

IWHSS18

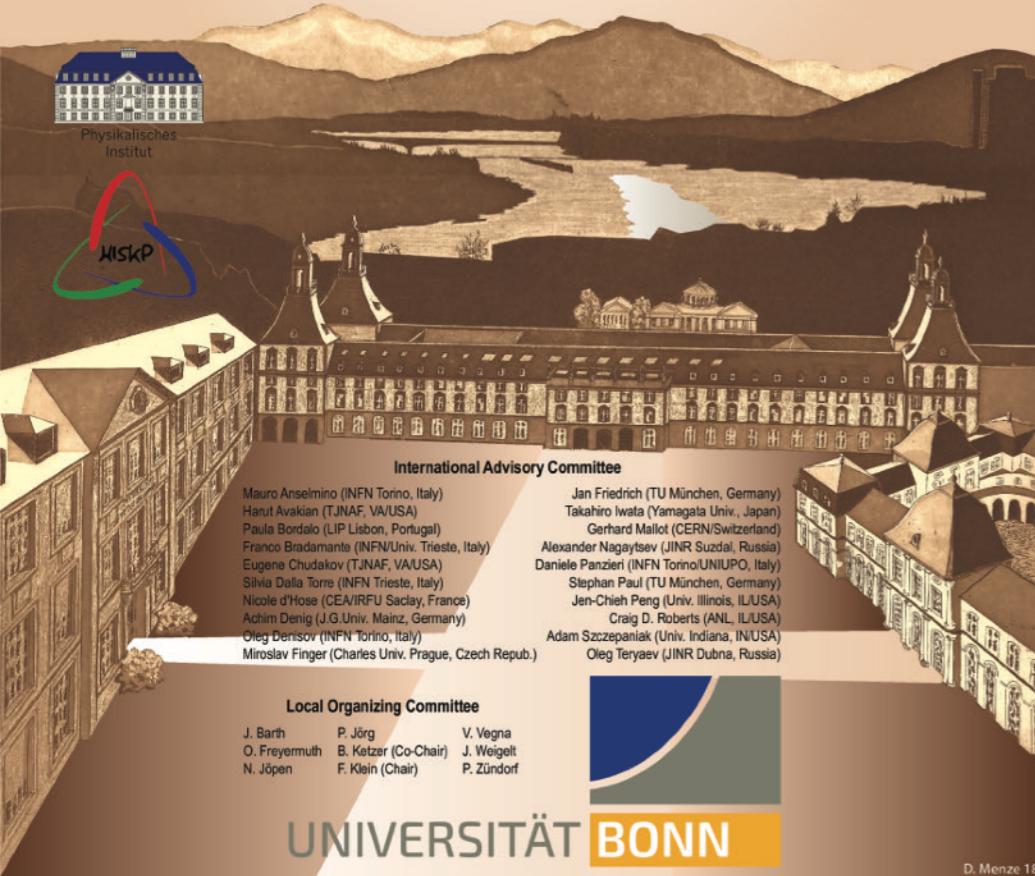
XV International
Workshop on Hadron
Structure and Spectroscopy

March 19-21, 2018
Bonn, Germany

@ iwhss2018@physik.uni-bonn.de
 <https://cern.ch/iwhss-2018>



Transverse Spin Structure of the Nucleon
TMD's, GPD's and GTMD's
Meson Structure
Meson Spectroscopy
Search for Exotics
New Opportunities for fixed Target Physics



Overview of DVCS and extraction of observables

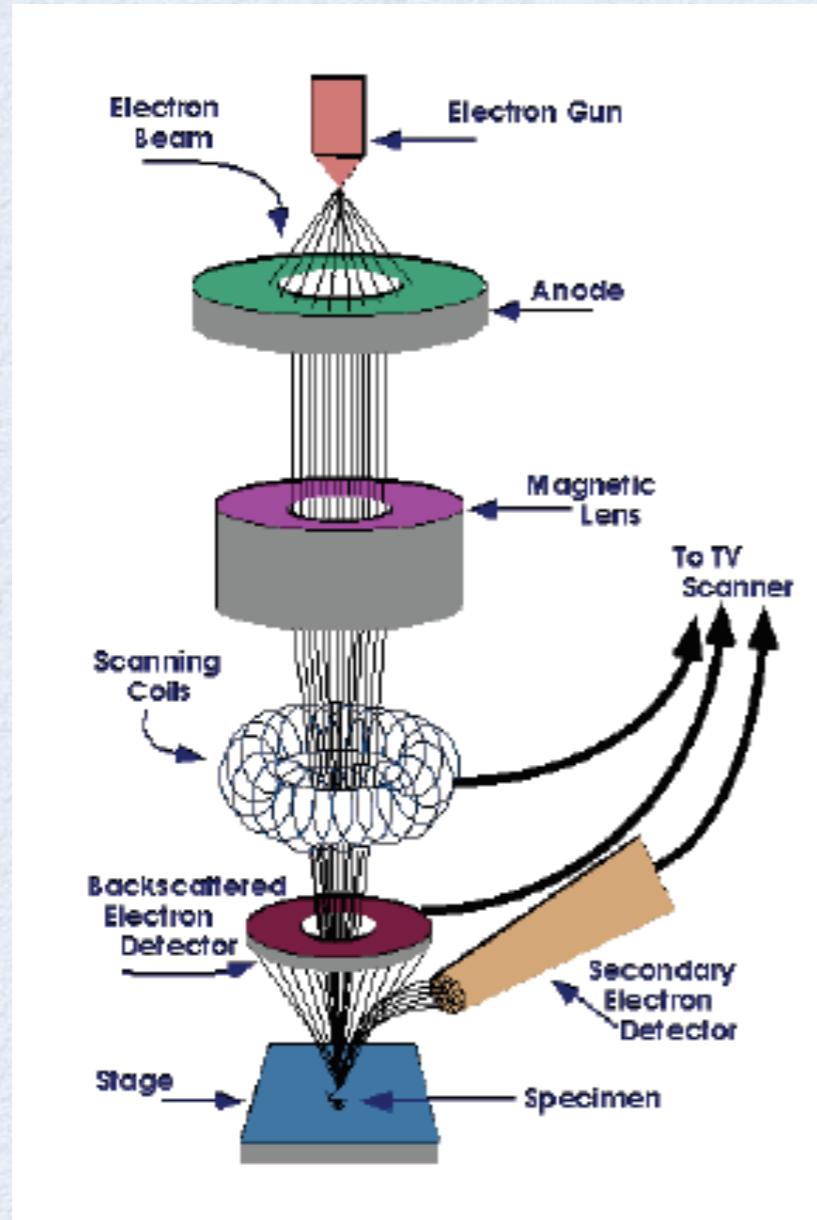
Marc Vanderhaeghen

COMPASS Workshop

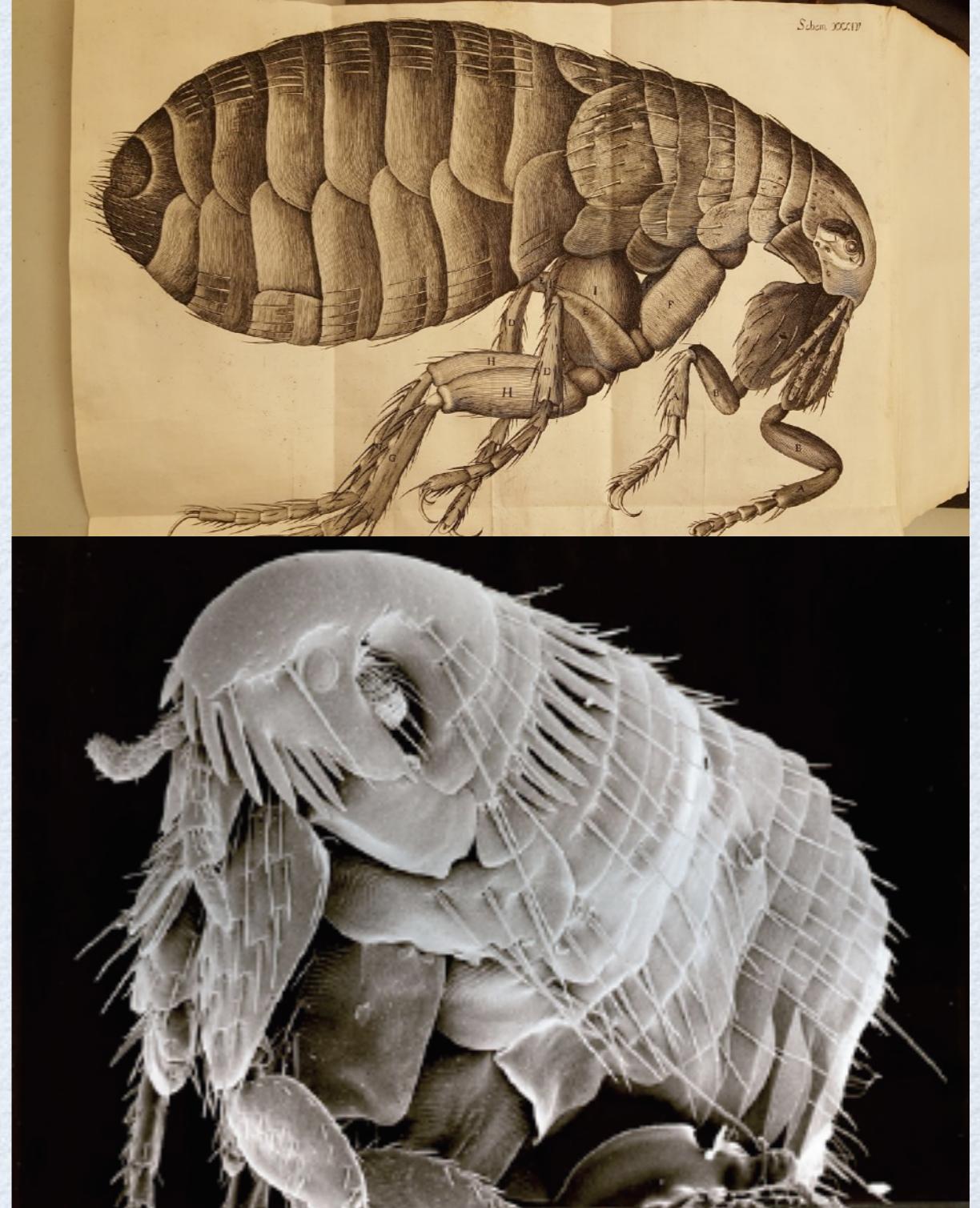
March 19-21, 2018, Bonn, Germany

how to image a system

R. Hooke (*Micrographia*, 1665)



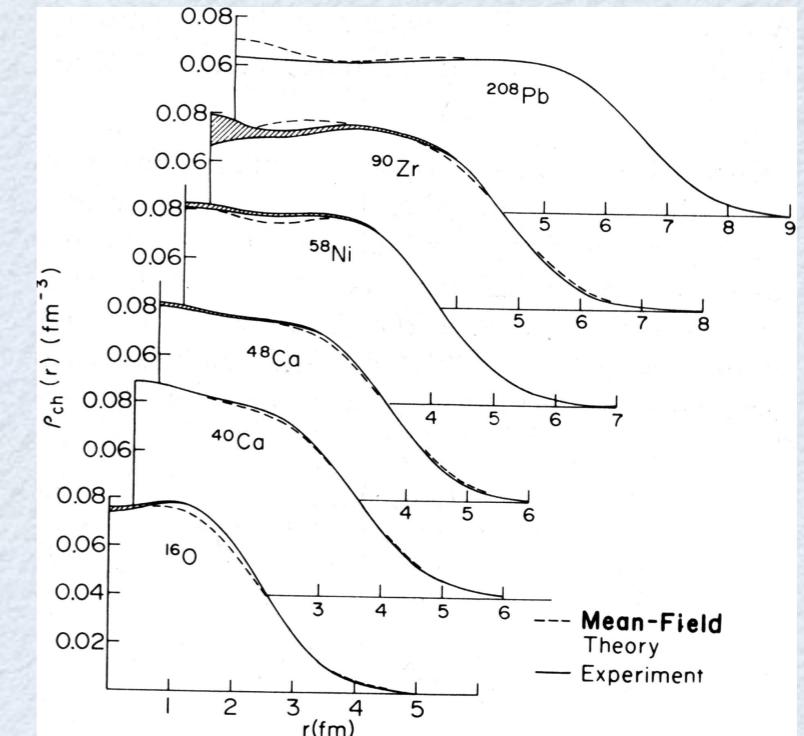
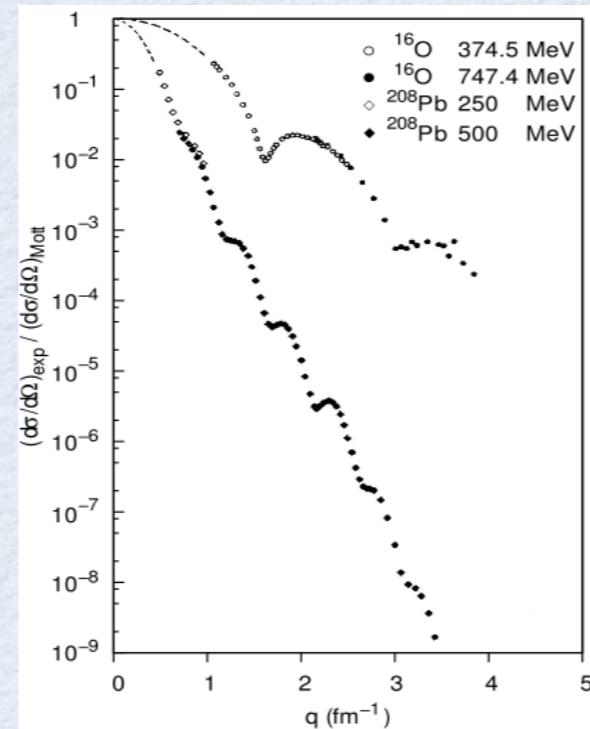
when target is static
($m_{\text{constituent}}, m_{\text{target}} \gg Q$)



