Hard Exclusive Processes : Perspectives

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Generalized Parton Distributions (GPDs) : 3D picture of nucleon

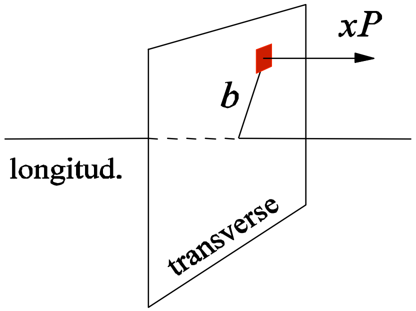
DIS
longitudinal
quark distribution
in momentum space

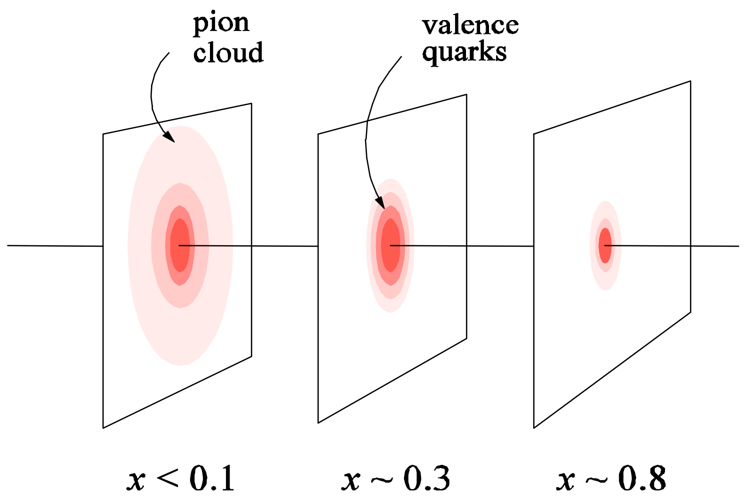
Unifying concept

GPDs

Elastic Scattering
transverse quark
distribution in
coordinate space

fully-correlated
quark distributions in **both**
coordinate and momentum space

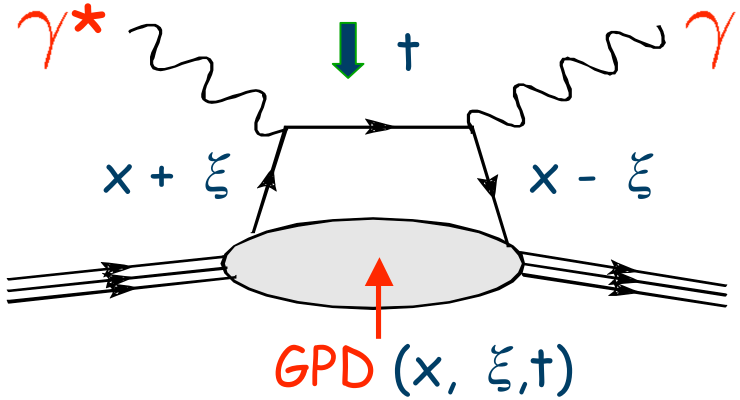




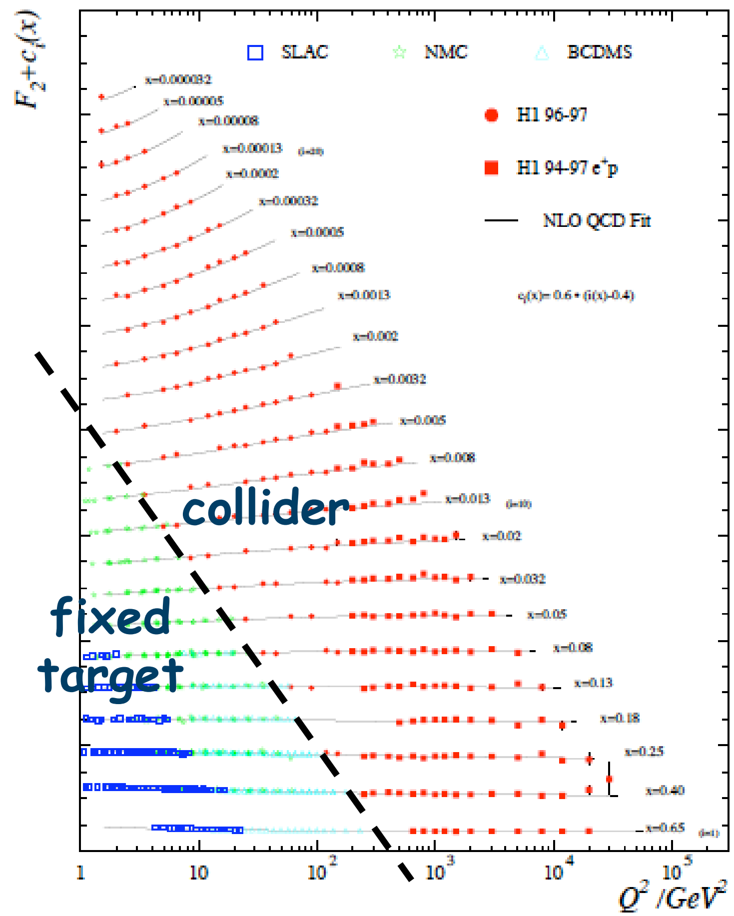
Burkardt (2000, 2003),
Belitsky, Ji, Yuan (2004)

QCD factorization : tool to access GPDs

$Q^2 >> 1\ GeV^2$



world data on proton F_2



- at large Q^2 : **QCD factorization theorem** :

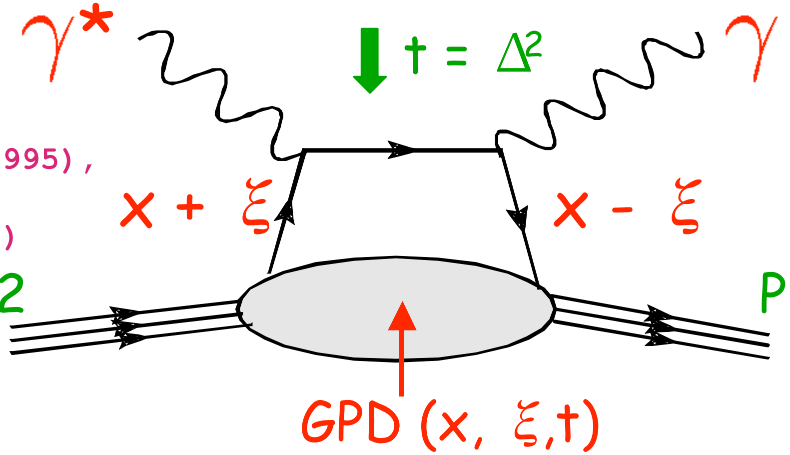
  hard exclusive process described by GPDs
  model independent !

  Müller et al. (1994),
  Ji (1995), Radyushkin (1995),
  Collins, Frankfurt, Strikman (1996)

- KEY Q^2 leverage required to test

  QCD scaling

Generalized Parton Distributions



➡ Müller et al. (1994), Ji (1995), Radyushkin (1995), Collins, Frankfurt, Strikman (1996)

low –t process : –t << Q²

$\Delta^+ = -(2\ \xi)\ P^+$

➡ light-cone dominance, $n^\mu(1, 0, 0, -1) / (2 P^+)$

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\,\langle P+\frac{\Delta}{2}\,|\,\bar{q}\left(-\frac{y}{2}\right)\,\gamma\cdot n\, q\left(\frac{y}{2}\right)\,|\,P-\frac{\Delta}{2}\rangle_{y^+=0,\, y_\perp=0}$$
$$= \bar{N}\left\{H(x,\xi,t)\,\gamma\cdot n\ +\ E(x,\xi,t)\, i\sigma^{\mu\nu}\frac{\Delta_\nu}{2M}n_\mu\right\} N$$

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\,\langle P+\frac{\Delta}{2}\,|\,\bar{q}\left(-\frac{y}{2}\right)\,\gamma\cdot n\,\gamma_5\, q\left(\frac{y}{2}\right)\,|\,P-\frac{\Delta}{2}\rangle_{y^+=0,\, y_\perp=0}$$
$$= \bar{N}\left\{\tilde{H}(x,\xi,t)\,\gamma\cdot n\,\gamma_5\ +\ \tilde{E}(x,\xi,t)\,\gamma_5\frac{\Delta^\mu}{2M}n_\mu\right\} N$$

known information on GPDs

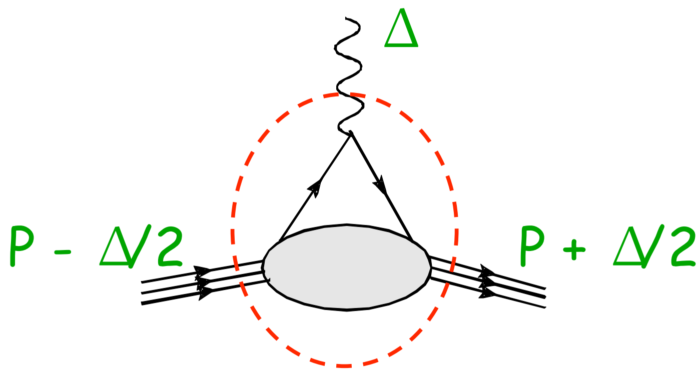
➡ forward limit : ordinary parton distributions

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

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

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

➡ first moments : nucleon electroweak form factors



ξ-independence :
Lorentz invariance

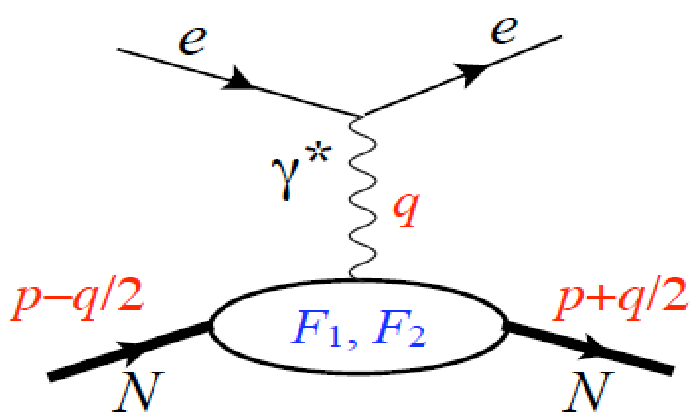
$$\int_{-1}^{1} dx\, H^q(x, \xi, t) = F_1^q(t) \quad \text{Dirac}$$

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

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

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

spin-1/2 electromagnetic form factors



- Elastic e p -> e p scattering is like an electron microscope to investigate nucleon structure

- In 1-photon exchange approximation : nucleon structure parameterized by 2 form factors

$$A^{\mu}_{\lambda\lambda'} = \langle p + \tfrac{1}{2}q, \lambda' | J^{\mu}(0) | p - \tfrac{1}{2}q, \lambda \rangle$$

$$= \bar{u}(p + \tfrac{1}{2}q, \lambda') \left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2) \frac{i}{2m} \sigma^{\mu\nu} q_{\nu} \right] u(p - \tfrac{1}{2}q, \lambda)$$

Dirac **Pauli**

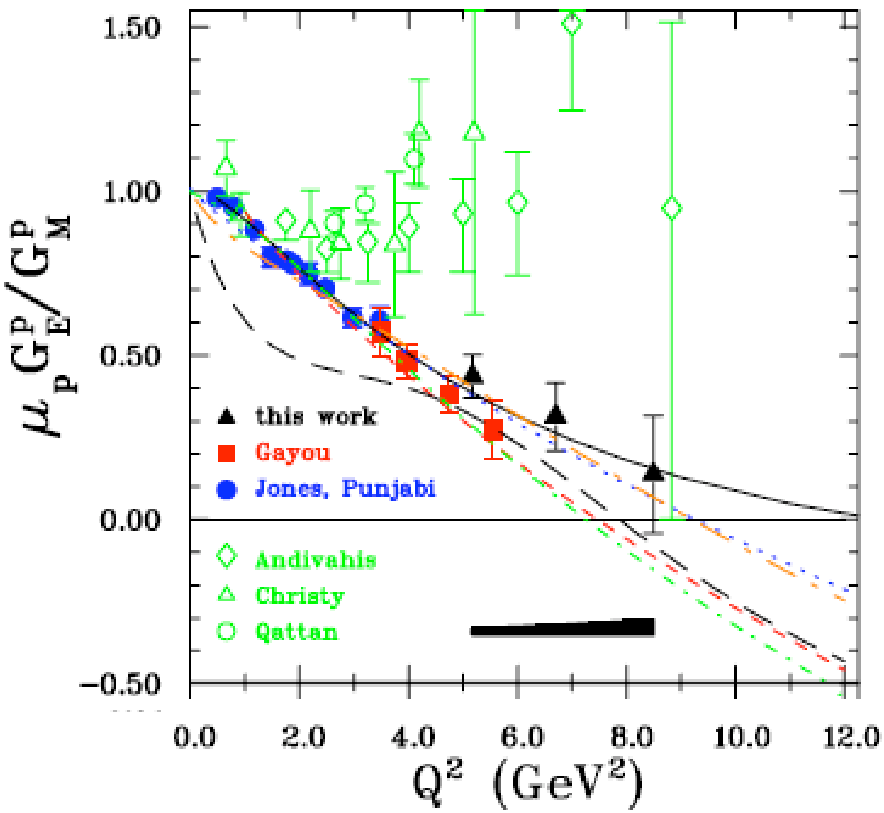
F_1 helicity conserving , F_2 helicity flip form factors

- Alternatively, the Sachs form factors

$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$, $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$, with $\tau = Q^2/4\,m^2$

Traditionally : it is assumed that in the Breit frame, and for non-relativistic systems with m >> Q, G_E and G_M are 3-dim Fourier transforms of charge- and current distributions.

Nucleon e.m. Form Factors :
new experiments

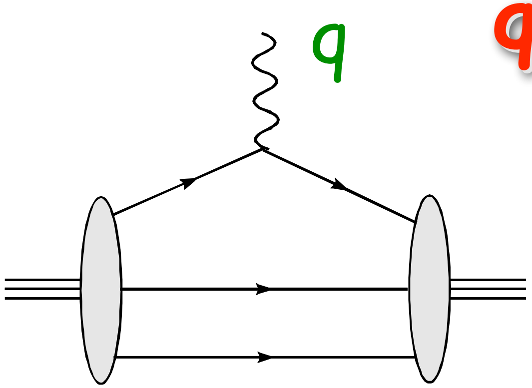


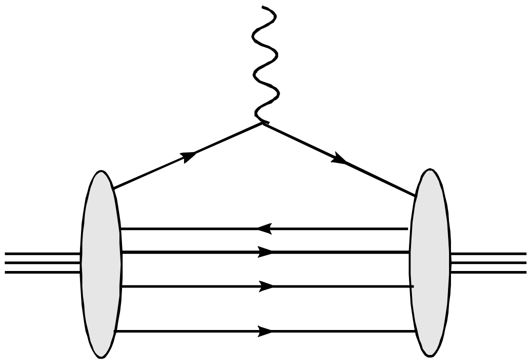
see talks :

Puckett, De Jager

Spin-1/2 transverse densities

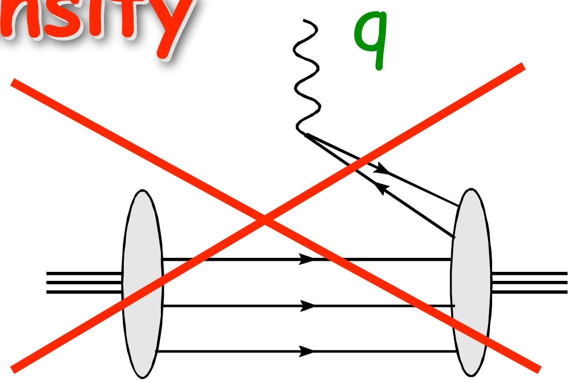
interpretation of Form Factor as quark density





overlap of wave function Fock components with same number of quarks

interpretation as probability/charge density



overlap of wave function Fock components with different number of constituents

NO probability/charge density interpretation

absent in a LIGHT-FRONT frame !

