Theory : phenomenology support JLab @ 12 GeV

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Outline

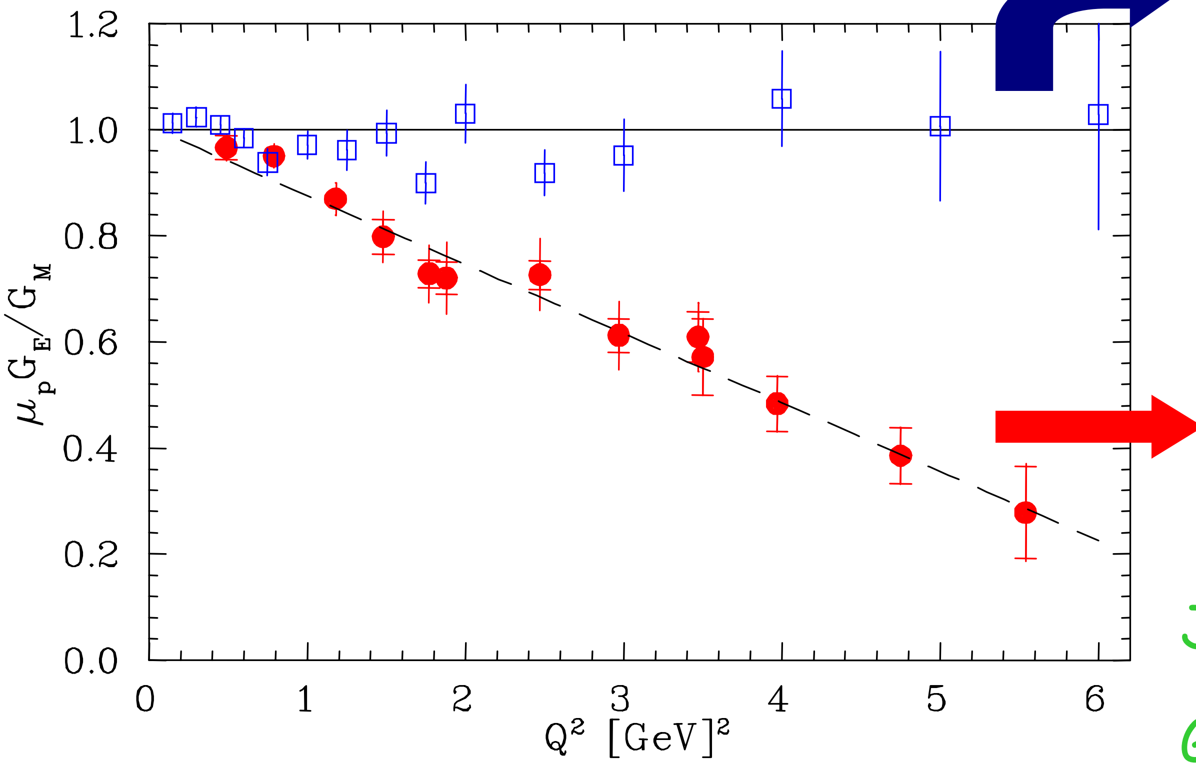
- Form factors at large momentum transfer,

➡ two-photon exchange observables

- Hard exclusive processes :

➡ deeply virtual Compton scattering
➡ mapping out nucleon Generalized Parton Distributions
➡ GPDs at large $-t$ / transition to PQCD

Rosenbluth vs polarization transfer measurements of G_E/G_M of proton



SLAC

Rosenbluth data

Jlab/Hall A
Polarization data

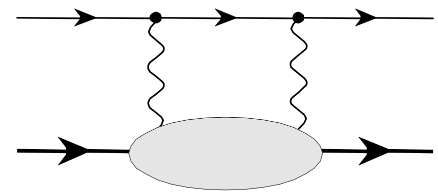
Jones et al. (2000)

Gayou et al. (2002)

Two methods, two different results !

