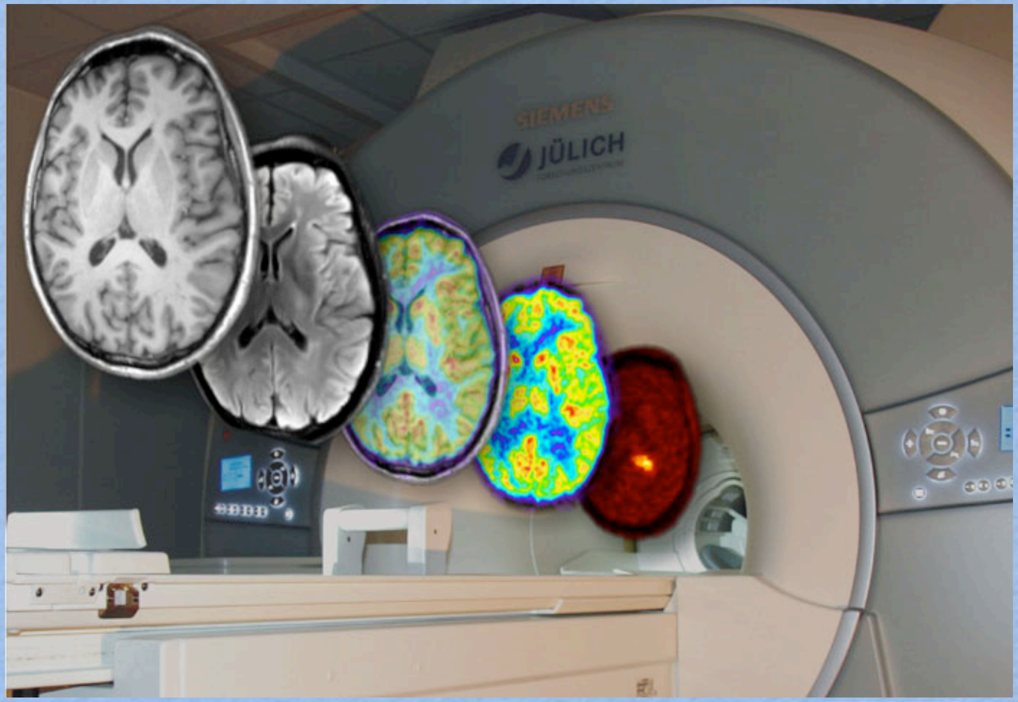
Spatial tomography of the proton from present data



Marc Vanderhaeghen

INT Workshop “Spatial and Momentum Tomography of Hadrons and Nuclei”

August 28 - September 29, 2017, Seattle, USA

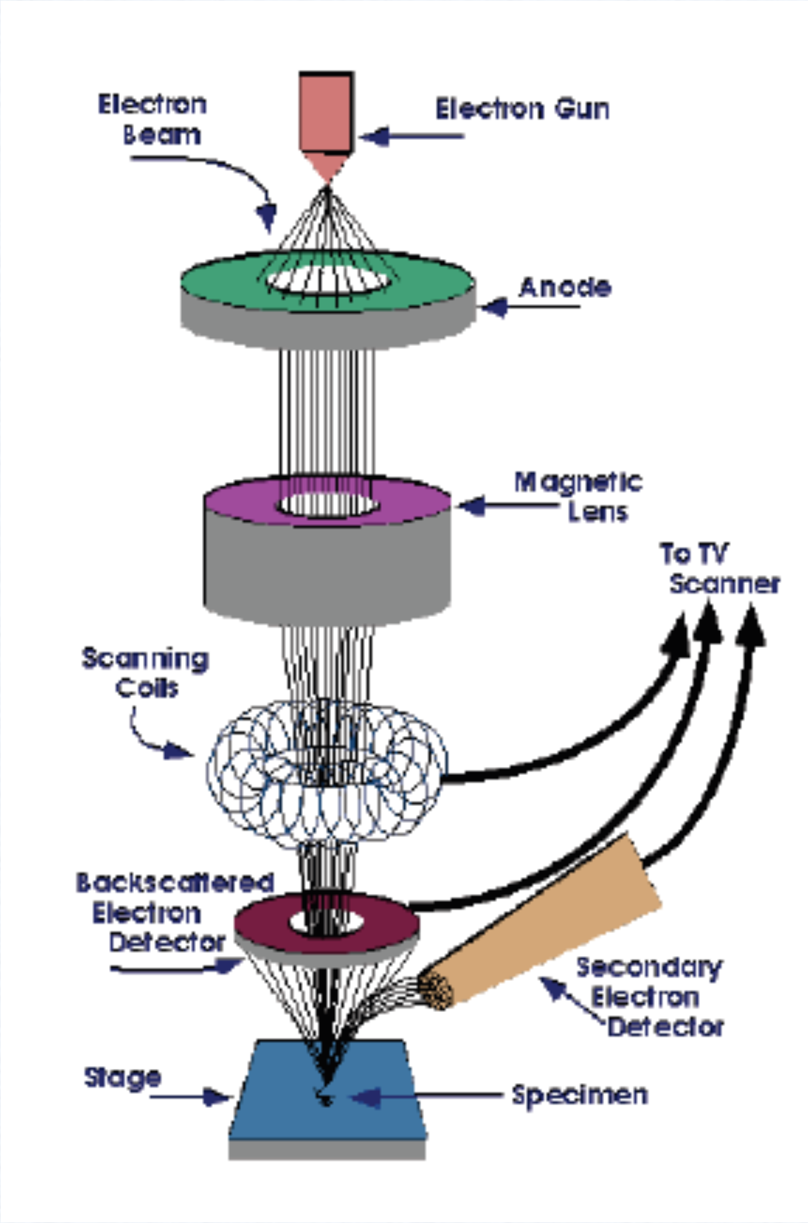
PRISMA

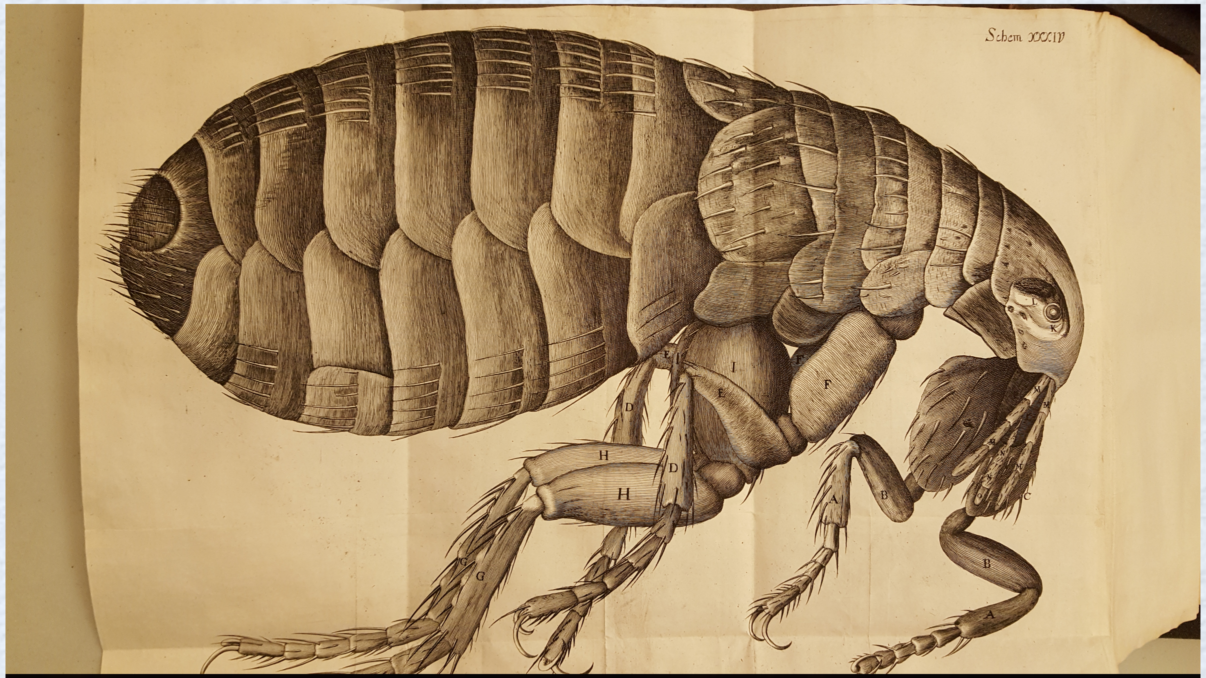
SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

how to image a system

R.Hooke (Micrographia, 1665)





when target is static

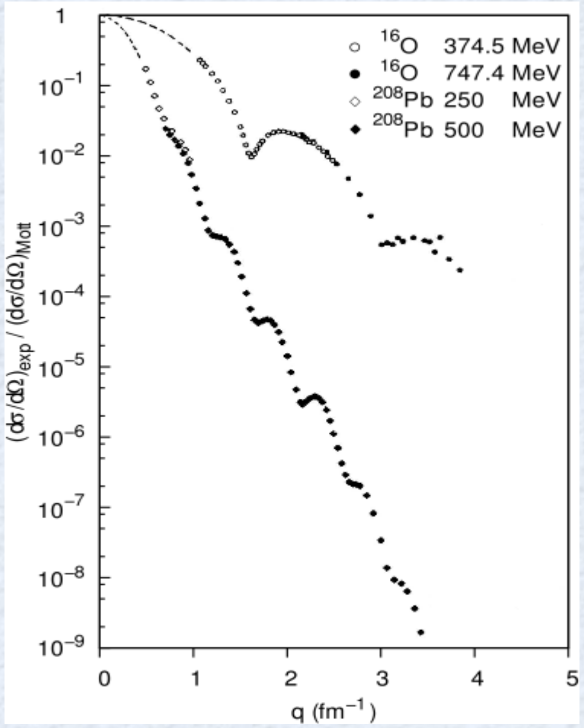
($m_{constituent}$, m_{target} >> Q)

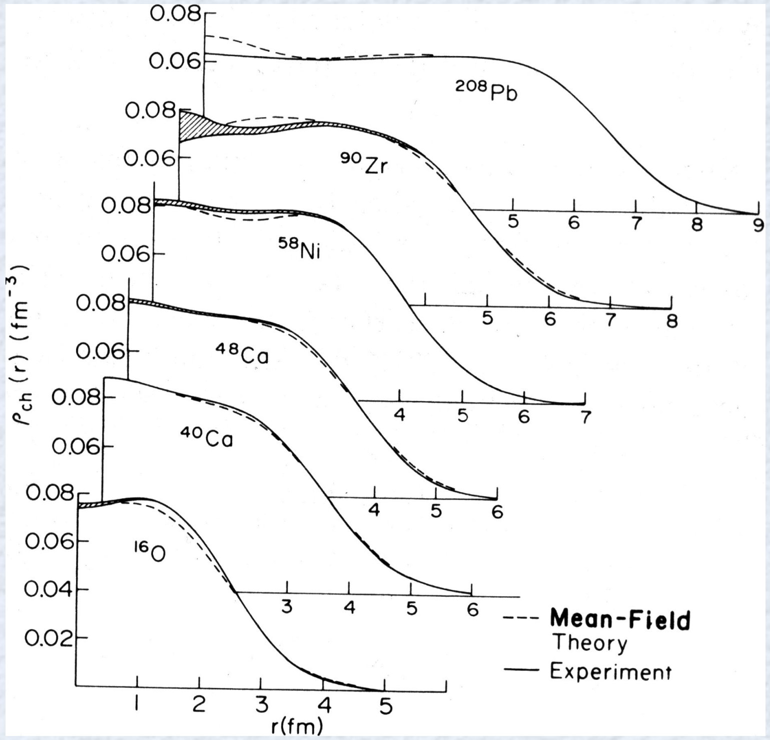
the 3D Fourier transform of **form factors**

gives the distribution of electric charge and magnetization

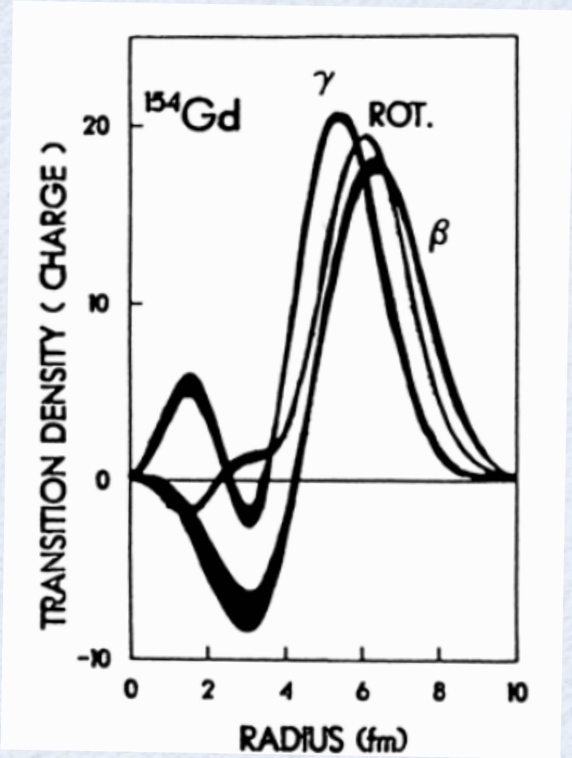
what do we know about spatial distributions of charges in nuclei?

