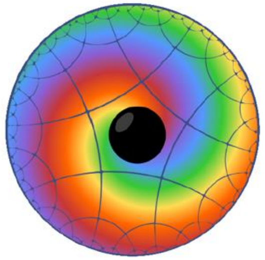
Gravitational form factor of the proton

Latifa Elouadrhiri
Jefferson Laboratory & Center of Nuclear Femography

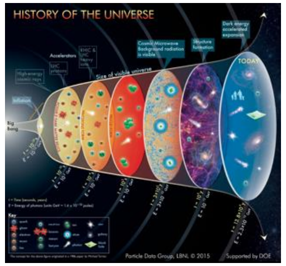
CENTER *for*
NUCLEAR FEMTOGRAPHY

Basic questions about the proton

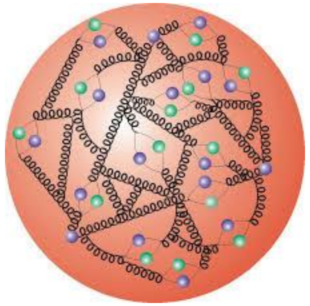
- Proton’s make up nearly 90% of the (normal) matter in the universe. Elementary valence quarks contribute only few percent to the proton mass. **What is the origin of its mass?**



- How did quarks hadronize and form protons as the universe cooled below the Hagedorn temperature? **What is the origin of confinement ?**

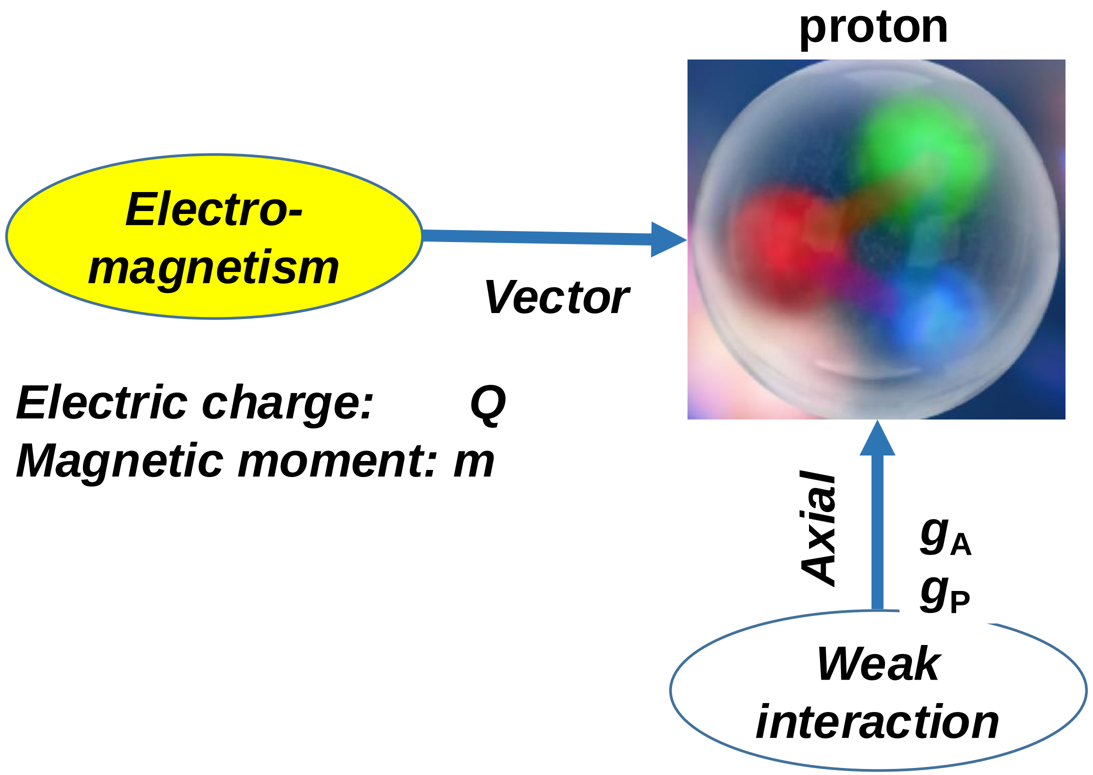


- **How are the strong forces distributed in space to keep quarks confined and make protons stable particles.**



Probing gravitational properties of the strong interaction

The proton has been studied in its *electromagnetic and weak* properties.

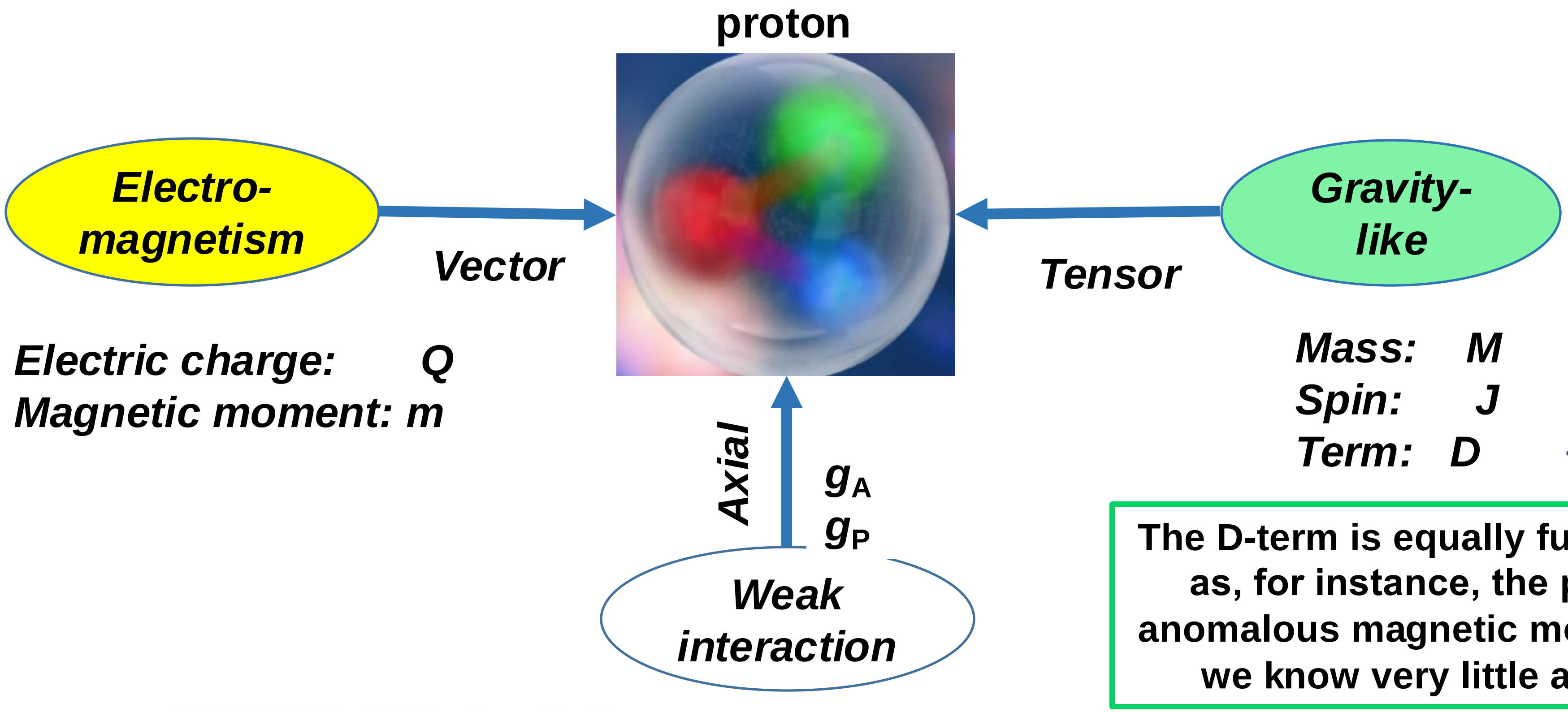


Electric charge: Q
Magnetic moment: m

Probing gravitational properties of the strong interaction

The proton has been studied in its *electromagnetic and weak* properties.

**If we could use *gravity* to probe the structure of the proton,
what would we learn?**



Electric charge: ***Q***
Magnetic moment: ***m***

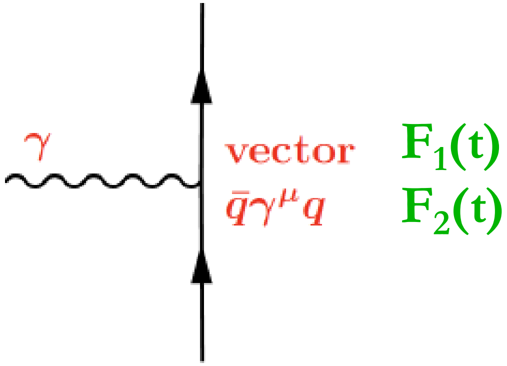
Mass: ***M***
Spin: ***J***
Term: ***D***

… what's that?

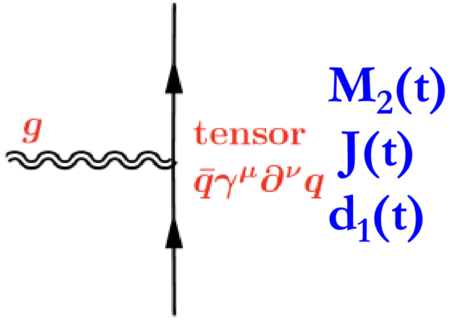
The D-term is equally fundamental as, for instance, the proton's anomalous magnetic moment. But we know very little about it.

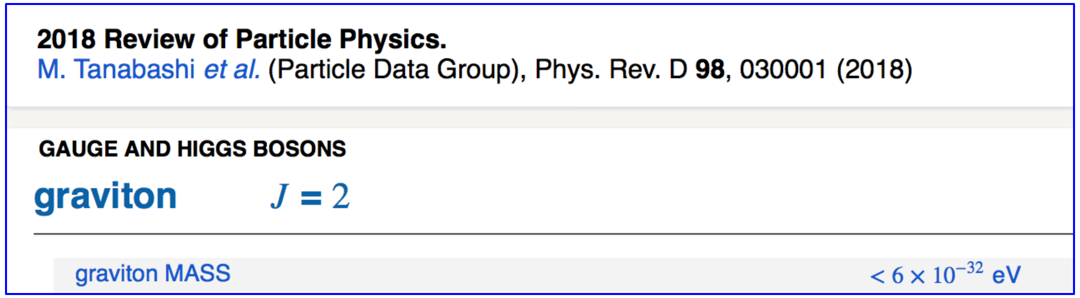
Probing basic properties of the proton

- **Electromagnetic properties:** probed with photons
  - **Charge** - electromagnetic form factors, inelastic structure functions, proton charge radius, charge densities and current densities for N & N*
  - **Magnetic moment** - helicity densities



- **Gravitational properties:** probed with gravitons
  - **Mass:** energy and mass densities
  - **Spin:** angular momentum distribution
  - **D-term:** dynamical stability, normal and shear forces, pressure distribution, mechanical radius.





