The gravitational structure of the proton

A new direction of experimental hadron physics

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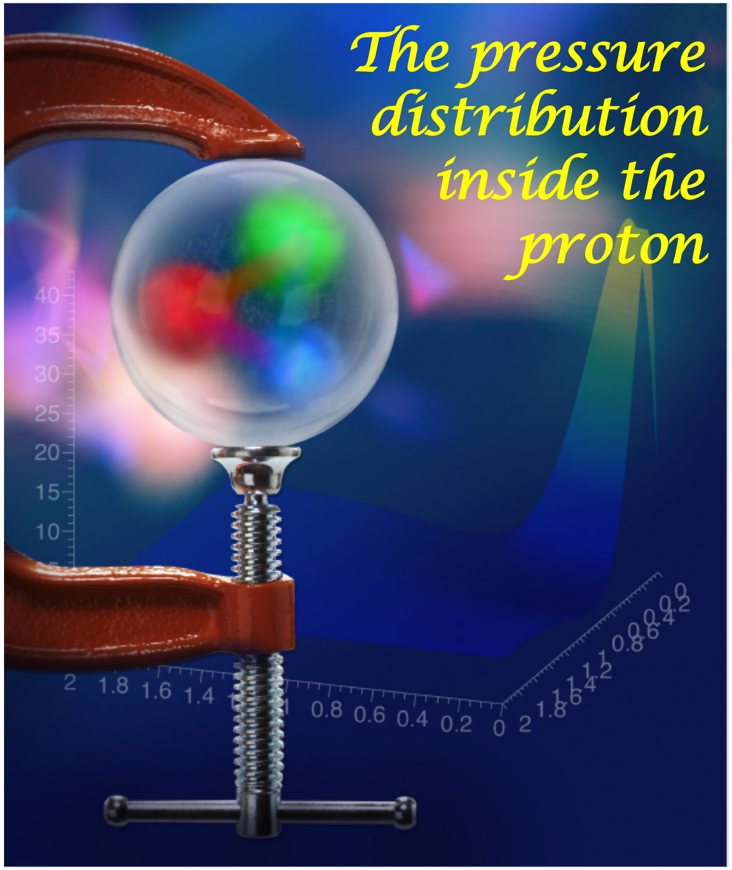
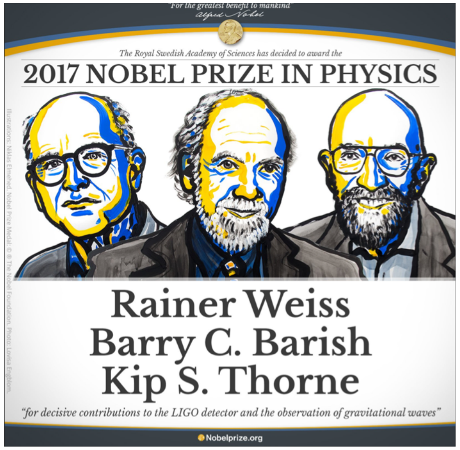


Gravitational waves observed

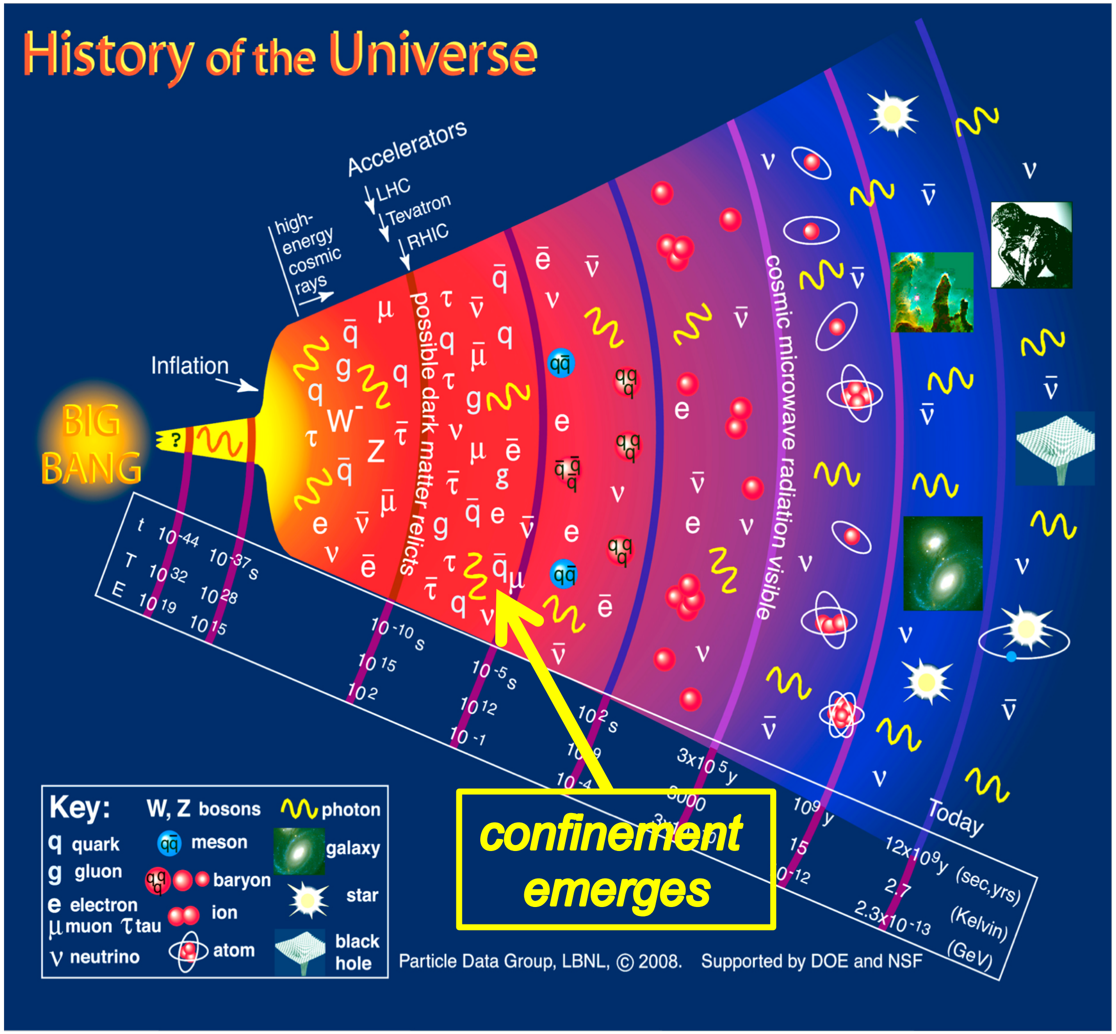


- Gravity governs movements of massive structures in the universe.
- Plays a decisive role in neutron stars leading to the most densely packed macroscopic objects in the universe.

The merger of two neutron stars generated gravitational waves that told us much about the equation-of-state of the neutron stars themselves.

Can we use gravitational waves to probe the interior of the proton and the distribution of the strong force?

The strong interaction is born



Crossover from the QGP phase to the hadron phase occurs just micro-seconds after the Big Bang

- chiral symmetry is broken
- quarks acquire dynamical mass
- confinement becomes manifest

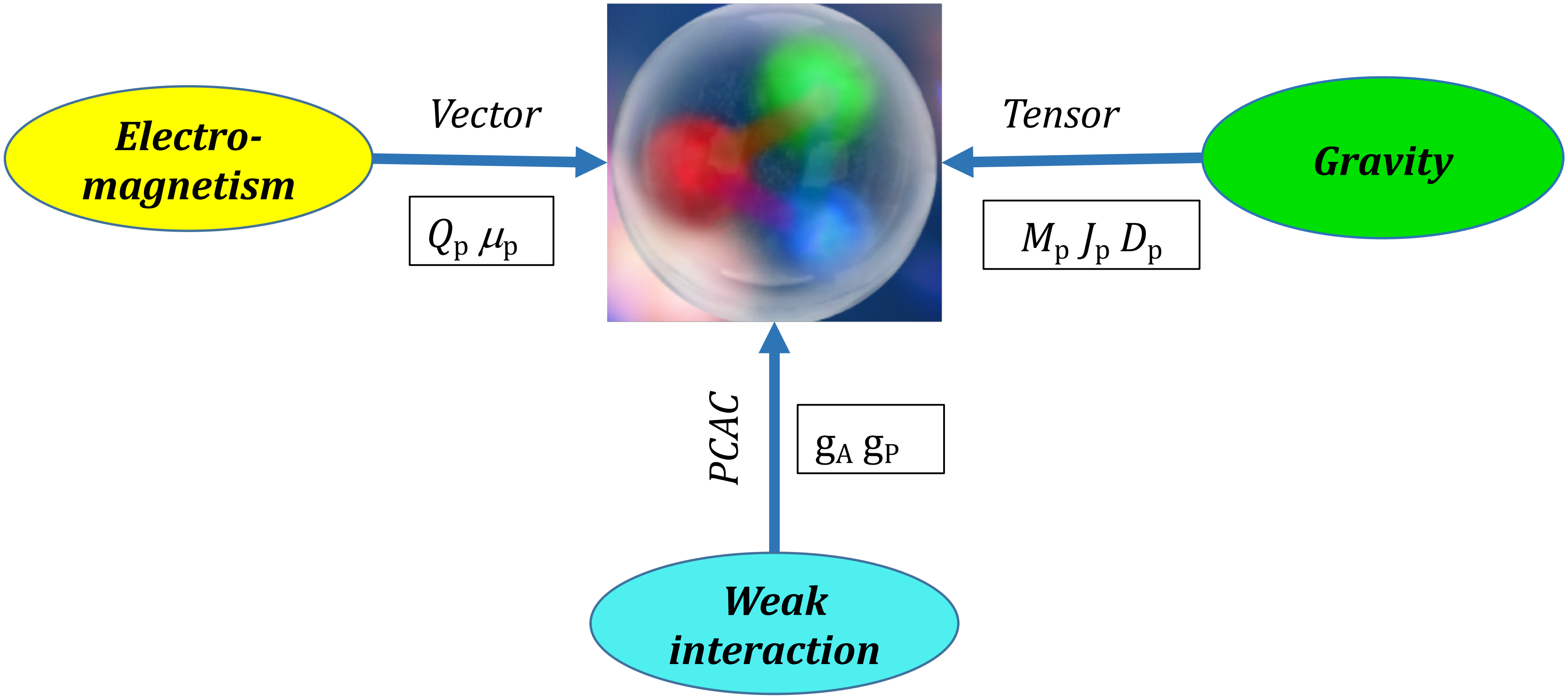
Hadrons (ground state or excited) emerge during this "cross over" period.