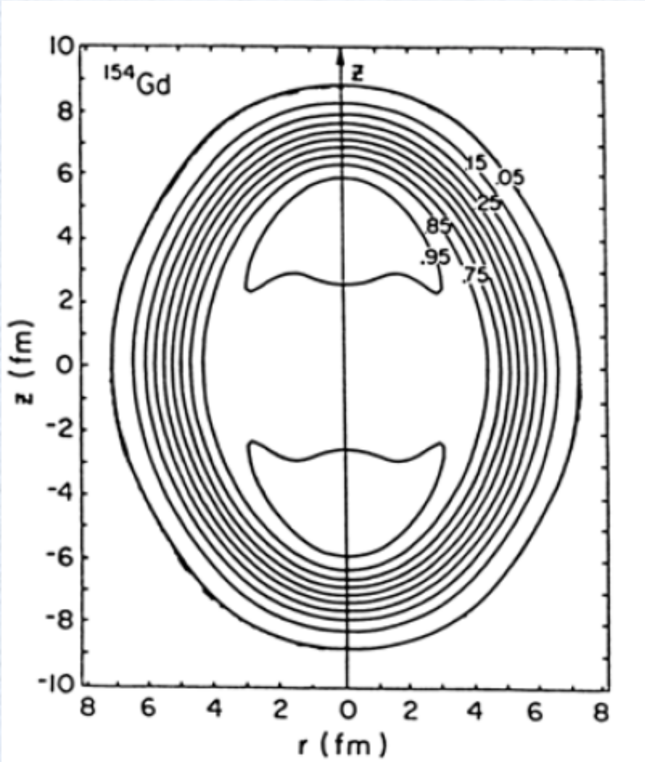
sizes of nuclei:
as revealed through
elastic electron scattering





shapes of nuclei:
as revealed through
inelastic electron scattering



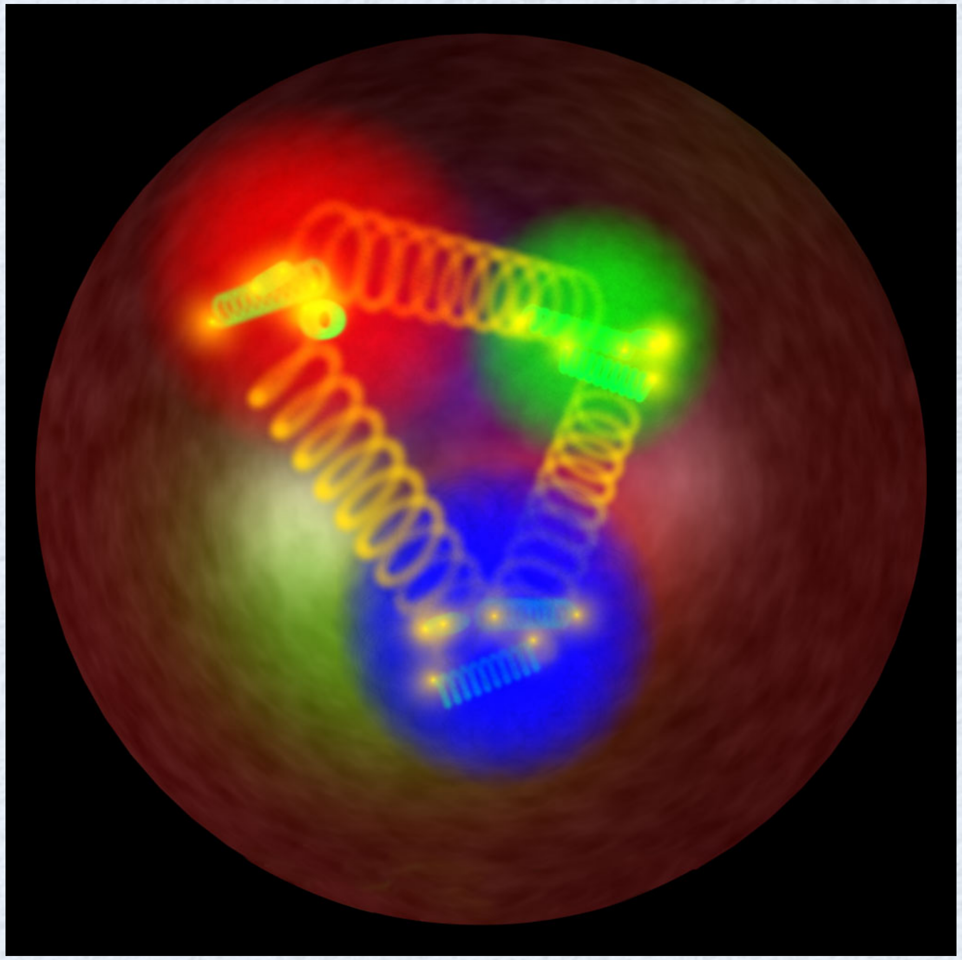


what do we know about the proton size and its charge distributions?

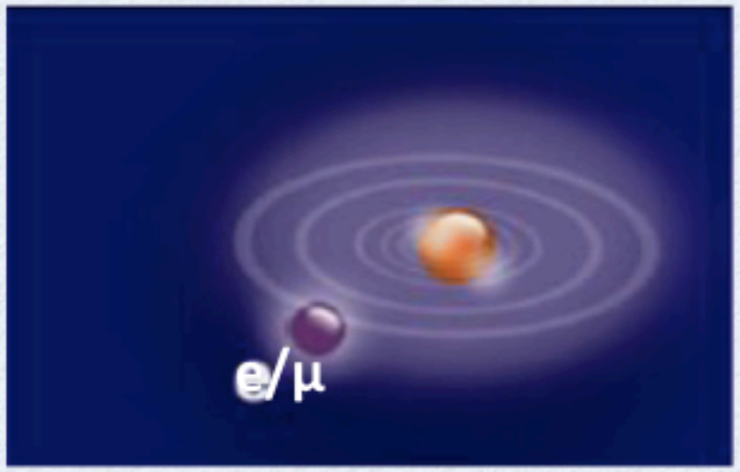
- proton **size**: charge radius R_E
  very low Q^2 **elastic** electron scattering,
  atomic spectroscopy (Lamb shift)

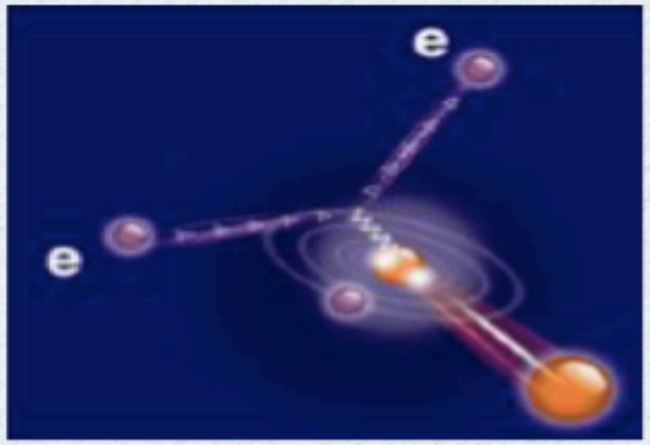
- proton **spatial (charge) distributions**
  elastic electron scattering
  e.m. FFs: $F_1(Q^2) \rightarrow \rho(\mathbf{b})$

- proton **3D transverse spatial/ longitudinal momentum distributions**
  deeply virtual Compton scattering
  GPDs $H(x, \xi, t) \rightarrow \rho(x, \mathbf{b})$ for $\xi=0$

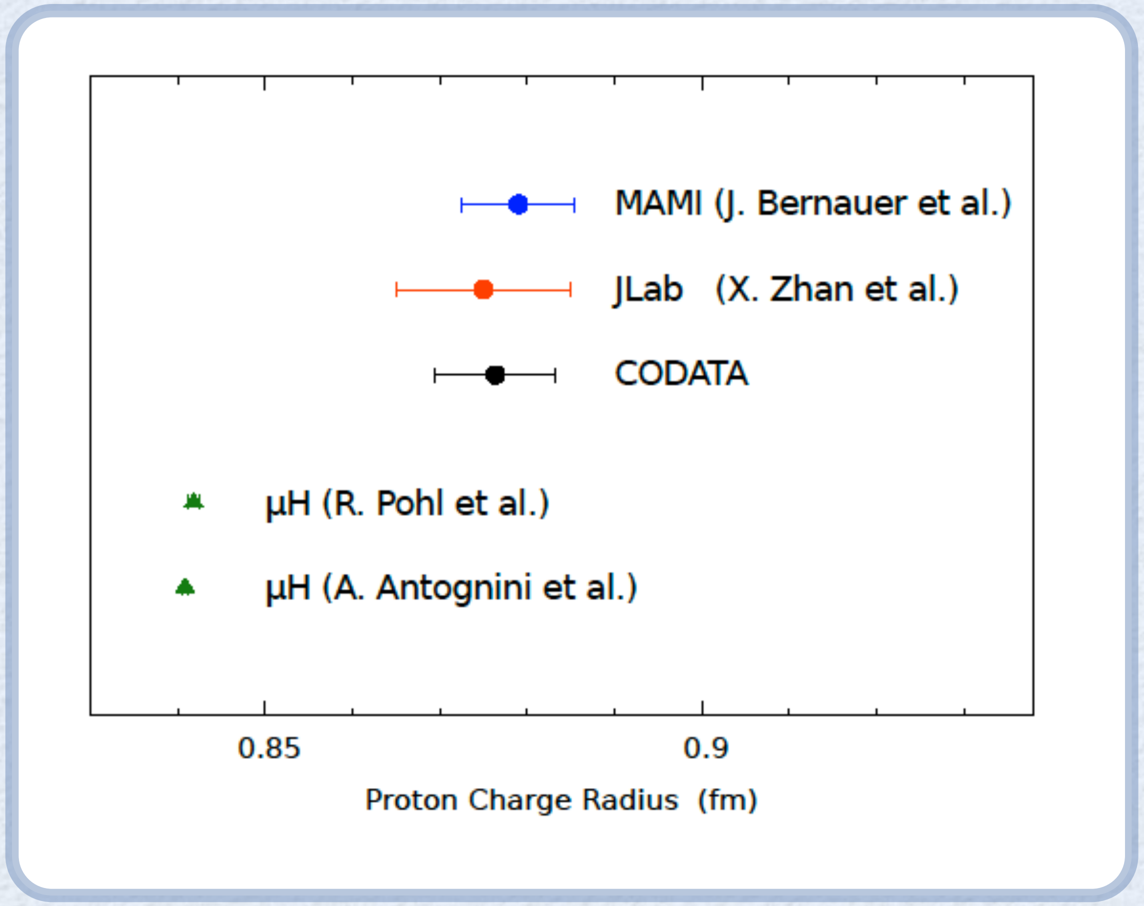


proton size,
proton radius puzzle





Proton radius puzzle



μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al. (2010)

Antognini et al. (2013)

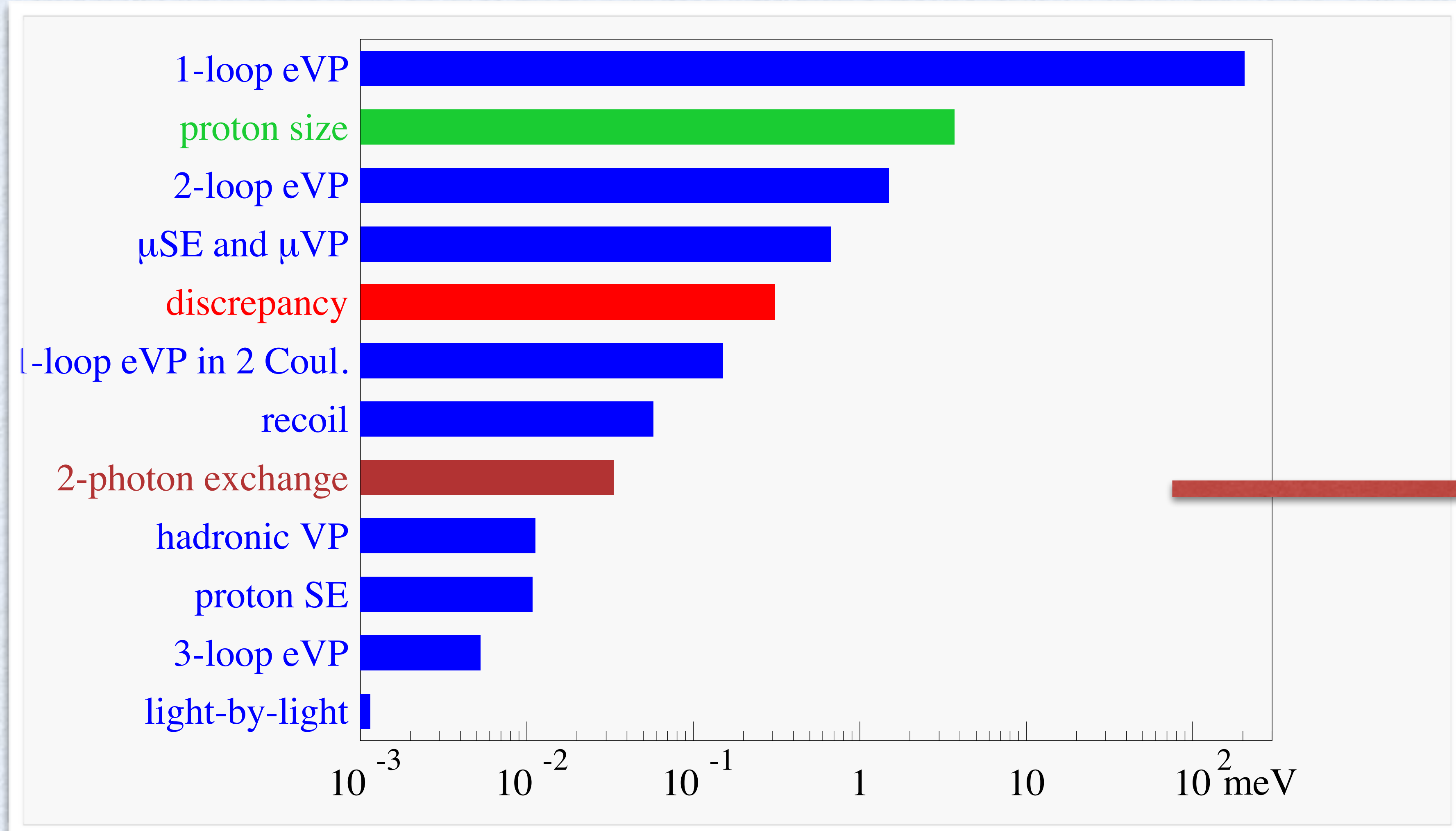
7 σ difference !?

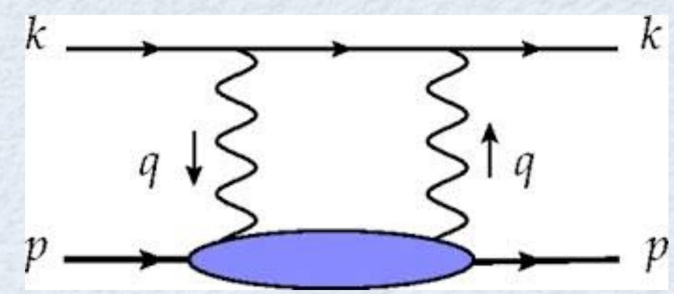
ep data: $R_E = 0.8775 \pm 0.0051$ fm

CODATA (2012)

Lamb shift: status of known corrections

μH Lamb shift: summary of corrections





largest theoretical uncertainty

- elastic contribution on 2S level: ΔE_{2S} = -23 μeV
- inelastic contribution: Carlson, Vdh (2011) + Birse, McGovern (2012)

total hadronic correction on Lamb shift

$\Delta E_{(2P-2S)} = (33 \pm 2)$ μeV

...or about 10% of needed correction

Proton radius puzzle: what's next ?

