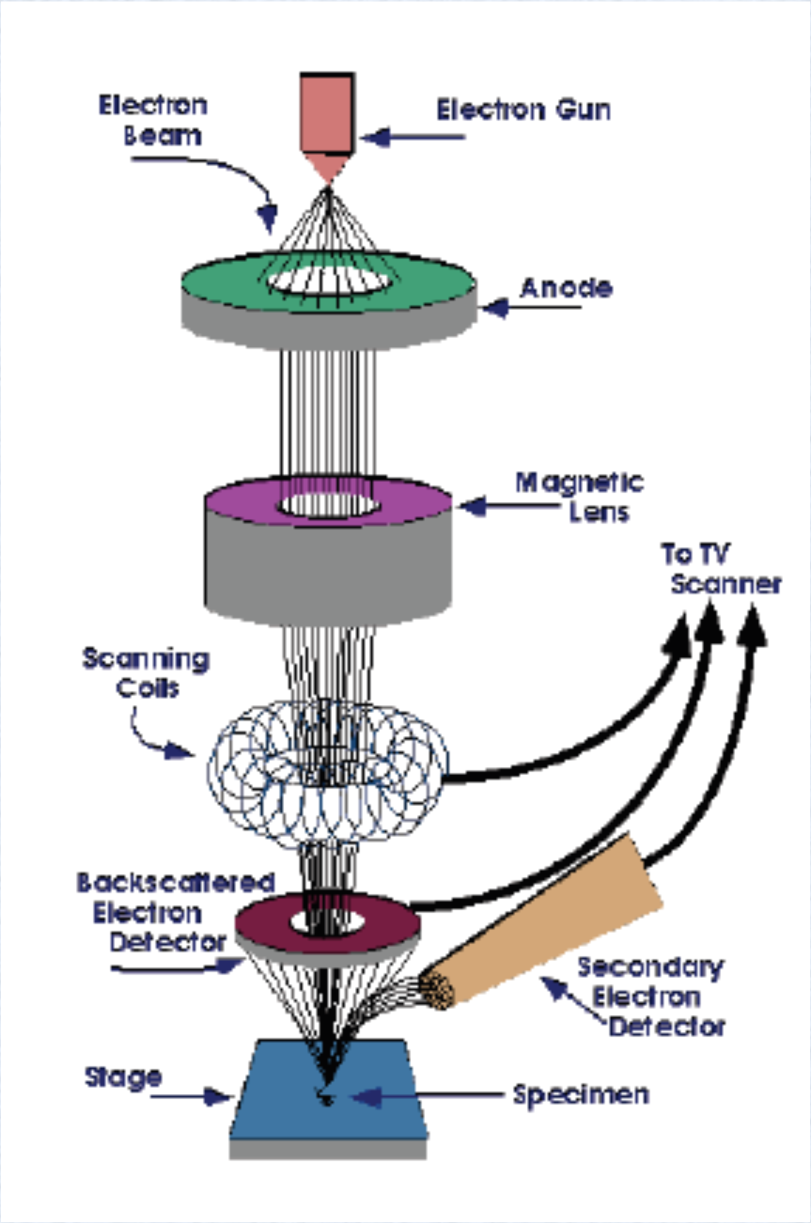
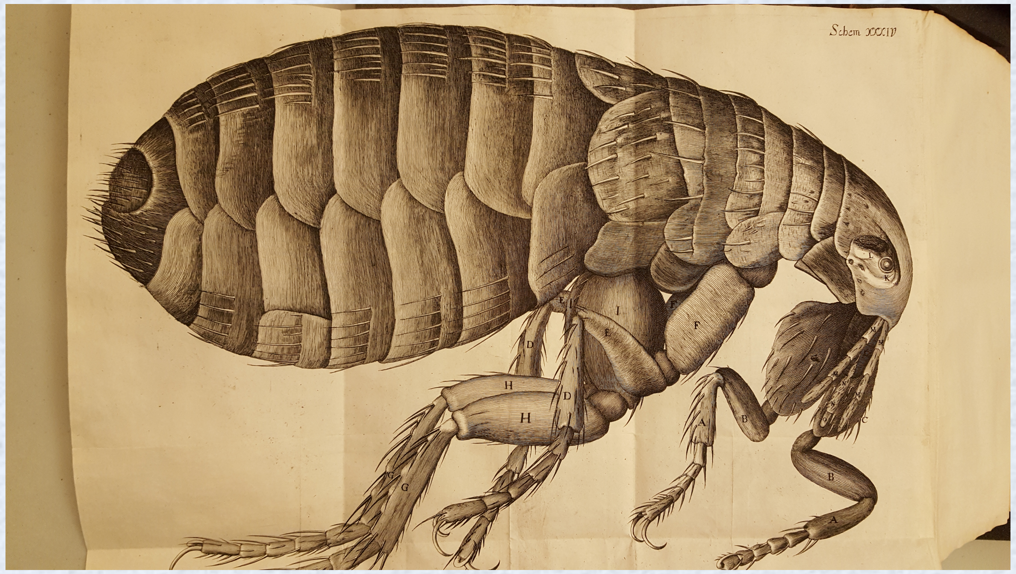
Partonic structure of nucleons

Towards precision imaging…

R.Hooke (Micrographia, 1665)





electron microscopy

when target is static

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

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

gives the distribution of

electric charge and magnetization

Genesis of hadron physics

1932-33: measurement of the g-factor of proton

Nobel Prize Physics 1943: Otto Stern

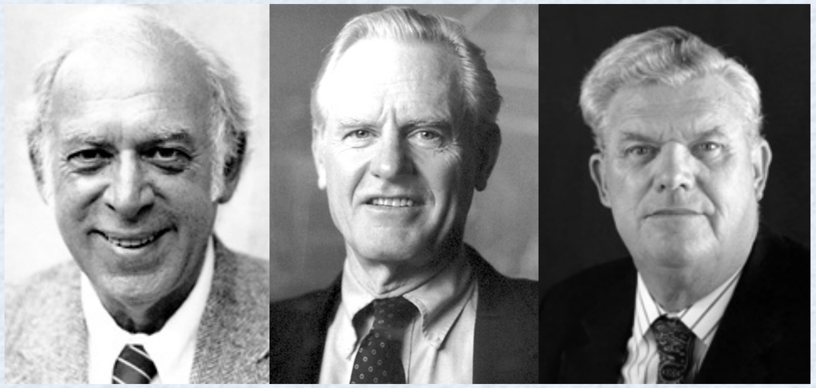
“for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