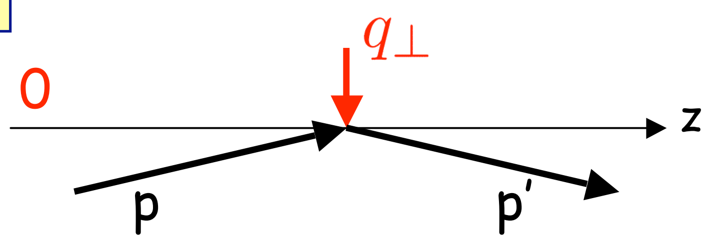
$$q^{+} = q^{0} + q^{3} = 0$$

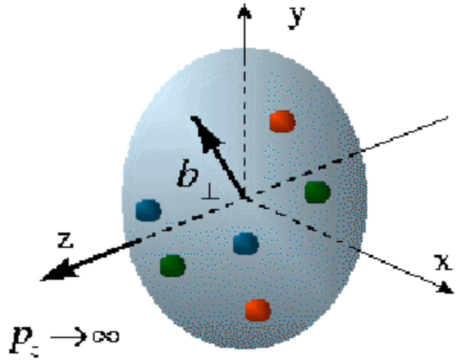
quark transverse charge densities in nucleon (I)

light-front

- $q^+ = q^0 + q^3 = 0$

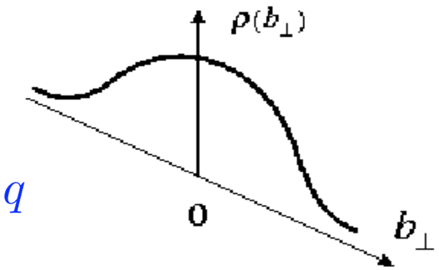
  $Q^2 \equiv \vec{q}_\perp^{\,2}$





photon only couples to forward moving quarks

- quark charge density operator



$$J^+ \equiv J^0 + J^3 = \bar{q}\gamma^+ q = 2\, q_+^\dagger\, q_+, \quad \text{with} \quad q_+ \equiv \frac{1}{4}\gamma^-\gamma^+ q$$

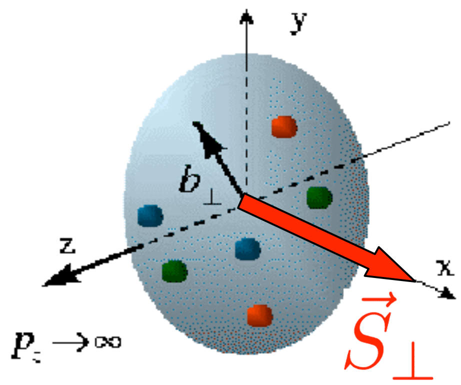
☆ longitudinally polarized nucleon

$$\rho_0^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\,\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+}\, \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle$$

$$= \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\, Q) F_1(Q^2)$$

Miller (2007)

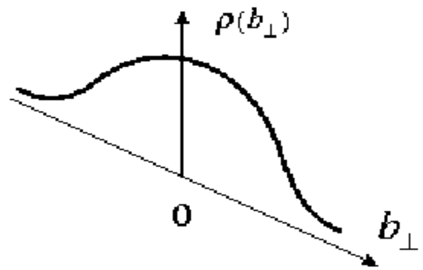
quark transverse charge densities in nucleon (II)



☆ transversely polarized nucleon

transverse spin $\vec{S}_\perp = \cos\phi_S\,\hat{e}_x + \sin\phi_S\,\hat{e}_y$

e.g. along x-axis : $\phi_S = 0$



$$\vec{b} = b\,(\cos\phi_b\,\hat{e}_x + \sin\phi_b\,\hat{e}_y)$$

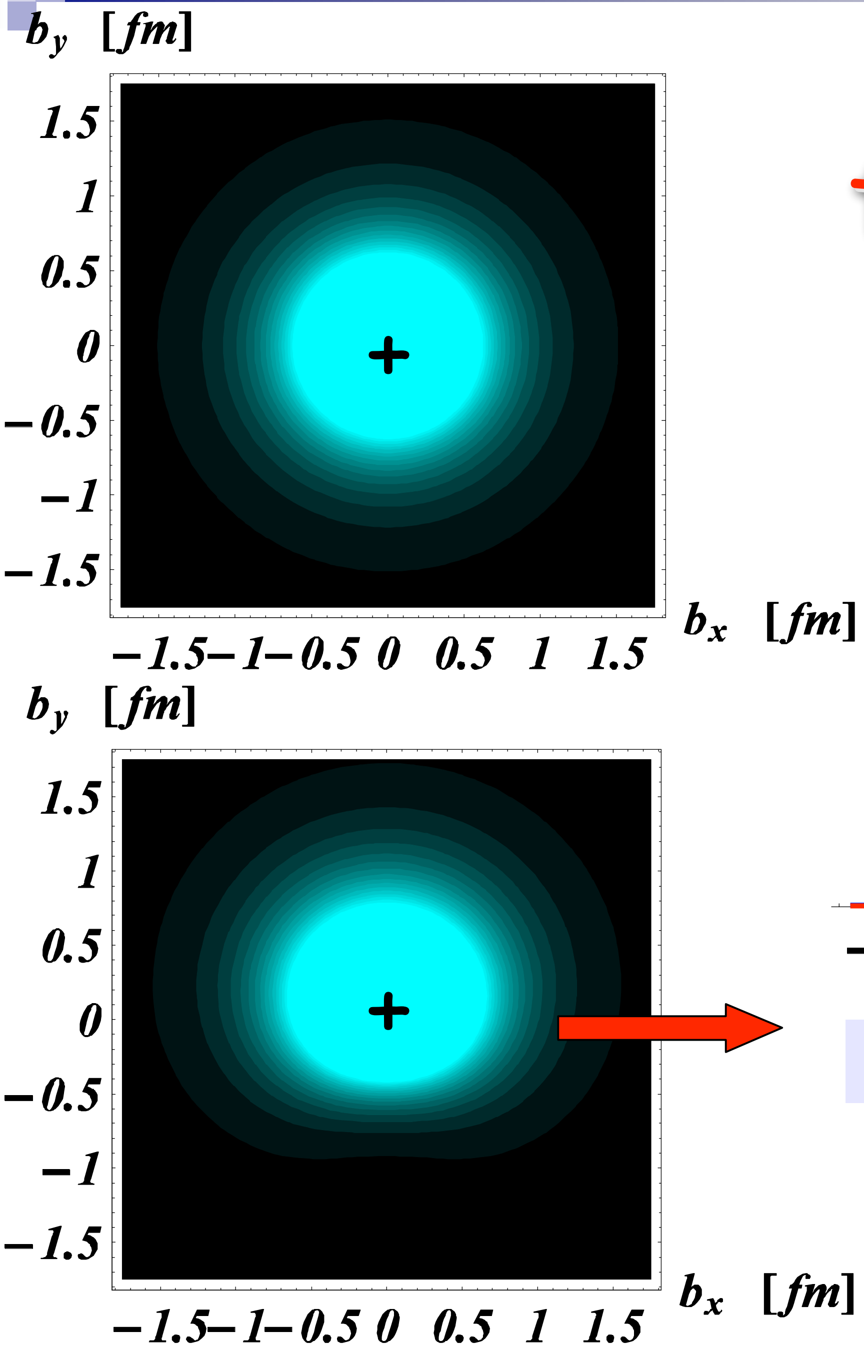
$$\rho_T^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\,\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+}\,\langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2}\,|\,J^+(0)\,|\,P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2}\rangle$$

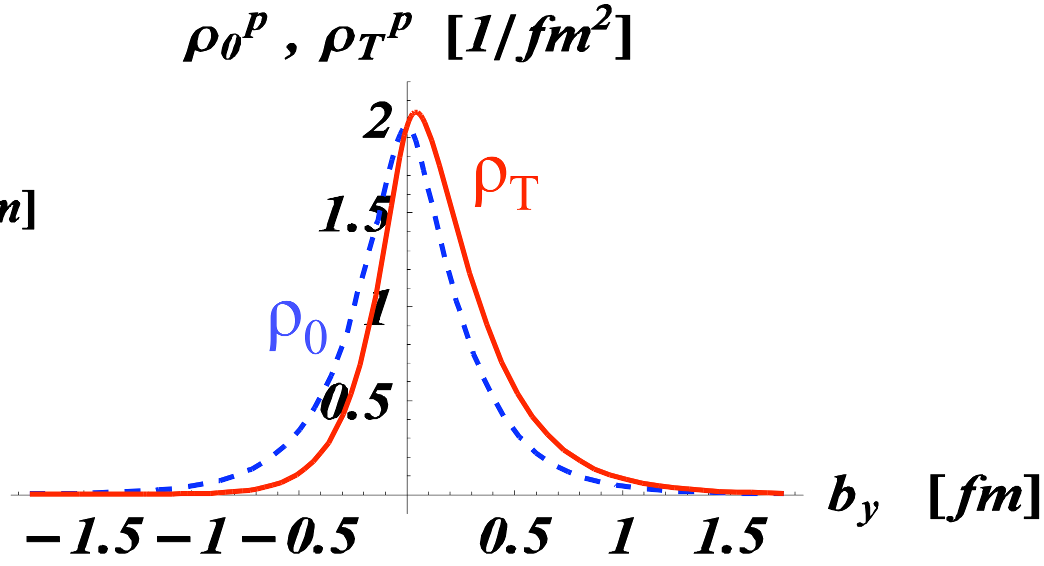
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S)\int_0^\infty \frac{dQ}{2\pi}\,\frac{Q^2}{2M_N}\,J_1(b\,Q)F_2(Q^2)$$

dipole field pattern

Carlson, Vdh (2007)

empirical quark transverse densities in proton



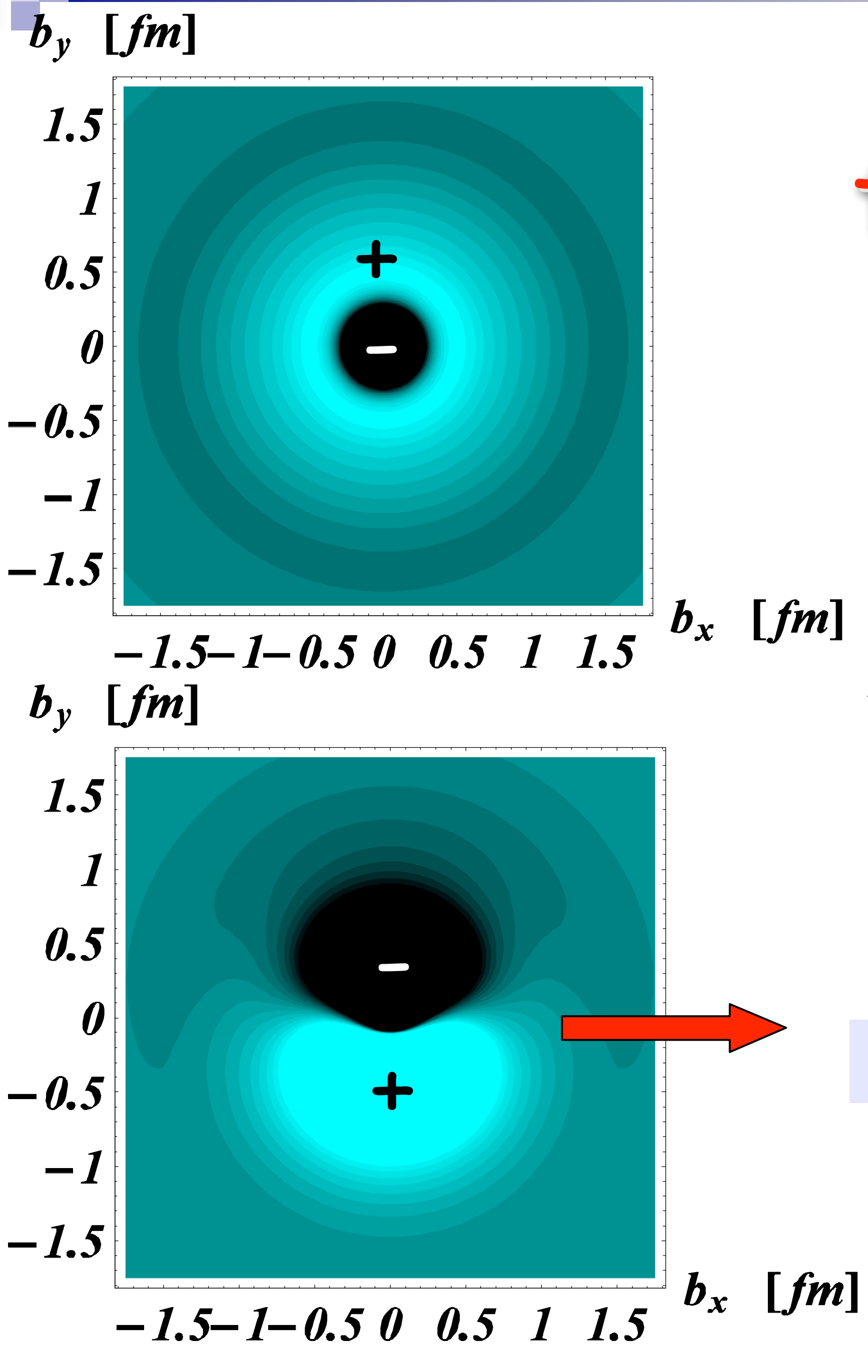


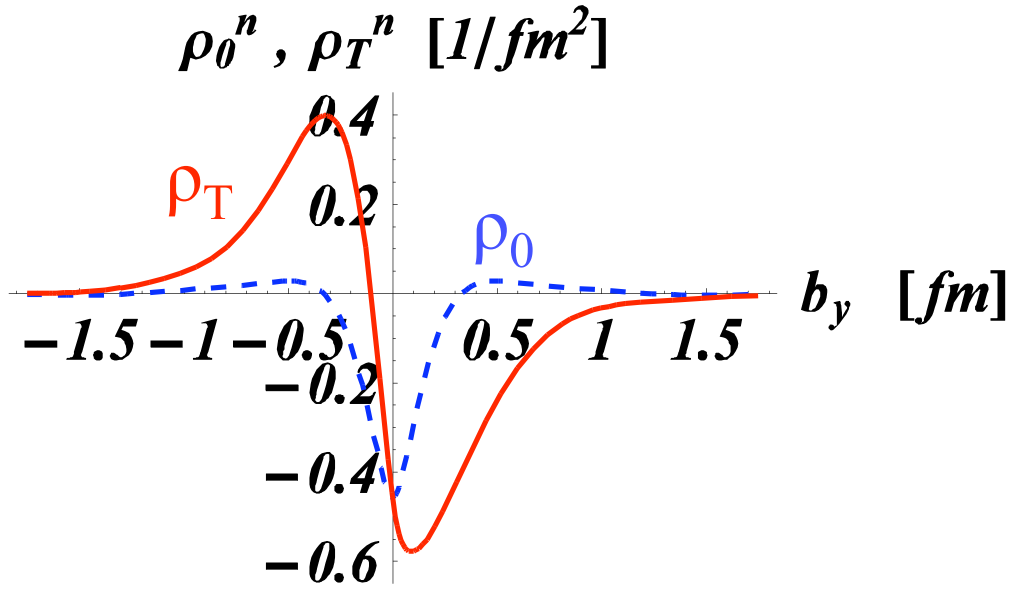
induced EDM : $d_y = F_{2p}(0) \cdot e / (2 M_N)$

data : Arrington, Melnitchouk, Tjon (2007)

densities : Miller (2007); Carlson, Vdh (2007)

empirical quark transverse densities in neutron





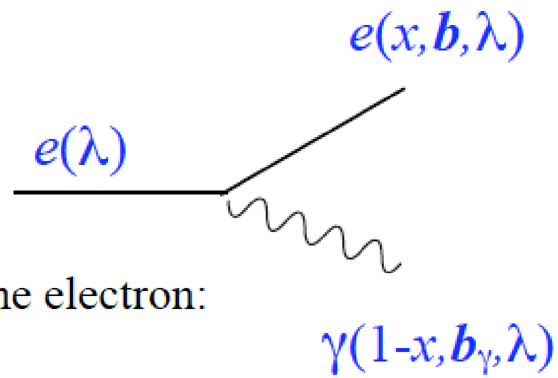
induced **EDM** : $d_y = F_{2n}(0) \,.\, e\,/\,(2\,M_N)$

data: Bradford, Bodek, Budd, Arrington (2006)

densities : Miller (2007); Carlson, Vdh (2007)

transverse densities of eγ Fock state in electron

Hoyer, Kurki (2009)