- μ atom Lamb shift: μ D, μ $^3He^+$, μ $^4He^+$ have been performed

- electronic H Lamb shift: higher accuracy measurements

- electron scattering analysis:
  - radius extraction fits (use fits with correct analytical behavior: 2π cut)
  - radiative corrections, two-photon exchange corrections

  new fit $R_E = 0.904\ (15)$ fm (4σ from μH)

- electron scattering experiments:

  new G_{Ep} experiments down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

  - MAMI/A1: Initial State Radiation (2013/4)
  - JLab/Hall B: HyCal, magnetic spectrometer-free experiment, norm to Møller (2016/7)
  - MESA: low-energy, high resolution spectrometers

- muon scattering experiments: MUSE@PSI (2018/9)

- e^-e^+ versus $\mu^-\mu^+$ photoproduction: lepton universality test

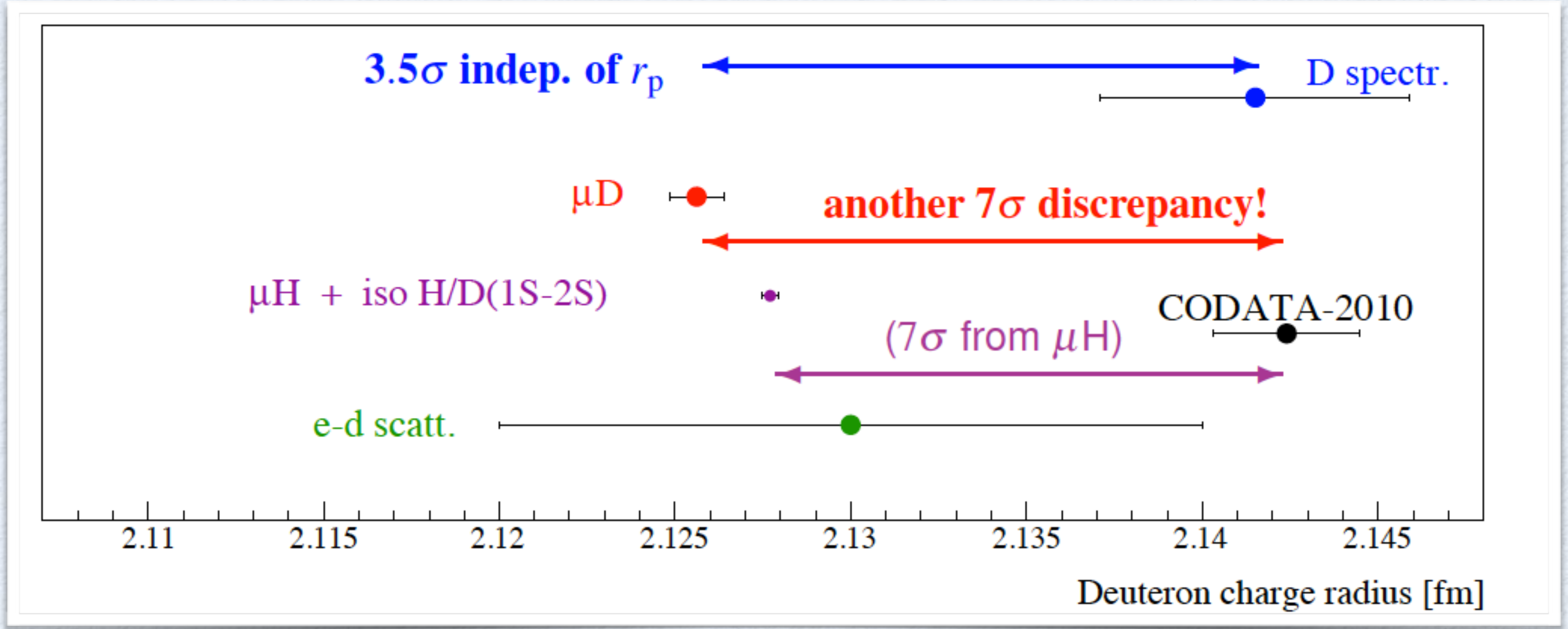
μD Lamb shift experiment

- H/D isotope shift (1S - 2S): $r_d{}^2 - r_p{}^2 = 3.82007\ (65)\ \mathrm{fm}^2$ Parthey et al. (2010)

- CODATA 2010: $r_d = 2.14240\ (210)$ fm

- r_p from μH + isotope shift : $r_d = 2.12771\ (22)$ fm

- new μD Lamb shift @ PSI: $r_d = 2.12562\ (13)_{theo}\ (77)_{theo}$ fm Pohl et al., Science 353,417 (2016)

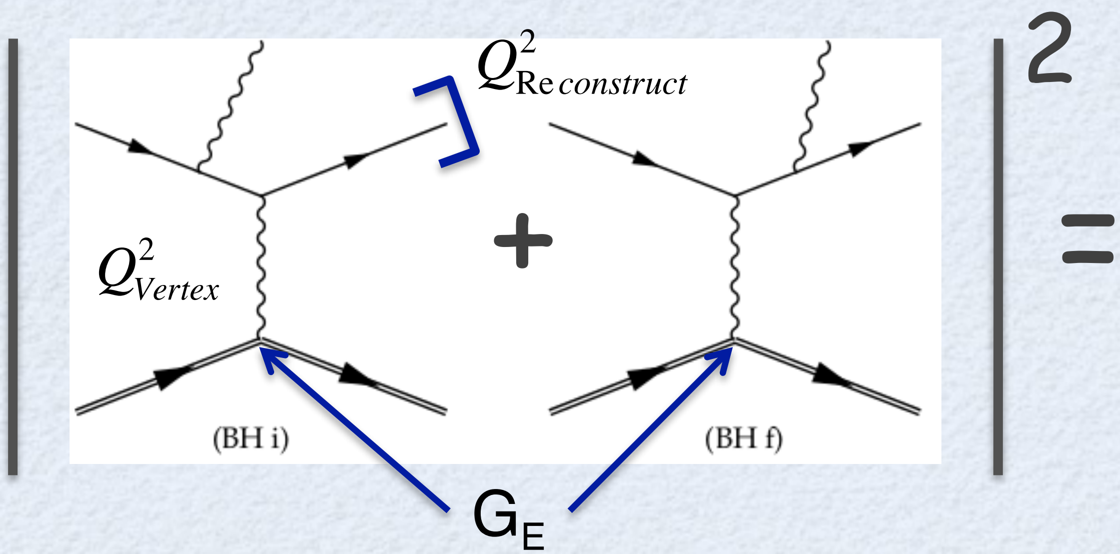


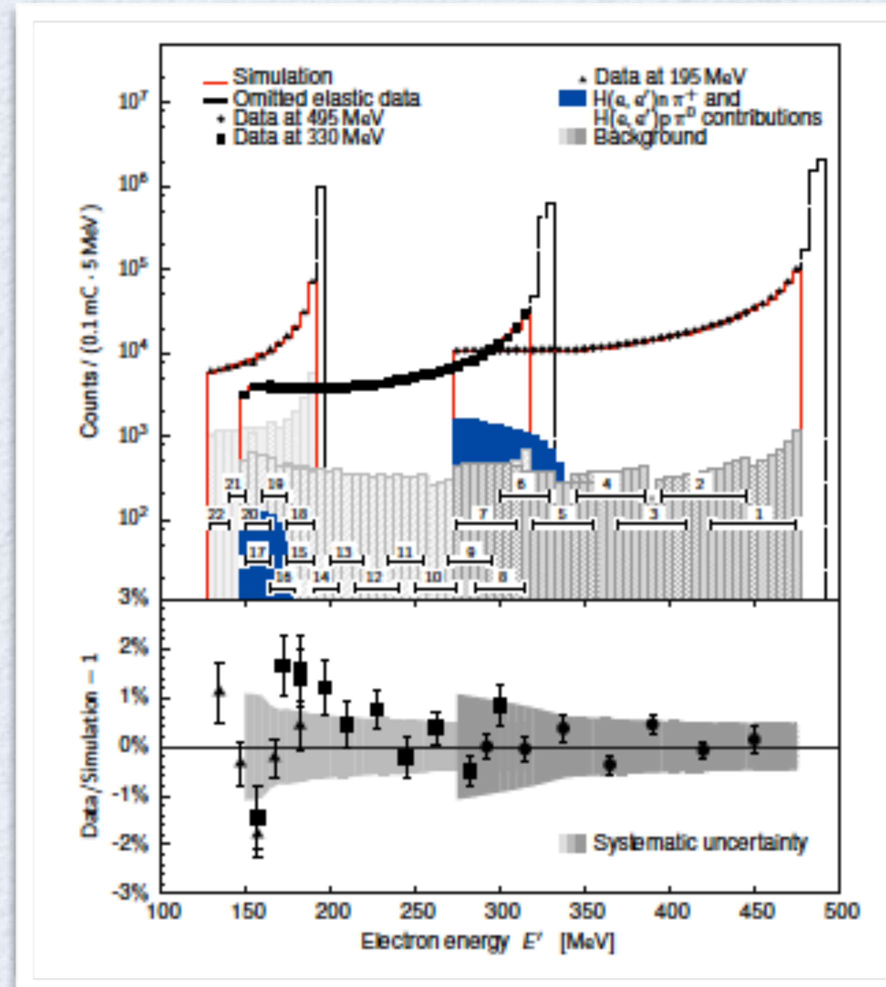
- electronic D (r_p indep.): $r_d = 2.14150\ (450)$ fm ← 3.5 σ Pohl et al. (2016)

- improved radius measurement from e-d scattering was performed @ MAMI (2014)

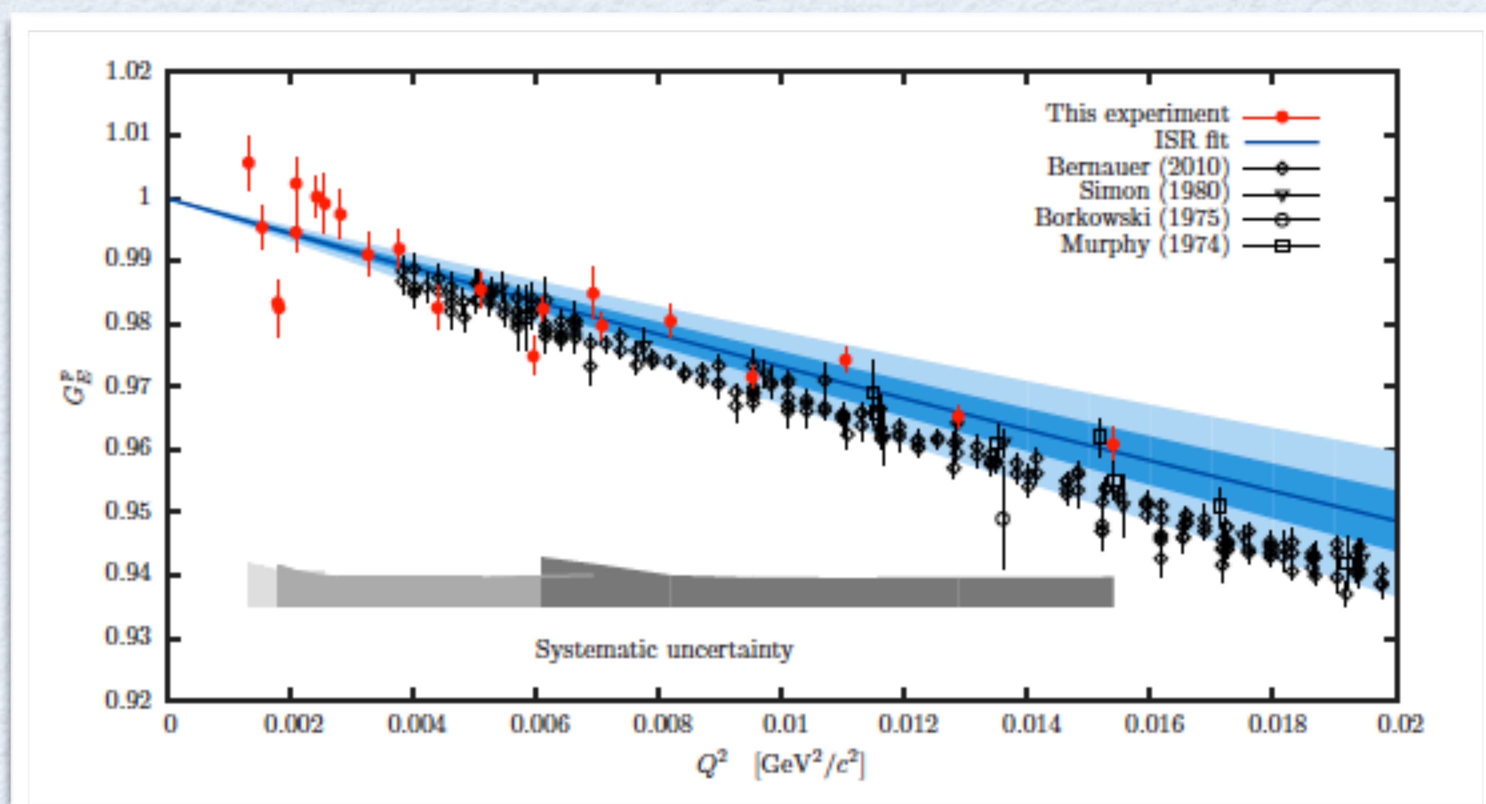
ISR@MAMI experiment

- **Extracting FFs from the radiative tail.**
- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams.





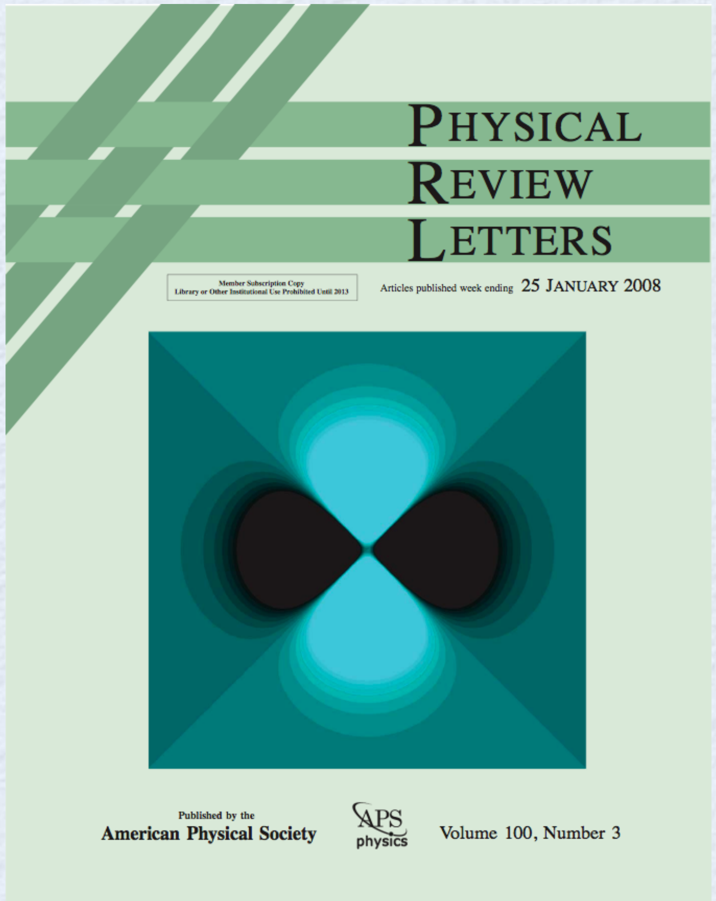
Mihovilovic et al.(2016)



good understanding of radiative tail (~ 1%)

follow up experiment: down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

proton e.m. form factors, charge distributions

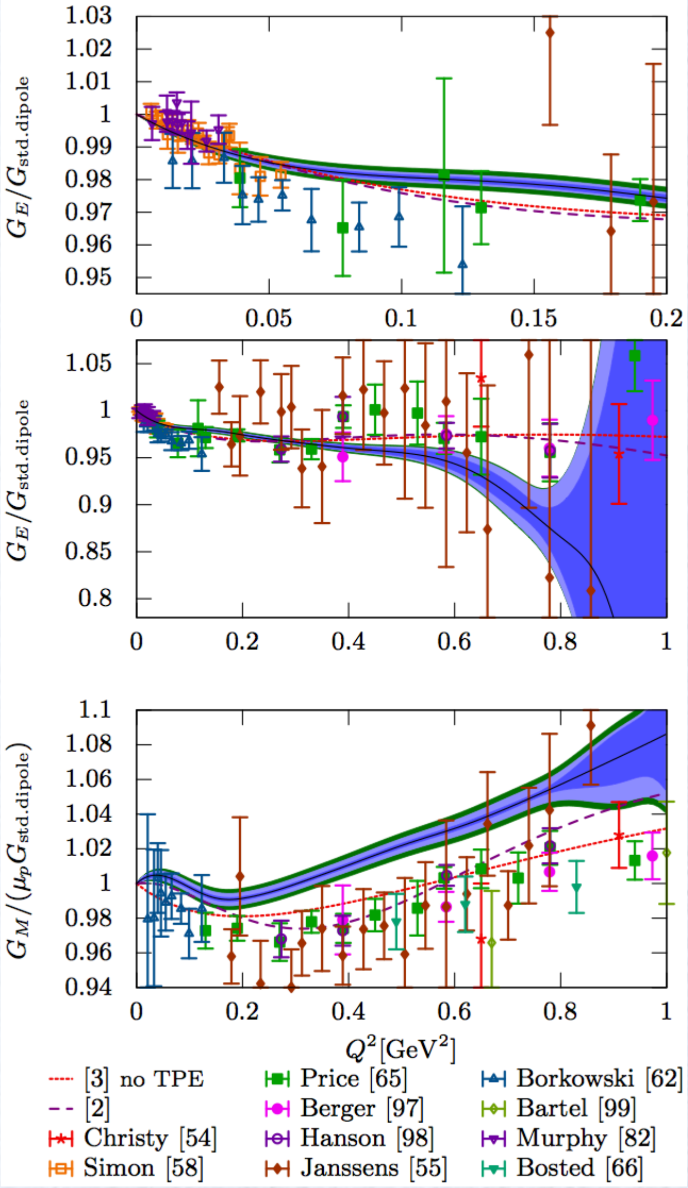


e⁻ scattering cross sections

Electron scattering facilities JLab (12 GeV), MAMI (1.6 GeV):