1955-56: elastic e-p scattering

Nobel Prize Physics 1961: Robert Hofstadter

“for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

1969: deep-inelastic e-p scattering



Nobel Prize Physics 1990: J.I. Friedman, H.W. Kendall, R.E. Taylor

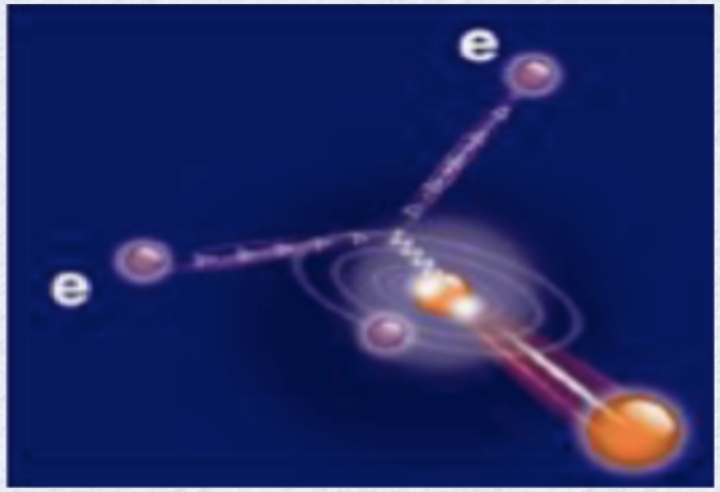
“for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

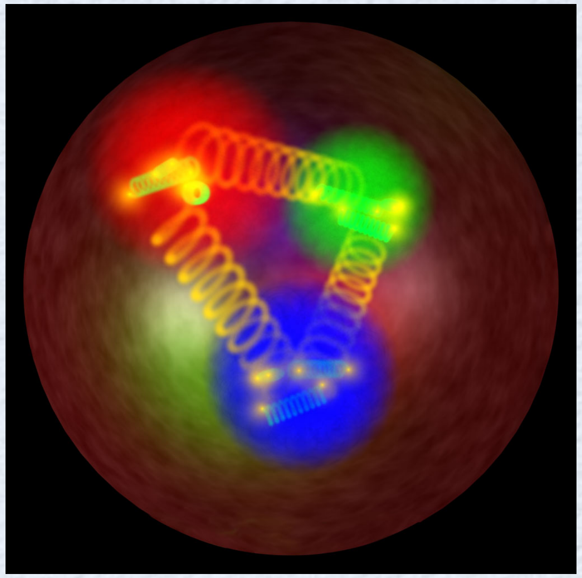
1974: QCD asymptotic freedom

Nobel Prize Physics 2004: D.J. Gross, H.D. Politzer, F.Wilczek

“for the discovery of asymptotic freedom in the theory of the strong interaction"

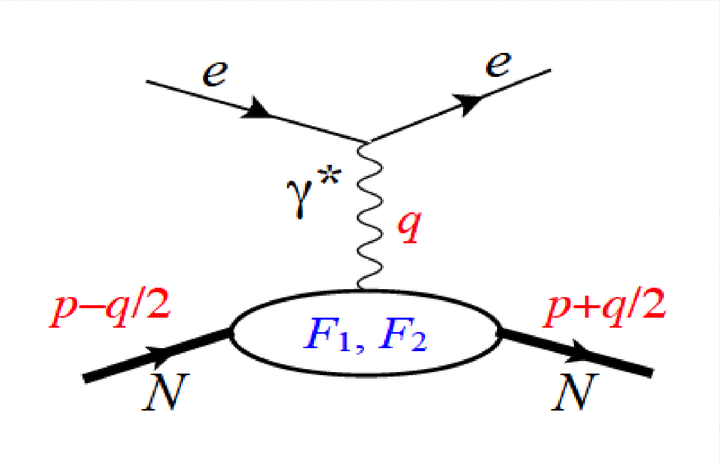
Elastic and (deep-) inelastic electron scattering off a nucleon





spin-1/2 electromagnetic form factors

- **(in)elastic electron scattering** is our microscope to investigate hadron structure



- in the **1-photon exchange approximation:**

nucleon (spin 1/2 target) structure is parameterized by 2 **form factors (FFs)**

$$\langle p+\frac{q}{2},\lambda'\,|\,J^\mu(0)\,|\,p-\frac{q}{2},\lambda\rangle \;=\; \bar{u}(p+\frac{q}{2},\lambda')\left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i}{2M}\sigma^{\mu\nu}q_\nu\right]u(p-\frac{q}{2},\lambda)$$

Dirac FF (F_1) **Pauli FF** (F_2)

for proton: $F_1(Q^2=0)=1$ $F_2(Q^2=0)=\kappa_p=1.79$

- equivalently: in experiment one often uses **Sachs FFs** with $\tau \equiv \frac{Q^2}{4M^2}$

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \longrightarrow \text{magnetic FF}$$
$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \longrightarrow \text{electric FF}$$

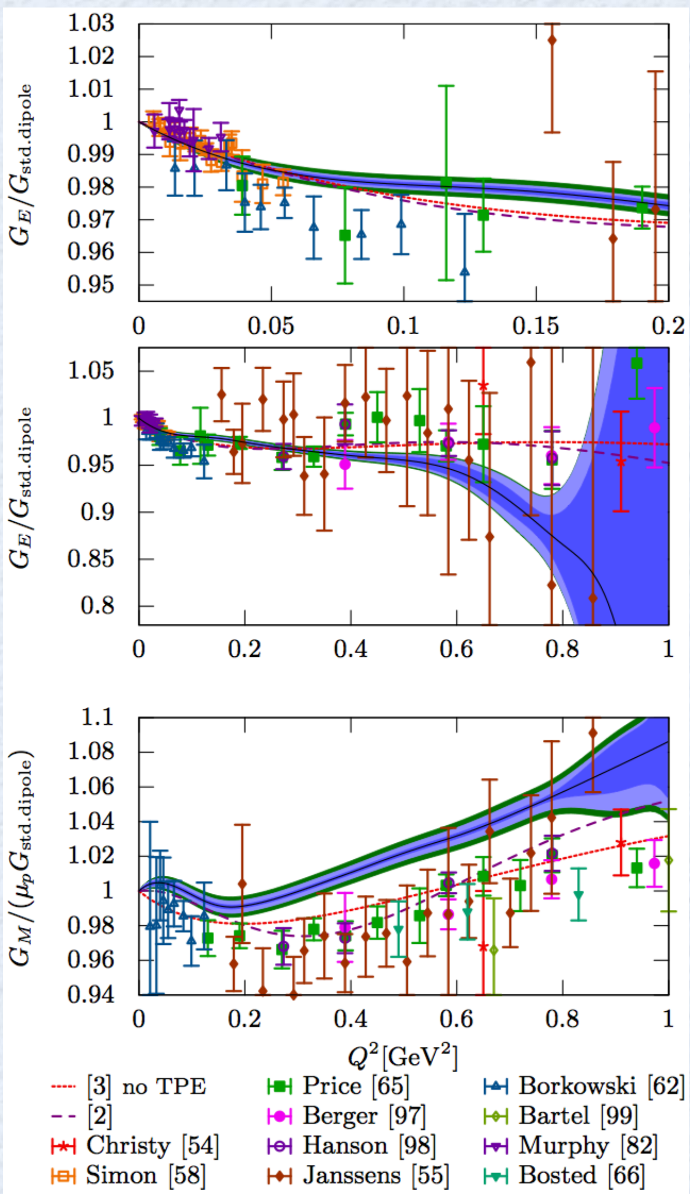
$$G_E(Q^2) = 1 - \frac{1}{6}\langle r_E^2\rangle\, Q^2 + \mathcal{O}(Q^4)$$

