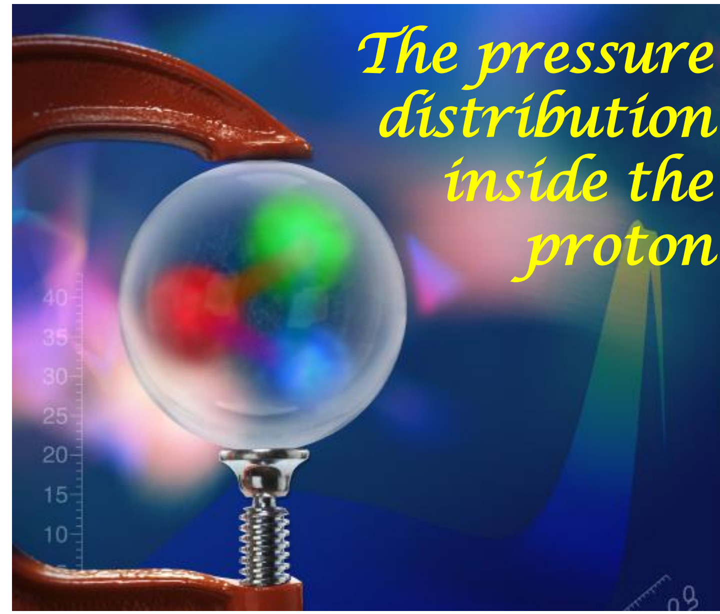
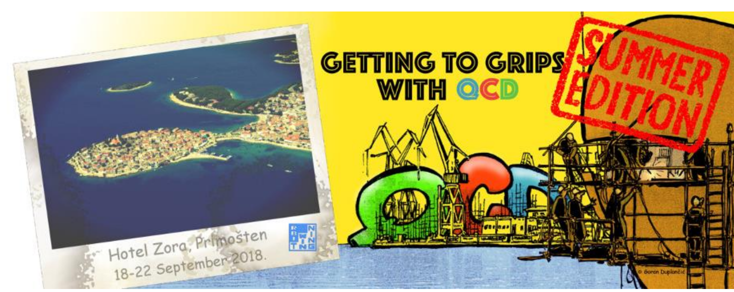
DVCS and the Gravitational Structure of the Proton

Hadron Physics Beyond 3-D Imaging

Volker Burkert
Jefferson Laboratory



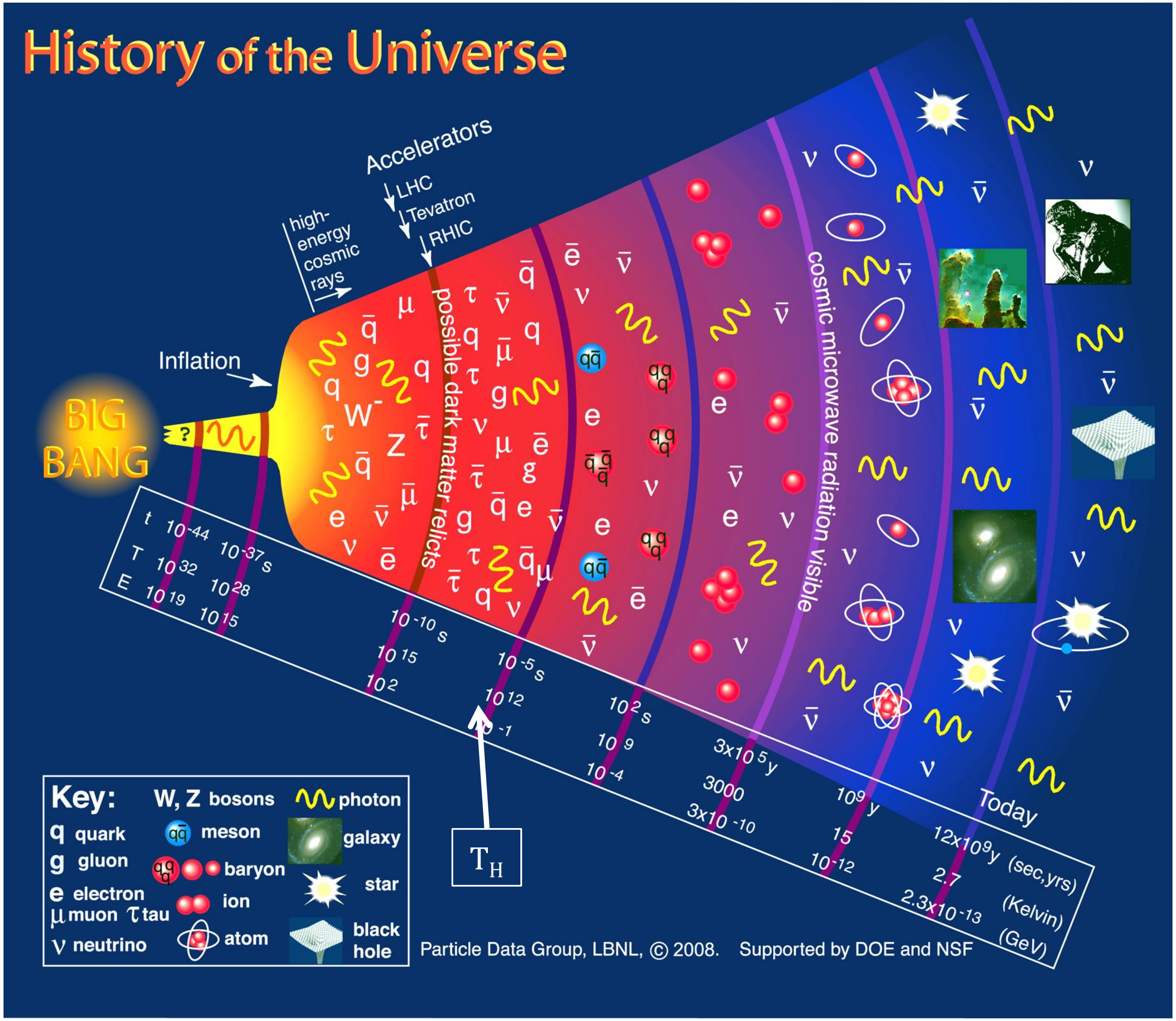


V.B., L. Elouadrhiri, F.X. Girod

Nature 557 (2018) no.7705, 396-399

9/22/2018

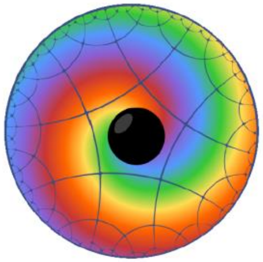
The emergence of confinement



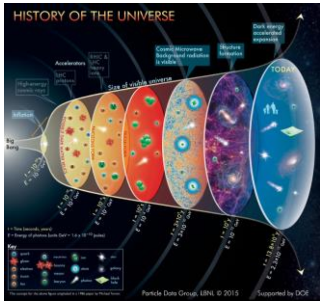
T_H

Basic questions about the proton

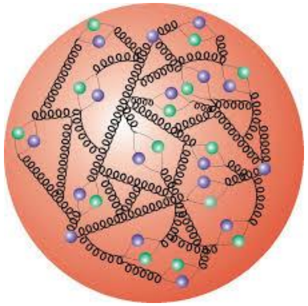
- Proton's make up nearly 90% of the (normal) matter in the universe. Elementary quarks contribute only few percent to the proton's mass. What is the origin of its mass?