The wave functions give the densities of the $|e\gamma\rangle$ Fock state of the electron:

$$\rho_0(x,\boldsymbol{b}) = \frac{\alpha m^2}{2\pi^2}\left[\frac{1+x^2}{1-x}K_1^2(mb) + (1-x)\,K_0^2(mb)\right]$$

LC Wavefunction :

Brodsky, Drell (1980)

$$\rho_x(x,\boldsymbol{b}) = \rho_0(x,\boldsymbol{b}) + \frac{\alpha m^2}{\pi^2}x\,\sin(\phi_b)\,K_0(mb)K_1(mb)$$

from which the Pauli form factor is obtained (exact at order α)

$$F_2(Q^2) = \frac{4\alpha m^3}{\pi Q}\int_0^1 dx\,x\int_0^\infty db\,b\,J_1(b\,Q)K_0(mb)K_1(mb)$$

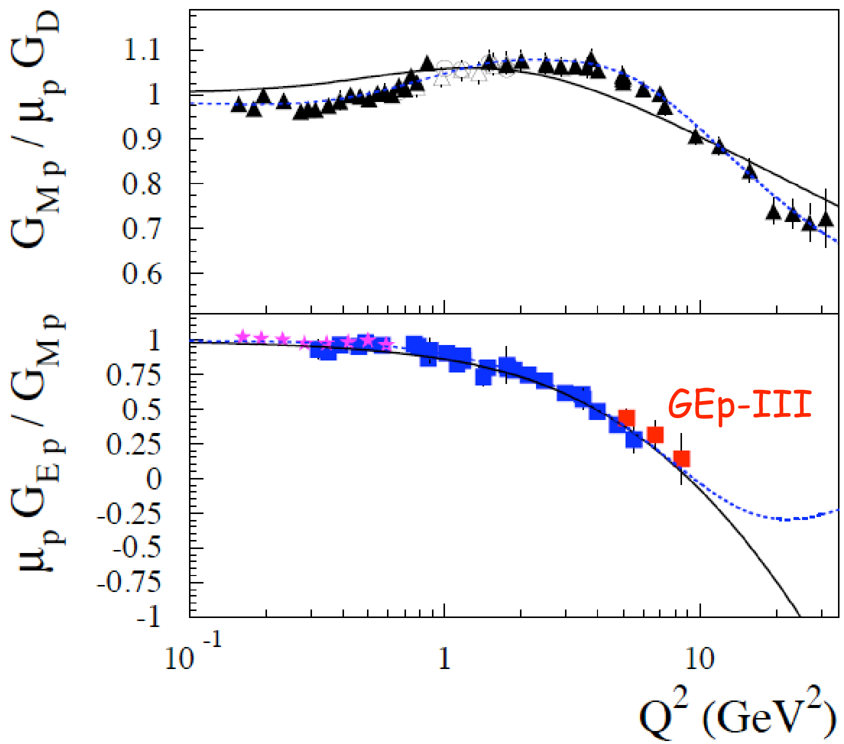
x- and b-dependence factorizes

$$= \frac{2\alpha m^2}{\pi}\frac{1}{Q\sqrt{Q^2+4m^2}}\log\left[\frac{1}{2m}\left(\sqrt{Q^2+4m^2}+Q\right)\right]$$

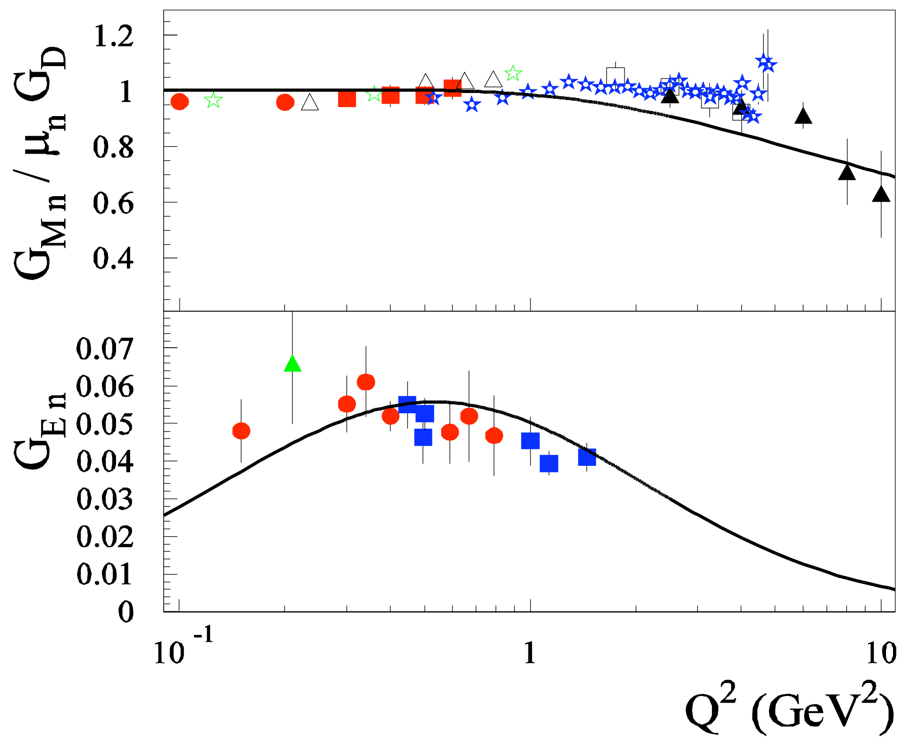
Exact expression from loop integral

electromagnetic form factors

PROTON



NEUTRON



→ modified Regge GPD parameterization

3-parameter fit
- 1 : Regge slope -> proton Dirac (Pauli) radius
- 2, 3 : large x behavior of GPD E^u, E^d -> large Q^2 behavior of F_{2p}, F_{2n}

Guidal, Polyakov, Radyushkin, Vdh (2005)

also Diehl, Feldmann, Jakob, Kroll (2005)

connection large Q^2 of FF <-> large x of GPD

$$I = \int_0^1 dx (1-x)^\nu \, e^{\alpha' Q^2 (1-x) \ln x} = \int_0^1 dx e^{\nu \ln(1-x) + \alpha' Q^2 (1-x) \ln x}$$

$$= \int_0^1 dx \, e^{f(x, Q^2)}$$

at large Q^2 : integral dominated by maximum of $f(x,Q^2)$, remainder region is exp. suppressed (method of steepest descent)

$f(x,Q^2)$ reaches maximum for : $x = x_0 \simeq 1 - \frac{\nu}{\alpha' Q^2}$

"Drell-Yan-West" relation for PDF/GPD :

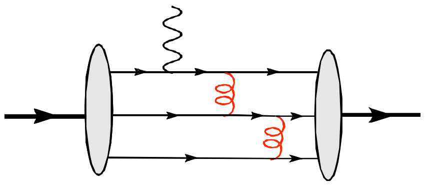
at large Q^2 : I is dominated by its behavior around x -> 1

$$I \simeq e^{f(x_0, Q^2)} \left(\frac{2}{f''(x_0, Q^2)} \right)^{1/2} \frac{\sqrt{\pi}}{2} \sim \left(\frac{1}{\alpha' Q^2} \right)^{(\nu+1)/2}$$

proton Dirac & Pauli FFs :

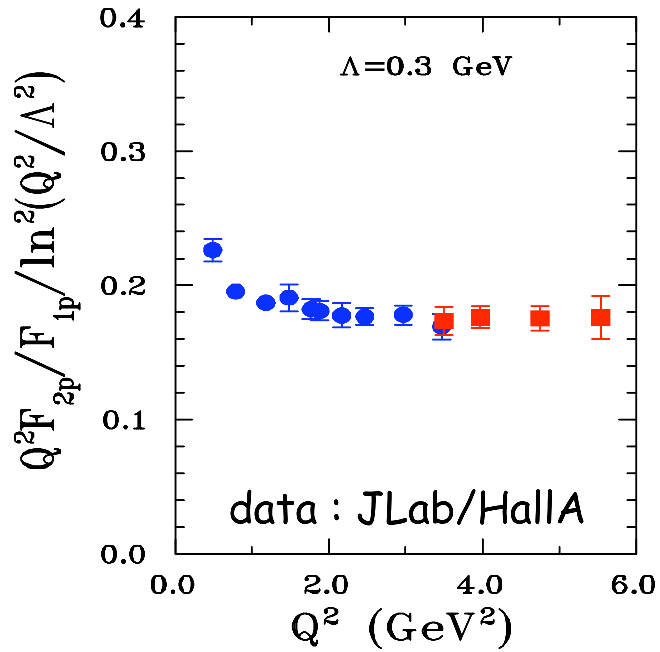
$$\begin{cases} G_M = F_1 + F_2 \\ G_E = F_1 - \left(\frac{Q^2}{4M_N^2}\right) F_2 \end{cases}$$

PQCD



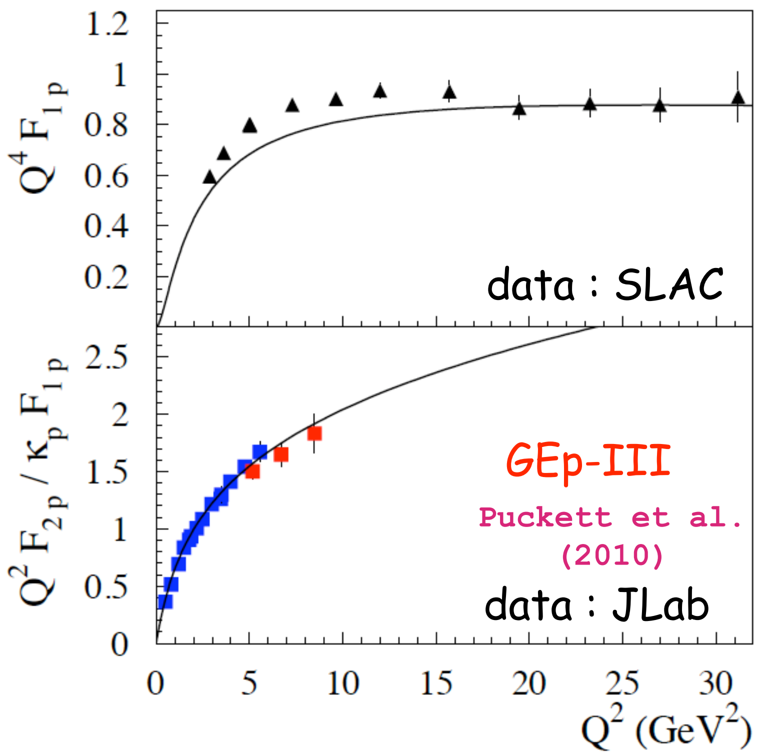
GPD framework

$$\frac{F_{2\,p}}{F_{1\,p}} \sim \frac{\ln^2(Q^2/\Lambda^2)}{Q^2}$$



Beltisky, Ji, Yuan (2003)

modified Regge GPD model



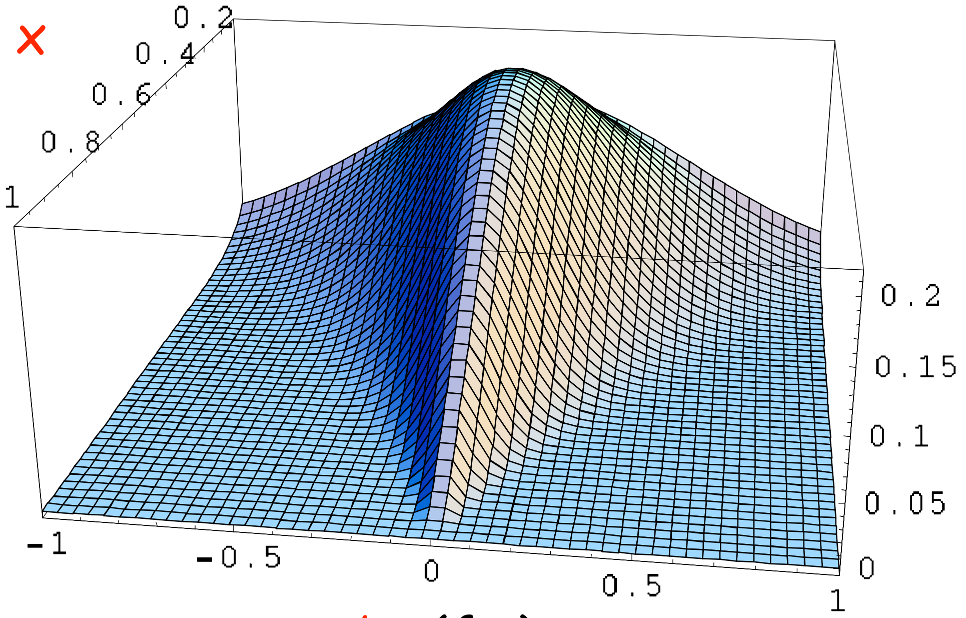
Guidal, Polyakov, Radyushkin, Vdh (2005)

GPDs : transverse image of nucleon

GPDs : quark distributions w.r.t. longitudinal momentum x and transverse position $b_\perp$

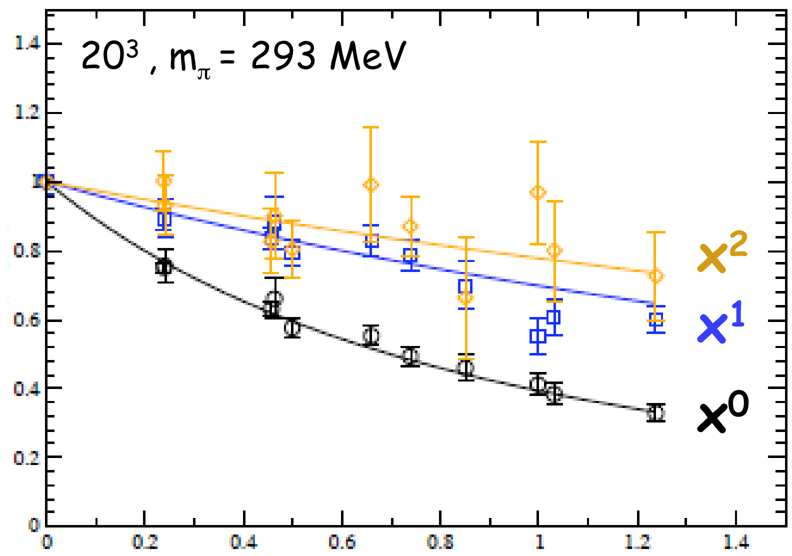
lattice QCD : moments of GPDs

$H^u(x, b_\perp)$



$b_\perp$ (fm)

x^n moment of H^{u-d}



$-t$ (GeV^2)

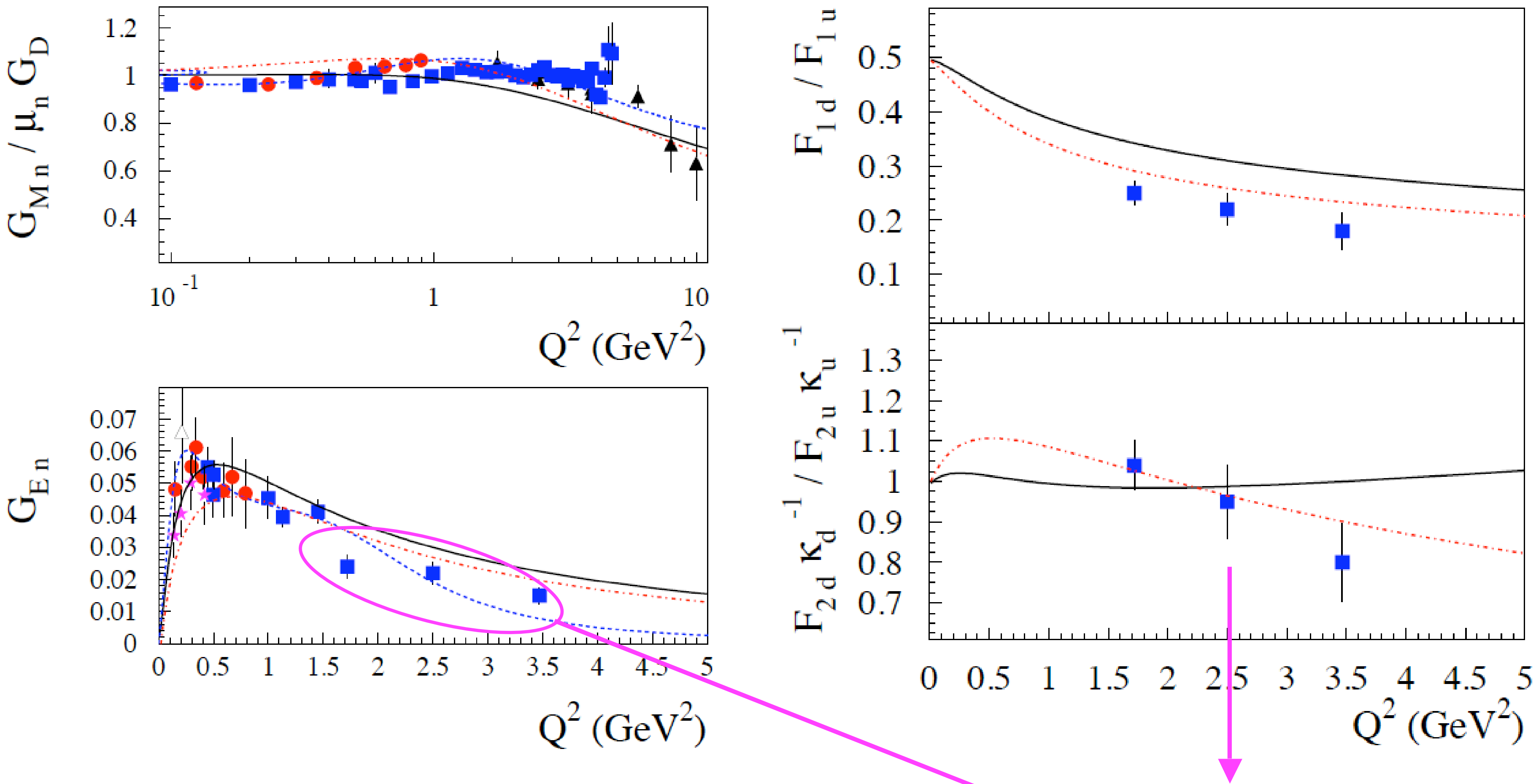
Fourier transform

LHPC Coll.