Observables including two-photon exchange

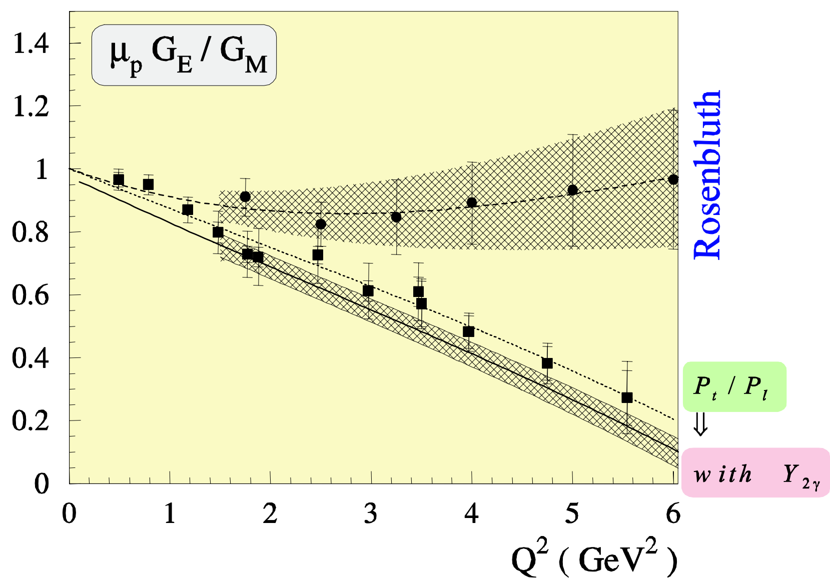
Real parts of two-photon amplitudes

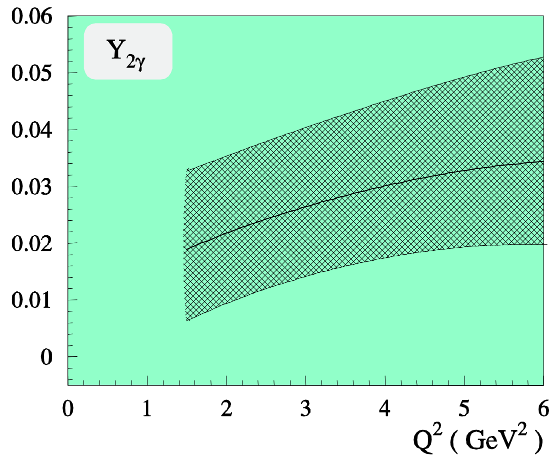


$$\sigma_R = G_M^2 \left(1 + 2 \frac{\mathcal{R}\left(\delta \tilde{G}_M\right)}{G_M} \right)$$
$$+ \varepsilon \left\{ \frac{1}{\tau} G_E^2 \left(1 + 2 \frac{\mathcal{R}\left(\delta \tilde{G}_E\right)}{G_E} \right) + 2 G_M^2 \left(1 + \frac{1}{\tau} \frac{G_E}{G_M} \right) \underbrace{\frac{\nu}{M^2} \frac{\mathcal{R}\left(\tilde{F}_3\right)}{G_M}}_{Y_{2\gamma}} \right\}$$
$$+ \mathcal{O}(e^4)$$

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\,\varepsilon}{\tau\,(1+\varepsilon)}} \left\{ \frac{G_E}{G_M} \left(1 - \frac{\mathcal{R}\left(\delta \tilde{G}_M\right)}{G_M} \right) + \frac{\mathcal{R}\left(\delta \tilde{G}_E\right)}{G_M} \right.$$
$$\left. + \left(1 - \frac{2\,\varepsilon}{1+\varepsilon} \frac{G_E}{G_M} \right) \underbrace{\frac{\nu}{M^2} \frac{\mathcal{R}\left(\tilde{F}_3\right)}{G_M}}_{Y_{2\gamma}} \right\}$$
$$+ \mathcal{O}(e^4)$$