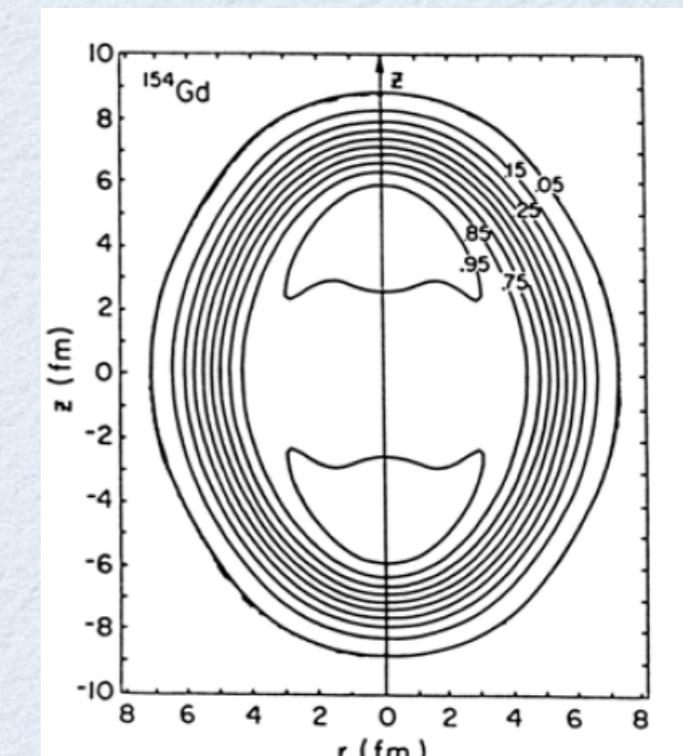
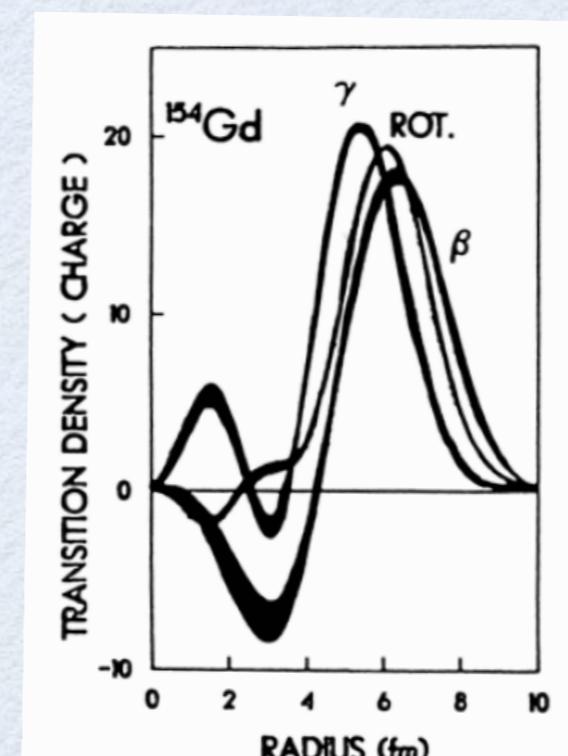
the 3D Fourier transform of form factors
gives the distribution of electric charge and magnetization

what do we know about spatial distributions of charges in nuclei?

sizes of nuclei:
as revealed through
elastic electron scattering

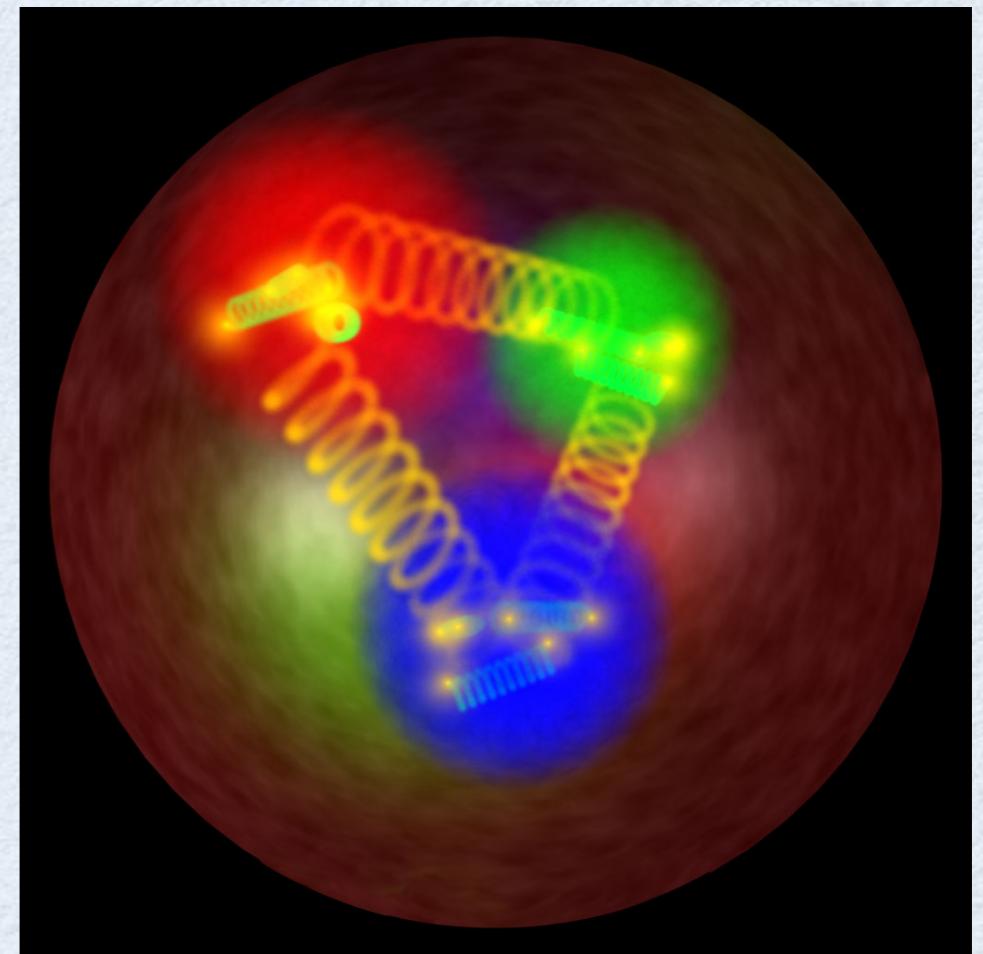


shapes of nuclei:
as revealed through
inelastic electron scattering

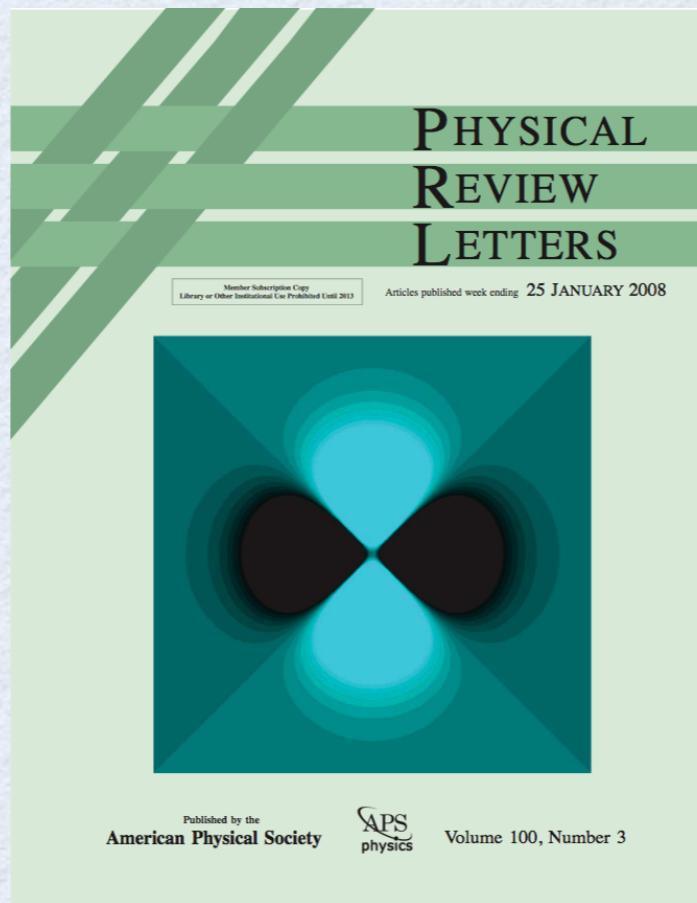


what do we know about the proton size and its charge distributions?

- proton **size**: charge radius R_E
very low Q^2 **elastic** electron scattering,
atomic spectroscopy (Lamb shift)
- proton **spatial (charge) distributions**
elastic electron scattering
e.m. FFs: $F_1(Q^2) \rightarrow \rho(b)$
- proton **3D transverse spatial/
longitudinal momentum distributions**
deeply virtual Compton scattering
GPDs $H(x, \xi, t) \rightarrow \rho(x, b)$ for $\xi=0$



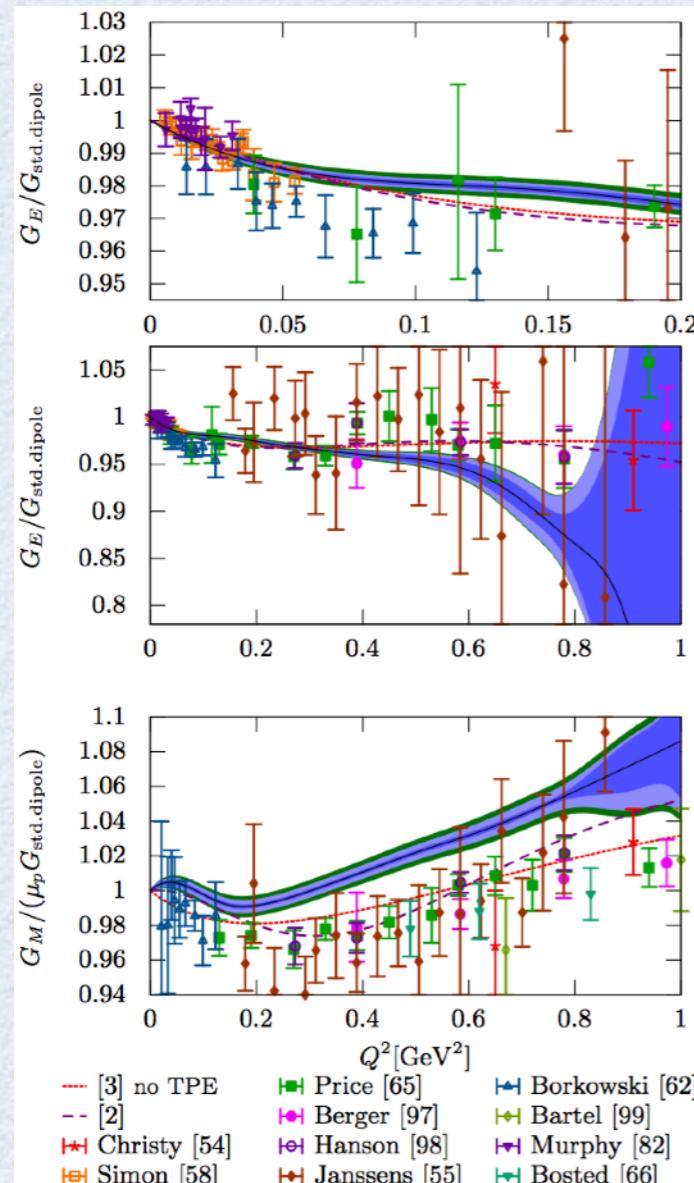
proton e.m. form factors, charge distributions



e^- scattering cross sections

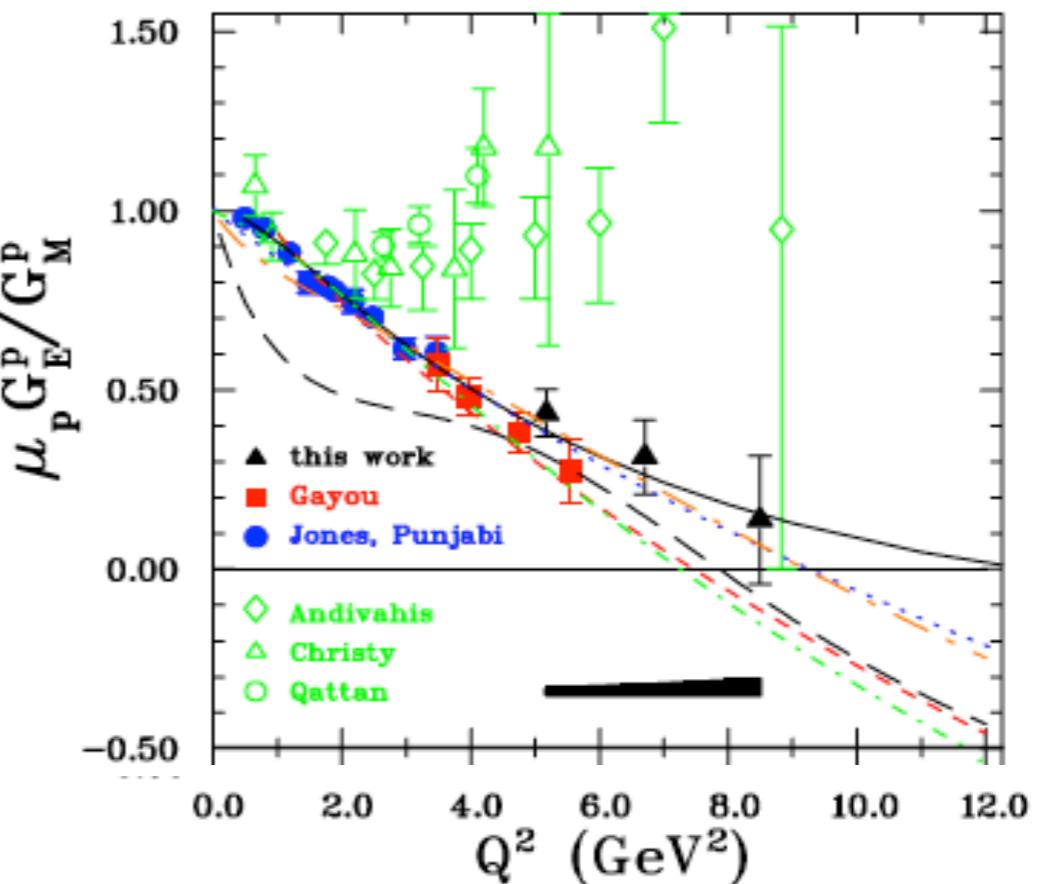
Electron scattering facilities JLab (12 GeV), MAMI (1.6 GeV):
uniquely positioned to deliver high precision data

MAMI/A1 achieved < 1% measurement
of proton charge radius R_E



Bernauer et al. (2010, 2013)

JLab polarization transfer measurements:
 G_{Ep} / G_{Mp} difference with Rosenbluth



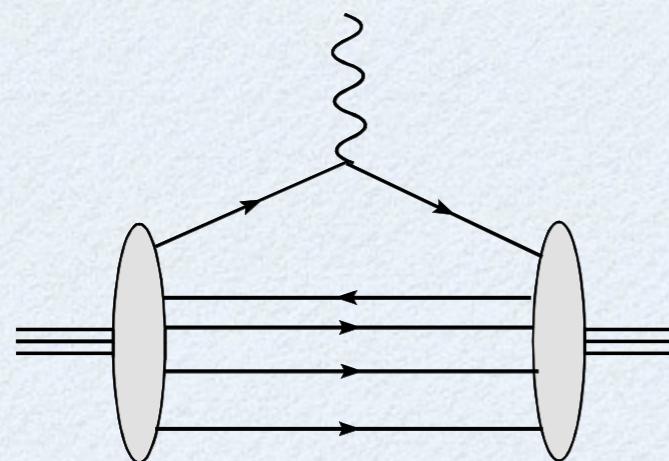
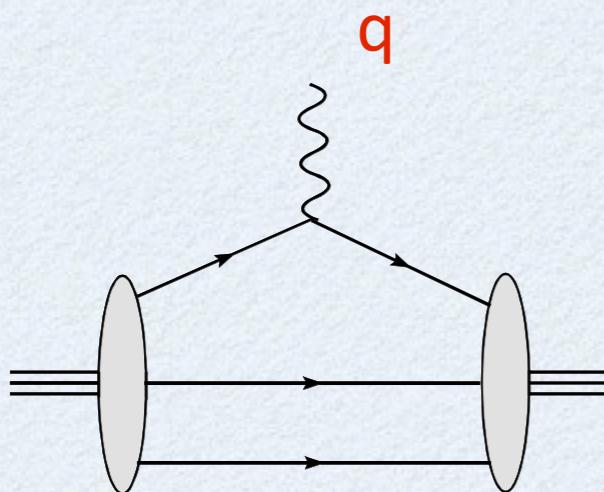
Jones et al. (2000)

