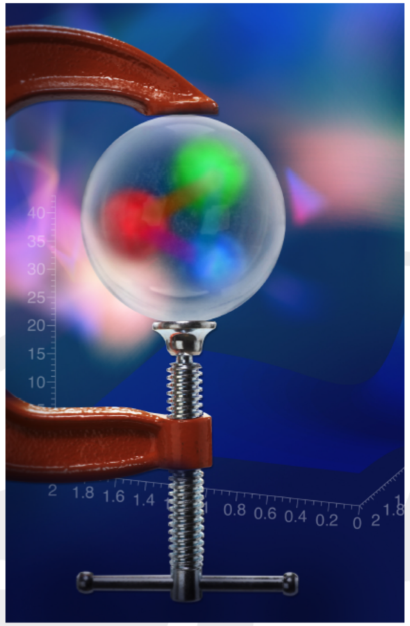
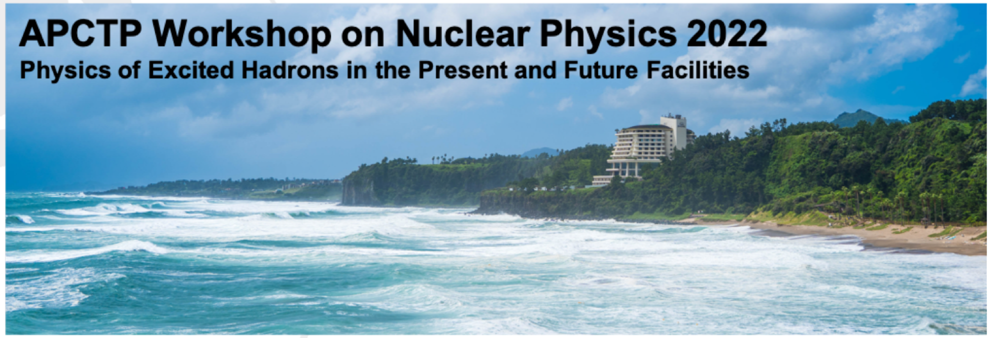
Towards mechanical properties of the proton



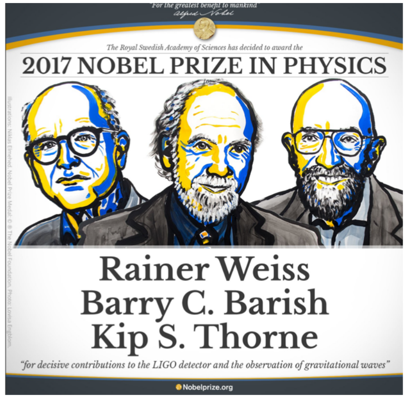
What have we learned from experiments?

Volker D. Burkert

Jefferson Laboratory



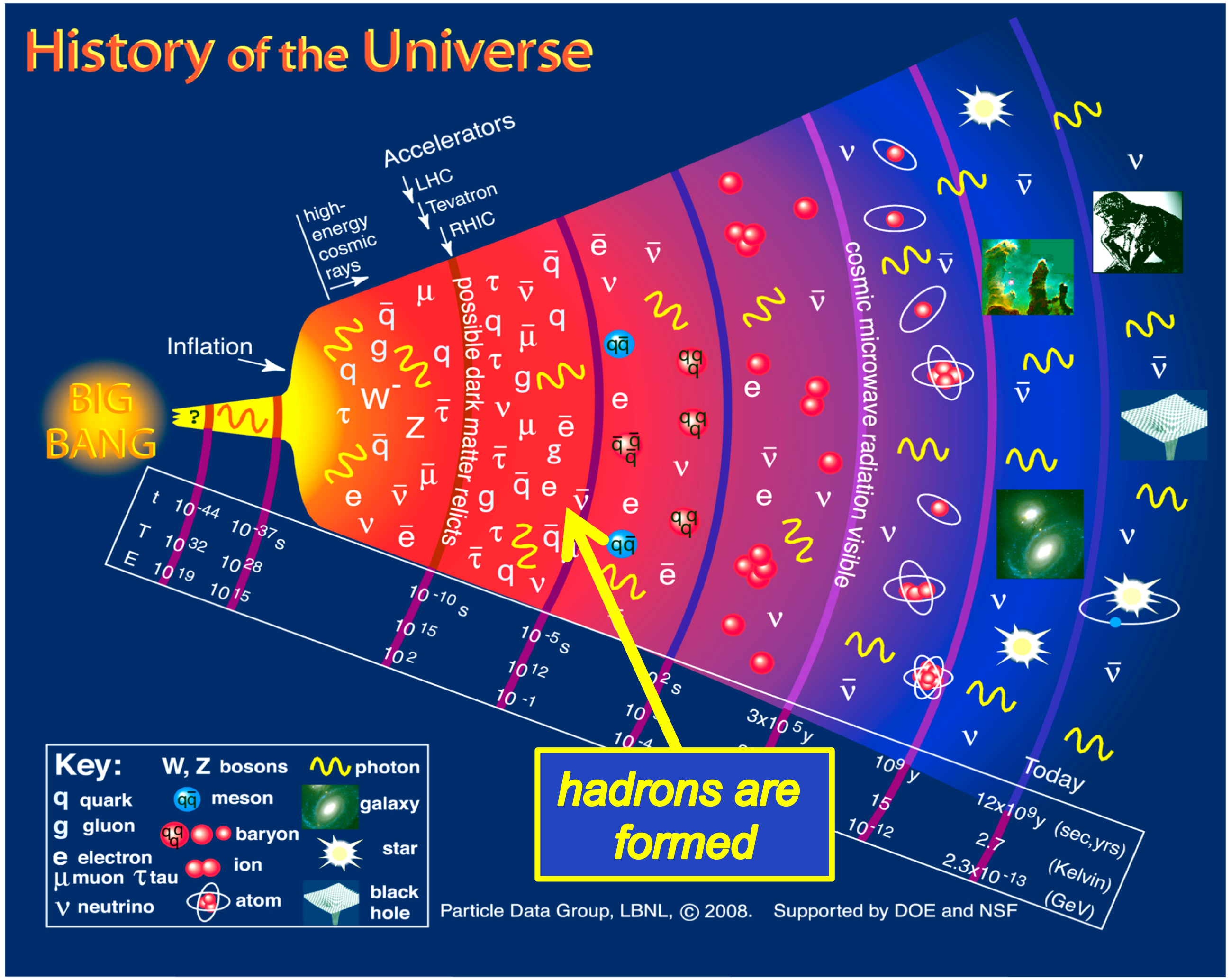
Gravitational waves observed



- **Gravity governs movements of massive structures in the universe.**
- **Gravity plays a decisive role in neutron stars leading to the most densely packed matter in the universe.**

- **The recently observed gravitational waves resulted from the merger of two neutron stars that told us much about their the equation of state of matter in neutron stars.**
- **Can we use gravitational waves to probe the mechanical properties of hadrons, e.g. the proton?**

Focus on the Proton



Hadrons are formed in the crossover from the QGP phase to the hadron phase μ–sec after the big bang.