Phenomenological analysis



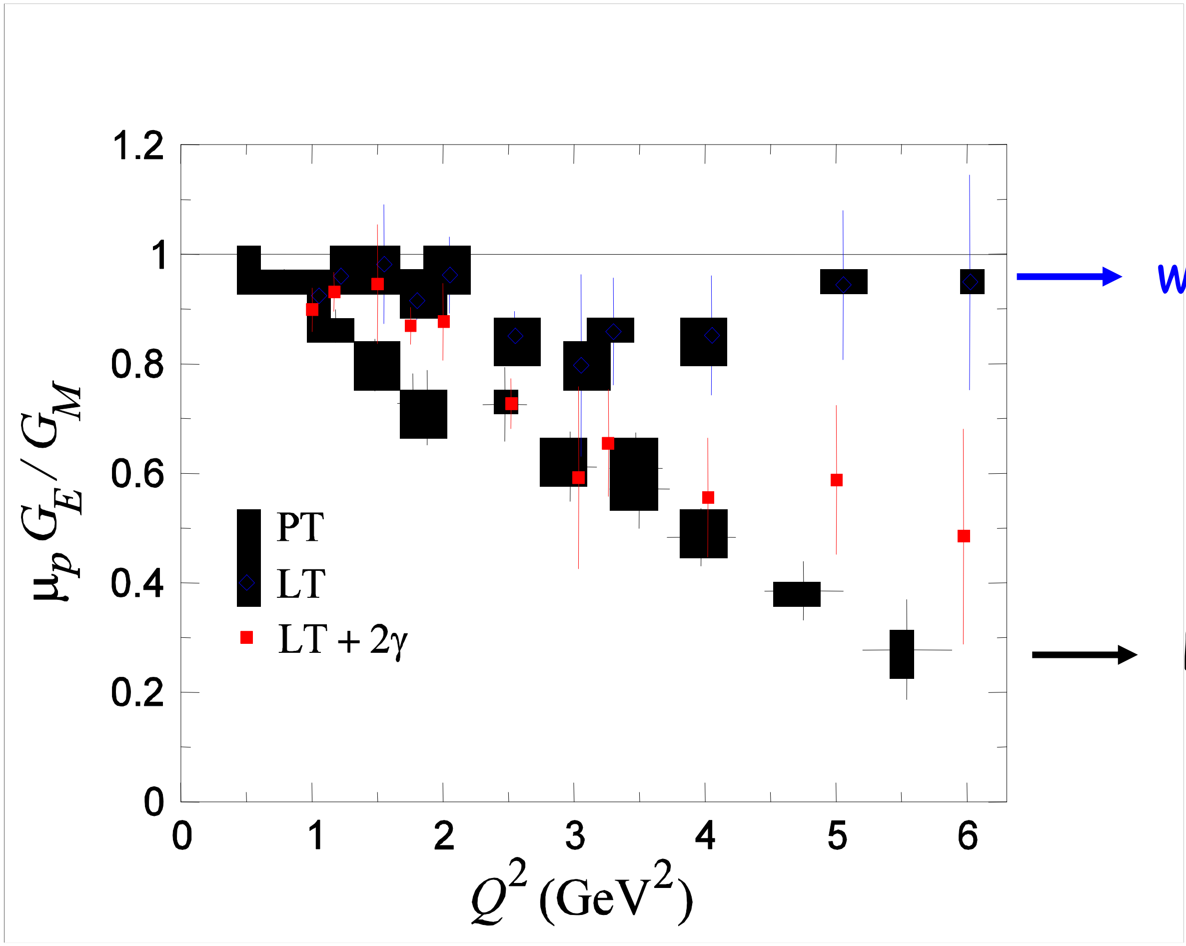


2-photon exchange is a good candidate to explain the discrepancy between both experimental methods

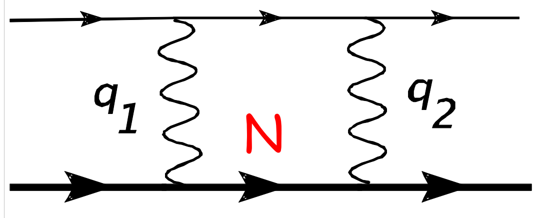
➡ relevance when extracting form factors at large Q^2

Guichon, Vdh (2003)

Two-photon exchange calculation : elastic contribution



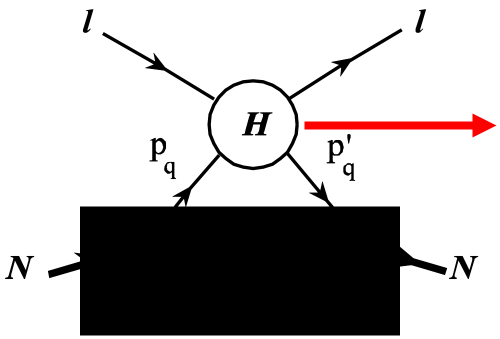
world Rosenbluth data



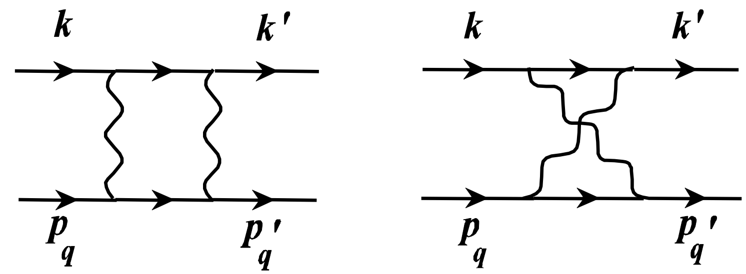
Polarization Transfer

Blunden, Tjon, Melnitchouk (2003, 2005)

Two-photon exchange : partonic calculation



hard scattering amplitude



GPD integrals

$$A \equiv \int_{-1}^{1} \frac{dx}{x} \frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)} \sum_q e_q^2 \, (H^q + E^q)$$

"magnetic" GPD

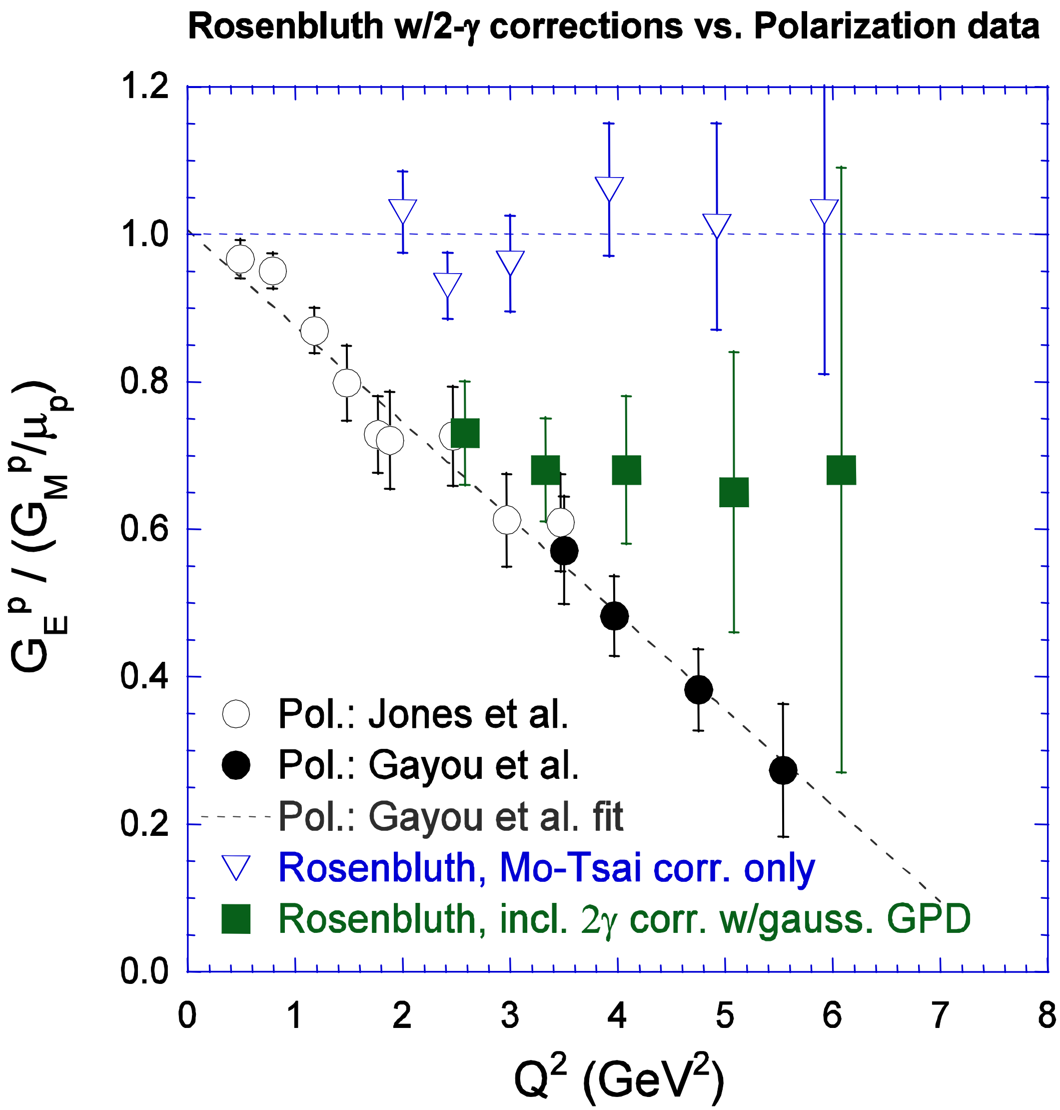
$$B \equiv \int_{-1}^{1} \frac{dx}{x} \frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)} \sum_q e_q^2 \, (H^q - \tau E^q)$$