charge radius ($\langle r_E^2\rangle$)

Elastic e⁻ scattering cross sections

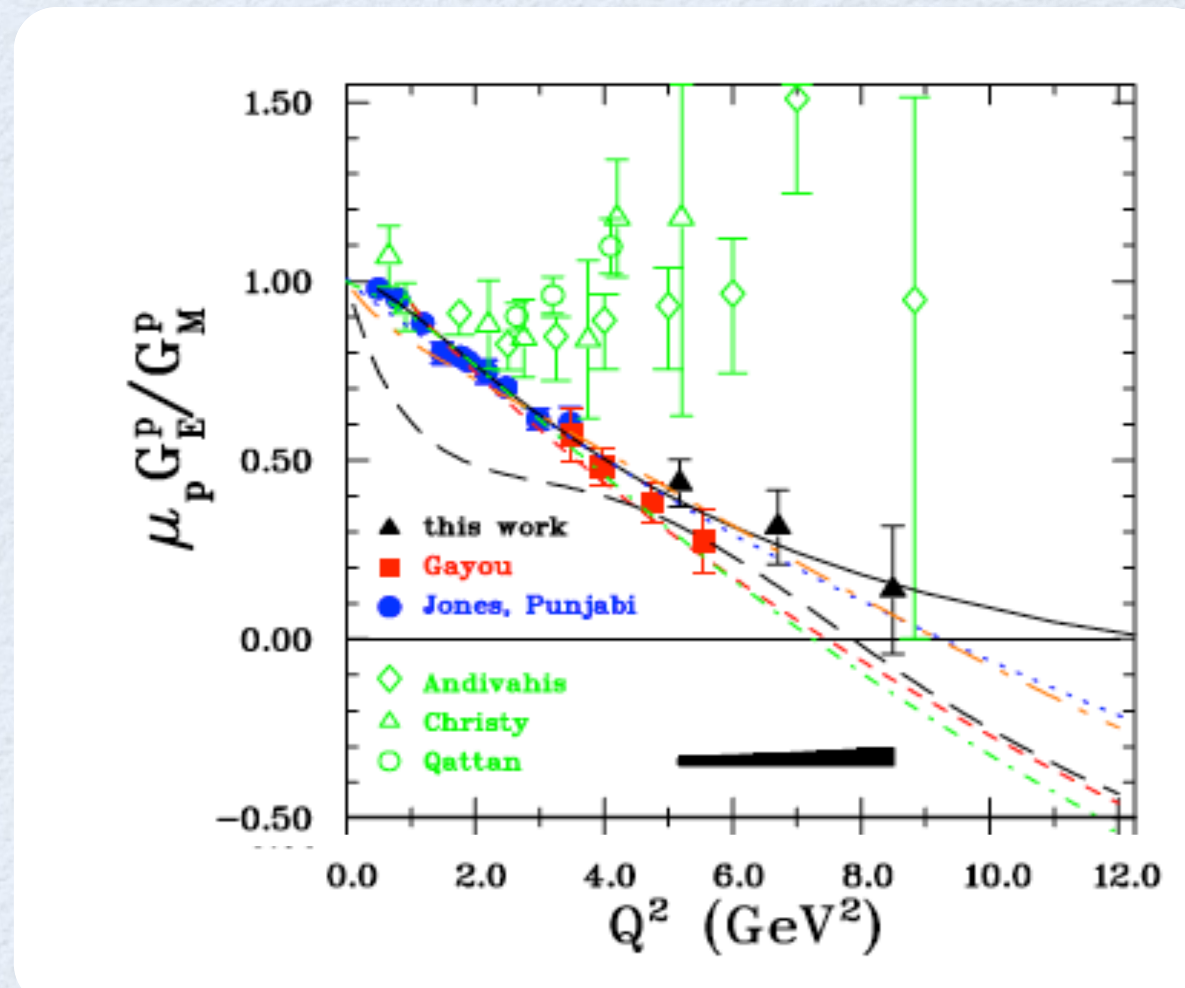
Electron scattering facilities JLab (12 GeV), MAMI (1.6 GeV):
uniquely positioned to deliver high precision data

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)

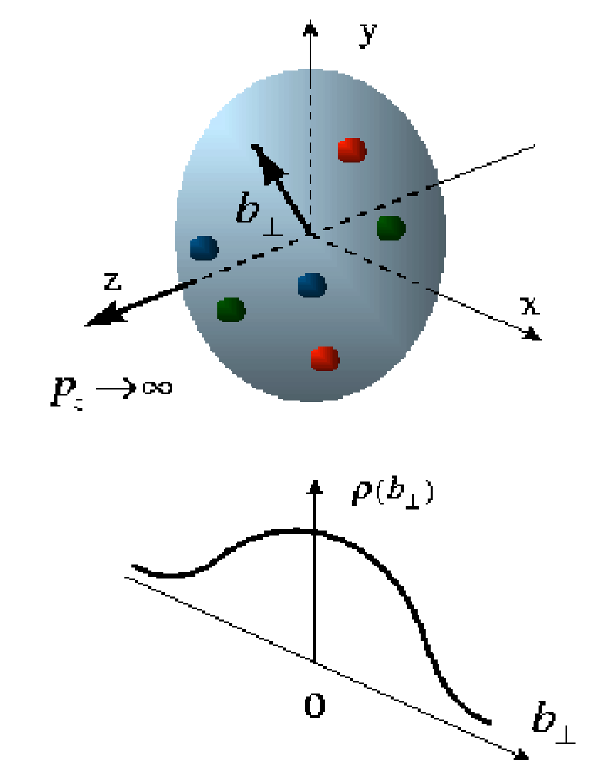
Quark transverse charge densities in nucleon

transverse c.m. can be fixed in a light-front frame !