The proton emerges as the most fundamental bound-state in nature.

It is the most suitable object to study the intrinsic forces.

Probing properties of the proton

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



Fundamental properties of the proton

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

The PDG edition of 2018 does not have an entry for the *D*-term

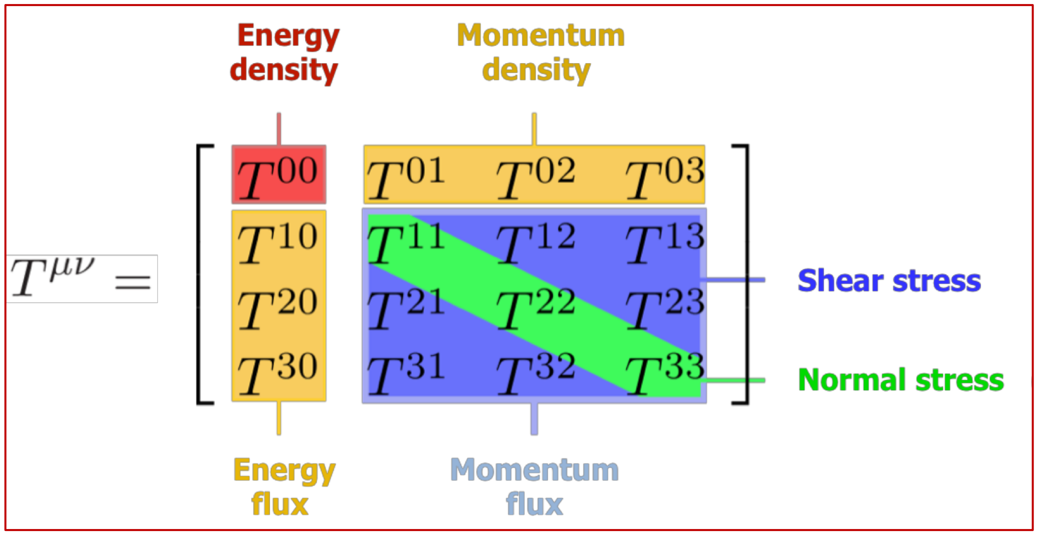
The *D*-term is the last unknown fundamental global property of the proton

How can we obtain any information about this property of the proton?

Gravitational 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
H. Pagels, Phys. Rev. 144 (1966) 1250-1260



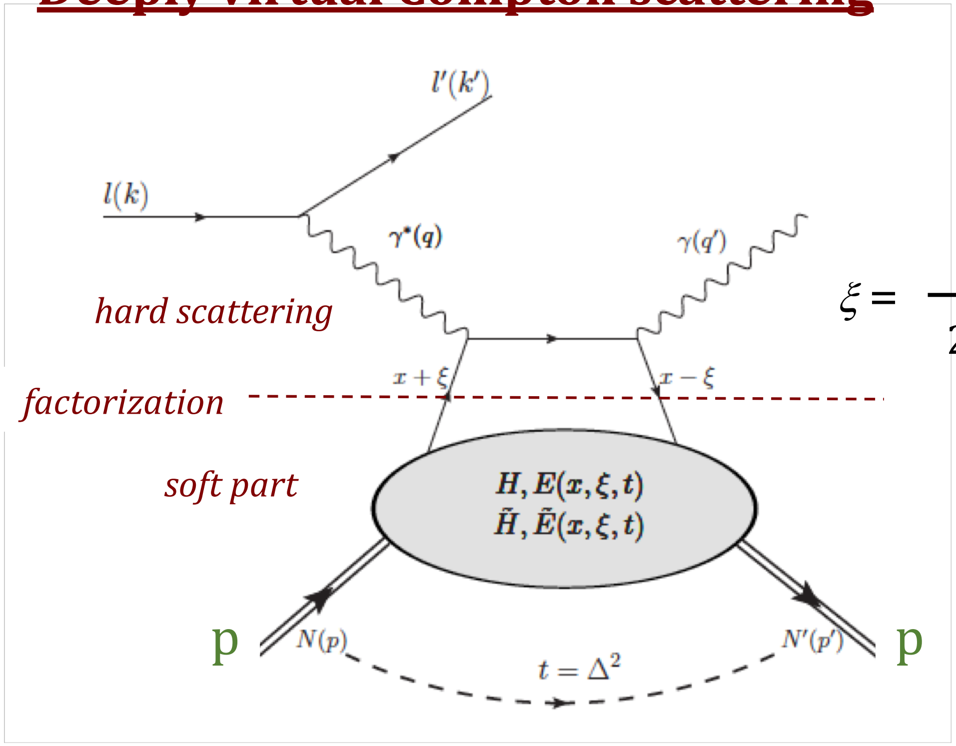
$$T_{ij}(\vec{r}\,) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\delta_{ij}\right) + p(r)\delta_{ij}$$

"….. , 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)*

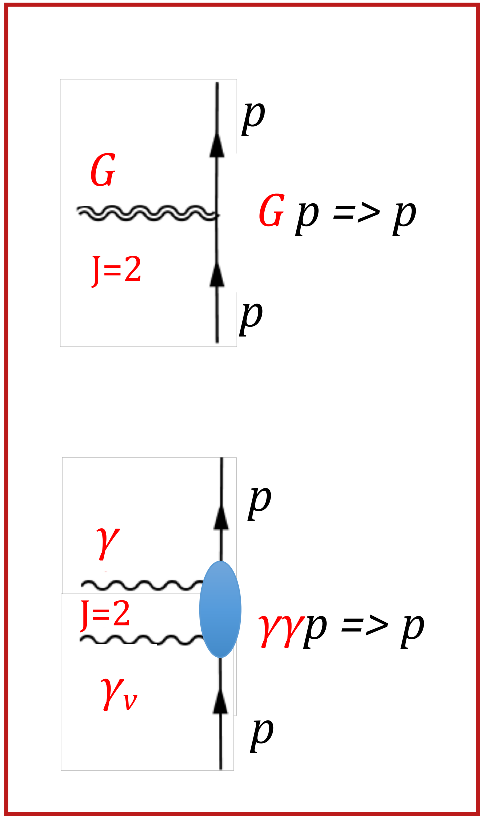
Generalized Parton Distributions (GPDs)

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

Deeply virtual Compton scattering



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



As the e.m. coupling is many orders of magnitude stronger than gravitation makes the DVCS process accessible in experiments.

GPDs – GFFs Relations

Proton matrix element of the Energy-Momentum Tensor contains three gravitational form factors (GFF) and can be written as:

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

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

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

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

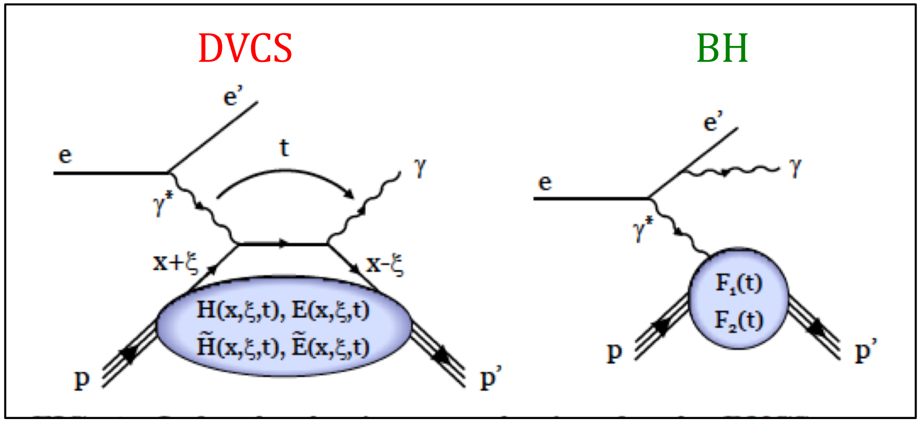
$$\int dx\, x H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t),$$

- GPDs not directly measurable from available DVCS data alone

GPDs & Compton Form Factors (CFF)

- We can determine the Compton Form Factor $\mathcal{H}(\xi, t)$ through an integral over the quark longitudinal momentum fraction *x*.

