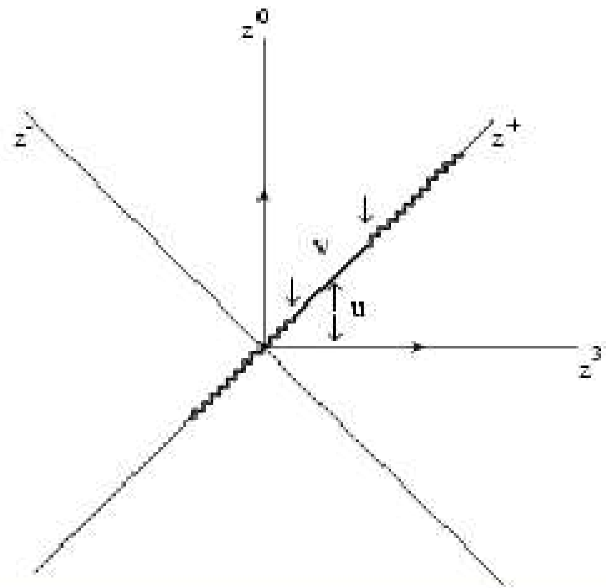
$$\Downarrow$$

We are aware of large Δz^+ only through the observation of nuclear shadowing

$\Rightarrow$ Study the interplay between Δz^+ and Δz_{GPD} in nuclei

Correlation Function in Coordinate Space

(work in progress...)



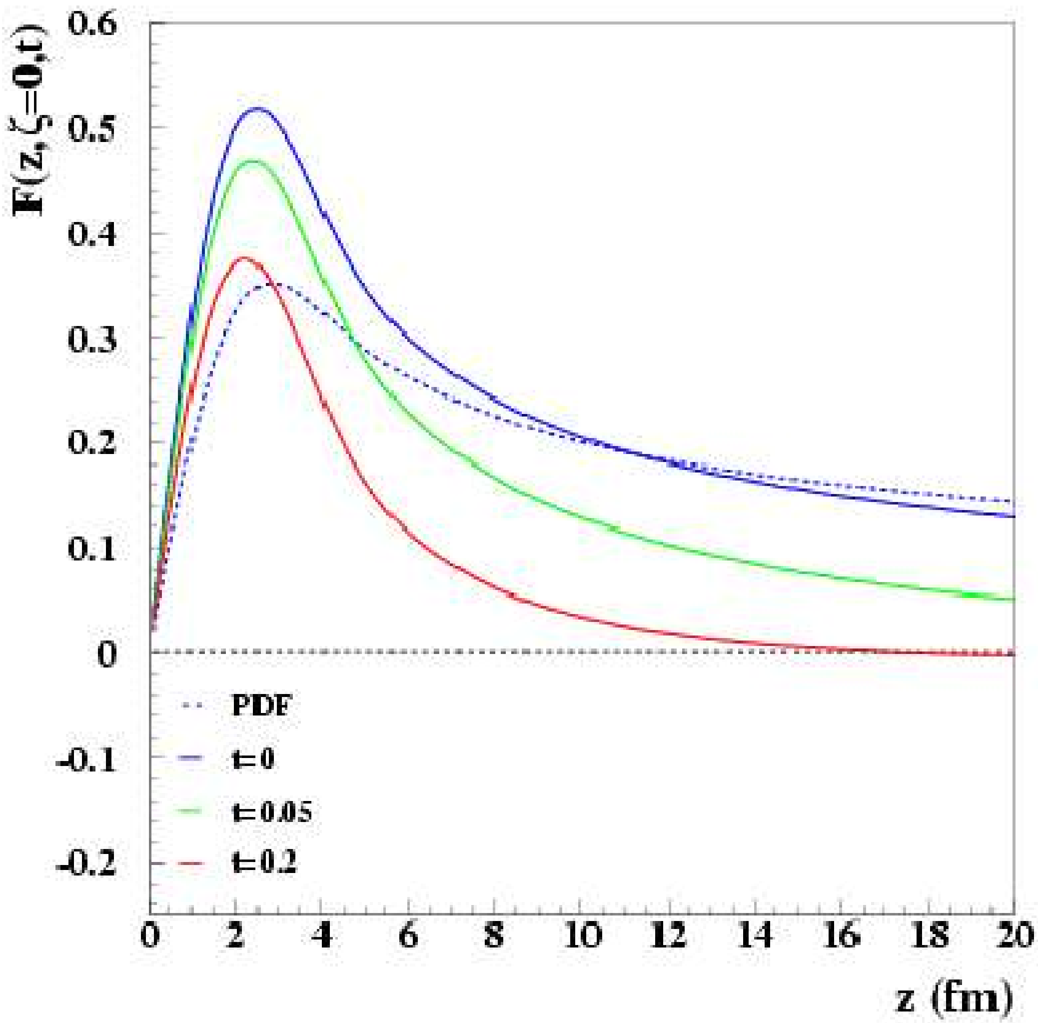
$$\langle P' \mid \overline{\Psi}\left(\frac{u+v}{2}z\right)\hat{z}\,\Psi\left(\frac{u-v}{2}z\right)\mid P\rangle_{z^2=0} = \overline{U}(P')\,\hat{z}\,U(P)\int d\zeta\, e^{iu\frac{\zeta}{2}(Pz)}F(vz,\zeta,t)$$

$$F(vz,\zeta,t) = \int dX\, H(X,\zeta,t)e^{ivX(Pz)}$$

$$\zeta = (\Delta z)/(Pz)$$

$$X = (kz)/(Pz)$$

Generalized Ioffe Time Distribution



S. Ahmad and S.L., preliminary

DVCS Cross Section

$$\frac{d^5\sigma(\lambda,\pm e)}{d^5\Phi} = \frac{d\sigma_0}{dQ^2 dx_B}\left|\mathcal{T}^{BH}(\lambda) \pm \mathcal{T}^{DVCS}(\lambda)\right|^2 / |e|^6$$

$$= \frac{d\sigma_0}{dQ^2 dx_B}\left[\left|\mathcal{T}^{BH}(\lambda)\right|^2 + \left|\mathcal{T}^{DVCS}(\lambda)\right|^2 \mp \mathcal{I}(\lambda)\right]\frac{1}{e^6}$$

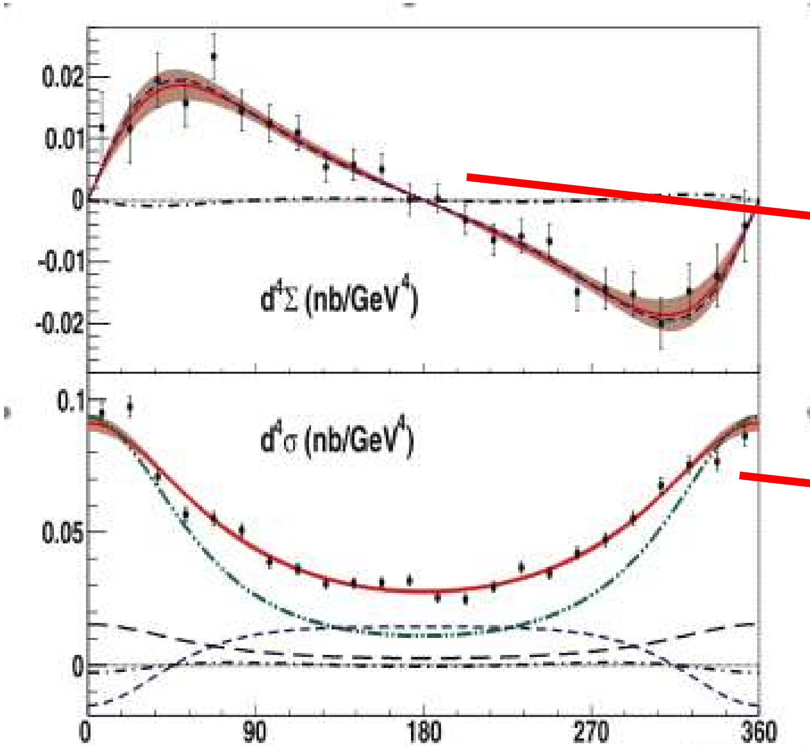
$$\frac{d^4\Sigma}{dQ^2 dx_{Bj} dt d\phi} \equiv \frac{d^4\sigma^+}{dQ^2 dx_{Bj} dt d\phi} - \frac{d^4\sigma^-}{dQ^2 dx_{Bj} dt d\phi} \propto \Im m\mathcal{H}$$

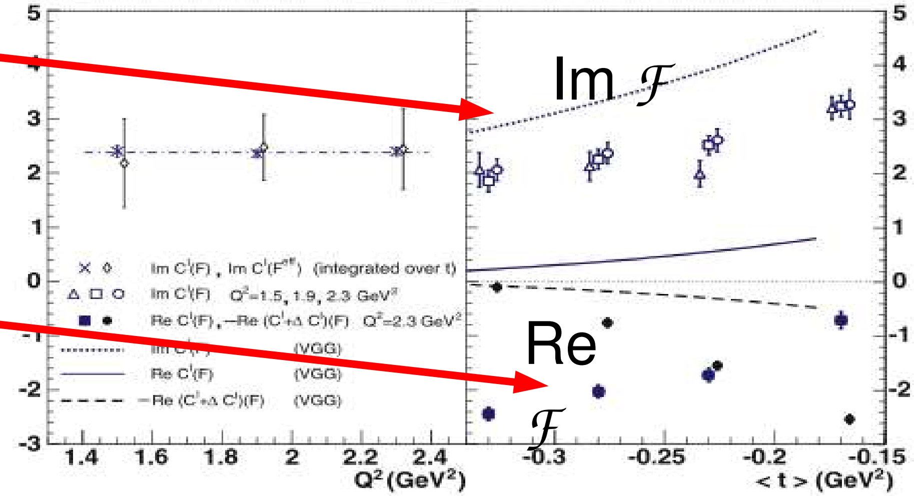
$$\frac{d^4\sigma}{dQ^2 dx_{Bj} dt d\phi} \equiv \frac{d^4\sigma^+}{dQ^2 dx_{Bj} dt d\phi} + \frac{d^4\sigma^-}{dQ^2 dx_{Bj} dt d\phi} \propto \Re e\mathcal{H}$$

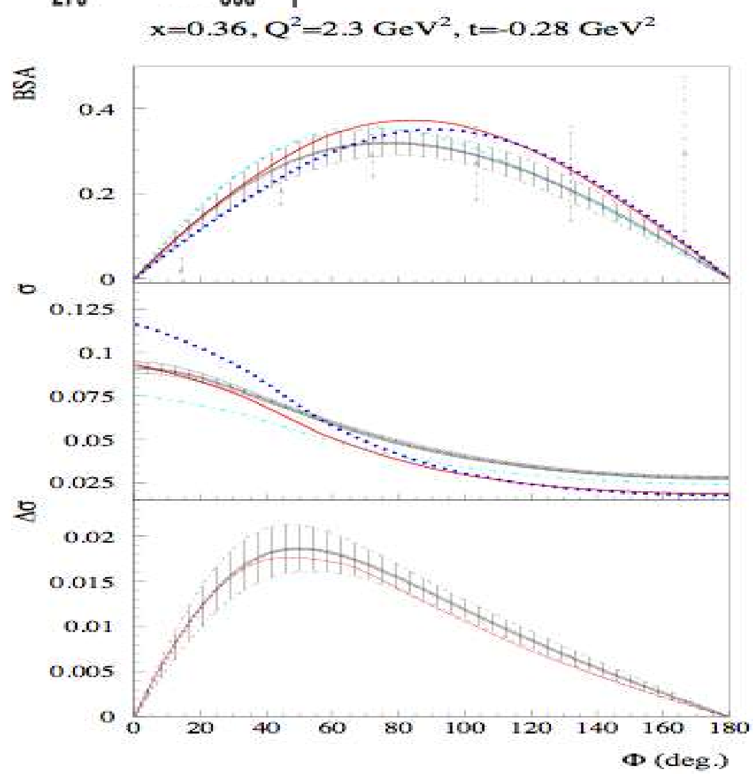
$$\mathcal{F}(\zeta,t) = -i\pi\sum_q e_q^2\left[F^q(\zeta,\zeta,t) - F^q(-\zeta,\zeta,t)\right] +$$

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

VGG Crisis: Cannot reproduce both!







Guidal (2008)

Polyakov and Vanderhaeghen (2008)

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" ← $R(X,t)$

Quark-Diquark ← $G(X,t)$

Q^2 Evolution is an essential element!!