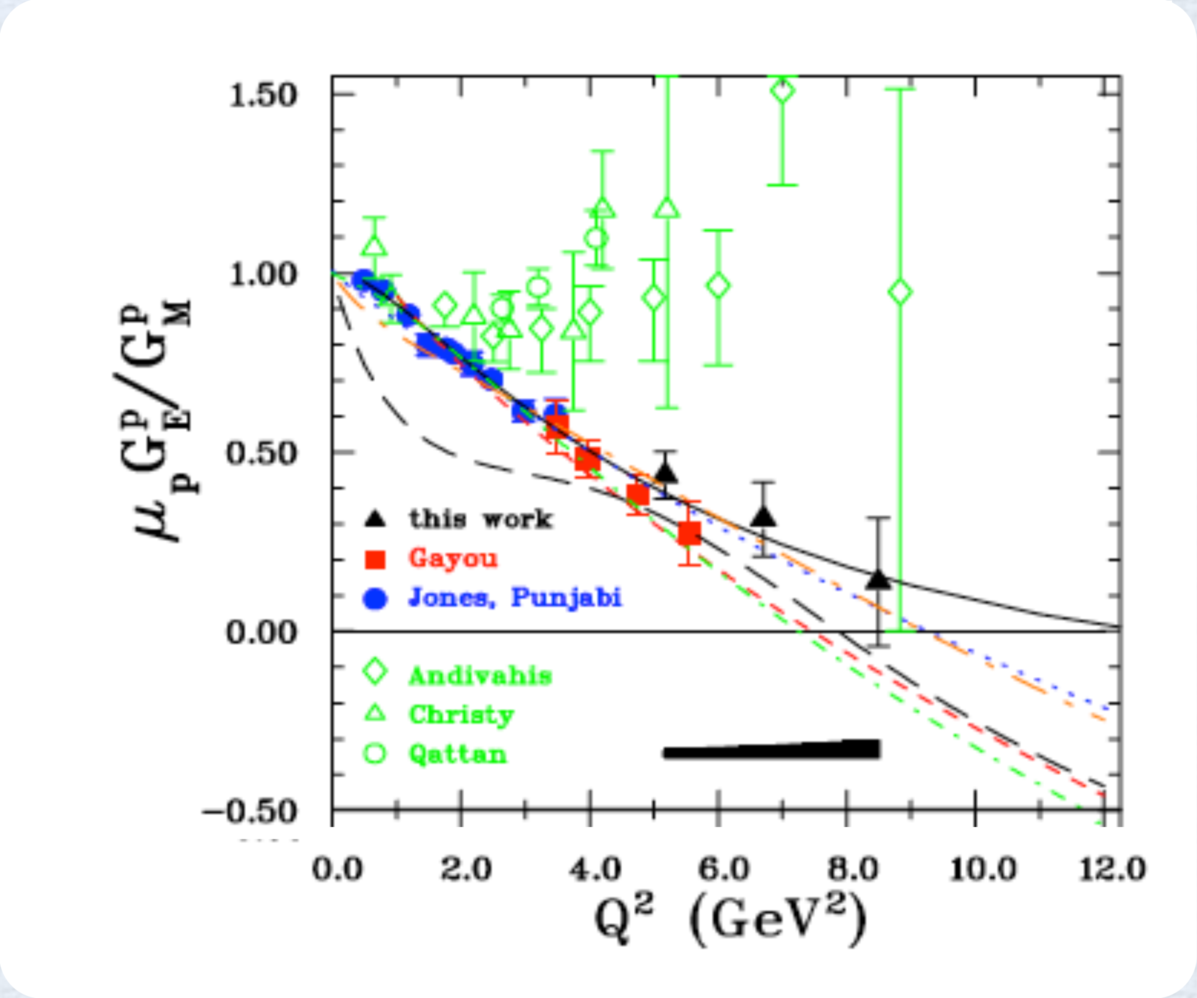
uniquely positioned to deliver high precision data

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



Bernauer et al.(2010, 2013)

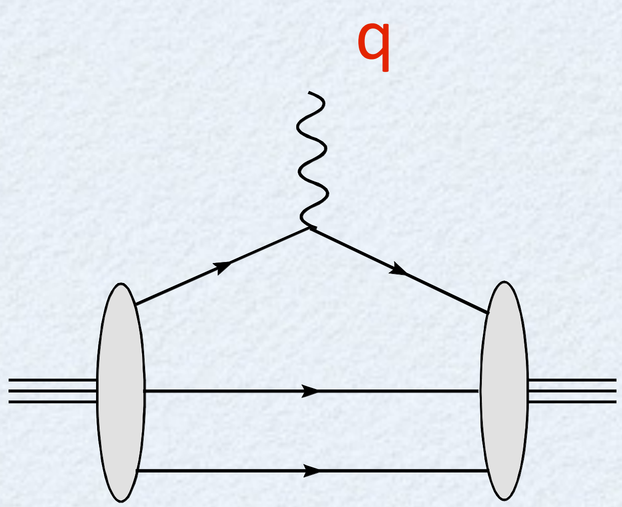
JLab polarization transfer measurements: G_{Ep} / G_{Mp} difference with Rosenbluth

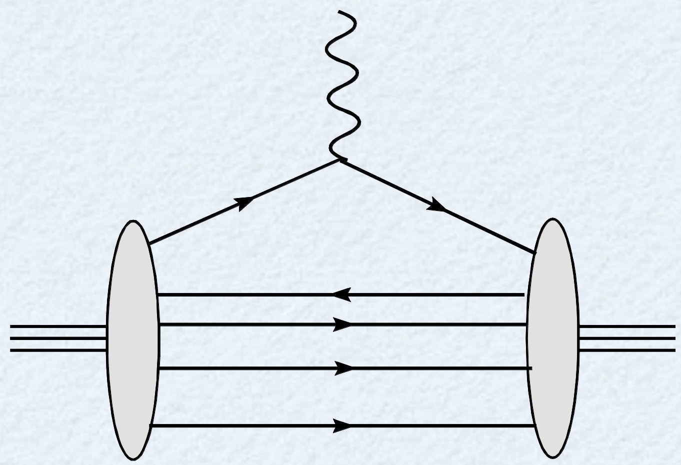


Jones et al.(2000) Punjabi et al.(2005)

Gayou et al.(2002) Puckett et al.(2010)

Interpretation of form factor as quark density

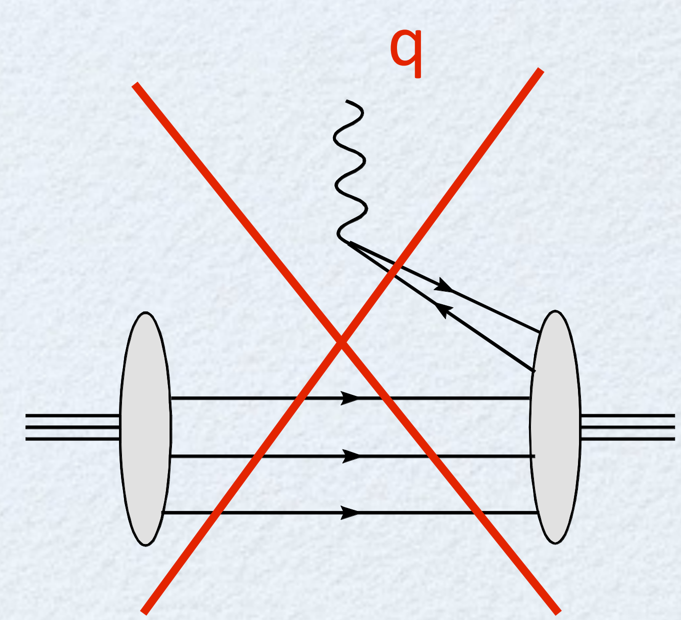




overlap of wave function

Fock components

with same number of quarks



overlap of wave function
Fock components

with different number of quarks

NO probability / charge density

interpretation

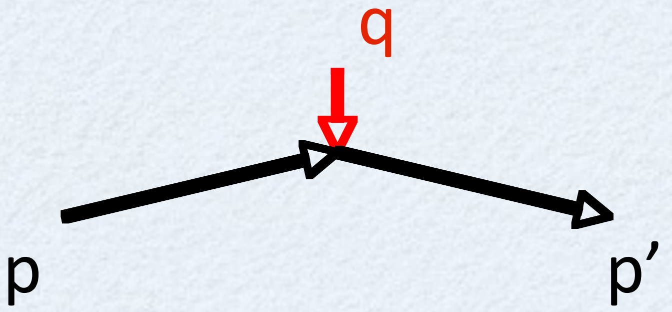
absent in a light-front frame!

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

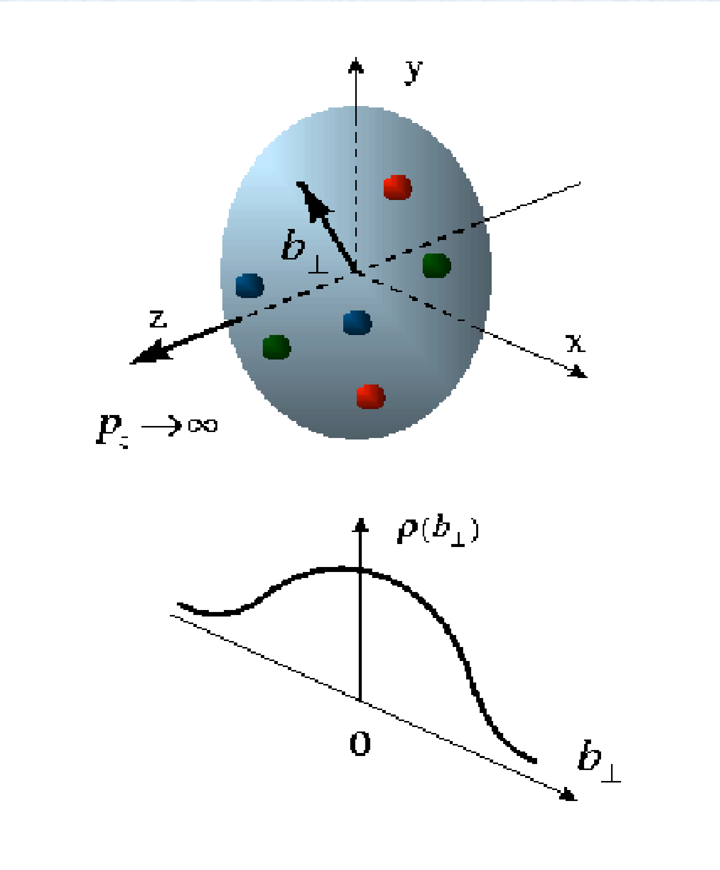
quark transverse charge densities in nucleon (1)

- light-front

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



photon only couples to forward moving quarks



- quark charge density operator

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

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

- longitudinally polarized nucleon

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

Soper (1997)

Burkardt (2000)

Miller (2007)

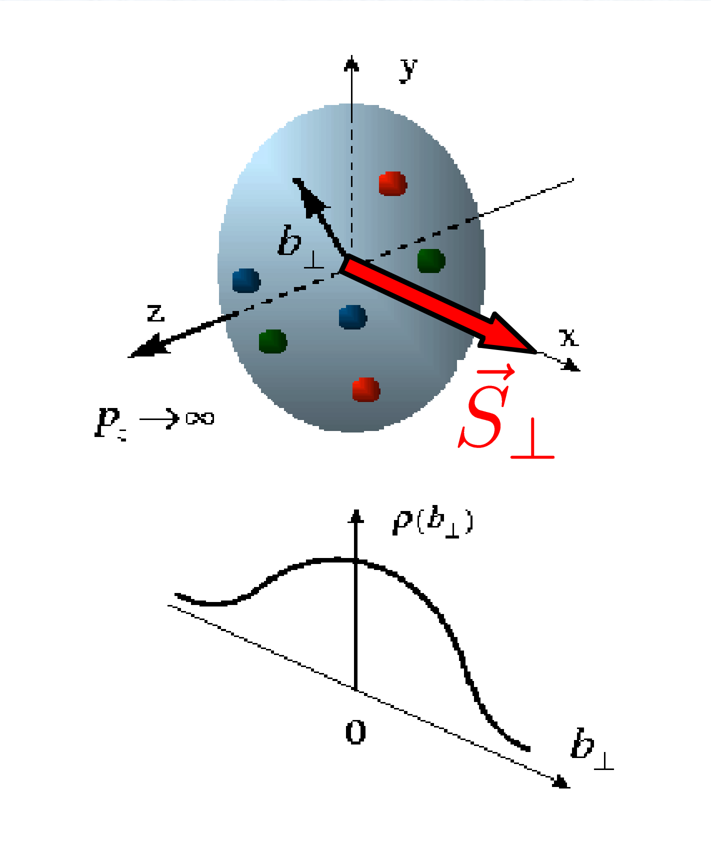
quark transverse charge densities in nucleon (2)