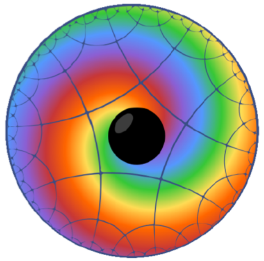
The proton emerges as the absolute stable, most fundamental bound-state in nature.

The proton's mechanical properties are of high interest to learn about the internal forces that provide its absolute stability $\tau > 10^{29}$ years.

Basic questions about the proton

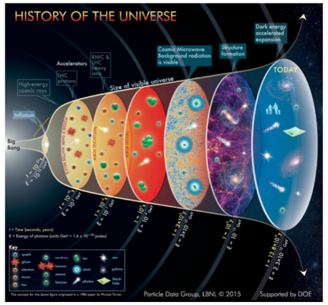
- Protons make up nearly 90% of the mass of ordinary matter in the universe. Elementary quarks contribute a fraction to the proton's mass

What is the origin of its mass?



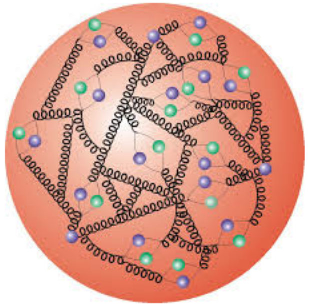
- Quarks and gluons formed stable protons as the universe cooled below 10^{12} K micro-seconds after the Big Bang

What is the origin of confinement ?



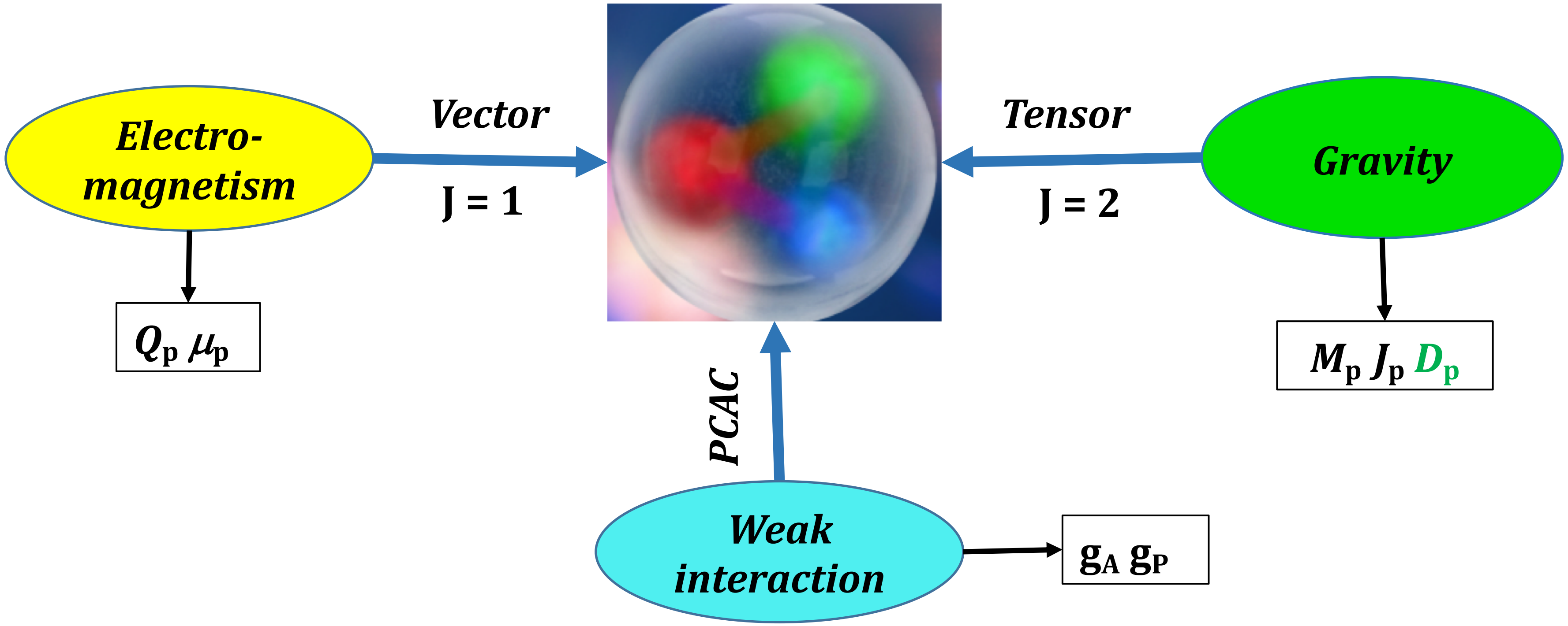
- The strong interaction is thought responsible for confinement

How does the distribution of strong forces contribute to the proton's stability and to confinement?



Probing the internal structure of the proton

The internal structure of strongly interacting quarks and gluons can be probed by means of the weaker, fundamental forces: *electromagnetic, weak,* and *gravity*.