Reaching a more advanced phase of extracting GPDs from data

(a bit of summary from ECT, June'08)*

- No longer simple models (D. Muller)
- Include Q^2 dependence (M. Diehl)
- Include all constraints from data DVCS, DVMP… (S.L.)
- Include new data as they become available… (S.L.)
- Use Lattice + Chiral Extrapolations (P. Hägler, A. Schaefer)
- Connect various experiments, separate valence from sea, flavors separation (T. Feldman)…
- New! Representation in terms of *dispersion relation* only necessary to measure imaginary part? Stronger polynomiality constraint (M. Diehl and Yu. Ivanov)

A similar program exists for TMDs (simpler partonic interpretation than GPDs) see M. Anselmino and collaborators

4. Extracting femtoimages requires new computational methods

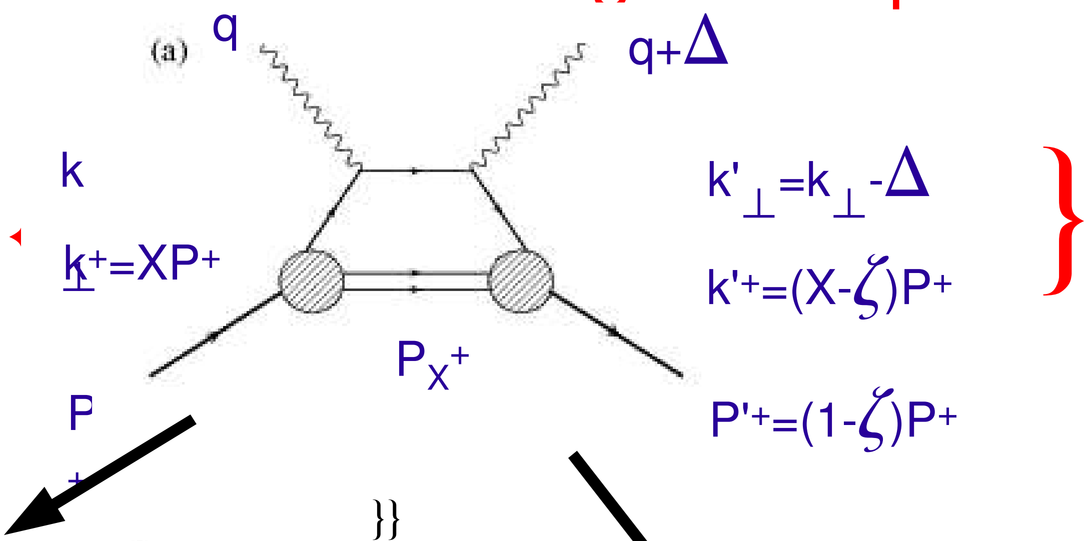
Proposed Strategy: Bottom-Up Approach

- Construct theoretically motivated parametrizations at a given *low* initial scale

- Merge data/information from:
  - Form factors $\zeta=0$
  - PDFs $\zeta=0$
  - Higher GPD moments (lattice calculations) $\zeta\neq0$
  - DVCS data $\zeta\neq0$

- Apply PQCD evolution to connect different sets of data

For ζ= 0 and in the DGLAP region ⇒ partonic picture



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

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

AHLT Parameterization

ζ=0

v1

$$H^I(X,t) = G_{M_X^I}^{\lambda^I}(X,t)\, X^{-\alpha^I - \beta_1^I (1-X)^{p_1^I} t}$$

$$E^I(X,t) = \kappa\, G_{M_X^I}^{\lambda^I}(X,t)\, X^{-\alpha^I - \beta_2^I (1-X)^{p_2^I} t}$$

7 + 1 (Q_o) parameters

v2

$$H^{II}(X,t) = G_{M_X^{II}}^{\lambda^{II}}(X,t)\, X^{-\alpha^{II} - \beta_1^{II} (1-X)^{p_1^{II}} t}$$

$$E^{II}(X,t) = G_{\widetilde{M}_X^{II}}^{\widetilde{\lambda}^{II}}(X,t)\, X^{-\widetilde{\alpha}^{II} - \beta_2^{II} (1-X)^{p_2^{II}} t}$$

10 + 1 (Q_o) parameters

$\zeta \neq 0$ $\Rightarrow$ **use v1 for DGLAP region (X > ζ)**

$$H^I(X,\zeta,t) = G_{M_X^I}^{\lambda^I}(X,\zeta,t)\, R_1^I(X,\zeta,t)$$

$$E^I(X,\zeta,t) = \kappa\, G_{M_X^I}^{\lambda^I}(X,\zeta,t)\, R_2^I(X,\zeta,t)$$

More details in AHLT, PRD 2007

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

Constraints from Polynomiality

$$H_n^q(\xi,t) = \sum_{i=0}^{\frac{n-1}{2}} A_{n,2i}^q(t)\xi^{2i} + \mathrm{mod}(n,2)\xi^n C_n^q(t)$$

$$E_n^q(\zeta,t) = \sum_{i=0}^{\frac{n-1}{2}} B_{n,2i}^q(t)\xi^{2i} - \mathrm{mod}(n,2)\xi^n C_n^q(t).$$

Constraints from PDFs

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

Further Theoretical Constraints:

- Sensible prediction for hadron shape at $x \to 1$
- Sensible prediction for k_T dependence (connection with TMDs!)

(SL and Taneja, 2004)

GPDs from available data 2

Parton Distribution Functions

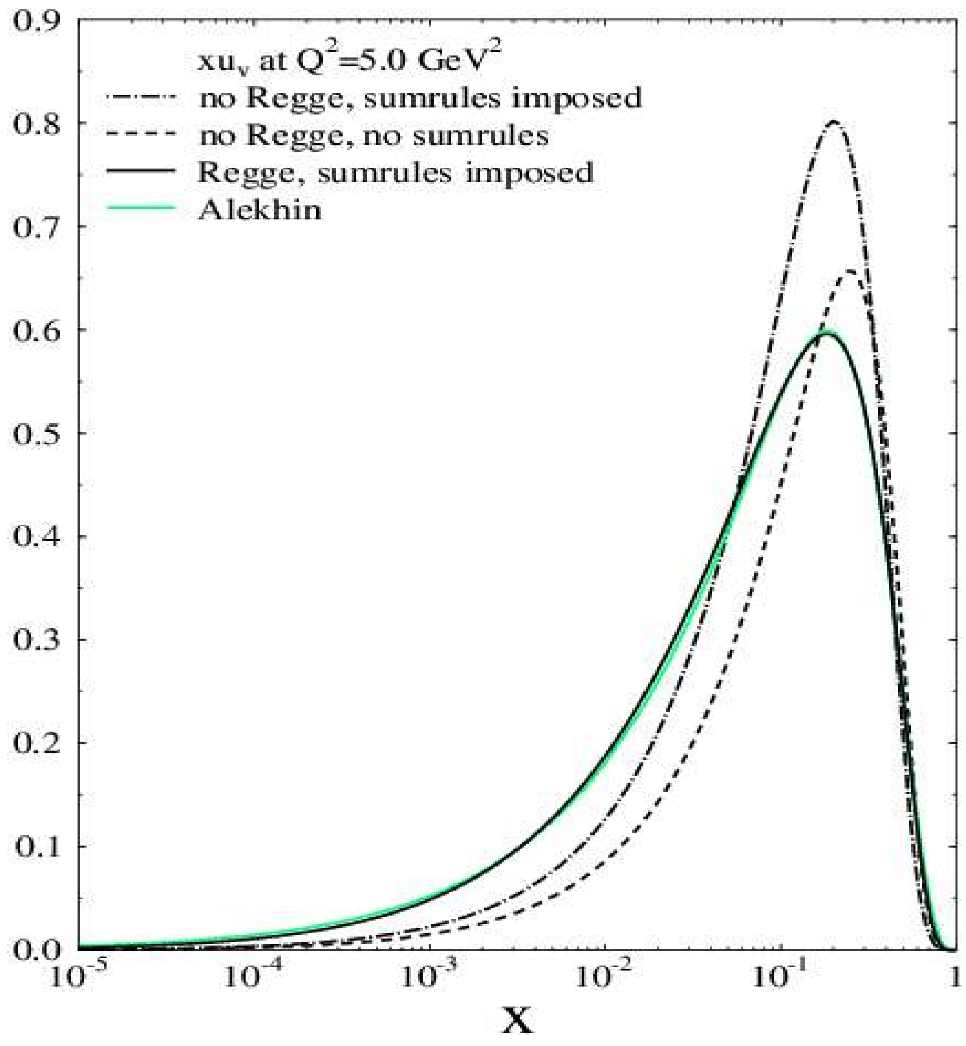
Notice! **GPD parametric form is given at $Q^2=\mu^2$ and evolved to Q^2 of data.**