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)

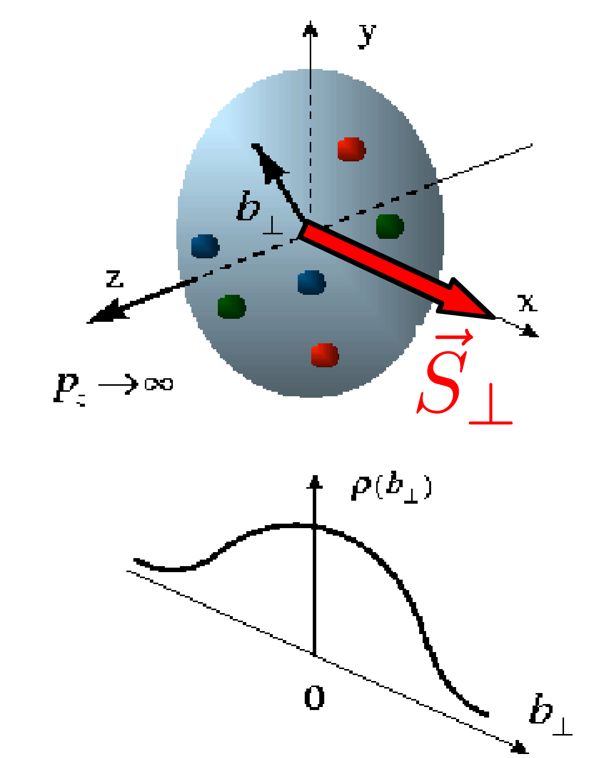


transversely polarized nucleon

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

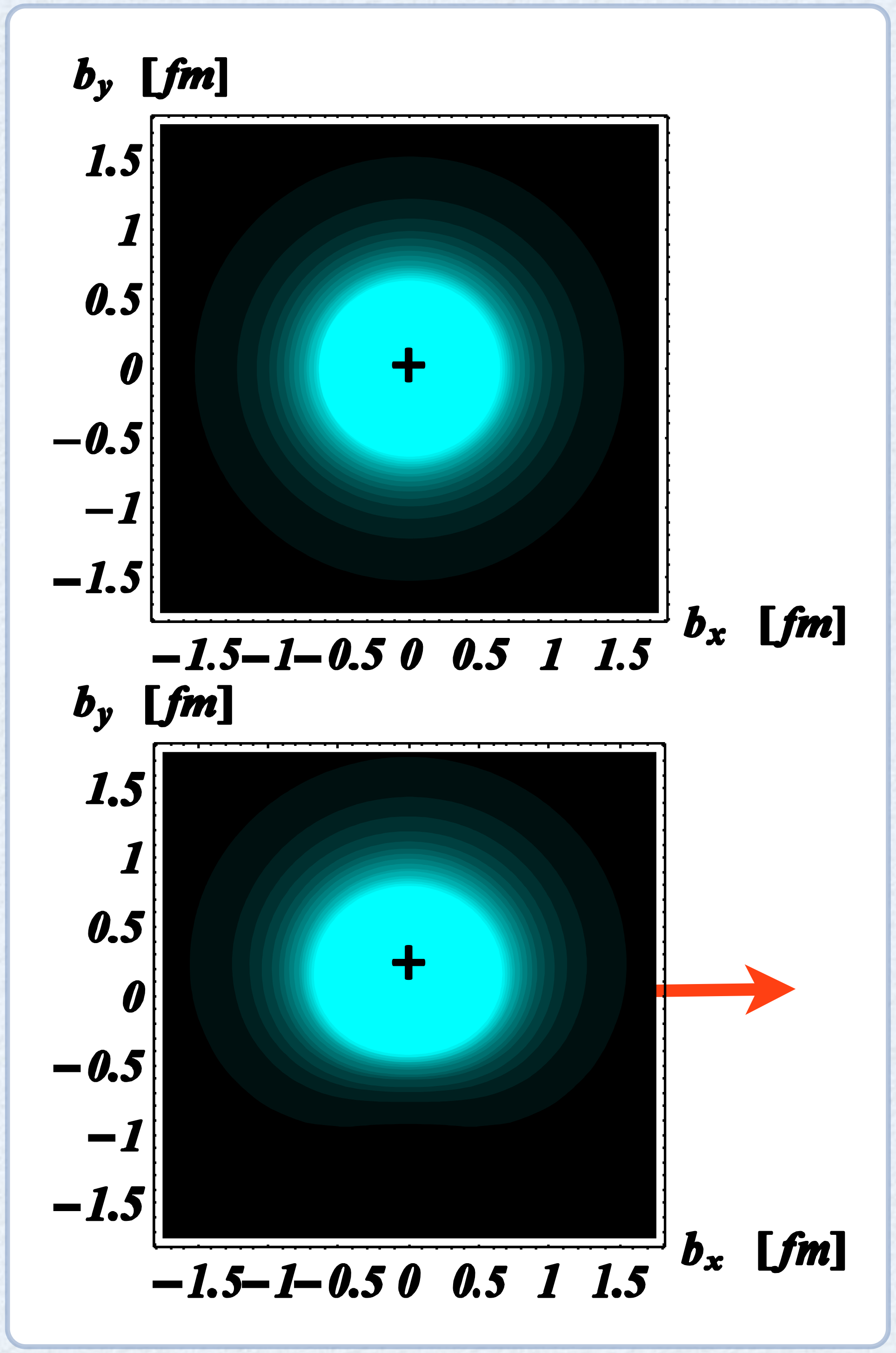
dipole field pattern

Carlson, Vdh (2007)