Guidal, Polyakov, Radyushkin, Vdh (2005),

Diehl, Feldmann, Jakob, Kroll (2005)

neutron e.m. form factors



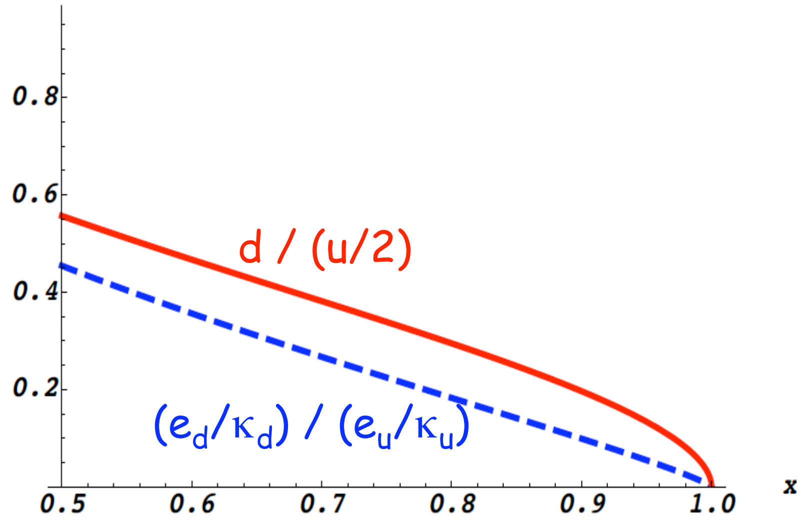
- - - - Phenomenological fit : Bradford et al.

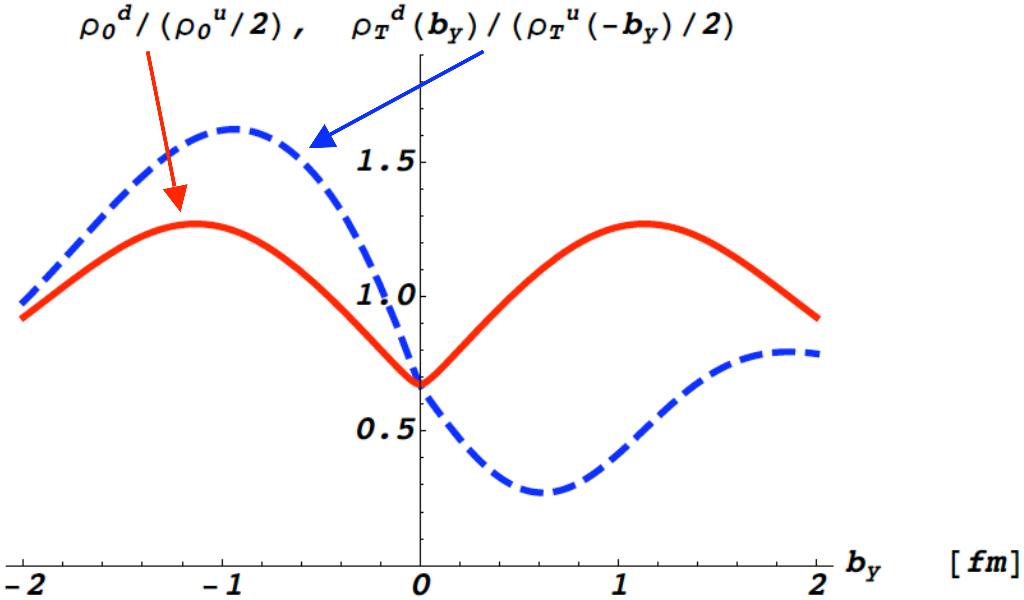
——— modified Regge GPD parameterization (3 parameters)

-·-·-· modified Regge GPD parameterization (6 parameters)

Jlab/HallA E02-013
preliminary

d/u quark densities





d-quark distr. : further spread out in proton than u-quark distr.

Opposite behavior for neutron

GPDs : total angular momentum sum rule

➡ total angular momentum $J^q = \frac{1}{2}\Delta q + L^q$ ← quark **orbital** angular momentum

X. Ji (1997)

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

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

➡ Valence parametrization for **GPD** ***E*** ^{q} :

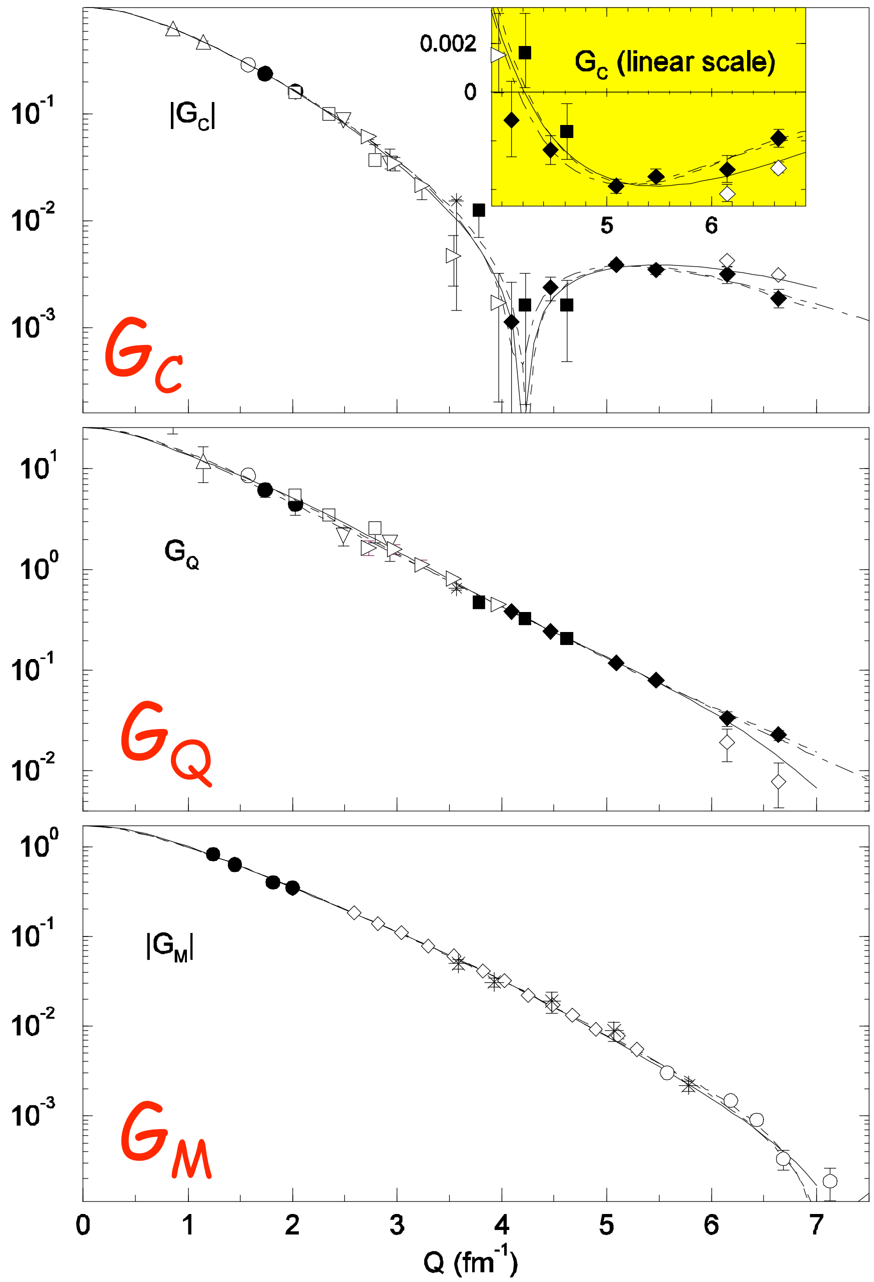
PROTON	M_2^q	$2\,J^q$ GPD model	$2\,J^q$ Lattice (LHPC) (4 GeV^2)
u	0.37	0.58	≈ 0.47
d	0.20	-0.06	≈ 0.00
s	0.04	0.04	
u + d + s	**0.61**	**0.56**	

lattice : full QCD,

no disconnected diagrams so far

see talk : Hägler

Higher Spin transverse densities



deuteron

e.m. FFs

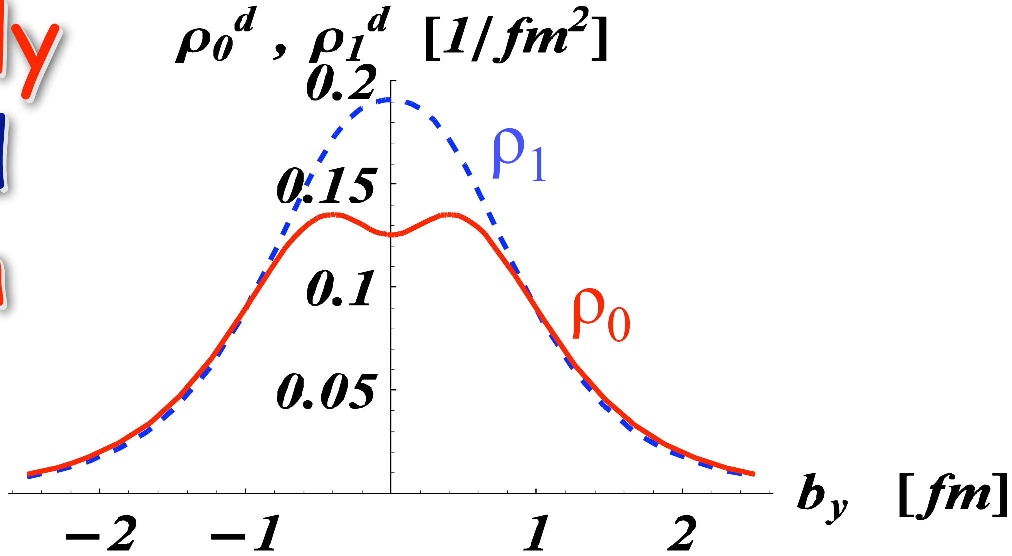
separated data (measuring t_{20})

up to about 2 GeV^2

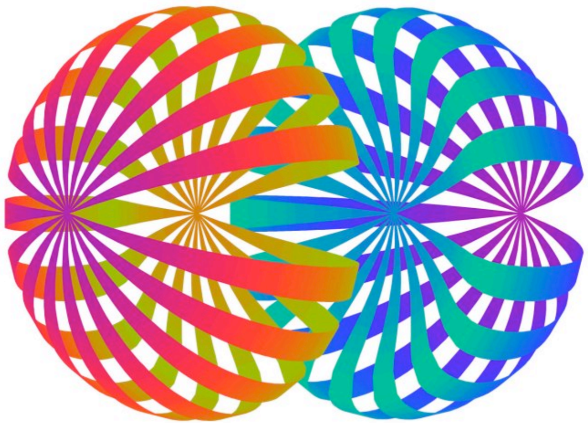
Abbott et al.(2000)

$$G_M(0) = 1.71$$
$$G_Q(0) = 25.84(3)$$

longitudinally polarized deuteron



$\lambda = \pm 1$



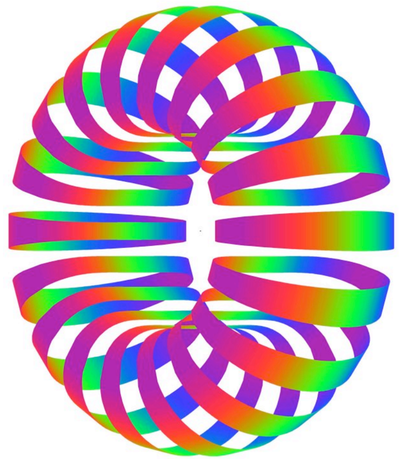
deuteron equidensity surfaces

(ρ_d = 0.24 fm^{-3})

from Argonne v_{18} :

Forest et al. (1996)

$\lambda = 0$



transversely polarized deuteron

$$Q^d_{s_\perp} \equiv e \int d^2\vec{b}\,(b_x^2 - b_y^2)\,\rho^d_{T\,s_\perp}(\vec{b})$$