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

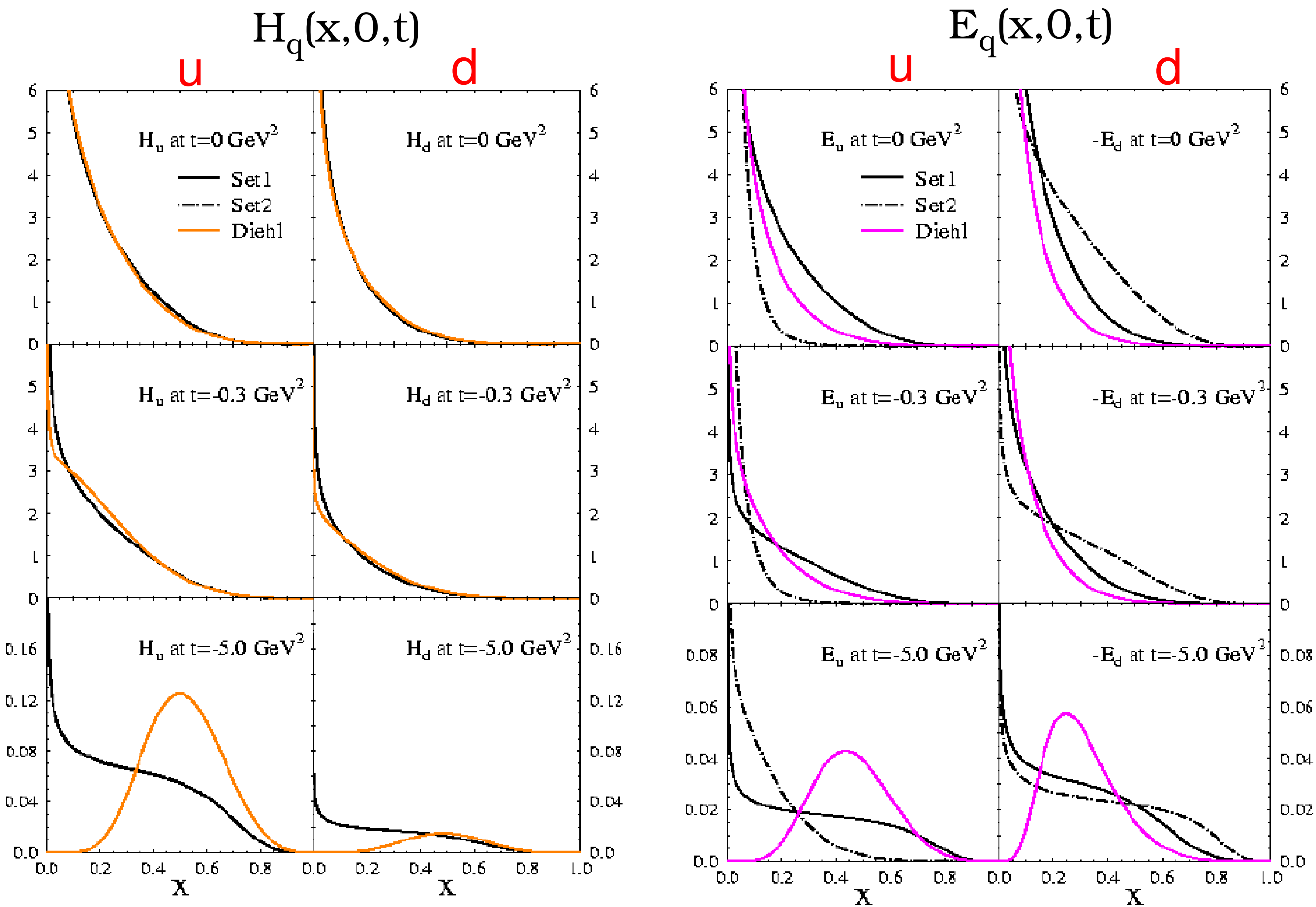
$$H_q(X,t) = R(X,t)\, G(X,t)$$

Regge

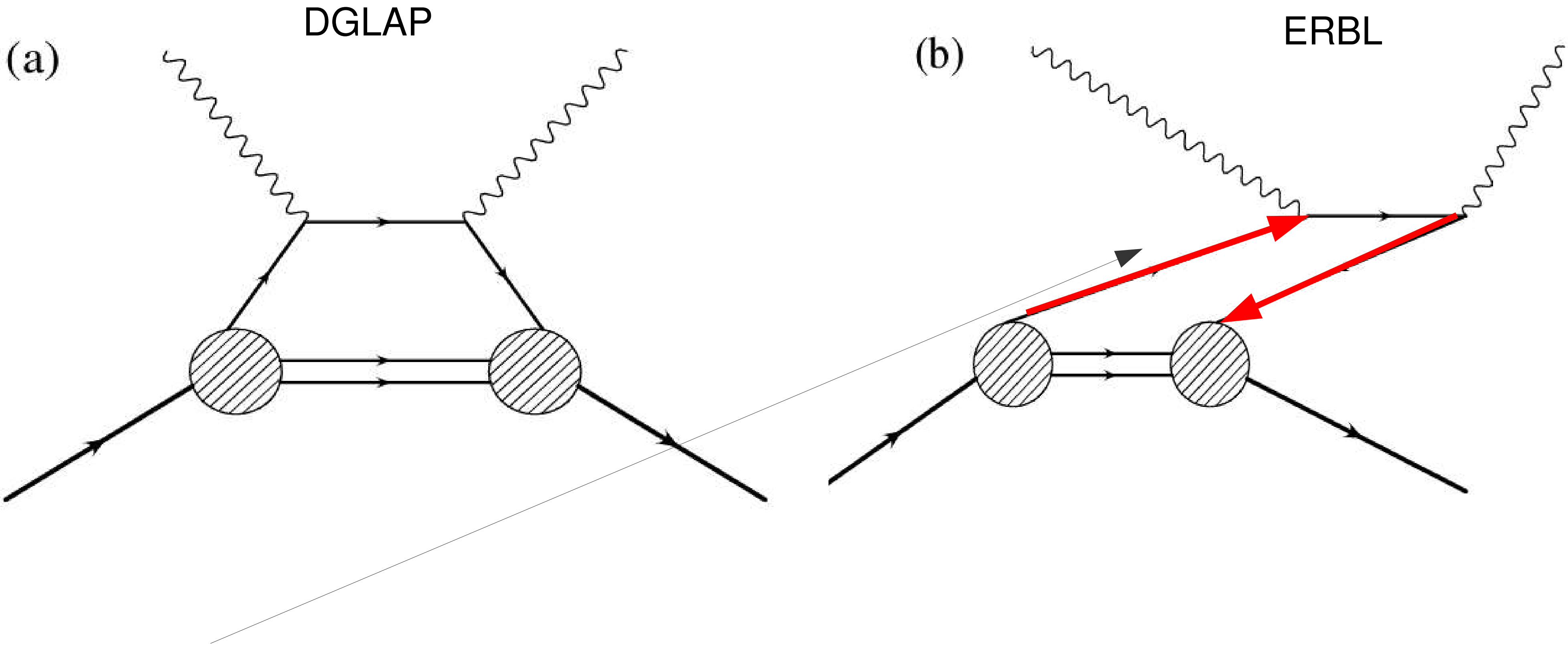
Quark-Diquark



Comparison with similar parametrizations at ξ=0

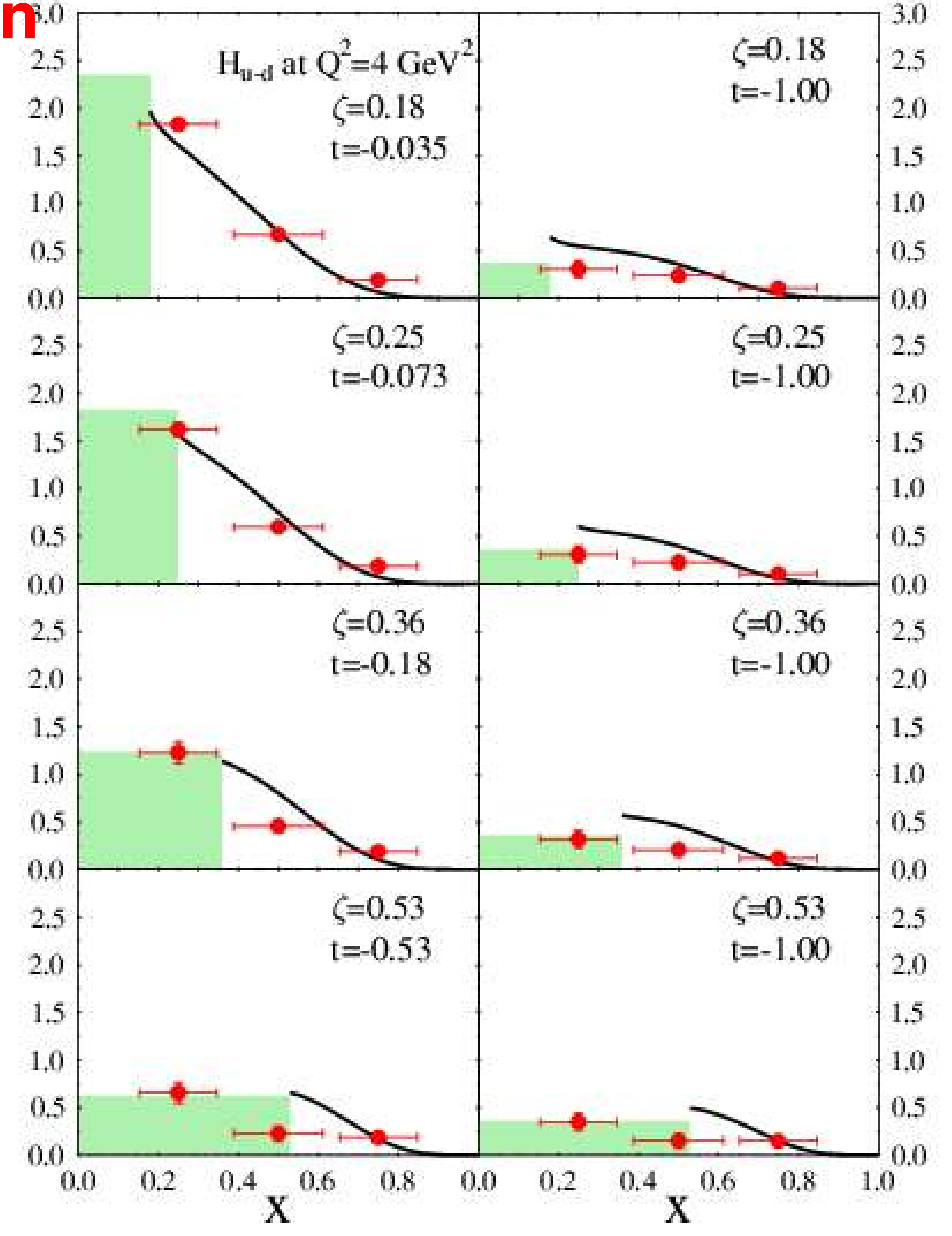


Two different time orderings/pole structure!



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

ERBL Region



H_{u-d} at Q^2=4 GeV^2
ζ=0.18
t=-0.035
ζ=0.18
t=-1.00
ζ=0.25
t=-0.073
ζ=0.25
t=-1.00
ζ=0.36
t=-0.18
ζ=0.36
t=-1.00
ζ=0.53
t=-0.53
ζ=0.53
t=-1.00
X
X

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

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

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

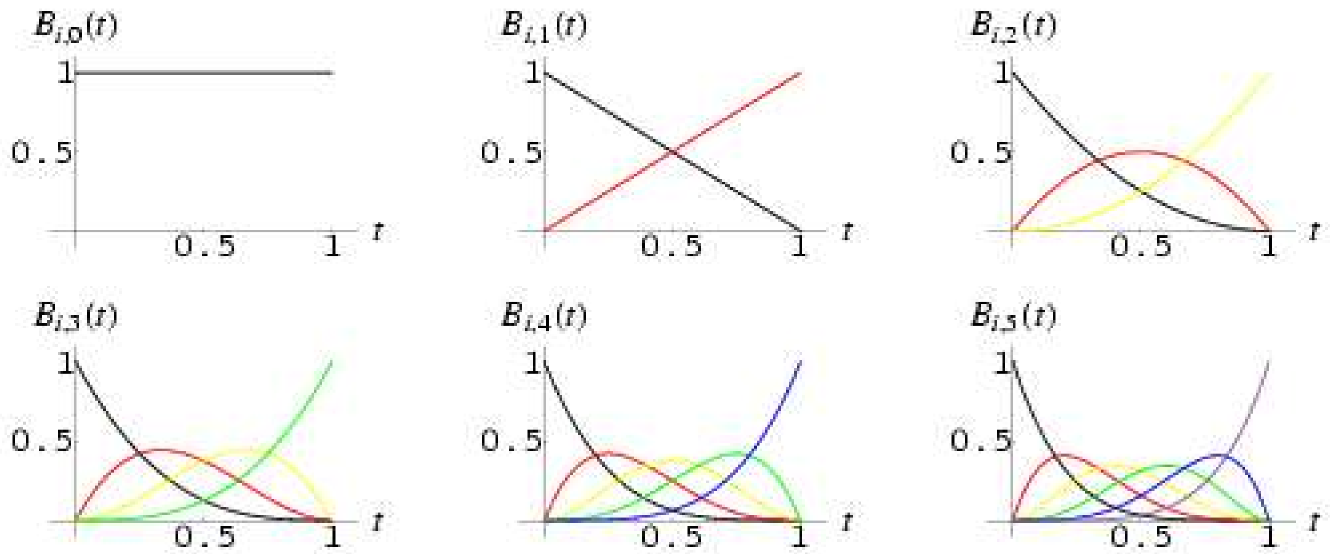
$$\overline{H}_{22}(X_{22}) = 3A_{30} + \left[\left(\frac{2\zeta}{2-\zeta}\right)^2 A_{32}\right].$$

First used for pdfs' in the '70s by Yndurain and collaborators

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

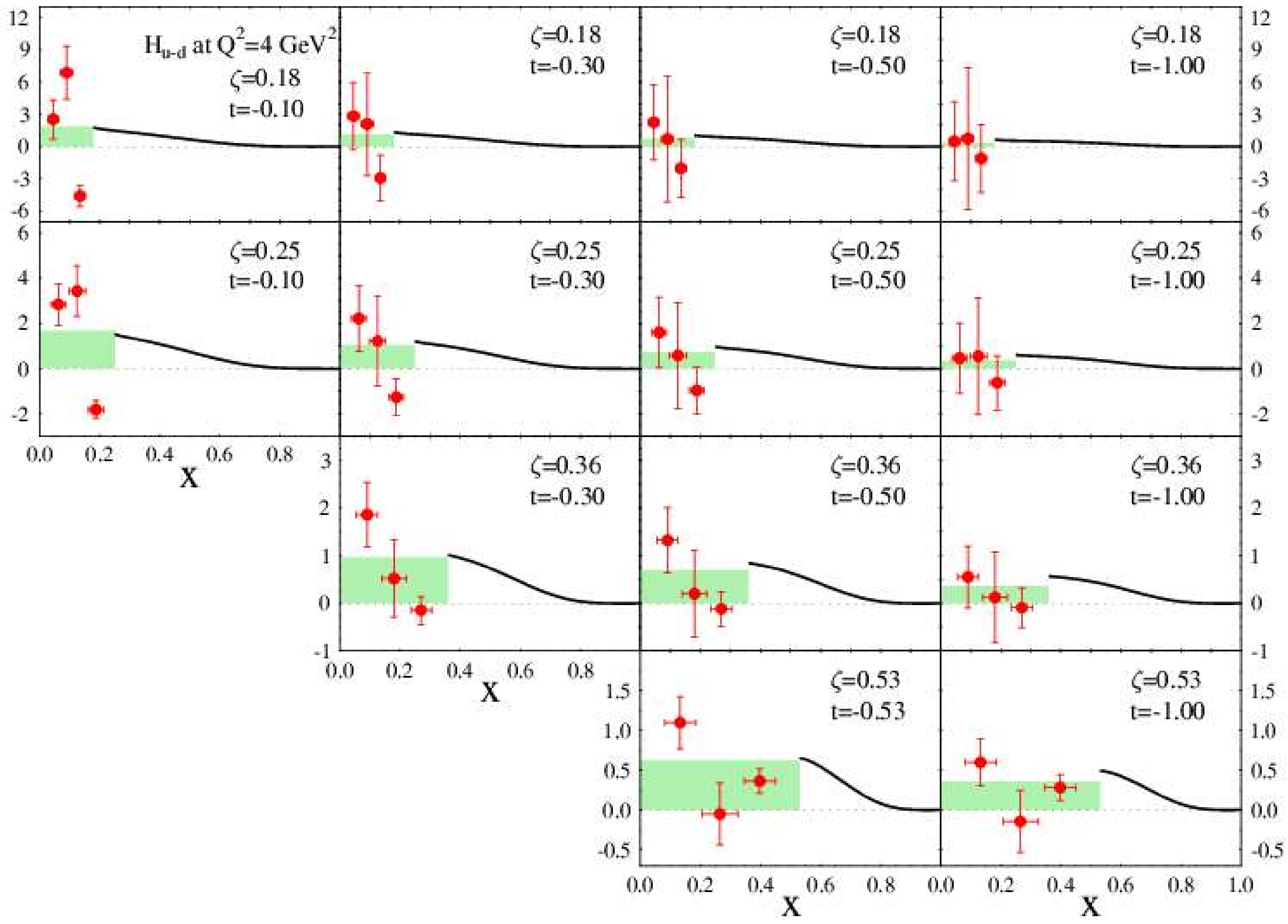
X-bin ⇒ $$\overline{X}_{k,n} = \int_0^1 X b_{k,n}(X) dX = \frac{k+1}{n+1},$$