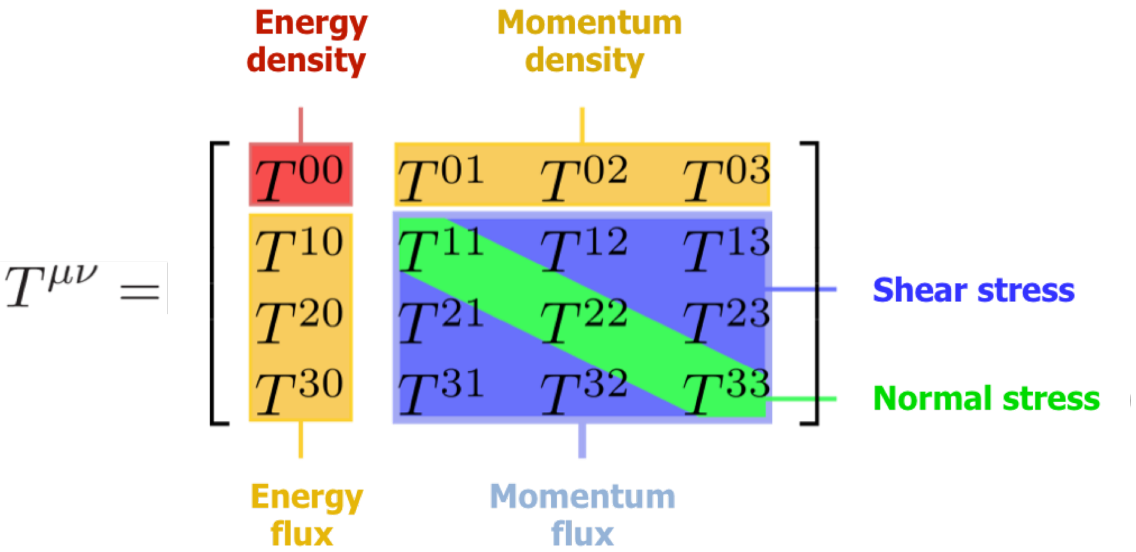
To learn experimentally more about the proton's mechanical properties

➔ we must probe its energy-momentum tensor (EMT)

Energy Momentum Tensor $T^{\mu\nu}$

The framework for probing the proton EMT was developed in the 1960's; but no data existed to put it to the test.

Yu. Kobzarev and L.B. Okun, JETP 16, 5 (1963)
H. Pagels, Phys. Rev. 144 (1966) 1250-1260



$$T^{ij}(\mathbf{r}) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right) s^Q(r) + \delta^{ij} p^Q(r)$$

$$\begin{aligned} d_1^Q(t) &= 5M_p \int d^3\mathbf{r} \frac{j_2(r\sqrt{-t})}{t} s^Q(r) \\ d_1^Q(t) &= 15M_p \int d^3\mathbf{r} \frac{j_0(r\sqrt{-t})}{2t} p^Q(r) \end{aligned}$$

$s^Q(r)$:** shear stress;* ***$p^Q(r)$: pressure
j_0, j_2: 0th, 2nd order spherical Bessel functions

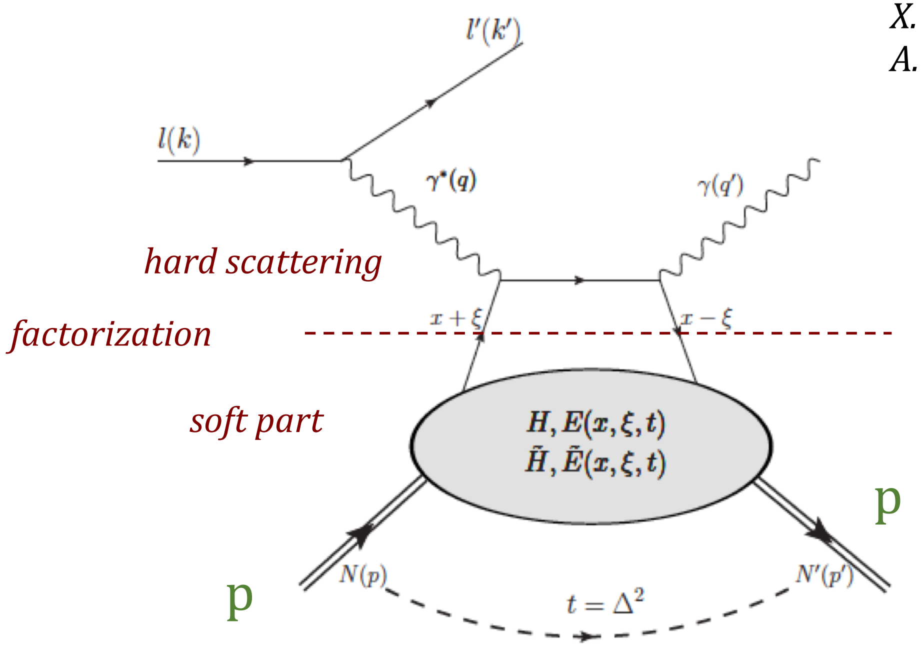
Extract: ***$s^Q(r)$, $p^Q(r)$*** with Fourier transform of ***$d_1^Q(t)$*** to coordinate space.

"... 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)

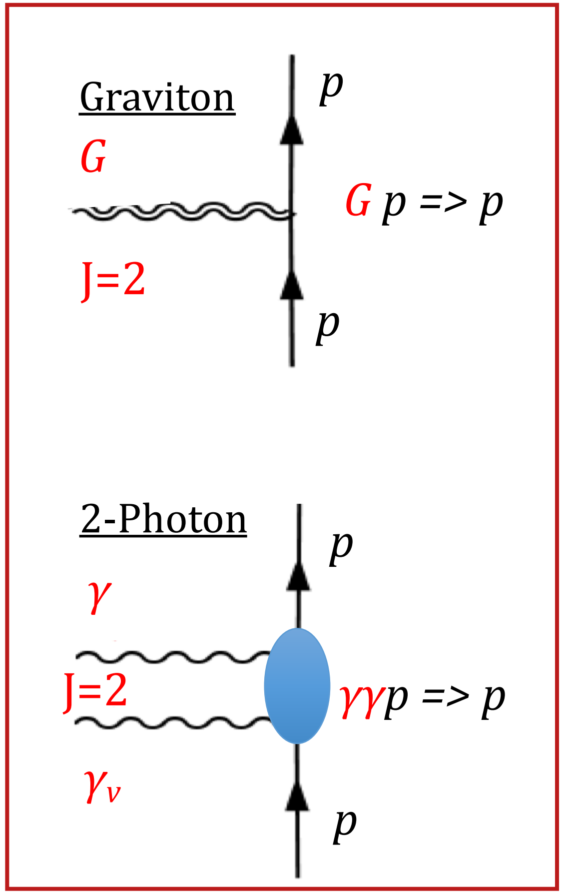
➔ Use a substitute that mimics gravity ➔ DVCS

GPDs, DVCS, and Gravity

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



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



4 chiral even GPDs describe soft part. GPD ***H** is* important to access gravitational form factor ***D(t)***.