- Quarks hadronize and form protons as the universe cooled below the Hagedorn temperature. What is the origin of confinement ?



- The strong interaction is thought responsible for confinement. How are the forces distributed in space to make the proton a stable particle.



Fundamental global properties of the proton

The structure of strongly interacting particles can be probed by means of the other fundamental forces: *electromagnetic*, *weak*, and *gravity*.

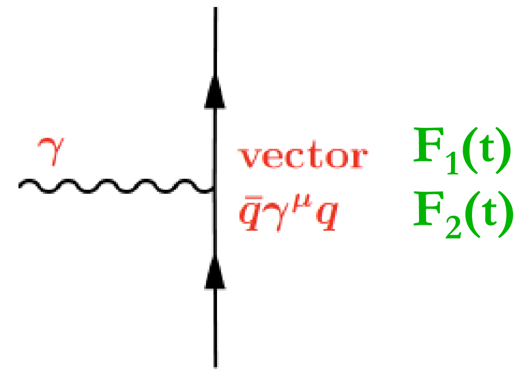
em:	$\partial_\mu J^\mu_{\text{em}} = 0$	$\langle N' \vert J^\mu_{\textbf{em}} \vert N \rangle$	$\longrightarrow$	Q_{prot}	$=$	$1.602176487(40) \times 10^{-19}\text{C}$
	vector			μ_{prot}	$=$	$2.792847356(23)\mu_N$
weak:	PCAC	$\langle N' \vert J^\mu_{\textbf{weak}} \vert N \rangle$	$\longrightarrow$	g_A	$=$	$1.2694(28)$
	axial			g_p	$=$	$8.06(0.55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\textbf{grav}} = 0$	$\langle N' \vert T^{\mu\nu}_{\textbf{grav}} \vert N \rangle$	$\longrightarrow$	M_{prot}	$=$	$938.272013(23)\,\text{MeV}/c^2$
				J	$=$	$\frac{1}{2}$
	tensor			D	$=$	?

P. Schweitzer et al., arXiv:1612.0672, 2016.

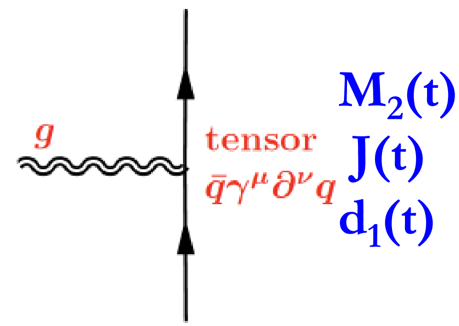
The D-term is the "last unknown global property" of the nucleon

Probing structure of the proton

- **Electromagnetic properties: probed with photons**
  - **Charge - electromagnetic form factors, inelastic structure functions, proton charge radius, charge and current densities.**
  - **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**



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

How to measure mechanical properties

Mass/weight

Shear stress

Angular momentum

Torque

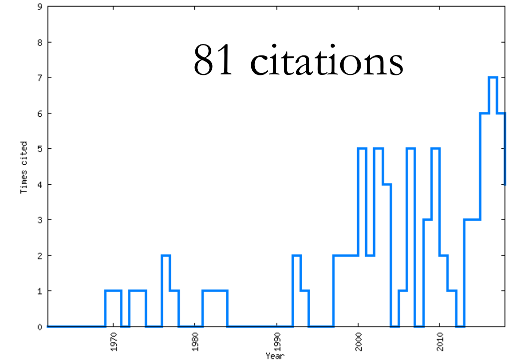
Pressure

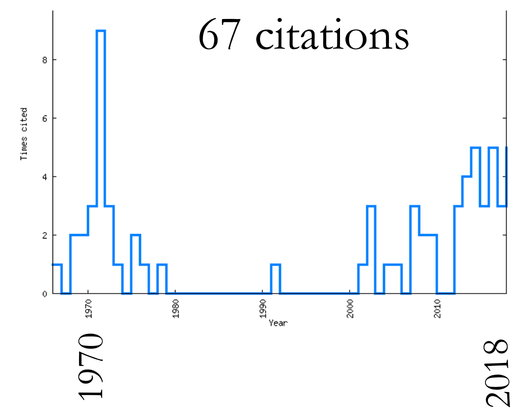
Probing mechanical properties of the proton?

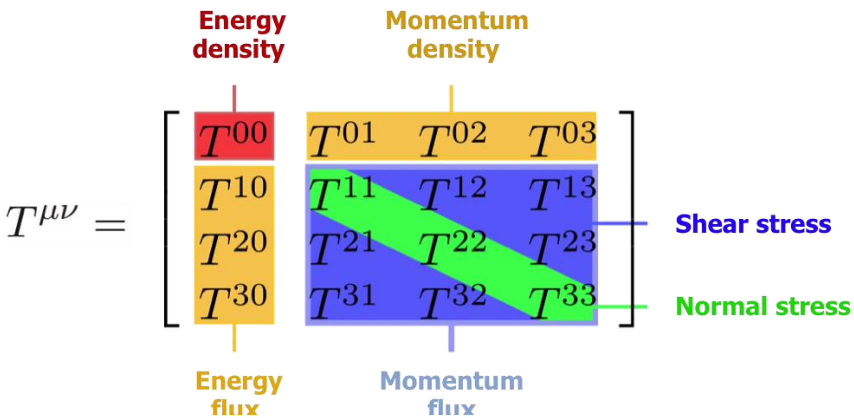
Gravitational Interaction of Fermions

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*







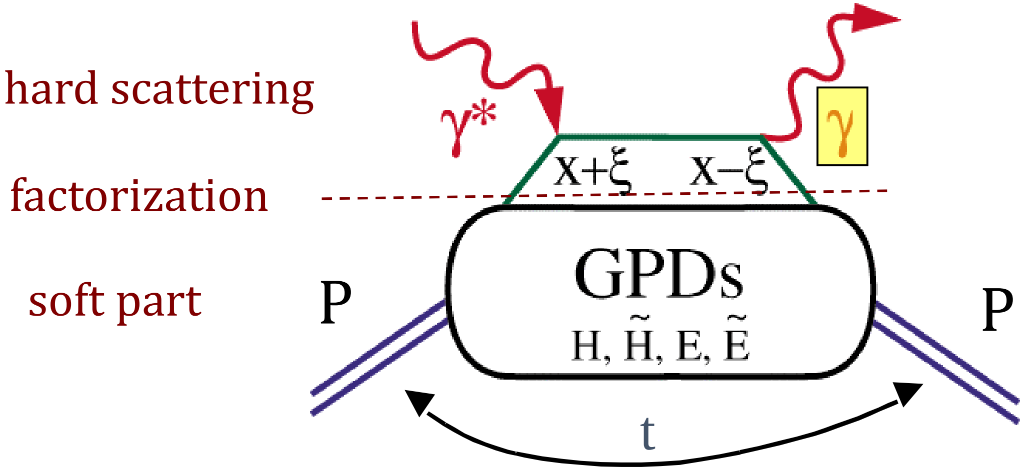
$$T_{ij}(\vec{r}\,) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\delta_{ij}\right) + p(r)\delta_{ij}$$