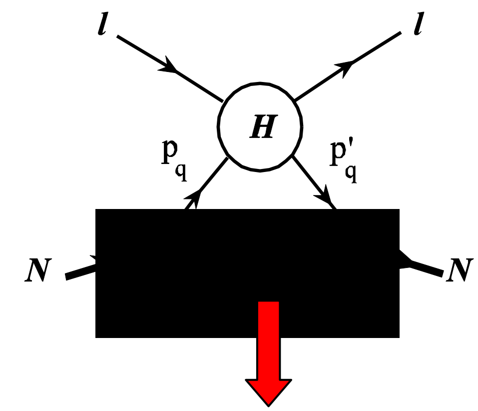
"electric" GPD

$$C \equiv \int_{-1}^{1} \frac{dx}{x} \tilde{f}_1^{hard} \, \mathrm{sgn}(x) \sum_q e_q^2 \, \tilde{H}^q$$

"axial" GPD

Two-photon exchange : partonic calculation





GPDs

Chen, Afanasev, Brodsky, Carlson, Vdh (2004)

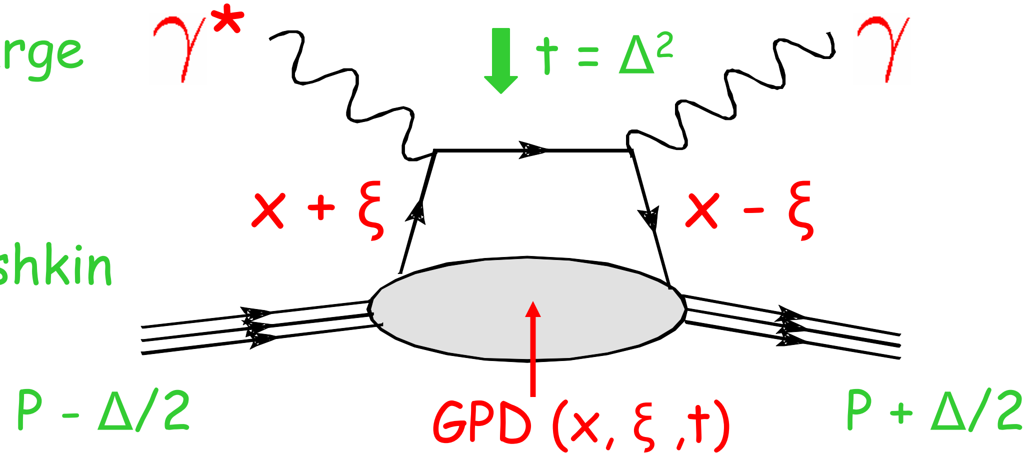
Generalized Parton Distributions

➡ Q^2 large

X. Ji ,

A. Radyushkin

(1996)



low –t process :
$-t \ll Q^2$

$(x + \xi)$ and $(x - \xi)$: longitudinal momentum fractions of quarks

➡ at large Q^2 : QCD factorization theorem ➡ hard exclusive process can be described by 4 transitions (GPDs) :