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

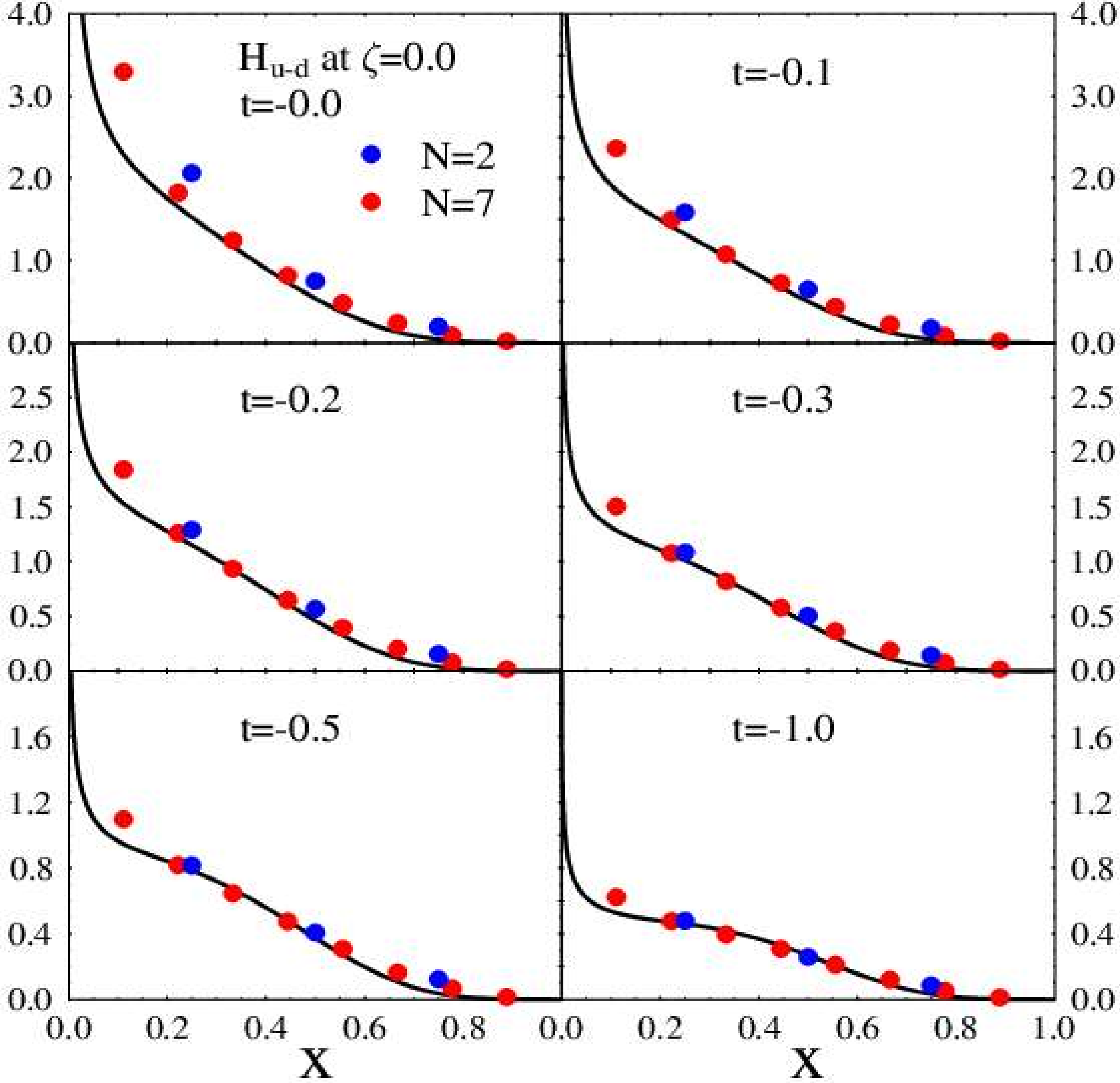


ERBL Region

AHLT arXiv:0708.0268



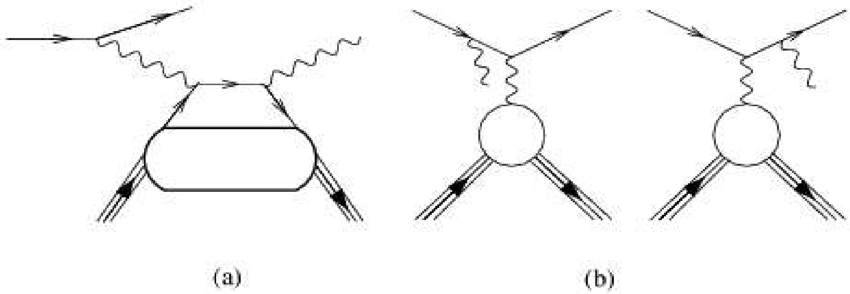
Determined from lattice moments up to n=3

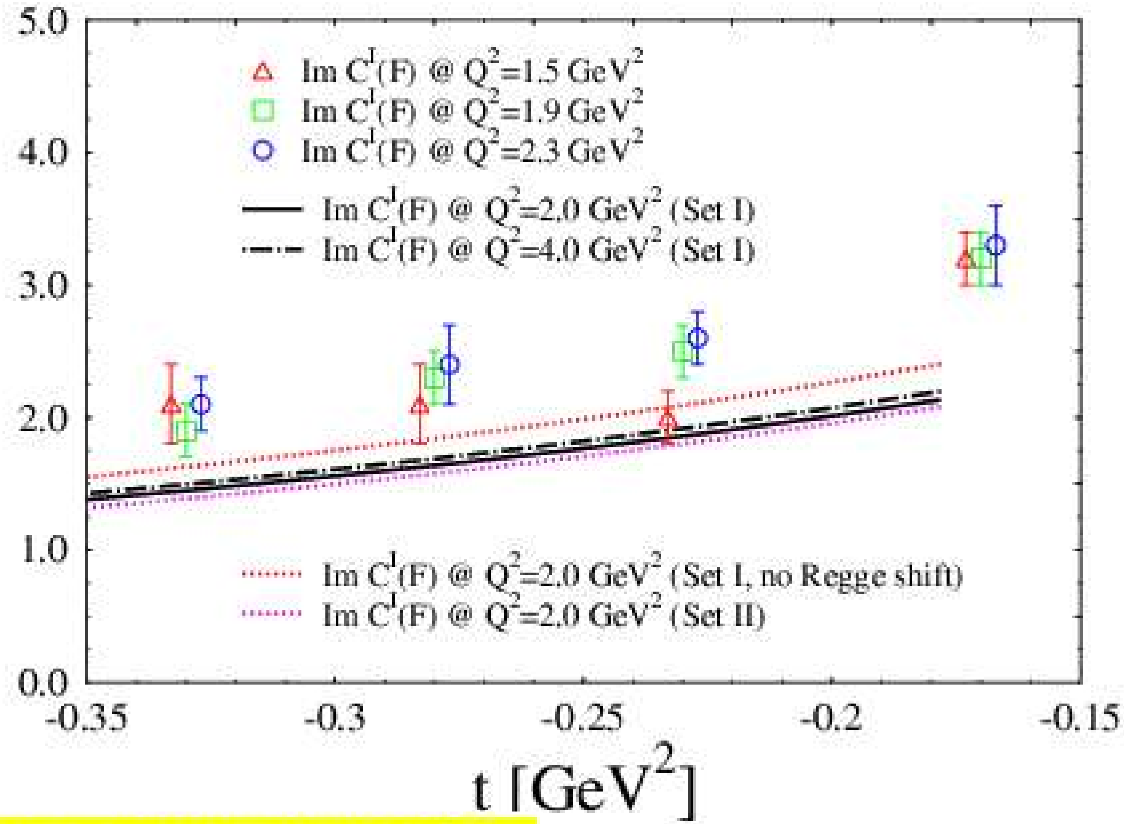


H_{u-d} at ζ=0.0
t=-0.0
N=2
N=7
t=-0.1
t=-0.2
t=-0.3
t=-0.5
t=-1.0
4.0
3.0
2.0
1.0
0.0
2.5
1.5
0.5
1.6
1.2
0.8
0.4
0.2
0.6
X

Comparison with Jlab Hall A data (proton)

Munoz Camacho et al., (2006)





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

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

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

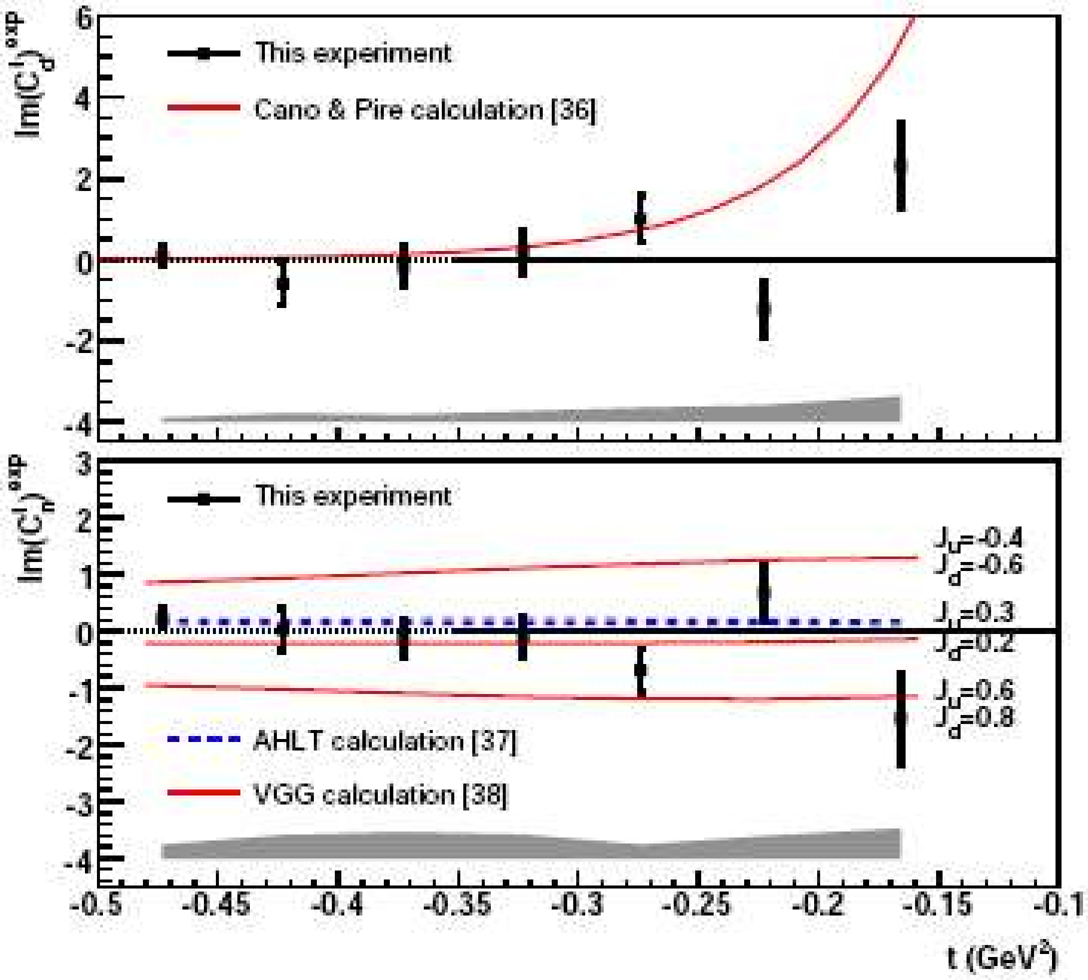
Note!!

Im $\mathcal{H}$ from asymmetry

Re $\mathcal{H}$ from x-section

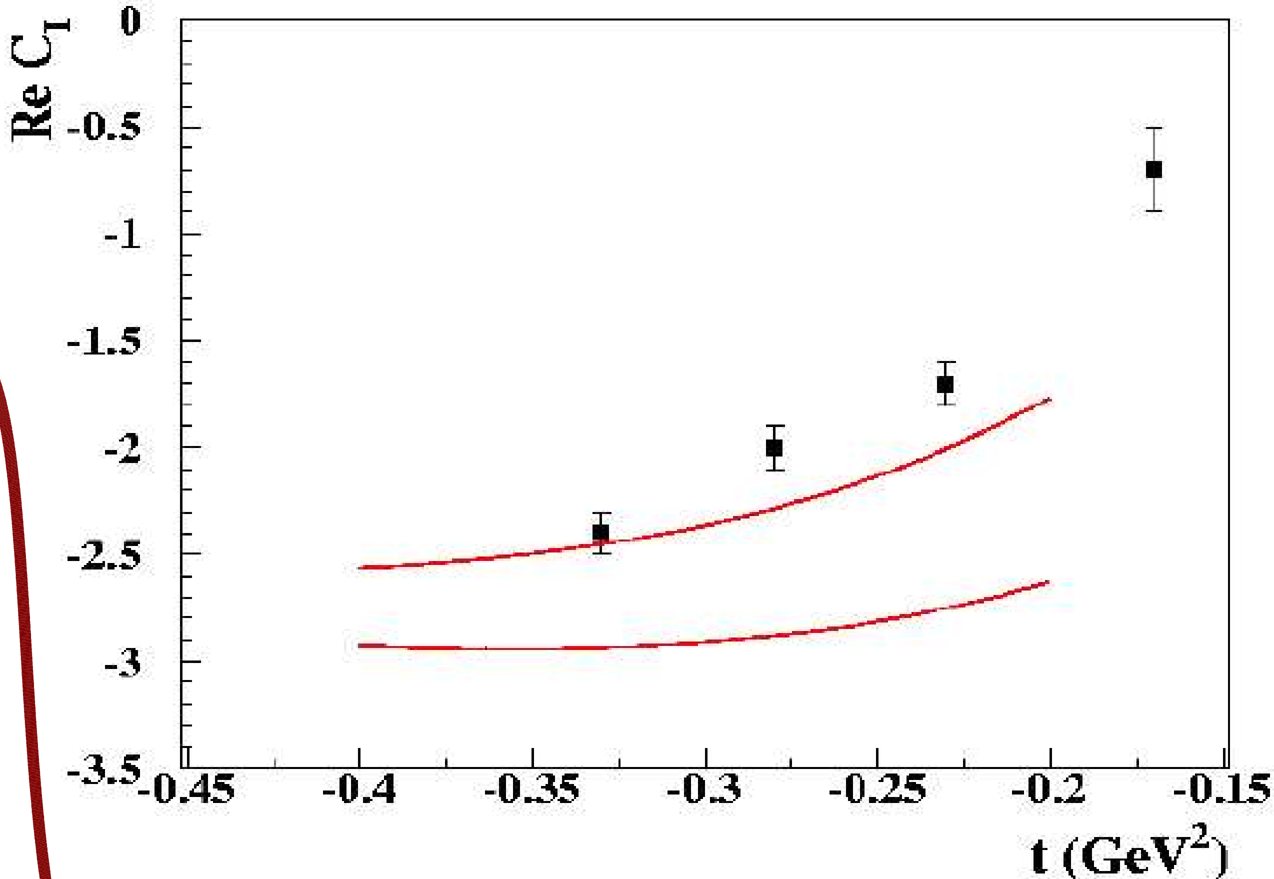
Comparison with Jlab Hall A data (neutron)

Mazouzet al., (2007)



Are the exclusive data "telling" us something?