- 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 $\phi_S = 0$

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



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

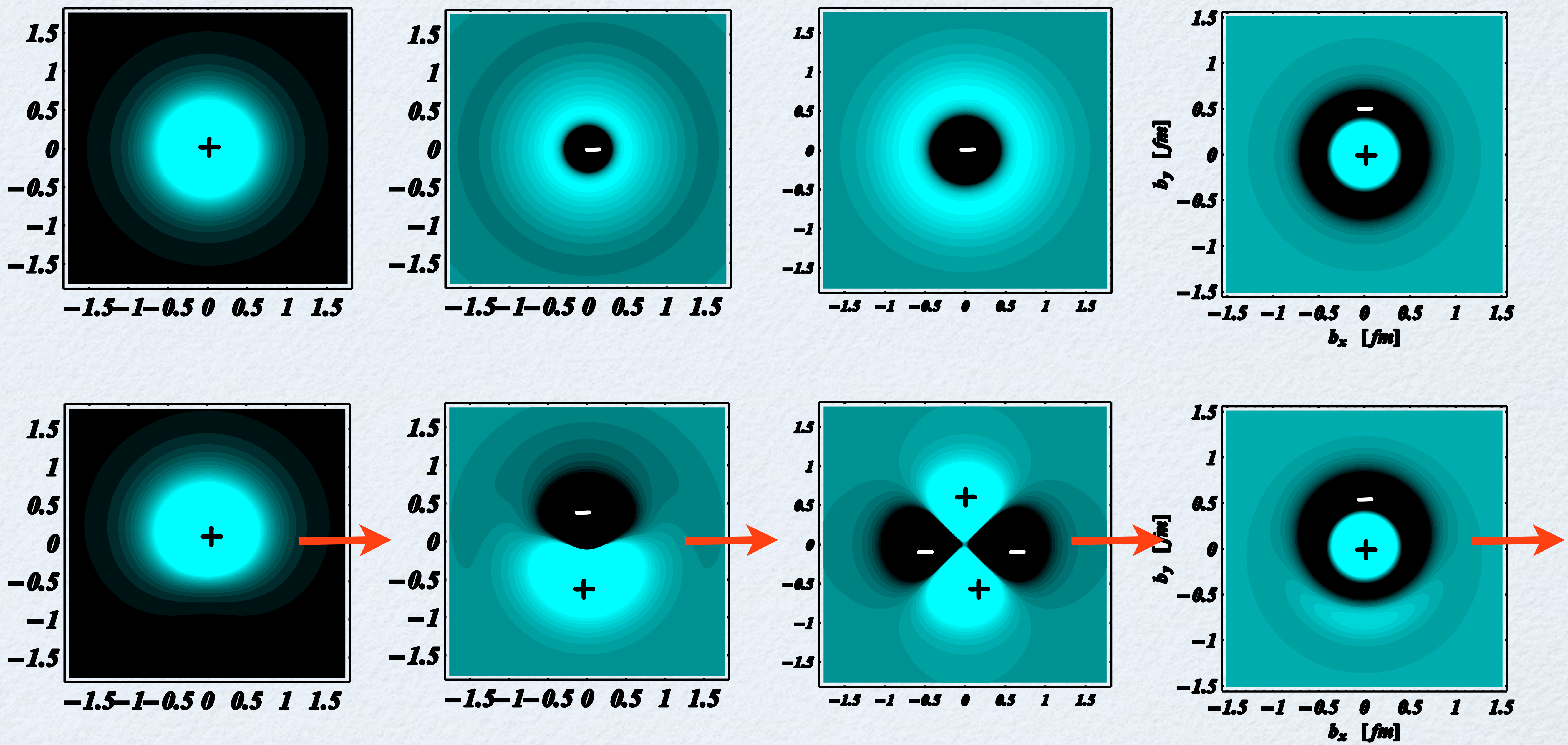
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S)\int_0^\infty \frac{dQ}{2\pi}\,\frac{Q^2}{2M} J_1(bQ) F_2(Q^2)$$

dipole field pattern

Carlson, Vdh (2007)

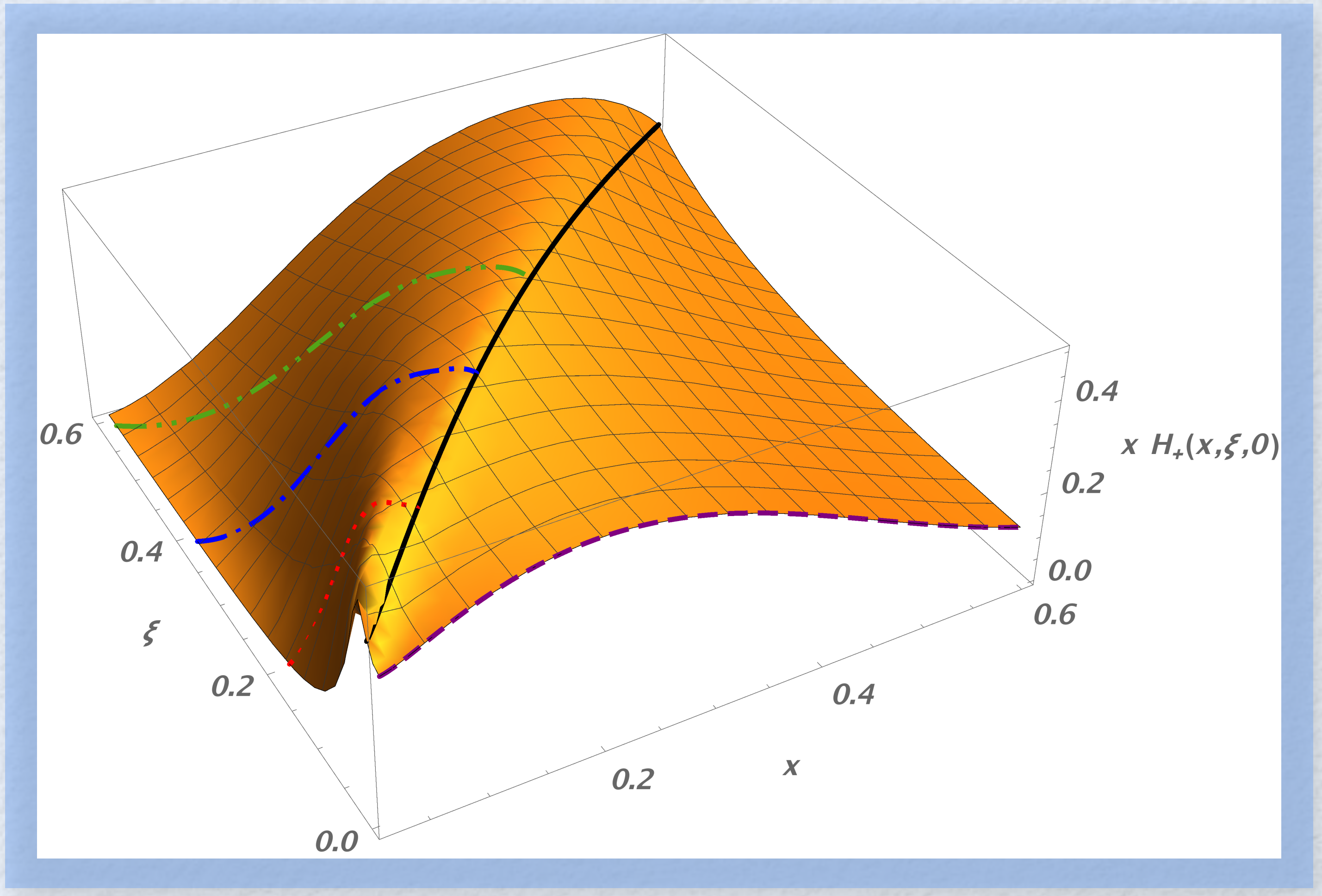
spatial imaging of hadrons

proton | neutron | p -> Δ^+ | p -> N^* (1440)



Miller(2007) | Carlson, Vdh(2007) | Tiator, Vdh(2007)

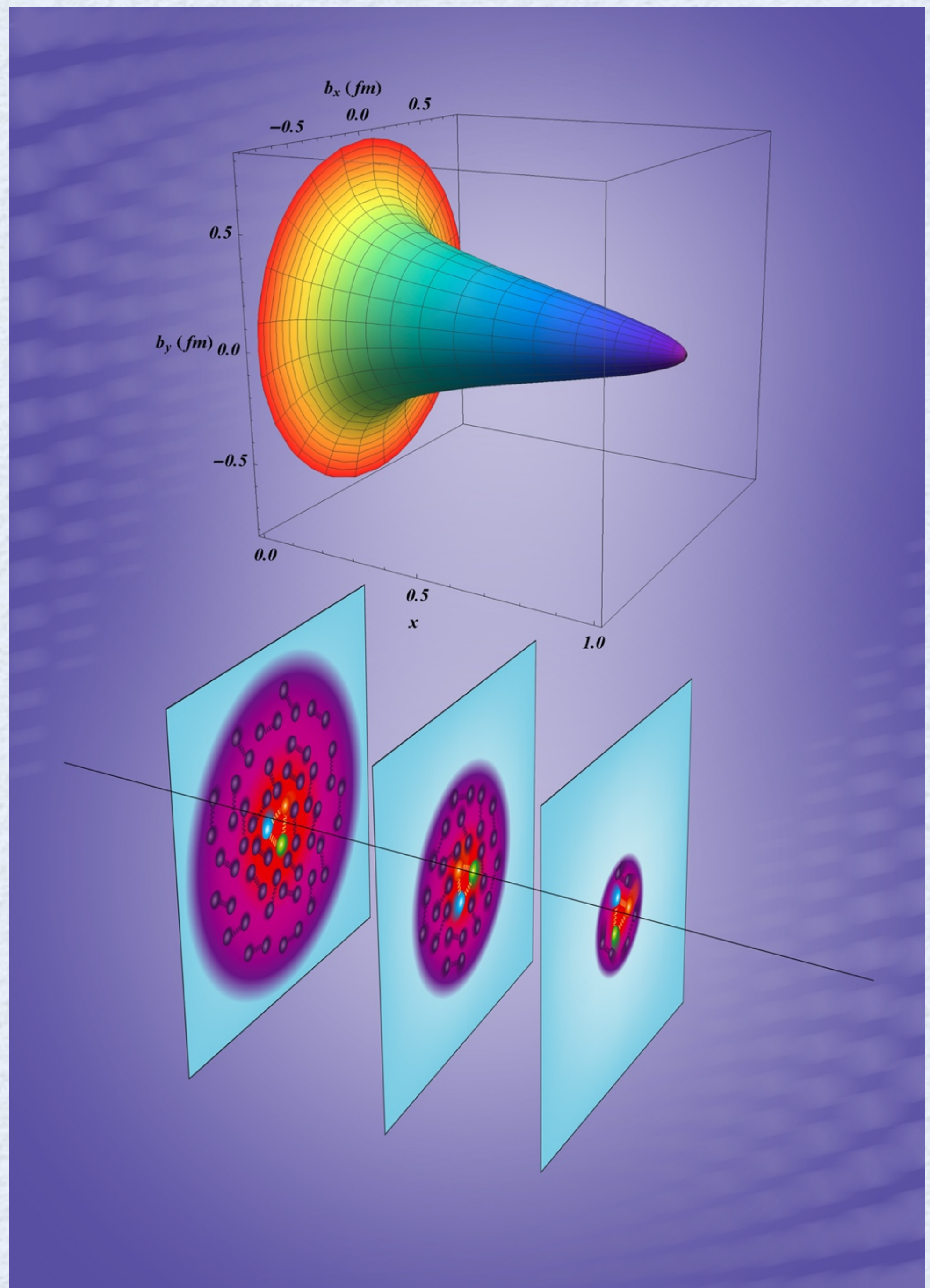
Generalized Parton Distributions



Correlations in transverse position/longitudinal momentum

elastic scattering → **GPDs** ← **DIS**

quark distributions in **transverse position space**



quark distributions in **longitudinal momentum**

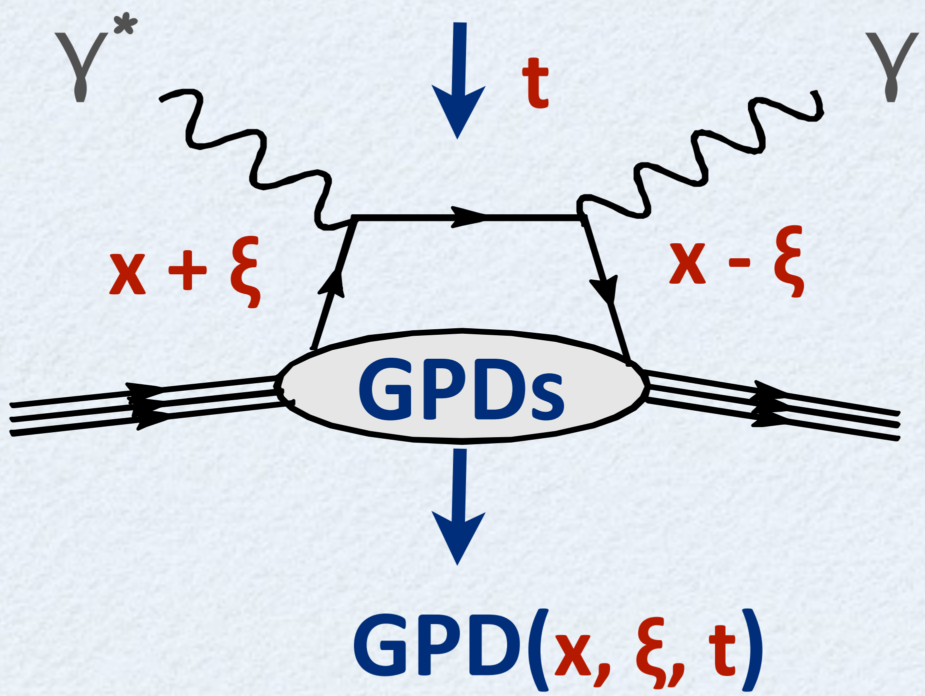
proton 3D imaging

Burkardt(2000, 2003)

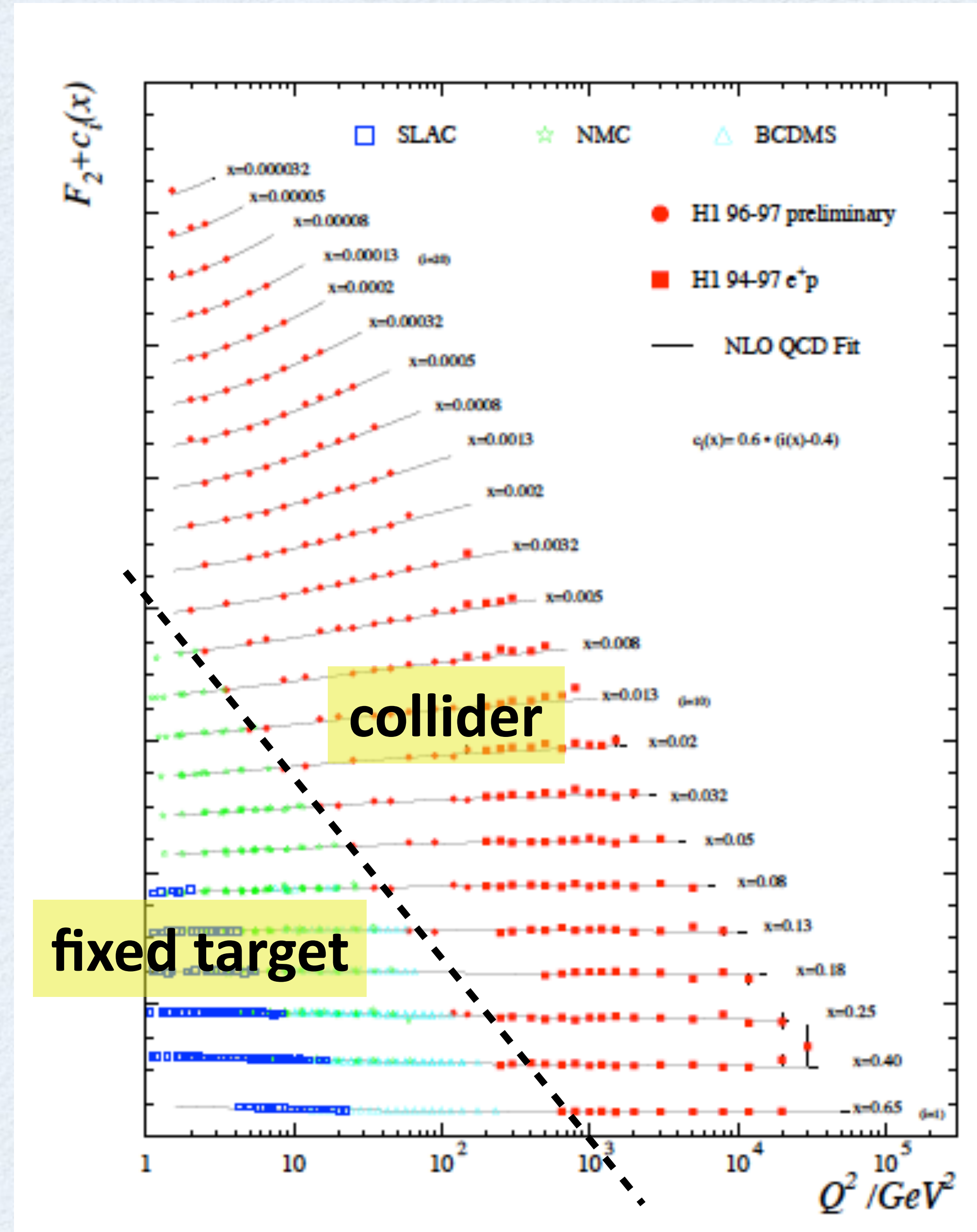
Belitsky, Ji, Yuan (2004)