"….. , 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, 1966)*

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

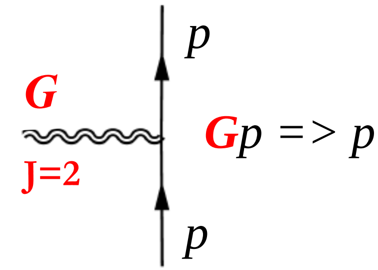
GPDs – GFFs Relations

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

Graviton – proton scattering

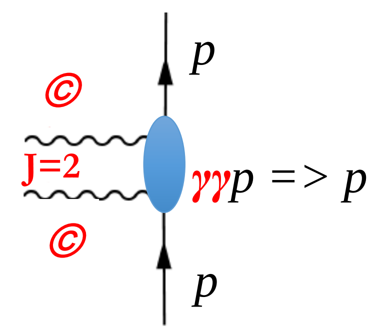


GPDs ⟺ *GFFs*

$$\int dx\, x\,[H(x,\xi,t)+E(x,\xi,t)] = 2J(t)$$

$$\int dx\, x H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t),$$

DVCS



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

GPD – GFF correspondence

Wikipedia:

"It can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field would couple to the stress–energy tensor in the same way that gravitational interactions do."

Except that the "spin-2" field from DVCS is many orders of magnitude stronger than gravitation.

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*.

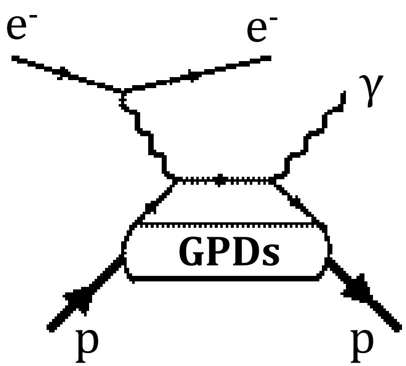
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx H(x,\xi,t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right)$$

To determine the complex CFF ***$\mathcal{H}(\xi, t)$*** we can exploit the interference of the DVCS amplitude with the Bethe-Heitler amplitude.

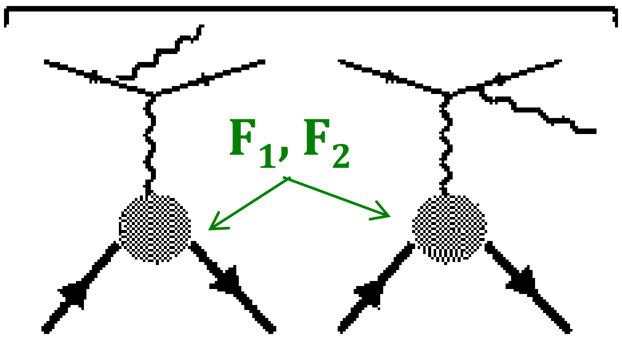
M. Polyakov, Phys. Lett. B555 (2003) 57

From GPD to GFF $d_1(t)$ to $p(r)$

DVCS



BH



F_1: Dirac FF; F_2: Pauli FF

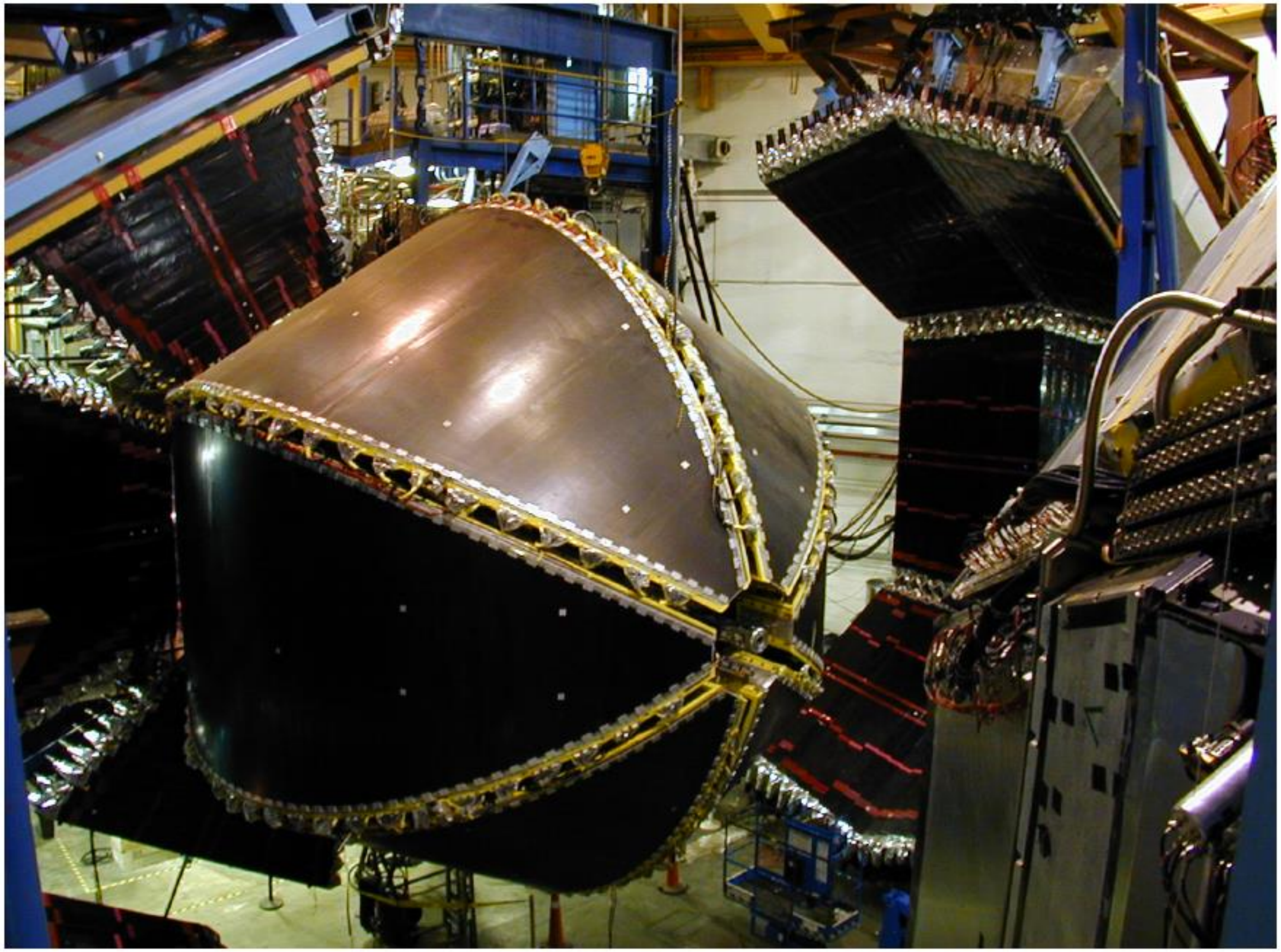
Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1 \mathcal{H} + ..\} \Rightarrow \mathcal{H}(\xi,t) \Rightarrow d_1(t)$$

Bessel Integral relates $d_1(t)$
to the radial pressure p(r).