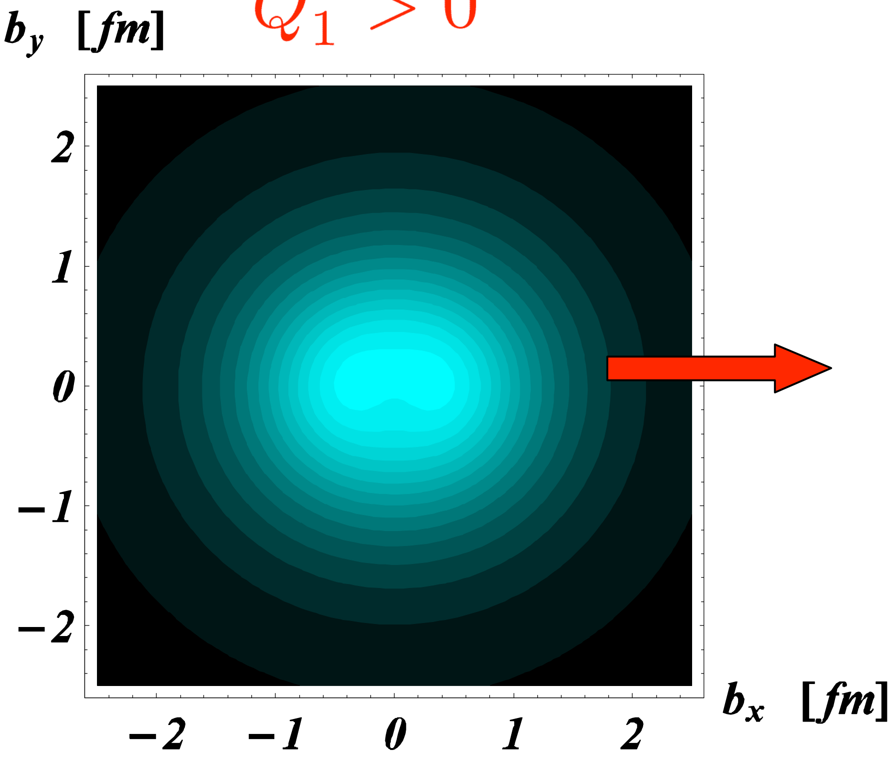
$$Q^d_1 = -\frac{1}{2} Q^d_0 = \frac{1}{2}\{[G_M(0) - 2] + [G_Q(0) + 1]\}\left(\frac{e}{M_d^2}\right)$$

experiment :

$$G_M(0) = 1.71$$
$$G_Q(0) = 25.84(3)$$

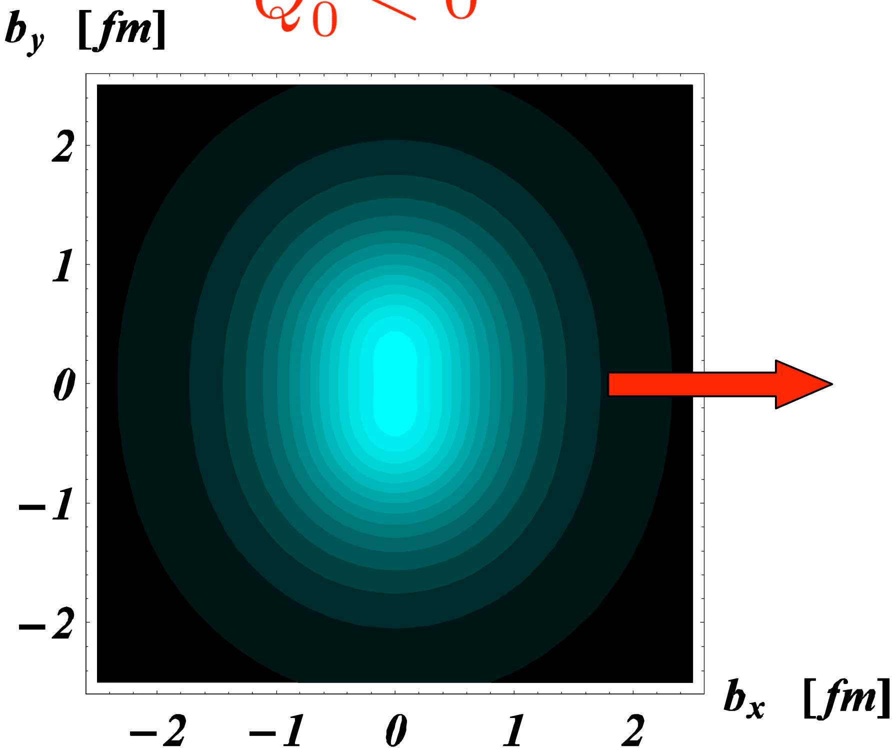
$s_\perp = +1$

$Q^d_1 > 0$



$s_\perp = 0$

$Q^d_0 < 0$



E.M. moments of W bosons

for spin-1 point particle

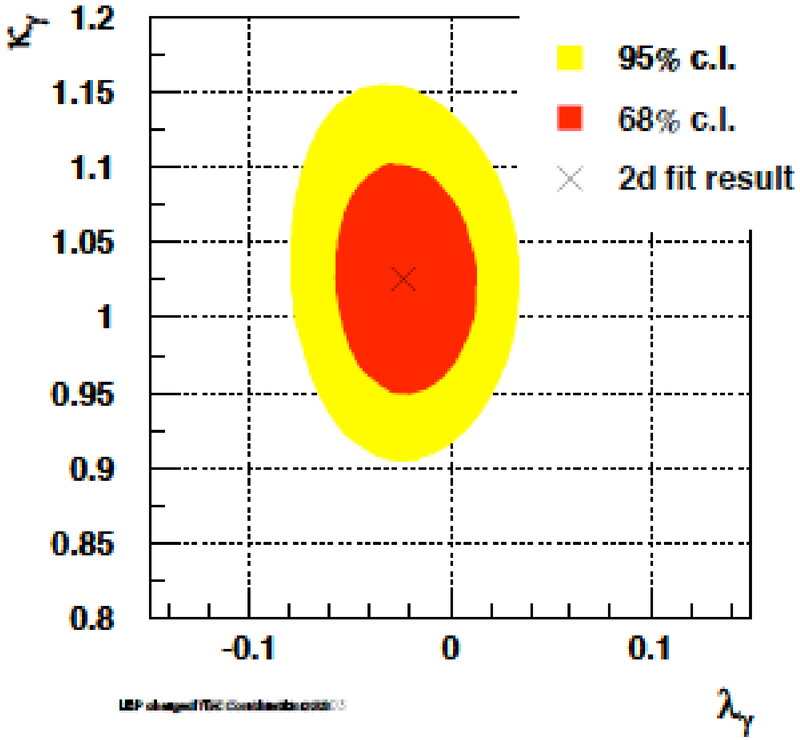
$G_M(0) = 2$ and $G_Q(0) = -1$

$$\mu = \frac{e}{2M_W}\{2 + (\kappa - 1) + \lambda\}$$

$$Q = -\frac{e}{M_W^2}\{1 + (\kappa - 1) - \lambda\}$$

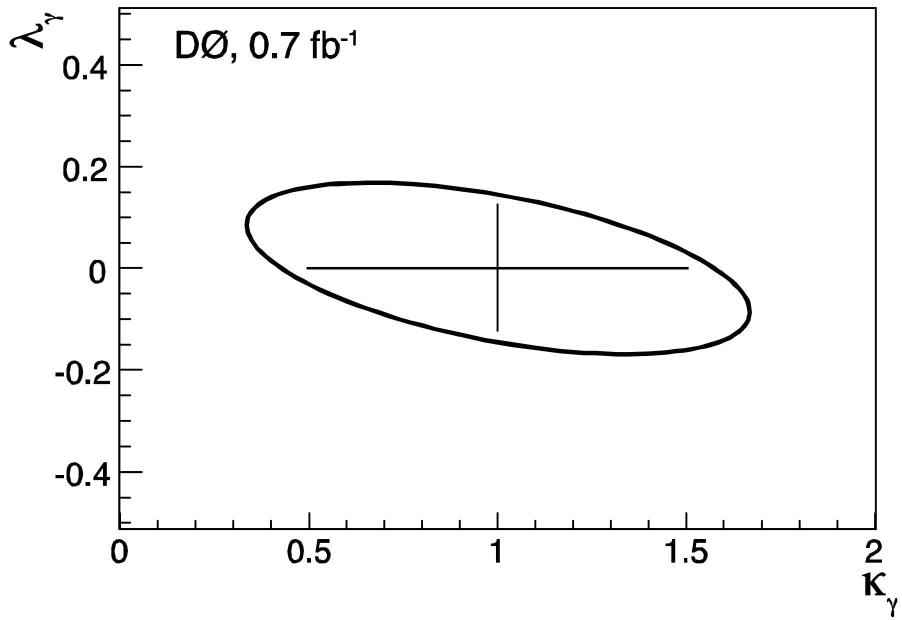
LEP Electroweak working group

hep-ex/0612034



D0 Collaboration

PRL100, 241805 (2008)



natural values for e.m. moments of point particle with spin j

Lorcé (2008)

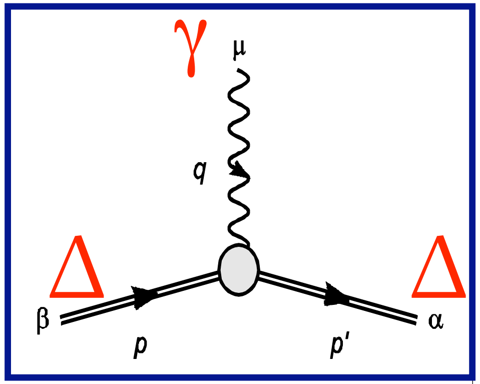
see talk : Lorcé

$$
\begin{aligned}
G_{E0}(0) &= 1 \\
G_{M1}(0) &= 2j \\
G_{E2}(0) &= -j(2j-1) \\
G_{M3}(0) &= -\frac{1}{3}j(2j-1)(2j-2)
\end{aligned}
$$

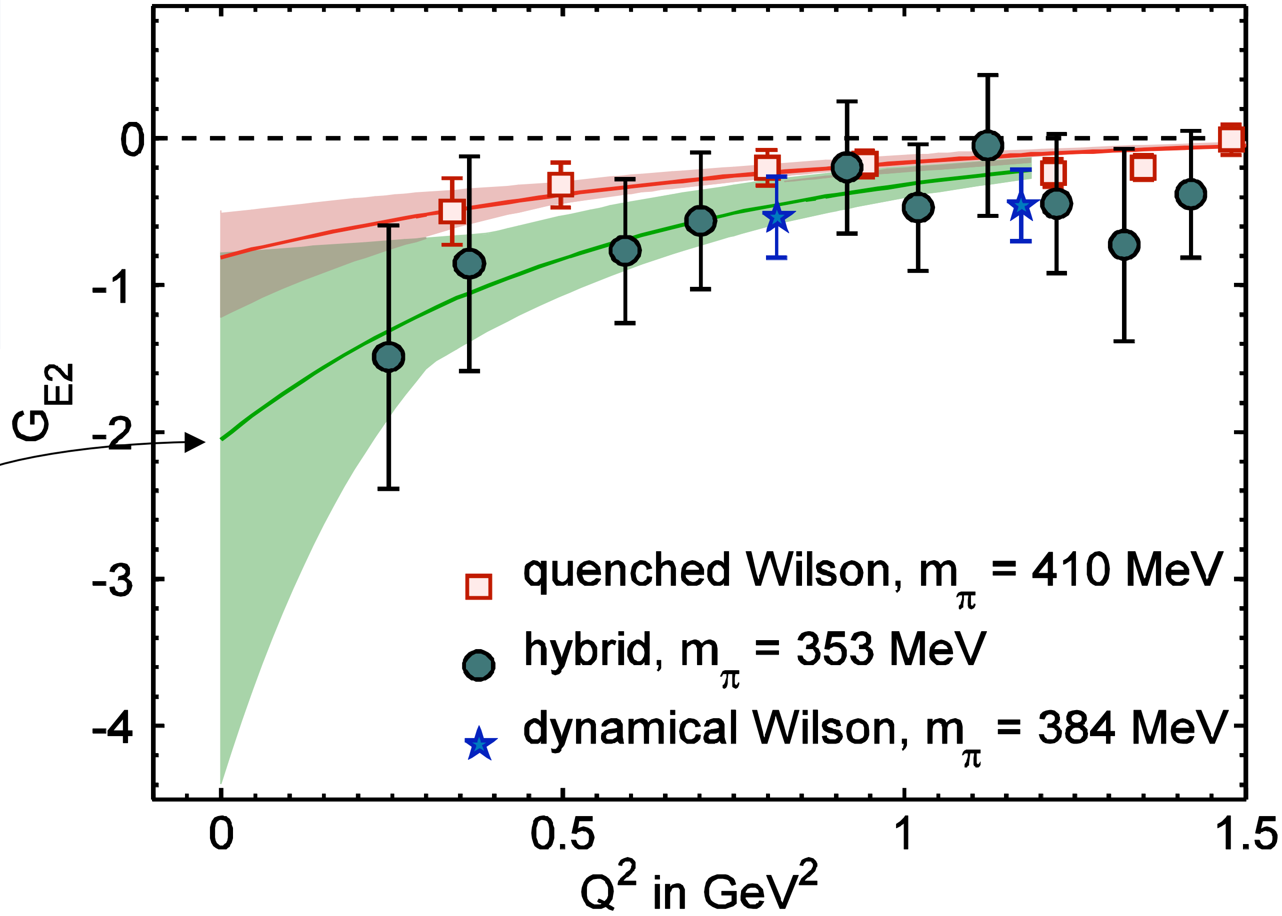
j	$G_{E0}(0)$	$G_{M1}(0)$	$G_{E2}(0)$	$G_{M3}(0)$	$G_{E4}(0)$	$G_{M5}(0)$	$G_{E6}(0)$
0	1	0	0	0	0	0	0
1/2	1	1	0	0	0	0	0
1	1	2	-1	0	0	0	0
3/2	1	3	-3	-1	0	0	0
2	1	4	-6	-4	1	0	0
5/2	1	5	-10	-10	5	1	0
3	1	6	-15	-20	15	6	-1
...							

➡ transverse charge densities depend only on anomalous values of e.m. moments ➡ reflect internal structure

Hadron shape : e.m. Δ to Δ transition



C0 , M1 ,
C2 , M3
transitions



lattice analysis :

Alexandrou, Korzec, Koutsou, Leontiou, Lorcé, Negele, Pascalutsa, Tsapalis, Vdh (2008)

quark transverse charge densities in Δ(1232)

$$\rho^{\Delta}_{T\,s_\perp}(\vec{b}) \;\equiv\; \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\,\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, s_\perp \rangle$$

$$Q^{\Delta}_{s_\perp} \equiv e \int d^2\vec{b}\, (b_x^2 - b_y^2)\, \rho^{\Delta}_{T\,s_\perp}(\vec{b})$$

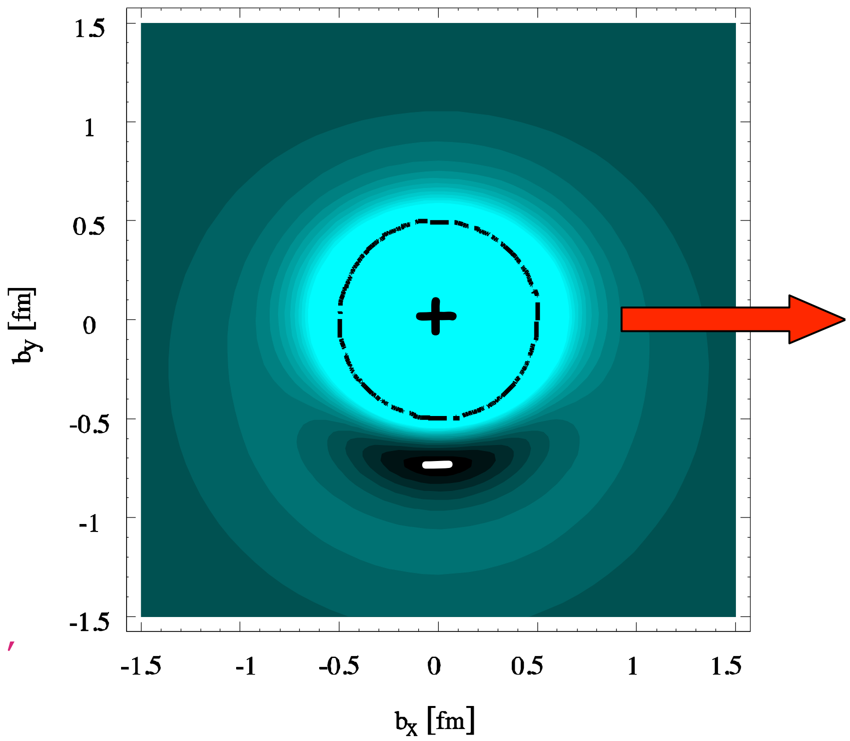
$$Q^{\Delta}_{\frac{3}{2}} = -Q^{\Delta}_{\frac{1}{2}} \;=\; \frac{1}{2}\, \{2\,[G_{M1}(0) - 3e_\Delta] + [G_{E2}(0) + 3e_\Delta]\} \left(\frac{e}{M_\Delta^2}\right)$$