Vector : $H(x, \xi, t)$ **Axial-Vector** : $\tilde{H}(x, \xi, t)$

Tensor : $E(x, \xi, t)$ **Pseudoscalar** : $\tilde{E}(x, \xi, t)$

known information on GPDs

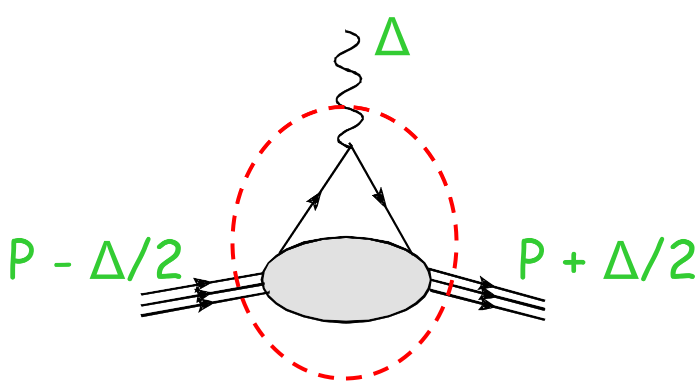
➡ forward limit : ordinary parton distributions

$$H^q(x, \xi = 0, t = 0) = q(x)$$ unpolarized quark distr

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$ polarized quark distr

E^q , $\tilde{E}^q$: do NOT appear in DIS ➡ additional information

➡ first moments : nucleon electroweak form factors



ξ independence :
Lorentz invariance

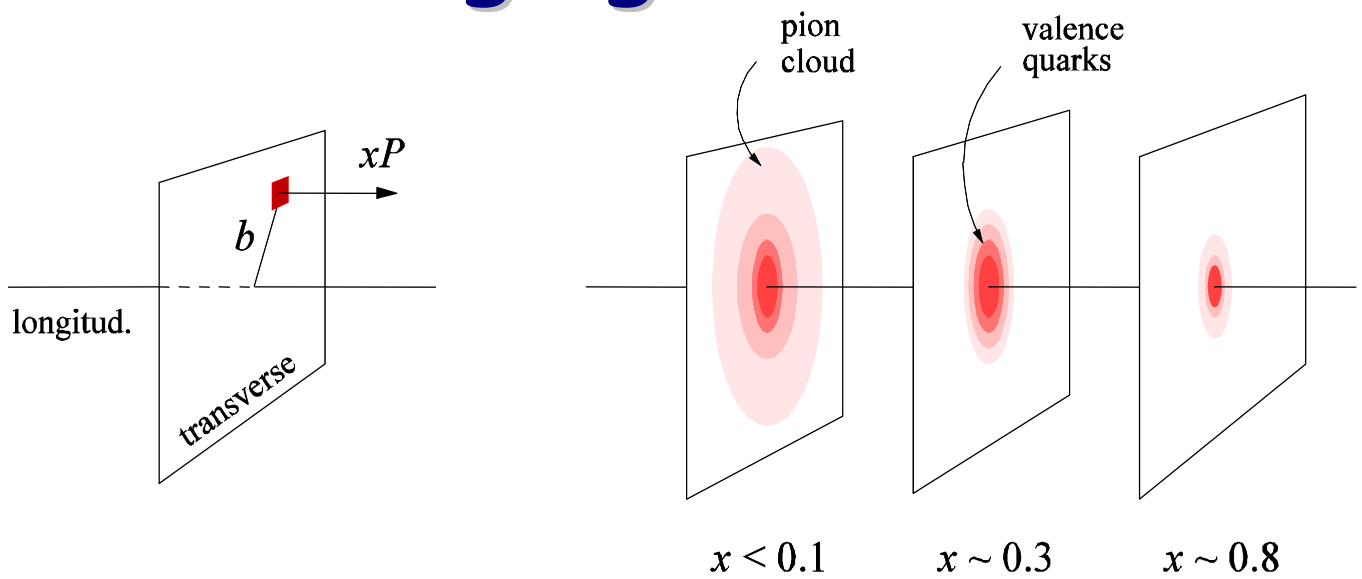
$$\int_{-1}^{1} dx\, H^q(x, \xi, t) = F_1^q(t)$$ Dirac