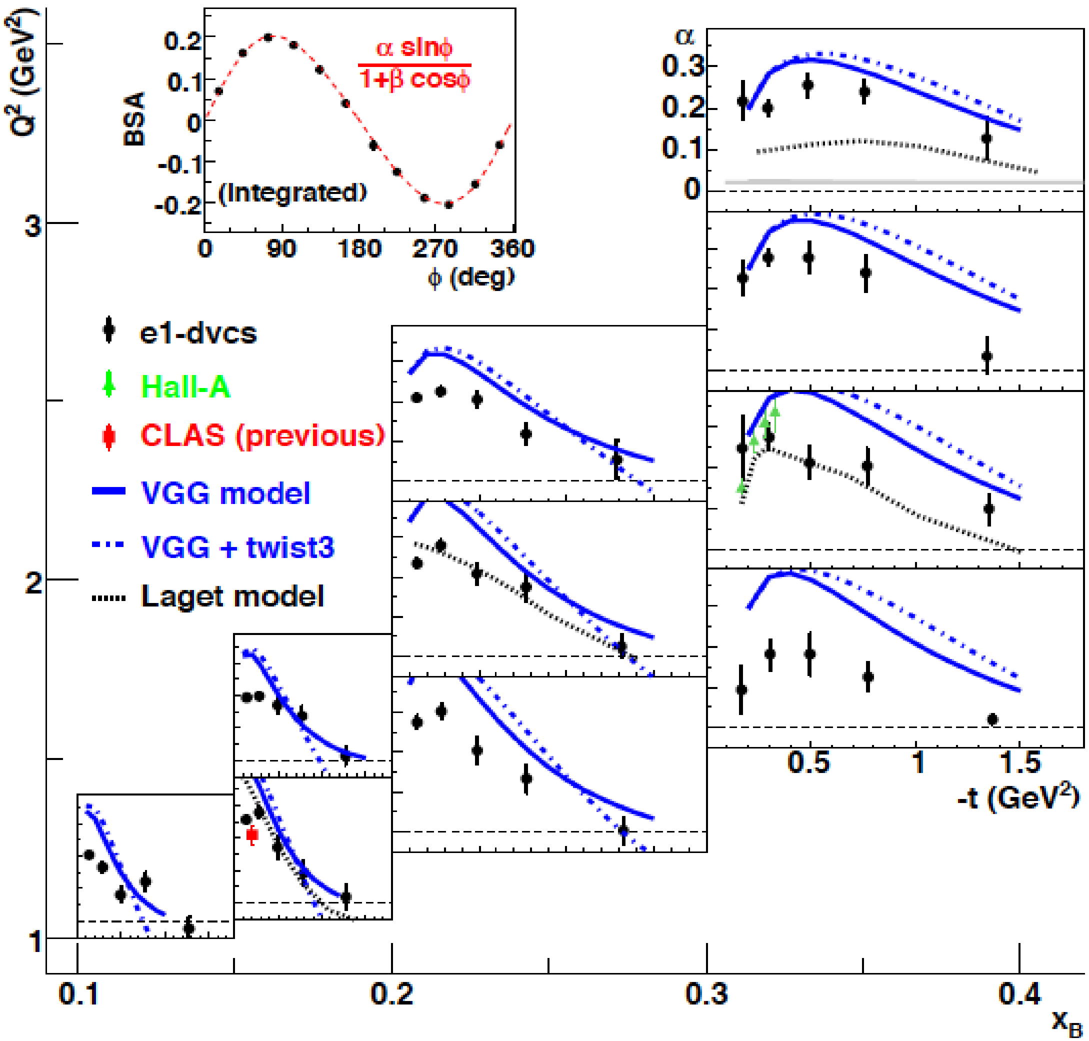
$$d_1(t) \propto \int d^3\mathbf{r} \, \frac{j_0(r\sqrt{-t})}{2t} \, p(r)$$

CLAS Experiment



In operation 1997 – 2012

DVCS Beam Spin Asymmetry

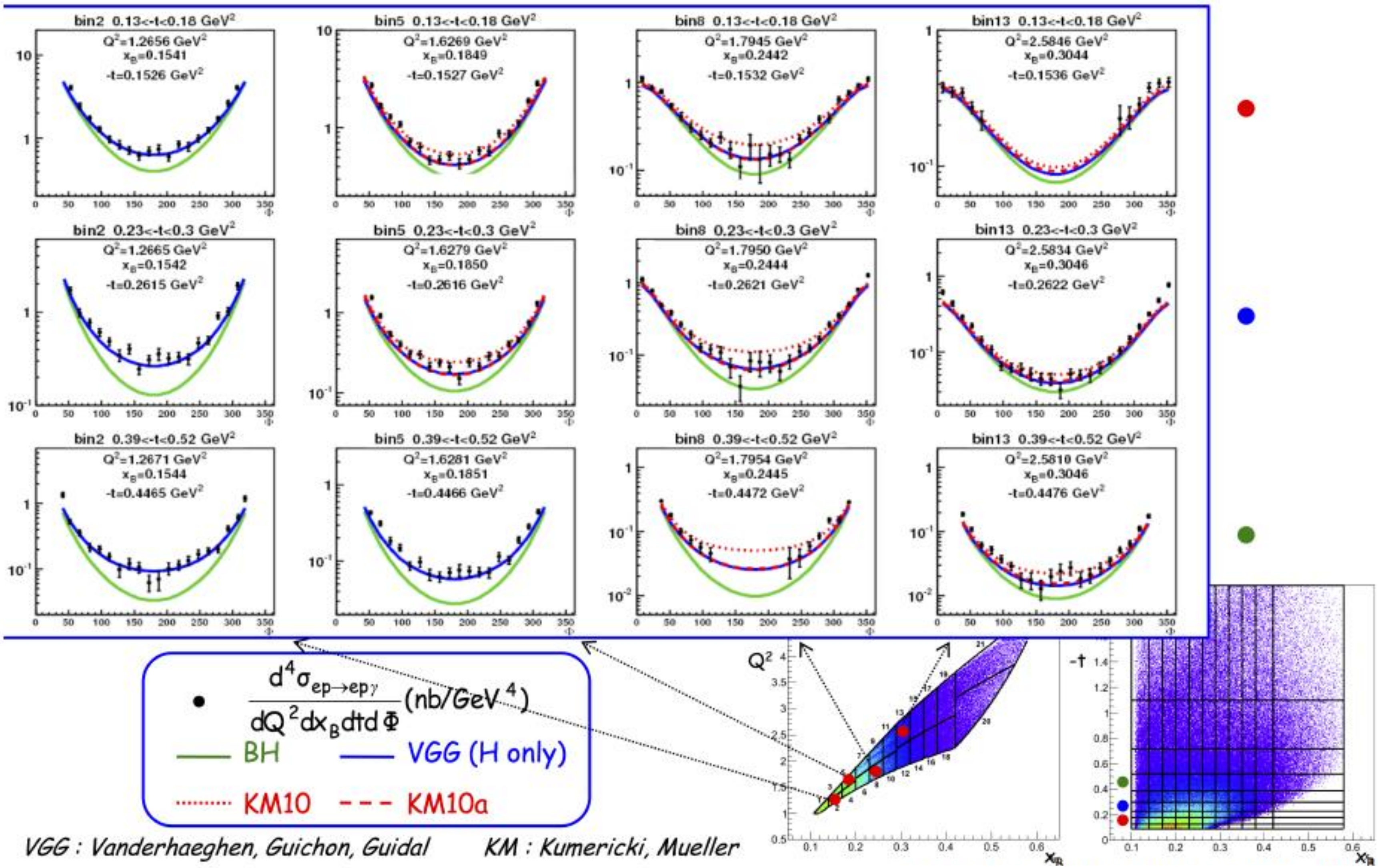


F.X. Girod et al., Phys.Rev.Lett. 100 162002 (2008)