DVCS: tool to access GPDs

$Q^2 >> 1$ GeV^2



world data on proton F_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

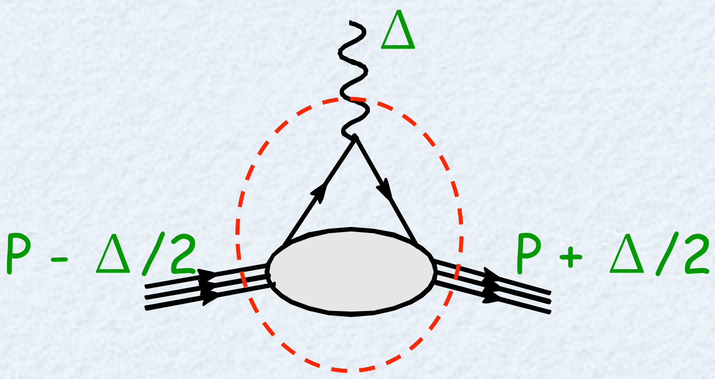
- in forward kinematics (ξ=0, t = 0) : **PDF limit**

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

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

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

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



$t = \Delta^2$

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

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

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

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

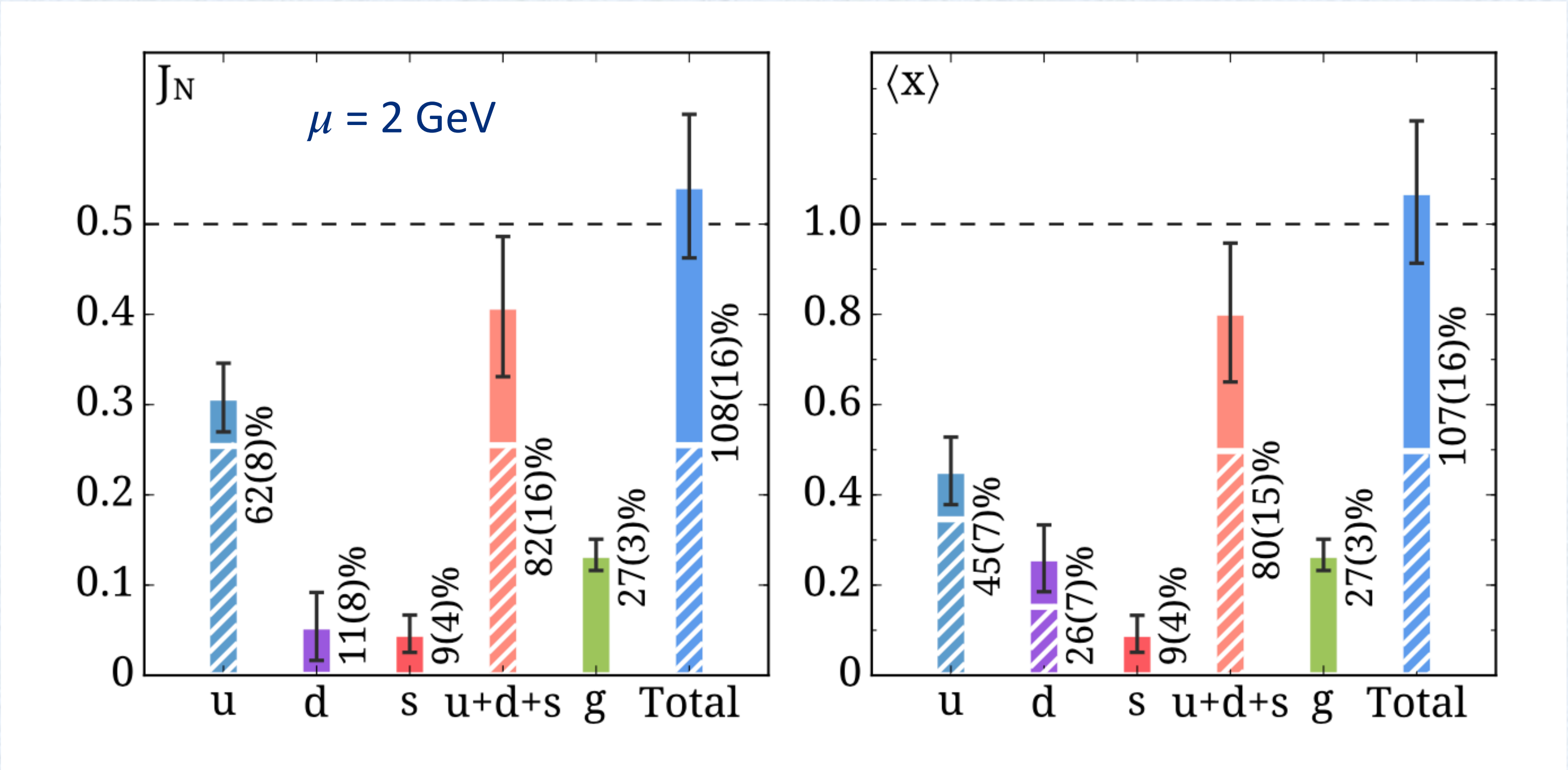
Polyakov(2003)

Goeke, Schweitzer et al.(2007)

- Ji's angular momentum sum rule

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

- lattice QCD calculations at the physical point   Alexandrou et al.(2017)

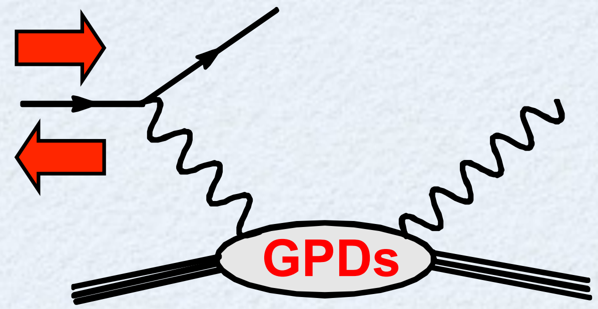


d, s-quarks carry very small total J in proton,
u-quark carries around 60%,
gluons around 30%

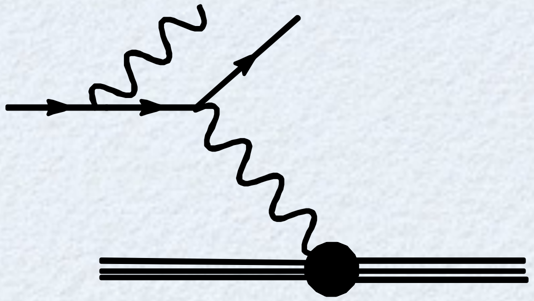
Sharing of momentum and total angular momentum between quarks and gluons identical in proton !

DVCS beam spin asymmetries: first observations around 2000

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

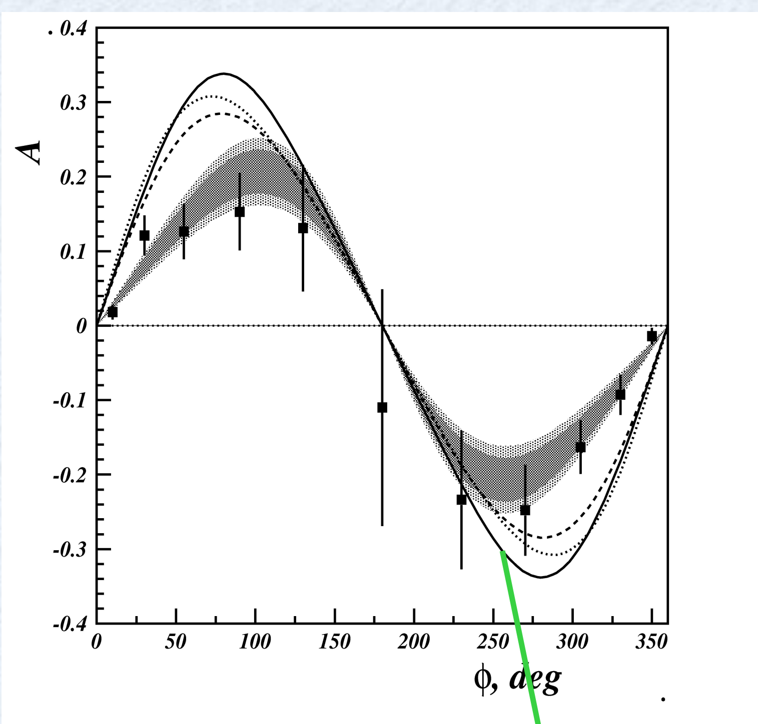


DVCS



Bethe-Heitler

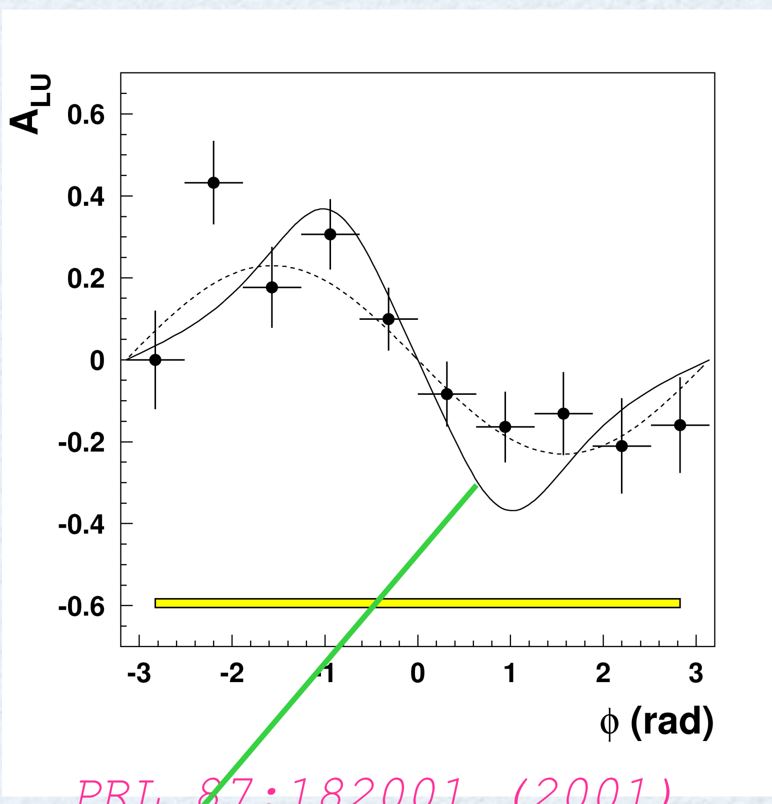
CLAS



Q^2 = 1.25 GeV^2 ,
x_B = 0.19,
$-t$ = 0.19 GeV^2

PRL 87:182002 (2001)

HERMES



Q^2 = 2.6 GeV^2 ,
x_B = 0.11,
$-t$ = 0.27 GeV^2

PRL 87:182001 (2001)

twist-2 + twist-3

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

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):

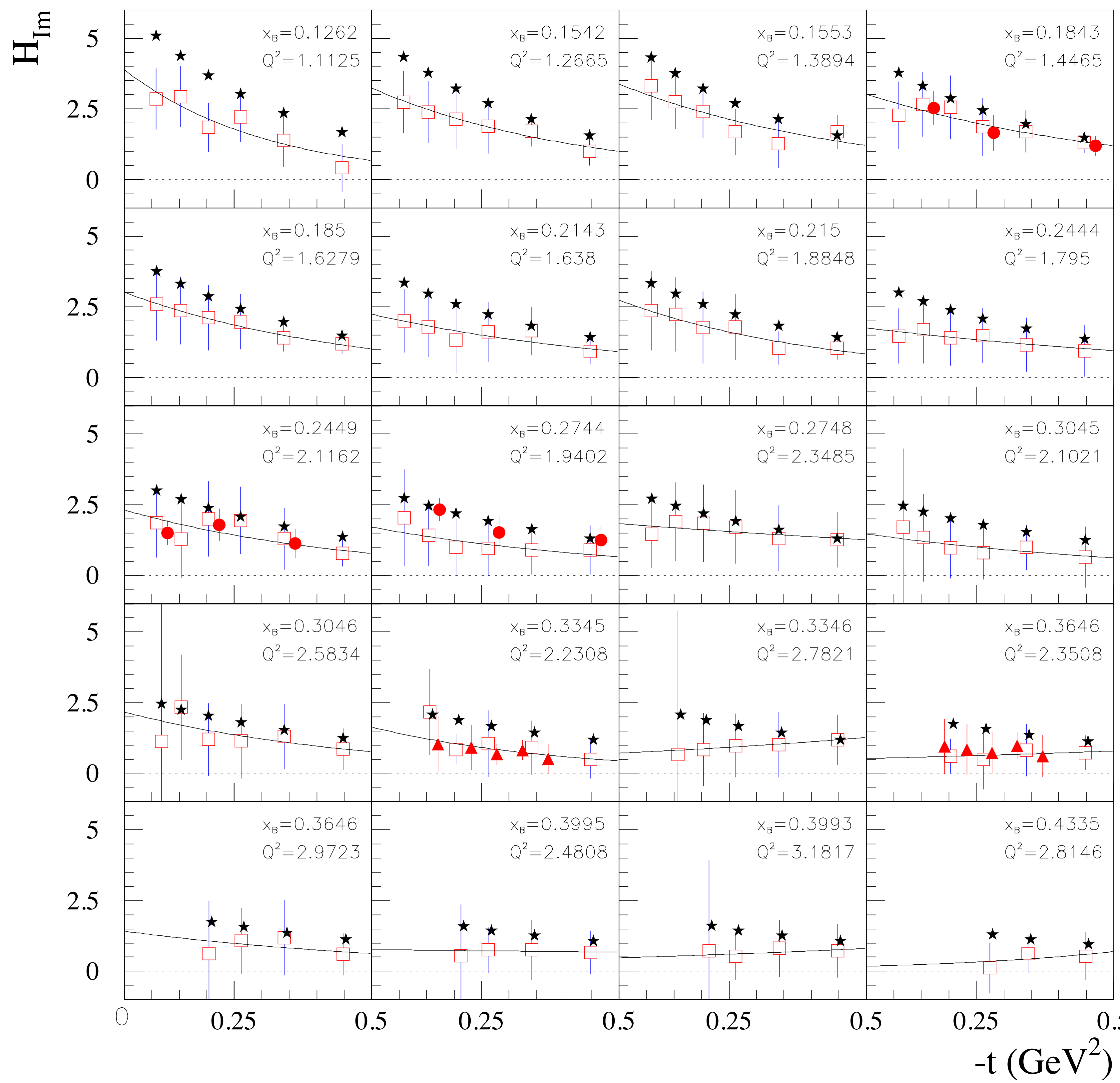
$$H_+(x,\xi,t) \equiv H(x,\xi,t) - H(-x,\xi,t)$$

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

CFF fit extractions from data: Guidal(2008,...) Guidal, Moutarde(2009,...)