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



Polarized beam:

$$\boxed{\Delta\sigma_{LU} \sim \mathrm{Im}\{F_1 \mathcal{H}(\xi,t) + \ldots\}}$$

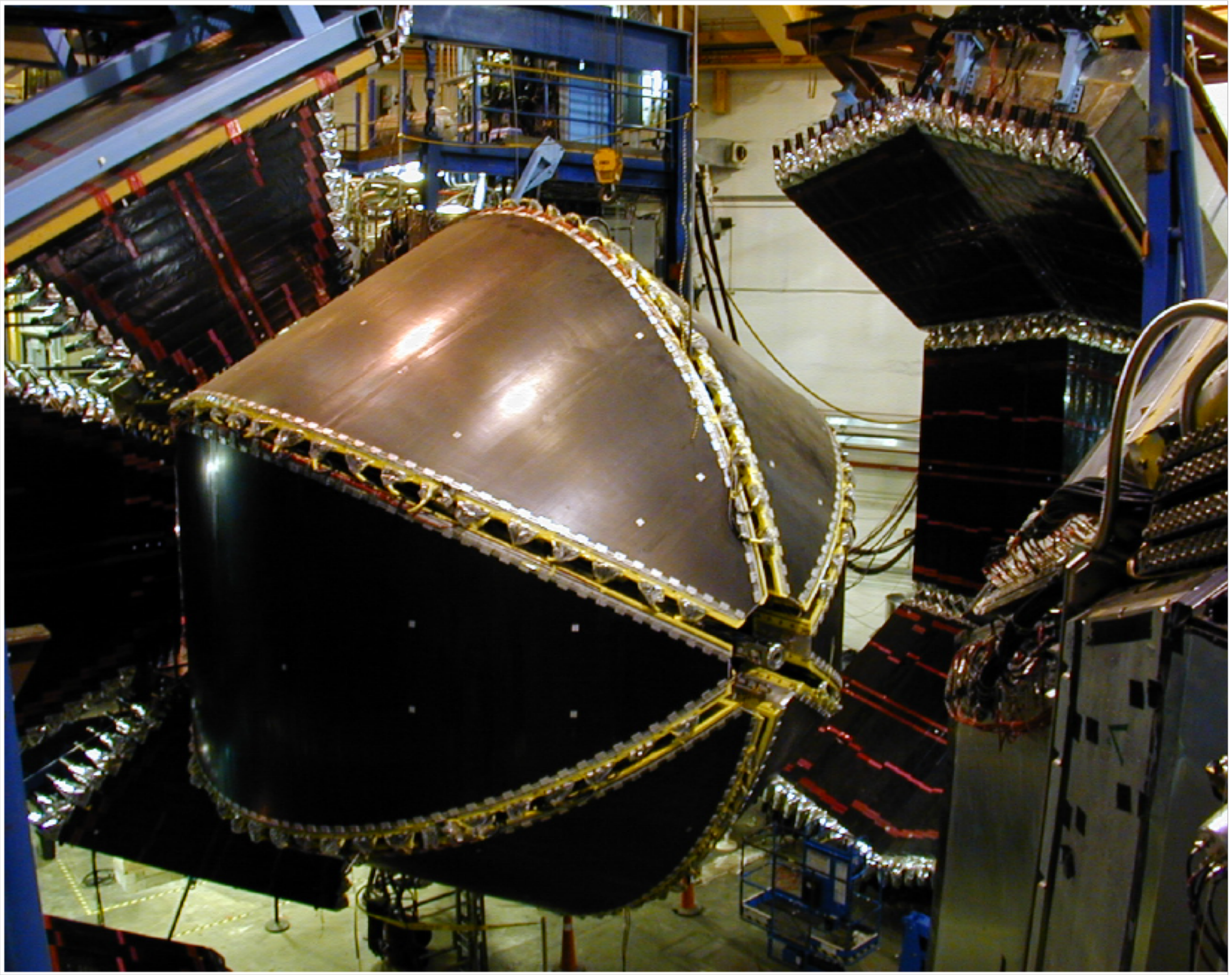
Unpolarized beam:

$$\boxed{d\sigma_U/dx_B dt \sim \{\mathrm{Re}\mathcal{H}(\xi,t) + \ldots\}}$$

$\Rightarrow$ $\mathcal{H}(\xi,t)$ $\Rightarrow$ $d_1(t)$

First suggestion to determine pressure and shear forces in hard exclusive processes.

The CLAS Detector (JLab)