2018 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

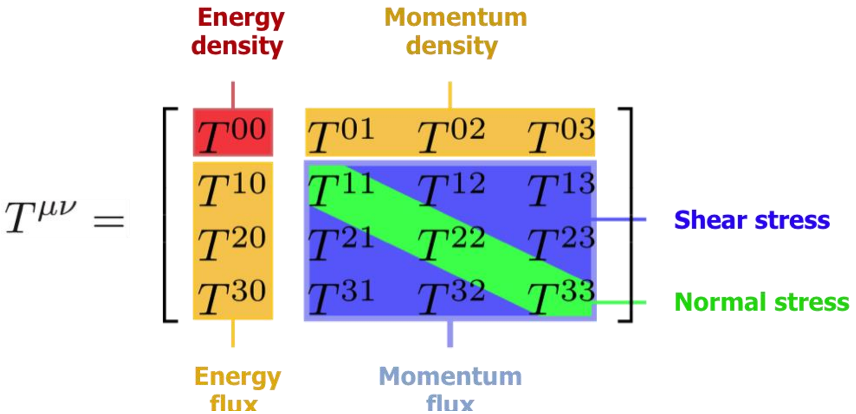
GAUGE AND HIGGS BOSONS

graviton $J = 2$

graviton MASS $< 6 \times 10^{-32}$ eV

Probing mechanical properties of the proton?

Gravitational Interaction of Fermions
Yu. Kobzarev and L.B. Okun, JETP 16, 5 (1963)
Energy-Momentum Structure Form Factors of Particles
Heinz Pagels, Phys. Rev. 144 (1966) 1250-1260



Energy density

Momentum density

$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

Shear stress

Normal stress

Energy flux

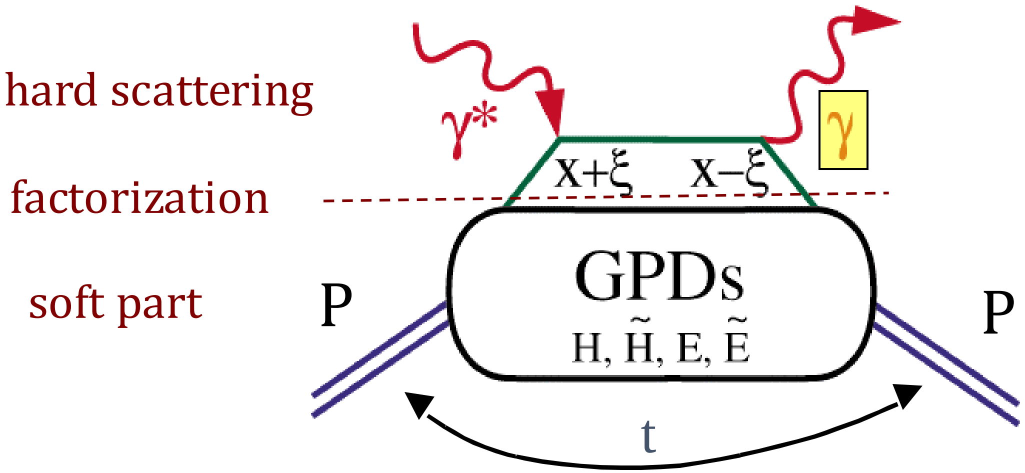
Momentum flux

$$T_{ij}(\vec{r}\,) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\delta_{ij}\right) + p(r)\delta_{ij}$$

"….. , there is very little hope of learning anything about the detailed mechanical structure of a particle, because of the extreme weakness of the gravitational interaction" (*H. Pagels)*

Generalized Parton Distributions (GPDs)

Deeply virtual Compton scattering (DVCS)



Proton stays intact

$$\xi = \frac{x_B}{2 - x_B}$$

(in the Bjorken regime)

GPD: *H(x,ξ, t)*, …

D. Müller (1994) *X. Ji (1996)* *A.Radyushkin (1996)*

D. Müller et al., F.Phys. 42,1994
X. Ji, PRL 78, 610, 1997
A. Radyushkin, PLB 380, 1996

GPDs – GFFs Relations

Nucleon matrix element of the Energy-Momentum Tensor contains three scalar form factors and can be written as:

$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{U}(p_2)\left[M_2^q(t)\frac{P_\mu P_\nu}{M} + J^q(t)\frac{\imath(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]U(p_1)$$

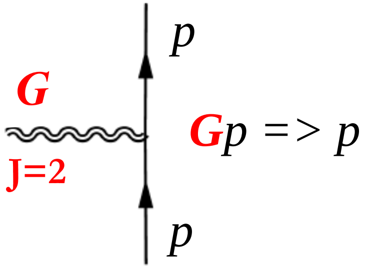
$M_2(t)$: Mass/energy distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Forces and pressure distribution

GPDs ⟺ GFFs

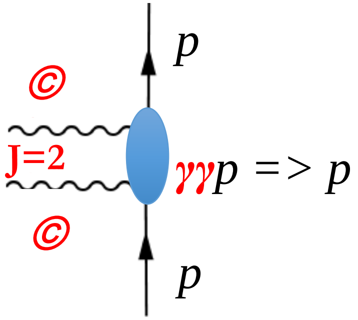
$$\int \mathrm{d}x\, x\,[\underline{H}(x,\xi,t) + \underline{E}(x,\xi,t)] \;=\; 2\underline{J}(t)$$
$$\int \mathrm{d}x\, x\underline{H}(x,\xi,t) \;=\; \underline{M_2}(t) + \frac{4}{5}\xi^2\underline{d_1}(t),$$

X. Ji, Phys. Rev. D55, 7114 (1997)

Graviton – proton scattering



DVCS



GPDs & Compton Form Factors

- GPDs cannot directly be determined from current DVCS measurements alone.
- We can determine the Compton Form Factor **$\mathcal{H}(\xi, t)$**
- **$\mathcal{H}(\xi, t)$** is related to the corresponding GPD **$H(x,\xi,t)$** through an integral over the quark longitudinal momentum fraction *x*.

$$\boxed{\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)}$$

M. Polyakov (2003)

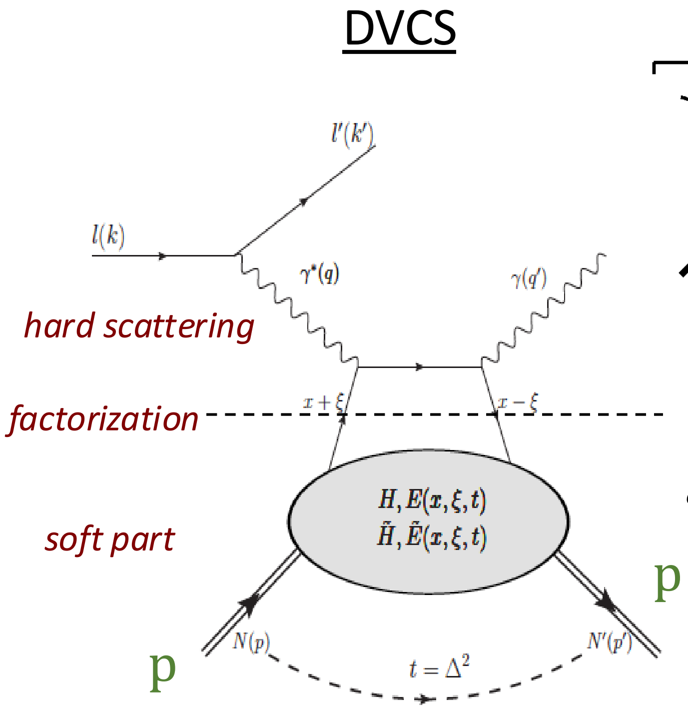
To determine the complex CFF **$\mathcal{H}(\xi, t)$** we exploit the interference of the DVCS amplitude with the Bethe-Heitler amplitude that results in a polarized beam spin asymmetry.

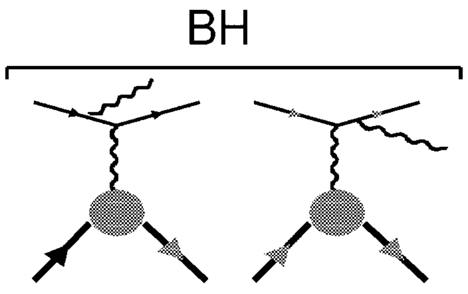
M. Polyakov, Phys. Lett. B555 (2003) 57

GPDs, DVCS, Compton Form Factors (CFFs)

D. Müller et al., F. Phys. 42,1994,
X. Ji, PRD 55 (1997) 7114

X. Ji, PRL 78 (1997) 610
A. Radyushkin, PRD 56 (1997) 5524





Elastic Form Factors

$$\xi = \frac{x_B}{2 - x_B}$$

In DVCS measurements the relevant quantities are not GPDs but **complex valued** integrals of GPDs, the Compton Form Factors (CFF).

$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx\, H(x,\xi,t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