Kumericki, Mueller, Passek-Kumericki(2008,...)

global analysis of JLab 6 GeV data



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

red solid circles:
CLAS: σ, 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

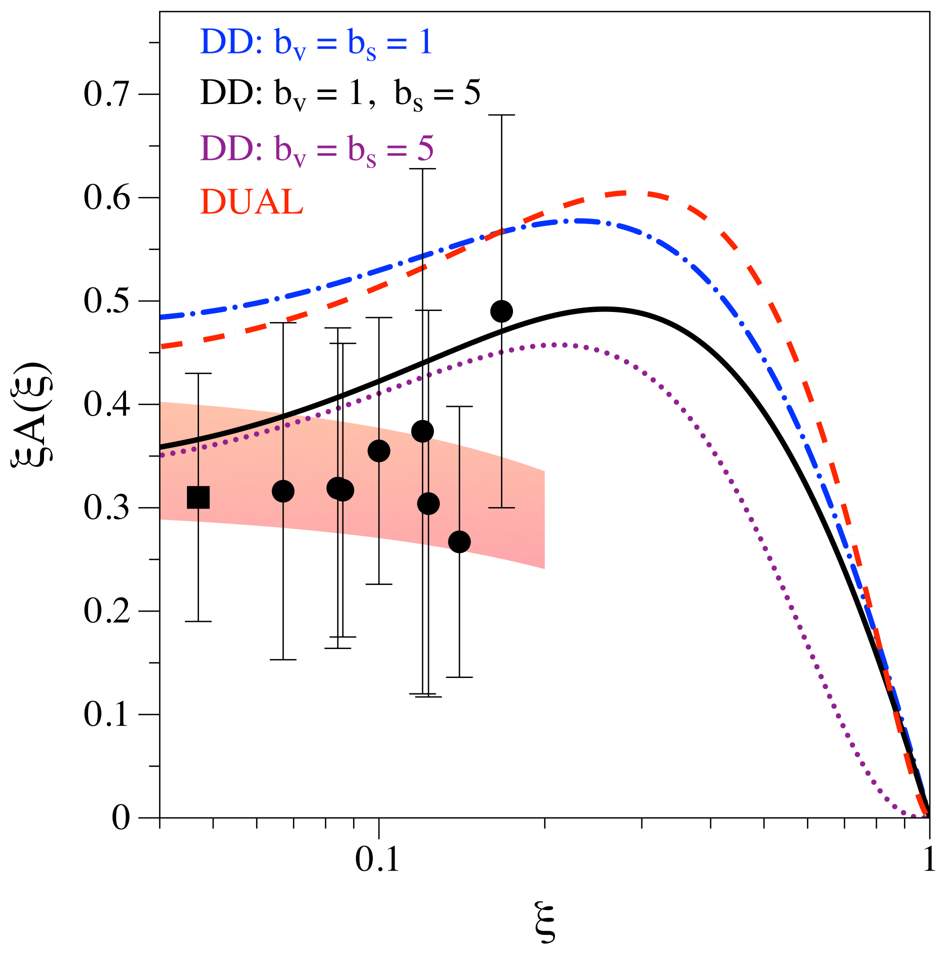
Dupré, Guidal, Vdh(2017)

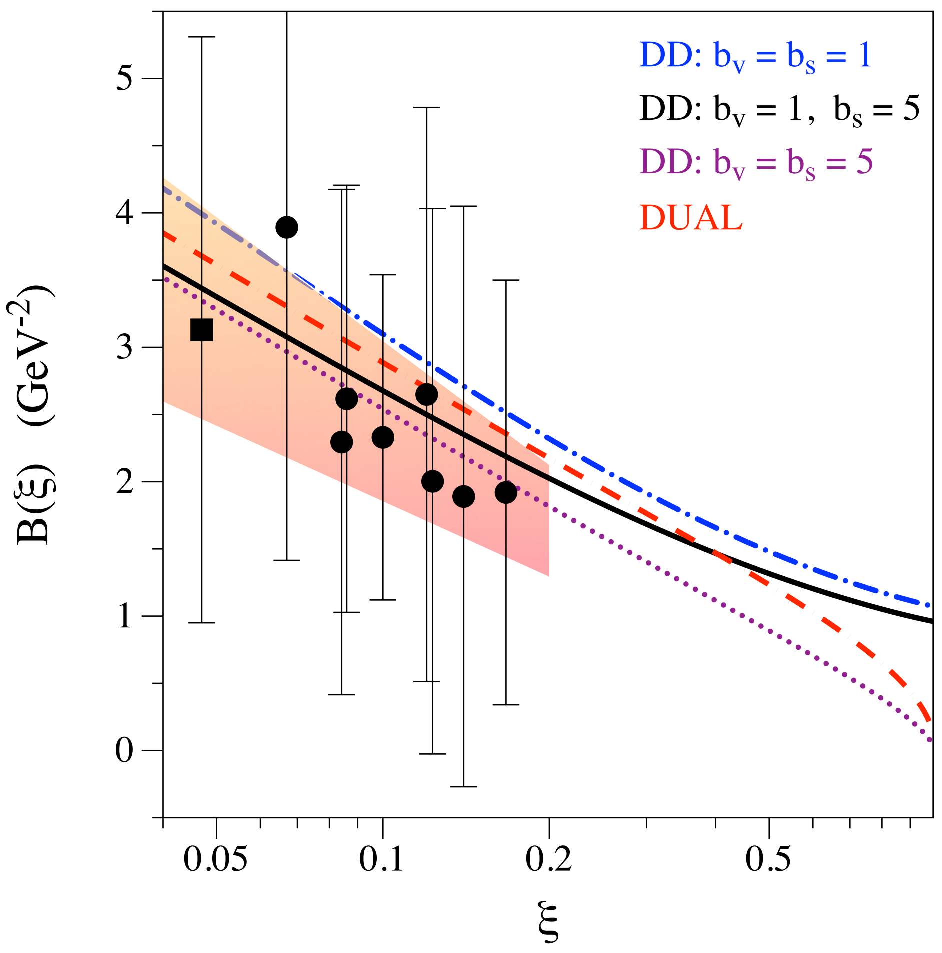
CFF $\mathcal{H}_{\rm Im}$:

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

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

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

Burkardt(2000)

number density of quarks (q) with longitudinal momentum x
at a transverse distance **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

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

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

x-independent radius

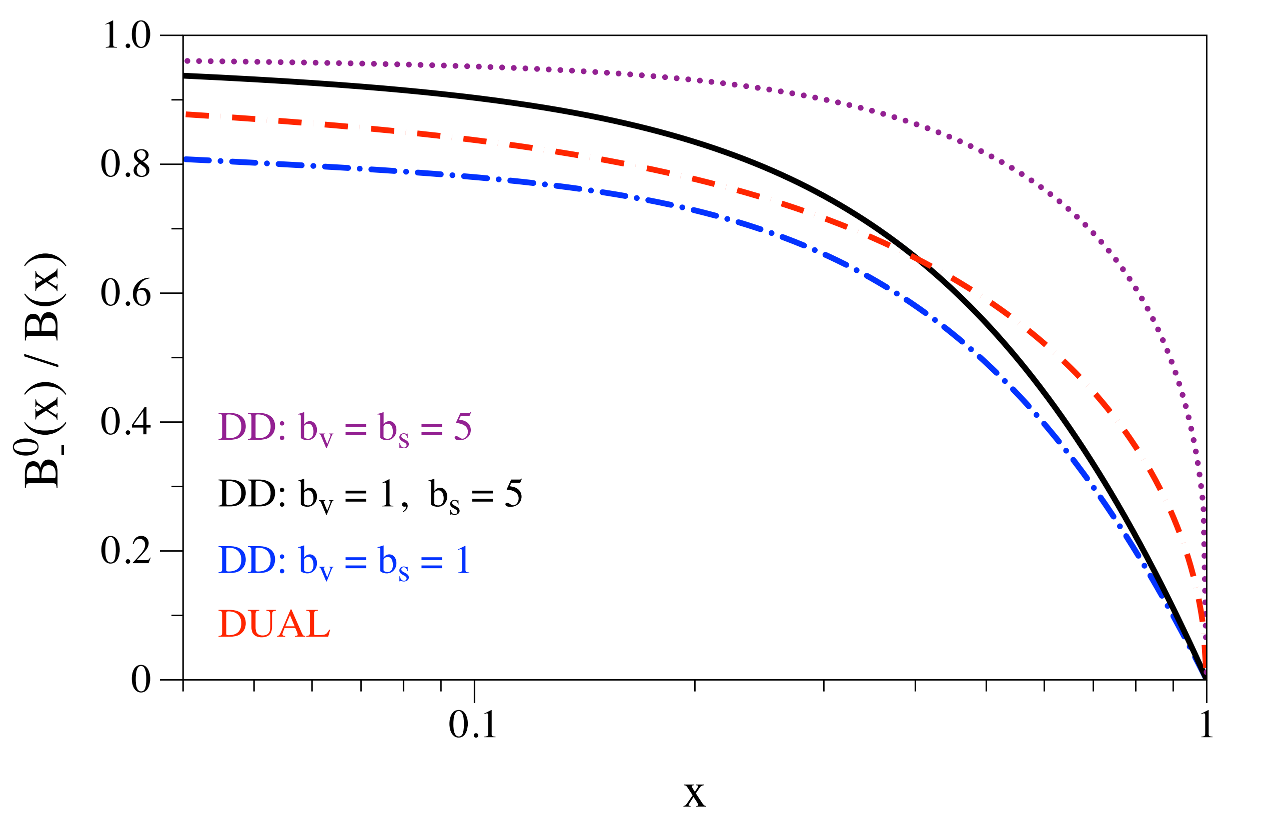
$$\langle b_\perp^2 \rangle^q = \frac{1}{N_q} \int_0^1 dx\, q_v(x)\, \langle b_\perp^2 \rangle^q(x)$$

$N_u=2$, $N_d=1$

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

Bernauer(2014)

x-dependent radius in proton

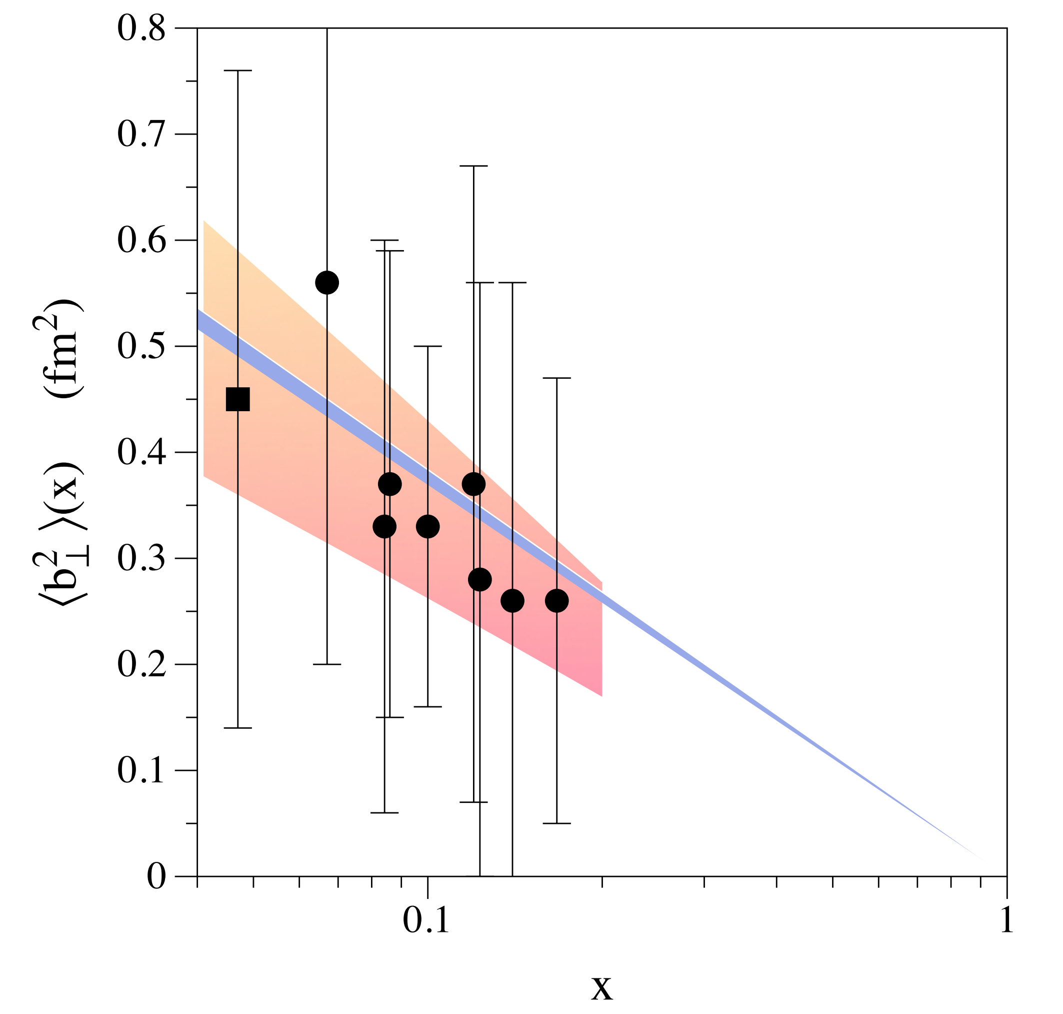


for x < 0.15: $B_0 / B > 0.9$

Dupré, Guidal, Niccolai, Vdh(2017)

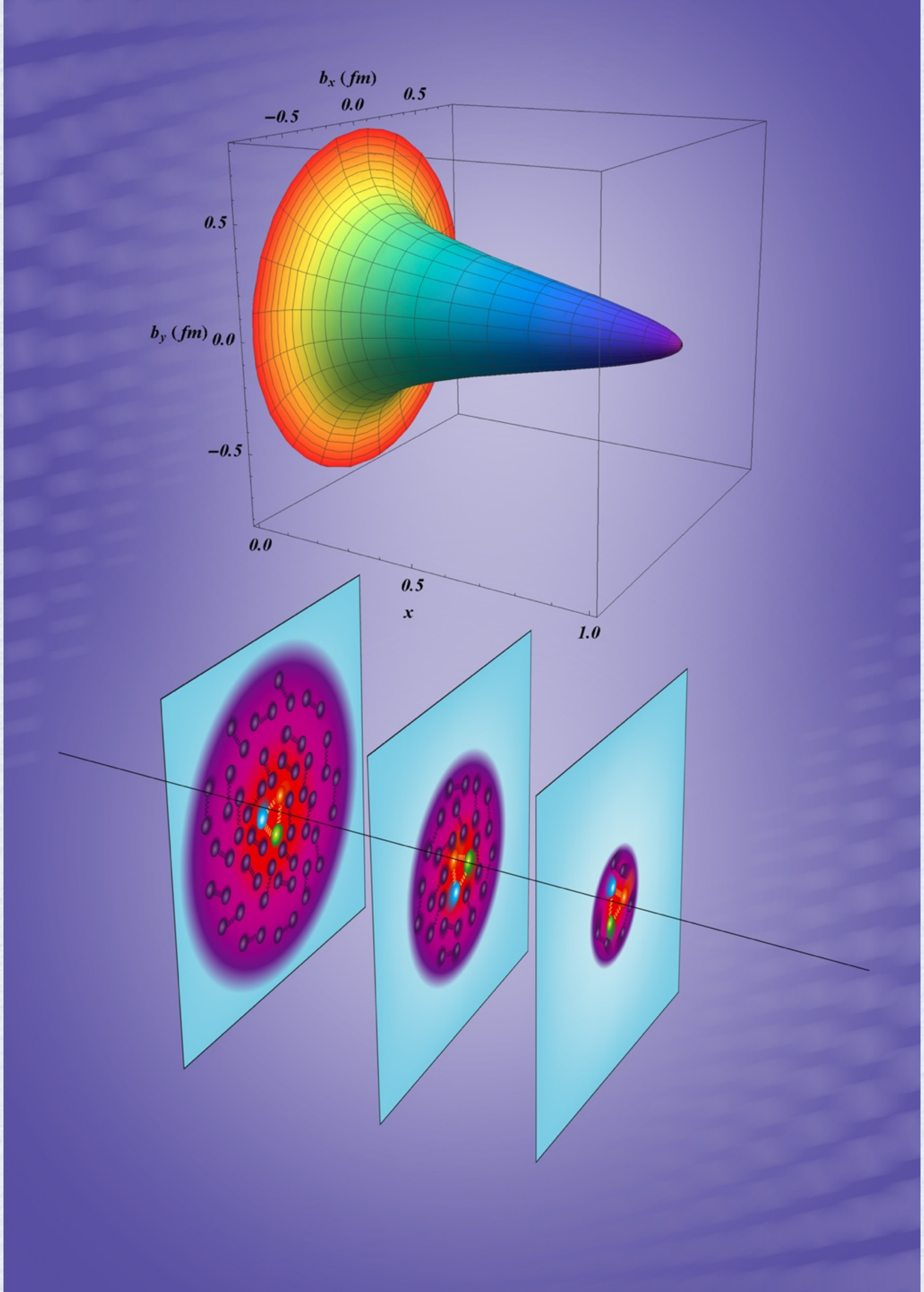
black circles: CFF fit of JLab data

black squares: CFF fit of HERMES data



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

a_{B_0} fixed from elastic scattering



3D imaging of proton

Dupré, Guidal, Vdh(2017)