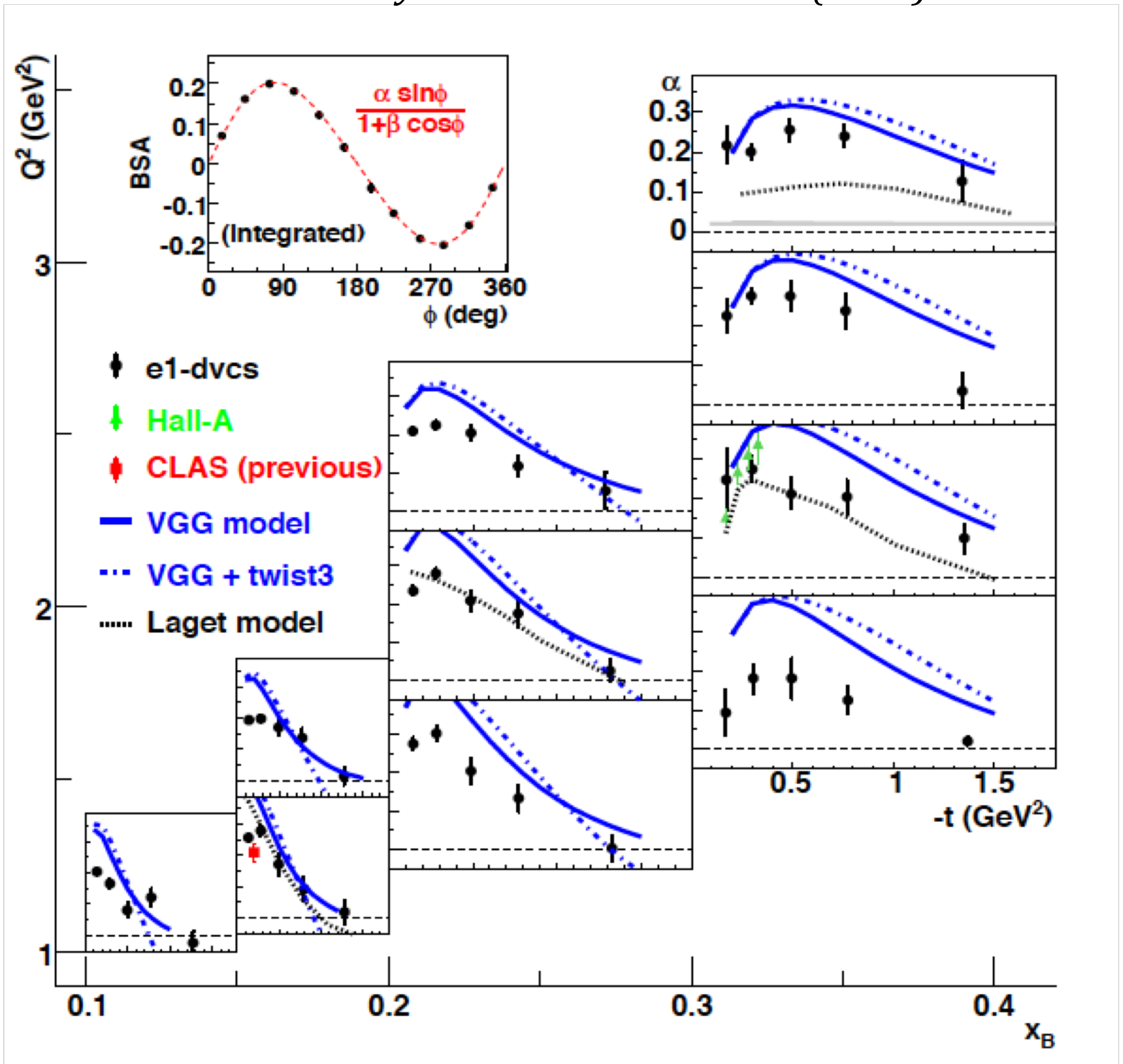


In operation from 1997 to 2012

- ✓ Large acceptance
- ✓ Good resolution
- ✓ Particle identification

DVCS Beam Spin Asymmetry

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



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

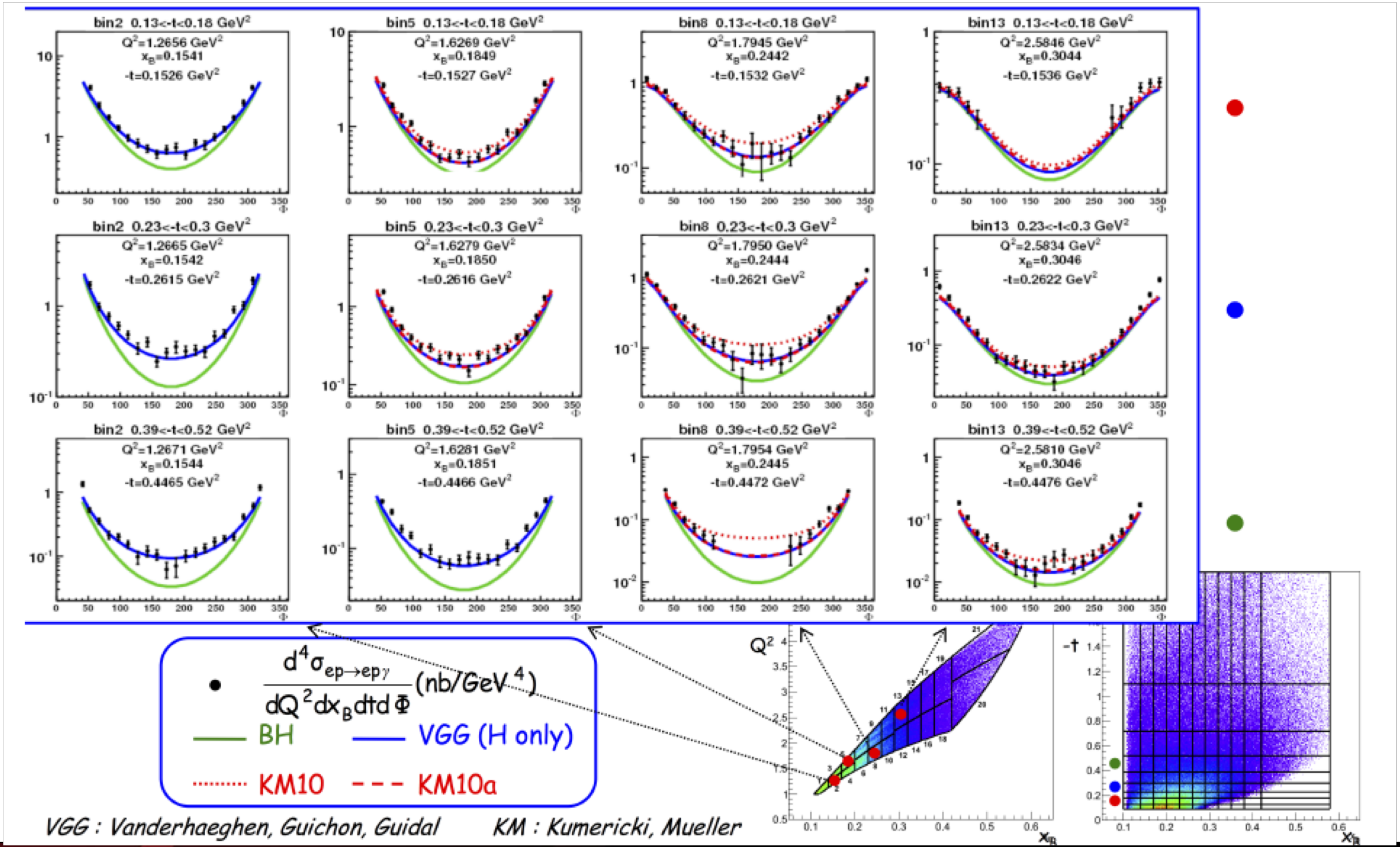
$$A = \frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{d^4\vec{\sigma} + d^4\overleftarrow{\sigma}}$$

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

small & suppressed

DVCS Unpolarized Cross-Sections

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



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

Extract CFF $\mathcal{H}(\xi,t)$ in Fits

Direct method: Extract CFF $\mathcal{H}$ directly in all ξ and t bins from the data

Step: 1 Fit global parameterization of BSA to determine Im$\mathcal{H}$

Step: 2 Fit differential DVCS cross sections to determine Re$\mathcal{H}$

*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

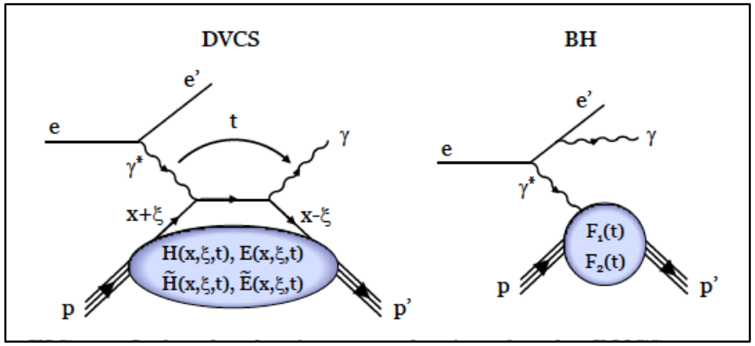
Step: 3 Use subtracted fixed-t dispersion relation to determine $D(t)$

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

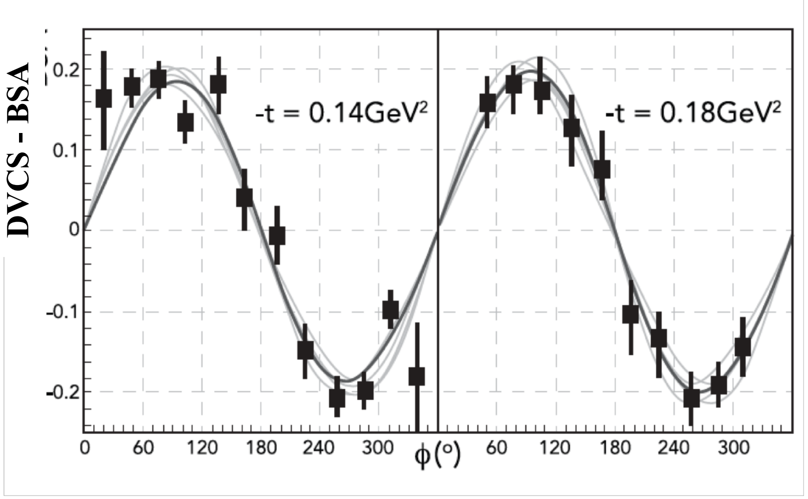
M. Polyakov: conjecture that subtraction term is related to the gravitational form factor $D^Q(t)$

I.V. Anikin and O.V. Teryaev, Phys.Rev.D76, 056007 (2007)
M. Diehl and D.Y. Ivanov, Eur. Phys. J. C52, 919, (2007)

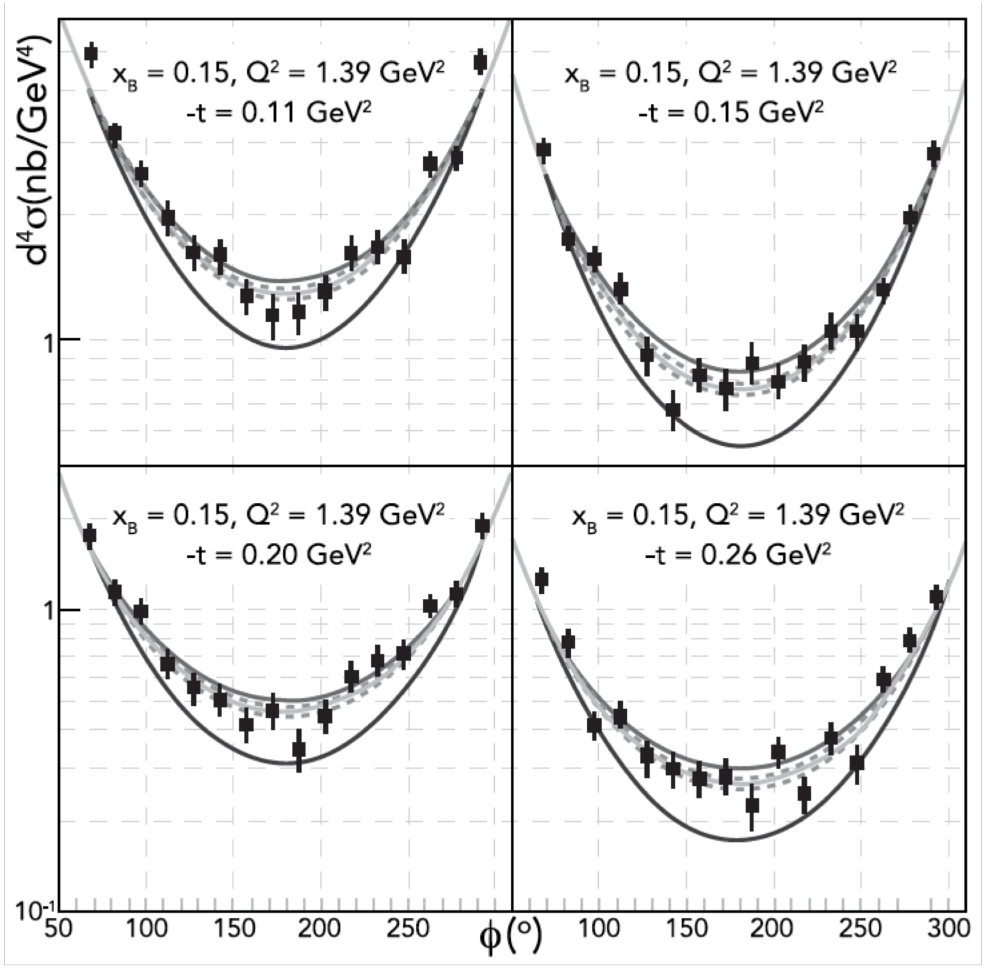
Fits to determine $\mathcal{H}(\xi, t)$ and $D(t)$