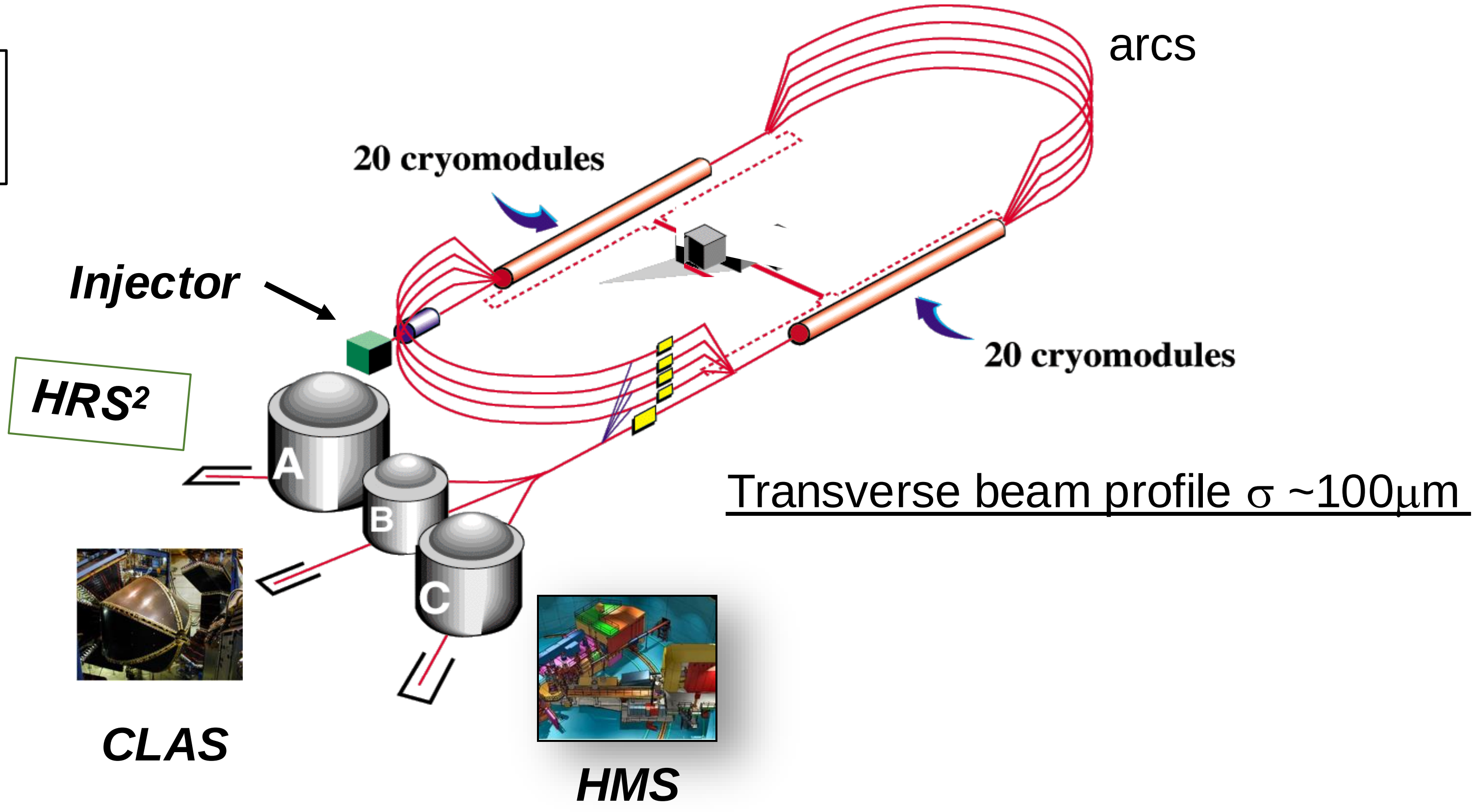
4 chiral even GPDs describe soft part
***H** is essential* for the parton spatial imaging
***E** is* essential for imaging the parton spin distributions

The original 6 GeV CEBAF with 3 experimental Halls

Racetrack design with two parallel linear accelerators each providing up to $\Delta E \sim 600$MeV, with 5 re-circulations through the arcs.

Continuous beam with up to 6 GeV polarized electrons to 3 Halls.

Photon energy tagging system in Hall B for the missing N* resonance program with CLAS.



Transverse beam profile $\sigma \sim 100\mu$m

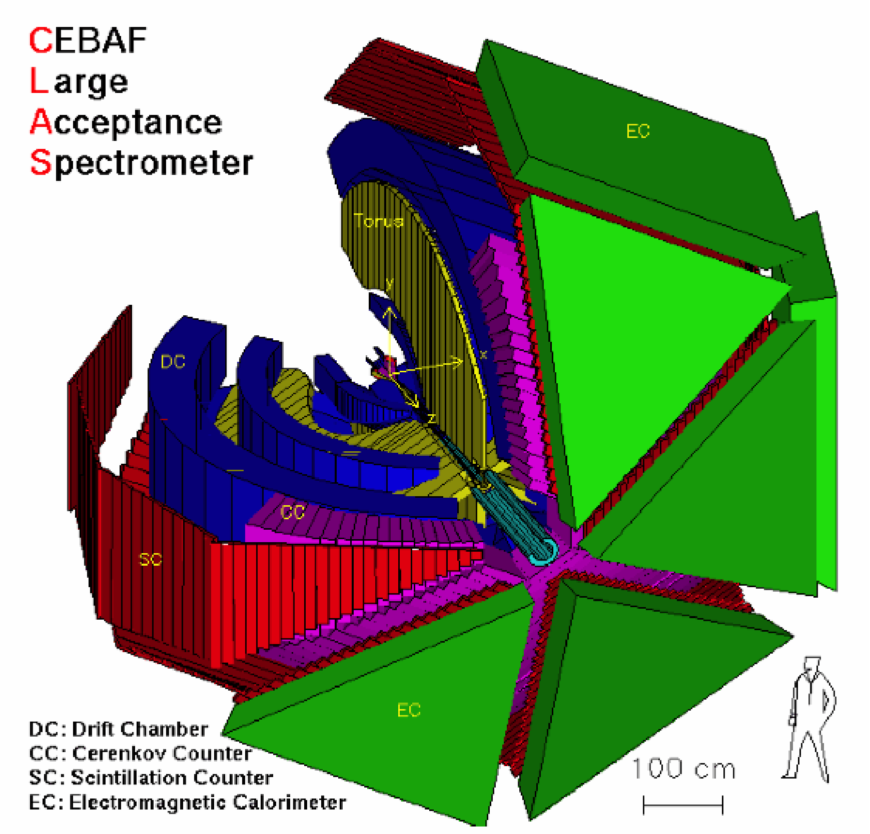
→ **Focus on Hall B and the CLAS Detector**

The CLAS Detector

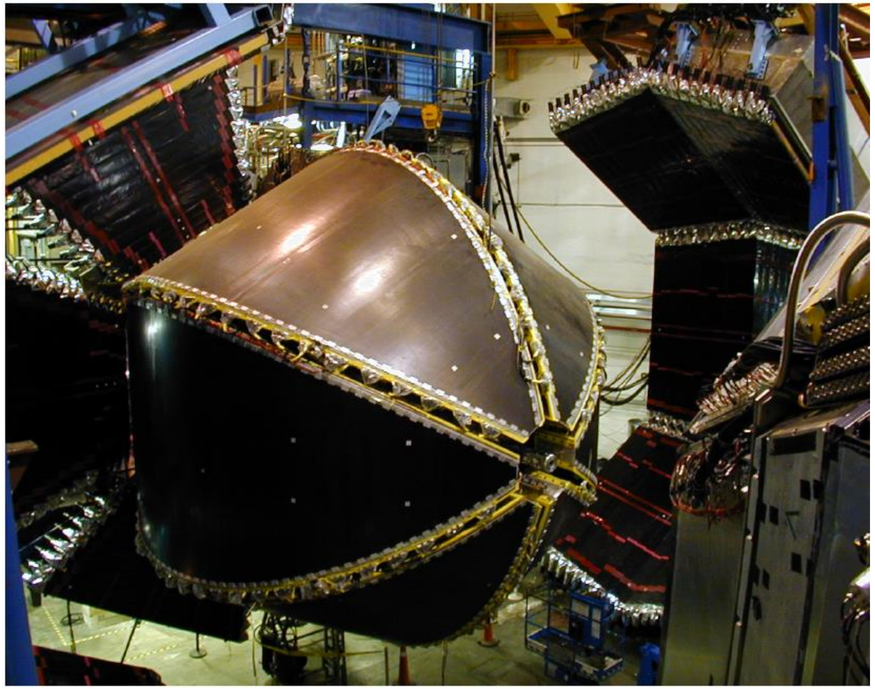
- ✓ Large acceptance
- ✓ Momentum reconstruction
- ✓ Charged particle identification
- ✓ Photon and neutron detection

In operation from 1997 to 2012 in two modes:

Photon beams: Search for excited states of the proton
Electron beams: Structure of the nucleon and excited states

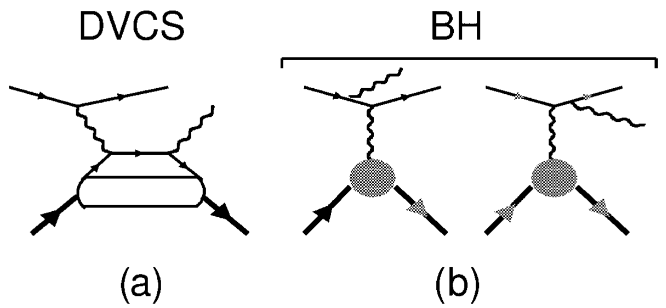


$\delta T = 100$psec
$\delta p/p = 0.005$
$\delta E/E = 0.1/\sqrt{E(\text{GeV})}$



Electron acceptance: $\theta_e = 10^o - 45^o$
Charged Hadron acceptance: $\theta_h = 10^o - 140^o$

First DVCS-BH BSA observed in 2001



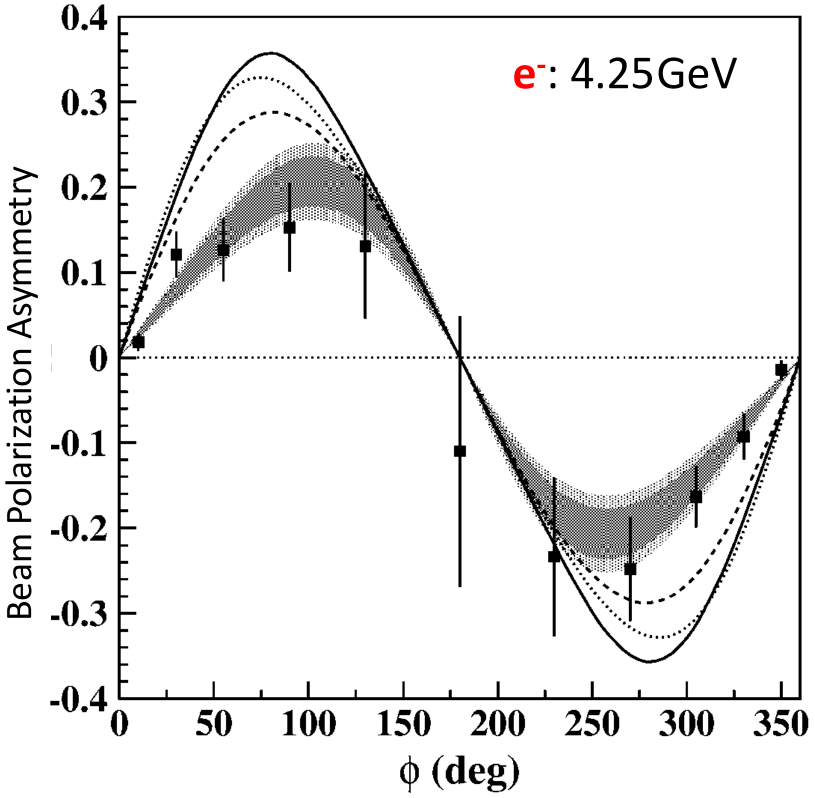
$\vec{e}p \to ep\gamma$

This opened a new era of hadron research in exclusive processes.