$s_\perp = +3/2$

for spin-3/2 point particle

$G_{M1}(0) = 3e_\Delta$ and $G_{E2}(0) = -3e_\Delta$

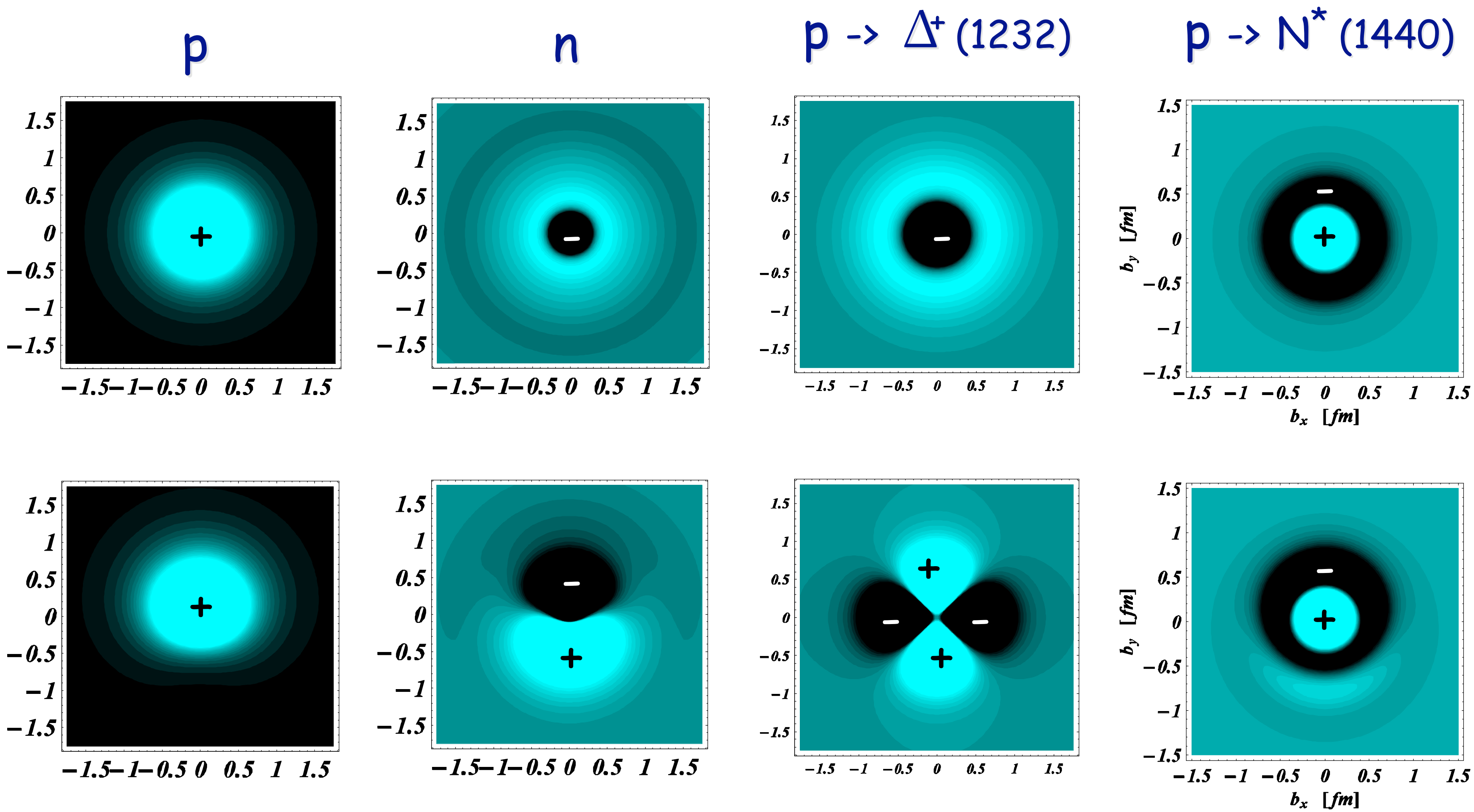
transverse charge densities
depend only on anomalous
values of e.m. moments
-> reflect internal structure



lattice analysis :

Alexandrou, Korzec, Koutsou, Leontiou, Lorcé, Negele, Pascalutsa, Tsapalis, Vdh (2008)

empirical transverse transition densities



Carlson, Vdh (2007)

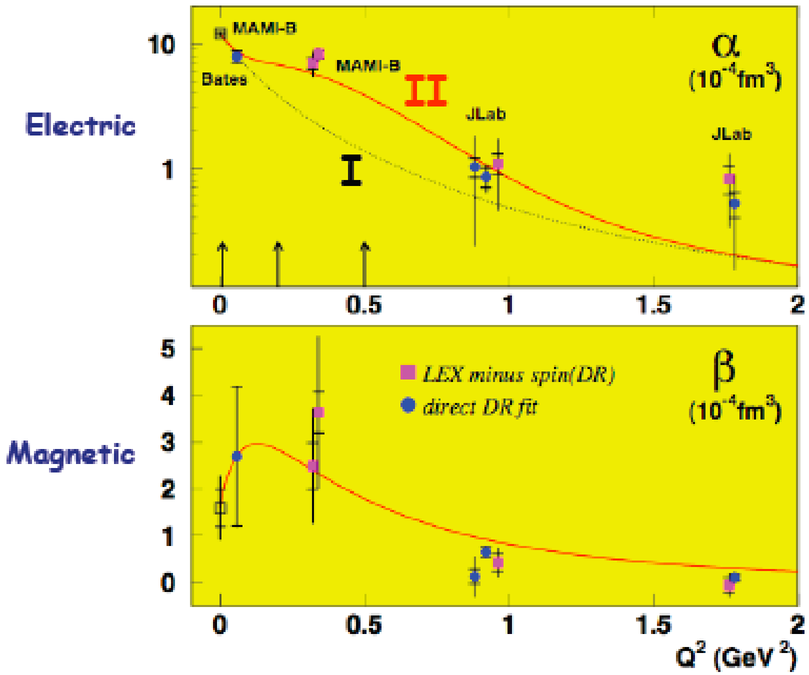
quadrupole pattern

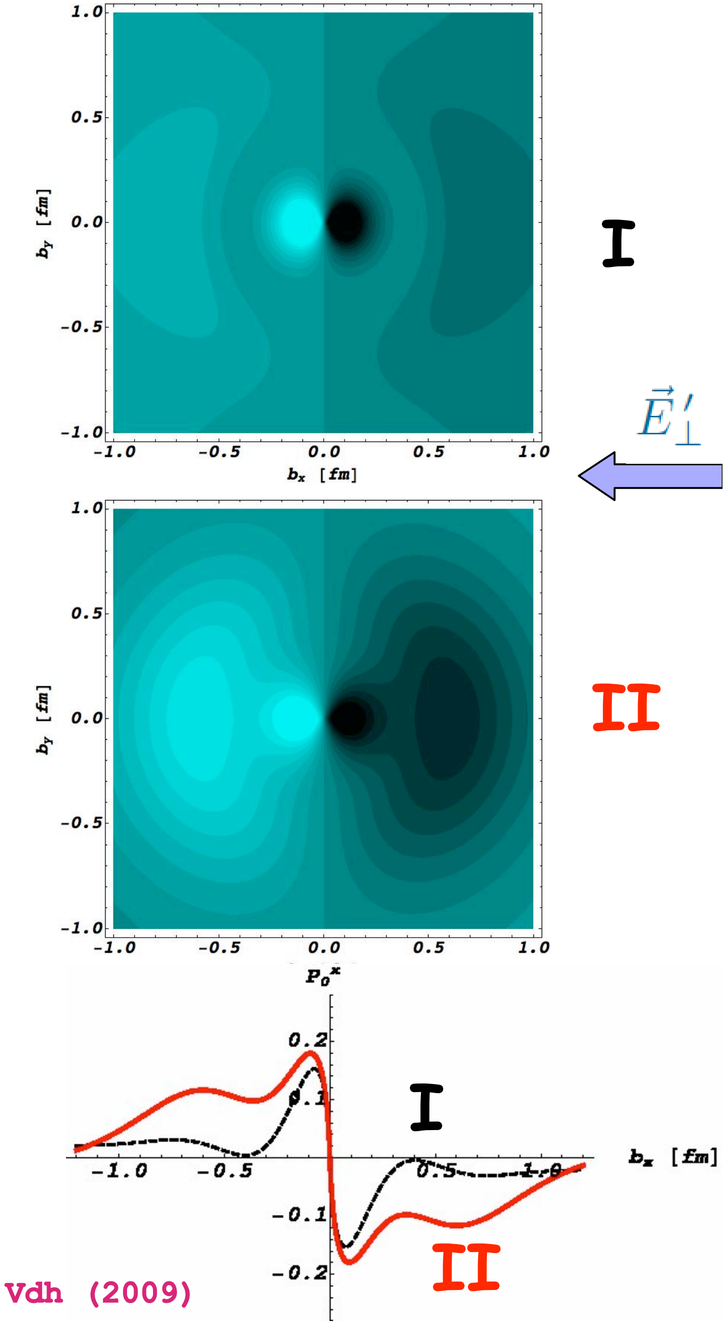
Tiator, Vdh (2008)

induced polarization
in proton

$$\vec{P}_0(\vec{b}) = \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\vec{q}_\perp\cdot\vec{b}}\, \vec{P}_0(\vec{q}_\perp)$$

$$= \hat{b} \int_0^\infty \frac{dQ}{(2\pi)}\, Q\, J_1(b\,Q)\, A(Q^2)$$





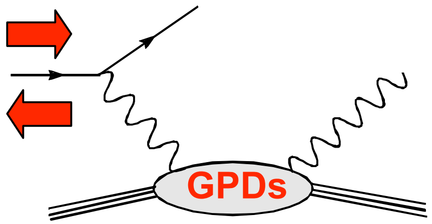
see talk : Lorcé

Gorchtein, Lorcé, Pasquini, Vdh (2009)

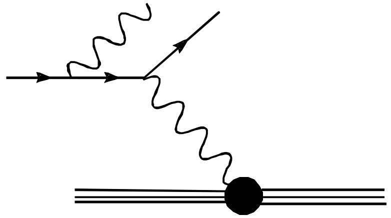
DVCS Observables

First observation of DVCS asymmetries in 2000

$$A_{LU} = \frac{(BH) * Im(DVCS) * \sin \Phi}{(BH^2+DVCS^2)}$$



DVCS



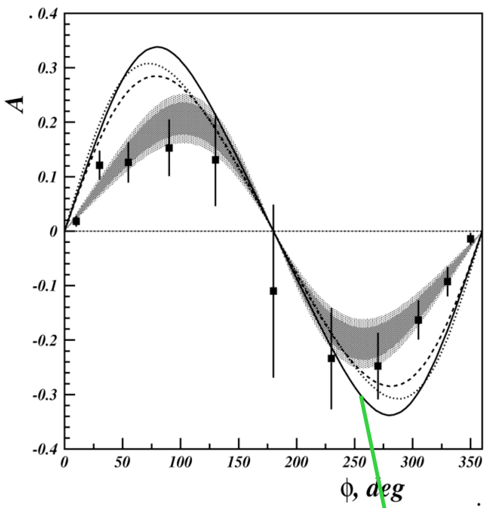
Bethe-Heitler

CLAS

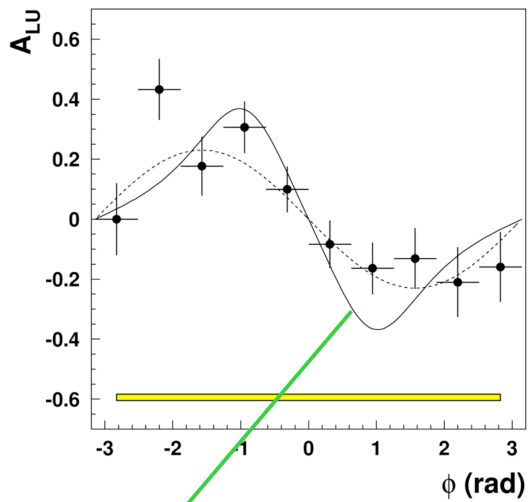
Q^2 = 1.25 GeV^2 ,

x_B = 0.19,

-t = 0.19 GeV^2



PRL 87:182002 (2001)



PRL 87:182001 (2001)

HERMES

Q^2 = 2.6 GeV^2 ,

x_B = 0.11,

-t = 0.27 GeV^2

twist-2 + twist-3

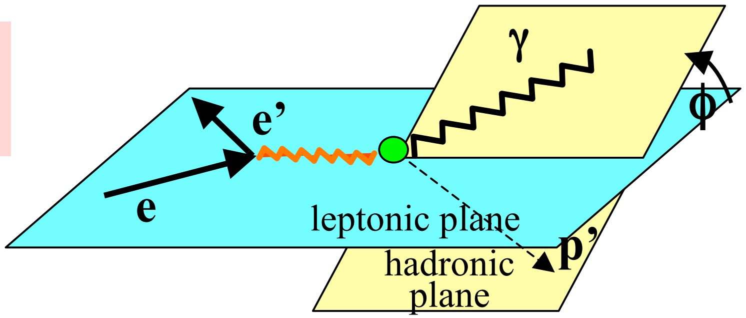
Vdh, Guichon, Guidal (1999)

Kivel, Polyakov, Vdh (2000)

Extracting GPDs from DVCS observables

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\xi = x_B/(2-x_B)$
$k = -t/4M^2$



Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi \longrightarrow H_p, \tilde{H}_p, E_p$$

Kinematically suppressed

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi \longrightarrow H_p, \tilde{H}_p$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi\,\mathrm{Im}\{k(F_2 H - F_1 E) + \ldots\}d\phi \longrightarrow H_p, E_p$$

Polarized beam, unpolarized neutron target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\}d\phi \longrightarrow H_n, \tilde{H}_n, E_n$$

Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PPD's of u and d quarks

$$H_p(x, \xi, t) = 4/9\ H_u(x, \xi, t) + 1/9\ H_d(x, \xi, t)$$
$$H_n(x, \xi, t) = 1/9\ H_u(x, \xi, t) + 4/9\ H_d(x, \xi, t)$$

In hard exclusive process @ leading twist : one accesses 8 GPD quantities Observables : Compton Form Factors

$$P\int_0^1 dx\,[H(x,\xi,t) - H(-x,\xi,t)]\,C^+(x,\xi), \quad (1)$$

$$P\int_0^1 dx\,[E(x,\xi,t) - E(-x,\xi,t)]\,C^+(x,\xi), \quad (2)$$

$$P\int_0^1 dx\left[\tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)\right]C^-(x,\xi), \quad (3)$$

$$P\int_0^1 dx\left[\tilde{E}(x,\xi,t) + \tilde{E}(-x,\xi,t)\right]C^-(x,\xi), \quad (4)$$

$$H(\xi,\xi,t) - H(-\xi,\xi,t), \quad (5)$$

$$E(\xi,\xi,t) - E(-\xi,\xi,t), \quad (6)$$

$$\tilde{H}(\xi,\xi,t) + \tilde{H}(-\xi,\xi,t), \quad (7)$$

$$\tilde{E}(\xi,\xi,t) + \tilde{E}(-\xi,\xi,t) \quad (8)$$

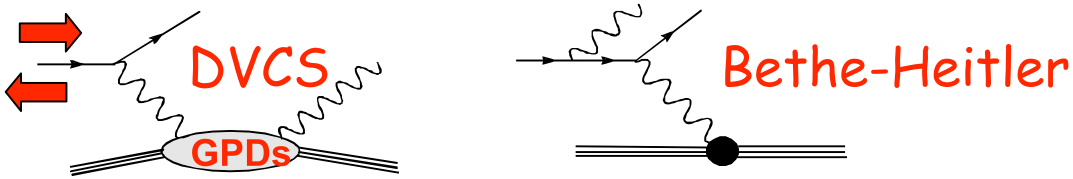
with

$$C^\pm(x,\xi) = \frac{1}{x-\xi} \pm \frac{1}{x+\xi} \quad (9)$$

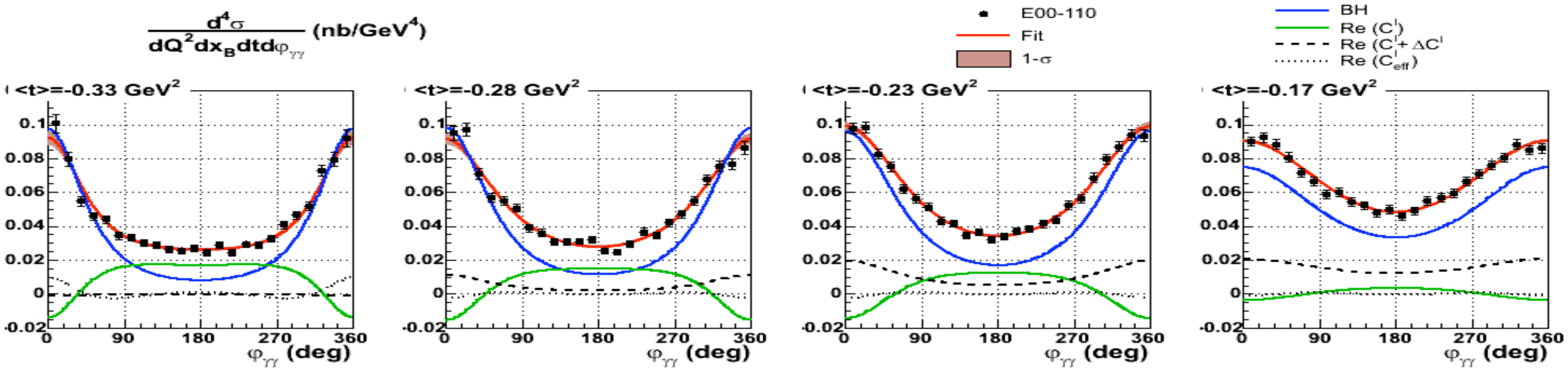
which we can call, respectively, in a symbolic notation, $Re(H)$, $Re(E)$, $Re(\tilde{H})$, $Re(\tilde{E})$, $Im(H)$, $Im(E)$, $Im(\tilde{H})$ and $Im(\tilde{E})$.