DVCS is a suitable probe of mechanical properties of particles

The 2γ field couples to the EMT as gravity does, with many orders of magnitude greater strength.

Moments of GPD & GFF Relations

The proton's matrix element of the EMT contains 3 gravitational form factors (GFF) and can be written as:

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

$M_2(t)$: Mass/energy distribution inside the proton
$J(t)$: Angular momentum distribution
$d_1(t)$: Shear forces and pressure distribution

M. Polyakov, PL B555 (2003) 57

GPDs $\Rightarrow$ GFFs

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

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

In DVCS, GPDs are not directly accessible at all x and ξ, but only at the constrained kinematics: $x = \pm\xi$

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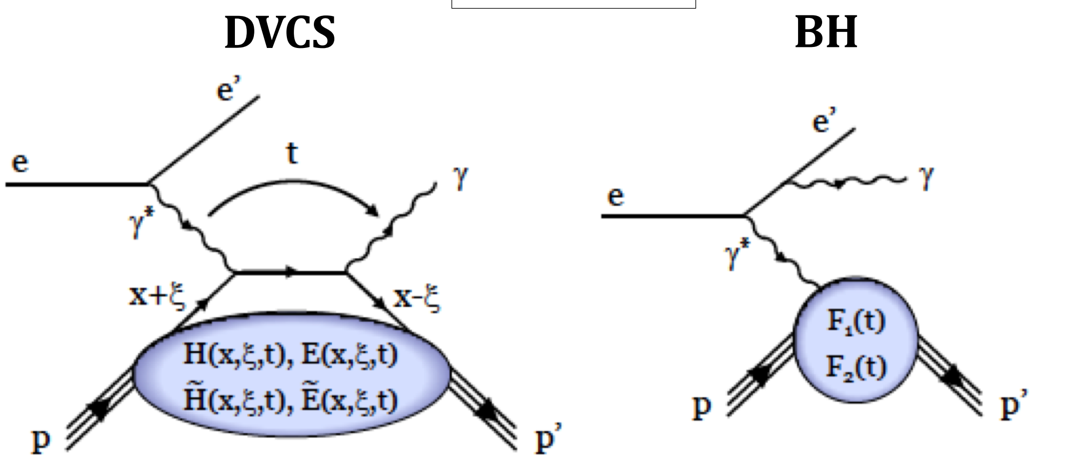
From GPDs to CFFs

GPDs do not appear directly in experimental observables related to DVCS, but through **complex** Compton Form Factors, e.g. $\mathcal{H}(\xi, t)$:

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

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



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

1) Polarized electron beam – BSA

$\Delta\sigma_{LU} \sim$ kin. $\sin\phi$ **Im**$[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}]\Delta\phi$

dominant

2) Unpolarized beam – cross section

$\Delta\sigma_{UU} \sim$ kin. $\sin\phi[\mathcal{H}\mathcal{H}^* + \ldots.\ ]\Delta\phi$

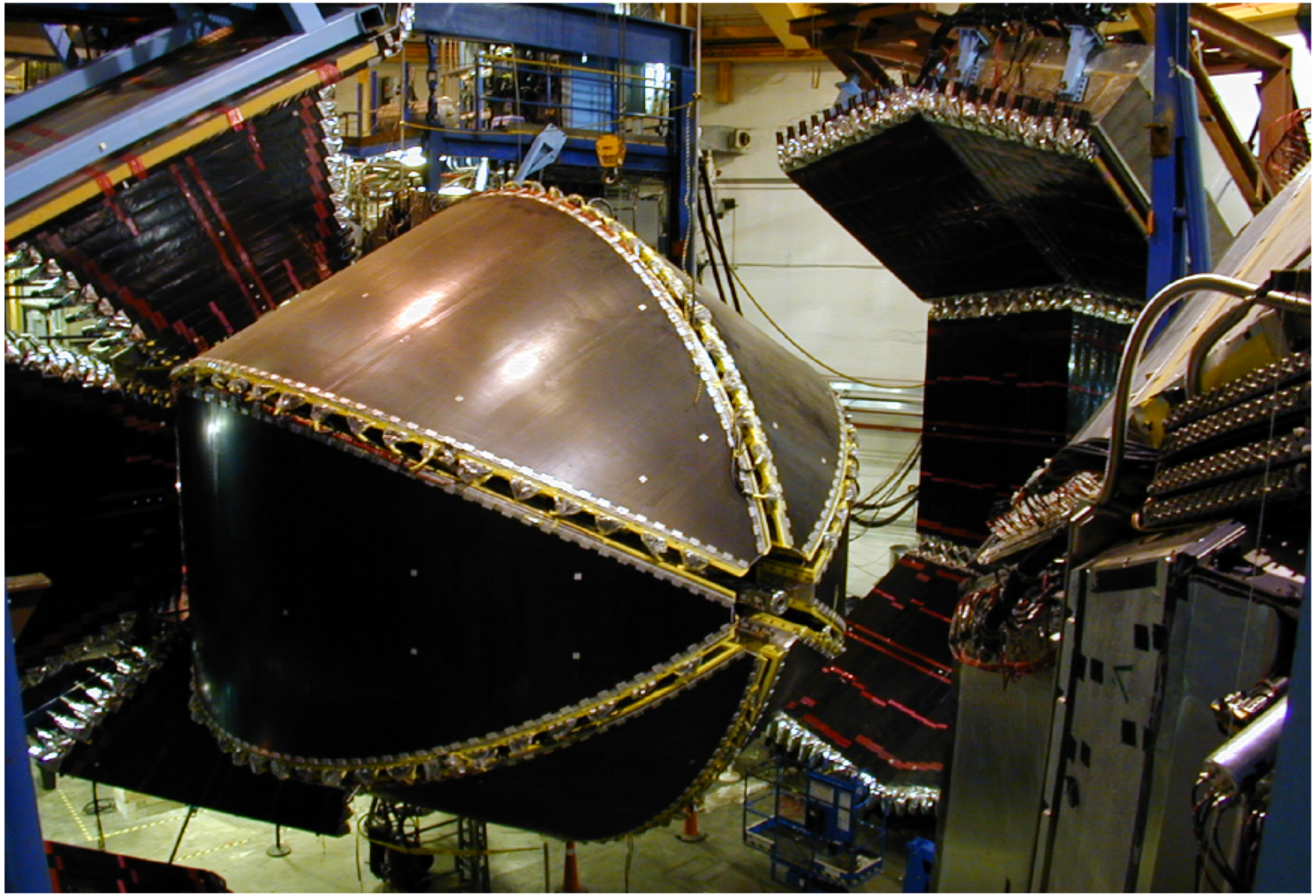
3) Fixed-t dispersion relation

$$\mathrm{Re}\mathcal{H}(\xi,t) = \boxed{\Delta(t)} + \frac{1}{\pi}\mathcal{P}\int_0^1 dx \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] \mathrm{Im}\mathcal{H}(x,t),$$