Observation of Exclusive Deeply Virtual Compton Scattering in Polarized Electron Beam Asymmetry Measurements

CLAS Collaboration

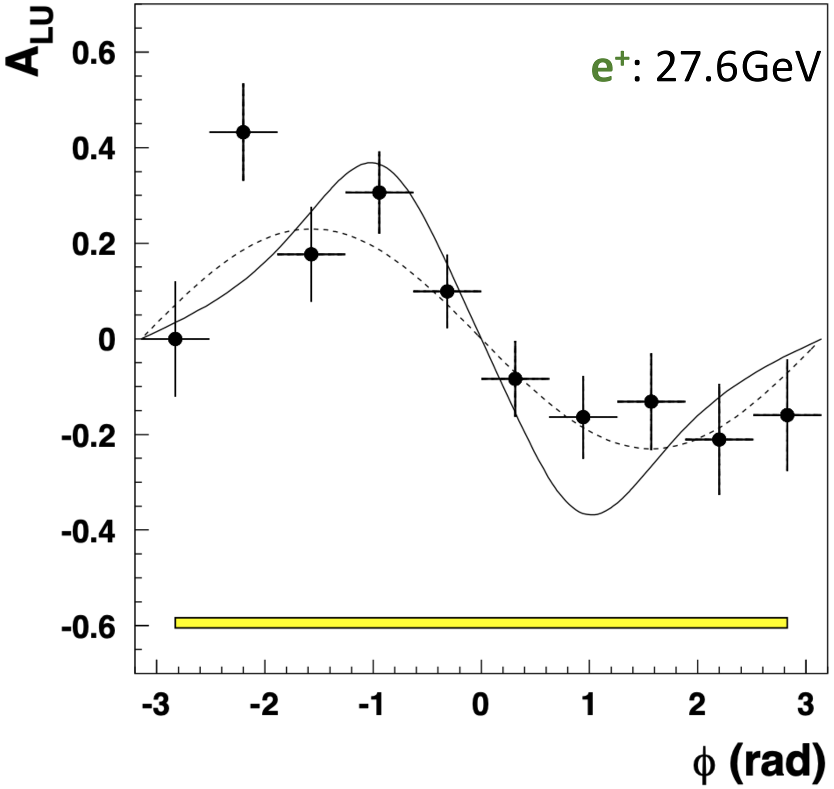
Phys.Rev.Lett. 87 (2001) 182002



https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.87.182002

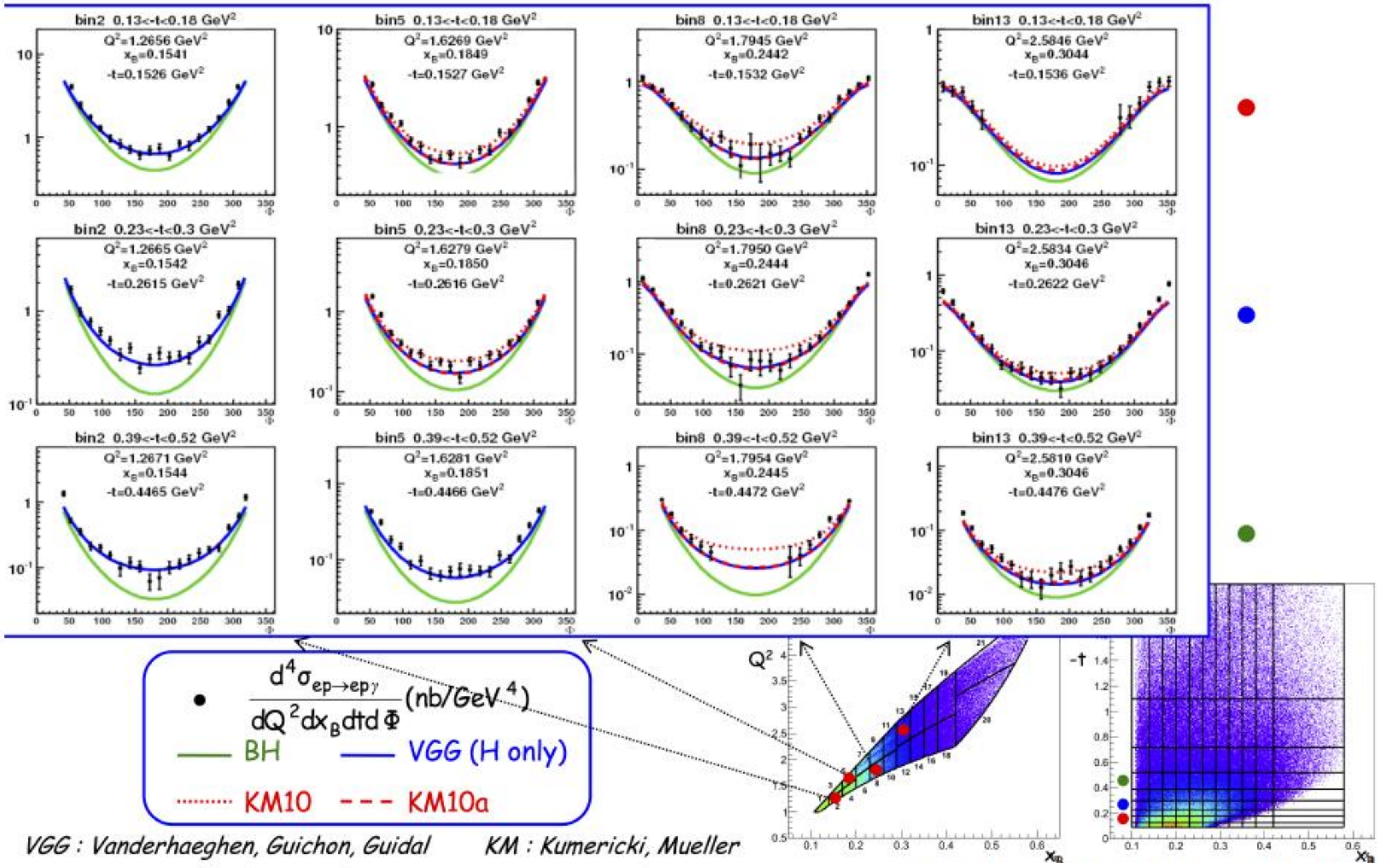
HERMES Collaboration

Phys.Rev.Lett. 87 (2001) 182001



https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.87.182001

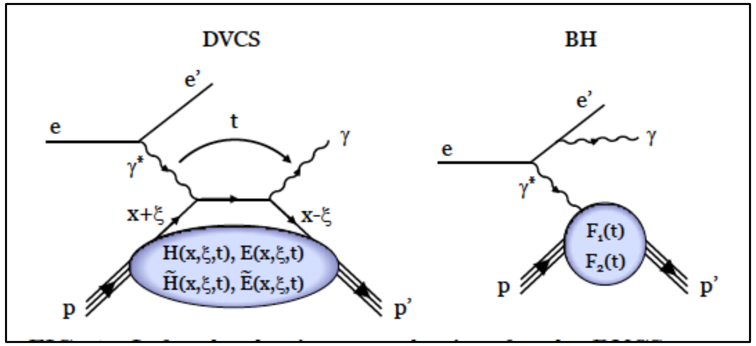
DVCS Unpolarized Cross-Sections



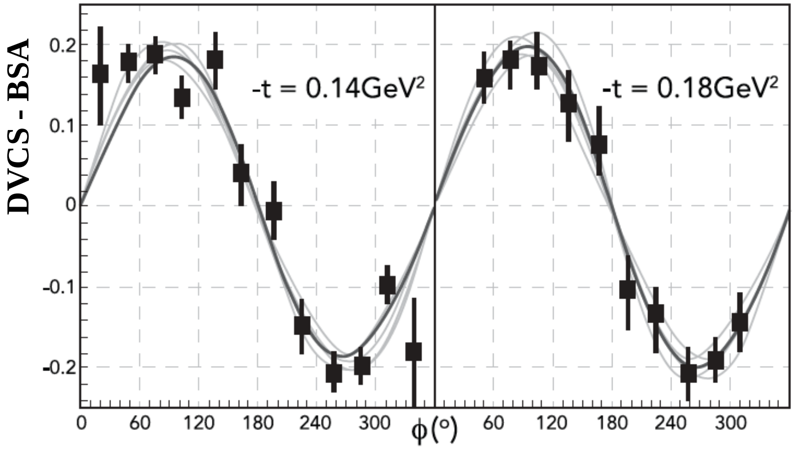
VGG : Vanderhaeghen, Guichon, Guidal KM : Kumericki, Mueller

H.S. Jo et al., Phys.Rev.Lett. 115 (2015)

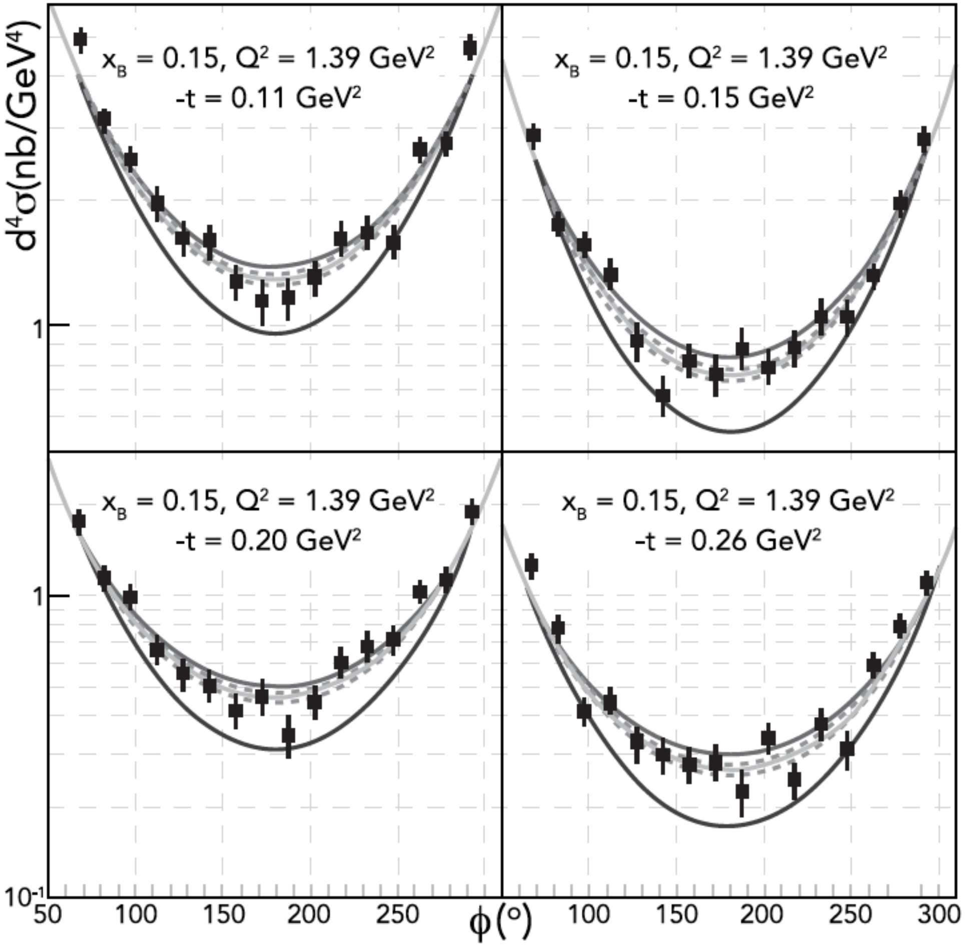
Fit to DVCS data to determine *D*-Term



Samples of Beam Spin Asymmetry



Samples of differential cross sections with fits



F.X. Girod et al., Phys.Rev.Lett. 100 (2008) 162002 ; H.S. Jo et al., Phys.Rev.Lett. 115 (2015) 212003,