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

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

$$\int_{-1}^{1} dx\, \tilde{E}^q(x, \xi, t) = G_P^q(t)$$ pseudo-scalar

GPDs : 3D quark/gluon imaging of nucleon

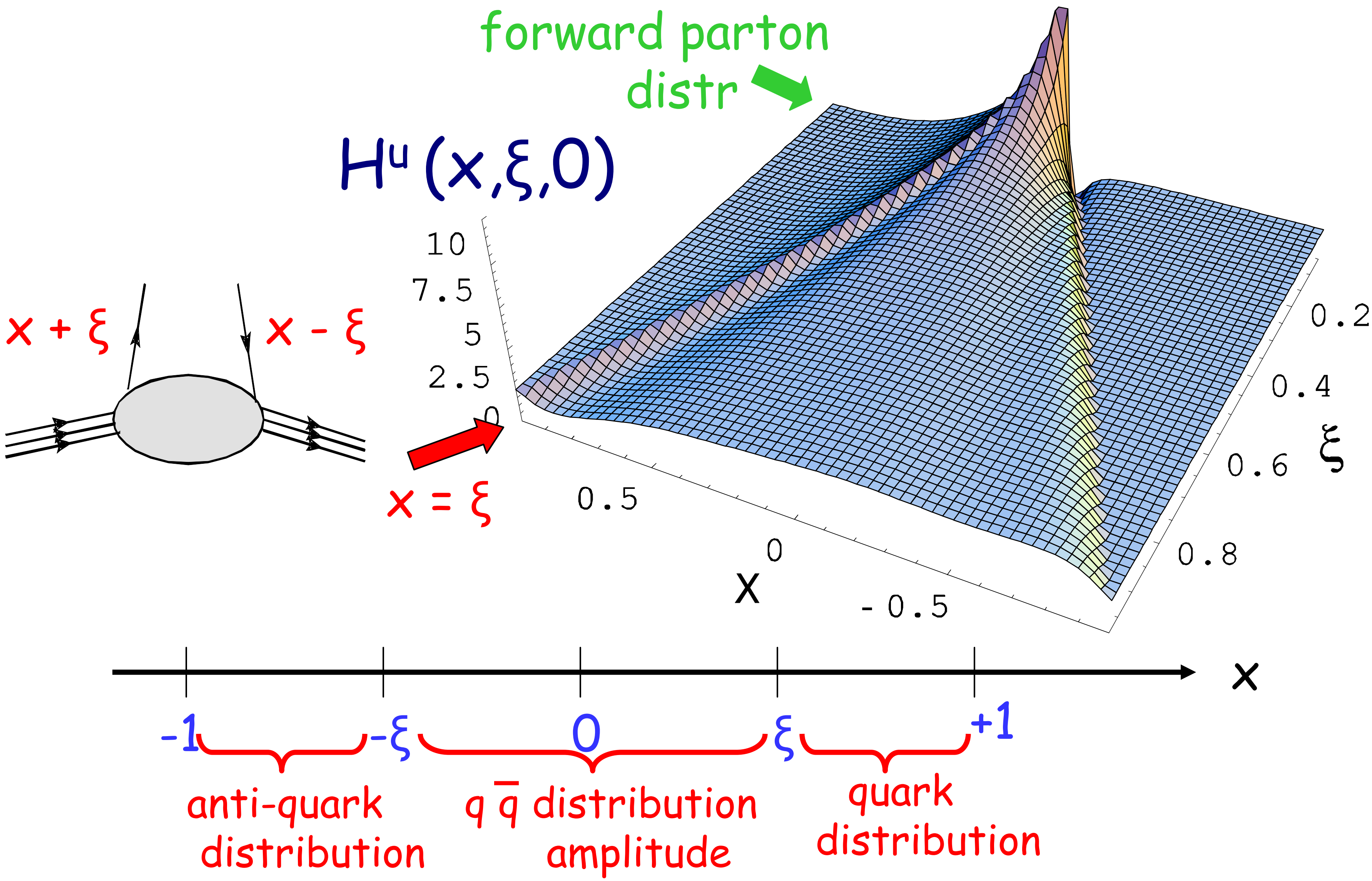


Fourier transform of GPDs :

simultaneous distributions of quarks w.r.t. longitudinal momentum x P and transverse position b

➡ theoretical parametrization needed

GPDs : x and ξ dependence



quark contribution to proton spin

$$2\, J^q = \int_{-1}^{1} dx\, x \left\{ H^q(x,0,0) + E^q(x,0,0) \right\}$$

X. Ji (1997)

$$\boxed{2\, J^q = M_2^q + \int_{-1}^{1} dx\, x\, E^q(x,0,0)}$$

with $M_2^q = \int_0^1 dx\, x\, [q(x) + \bar{q}(x)]$

parametrizations for E^q

M1 : $E^q(x,0,0) = \kappa_q\, q_v(x)$

M2 : $E^q(x,0,0) = \kappa_q / N_q\, (1-x)^{\eta_q}\, q_v(x)$

PROTON	M_2^q	$2\,J^q$ valence model M1 (GPV 01)	$2\,J^q$ valence model M2 (GPRV 04)	$2\,J^q$ Lattice QCDSF 03
u	0.40	0.69	0.63	0.734 ± 0.135
d	0.22	-0.07	-0.06	-0.085 ± 0.088
s	0.03	0.03	0.03	
u + d + s	**0.65**	**0.65**	**0.60**	**0.65 ± 0.16**

orbital angular momentum carried by quarks : resolving the spin crisis

$$J^q = \frac{1}{2}\Delta q + L^q$$

evaluated at $\mu^2 = 2.5$ GeV^2

PROTON	**2 J^q** valence model M1 (GPV 01)	**Δq** HERMES (1999)	**2 L^q**
u	0.61	0.57 ± 0.04	0.04 ∓ 0.04
d	-0.05	-0.25 ± 0.08	0.20 ∓ 0.08
s	0.04	-0.01 ± 0.05	0.05 ∓ 0.05
u + d + s	**0.60**	**0.30 ± 0.10**	**0.30 ∓ 0.10**

GPDs : t dependence (small -t)

➡ small -t (-t < 1 GeV^2) : Regge parametrization

Goeke, Polyakov, Vdh (2001)

- t = 0 : $H^q(x,0,0) + H^q(-x,0,0) = q_v(x) \sim \frac{1}{x^{\alpha(0)}}$

valence quarks $\alpha(0) \simeq 0.5$

- t ≠ 0 : $H^q(x,0,t) + H^q(-x,0,t) \sim \frac{1}{x^{\alpha(t)}}$

$\alpha(t) = \alpha(0) + \alpha' \, t$

Regge trajectory $\alpha' \simeq 0.9 \text{ GeV}^{-2}$

➡ $$\boxed{F_1^q(t) = \int_0^1 dx \, q_v(x) \frac{1}{x^{\alpha_1' \, t}} \qquad F_2^q(t) = \int_0^1 dx \, \kappa_q \, q_v(x) \frac{1}{x^{\alpha_2' \, t}}}$$

valence model for E

Regge slopes : α_1' , α_2' determined from rms radii

GPDs : t dependence (large -t)

modified Regge parametrization : Guidal, Polyakov, Radyushkin, Vdh (2004)

$$H^q(x,0,t) = q_v(x)\, x^{-\alpha_1'\,(1-x)\,t}$$
$$E^q(x,0,t) = \frac{\kappa_q}{N_q}\,(1-x)^{\eta_q}\, q_v(x)\, x^{-\alpha_2'\,(1-x)\,t}$$