Samples of Beam Spin Asymmetry with fits



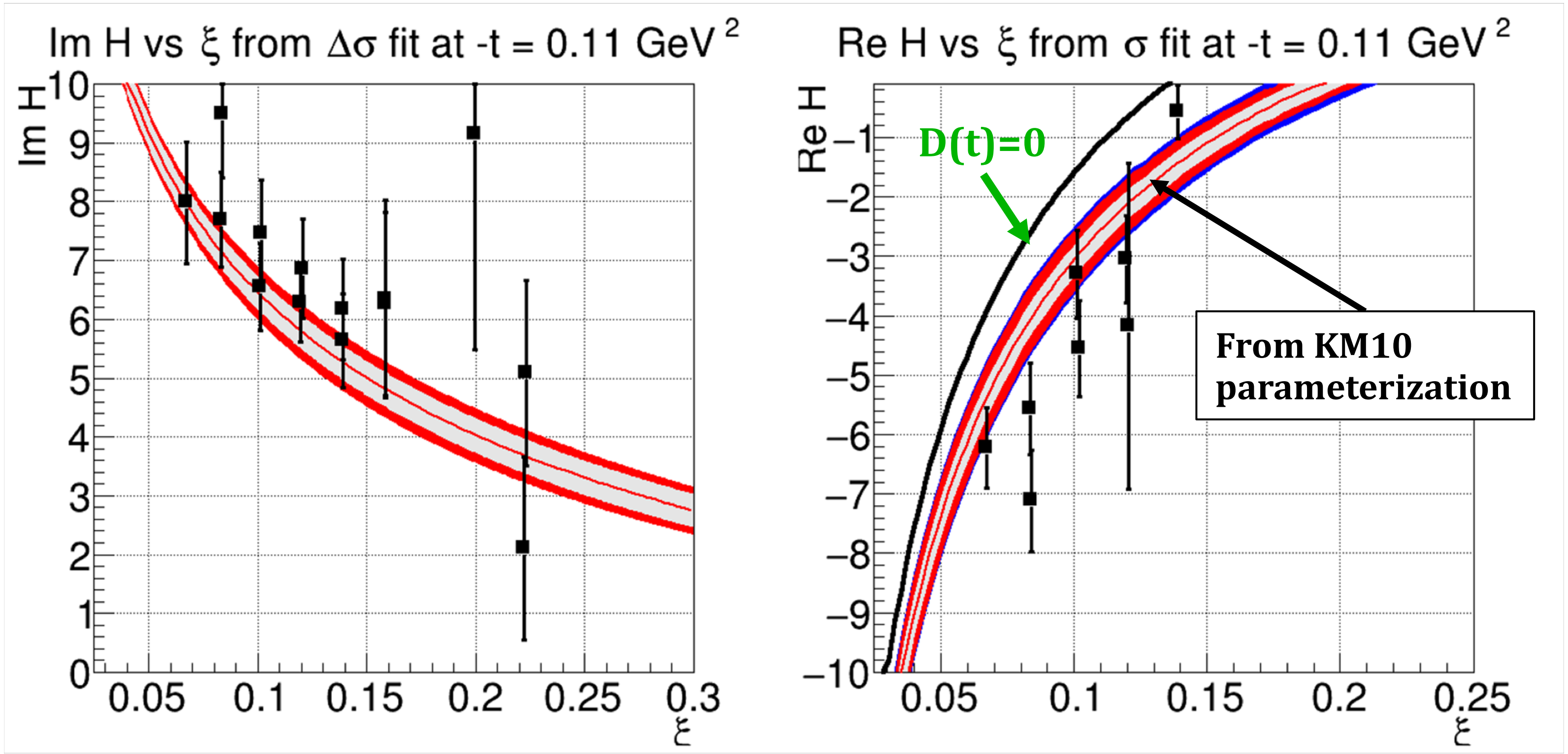
Samples of differential cross sections with fits



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

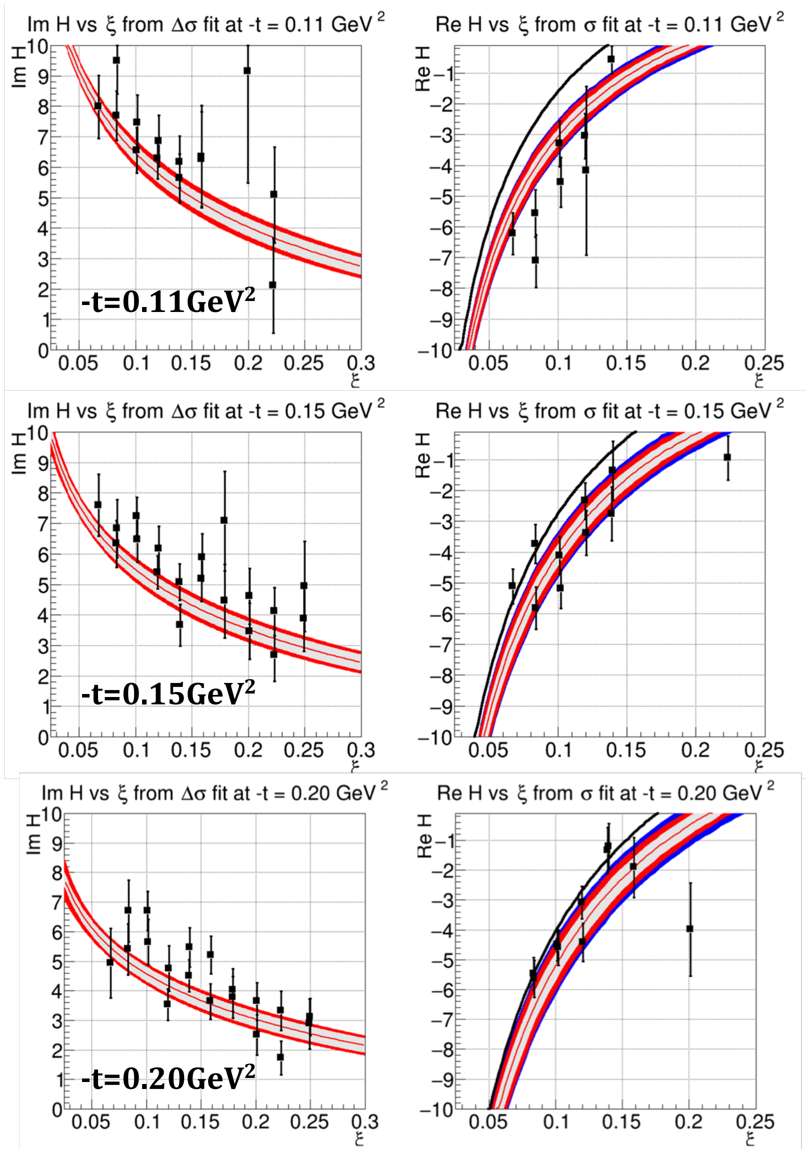
Extraction of Compton Form Factor $\mathcal{H}(\xi,t)$

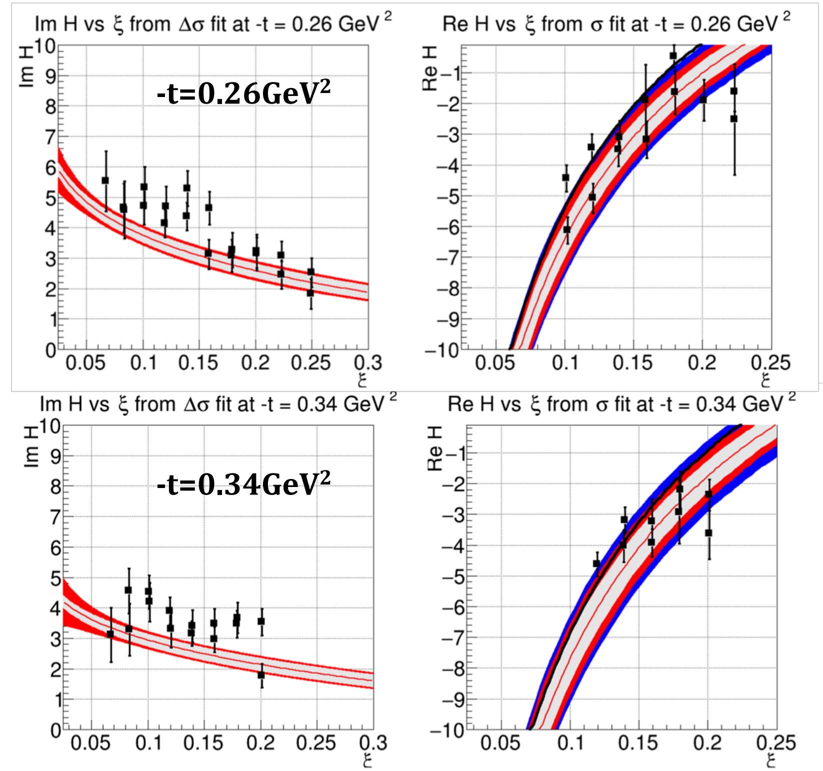
Data point closest to t=0



Markers: Determination from beam asymmetry and unpolarized cross section.
Curves: Using KM10 parameterization. Bands from estimates of contributions from other GPDs.