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

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

The CLAS Detector - in operation from 1997 to 2012



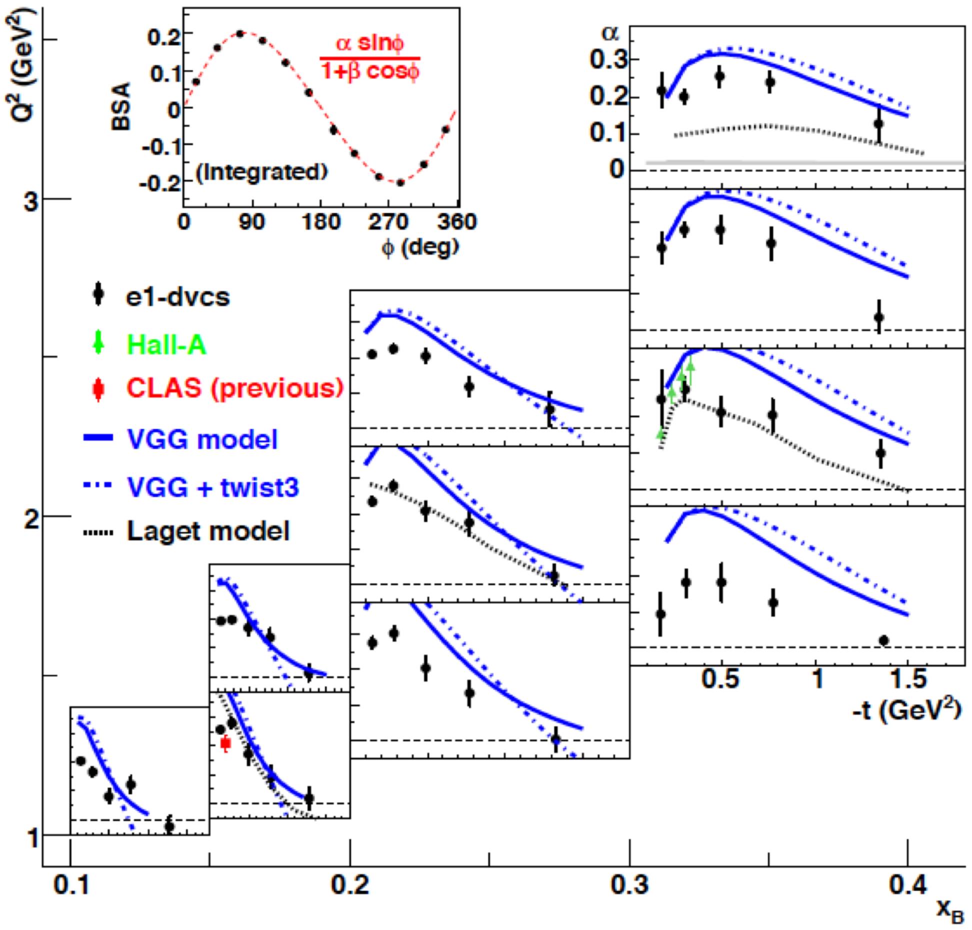
B. Mecking et al., Nuclear Instr. Meth. A 503 (2003) 513-553

- **Large program in N* physics both in photo- and electroproduction. The program contributed to the discovery and confirmation of many N* candidate states.**
- **Polarized photon beams and polarized targets.**
- **Pioneered deeply virtual Compton Scattering (DVCS) leading to first extraction of a gravitational form factor.**
  => focus of this presentation