- Input : forward parton distributions at $\mu^2 = 1\ GeV^2$ (MRST2002 NNLO)
- Drell-Yan-West relation : exp(- α´ t) -> exp(- α´ (1 - x) t) M. Burkardt (2001)
- parameters :

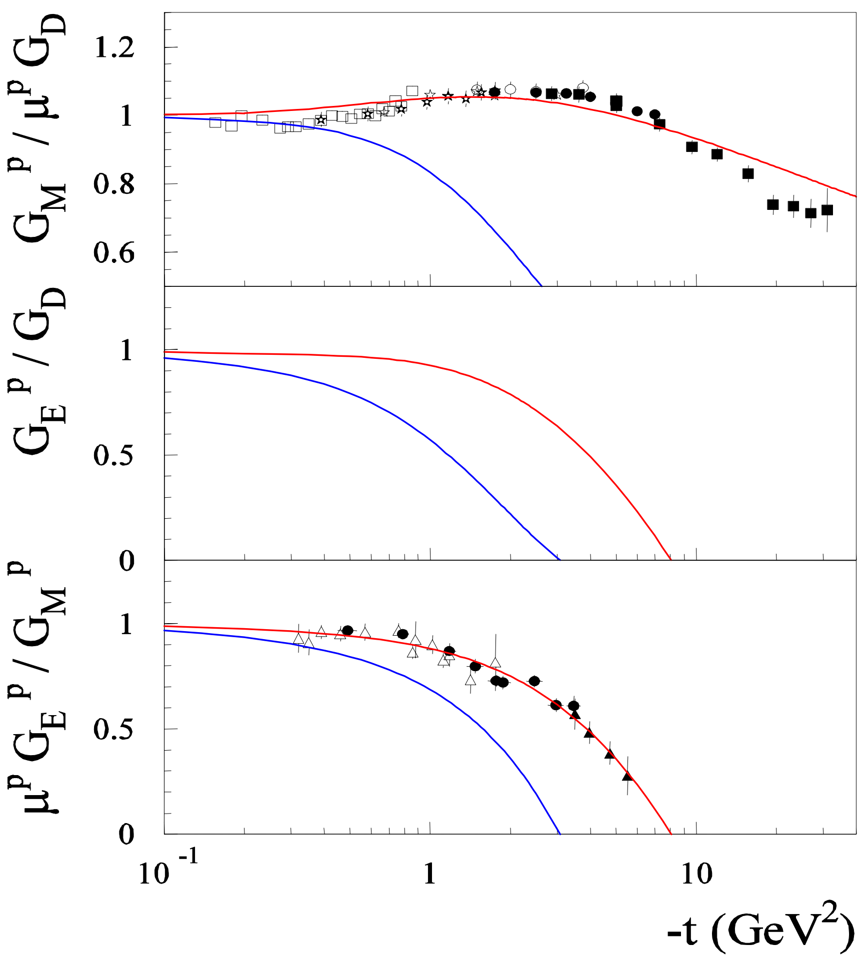
  regge slopes : α_1', α_2' determined from rms radii

  η_u , η_d determined from F_2 / F_1 at large -t

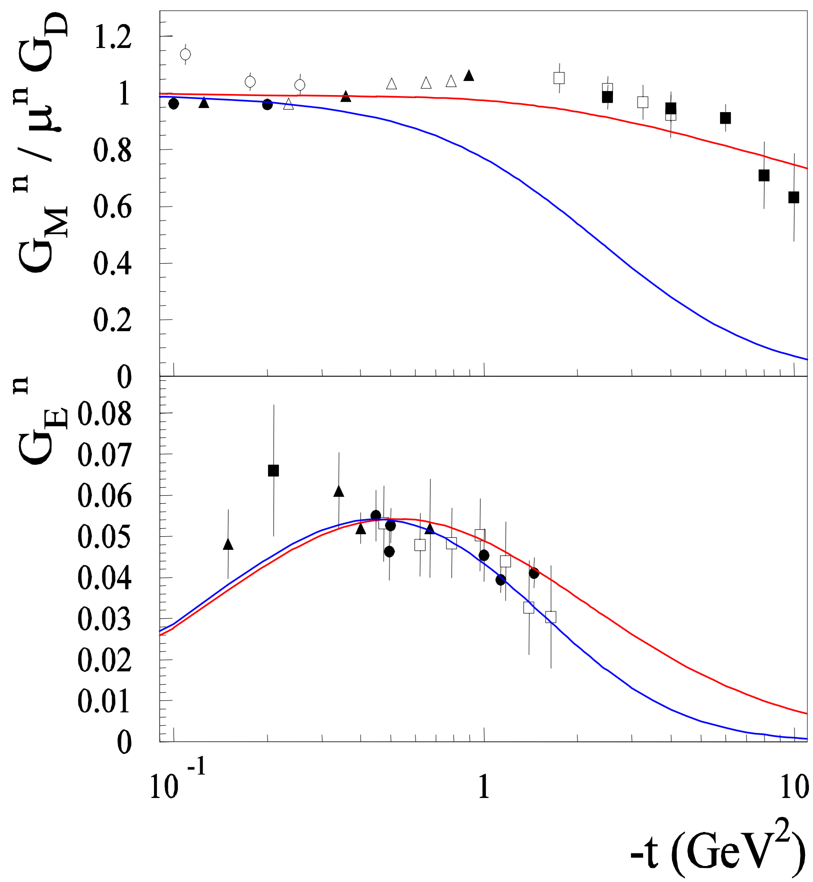
- future constraints : moments from lattice QCD see D. Richards