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

Precision in a large phase space Q^2, x_B, t

DVCS Unpolarized Cross-Sections



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

Dispersion Relation Analysis and Global Fits

Compton Form Factor $\mathcal{H}$

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

Beam Spin Asymmetries

$$\mathrm{Im}\mathcal{H}(\xi,t) = \frac{r}{1+\xi}\left(\frac{2\xi}{1+\xi}\right)^{-\alpha(t)}\left(\frac{1-\xi}{1+\xi}\right)^{b}\left(\frac{1-\xi}{1+\xi}\frac{t}{M^2}\right)^{-1}$$

K. Kumericki, D. Müller, Nucl. Phys. B ***841,*** *1-58, 2010*
D. Müller, T. Lautenschlager, K, Passek-Kumericki, G. Schaefer, Nucl.B. 884, 438, 2014

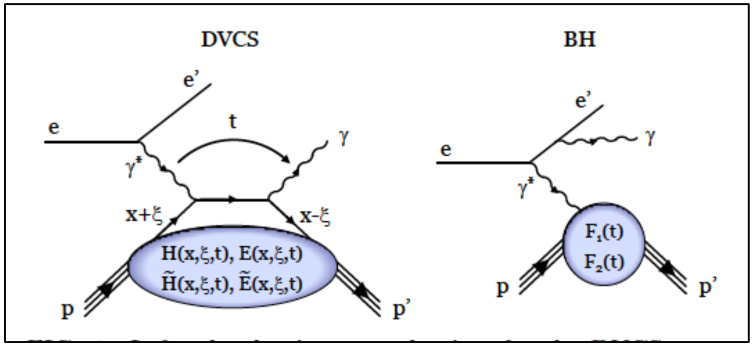
Unpolarized cross sections

Use Dispersion Relations:

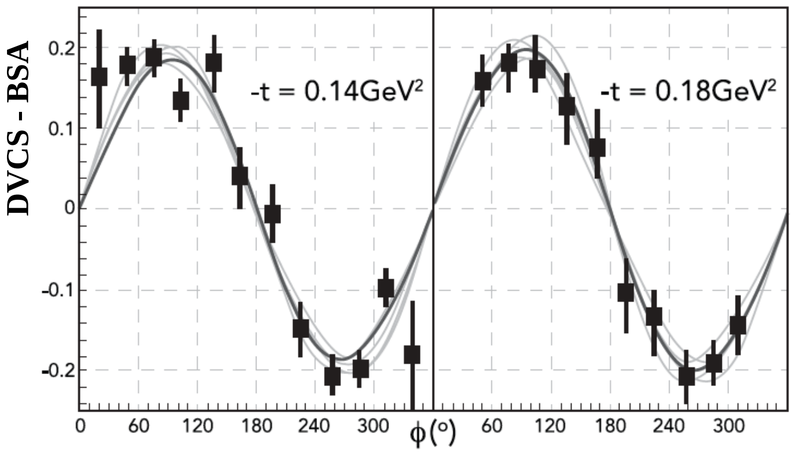
$$\mathrm{Re}\mathcal{H}(\xi,t) \overset{\mathrm{LO}}{=} D(t) + \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(x,t)$$