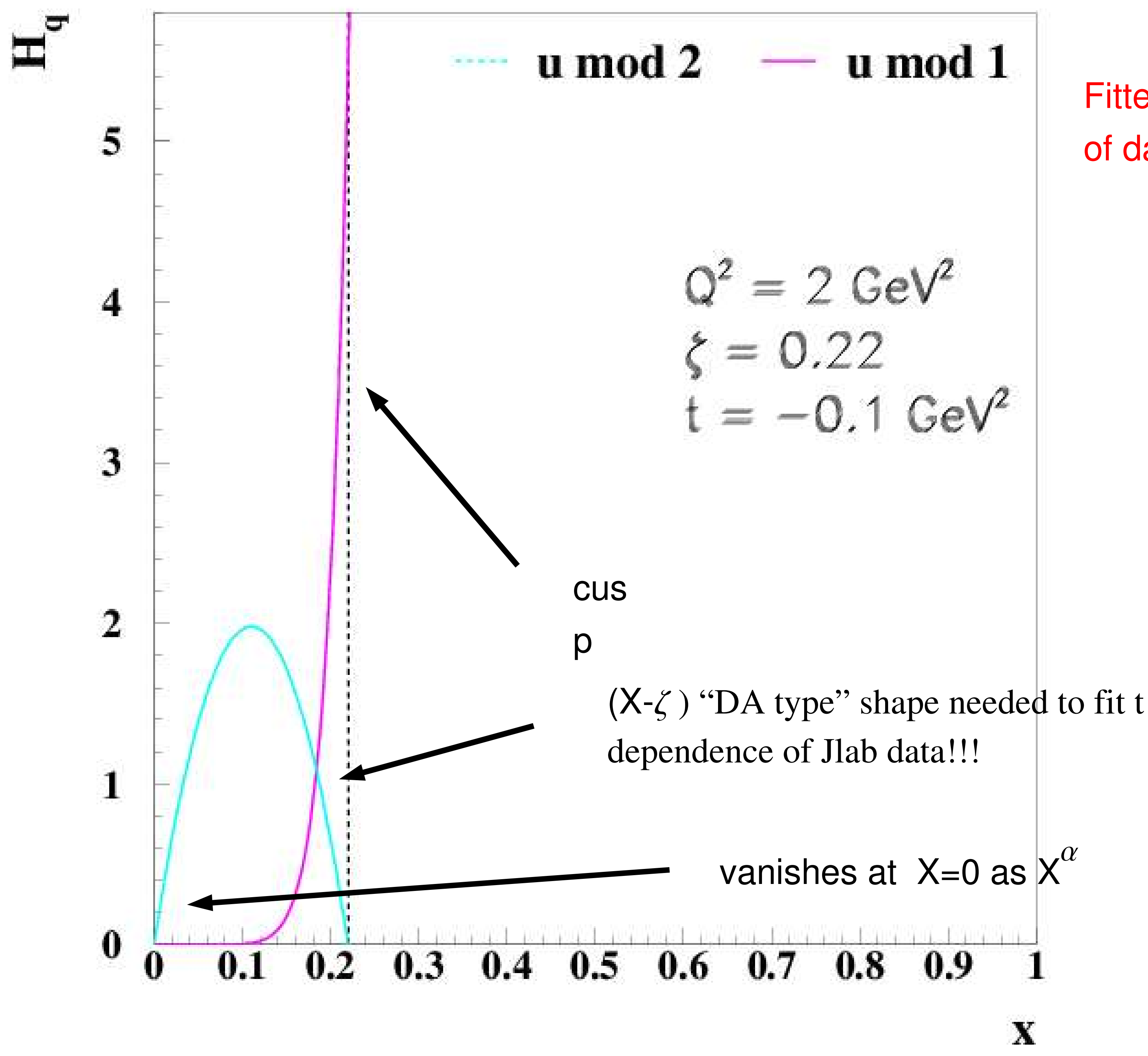
Real Part *(S.Ahmad, S.L., preliminary)*



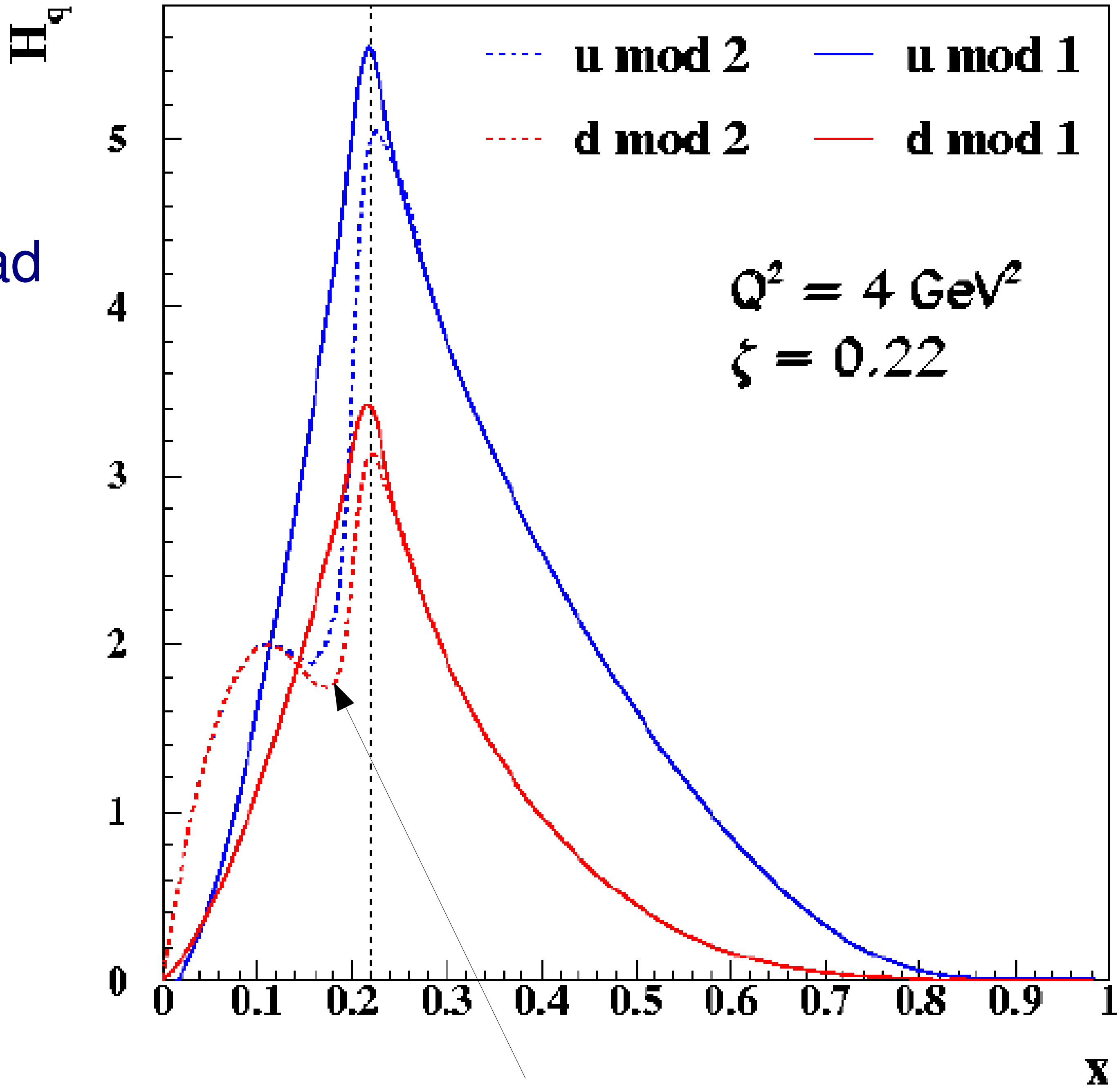
$$\mathcal{F}(\zeta,t) = -i\pi \sum_q e_q^2 \left[F^q(\zeta,\zeta,t) - F^q(-\zeta,\zeta,t)\right] +$$

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

Fitted directly at Q of data



S. Ahmad

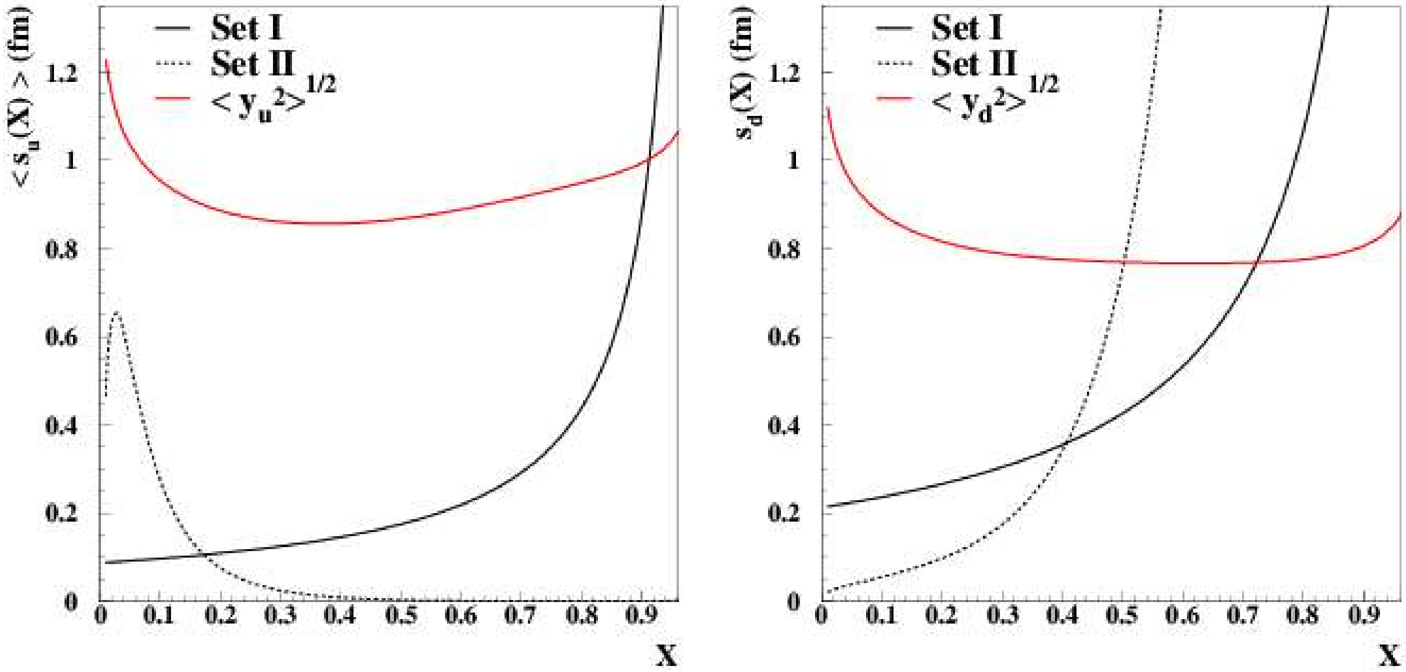


- Behavior determined by Jlab data on Real Part and Q^2 dependence
- Consistent with lattice determination!

Evaluation of interparton distances

y is the average distance of quark **q** from the spectator quarks

s is the average shift of quark along the y-axis when proton is (transversely) polarized along the x-axis



Sensitive to E!