Gayou et al. (2002)

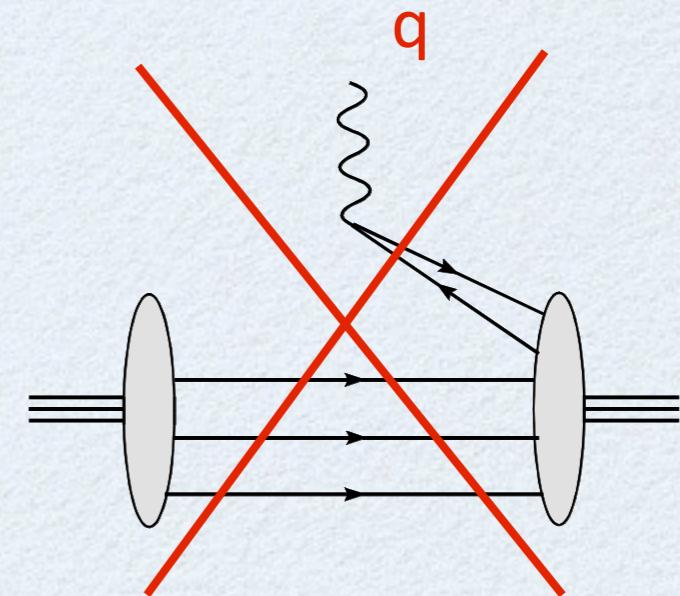
Punjabi et al. (2005)

Puckett et al. (2010)

Interpretation of form factor as quark density



overlap of wave function
Fock components
with **same** number of quarks



overlap of wave function
Fock components
with **different** number of quarks
NO probability / charge density
interpretation

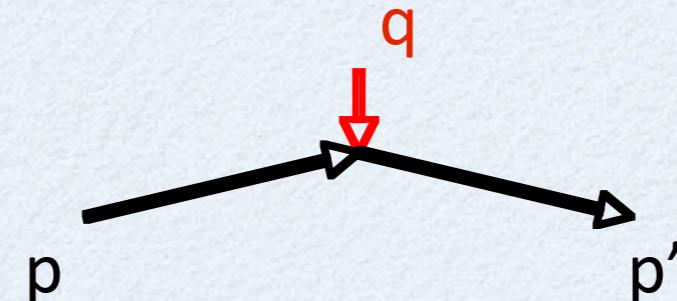
absent in a light-front frame!

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

quark transverse charge densities in nucleon (1)

→ light-front

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

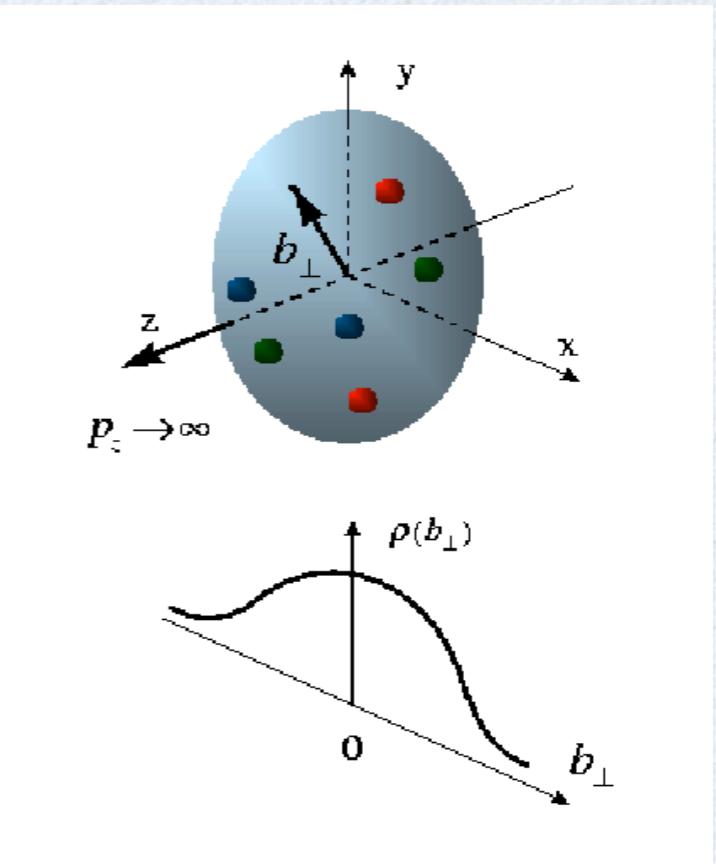


photon only couples to forward moving quarks

→ quark **charge density** operator

$$J^+ = J^0 + J^3 = \bar{q} \gamma^+ q = 2 q_+^\dagger q_+$$

$$\text{with } q_+ \equiv \frac{1}{4} \gamma^- \gamma^+ q$$



→ longitudinally polarized nucleon

$$\begin{aligned} \rho_0^N(\vec{b}) &\equiv \int \frac{d^2 \vec{q}_\perp}{(2\pi)^2} e^{-i \vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle \\ &= \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2) \end{aligned}$$

Soper (1997)

Burkardt (2000)

Miller (2007)

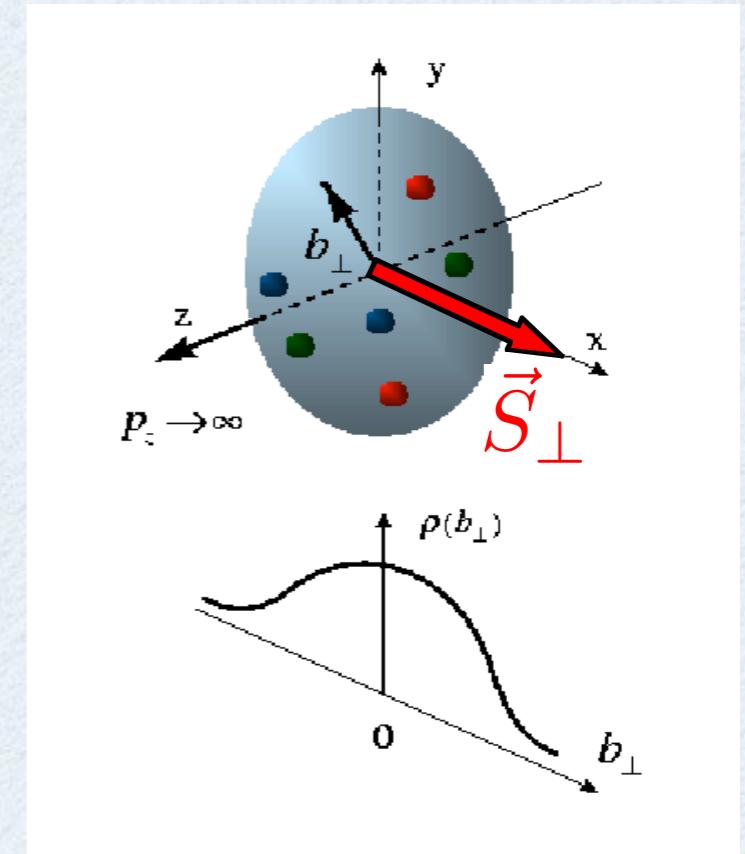
quark transverse charge densities in nucleon (2)

→ 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 $\phi_S = 0$

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



→

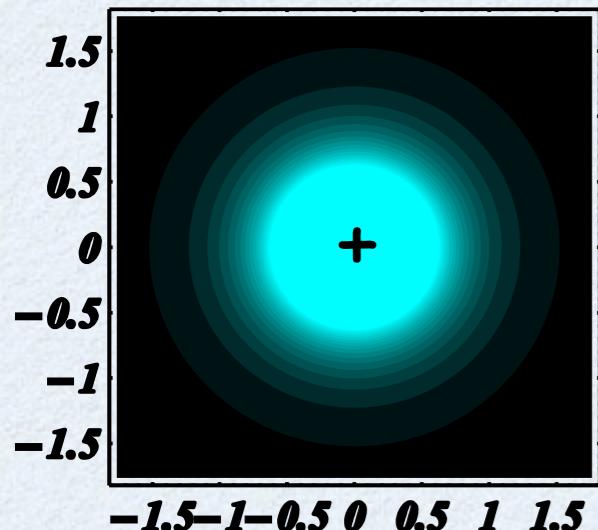
$$\begin{aligned} \rho_T^N(\vec{b}) &\equiv \int \frac{d^2 \vec{q}_\perp}{(2\pi)^2} e^{-i \vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} \rangle \\ &= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M} J_1(bQ) F_2(Q^2) \end{aligned}$$

dipole field pattern

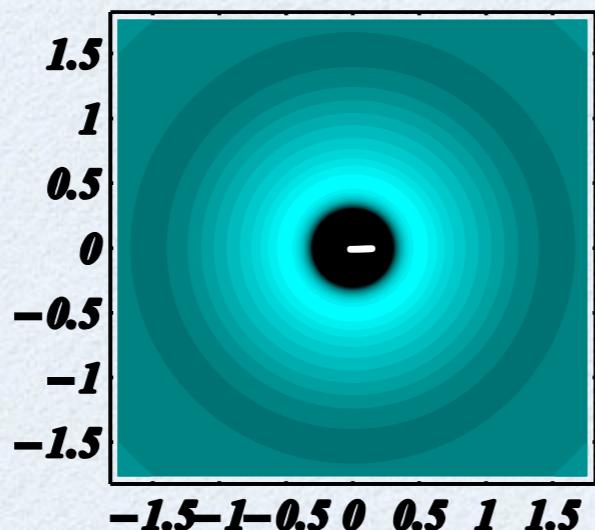
Carlson, vdh (2007)

spatial imaging of hadrons

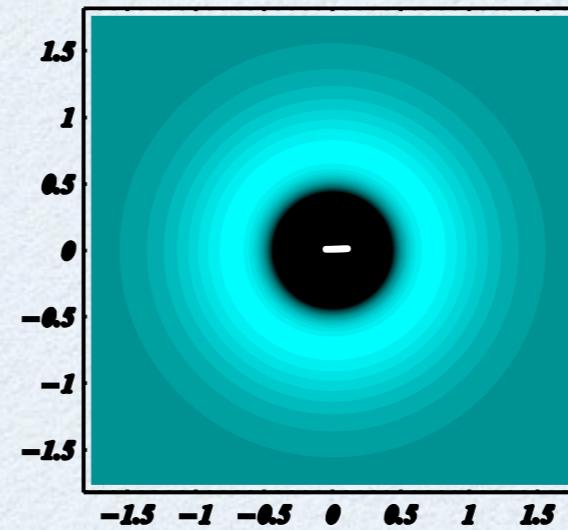
proton



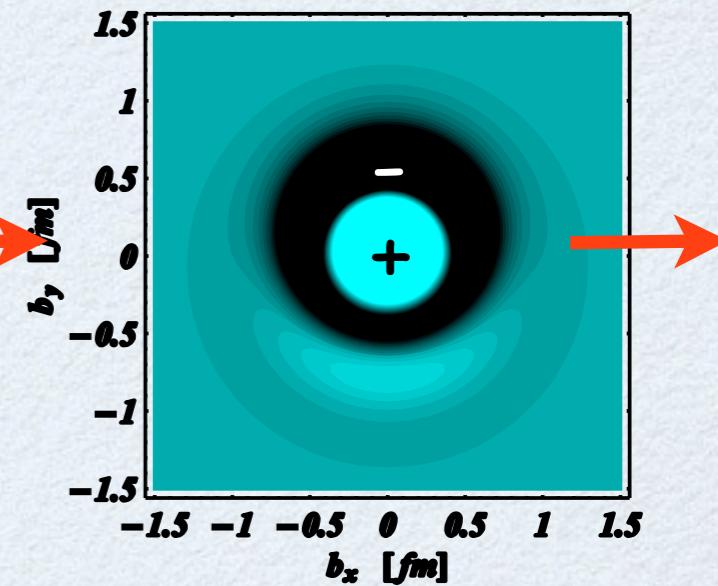
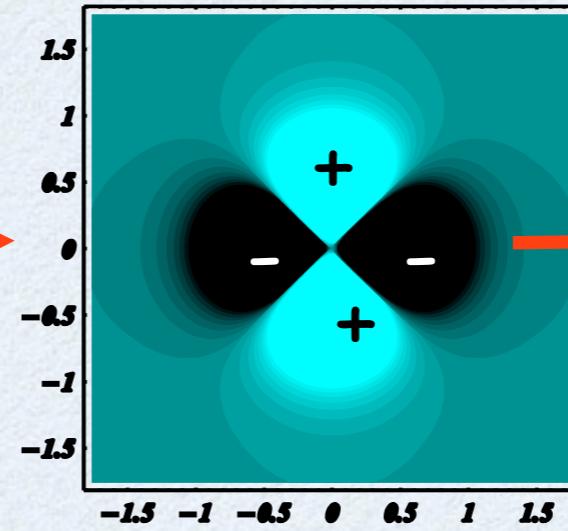
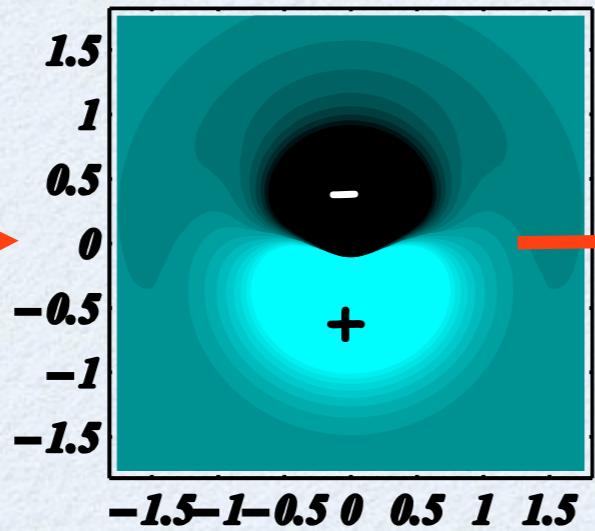
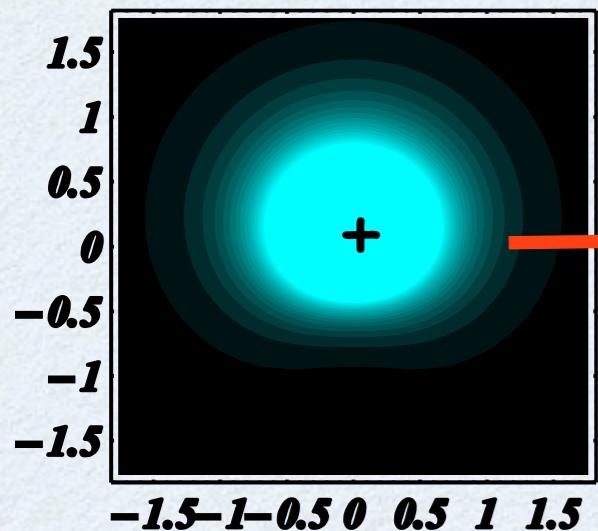
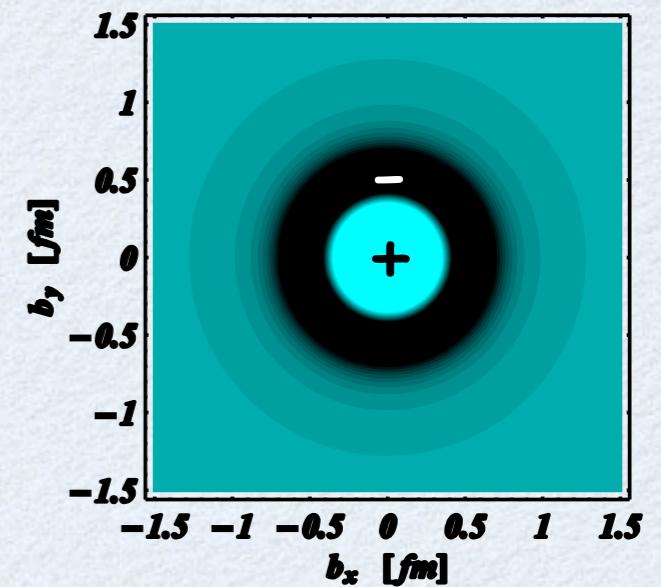
neutron