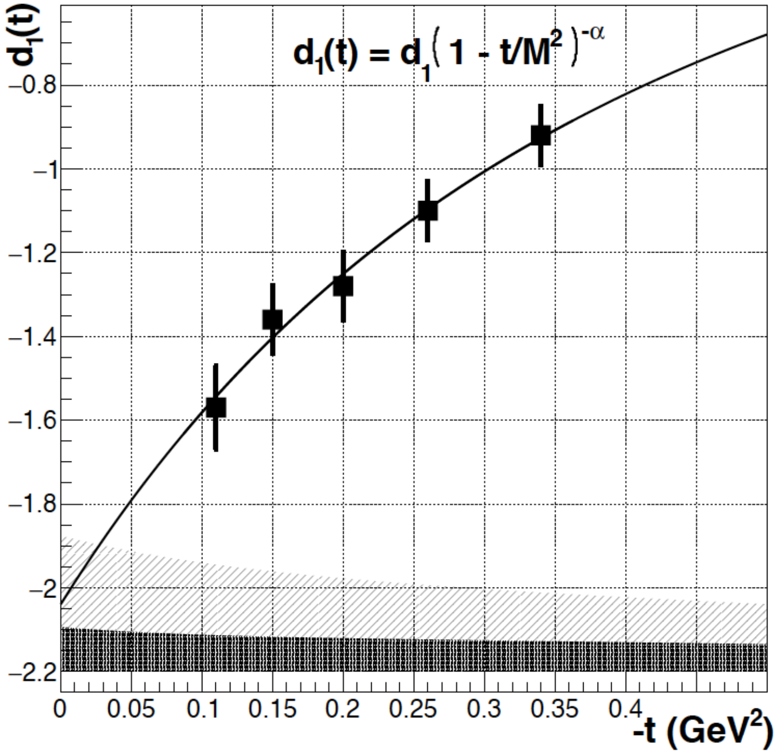
$d^Q_1(t)$ - Gravitational Form Factor

Expansion in Gegenbauer polynomials

$$D(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}z \frac{D(z,t)}{1-z} \qquad \text{with}$$

$$D(z,t) = (1-z^2)\left[d_1(t)C_1^{3/2}(z) + \cdots\right]$$

$$-1 < z = \frac{x}{\xi} < 1$$



$d_1(0) < 0$ dynamical stability of bound state

$d^Q_1(0) = -2.04 \pm 0.14 \pm 0.33$

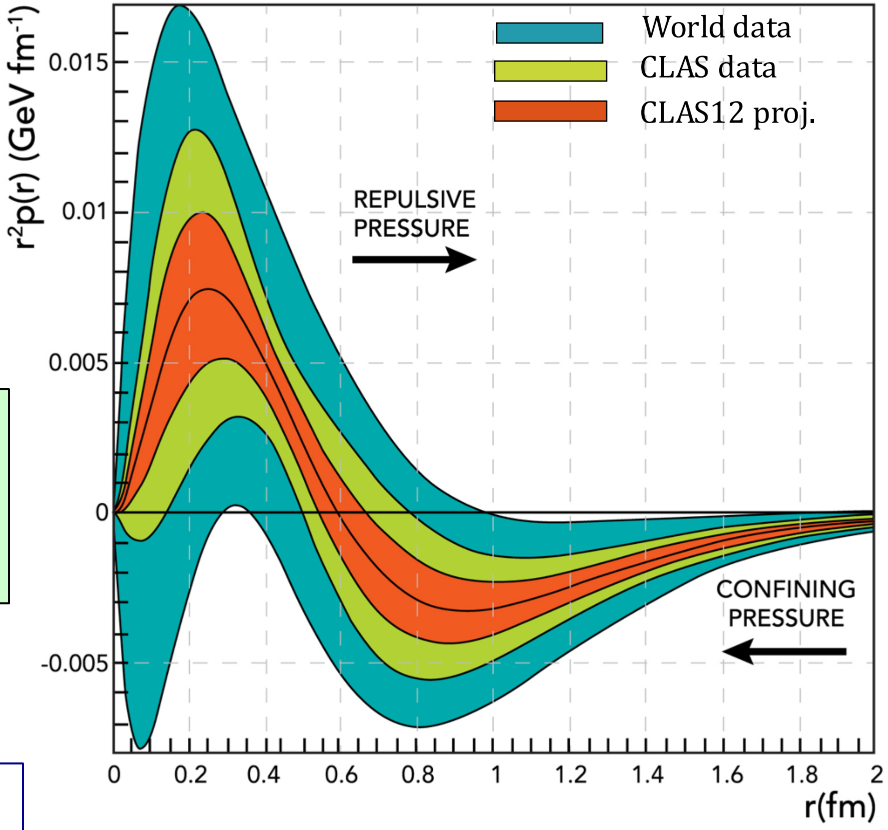
First determination of new fundamental quantity.

The pressure distribution inside the proton

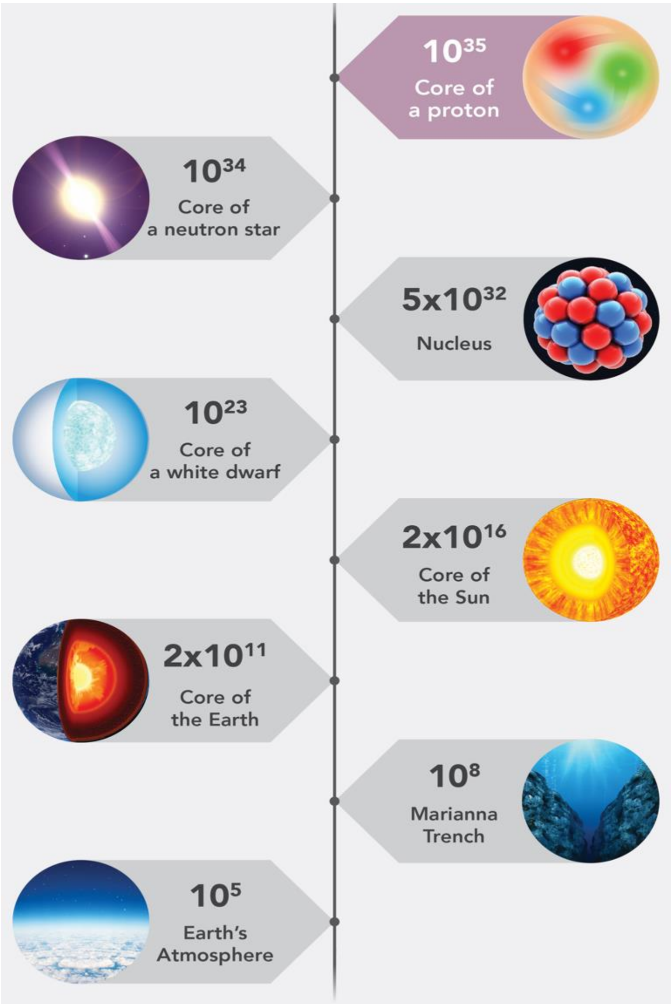
$$d_1(t) \propto \int \mathrm{d}^3\mathbf{r}\, \frac{j_0(r\sqrt{-t})}{2t}\, p(r)$$

Repulsive pressure near center
$p(r{=}0) = 10^{35}$ Pa
Confining pressure at r > 0.6 fm

Atmospheric pressure: 10^5 Pa
Pressure in the center of neutron stars ≤ 10^{34} Pa