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

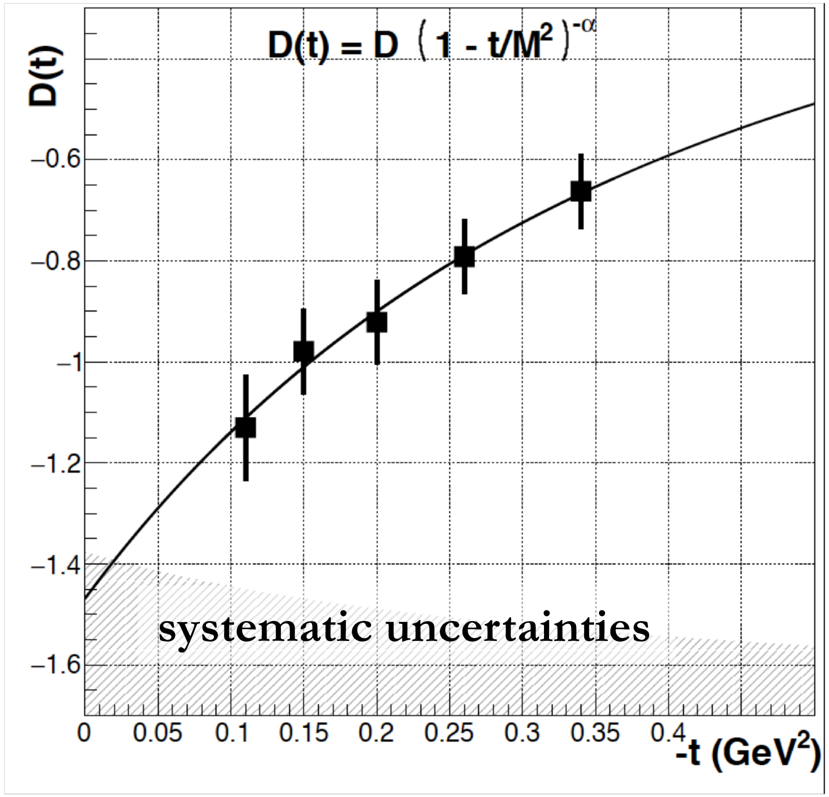




The Real and Imaginary parts of Compton Form $\mathcal{H}(\xi,t)$ for different ξ and t values, resulting from the fit to the BSA and cross section data.

Extraction of D(t) for quark distribution

D(t) from CLAS 6 GeV data



$D^Q(0) = -1.47 \pm 0.10 \pm 0.22$

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

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

$\underline{D^Q(0) < 0}$

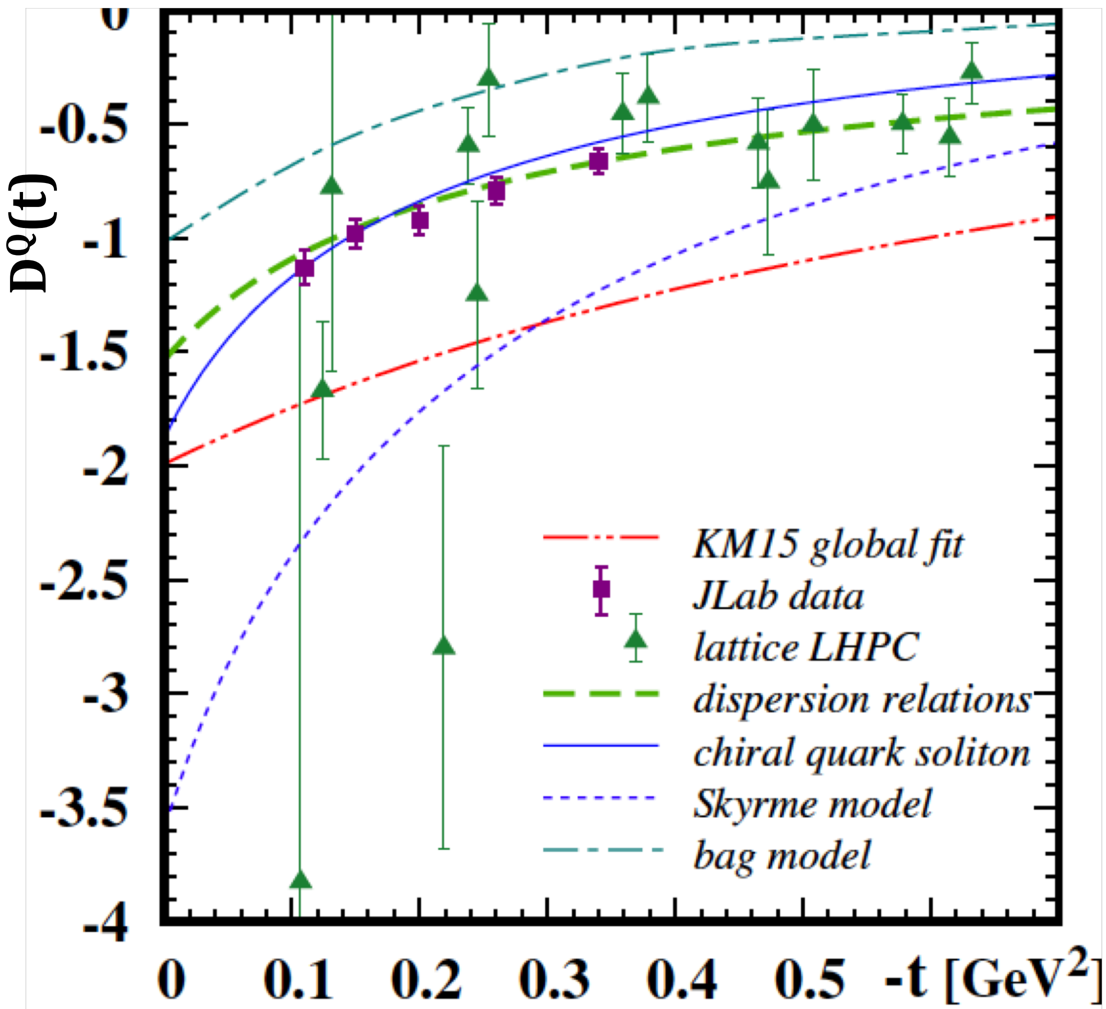
This is a critical results, required for dynamical stability of the proton.

Deeply rooted in chiral symmetry breaking.

First determination of the proton's D-term D(0), and its form factor D(t).

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

M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)



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

Global properties of the Proton

Q_{prot}	$=$	$1.602176487(40) \times 10^{-19}\text{C}$
μ_{prot}	$=$	$2.792847356(23)\mu_N$
g_A	$=$	$1.2694(28)$
g_p	$=$	$8.06(0.55)$
M_{prot}	$=$	$938.272013(23)\,\text{MeV}/c^2$
J	$=$	$\frac{1}{2}$
D	$=$	**-1.47 (10) (22)**

$d_1(t)$ - Gravitational Form Factor

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

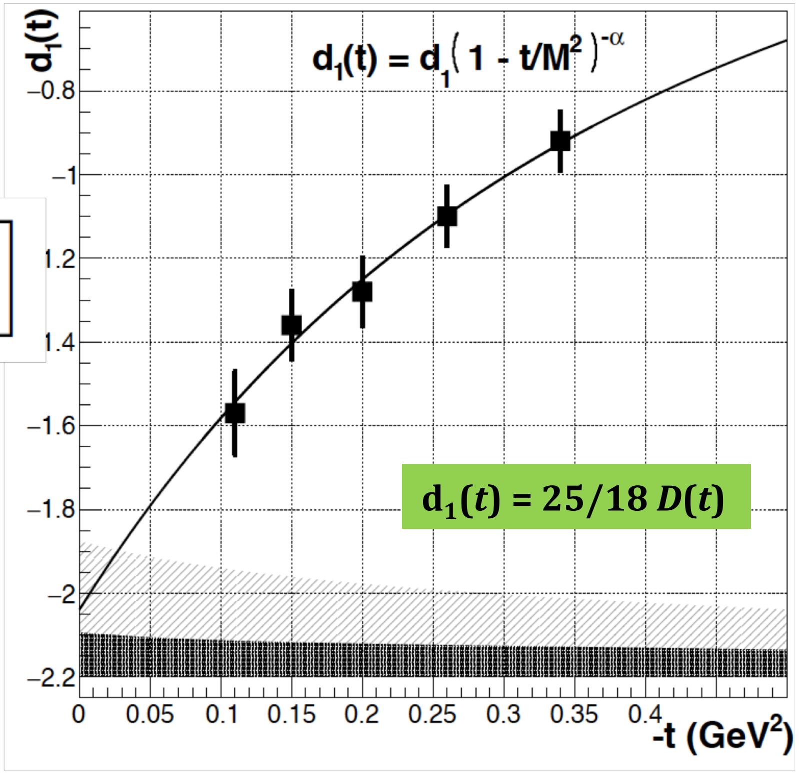
Expansion in Gegenbauer polynomials

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

$$D(t) = \frac{1}{2}\int_{-1}^{1} dz \frac{D(z,t)}{1-z} \qquad -1 < z = \frac{x}{\xi} < 1$$

(From model estimates next order term $d_3 << d_1$)