$p \rightarrow \Delta^+$



$p \rightarrow N^*(1440)$

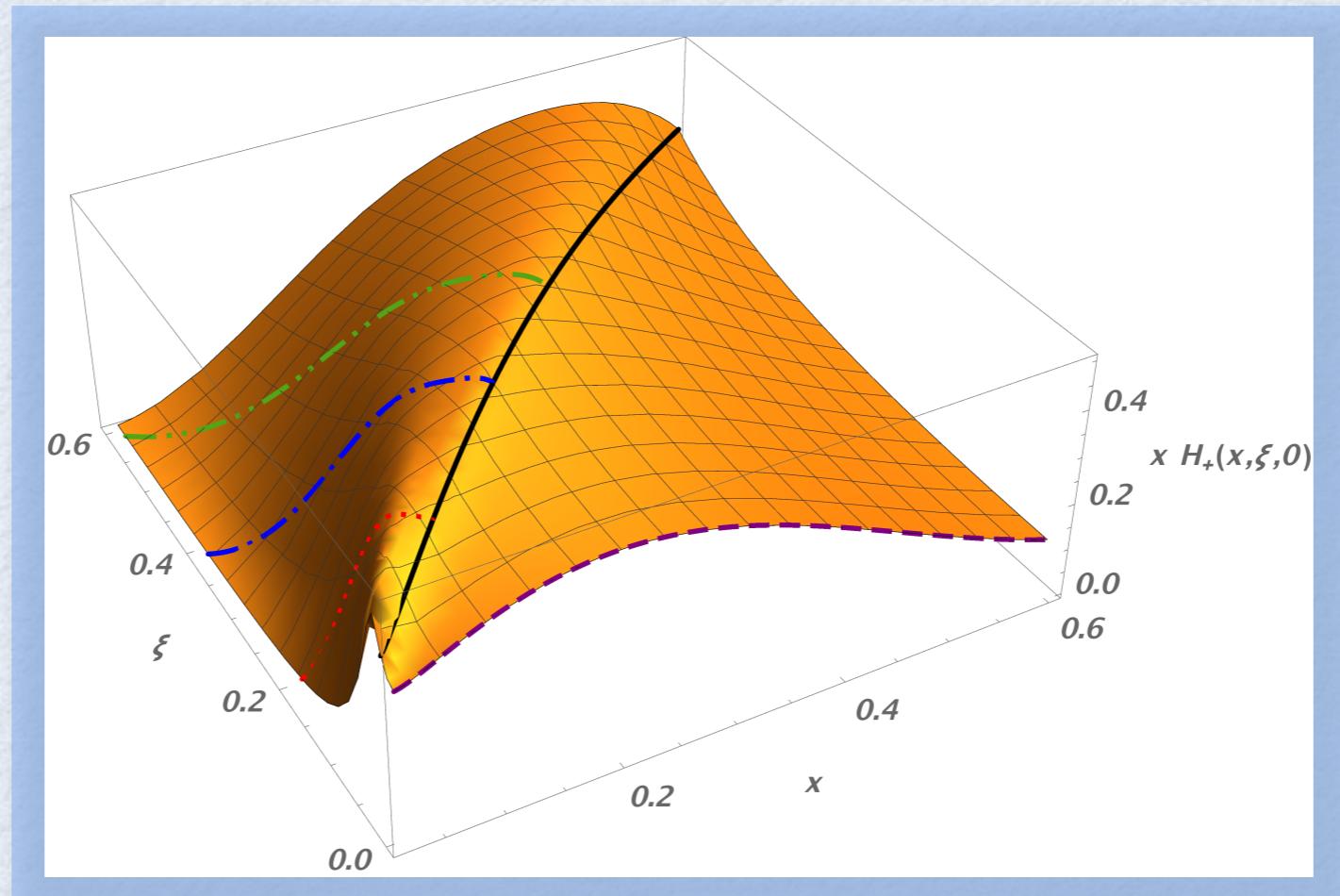


Miller (2007)

Carlson, Vdh (2007)

Tiator, Vdh (2007)

Generalized Parton Distributions



Correlations in transverse position/longitudinal momentum

elastic
scattering



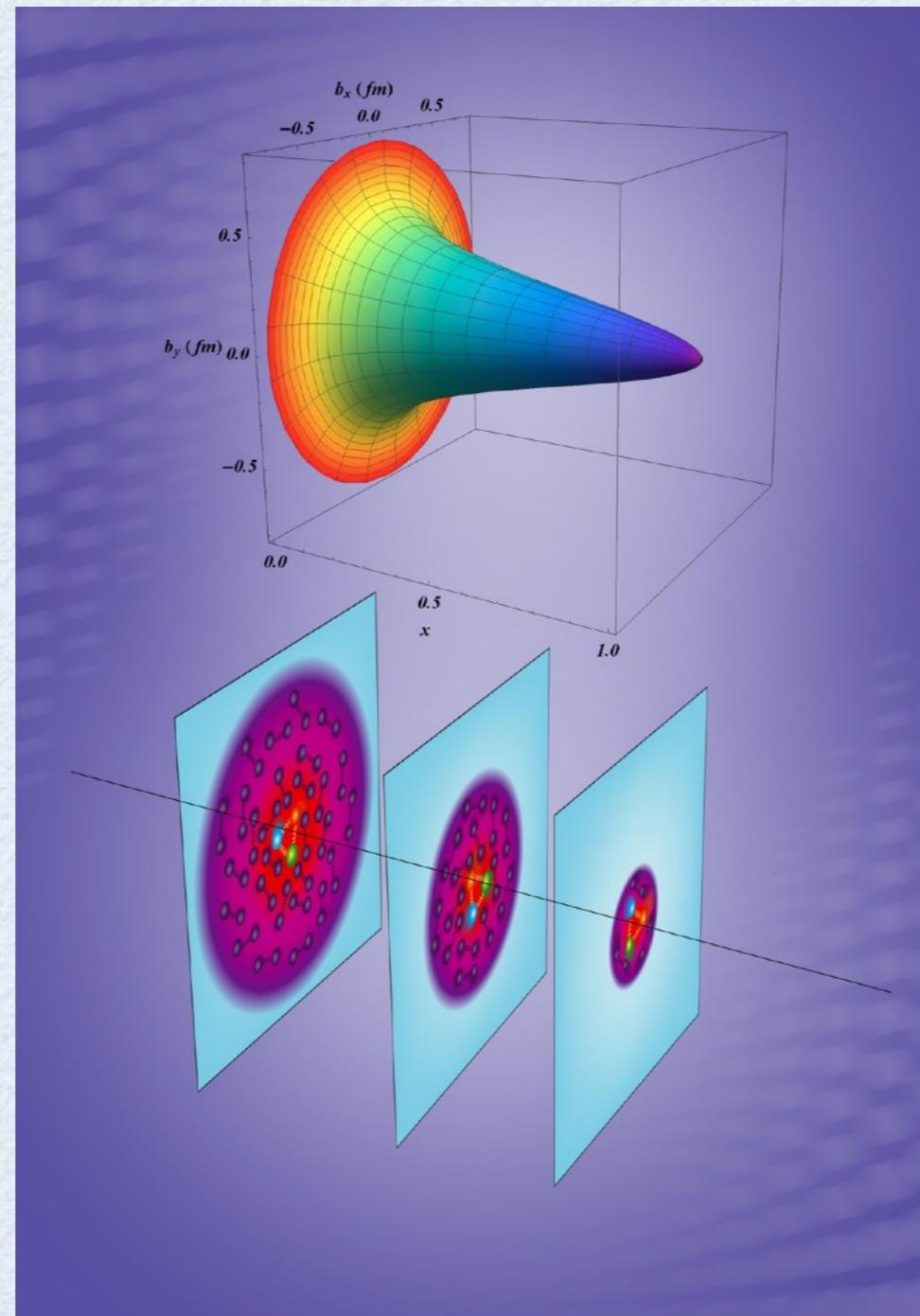
quark
distributions in
transverse
position space

proton
3D imaging

Burkardt (2000, 2003)

Belitsky, Ji, Yuan
(2004)

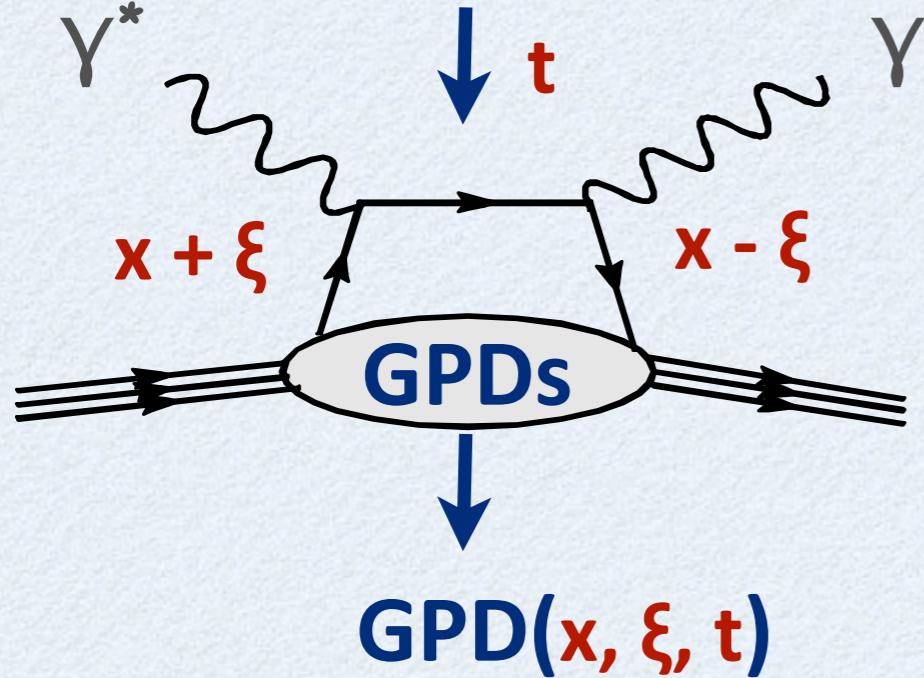
quark
distributions in
longitudinal
momentum



DVCS: tool to access GPDs

world data on proton F_2

$Q^2 \gg 1 \text{ GeV}^2$



→ at large Q^2 : QCD factorization theorem

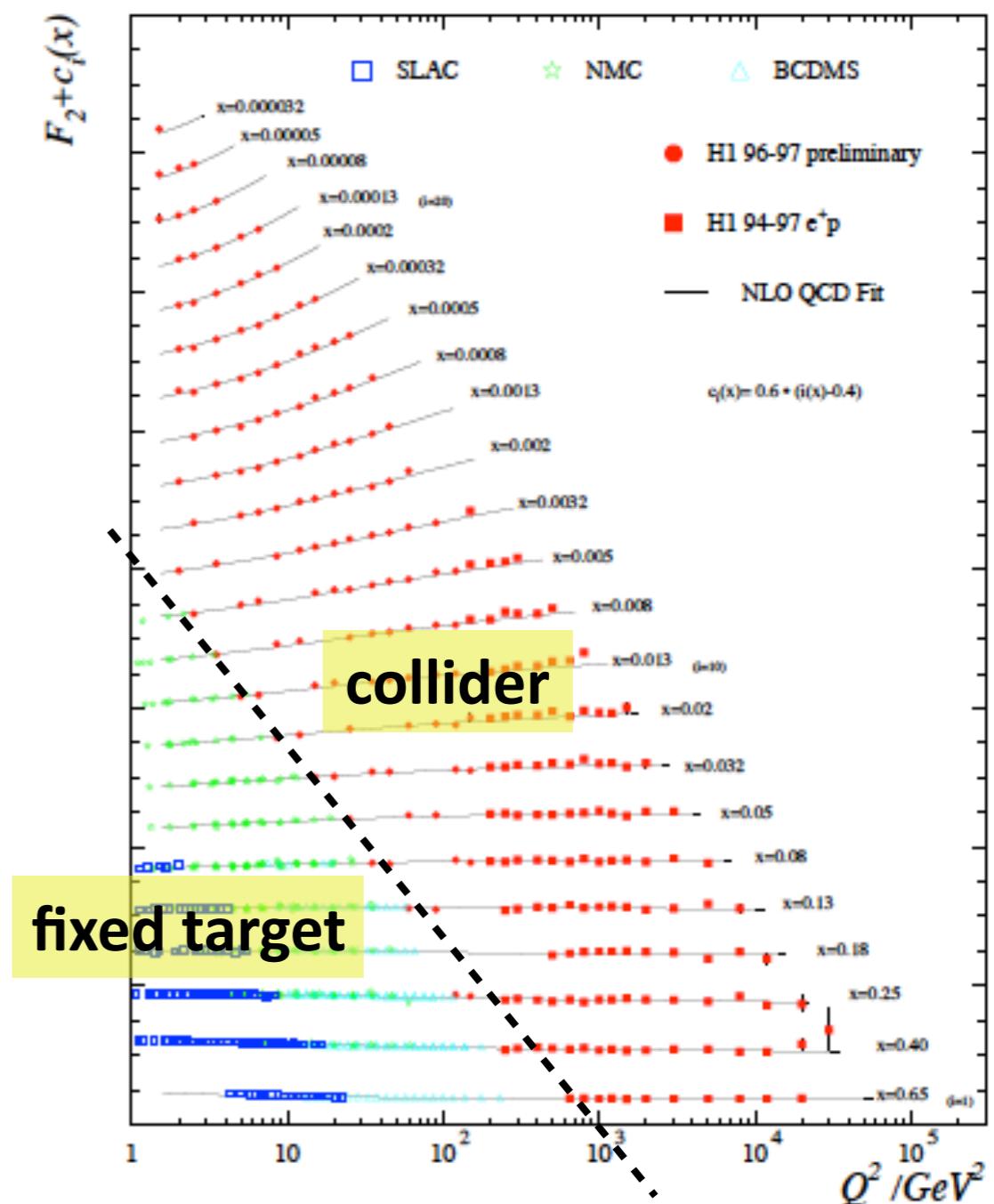
Müller et al (1994)