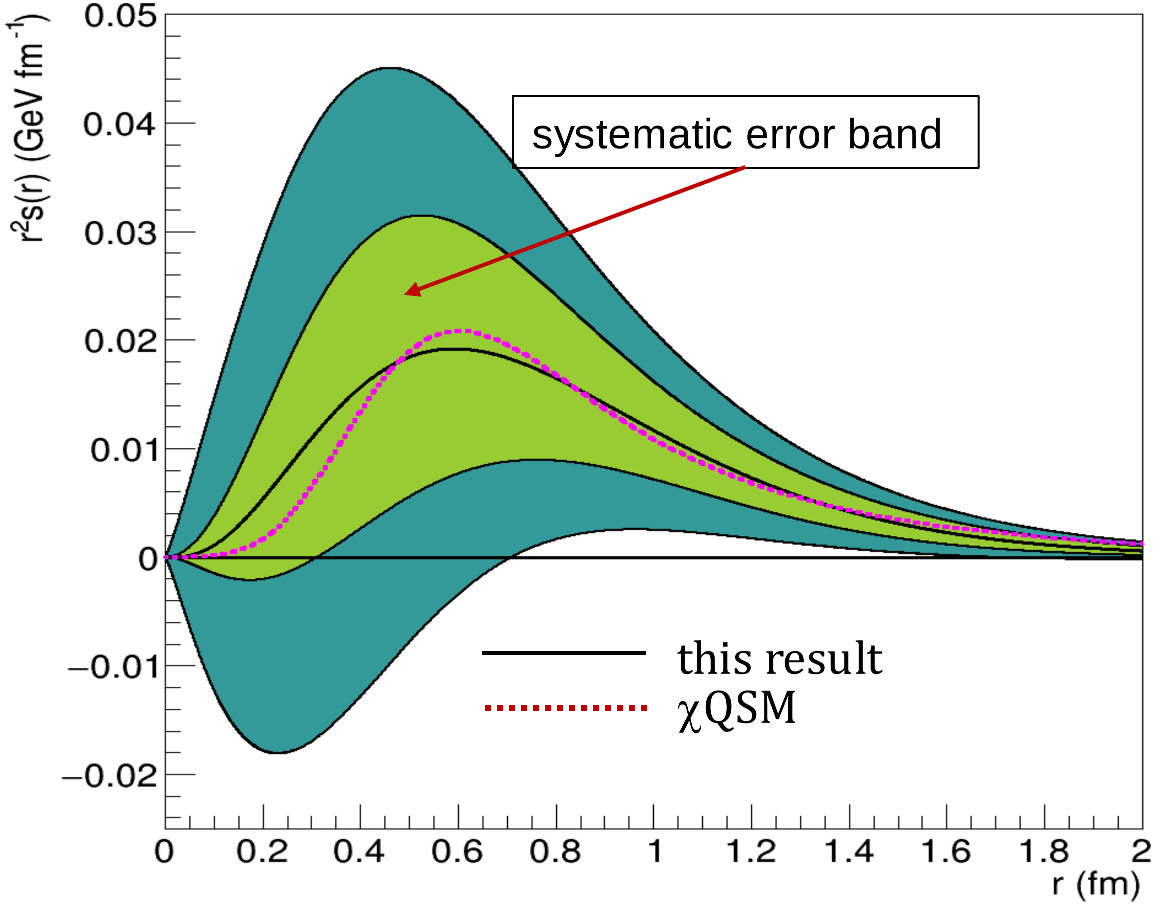


V.B., L. Elouadrhiri, F.X. Girod
Nature 557 (2018) no.7705, 396-399



Shear Stress on quarks in proton

Shear stress $r^2 s^Q(r)$



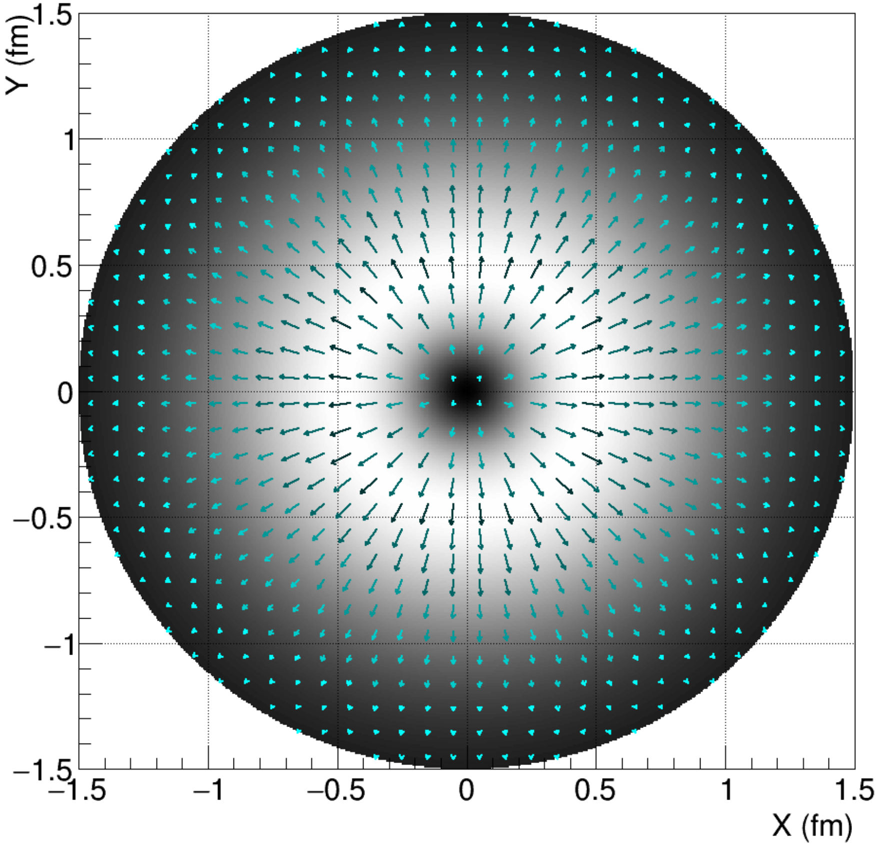
Shear stress at $r = 0.6$fm:
$4\pi r^2 s(r) = 0.238$GeV/fm

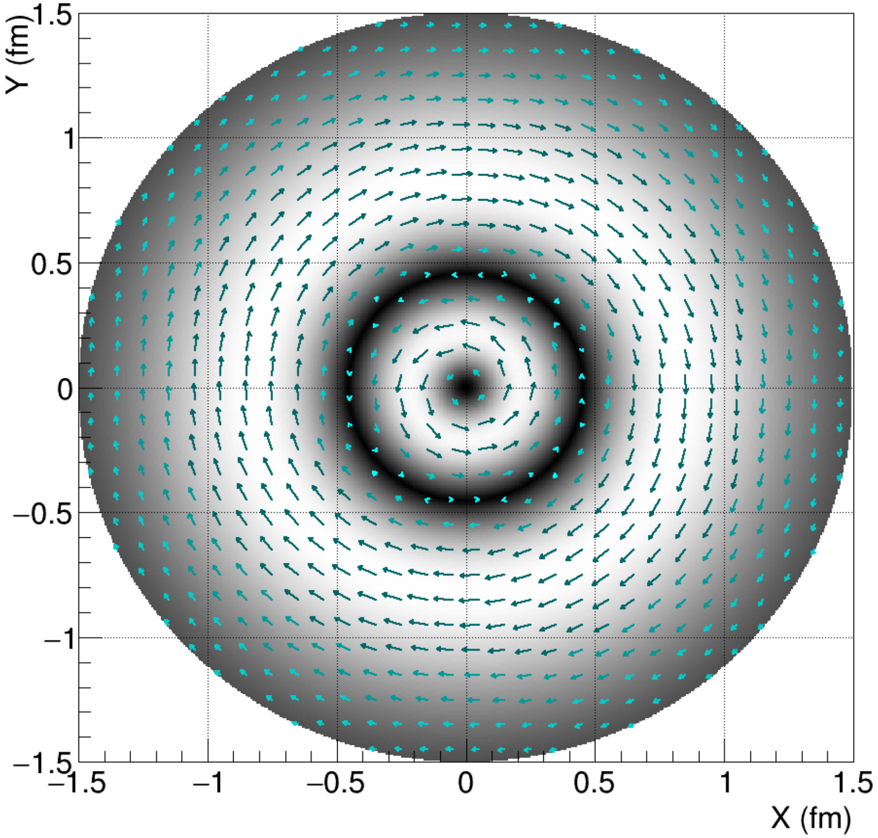
$\sim 38 \times 10^3$ Newton

Normal & Tangential Stress on Quarks

Normal stress: $F_n = 4\pi r^2[2/3\ s(r) + p(r)]$

Tangential stress: $F_t = 4\pi r^2[-1/3\ s(r) + p(r)]$



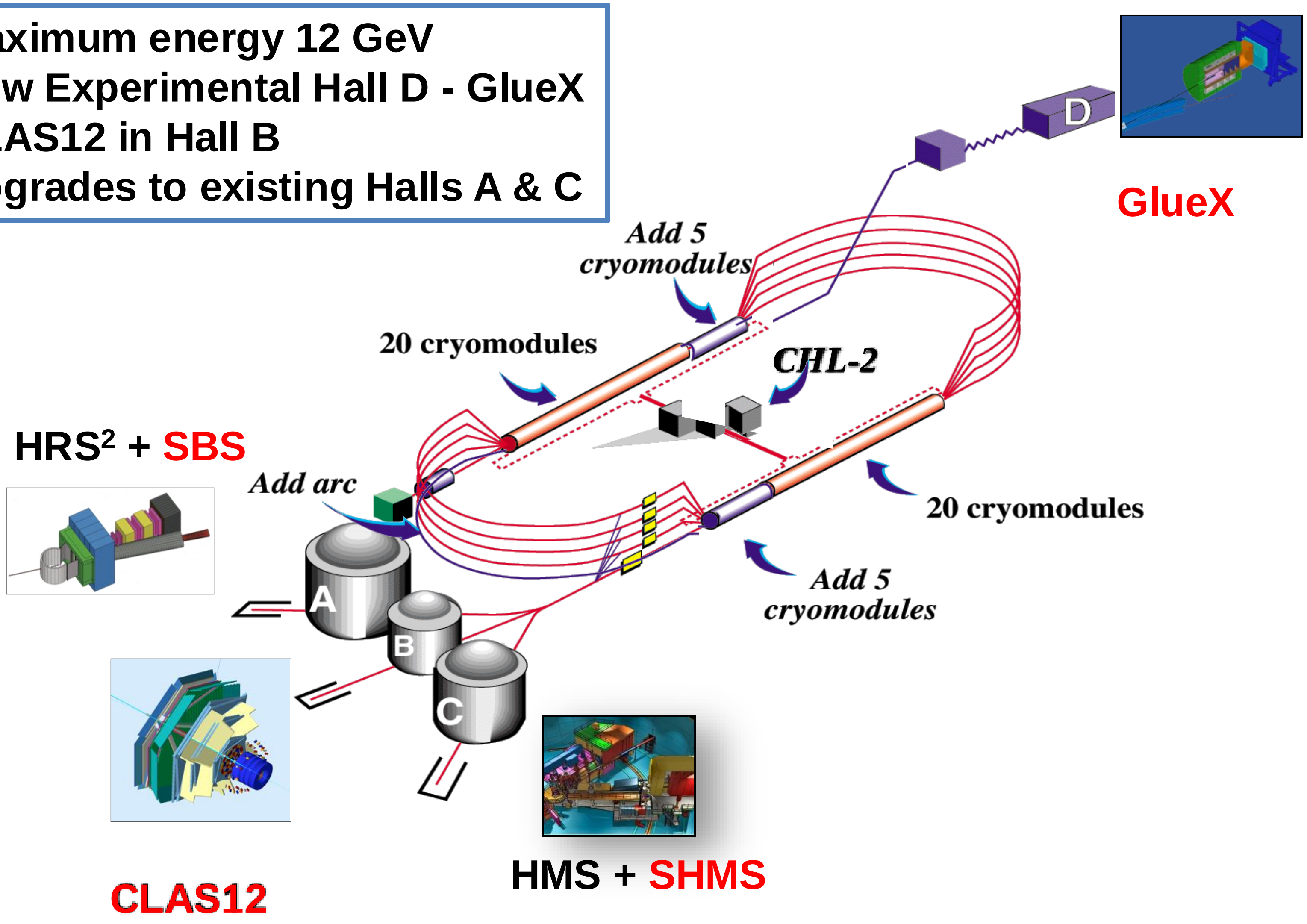


Normal stress is positive at all r

Tangential stress changes direction near r ~ 0.45 fm

The Jefferson Lab Energy Upgrade

Maximum energy 12 GeV
New Experimental Hall D - GlueX
CLAS12 in Hall B
Upgrades to existing Halls A & C