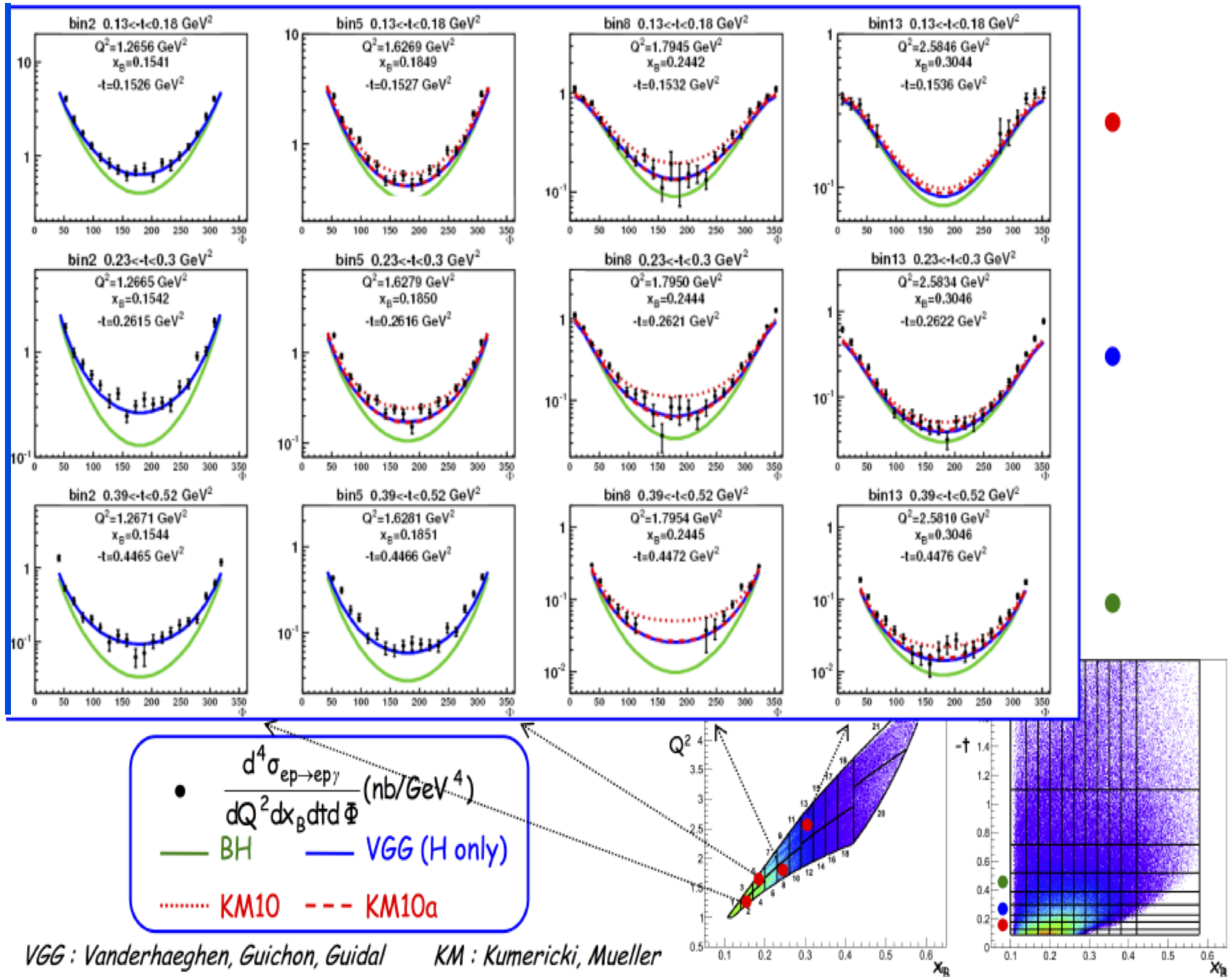
$L \sim 10^{34} cm^{-2} s^{-1}$

DVCS-BH BSA & Cross-Sections

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



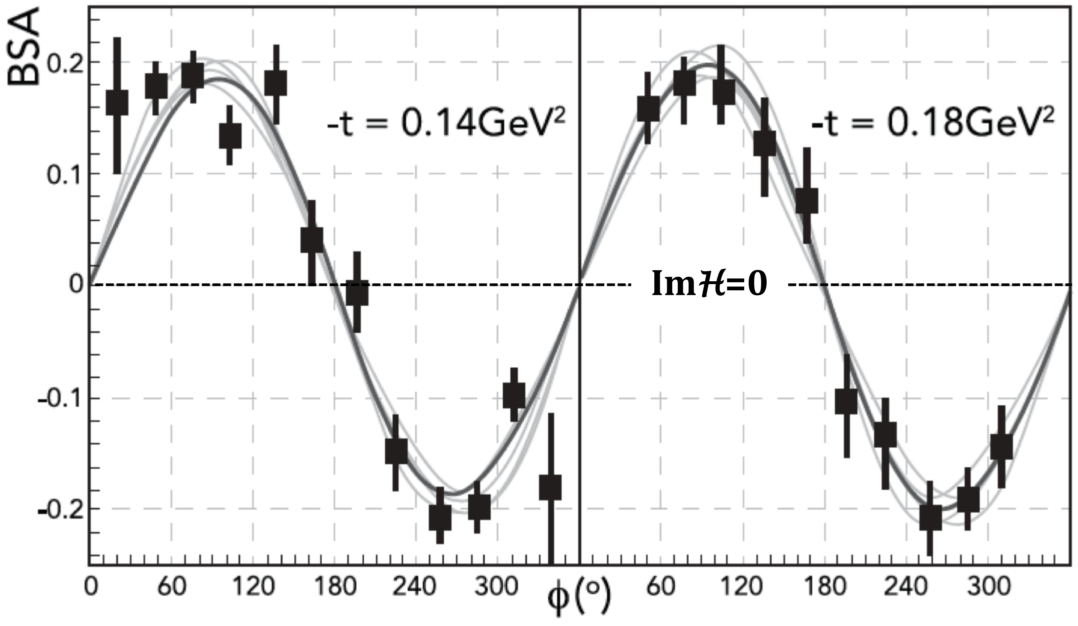
H.S. Jo et al., Phys.Rev.Lett. 115 (2015)



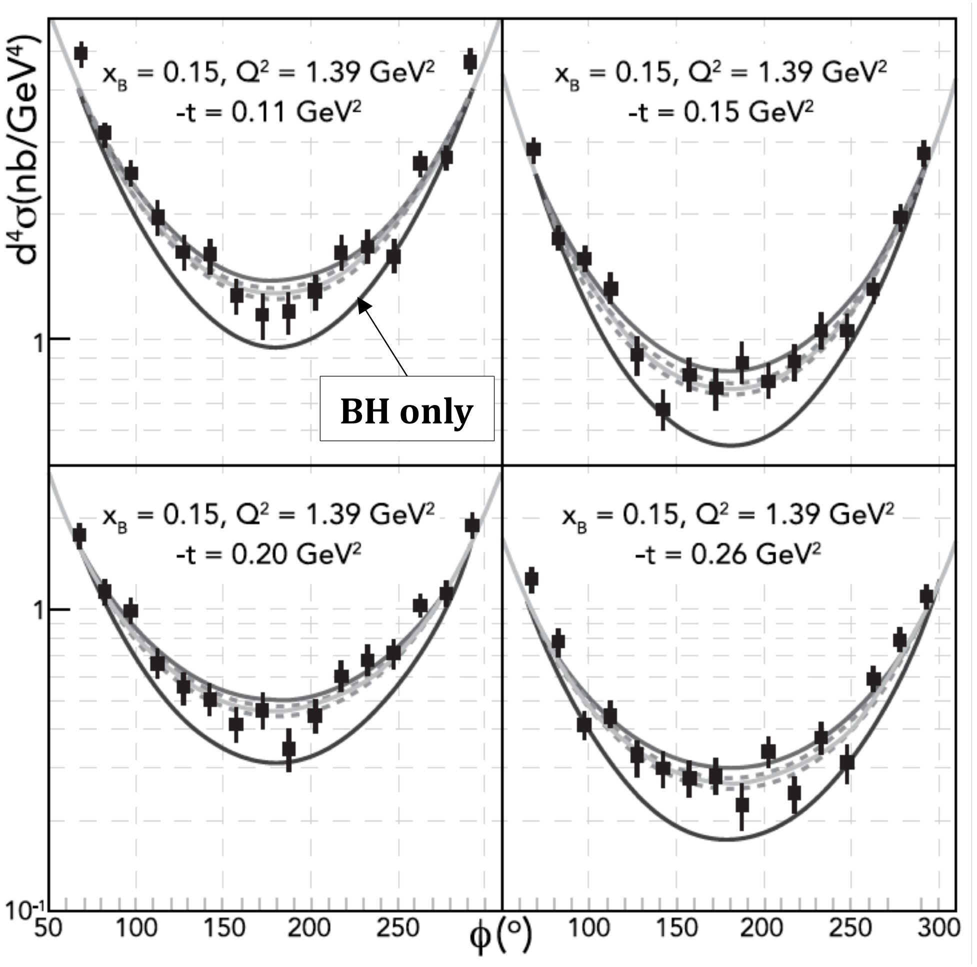
VGG : Vanderhaeghen, Guichon, Guidal KM : Kumericki, Mueller