Ji (1995) Radyushkin (1996)

Collins, Frankfurt, Strikman (1996)

at twist-2: 4 quark helicity conserving GPDs

→ key: Q^2 leverage needed to test QCD scaling



GPDs: known limits

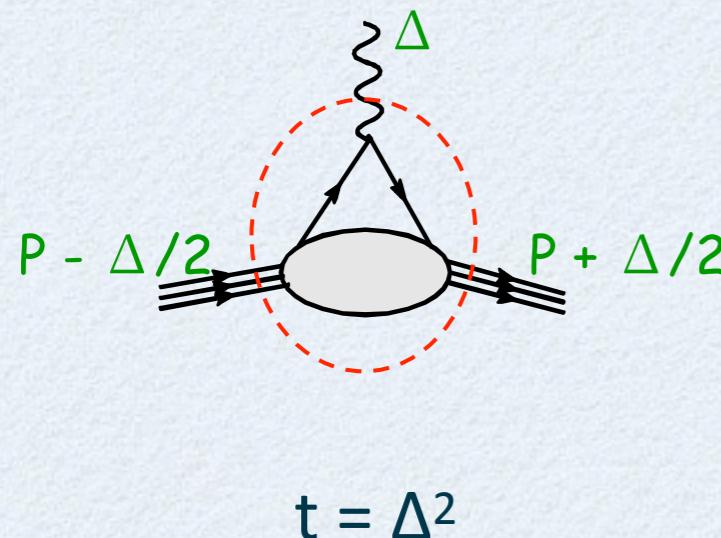
→ in forward kinematics ($\xi=0, t = 0$) : **PDF limit**

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

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

E, \tilde{E}^q do not appear in forward kinematics (DIS) → **new information**

→ first moments of GPDs : **elastic form factor limit**



$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t)$$
$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t)$$
$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t)$$
$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t)$$

→ Dirac FF
→ Pauli FF
→ axial FF
→ pseudoscalar FF

GPDs: moments, total angular momentum



$$\int_{-1}^{+1} dx x H^q(x, \xi, t) = A(t) + \xi^2 C(t)$$

$$\int_{-1}^{+1} dx x E^q(x, \xi, t) = B(t) - \xi^2 C(t)$$

form factors of energy-momentum tensor

Polyakov, Weiss (1999)

Polyakov (2003)



Ji's angular momentum sum rule

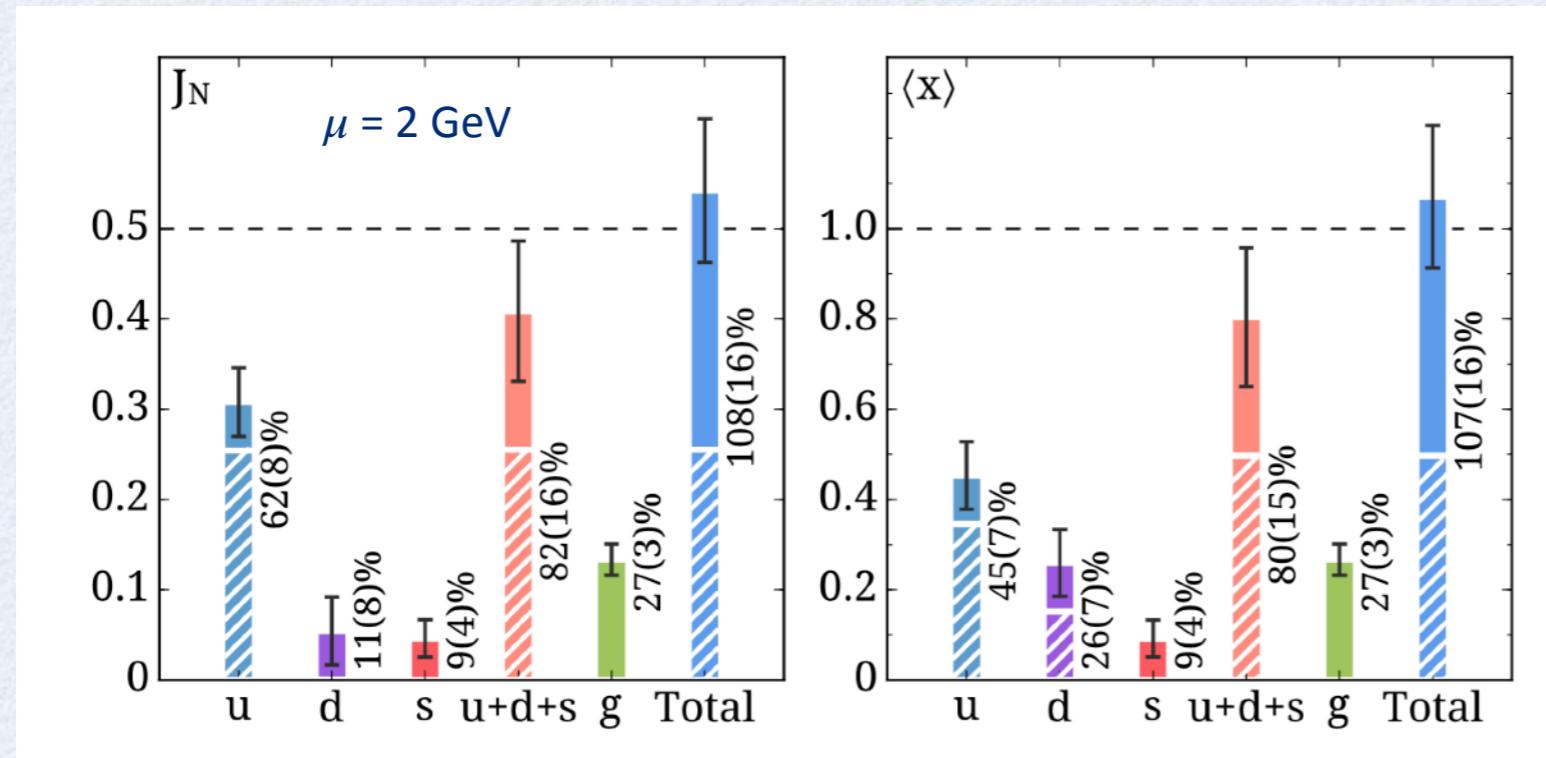
Goeke, Schweitzer et al. (2007)

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



lattice QCD calculations at the physical point

Alexandrou et al. (2017)

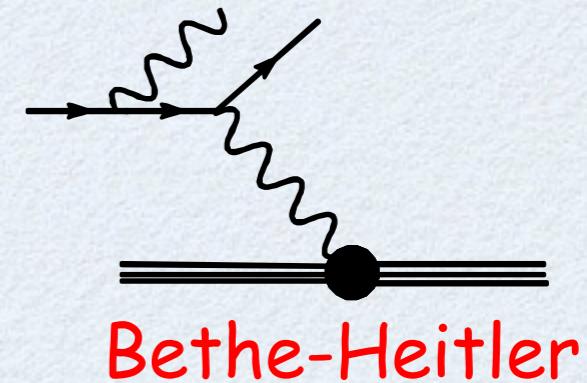
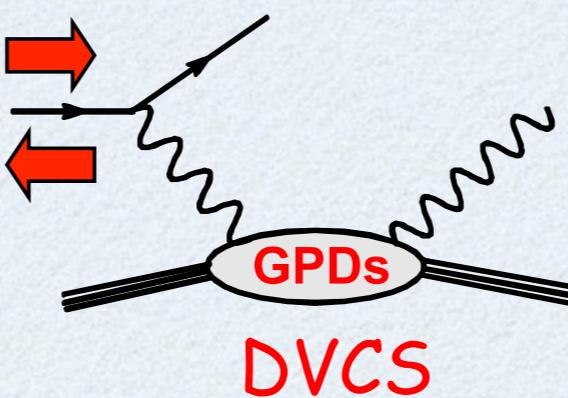


d, s-quarks carry very small total J in proton,
u-quark carries around 60%,
gluons around 30%

Sharing of momentum and total angular momentum between quarks and gluons identical in proton !

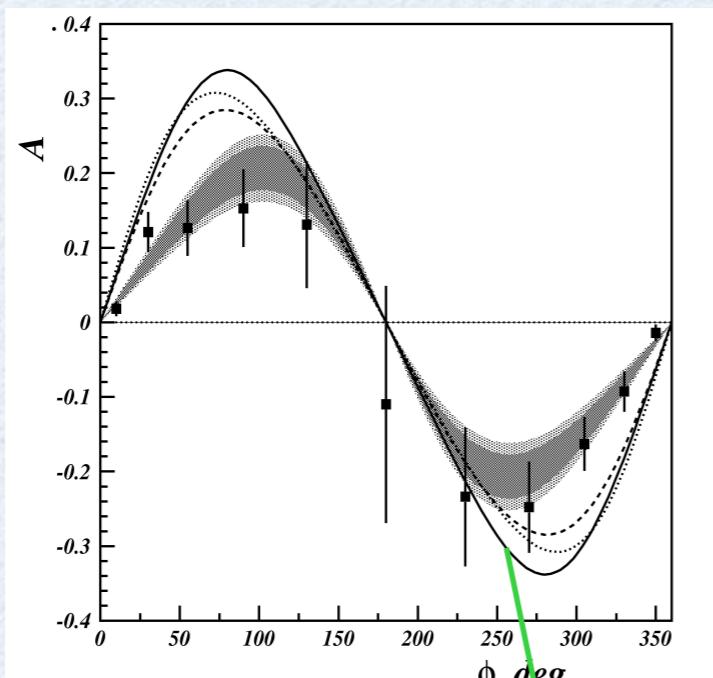
DVCS beam spin asymmetries: first observations around 2000

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

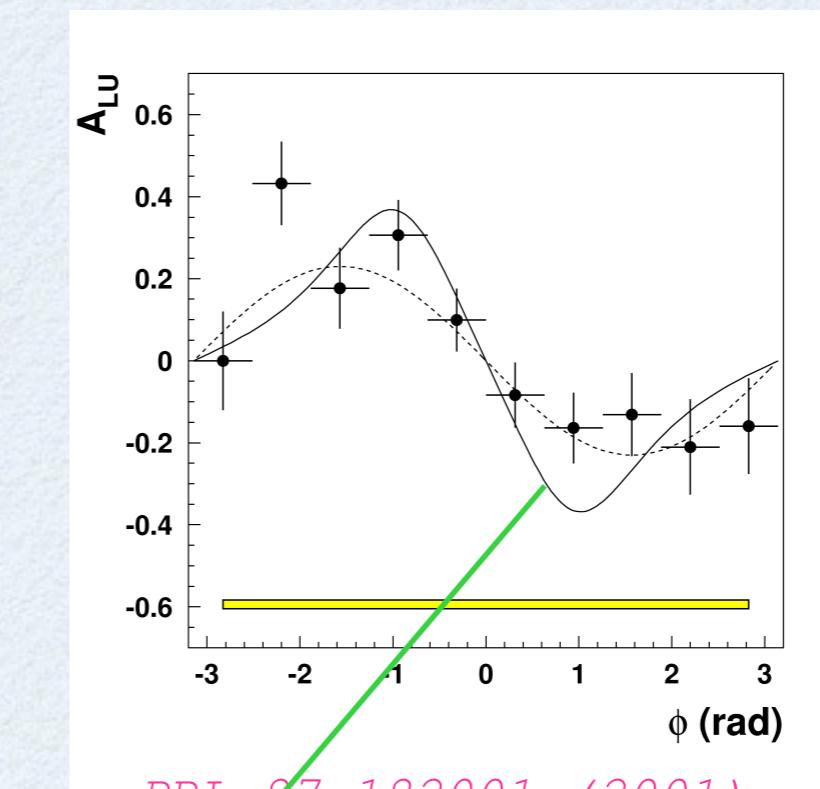


CLAS

$Q^2 = 1.25 \text{ GeV}^2$,
 $x_B = 0.19$,
 $-t = 0.19 \text{ GeV}^2$



PRL 87:182002 (2001)



PRL 87:182001 (2001)

HERMES

$Q^2 = 2.6 \text{ GeV}^2$,
 $x_B = 0.11$,
 $-t = 0.27 \text{ GeV}^2$

twist-2 + twist-3

Vdh, Guichon, Guidal (1999)
Kivel, Polyakov, Vdh (2000)

DVCS observables

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

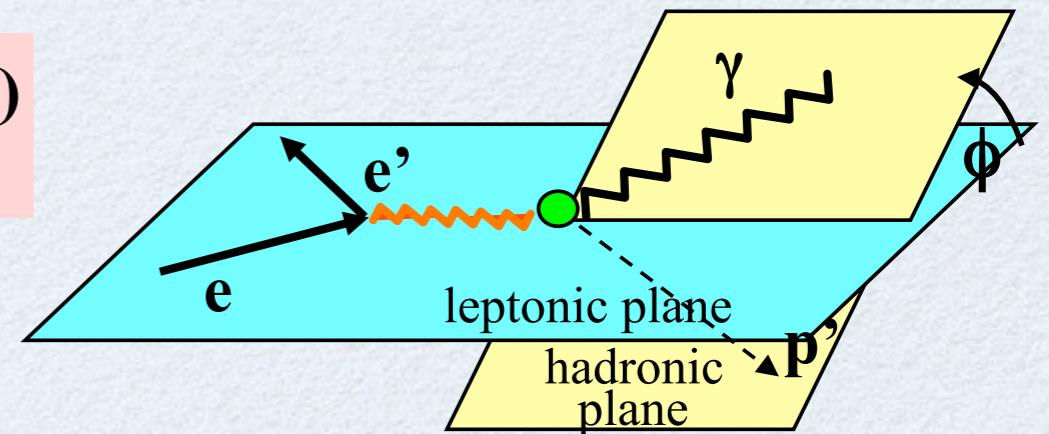
$$\xi = xB/(2-xB)$$

$$k = -t/4M^2$$

Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi \operatorname{Im}\{F_1H + \xi(F_1+F_2)\tilde{H} + kF_2E\}d\phi$$

Kinematically suppressed



$$H_p, \tilde{H}_p, E_p$$

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi \operatorname{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \dots)\}d\phi$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi \operatorname{Im}\{k(F_2H - F_1E) + \dots\}d\phi$$

Polarized beam, unpolarized neutron target:

$$\Delta\sigma_{LU} \sim \sin\phi \operatorname{Im}\{F_1H + \xi(F_1+F_2)\tilde{H} - kF_2E\}d\phi$$