M. Polyakov , C. Weiss, Phys.Rev. D60 (1999) 114017

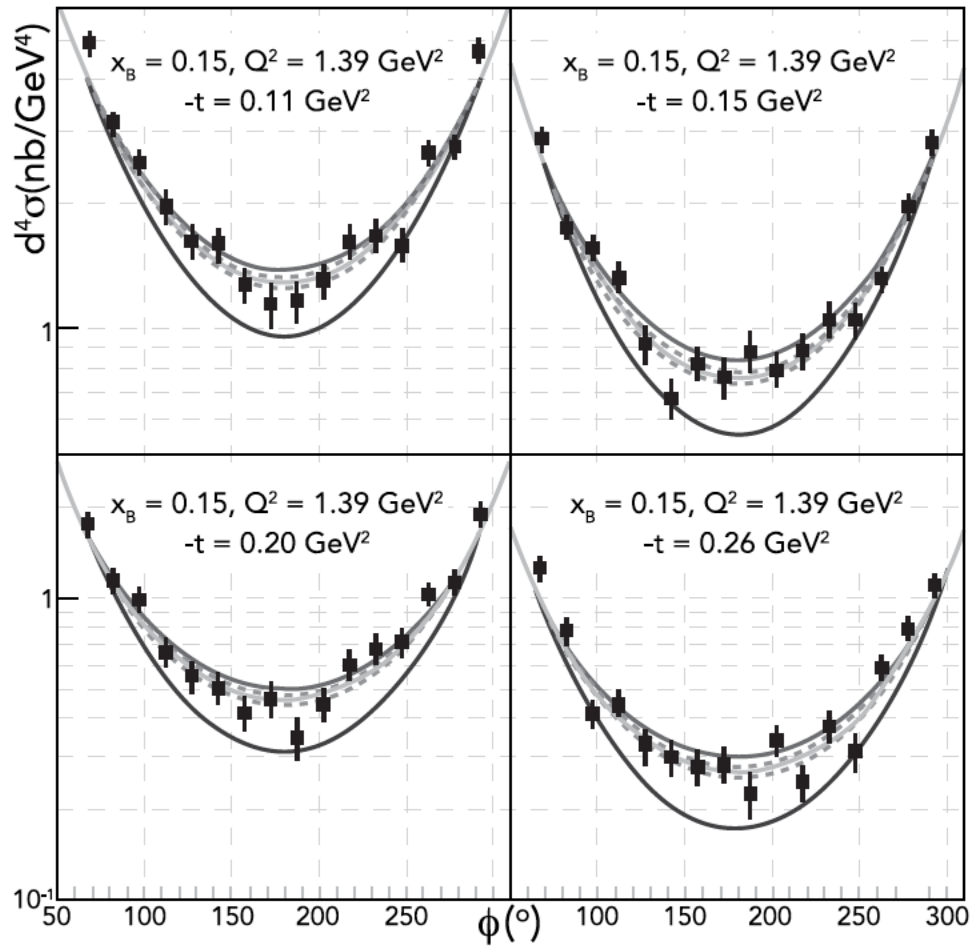
Fit to DVCS data to determine *D*-Term



Samples of Beam Spin Asymmetry

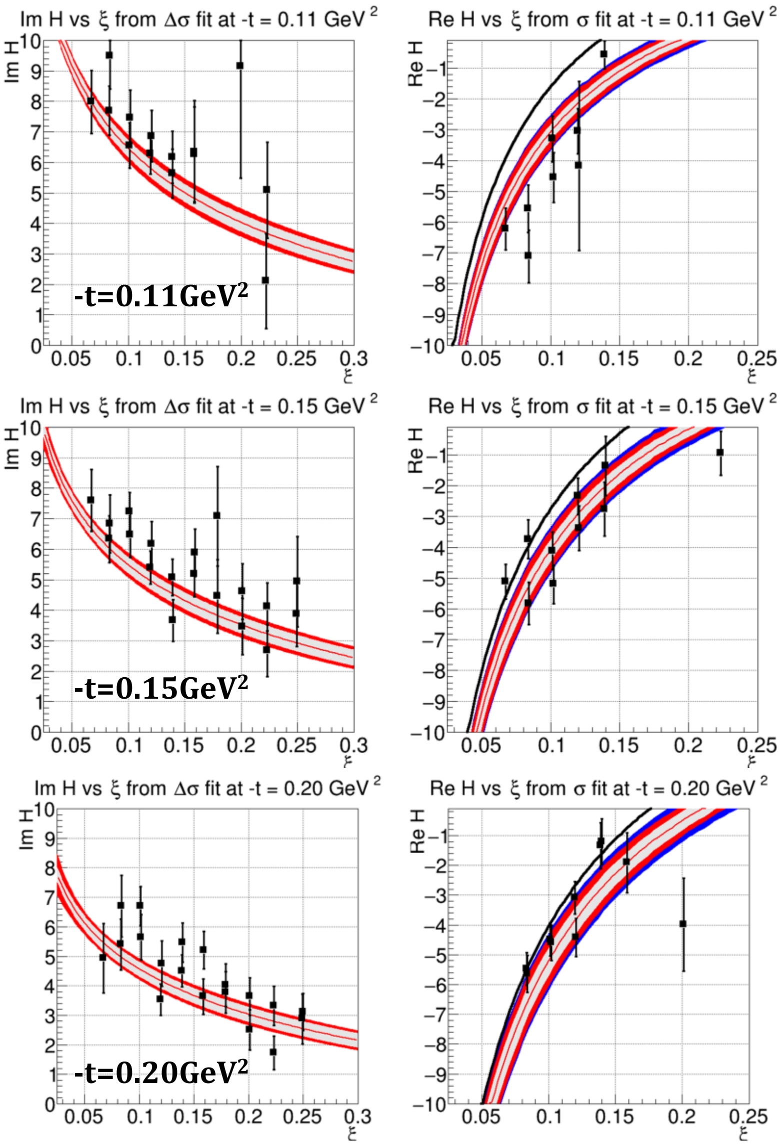


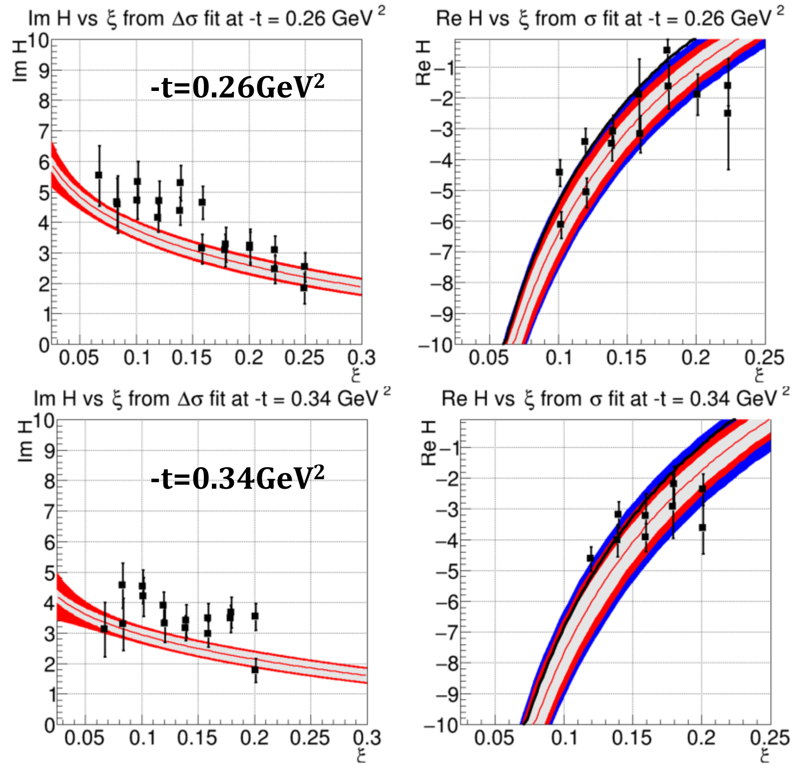
Samples of differential cross sections with fits



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

Extraction of Compton Form Factor $\mathcal{H}(\xi,t)$

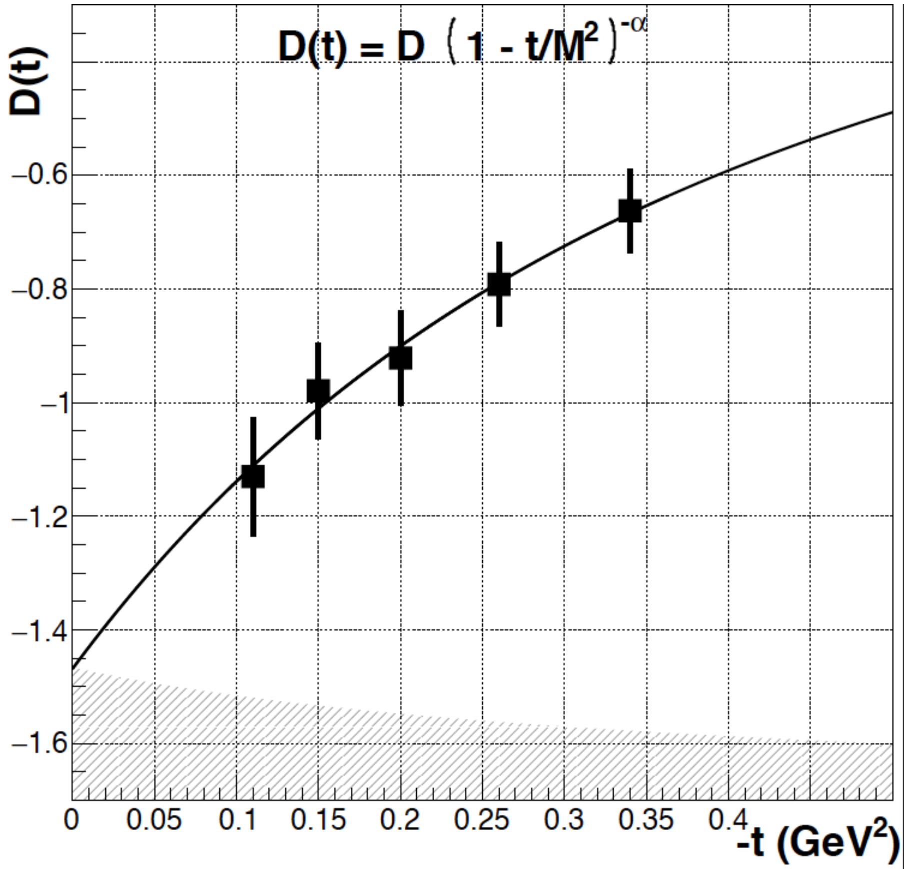




The Real and Imaginary parts of Compton FF $\mathcal{H}(\xi,t)$ for different ξ and t values, resulting from the fit to the BSA and cross section data.