3. Nuclei

Deuteron: New sum rules

S.K.Taneja

$$\frac{1}{2}\int \frac{d\lambda}{2\pi}\, e^{ix(Pz)} \langle p' |\, \bar{q}(-\tfrac{1}{2}z)\, \not{n}_-\, q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z=\lambda n_-} = -(\epsilon'^* \epsilon)\, H_1$$

$$+ \frac{(\epsilon n_-)(\epsilon'^* P) + (\epsilon'^* n_-)(\epsilon P)}{P n_-} H_2 - \frac{2(\epsilon P)(\epsilon'^* P)}{m^2} H_3$$

$$+ \frac{(\epsilon n_-)(\epsilon'^* P) - (\epsilon'^* n_-)(\epsilon P)}{P n_-} H_4$$

$$+ \left[m^2 \frac{(\epsilon n_-)(\epsilon'^* n_-)}{(P n_-)^2} + \frac{1}{3}(\epsilon'^* \epsilon) \right] H_5\,,$$

Cano and Pire (2001)

Form Factors

$$\int_{-1}^{1} dx\, H_i(x,\xi,t) = G_i(t) \qquad (i = 1,2,3)$$

$$G_C = G_1 + \frac{2}{3}\eta\, G_Q,$$

$$G_Q = G_1 - G_2 + (1+\eta) G_3,$$

$$G_M = G_2$$

Energy momentum tensor

$$\langle p'|\theta^{\mu\nu}|p\rangle = -\frac{1}{2}\left[P^\mu P^\nu - \frac{g^{\mu\nu}}{4}P^2\right](\epsilon'^*\epsilon)G_{1,2}(t) - \frac{1}{4}\left[P^\mu P^\nu - \frac{g^{\mu\nu}}{4}P^2\right]\frac{(\epsilon P)(\epsilon'^* P)}{M^2}G_{2,2}(t) \tag{2}$$
$$-\frac{1}{2}\left[\Delta^\mu\Delta^\nu - \frac{g^{\mu\nu}}{4}\Delta^2\right](\epsilon'^*\epsilon)G_{3,2}(t) - \frac{1}{4}\left[\Delta^\mu\Delta^\nu - \frac{g^{\mu\nu}}{4}\Delta^2\right]\frac{(\epsilon P)(\epsilon'^* P)}{M^2}G_{4,2}(t)$$
$$+\frac{1}{4}\left[\left(\epsilon'^{*\mu}(\epsilon P) + \epsilon^\mu(\epsilon'^* P)\right)P^\nu + \mu \leftrightarrow \nu - g^{\mu\nu}(\epsilon P)(\epsilon'^* P)\right]G_{5,2}(t)$$
$$+\left[\left(\epsilon'^{*\mu}(\epsilon P) - \epsilon^\mu(\epsilon'^* P)\right)\Delta^\nu + \mu \leftrightarrow \nu + g^{\mu\nu}(\epsilon P)(\epsilon'^* P) - \left(\epsilon'^{*\mu}\epsilon^\nu + \epsilon'^{*\nu}\epsilon^\mu\right)\Delta^2 + \frac{g^{\mu\nu}}{2}(\epsilon'^*\epsilon)\Delta^2\right]G_{6,2}(t)$$

.. and relation with deuteron GPDs:

$$\int dx\, x H_1(x,\xi,t) - \frac{1}{3}\int dx\, x H_5(x,\xi,t) = G_{1,2}(t) + \xi^2 G_{3,2}(t)$$
$$\int dx\, x H_2(x,\xi,t) = G_{5,2}(t)$$
$$\int dx\, x H_3(x,\xi,t) = G_{2,2}(t) + \xi^2 G_{4,2}(t)$$
$$\frac{1}{4\xi}\int dx\, x H_4(x,\xi,t) = \frac{M^2}{t}\int dx\, x H_5(x,\xi,t) = G_{6,2}(t)$$

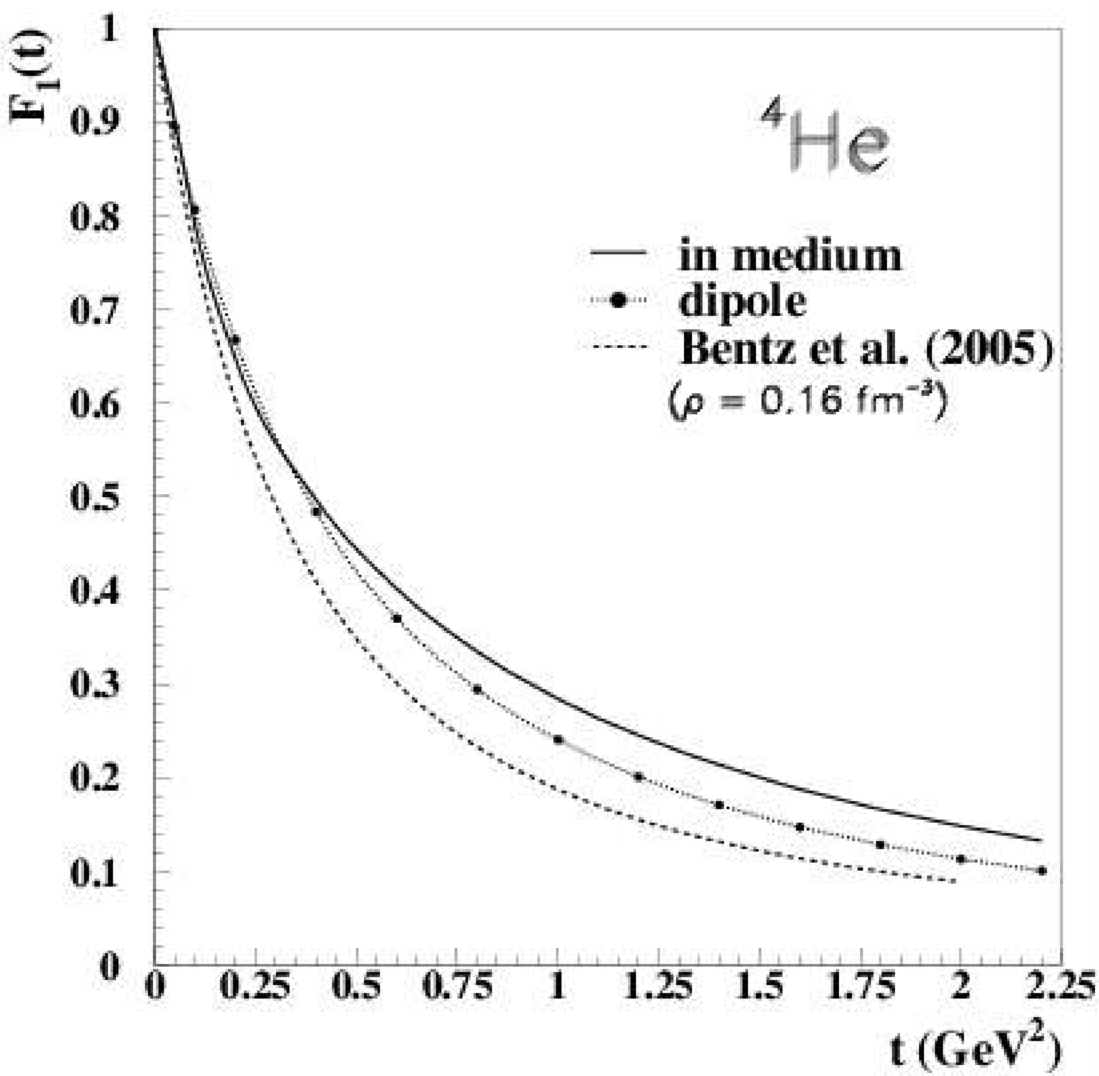
...inserting the energy momentum tensor i $\langle p'| \int d^3x (\vec{x} \times \vec{T}^{0i}_{q,g})_z |p\rangle$

$$\Downarrow$$

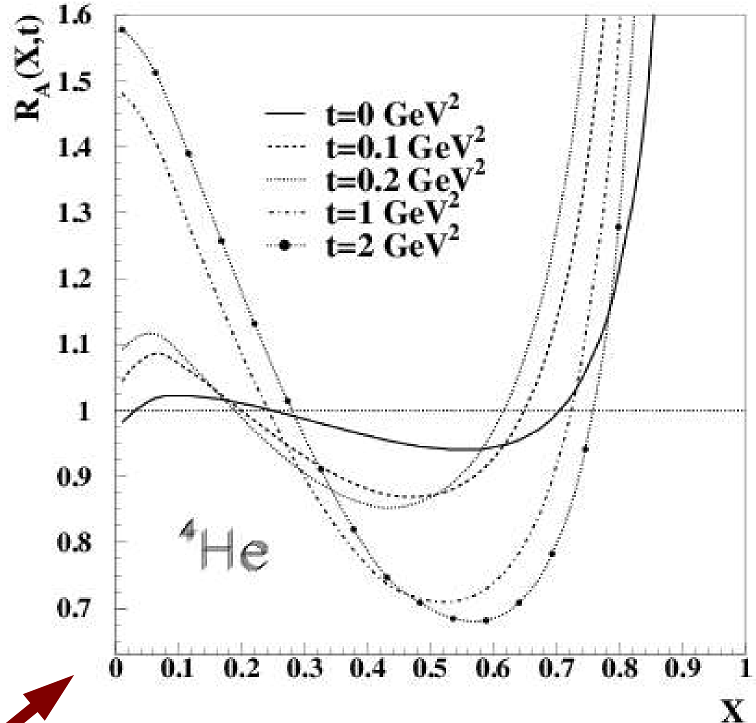
$$J_q = \frac{1}{2} \int dX\, X\, H_2^q(X,0,0) \equiv \frac{1}{2} G_{5,2}(0)$$

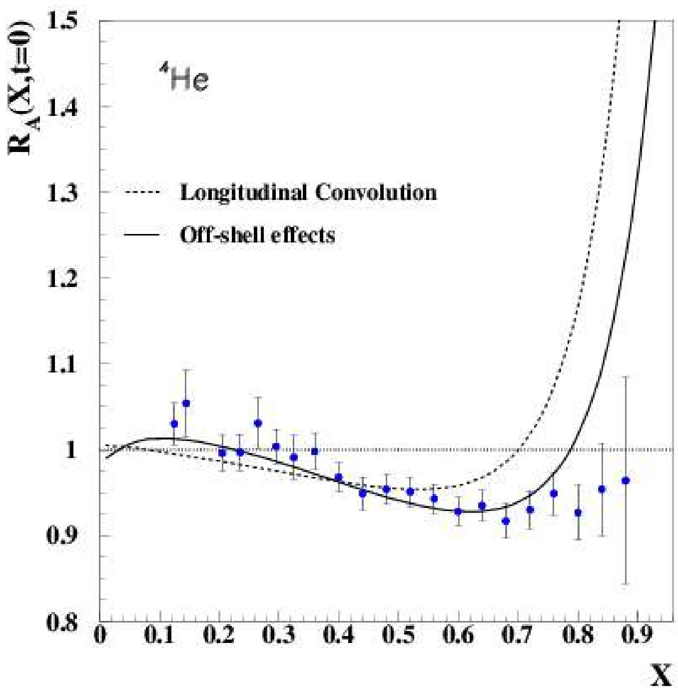
An essential piece of information for extracting quarks angular momentum!

4He: nuclear GPDs as tools to study in medium modifications

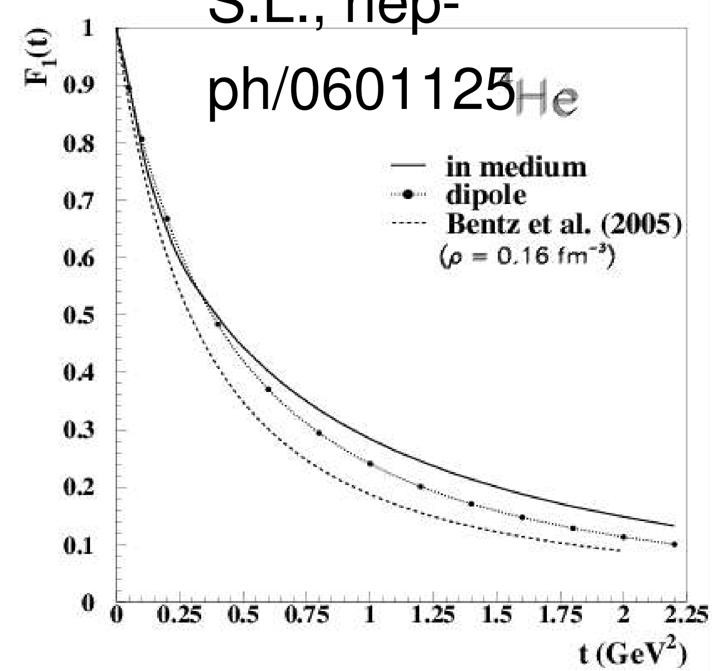


S.L., S.K. Taneja,
PRC72, 032201 (2005)