CFF $\mathcal{H}_{\mathrm{Re}}$: 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 $\mathcal{H}_{Im}(x,t)$

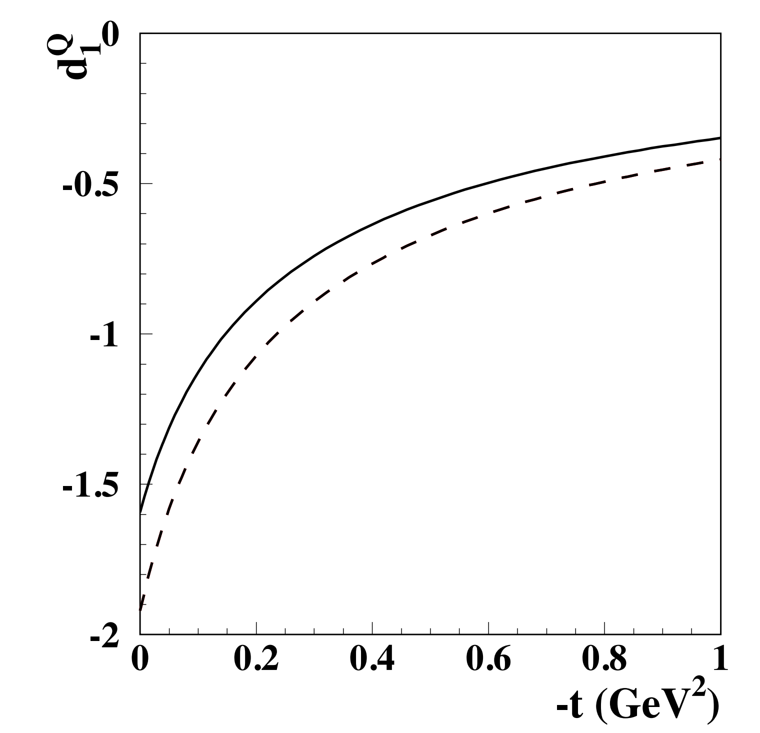
$$\Delta(t) \equiv \frac{2}{N_f}\int_{-1}^{1} dz\, \frac{D(z,t)}{1-z}$$

D-term

Polyakov, Weiss (1999)

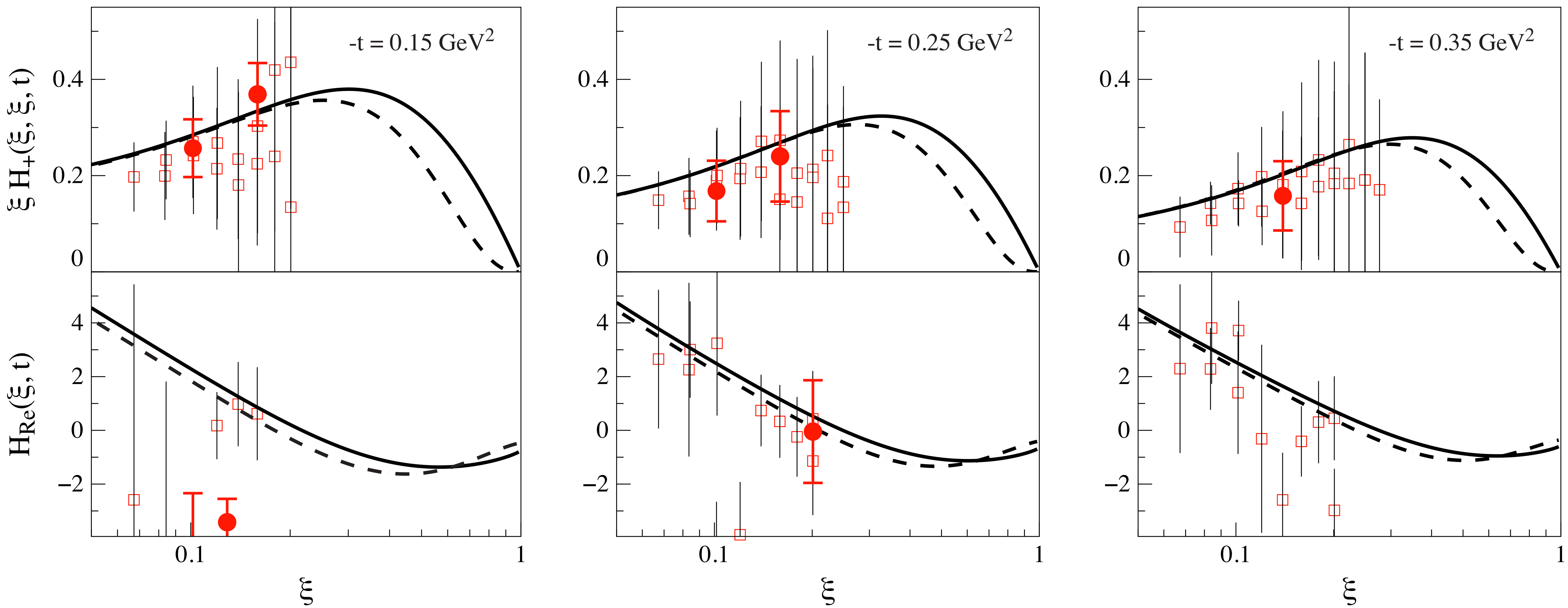
$$D(z,t) = (1-z^2)\sum_{\substack{n=1 \\ n\ odd}}^{\infty} d_n(t)\, C_n^{3/2}(z)$$

Pasquini,Polyakov,Vdh(2014)



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

red solid circles: CLAS: σ, A_{LU}, A_{UL}, A_{LL} red open squares: CLAS: σ, A_{LU}

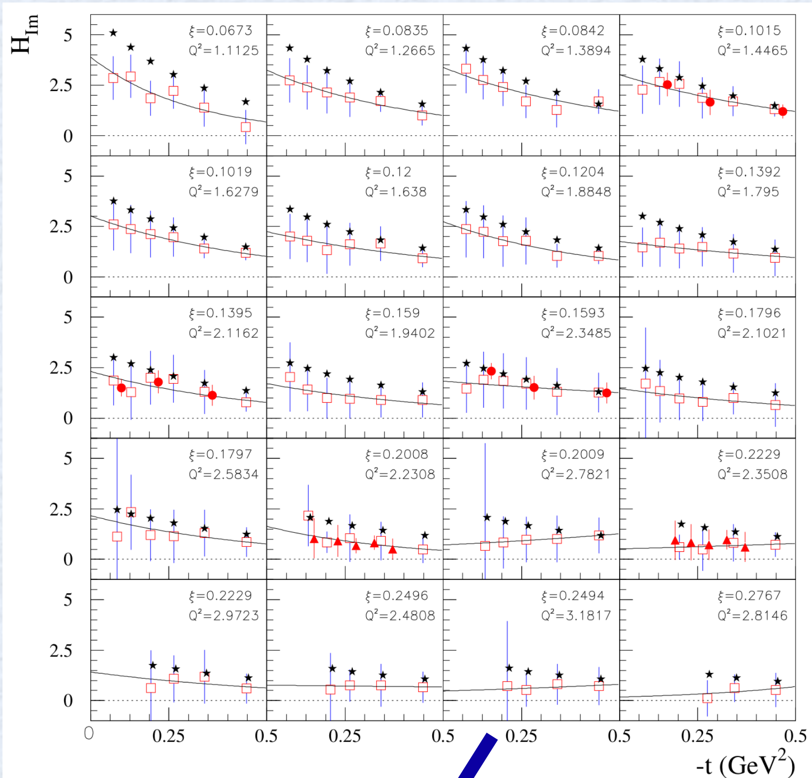


Curves for Δ(t) = 0; Δ(t) < 0 would shift H_{Re} curves up !

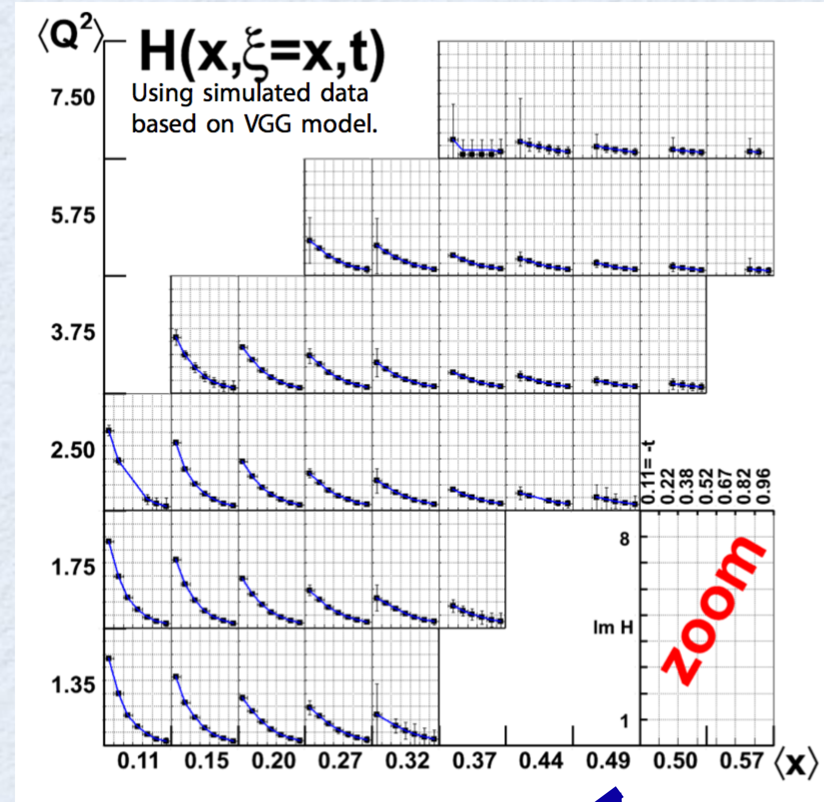
Dupré, Guidal, Niccolai, Vdh (2017)

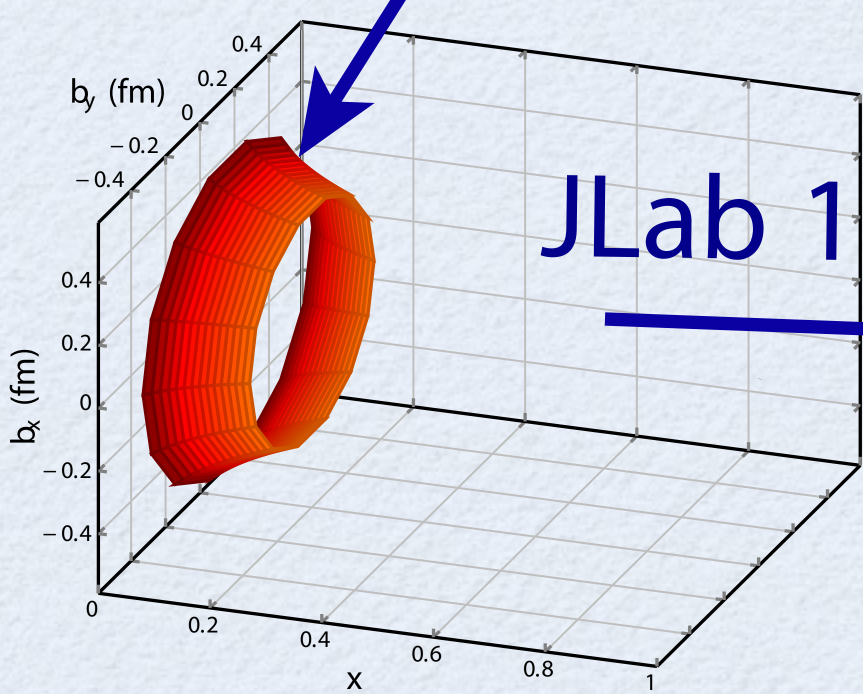
Projections for CFFs at JLab 12 GeV

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

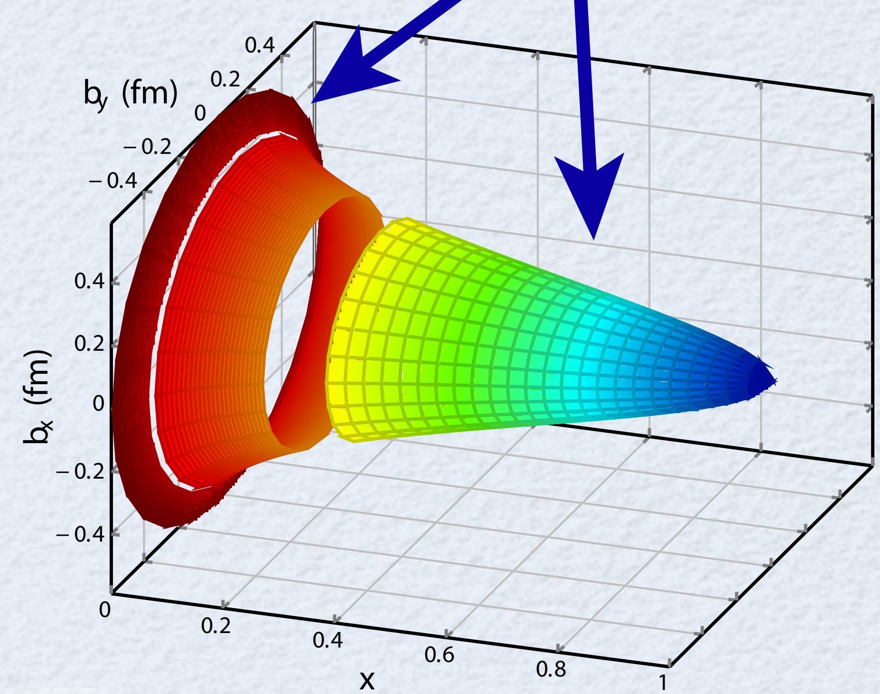


CLAS12 projections E12-06-119 with DVCS A_{UL} and A_{LU}





JLab 12 GeV



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