Suppressed because $F_1(t)$ is small

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

$$H_p(x, \xi, t) = \frac{4}{9} H_u(x, \xi, t) + \frac{1}{9} H_d(x, \xi, t)$$

$$H_n(x, \xi, t) = \frac{1}{9} H_u(x, \xi, t) + \frac{4}{9} H_d(x, \xi, t)$$

DVCS accesses Compton Form Factors: 8 CFFs at twist-2



$$\mathcal{H}_{Re}(\xi, t) \equiv \mathcal{P} \int_0^1 dx \left\{ \frac{1}{x - \xi} + \frac{1}{x + \xi} \right\} H_+(x, \xi, t)$$

$$\mathcal{H}_{Im}(\xi, t) \equiv H_+(\xi, \xi, t)$$

$$\tilde{\mathcal{H}}_{Re}(\xi, t) \equiv \mathcal{P} \int_0^1 dx \left\{ \frac{1}{x - \xi} - \frac{1}{x + \xi} \right\} \tilde{H}_+(x, \xi, t)$$

$$\tilde{\mathcal{H}}_{Im}(\xi, t) \equiv \tilde{H}_+(\xi, \xi, t)$$

and analogous formulas for GPDs E, \tilde{E}^q respectively

with singlet GPD combinations
(quark + anti-quark):

$$H_+(x, \xi, t) \equiv H(x, \xi, t) - H(-x, \xi, t)$$

$$\tilde{H}_+(x, \xi, t) \equiv \tilde{H}(x, \xi, t) + \tilde{H}(-x, \xi, t)$$



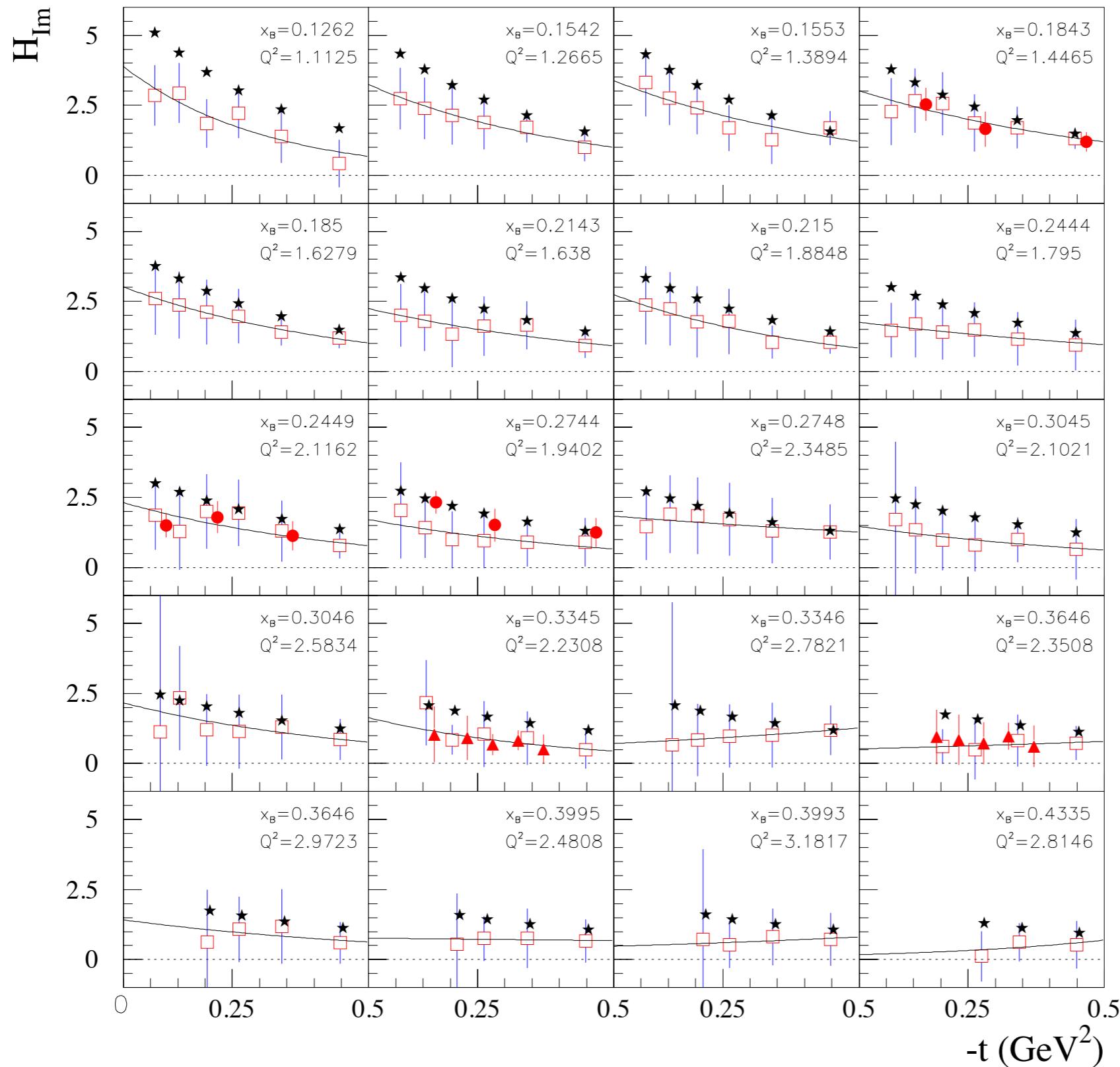
CFF fit extractions from data:

[Guidal \(2008, ...\)](#)

[Guidal, Moutarde \(2009, ...\)](#)

[Kumericki, Mueller, Paszek-Kumericki \(2008, ...\)](#)

global analysis of JLab 6 GeV data



$$\mathcal{H}_{Im}(\xi, t)$$

red solid circles:
CLAS: $\sigma, A_{LU}, A_{UL}, A_{LL}$

red open squares:
CLAS: σ, A_{LU}

red triangles:
Hall A: σ, A_{LU}

black stars
VGG model values

Dupré, Guidal,
vdh (2017)

CFF \mathcal{H}_{Im} :

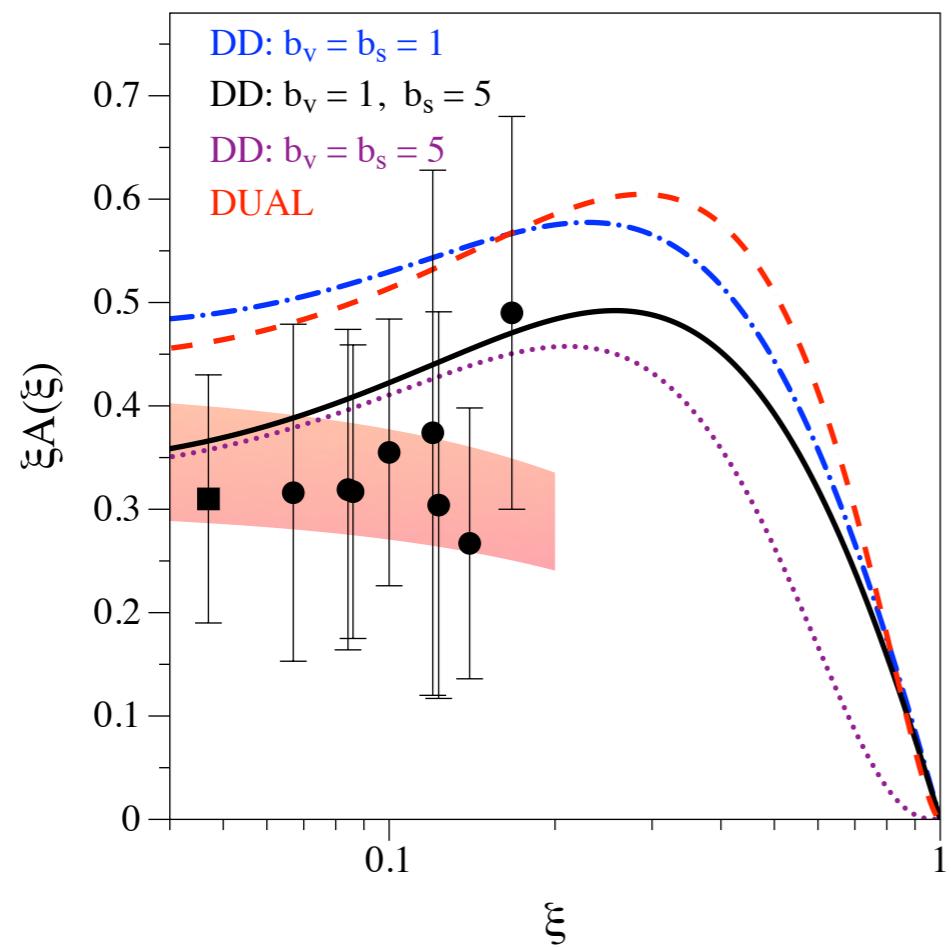
$$\mathcal{H}_{Im}(\xi, t) = A(\xi) e^{B(\xi)t}$$

black circles: CFF fit of JLab data

Dupré, Guidal, Vdh (2017)

black squares: CFF fit of HERMES data

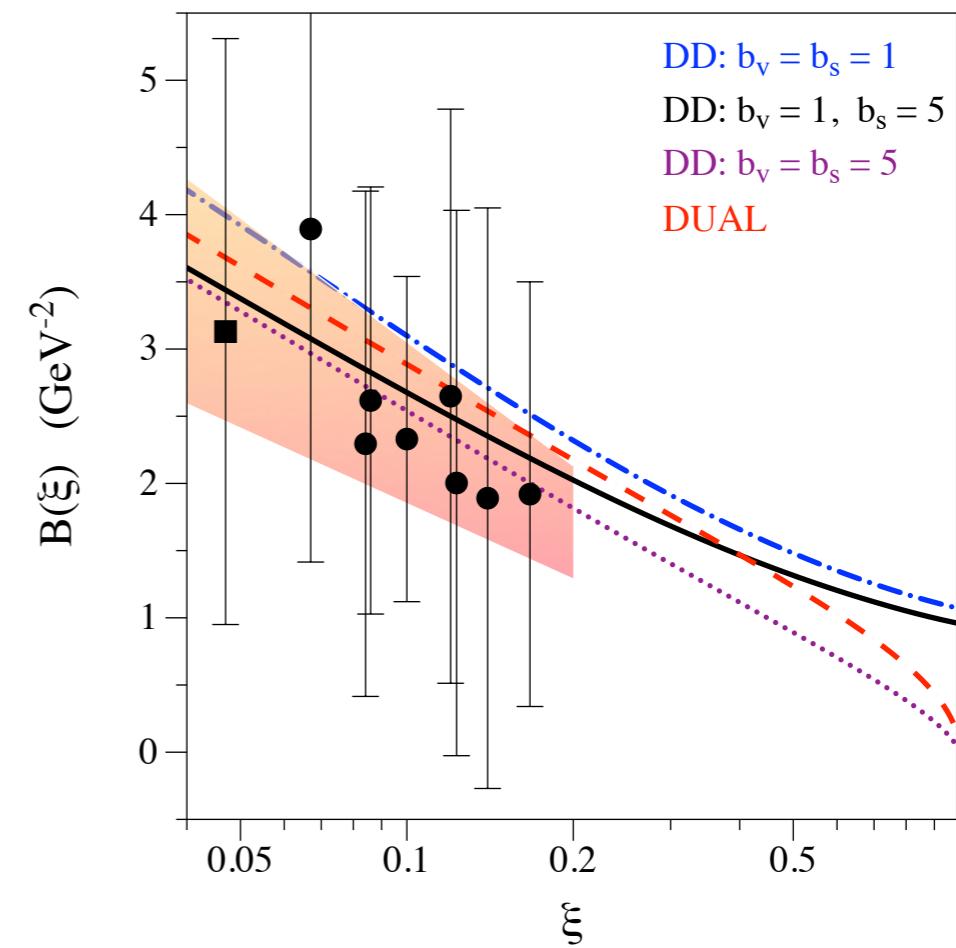
Guidal, Moutarde (2009)



$$A(\xi) = a_A (1 - \xi)/\xi$$

red bands:
1- parameter
fits of data

$$B(\xi) = a_B \ln(1/\xi)$$



3D imaging



$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i \mathbf{b}_\perp \cdot \Delta_\perp} H_-^q(x, \xi = 0, -\Delta_\perp^2)$$

Burkardt (2000)

number density of quarks (q) with longitudinal momentum x
at a transverse distance \mathbf{b}_\perp in proton



non-singlet (valence quark) GPDs: $H_-^q(x, 0, t) \equiv H^q(x, 0, t) + H^q(-x, 0, t)$



x-dependent radius

$$\langle b_\perp^2 \rangle^q(x) \equiv \frac{\int d^2 \mathbf{b}_\perp \mathbf{b}_\perp^2 \rho^q(x, \mathbf{b}_\perp)}{\int d^2 \mathbf{b}_\perp \rho^q(x, \mathbf{b}_\perp)} = -4 \frac{\partial}{\partial \Delta_\perp^2} \ln H_-^q(x, 0, -\Delta_\perp^2) \Big|_{\Delta_\perp=0}$$

$$H_-^q(x, 0, t) = q_v(x) e^{B_0(x)t} \longrightarrow \langle b_\perp^2 \rangle^q(x) = 4B_0(x)$$



x-independent radius

$$\langle b_\perp^2 \rangle^q = \frac{1}{N_q} \int_0^1 dx q_v(x) \langle b_\perp^2 \rangle^q(x)$$

$N_u=2, N_d=1$

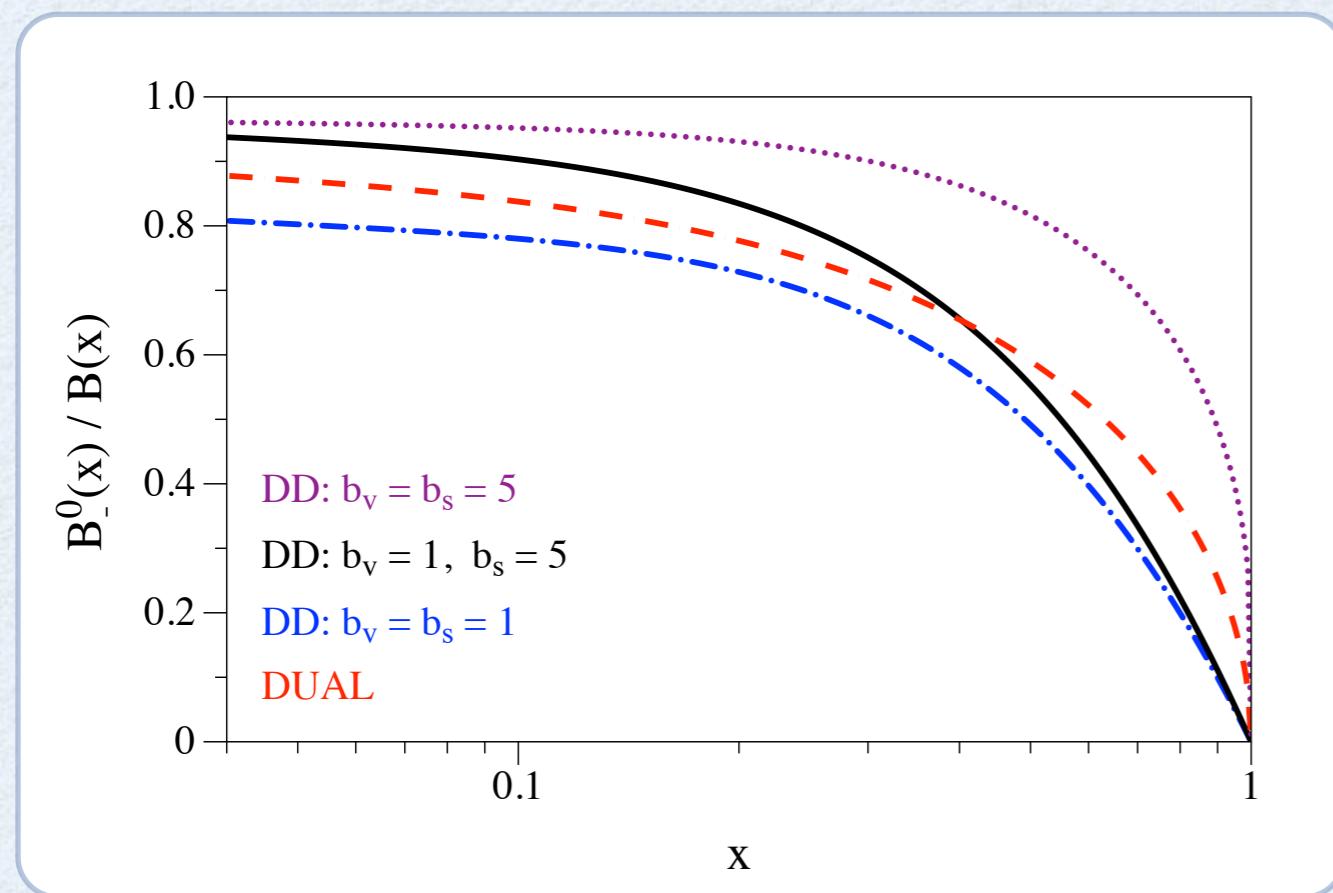
$$\langle b_\perp^2 \rangle = 2e_u \langle b_\perp^2 \rangle^u + e_d \langle b_\perp^2 \rangle^d = 2/3 \langle r_1^2 \rangle = 0.43 \pm 0.01 \text{ fm}^2$$