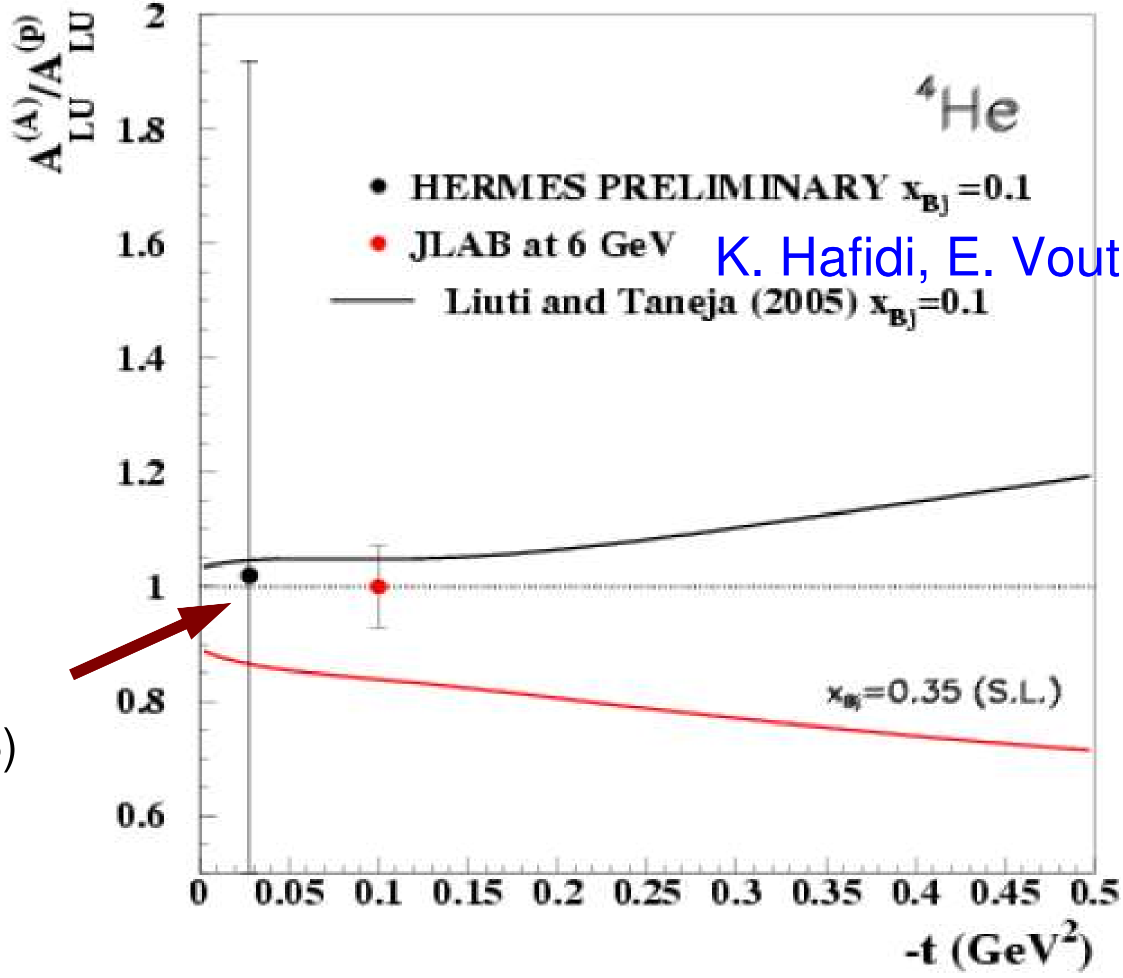




S.L., hep-ph/0601125



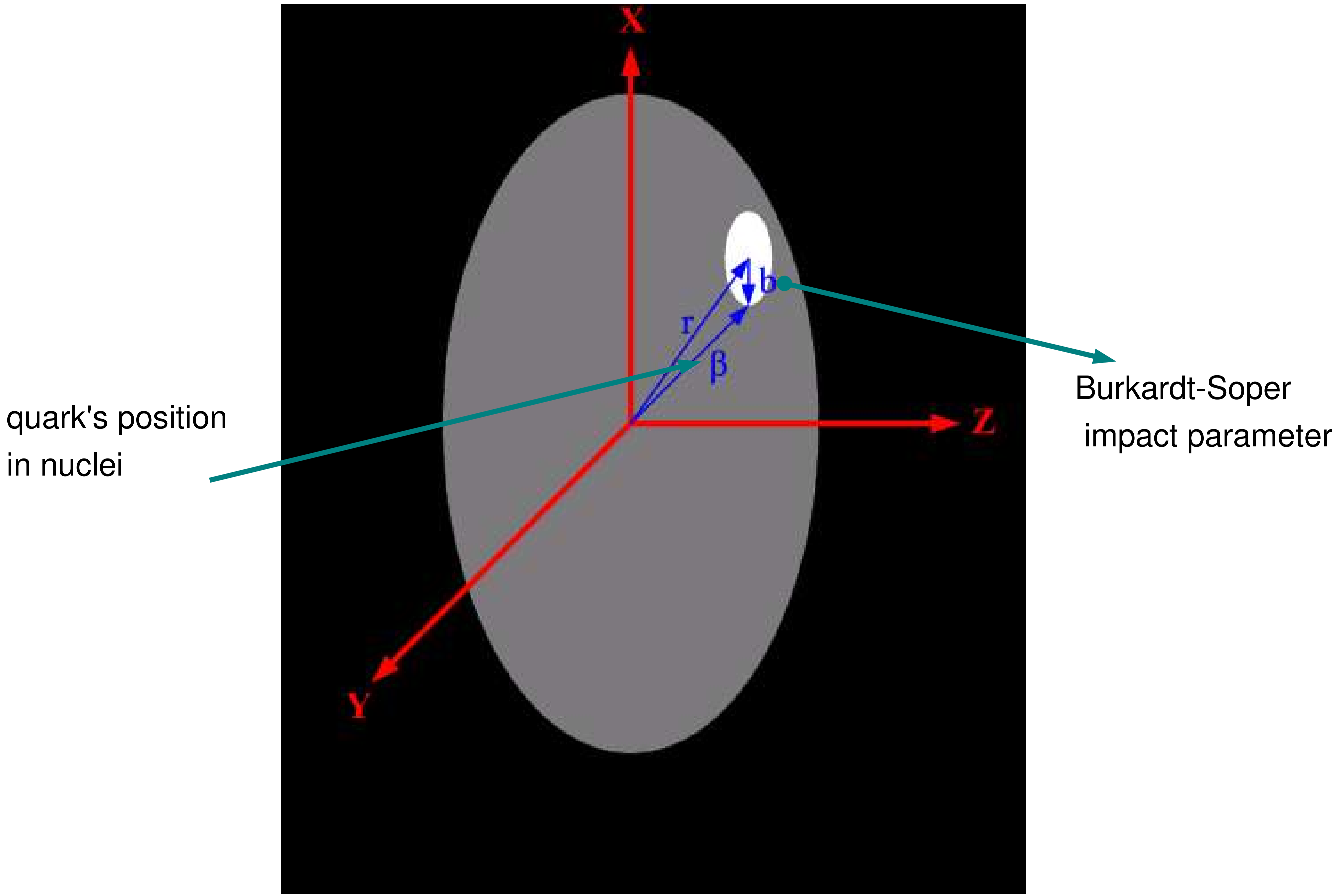
Experiments on ^{4}He are feasible at Jlab:



K. Hafidi, E. Voutier

HERMES (2006)

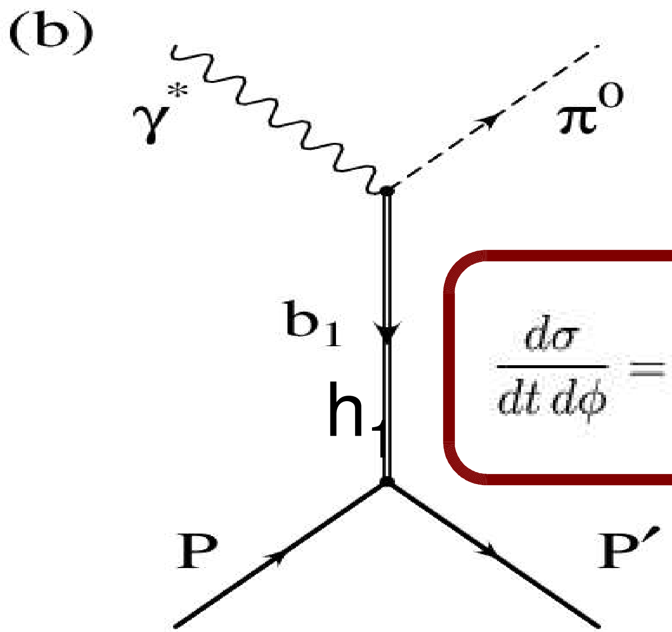
Spatial structure of quarks and gluons in nuclei



π^o Electroproduction Observables and GPDs

Exclusive π^o electroproduction

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



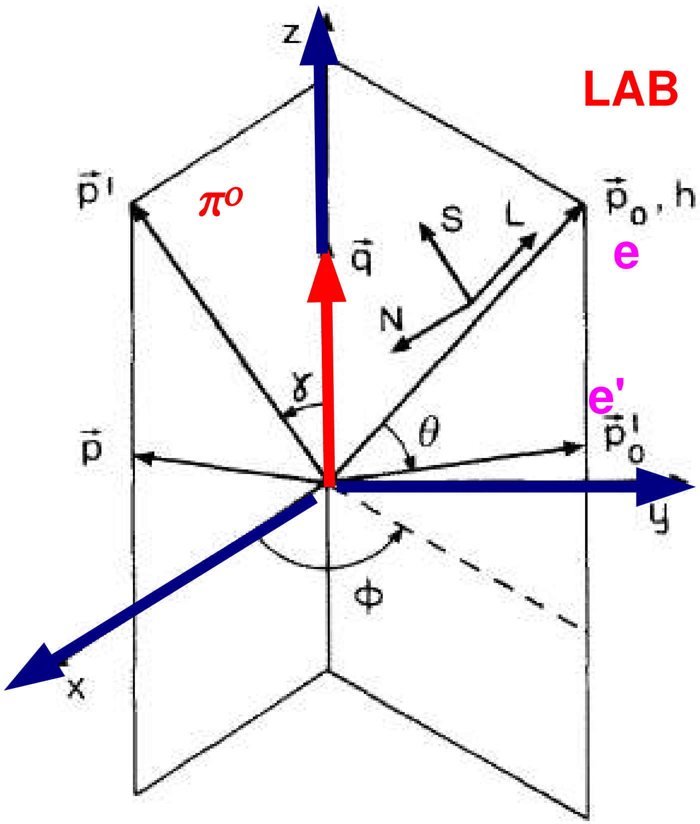
$$\frac{d\sigma}{dt\,d\phi} = \left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi$$

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

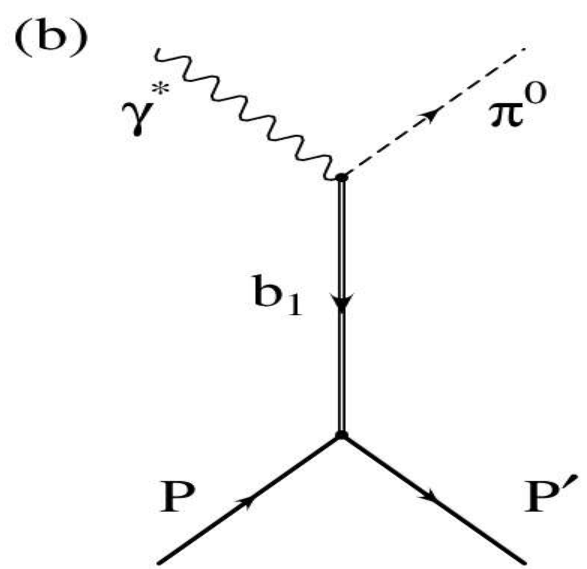
$L_{\mu\nu}^{h=\pi^o} \;\approx\; \gamma^*$ polarization density matrix

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

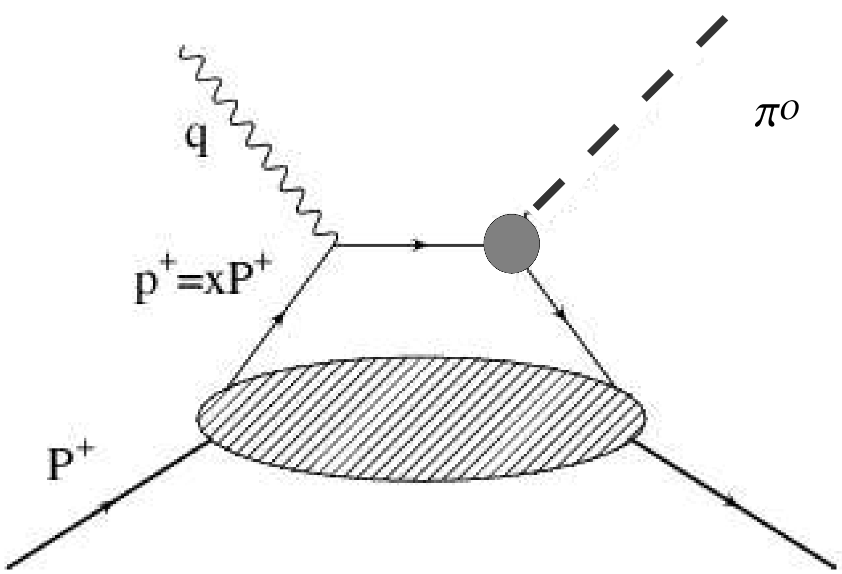
$$\frac{d\sigma_{TT}}{dt} = W_{yy} - W_{xx} \equiv 2\Re e(J_1 J_{-1}*)$$



Dual Representation?