GlueX

Add 5 cryomodules

20 cryomodules

CHL-2

HRS^2 + SBS

Add arc

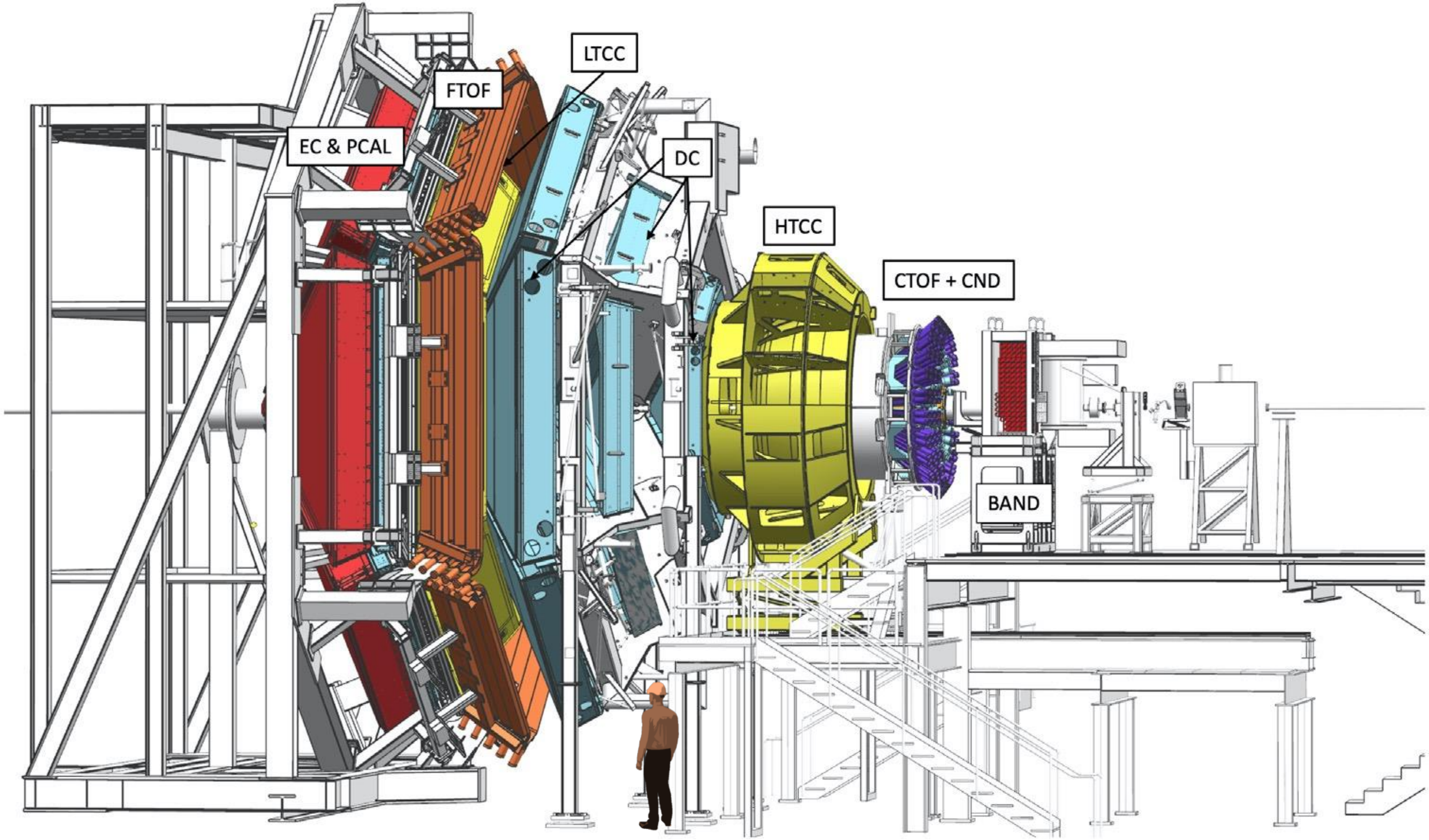
20 cryomodules

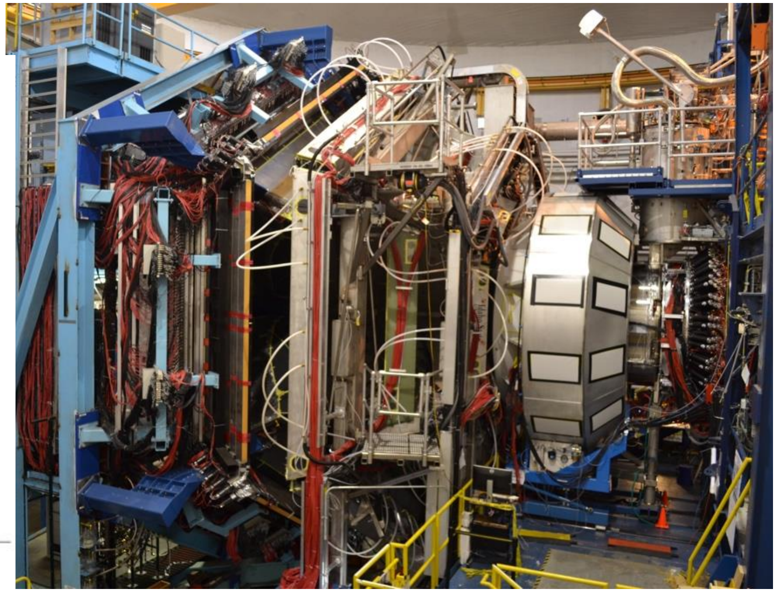
Add 5 cryomodules

CLAS12

HMS + SHMS

CLAS12



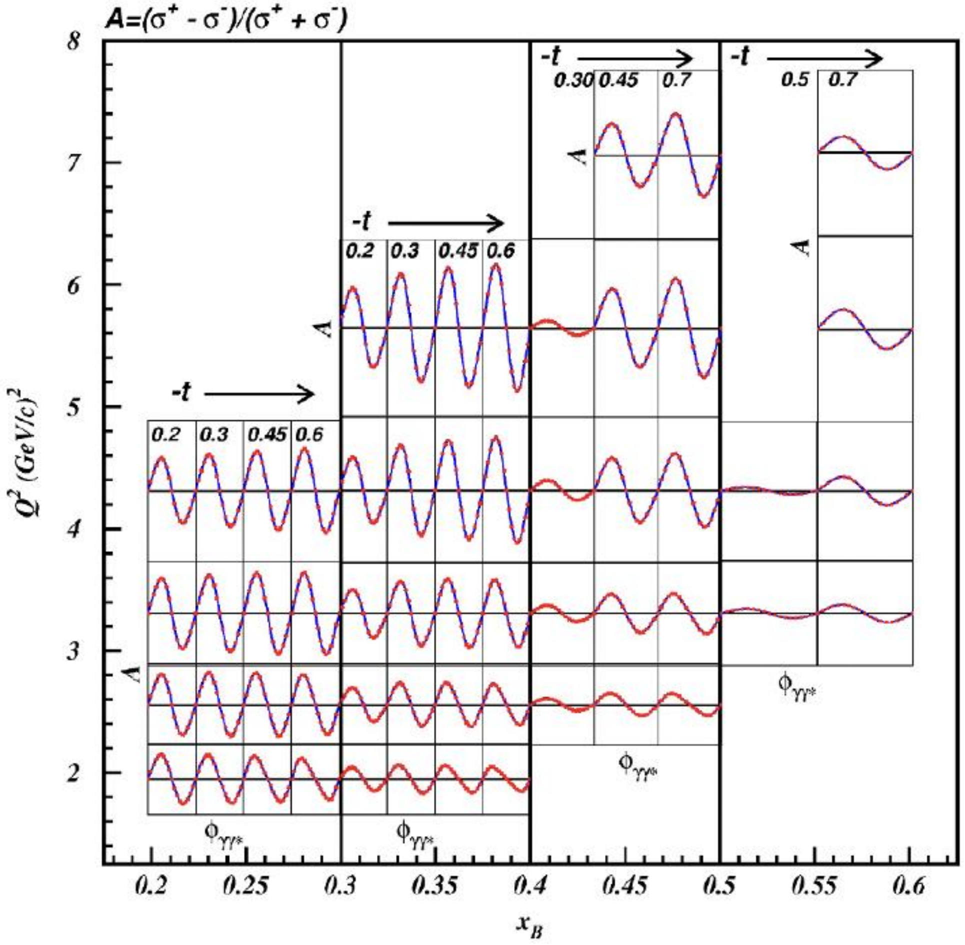


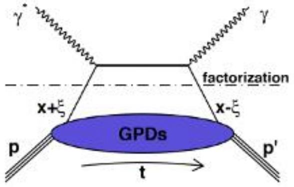
- Luminosity - 10^{35}cm^{-2}s^{-1}
- Polarized target operation at 5T
- Charged particle tracking and ID
- Neutron and photon detection
- Data rate 1 Gigabyte/sec
- Charged Particle ID to 8 GeV/c