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



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

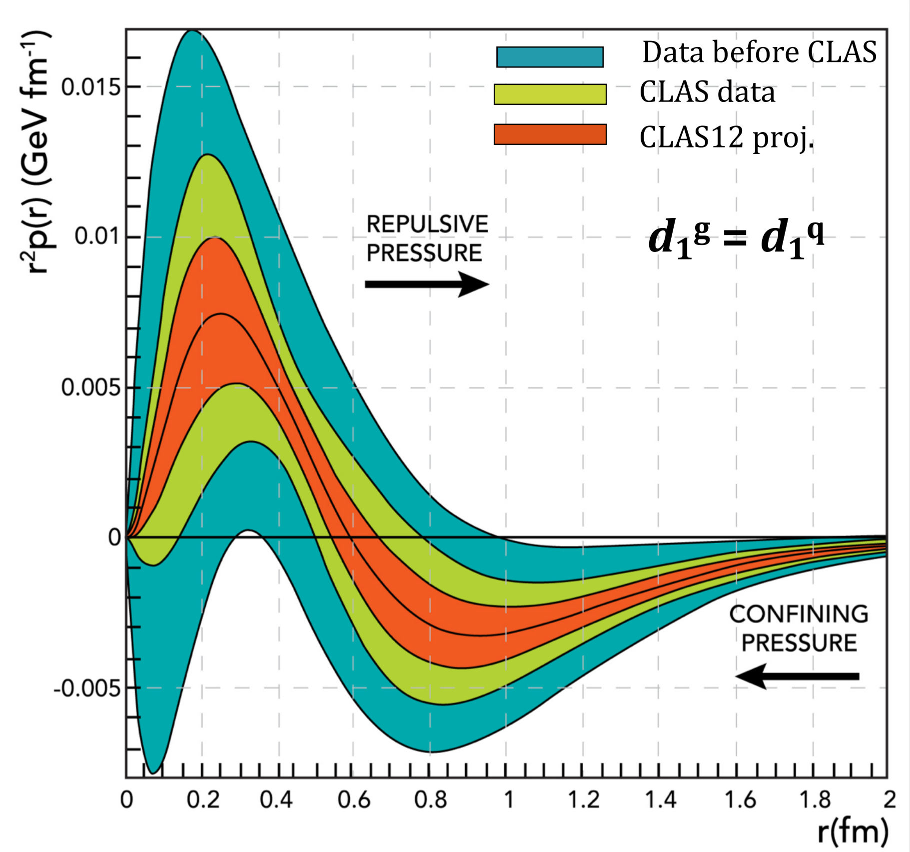
Pressure distribution inside the proton

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

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

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



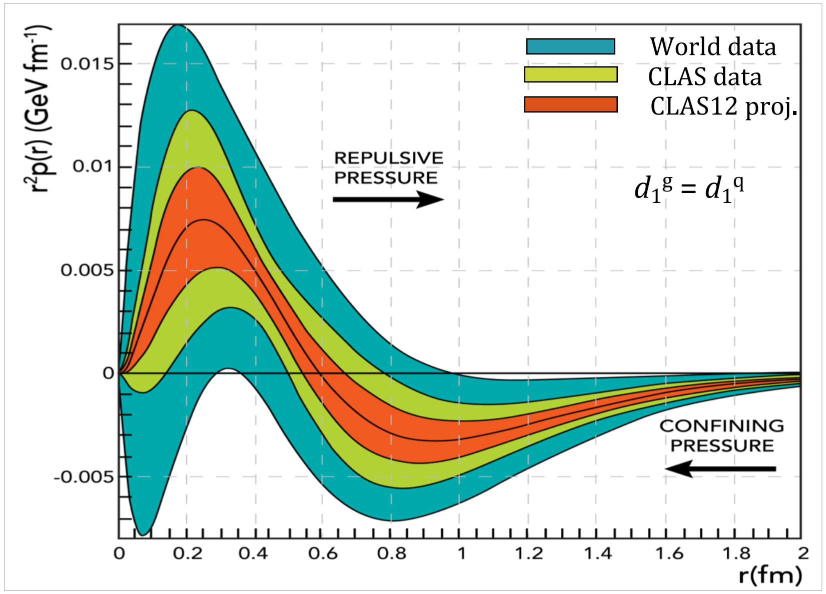
von Laue condition: $\int r^2 p(r) dr = 0$
verified within uncertainties

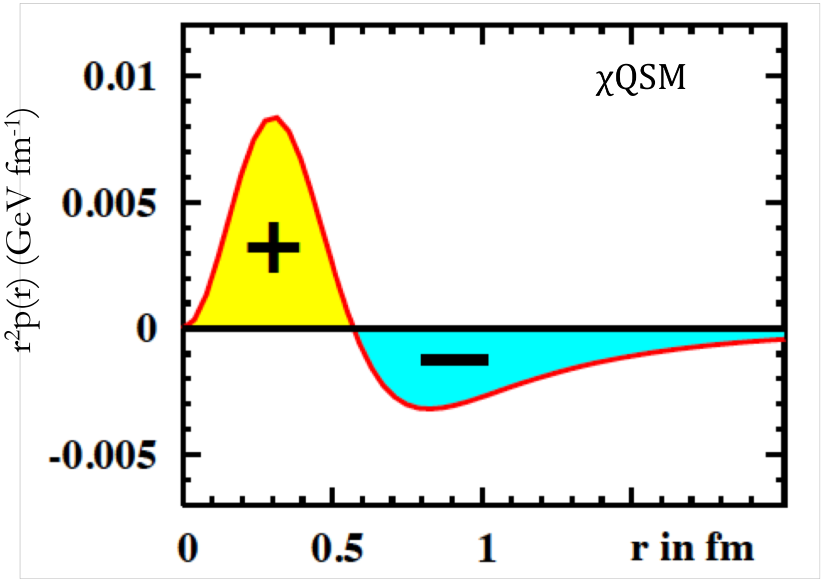
V.B., L. Elouadrhiri, F.X. Girod
Nature 557 (2018) no.7705, 396-399

Comparison with χQSM

- **Gravitational form factors have been computed in Lattice QCD and various models.**

K. Goeke et al, Phys.Rev. D75 (2007) 094021



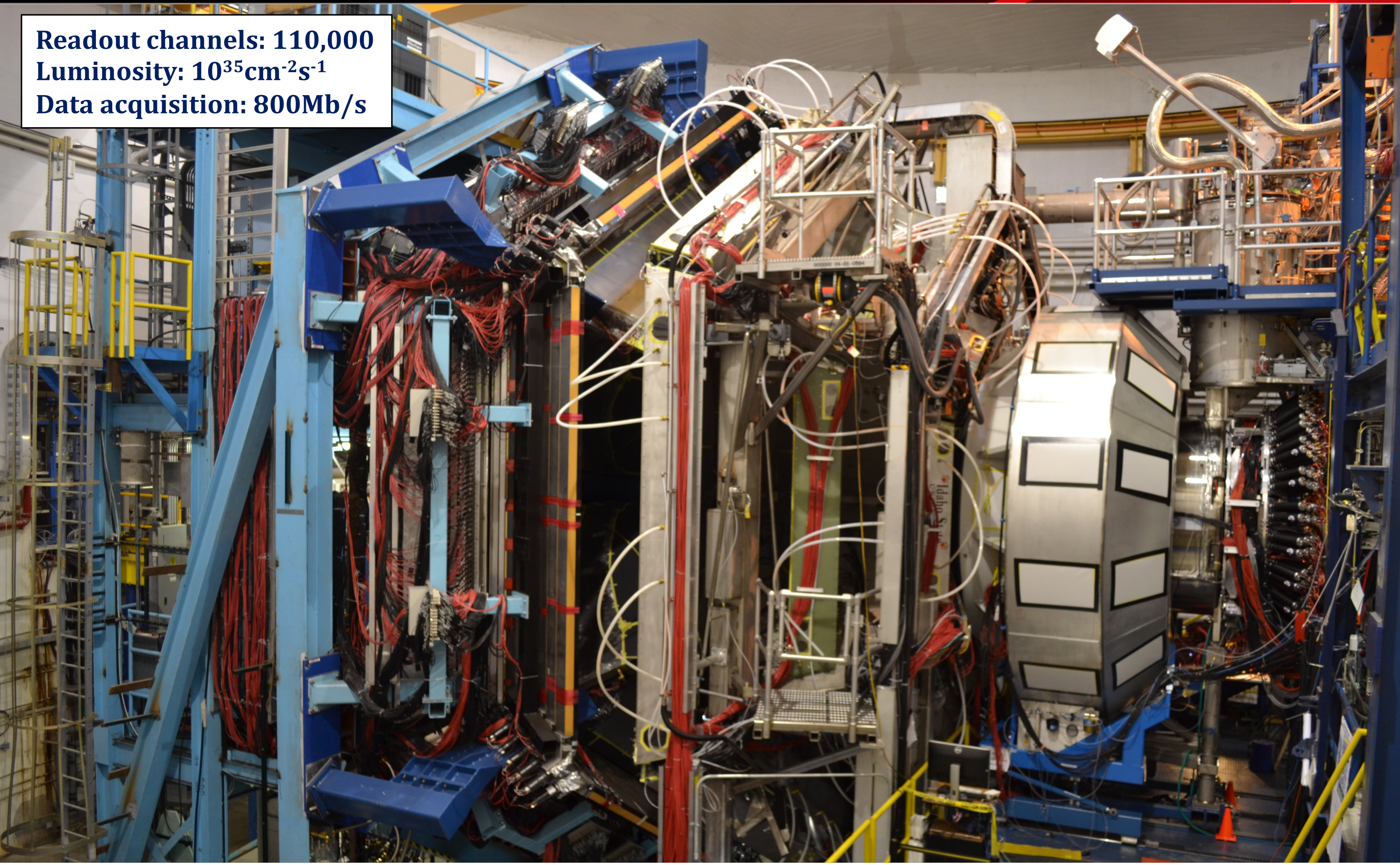


Similar p(r) dependence

In the χQSM the pion field provides the confining pressure at the proton's periphery.

CLAS12 @ JLab

Readout channels: 110,000
Luminosity: $10^{35}cm^{-2}s^{-1}$
Data acquisition: 800Mb/s



Summary and Outlook

- **First determination of a mechanical property** of the proton opens a new perspective on experimental hadron physics
- It puts limits on **the last unknown global property** of the proton
- It gives access the partonic energy momentum tensor and opens a new avenue **to test confinement mechanism**
- A **flurry of theory papers appeared** following the publication in Nature.