electromagnetic form factors

PROTON



NEUTRON



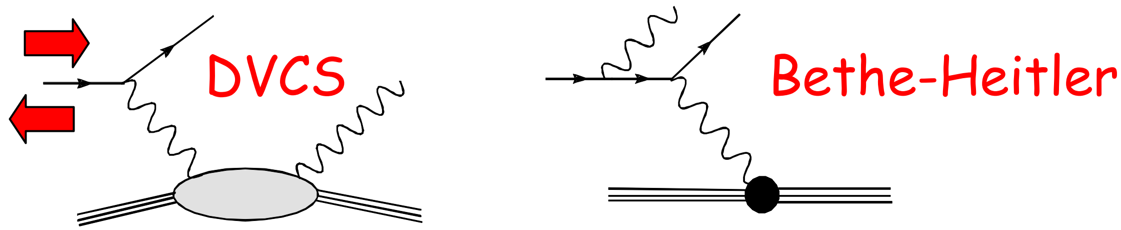
modified Regge parametrization

Regge parametrization

DVCS : beam spin asymmetry

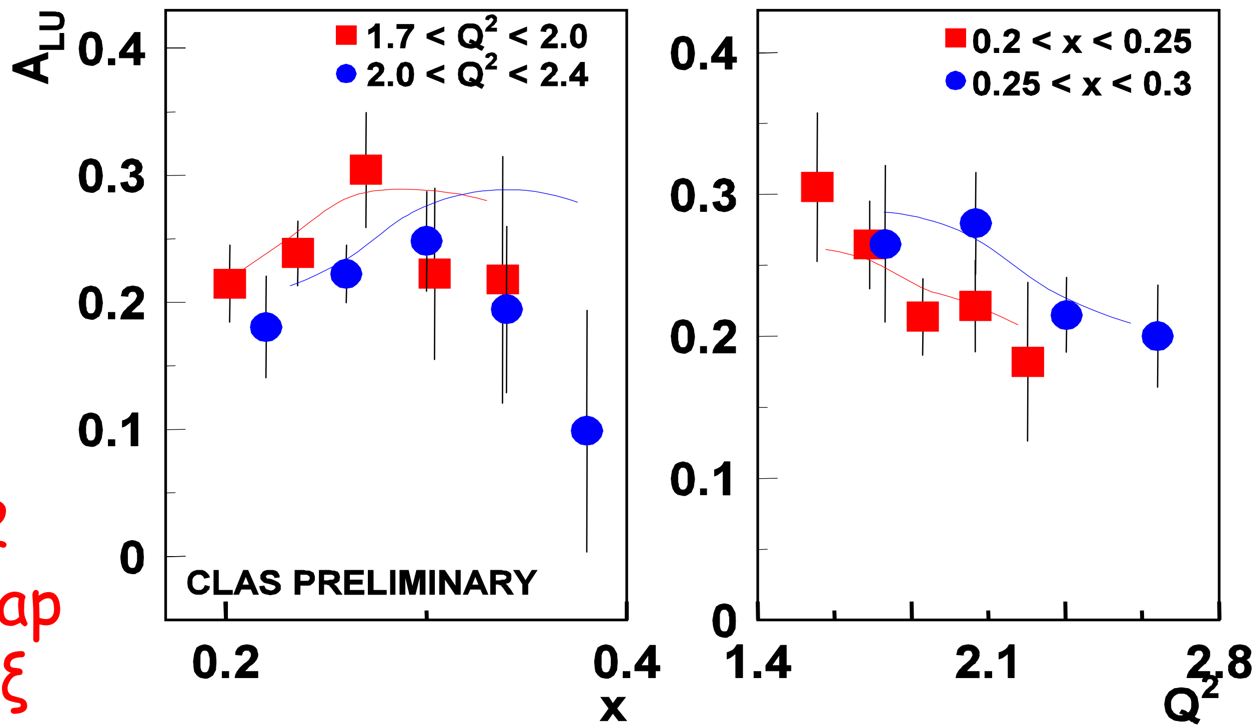
A_{LU} =

(BH) * Im(DVCS) * sin Φ



Process under theoretical control including twist-3 corrections

Extract twist-2 component and map out GPDs at x = ξ



twist-2 + twist-3 : Kivel, Polyakov, Vdh (2000)

Summary and outlook

- Form factors at large momentum transfer :

➡ extend analysis of two-photon exchange observables to larger Q^2 and to transition form factors , such as N -> Δ

- Hard exclusive processes :

➡ quantify power corrections (higher twist) to observables

➡ general parametrizations for Generalized Parton Distributions
inclusion of all constraints possible : form factors, lattice QCD calculations for higher moments, positivity

➡ mapping out nucleon GPDs :
get 3D image of transverse positions of quarks in nucleon for given longitudinal momentum (via Fourier transforms)