Extraction of $D^q(t)$ for quark distribution

$D^Q(t)$ from CLAS 6 GeV data



$D^Q(0) = -1.47 \pm 0.10 \pm 0.24$

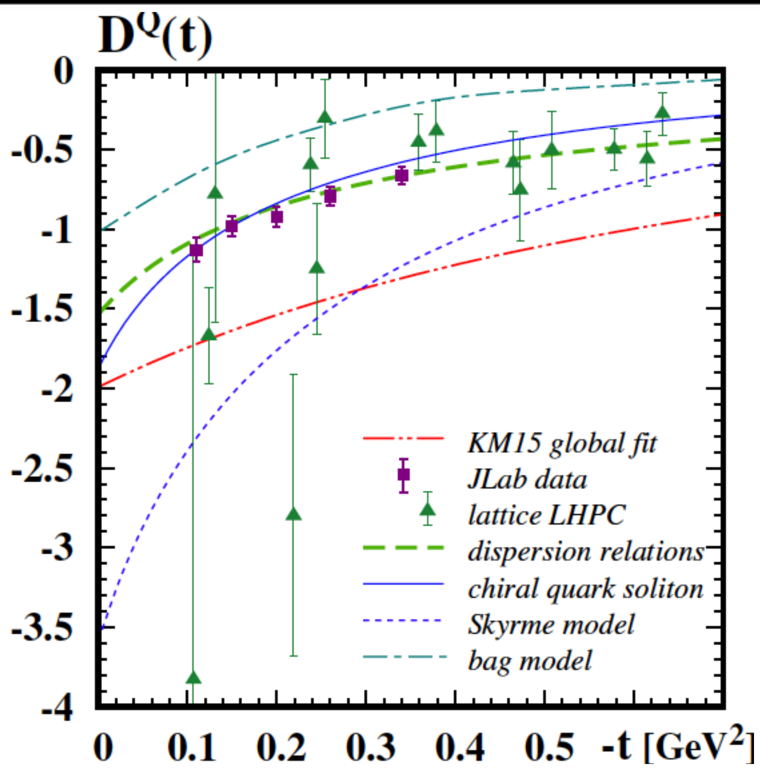
$M^2 = 1.06 \pm 0.10 \pm 0.15$

$\alpha = 2.76 \pm 0.25 \pm 0.50$

How about gluons?

Expect LQCD results for $D^G(t)$ this week. (Phiala Shanahan)

Comparison of $D^Q(t)$ with models



- Chiral Quark Soliton Model
- Dispersion Relations, normalized at t=0.
- Lattice QCD LHPC, no disconnected diagrams
- Global fit – *K.L.M. EPJ A52 (2016) 6 , 157*

M.V. Polyakov, P. Schweitzer
arXiv:1805.06596

em:	$\partial_\mu J^\mu_{\rm em} = 0$	$\langle N' \vert J^\mu_{\rm em} \vert N\rangle$	$\longrightarrow$	$Q = 1.602176487(40) \times 10^{-19}\,\mathrm{C}$
				$\mu = 2.792847356(23)\mu_N$
weak:	PCAC	$\langle N' \vert J^\mu_{\rm weak} \vert N\rangle$	$\longrightarrow$	$g_A = 1.2694(28)$
				$g_p = 8.06(55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\rm grav} = 0$	$\langle N' \vert T^{\mu\nu}_{\rm grav} \vert N\rangle$	$\longrightarrow$	$m = 938.272013(23)\,\mathrm{MeV}/c^2$
				$J = \frac{1}{2}$
				$D = ?$

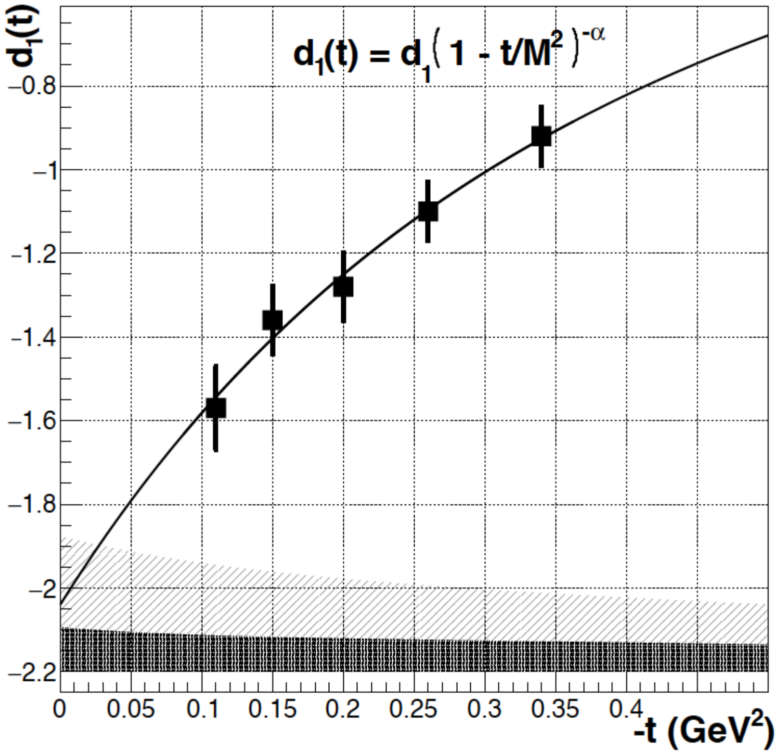
$d^Q_1(t)$ - Gravitational Form Factor

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

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

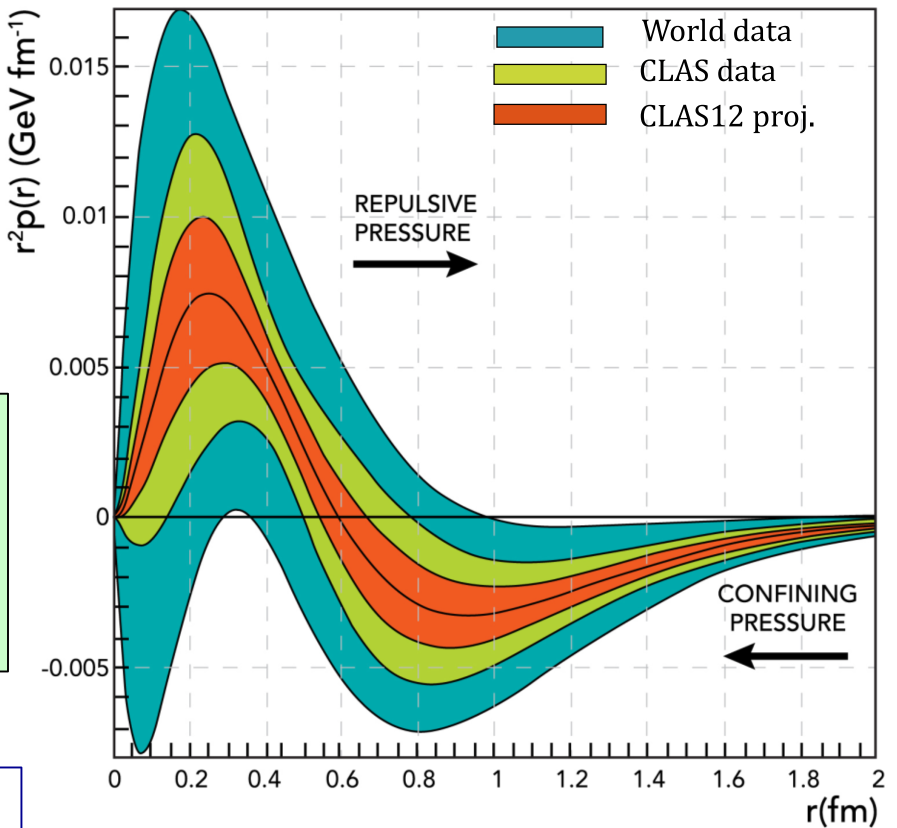
First determination of new fundamental quantity.