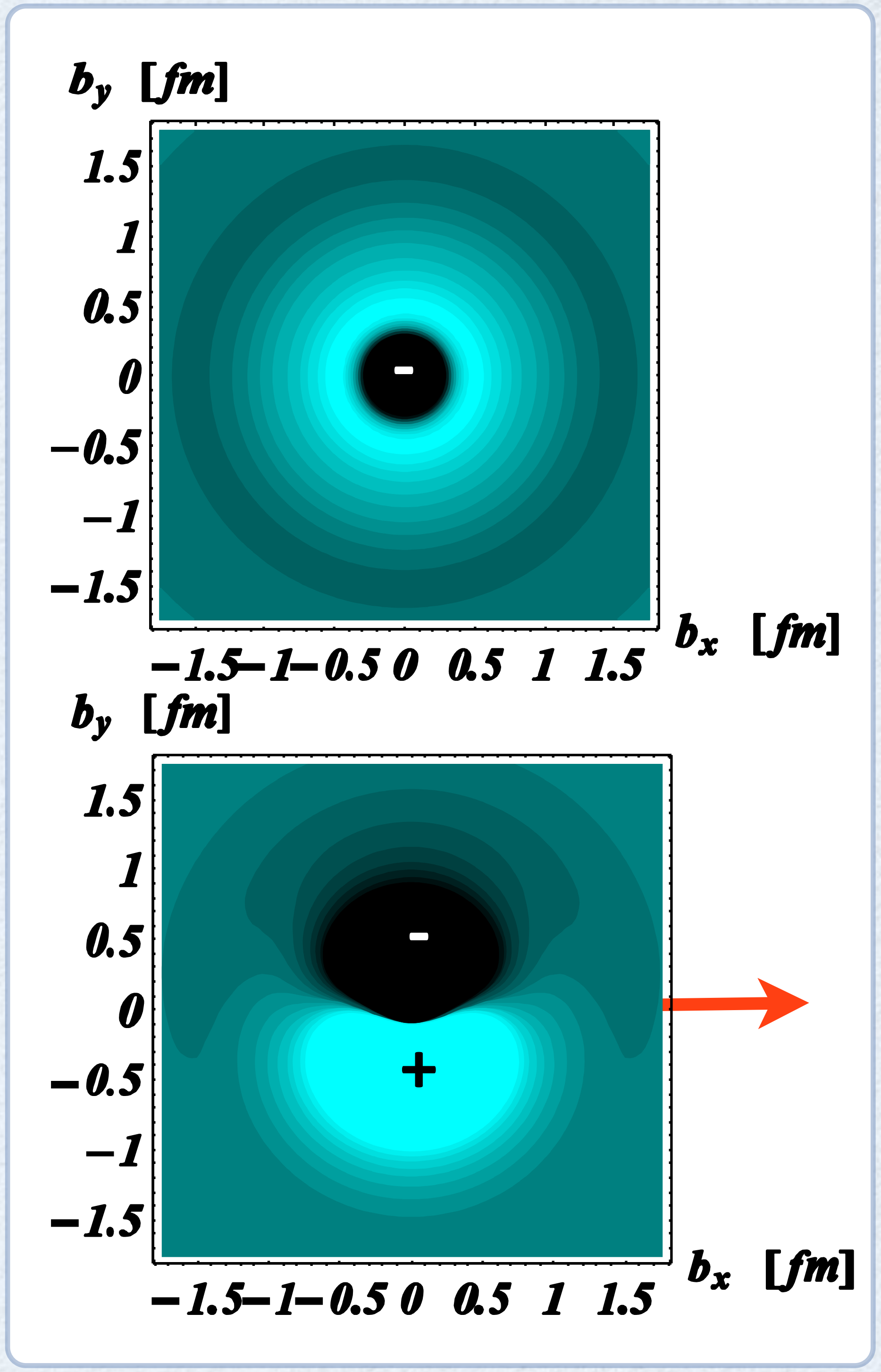


Spatial imaging of nucleons

proton



neutron



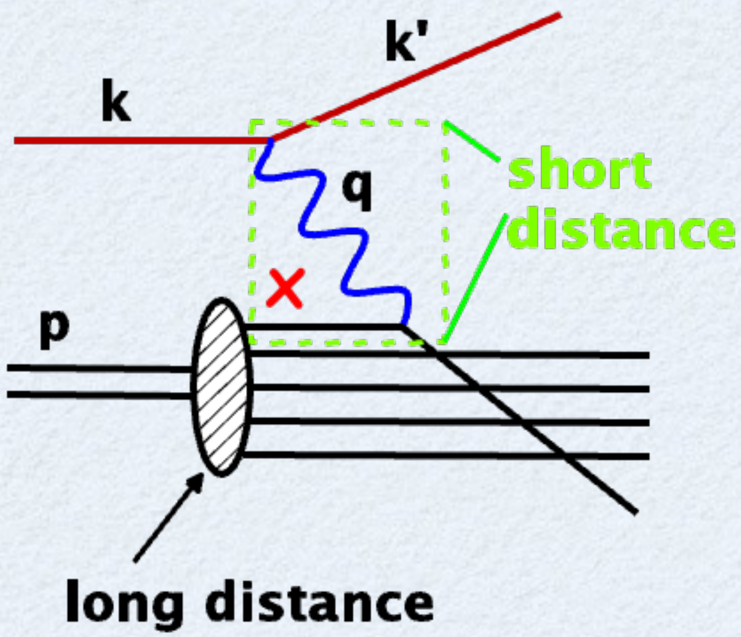
induced electric dipole moment:

$$d_y = \kappa \frac{e}{2M}$$

Miller (2007) Carlson, Vdh (2007)

Quarks seen through deep-inelastic scattering

➡ Inclusive Deep Inelastic Scattering of leptons from nucleon



$q(\nu, \vec{q}) \qquad p(M, \vec{0})$

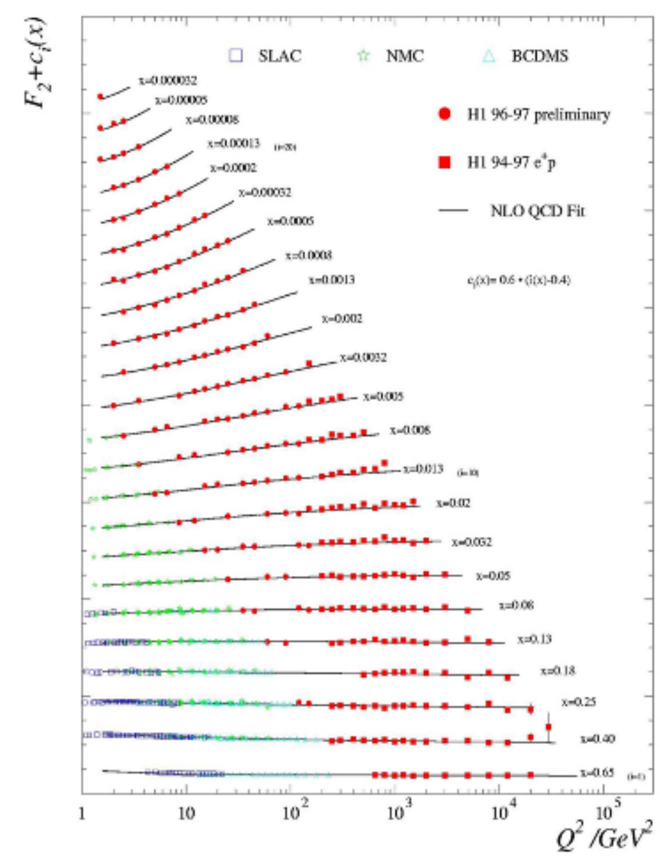
$Q^2 = \vec{q}^{\,2} - \nu^2$: large, $\qquad x = \dfrac{Q^2}{2p \cdot q} = \dfrac{Q^2}{2M\nu}$: fixed