Bernauer (2014)

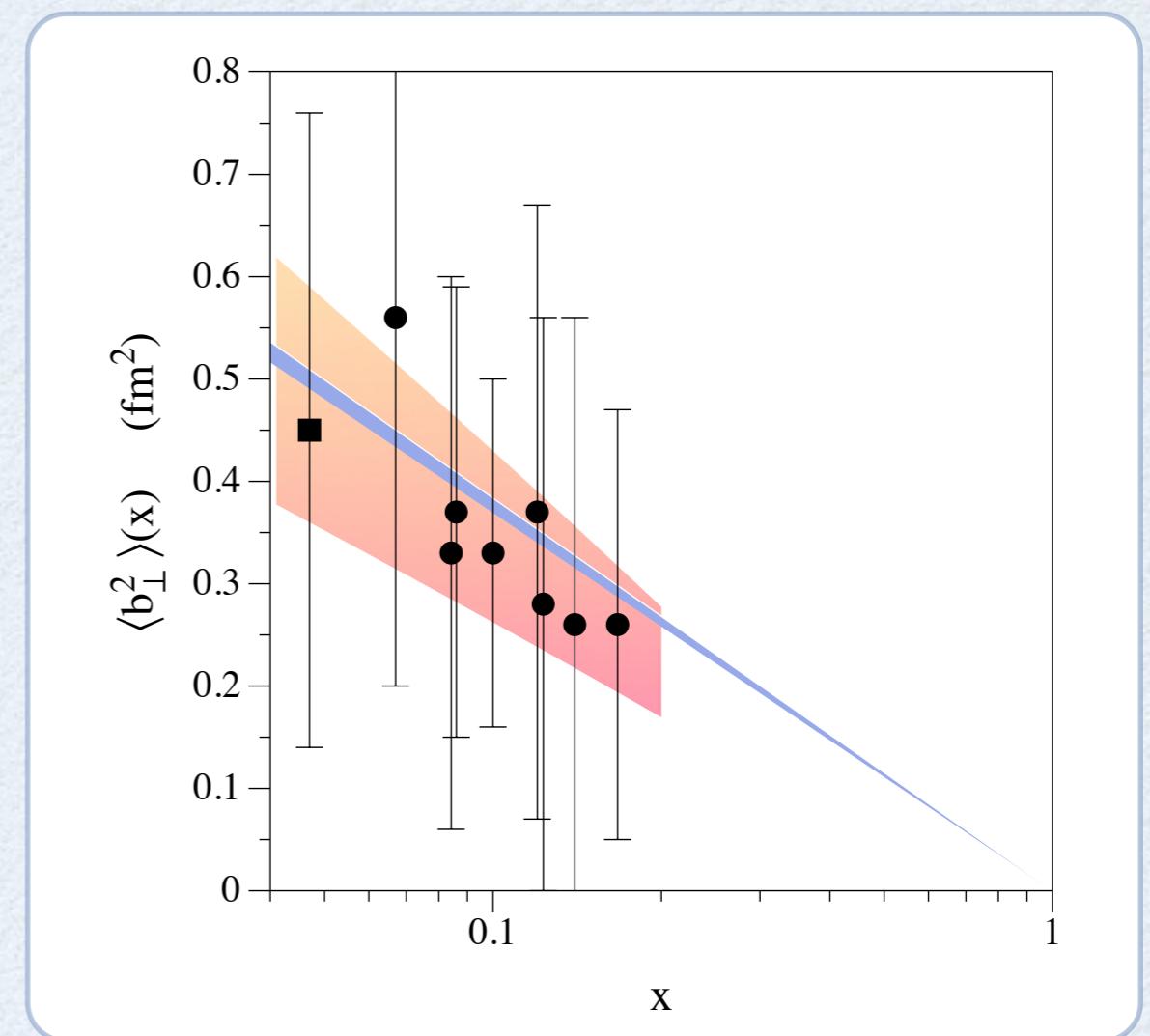
x -dependent radius in proton

black circles: CFF fit of JLab data

black squares: CFF fit of HERMES data



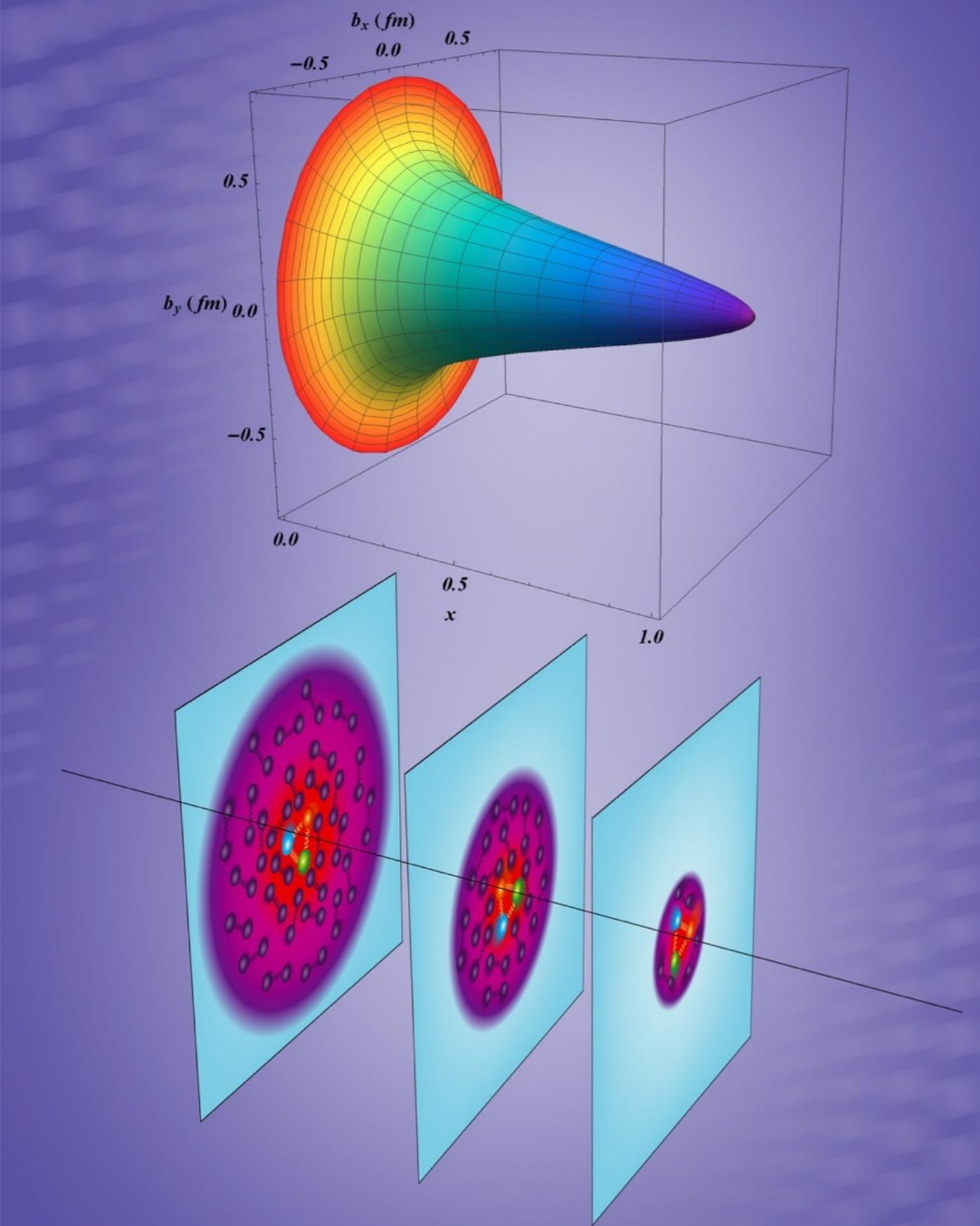
for $x < 0.15$: $B_0 / B > 0.9$



narrow band: using $B_0(x) = a_{B_0} \ln(1/x)$

a_{B_0} fixed from elastic scattering

Dupré, Guidal, Niccolai, Vdh (2017)



3D imaging of proton

Dupré, Guidal, vdh (2017)

CFF \mathcal{H}_{Re} : dispersion relation formalism

Anikin, Teryaev (2007)

Diehl, Ivanov (2007)

Polyakov, Vdh (2008)

Kumericki-Passek, Mueller, Passek (2008)

Goldstein, Liuti (2009)

Guidal, Moutarde, Vdh (2013)

→ once-subtracted fixed-t dispersion relation

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

ξ -independent subtraction function known from CFF
 $\mathcal{H}_{Im}(x, t)$

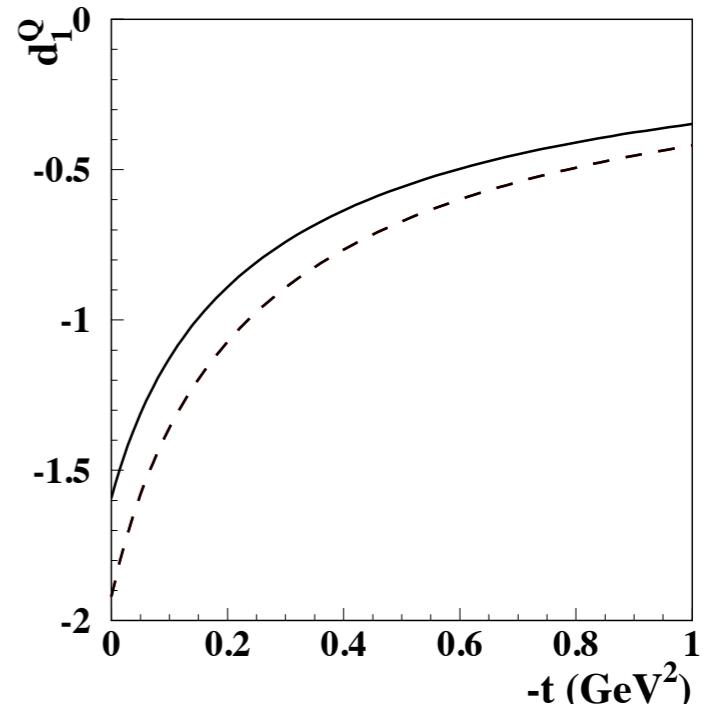
$$\Delta(t) \equiv \frac{2}{N_f} \int_{-1}^1 dz \frac{D(z, t)}{1 - z}$$

D-term

Polyakov, Weiss (1999)

$$D(z, t) = (1 - z^2) \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} d_n(t) C_n^{3/2}(z)$$

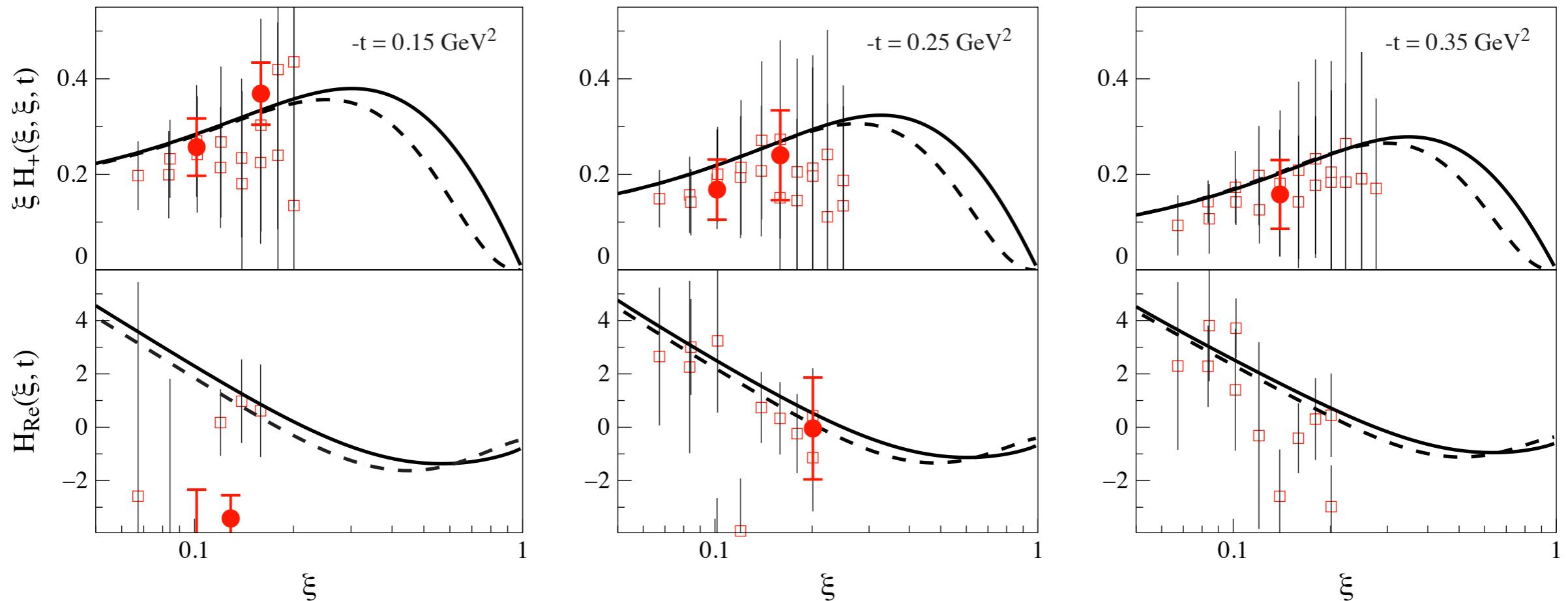
Pasquini, Polyakov, Vdh (2014)



experimental strategy for CFF \mathcal{H}_{Re} : direct extraction vs dispersion formalism