DVCS : observables

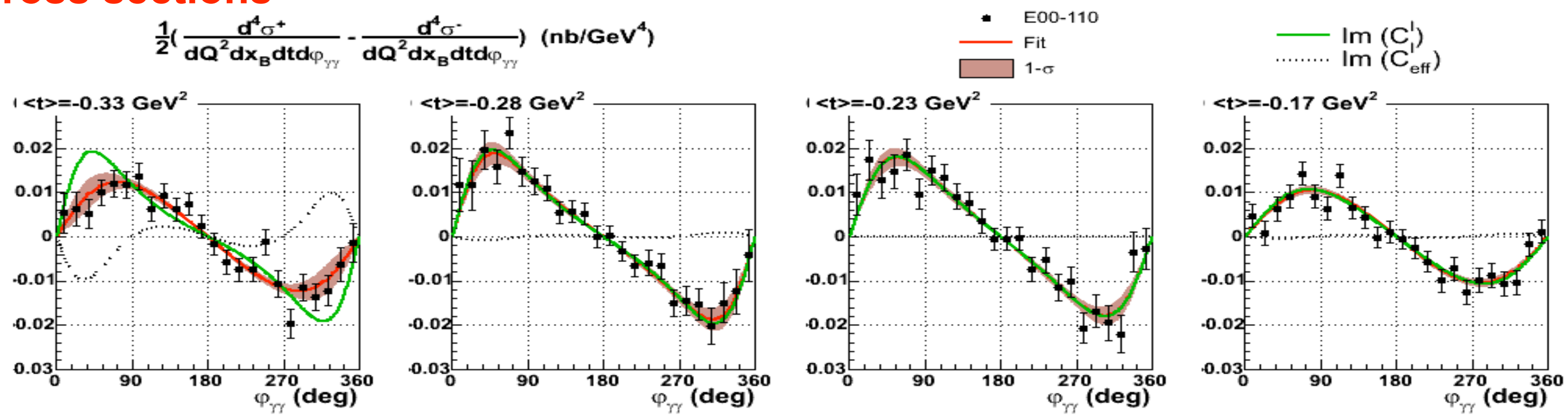
Jlab/Hall A



Unpolarized cross sections

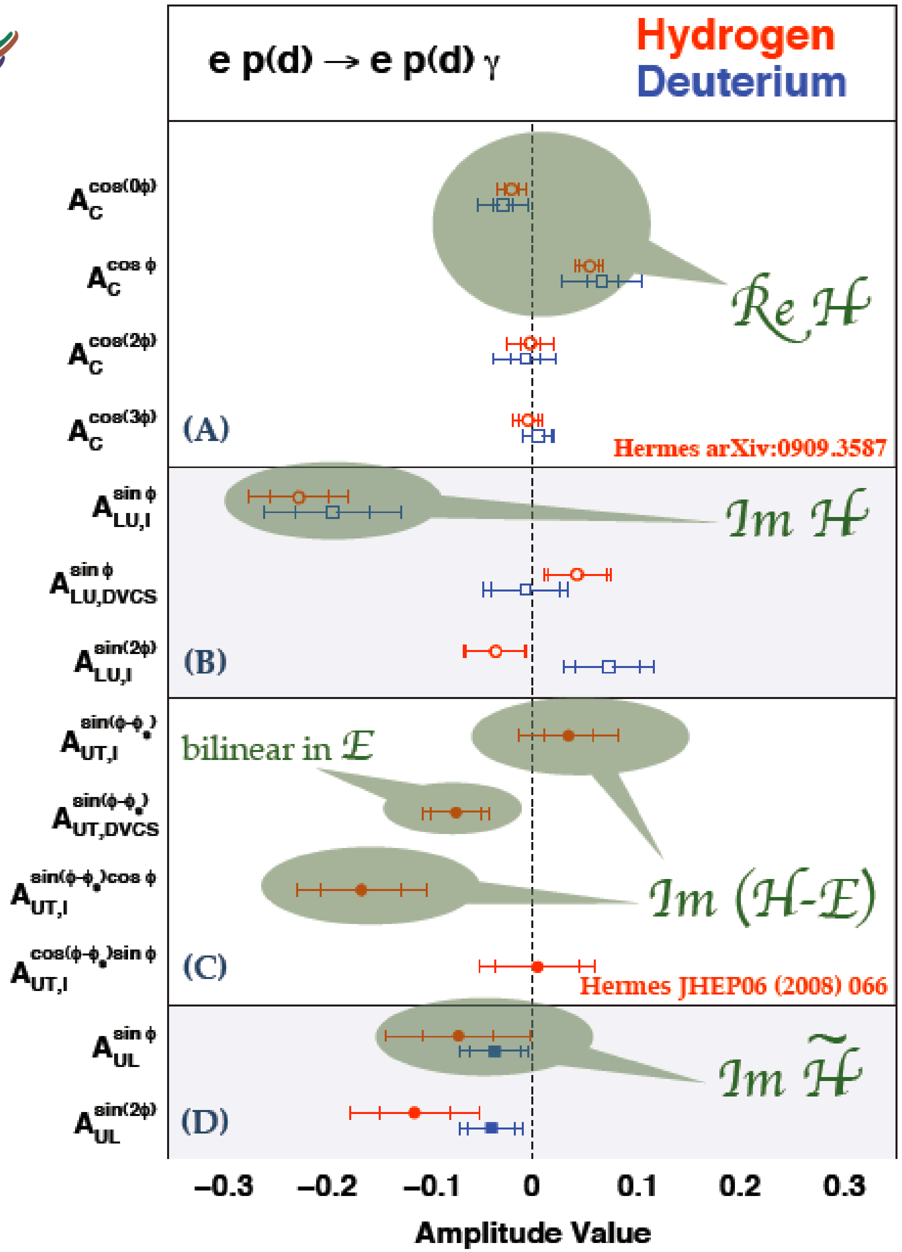


Difference of polarized cross sections



Munoz Camacho et al. (2006)

DVCS : asymmetries



beam *charge* asymmetry

beam *spin* asymmetry

T target spin asymmetry

L target spin asymmetry

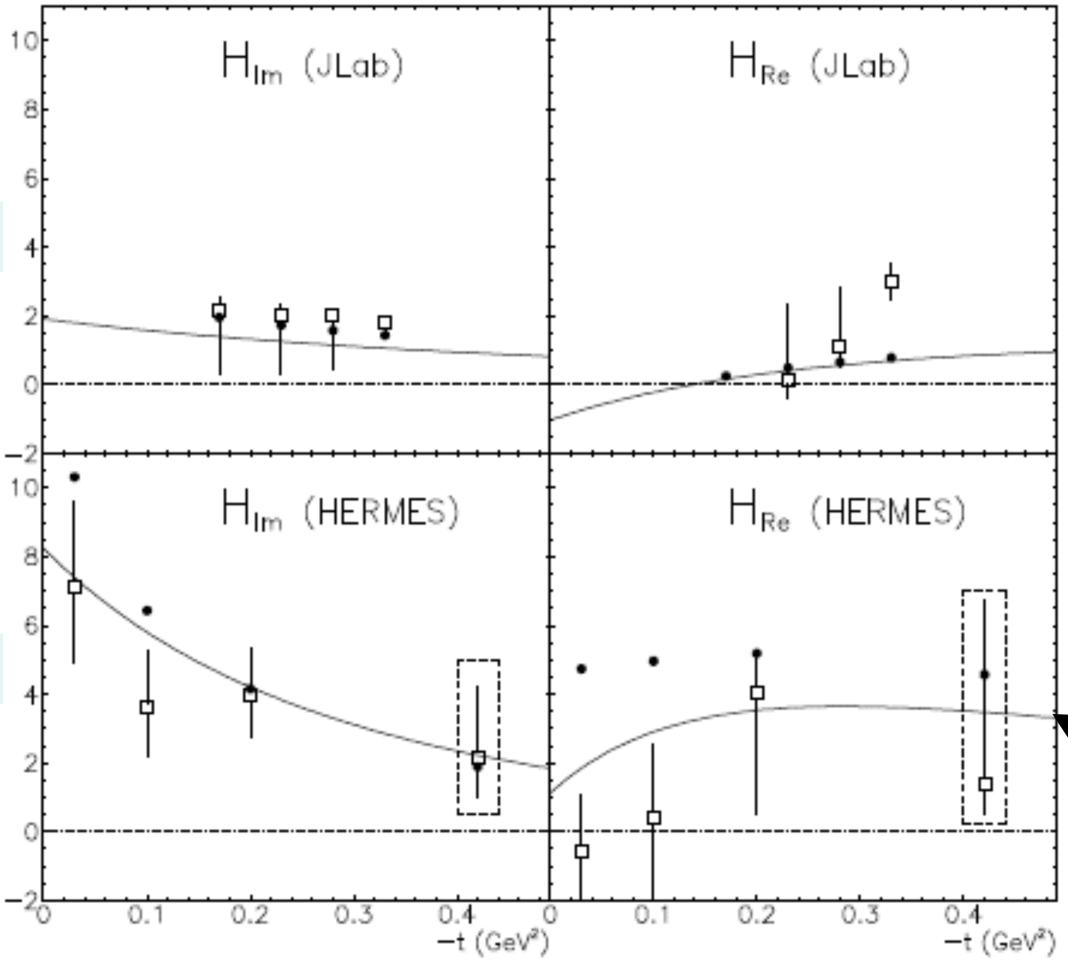
CFF from DVCS : model independent fit extractions (I)

JLab

$x_B=0.36, Q^2=2.3$

HERMES

$x_B=0.09, Q^2=2.5$



Guidal, Moutarde (2009)

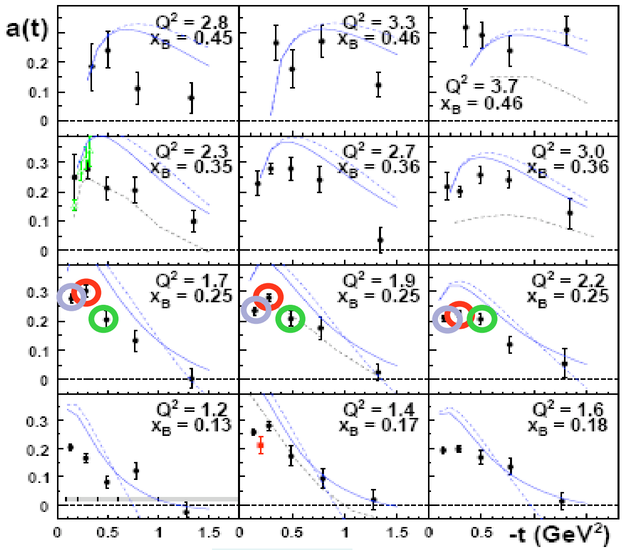
as energy increases:

- « Shrinkage » of Im(H)
- Im(H) > Re(H)
- different t-behavior for Im(H) & Re(H)

solid circles : VGG (1998)

model dependent fit of D. Muller, K.Kumericki (2009)

CFF from DVCS : fits (II)

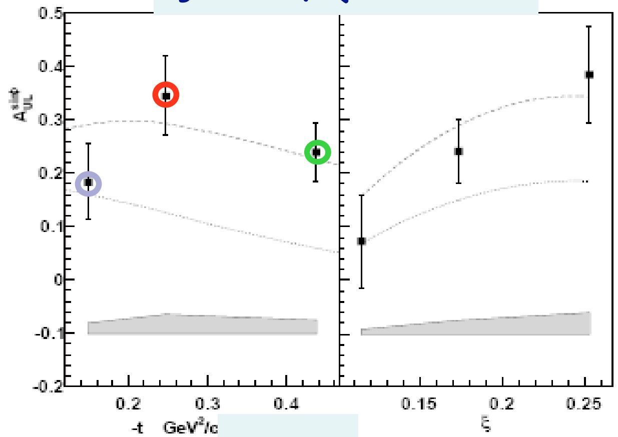


Jlab/CLAS

Girod et al. (2006)

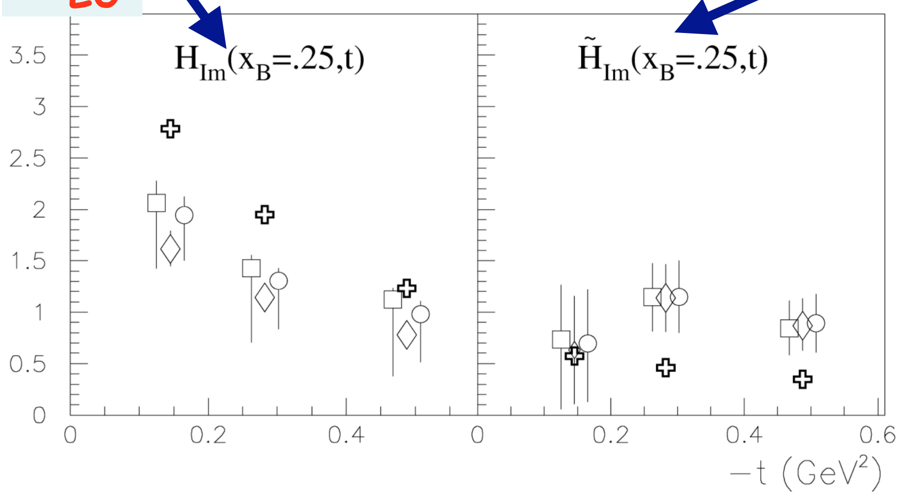
Chen et al. (2008)

ξ=0.16, Q^2=1.82



A_{UL}

A_{LU}

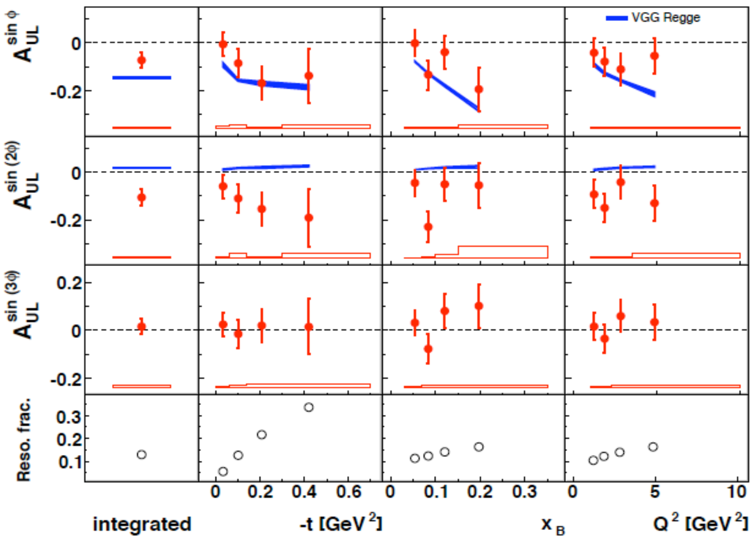


- □ Fit with 7 CFFs (bounds 5xVGG CFFs)
- ○ Fit with 7 CFFs (bounds 3xVGG CFFs)
- ◇ Fit with ONLY $\tilde{H}$ and H CFFs
- ✣ VGG prediction