structure functions

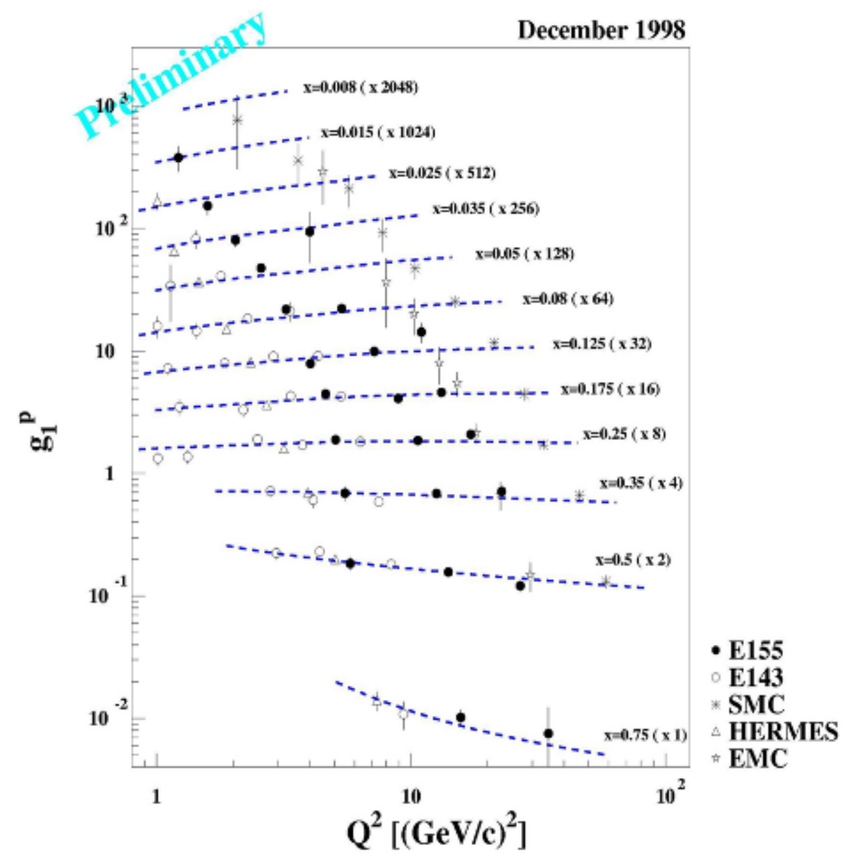
F_1, F_2 (unpolarized)

g_1, g_2 (polarized)