red solid circles: CLAS: $\sigma, A_{LU}, A_{UL}, A_{LL}$

red open squares: CLAS: σ, A_{LU}

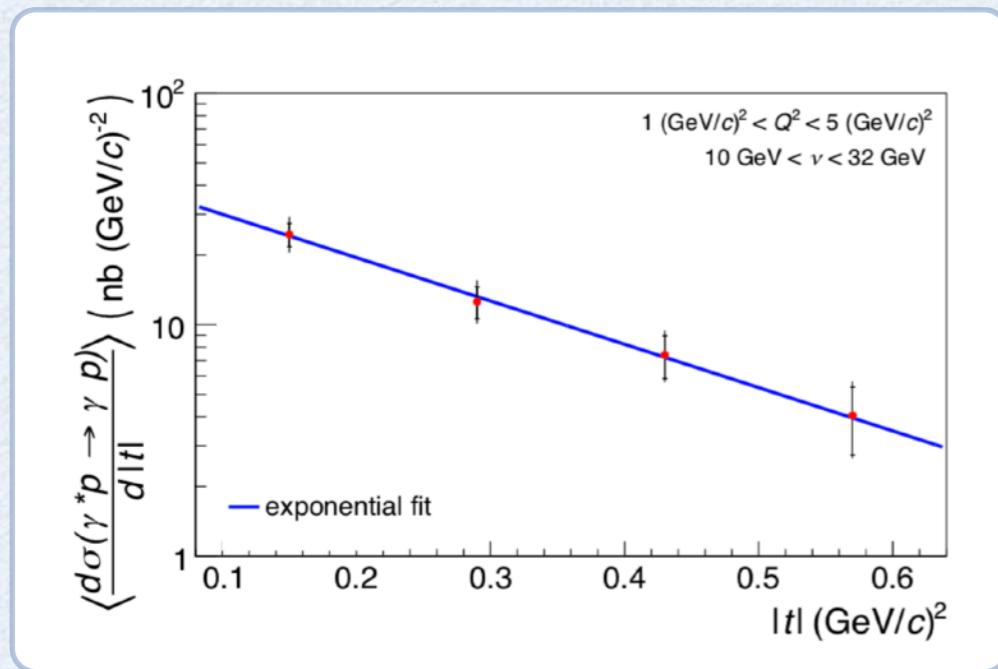


Curves for $\Delta(t) = 0$; $\Delta(t) < 0$ would shift H_{Re} curves up !

Dupré, Guidal, Niccolai, vdh (2017)

COMPASS DVCS results

→ Talk N. d' Hose



$$\frac{d\sigma}{dt} \sim e^{B_\sigma(\xi)t}$$

$$\mathcal{H}_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

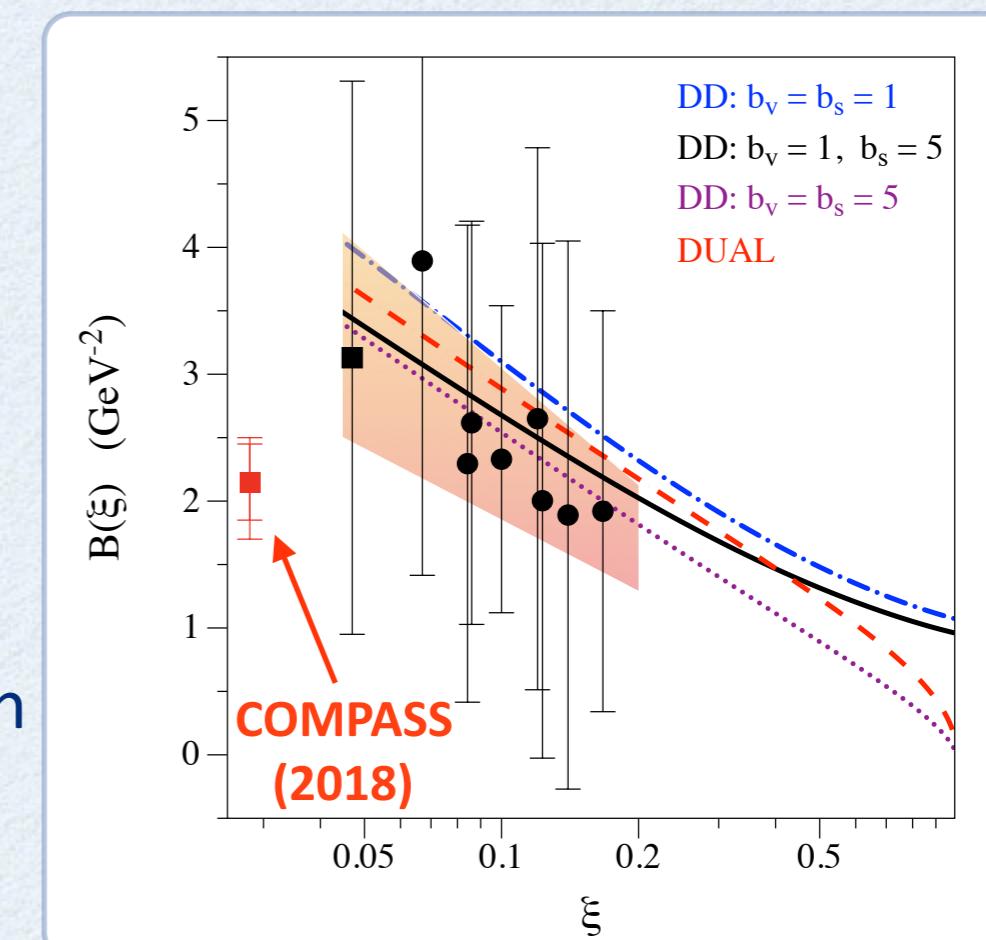
when only \mathcal{H}_{Im}
contributes

$$B_\sigma(\xi) = 2B(\xi)$$

B_σ : t-slope of squared amplitude,
weighted average of different contributions

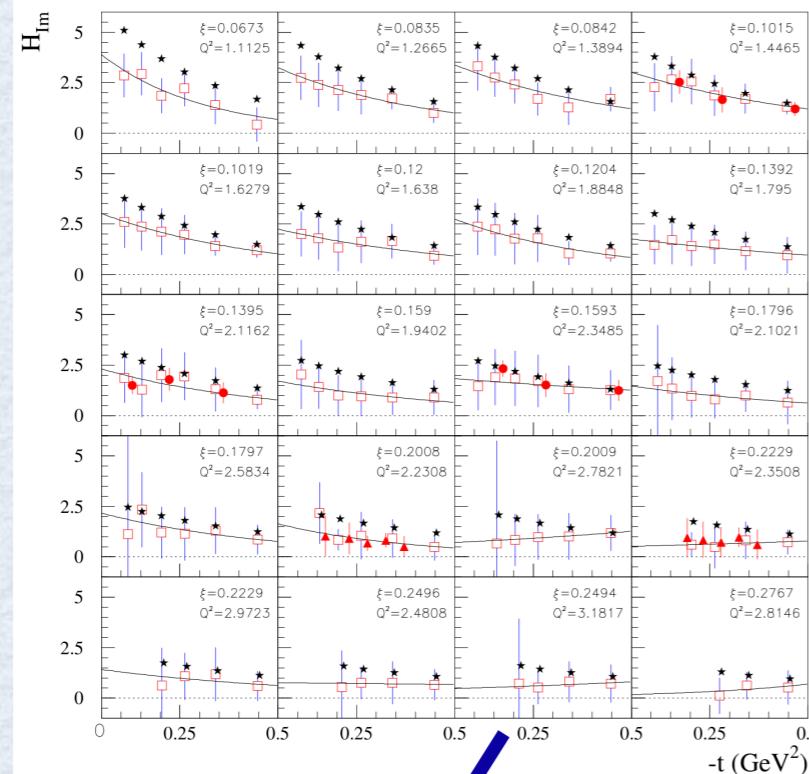
COMPASS regime $\xi \approx 0.03$ allows
to address interesting questions:

- How does the gluonic radius (HERA) differ from the valence quark radius (JLab) in overlap region
- Do CFFs H_{Re} and H_{Im} have significantly different t-slopes? → separation necessary

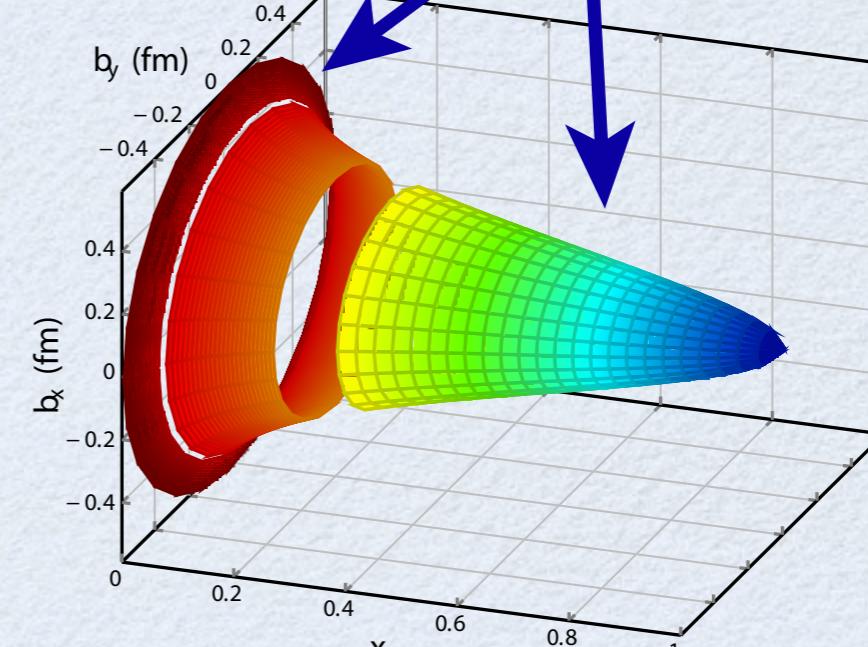
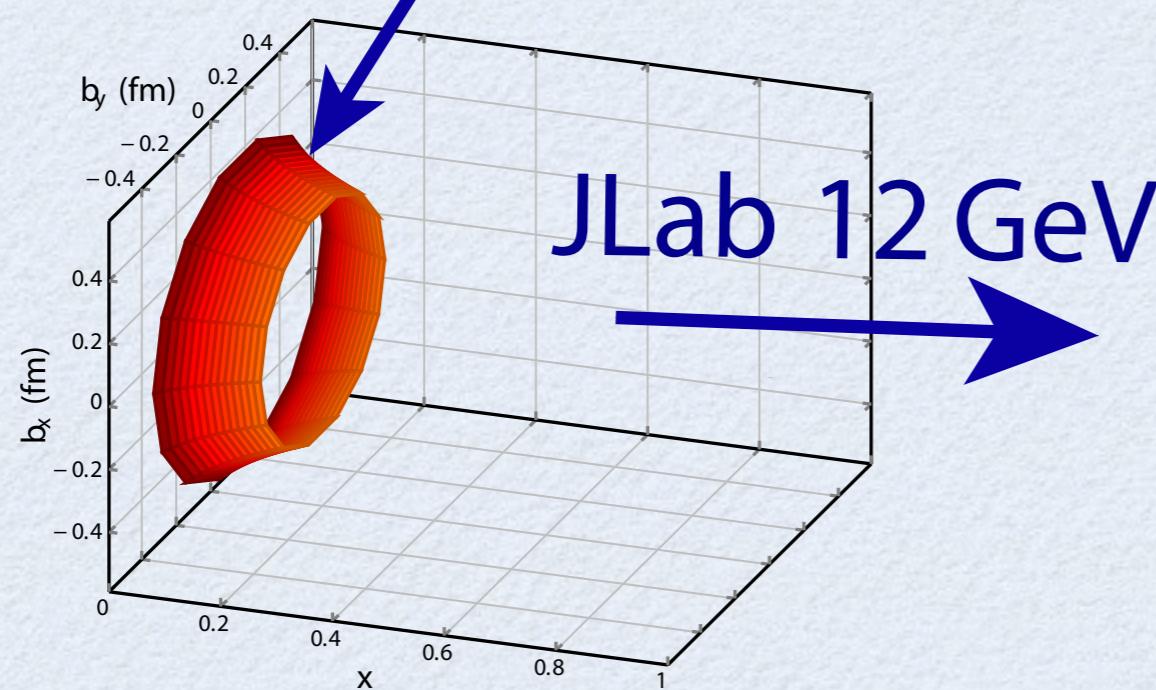
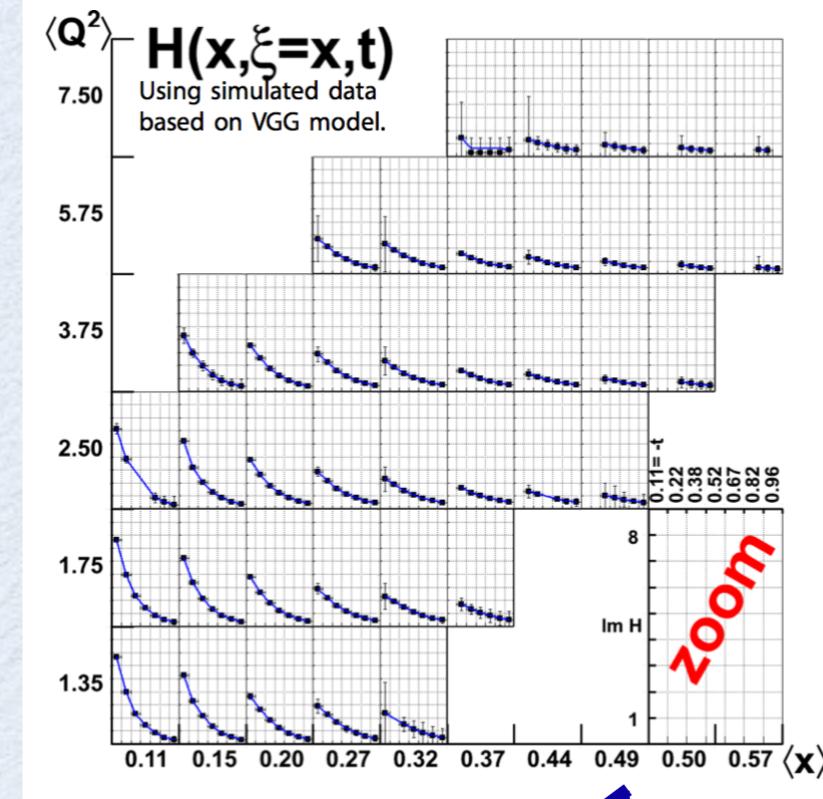


Projections for CFFs at JLab 12 GeV

Düpré-Guidal-Vanderhaeghen-PRD **95** 011501 (R) (2017)



CLAS12 projections E12-06-119 with DVCS A_{UL} and A_{LU}



courtesy of Z.E. Meziani

Outlook

- ➡ elastic / transition FFs have allowed to get a first glimpse at the spatial distributions of quarks in nucleons
- ➡ GPDs allow for a proton imaging in longitudinal momentum and transverse position
- ➡ global analysis of JLab 6 GeV data have shown a proof of principle of such 3D imaging (tools available: fitters, dispersive analyses)
- ➡ systematic 3D imaging is possible now: COMPASS, JLab 12 GeV,...EIC