$t=-\Delta^2$

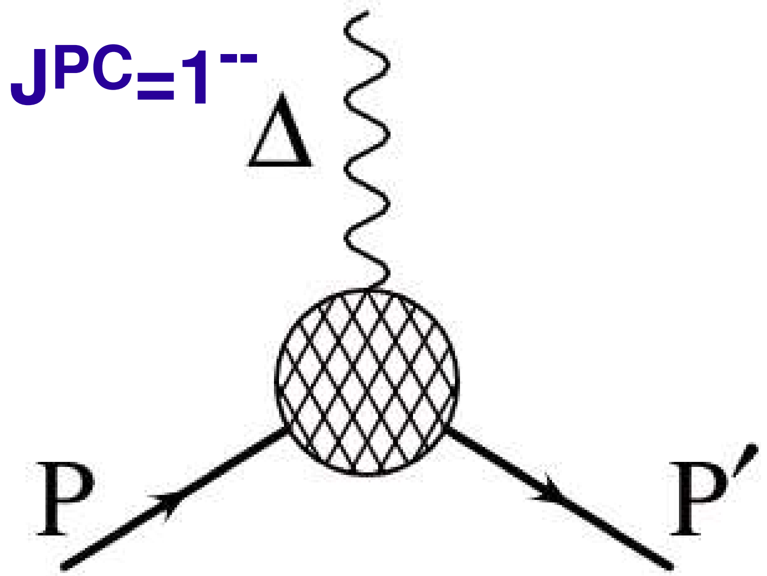


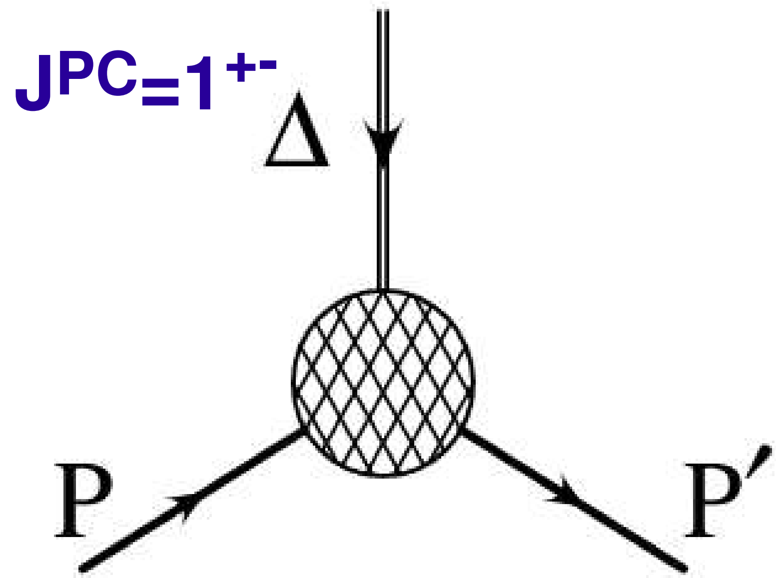
$$f_{1,\Lambda;0,\Lambda'} = \sum_{\lambda,\lambda'} g_{1,\lambda;0,\lambda'} A_{\Lambda',\lambda';\Lambda,\lambda}$$

helicity amps.

"Quark-Hadron" Helicity Amplitudes (Marcus Diehl)

Only chiral-odd GPDs!!!





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

γ_5 $\Leftrightarrow$ $J^{PC}=1^{++}$, ... (a_1-type exchange) $\Leftrightarrow$ H, E, ...

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

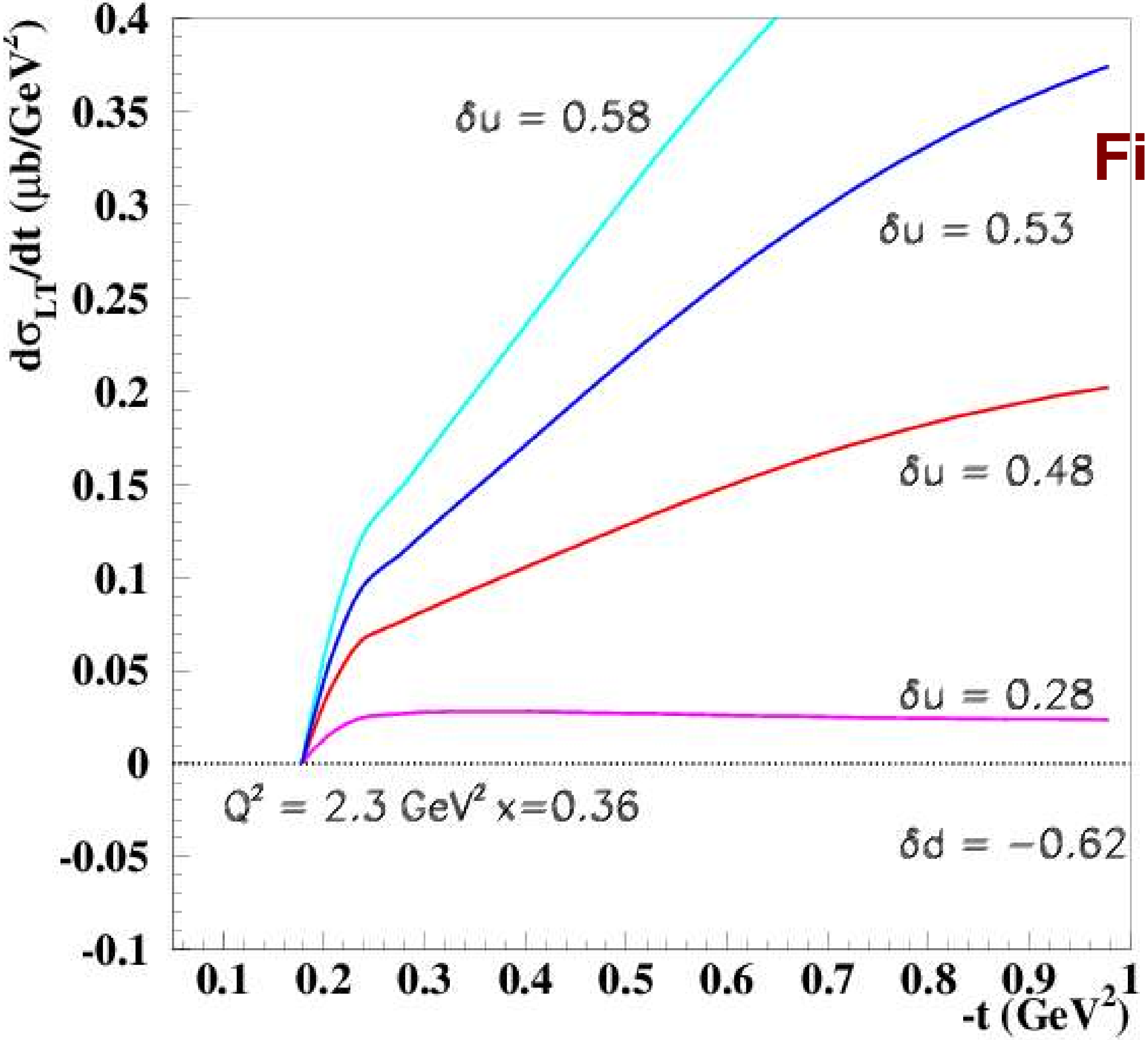
$\int h_1(X,Q^2)\, dX = \delta q =$ tensor charge

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

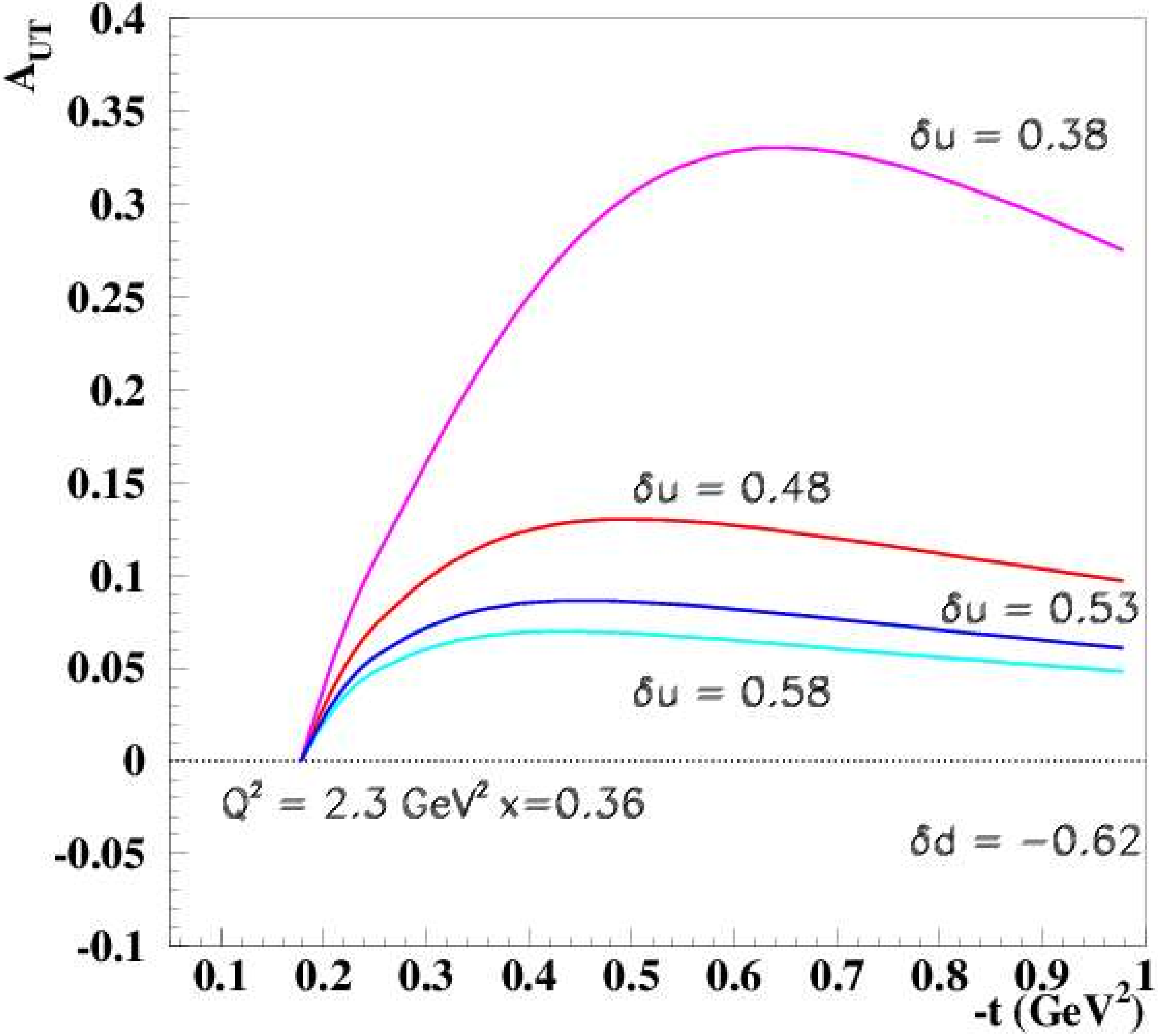
$\int E_2(X,0,0)\, dX = \kappa_T$ = Burkardt's moment

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

Main Result: Tensor Charge and Anomalous Transverse Moment treated as free parameters to be extracted form data ⟹Show sensitivity!



Fixed κ_u and κ_d



A_UT
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-t (GeV^2)
δu = 0.38
δu = 0.48
δu = 0.53
δu = 0.58
Q^2 = 2.3 GeV^2 x=0.36
δd = −0.62

GPDs & hadron tensor for Spin 0 nuclear target (Liuti and Taneja, PRC 2005)

π^o production (with G. Goldstein)

- 1st consider nucleon target GPDs & Regge Cuts
  - Like π+N$\rightarrow\pi$+N
    - 2 invariant amps (A,B)-> 2 leading twist GPDs
    - Like ~ $H(x,\zeta,t)$ & $E(x,\zeta,t)$ or $H_T(x,\zeta,t)$
  - H(x,0,0)~A(x), $H_T(x,0,0)$~B(x) ($p+\pi$?)flips 1/2 particle helicity
    - E_T more like Chiral-odd GPDs for nucleons than E
  - Carries over to 4He$\rightarrow$q q′$\rightarrow$4He′
  - Can coherent e+^{4}He$\rightarrow$e′+π^0+^{4}He′ be treated as pure spin 0 target?
  - Need 2 steps involving ^{4}He$\rightarrow$N==N′$\rightarrow$^{4}He′ & N$\rightarrow$q==q′$\rightarrow$N′

    and (PQCD?) γ^*+q$\rightarrow\pi^0$+q′
  - 2 helicity amps longitudinal & transverse γ^*
  - How can these distinguish H from chiral odd, C=parity odd structures?

Conclusions and Outlook

- Comparison between GPD models and data is indeed possible…GPD extraction is possible!!!
- Approaching “Global Analysis”
- Interesting connections between TMDs and GPDs
- Proposed extraction of tensor charge and transverse anomalous moment from neutral pion production data
- Spatial structure of Nuclei