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
(in χQSM due to the pion field)

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



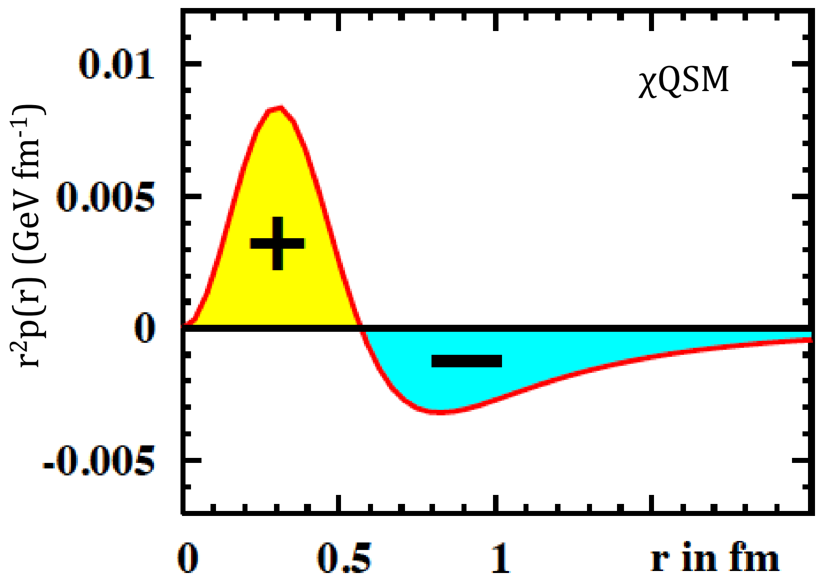
V.B., L. Elouadrhiri, F.X. Girod
Nature 557 (2018) no.7705, 396-399

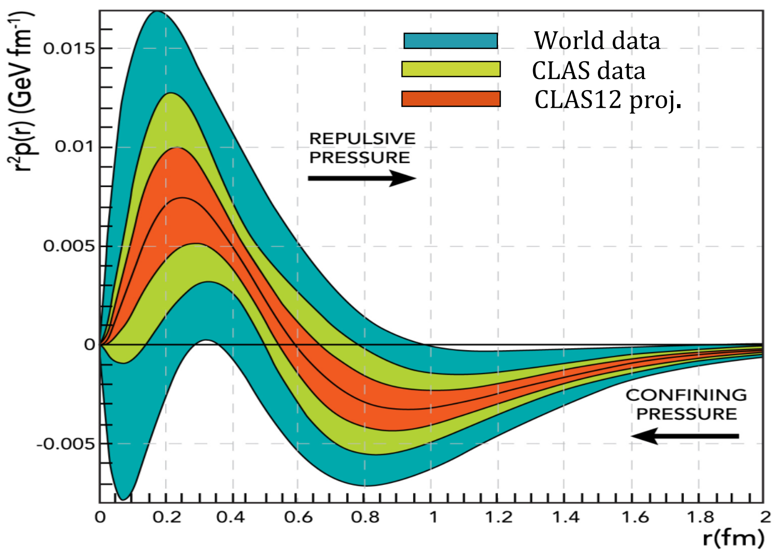
A new direction in experimental nuclear/hadronic physics.

Comparison with χQSM

- Gravitational form factors may be computed in Lattice QCD. No results exist for *p(r)*.
- In the chiral quark-soliton model (χQSM) the proton is modeled as a chiral soliton with the constituent quarks bound by a self-consistent pion field.

K. Goeke, M. Polyakov, ...,Phys.Rev. D75 (2007) 094021





The $d_1(t=0) < 0$ is rooted in the spontaneous chiral symmetry breaking (χSB).
In the χQSM the pion field provides the confining pressure at the proton's periphery.

CLAS12 GPD program

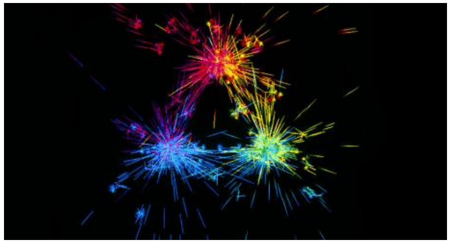
Number	Title	Contact	Days	Energy	Target
E12-06-108	Hard Exclusive Electroproduction of π^0 and η	Kubarovski	80	11	lH_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	80	11	lH_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	120	11	NH_3
E12-11-003	DVCS on Neutron Target	Niccolai	90	11	lD_2
E12-12-001	Timelike Compton Scat. & J/Ψ prod. in e^+e^-	Nadel-Turonski	120	11	lH_2
E12-12-007	Exclusive ϕ meson electroproduction	FXG	60	11	lH_2
C12-12-010	DVCS with a transverse target	Elouadrhiri	110	11	HD-ice
E12-16-010	DVCS with CLAS12 at 6.6 GeV and 8.8 GeV	Elouadrhiri	50+50	6.6 & 8.8	lH_2

Summary and Outlook

- A new perspective on experimental exclusive reaction physics
- **First determination of the proton Gravitational Form Factor $D^Q(t)$**
- Opens a new avenue to test Confinement Mechanism
- Access the Partonic Energy Momentum Tensor
- New published DVCS data double the t-range
- Exciting times at the beginning of the 12 GeV high precision era
- Will be essential part of the EIC program as well

A lots of responses from News outlets

Just one example:



ScienceNews

https://www.sciencenews.org/

.. the proton's internal pressure distribution has been a largely unexplored frontier, even though pressure is one of the proton's fundamental properties. **"It's as important as electric charge or mass," says physicist Peter Schweitzer of the University of Connecticut** in Storrs, but was unknown until now.

This pressure pattern parallels what happens in much larger objects: **"In some sense, it's looking like a star," says physicist Oleg Teryaev of the Joint Institute for Nuclear Research in Dubna,** Russia. Stars also have pressures that push outward in their centers, which counteract the inward pull of gravity.

Protons are held together by the strong force, just as stars are held together by gravity. But the tiny protons are a different beast**. So "it's natural, but it's not completely trivial" that the two objects would have similarities pressure-wise, Teryaev says.**