Sample fits to determine Im$\mathcal{H}$ and Re$\mathcal{H}$

Samples of Beam Spin Asymmetry with fits



Samples of differential cross sections with fits



Global fit:

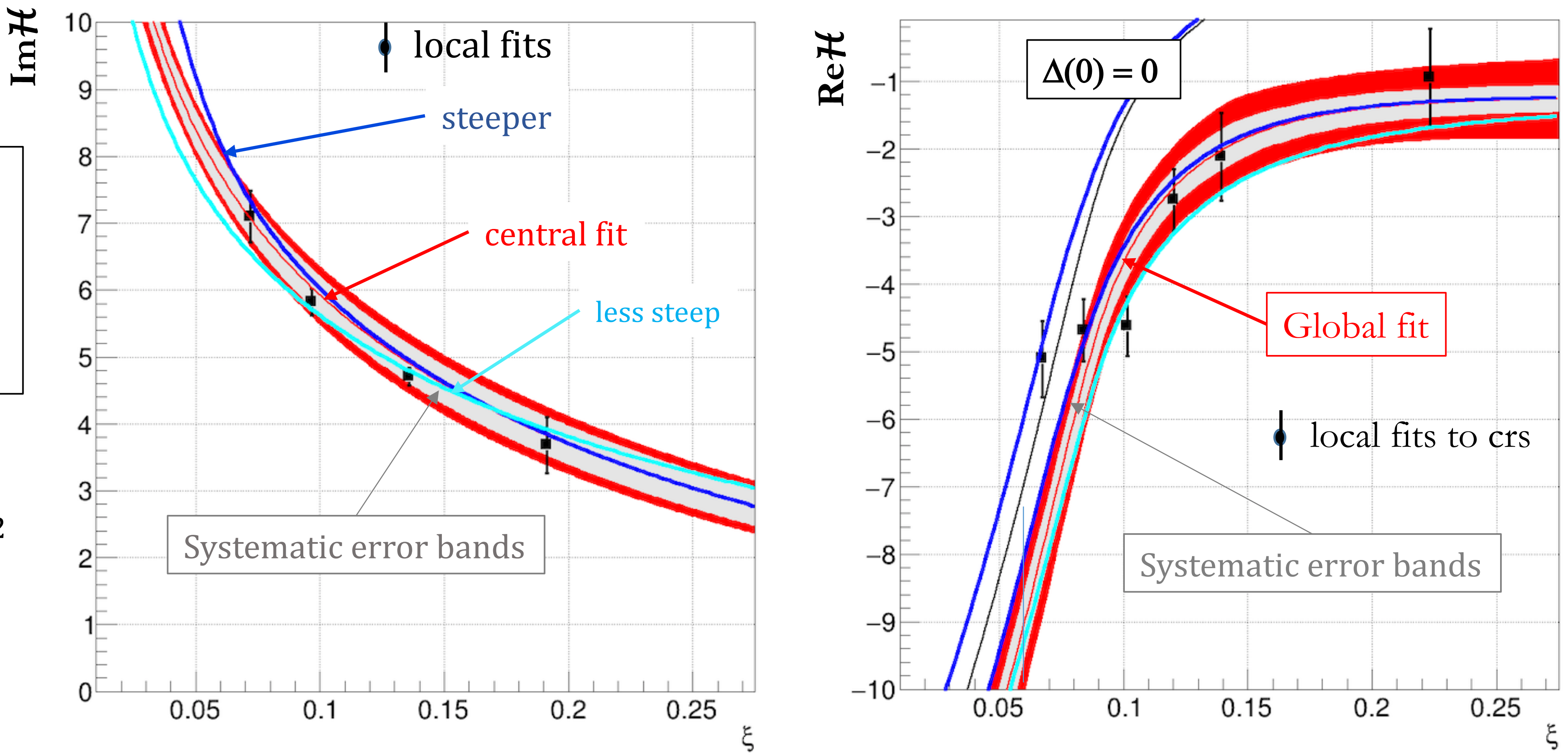
$$\mathrm{Im}\mathcal{H}(\xi,t) = \frac{N}{1+\xi}\left(\frac{2\xi}{1+\xi}\right)^{-\alpha(t)}\left(\frac{1-\xi}{1+\xi}\right)^{b}\frac{1}{\left(1-\frac{1-\xi}{1+\xi}\frac{t}{M^2}\right)^{p}}$$

K. Kumericki et al, EPJ A 52, 159 (2016)

Uncertainties for cross section are larger

Extracting CFF Im$\mathcal{H}$ and Re$\mathcal{H}$

-t= 0.13 – 0.15 GeV²



Global parameterizations:

BSA to determine Im$\mathcal{H}$

Differential cross sections to determine Re$\mathcal{H}$

K. Kumericki and D. Müller, EPJ Web Conf. 112 (2016) 01012

Re$\mathcal{H}$ has strong sensitivity to Δ(t)