World data on F_1^p



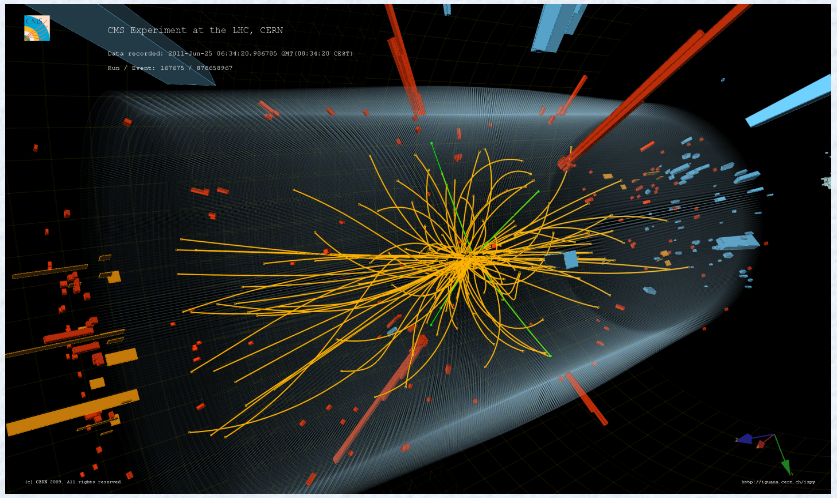
World data on g_1^p



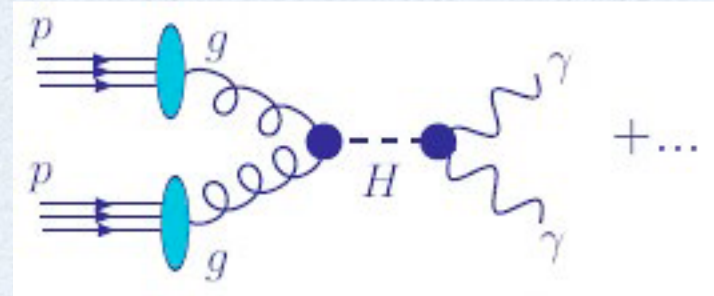
➡ Bjorken scaling

$$F_{1,2}(x, Q^2) \longrightarrow F_{1,2}(x)$$

$$g_{1,2}(x, Q^2) \longrightarrow g_{1,2}(x)$$



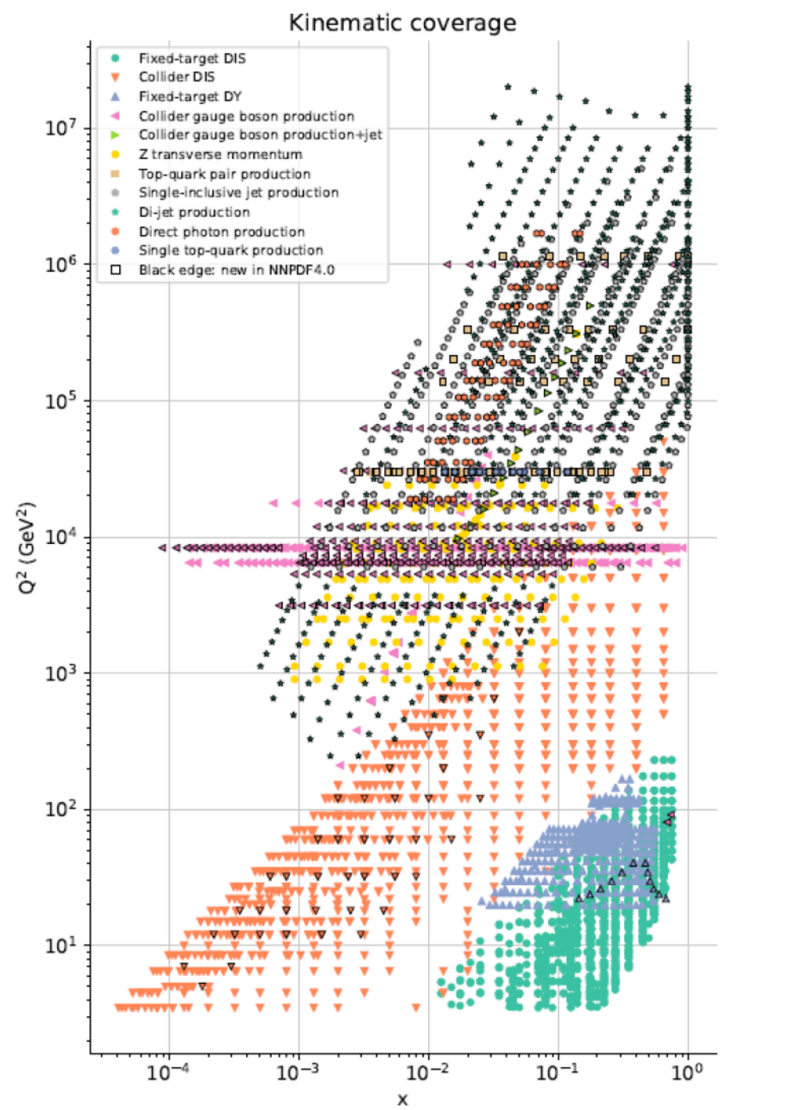
High-energy frontier

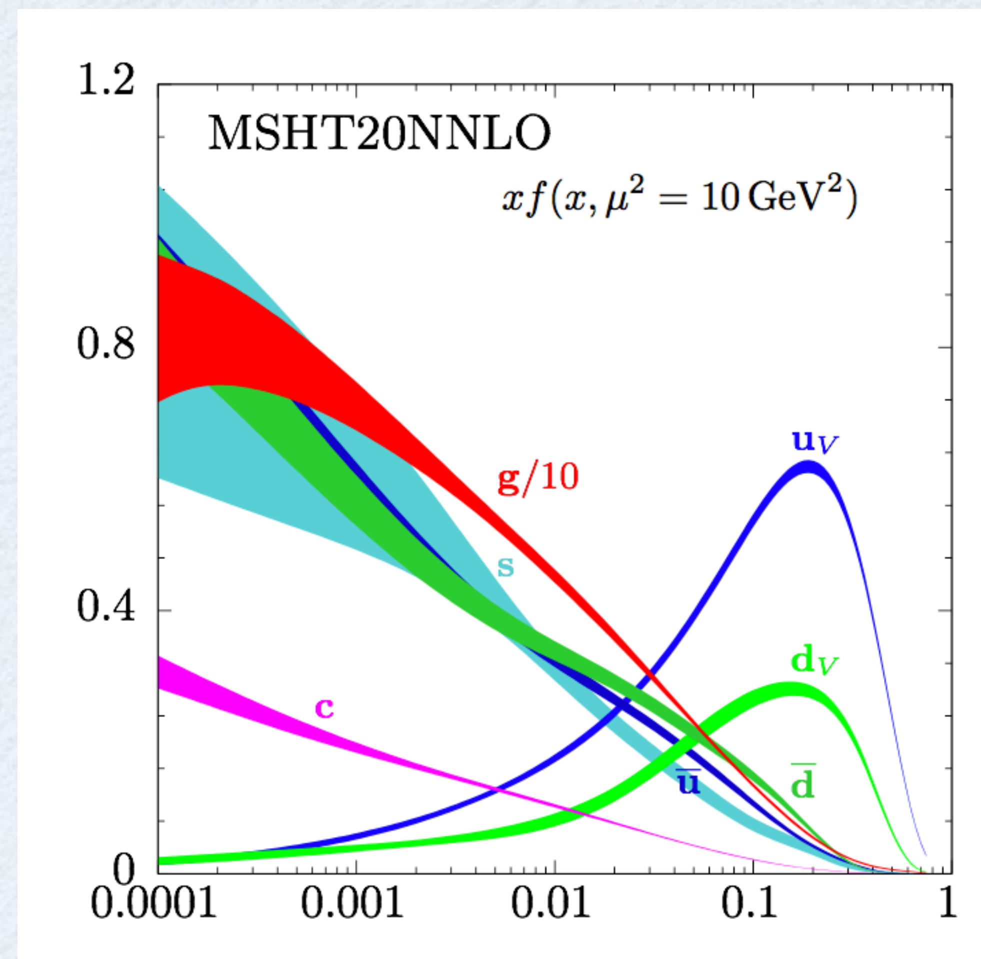


Accurate parton distributions needed!