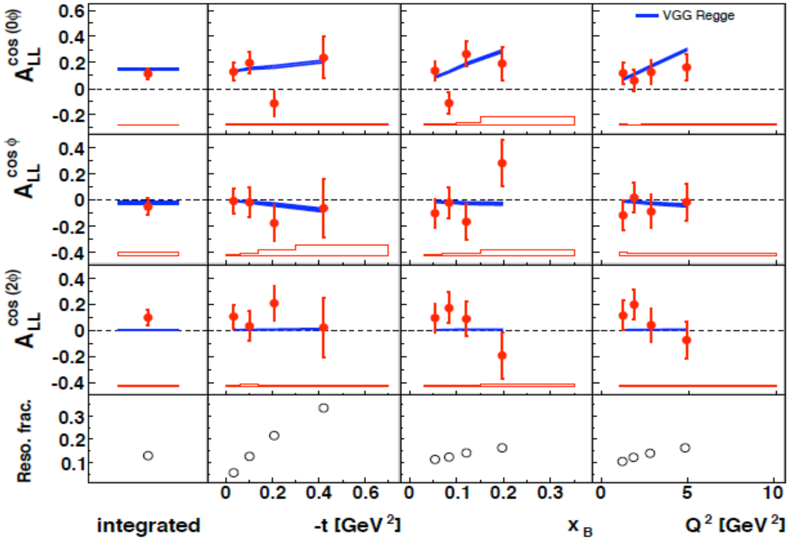
Guidal (2010)

arXiv:1003.0307[hep-ph]

CFF from DVCS : fits (III)

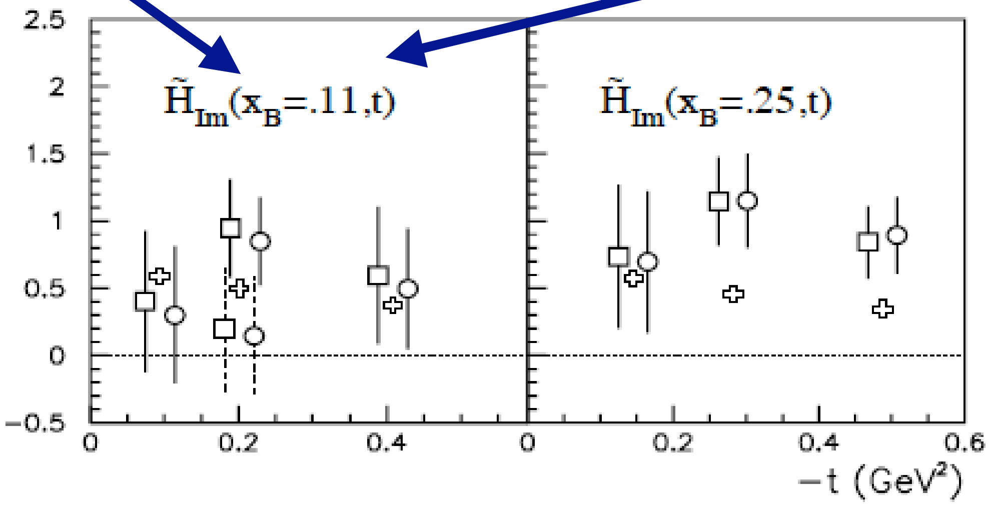


HERMES
(2010)



A_{UL}

A_{LL}



Guidal (2010)

open crosses :
VGG(1998)

Dispersion Relations for DVCS

➡ once subtracted fixed-t dispersion relation in variable x

$$Re A(\xi, t) = \Delta(t) + \frac{2}{\pi} PV \int_0^1 \frac{dx}{x} \frac{Im A(x,t)}{(\xi^2/x^2 - 1)}$$

subtraction constant

accessible through spin asymmetries

➡ link with twist-2 GPD : $Im A(x,t) = \pi \, H^{(+)}(x,x,t)$

$$Re A(\xi, t) = \Delta(t) - PV \int_0^1 dx \, H^{(+)}(x,x,t) \left[\frac{1}{x - \xi} + \frac{1}{x + \xi} \right]$$

DR for DVCS amplitudes (in terms of GPDs)

see talk : Mueller

Anikin, Teryaev (2007) Diehl, Ivanov (2007) Polyakov, Vdh (2008)

Kumericki-Passek, Mueller, Passek (2008) Goldstein, Liuti (2009) …

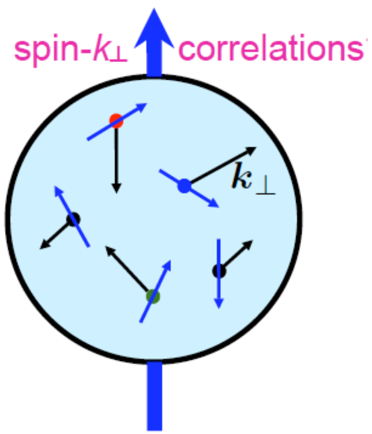
DR for 12 VCS amplitudes : Drechsel, Gorchtein, Metz, Pasquini, Vdh (2000)

Transverse Momentum Dependent Parton distributions

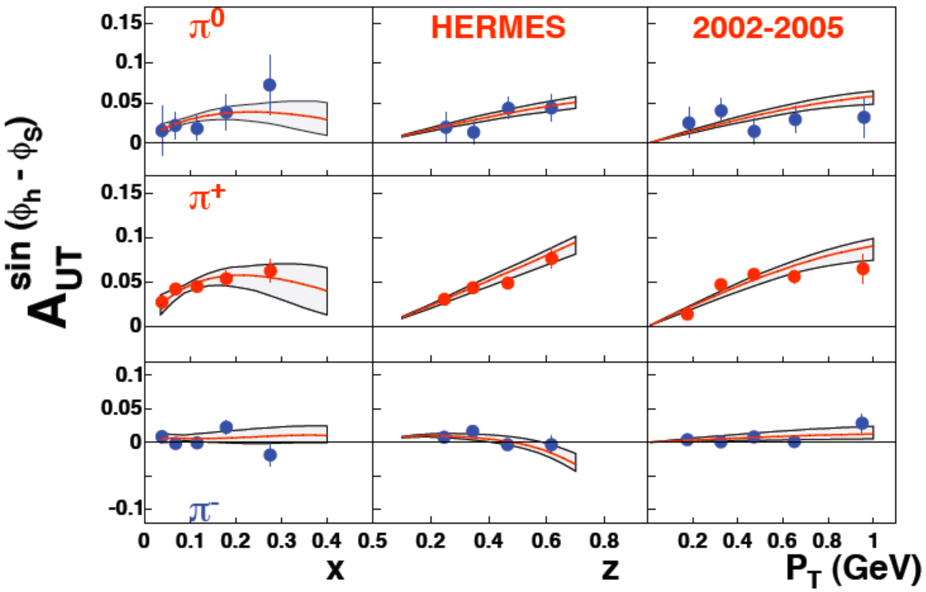
Quark distribution functions

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^{\perp}$
nucleon	L		g_1	$h_{1L}^{\perp}$
nucleon	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Sivers DF



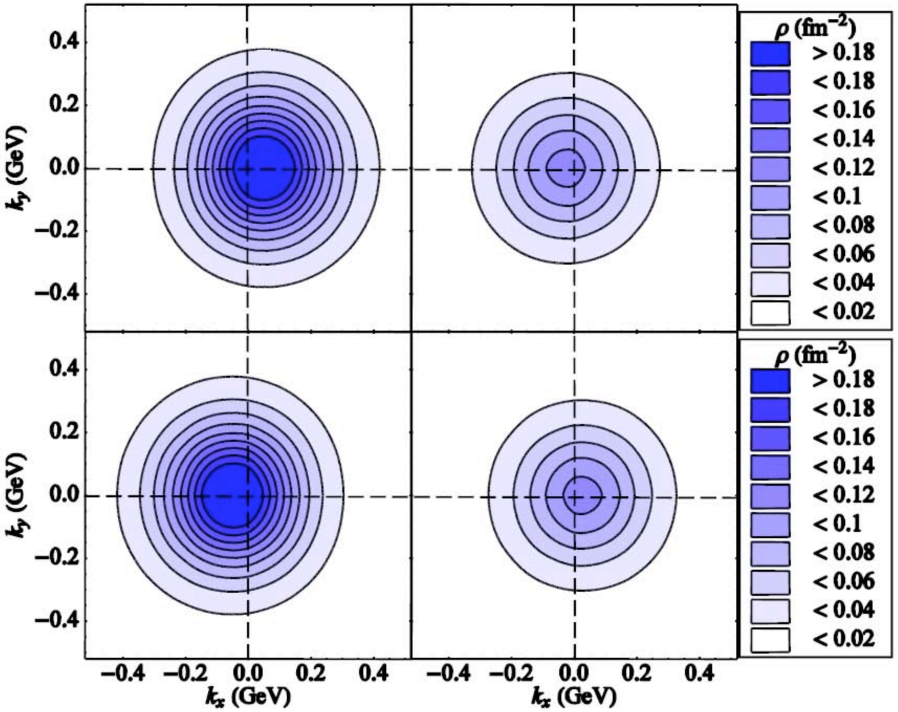
➡ accessible in **semi-inclusive DIS**



theory curves : Anselmino et al.(2009)

Light-cone quark model

up down



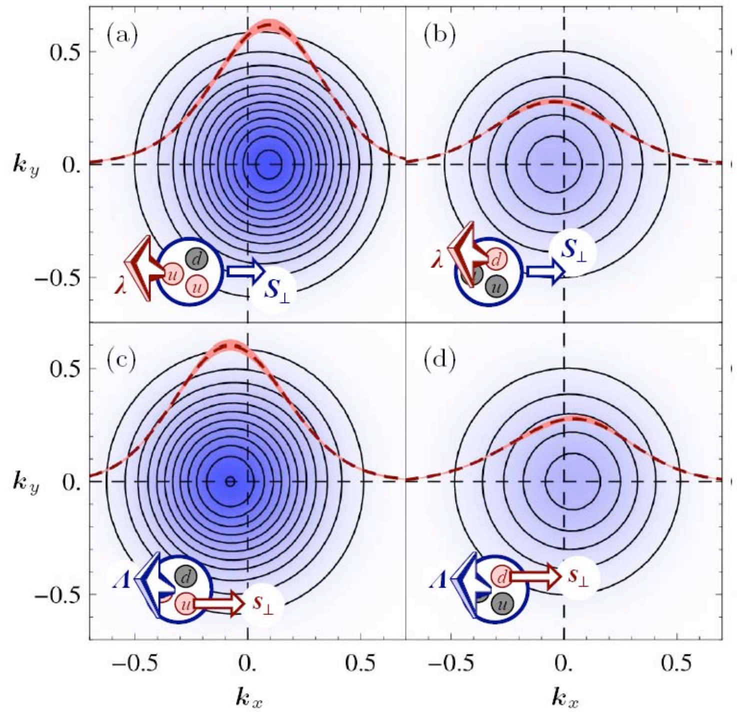
BP, Cazzaniga, Boffi, PRD78 (2008)

Lattice QCD

up down

$g_{1T}(x, k_\perp)$

$h_{1L}^{\perp}(x, k_\perp)$



Haegler, Musch, Negele, Schaefer, Europhys. Lett. 88 (2009)

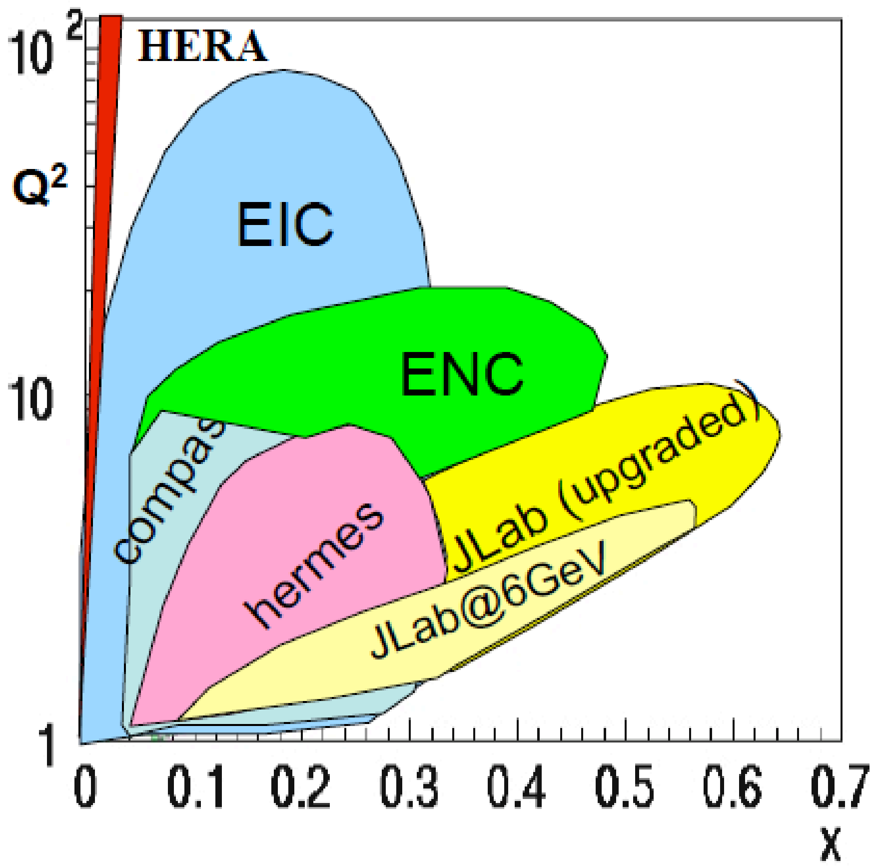
$\langle k_x^u \rangle = 55.8\,\mathrm{MeV}$ $\langle k_x^d \rangle = -27.9\ \mathrm{MeV}$

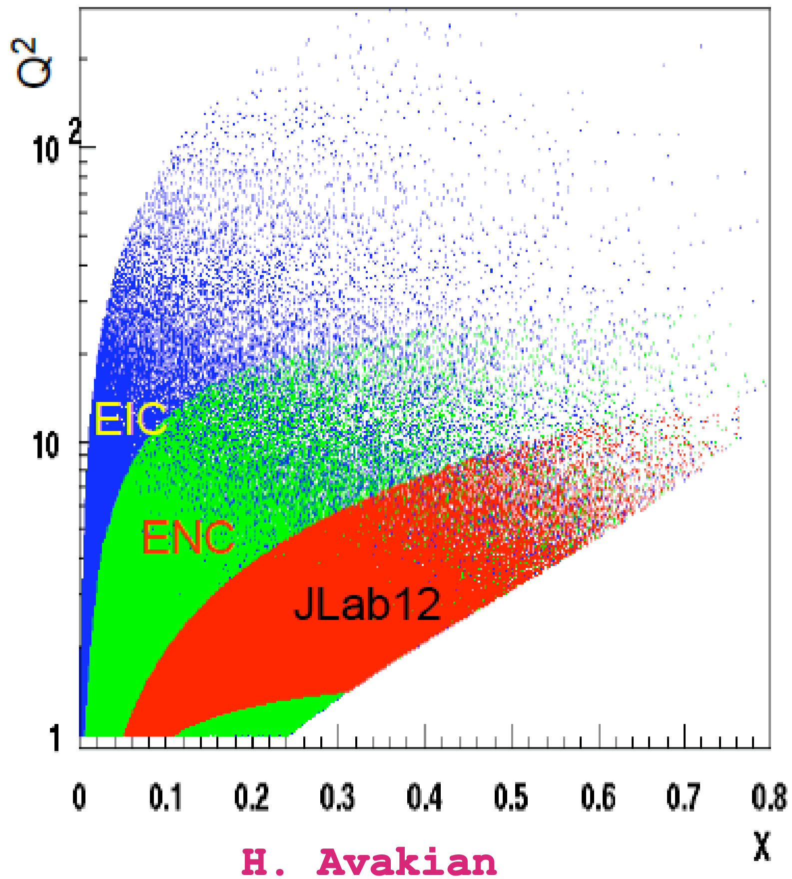
$\langle k_x^u \rangle = 67(5)\,\mathrm{MeV}$ $\langle k_x^d \rangle = -30(5)\,\mathrm{MeV}$

- g_{1T}, $h_{1L}^{\perp}$ $\not\Leftrightarrow$ GPDs $\Rightarrow$ genuine effect of intrinsic transverse momentum of quarks

see talks : Pasquini, Musch

The Energy / Luminosity Frontier





H. Avakian

Hard exclusive reactions :
high energy and high luminosity required + polarization