- This is an exciting time at the beginning of the **12 GeV high precision era** at Jefferson Lab.

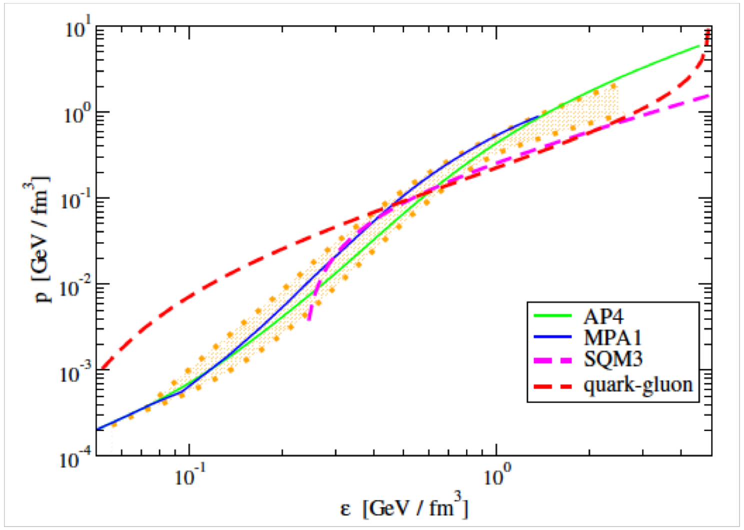
- It will be an **essential part of the EIC program** as well, to measure the gluon contributions to the EMT.

Some papers following the Nature paper

- **Hadron tomography in meson-pair production** and gravitational form factors
  S. Kumano, Qin-Tao Song, O.V. Teryaev, arXiv:1902.04333
- **Probing gravity at sub-femtometer scales** through the pressure distribution inside the proton
  P.P. Avelino, arXiv:1902.01318
- **Gravitational form factors within light-cone sum rules** at leading order , I.V. Anikin, arXiv:1902.00094
- **Bounds on the Equation of State of Neutron Stars** from High Energy Deeply Virtual Exclusive Experiments, S. Liuti, A. Rajan, K. Yagi, arXiv:1812.01479
- **Revisiting the mechanical properties of the nucleon**, C. Lorcé , H. Moutarde, A. P. Trawiński, Eur.Phys.J. C79 (2019) no.1, 89
- **Pressure Distribution and Shear Forces inside the Proton**, P. E. Shanahan, W. Detmold, Phys.Rev.Lett. 122 (2019)
- **Gluon gravitational form factors of the nucleon and the pion from lattice QCD,** P. E. Shanahan, W. Detmold, Phys.Rev. D99 (2019) no.1, 014511
- **Nucleon gravitational form factors from instantons**: forces between quark and gluon subsystems, M. Polyakov, H.-D. Son, JHEP 1809, JHEP 2018.
- Operator relations for **gravitational form factors of a spin-0 hadron**, Kazuhiro Tanaka, Phys.Rev. D98 (2018)
- **Forces inside hadrons:** pressure, surface tension, mechanical radius, and all that, M. Polyakov, P. Schweitzer, Int.J.Mod.Phys.A33 (2018)
- **On the desert between neutron star and black hole remnants**, R. Caimmi, Appl. Math. Sci. 2018

Applications to Cosmology

Bounds on EoS of Neutron Stars from high energy deeply virtual exclusive processes.
S. Liuti, A. Rajan, & K. Yogi, arXiv:1812.01479

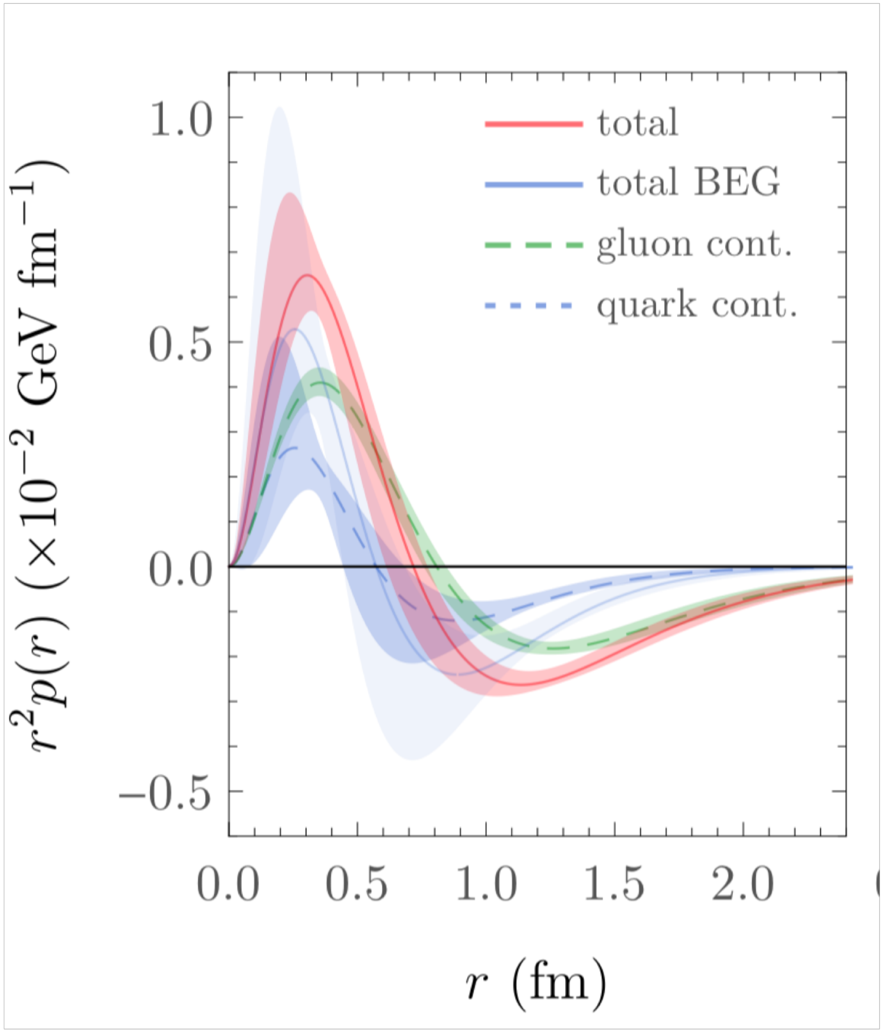


Probing gravity at sub-femtometer scales through the pressure distribution inside the proton.
P.P. Avelino, arXiv:1902.01318 (2019)

Maximum pressure in Proton provides limit on the single parameter **κ** used in theories of gravitation that depart from general relativity at very short distances.

$$|\kappa| < 0.1\ \mathrm{m^5\,kg^{-1}\,s^{-2}}$$

Adding LQCD gluons to $D^q(t)$



PRL calculations of gluon contributions to LQCD, P. Shanahan, W. Detmold Phys.Rev.Lett. 122 (2019) no.7, 072003

BEG pressure results had to make assumptions on gluon contributions as no experimental data exist.

Adding the LQCD gluons to BEG quark results gives similar distribution but gluons add much strength at large r to the negative, 'confining' pressure.

Quark orbital angular momentum

- So far we have considered only mechanical properties that required knowledge of the Compton Form Factor $\mathcal{H}$ to determine GFF $d_1(t)$.
- **To get the more complex angular momentum distribution defined in the Ji sum rule requires information on CFF $\mathcal{E}$**

$$\boxed{\int \mathrm{d}x\, x\, [H(x,\xi,t) + E(x,\xi,t)] \;=\; 2J(t)}$$

Determination of $\mathcal{E}$ requires DVCS measurements with a transversely polarized proton target.

$$\boxed{\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi)\ k\ \mathrm{Im}\{F_2\mathcal{H} - F_1\mathcal{E}\}}$$

With CFF $\mathcal{H}$ known, determination of $\mathcal{E}$ requires DVCS measurements with a transversely polarized proton target.

What we know about the D-term

- A fundamental quantity and characteristic for each particle
- For bound system the D-term must be negative
- A finite D-term is generated by internal dynamical interaction

Particle	D-Term	Source	Comment
Proton	-1.47±0.10±0.24	Experiment	Quarks
Δ(1232)	< 0	Theory	Applies to resonances
Free Boson	-1	Theory	
Free point-like fermion	0	Theory	No free quarks ?
Any bound system	< 0	Theory	

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

Relativistic corrections

particle	J^π	mass [GeV]	size [fm]	$\delta_{\rm rel}$
pion	0^-	0.14	0.67	2.2
kaon	0^-	0.49	0.56	2.5×10^{-1}
η-meson	0^-	0.55	0.68	1.4×10^{-1}
η_c-meson	0^-	2.98	0.26	3.8×10^{-2}
proton	$\frac{1}{2}^+$	0.94	0.89	2.8×10^{-2}
deuteron	1^+	1.88	2.14	1.2×10^{-3}
^{6}Li	1^+	5.60	2.59	9.3×10^{-5}
^{4}He	0^+	3.73	1.68	5.0×10^{-4}
^{12}C	0^+	11.2	2.47	2.6×10^{-5}
^{20}Ne	0^+	18.6	3.01	6.2×10^{-6}
^{32}S	0^+	29.8	3.26	2.1×10^{-6}
^{56}Fe	0^+	52.1	3.74	5.1×10^{-7}
^{132}Xe	0^+	123	4.79	5.6×10^{-8}
^{208}Pb	0^+	194	5.50	1.7×10^{-8}
^{244}Pu	0^+	227	5.89	1.1×10^{-8}