DVCS Experiment – Projections

80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam

$A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$

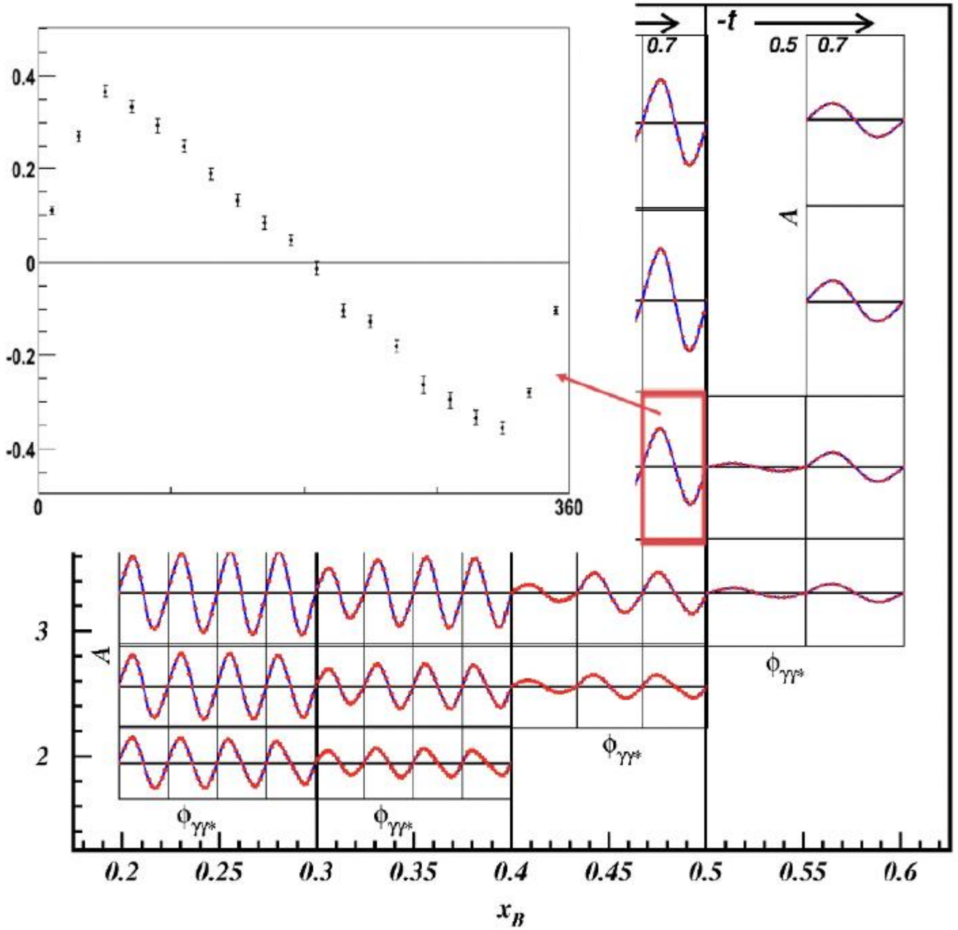




Projections for CLAS12

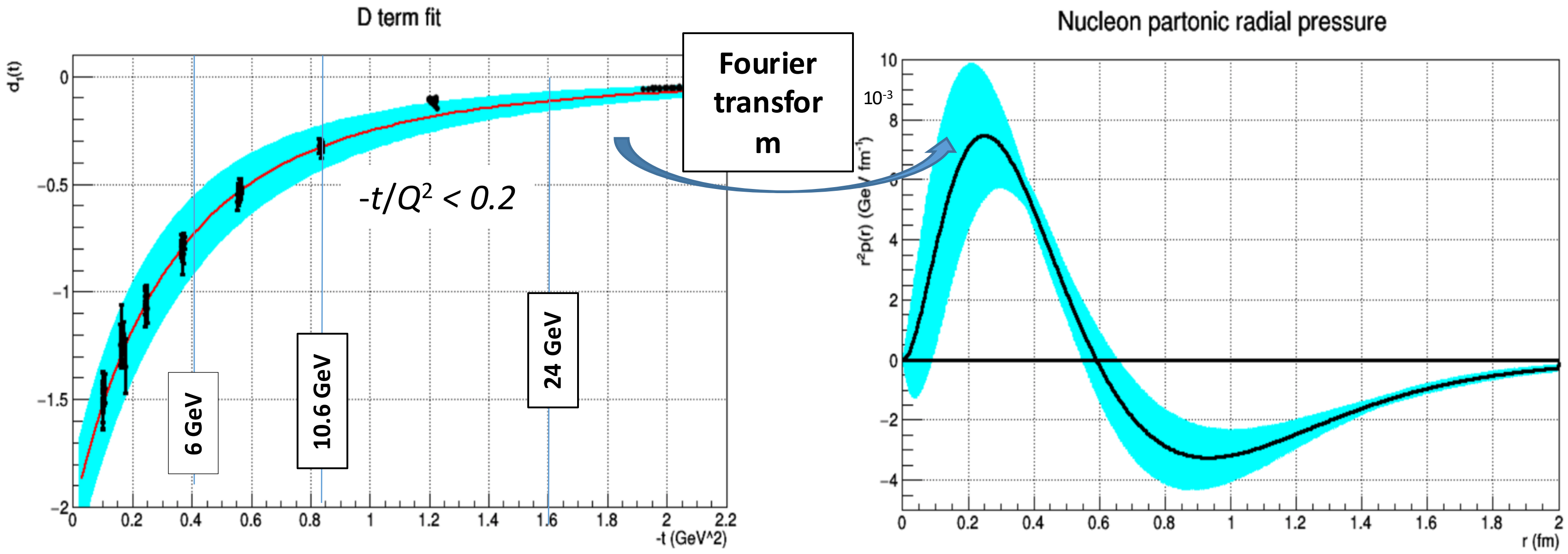
Statistical uncertainties : from 1 % (low Q^2) to 10 % (high Q^2)

Unprecedented statistics over the full ϕ range up to high $x = 0.6$



From GFF $D_q(t)$ to distribution of forces (pressure)

Fitting the dispersion relation to $\mathrm{Im}\mathcal{H}(\xi,t)$, $\mathrm{Re}\mathcal{H}(\xi,t)$



Fourier transform

$-t/Q^2 < 0.2$

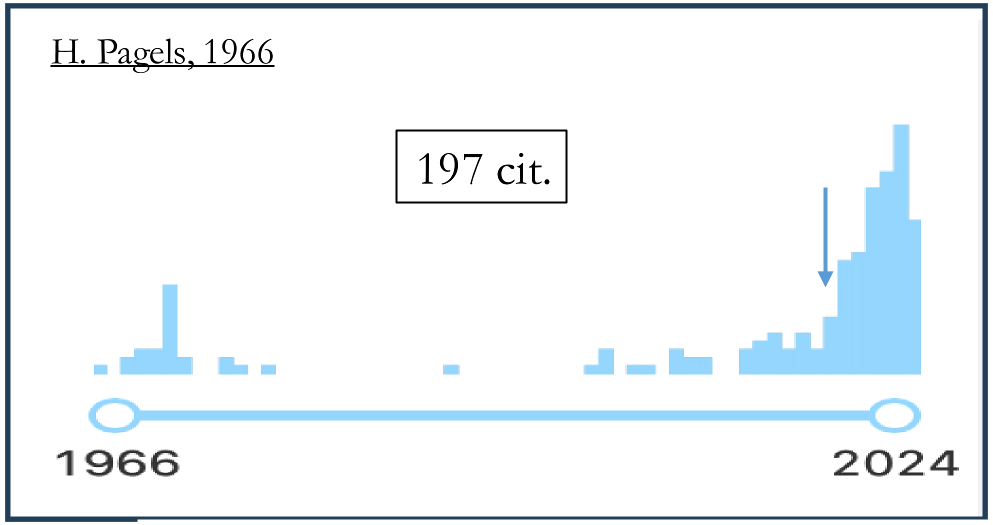
6 GeV

10.6 GeV

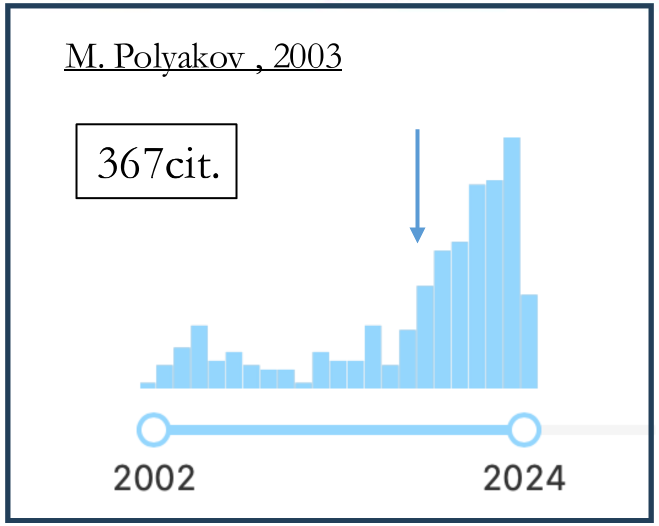
24 GeV

22 GeV required to cover sufficient range in t for extraction of mechanical properties.

Citations of theory papers on gravitational proton FF, and BEG results

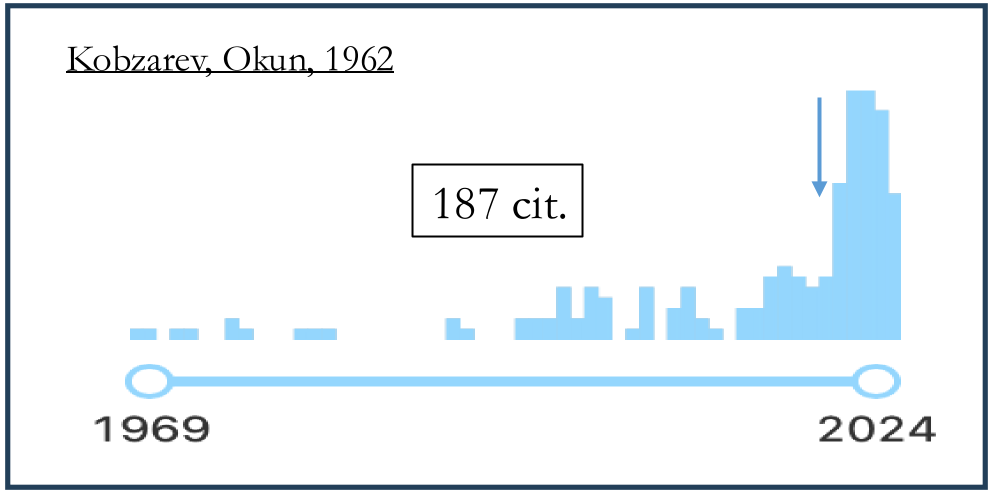

H. Pagels, 1966

197 cit.

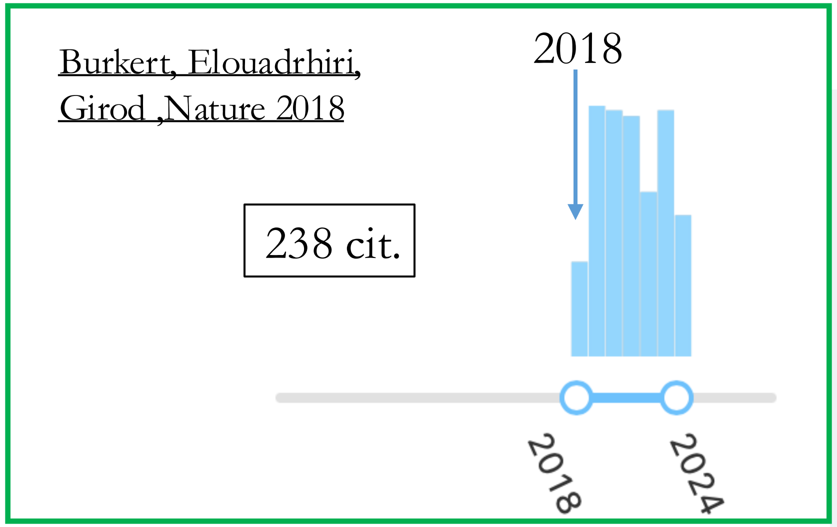

M. Polyakov , 2003

367cit.

A new direction in experimental nuclear/hadronic physics.


Kobzarev, Okun, 1962

187 cit.


Burkert, Elouadrhiri, Girod ,Nature 2018

2018

238 cit.

Summary and Outlook

- The first determination of the proton's Gravitational Form Factor DQ(t) marks a pioneering effort in extracting the internal pressure and force distributions within the proton.

- Utilizing new CLAS12 DVCS (Deeply Virtual Compton Scattering) data, this research expands the kinematic range and enables measurements across various beam energies, target types, and beam polarizations.

- This research program is a crucial component of the Jefferson Lab's 22 GeV and positron beam program.

- This work opens-up a new frontier in hadron physics.