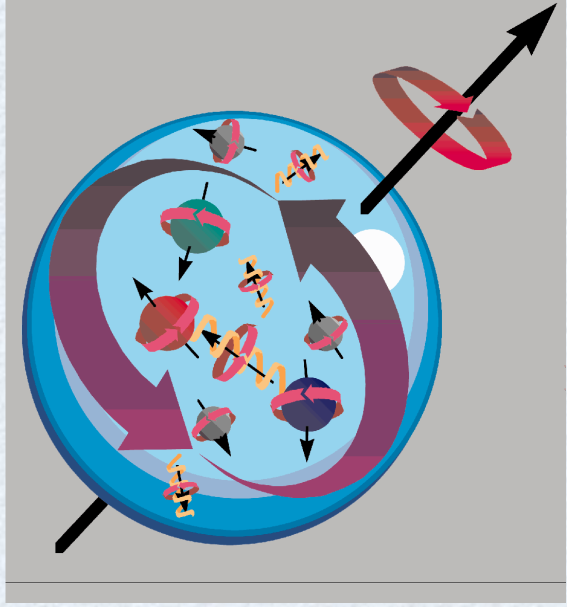
$F_2(Q^2, x_B)$

Data in the NNPDF4.0





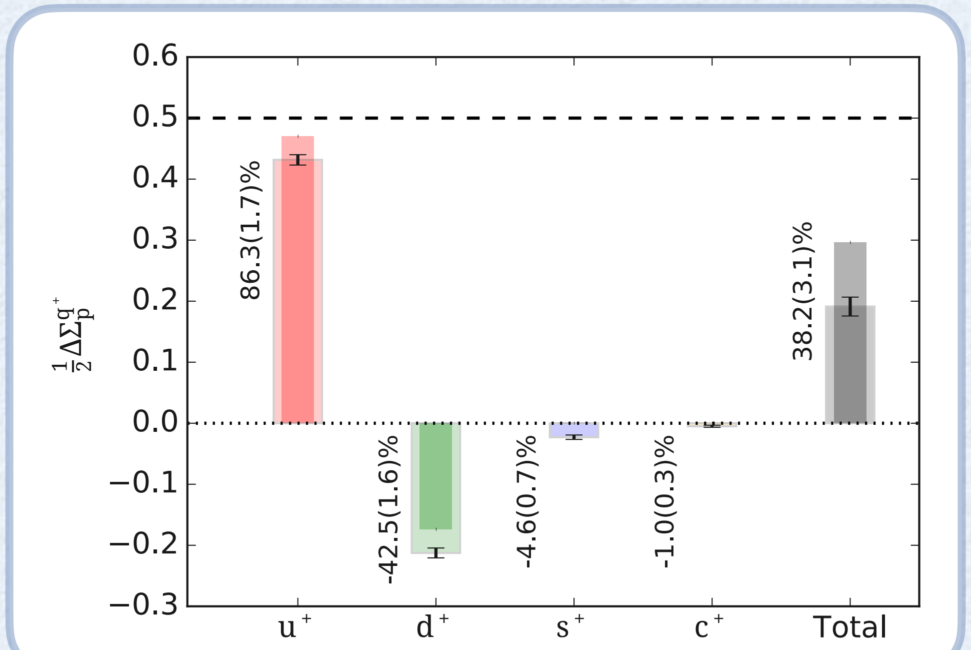
Nucleon spin and orbital angular momentum



- Deep-inelastic experiments:

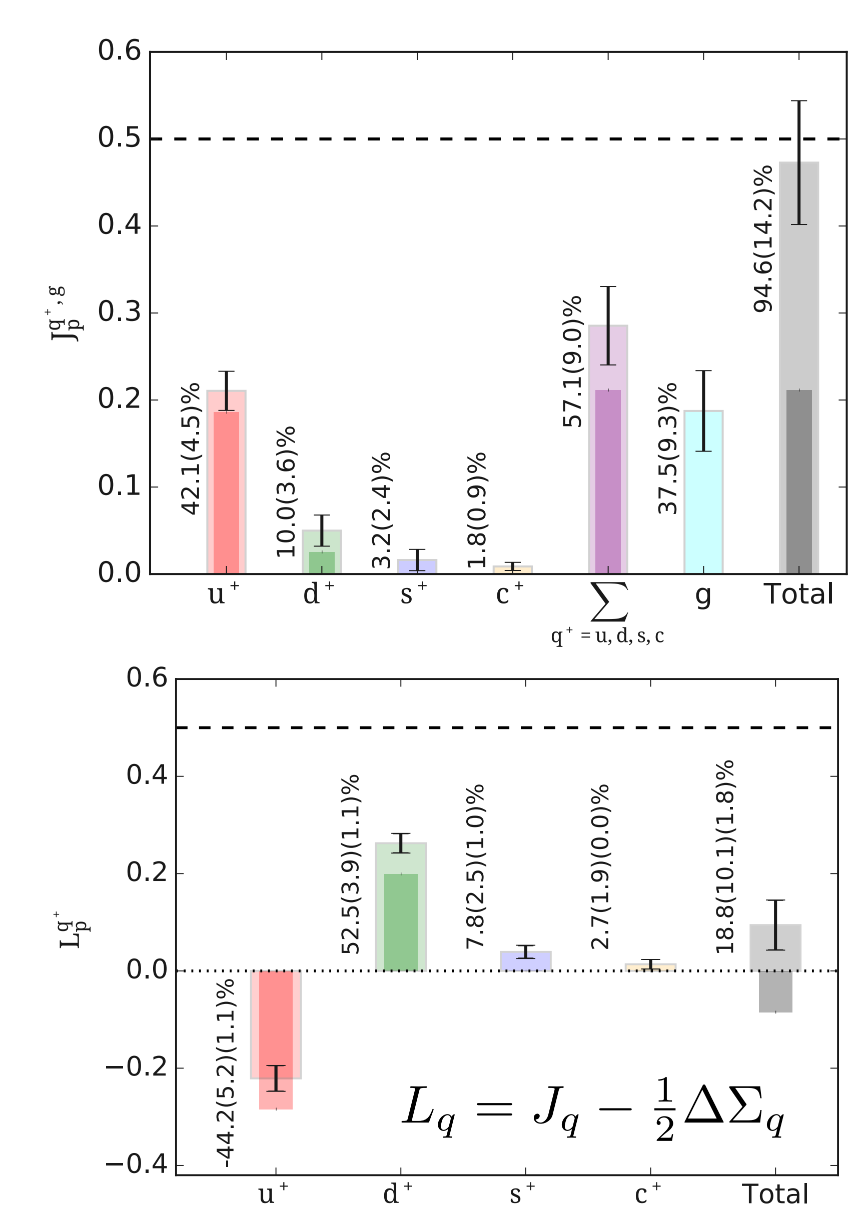
$$\Delta q \sim 30\% \quad (SIDIS/DIS)$$
$$\Delta G \sim 40\% \quad (RHIC)$$

- lattice QCD calculations at the physical point



Alexandrou et al.(ETMC) (2020)

total J in proton:
u-quark carries around 45%,
d, s-quarks carry small ≈ 15%,
gluons around 40%

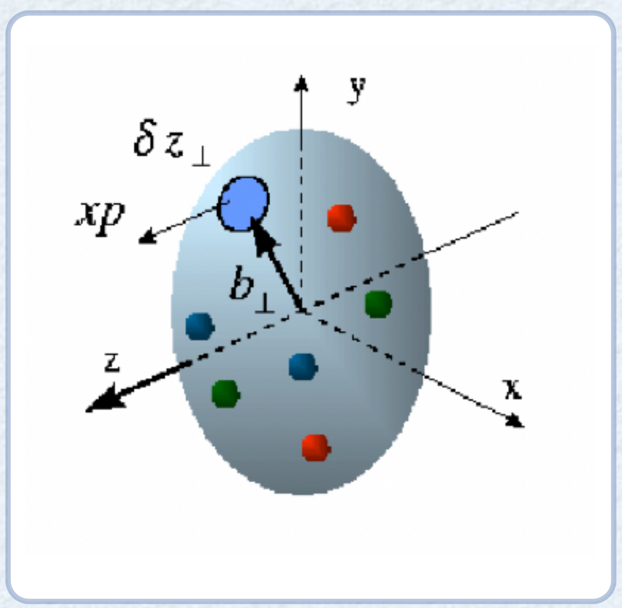


Correlations in transverse position/longitudinal momentum

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

quark distributions in **transverse position space**

quark distributions in **longitudinal momentum**



Burkardt(2000, 2003)

Belitsky, Ji, Yuan (2004)