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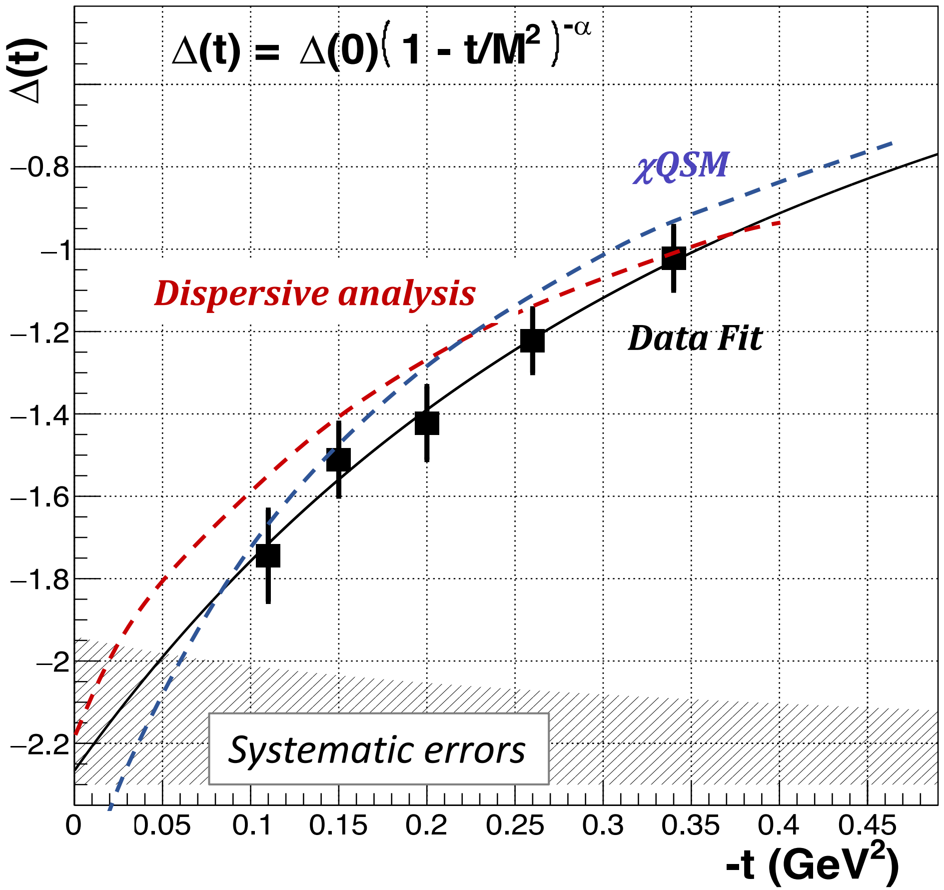
Extraction of $\Delta(t)$ and $d_1(t)$ for quark distribution

Δ(t) from CLAS 6 GeV DVCS data



Significance of results:

$\Delta(0)/(0.16^2+0.36^2)^{1/2} = 2.27/0.39 \sim 5.8$

$\Delta(0)$	=	**-2.27**	$\pm$ 0.16	$\pm$ 0.36
M^2	=	**1.02**	$\pm$ 0.13	$\pm$ 0.21
α	=	**2.76**	$\pm$ 0.23	$\pm$ 0.48

Δ(t)* ∝ *$d_1^Q(t)$ in double-distribution parameterization

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

$-1 < z = x/\xi < 1$

$$D(z,t) = (1-z^2)\,[e_u^2 + e_d^2]\,\frac{d_1^Q(t)}{2}3z$$

$$\boxed{d_1^Q(t) \approx \frac{9}{10}\Delta(t)}$$

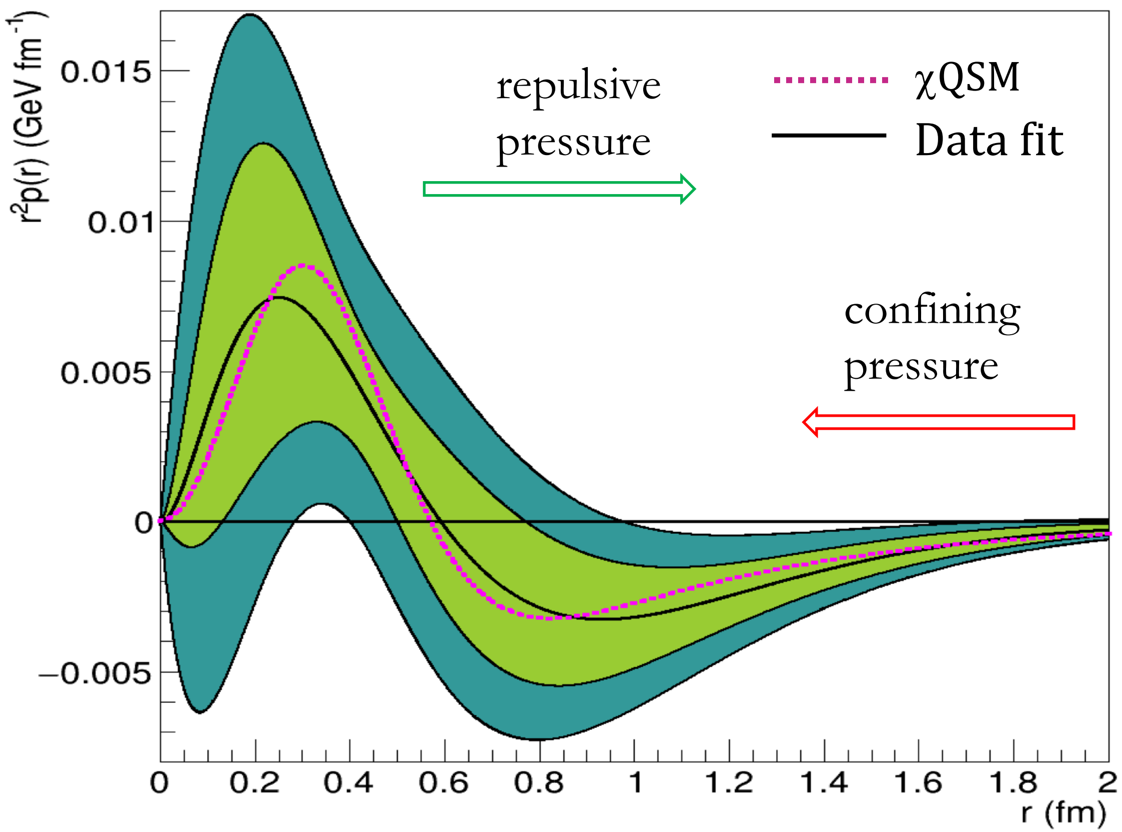
$d_1^Q(t)$ - first coefficient in Gegenbauer polynomial expansion.

Estimate of next to leading term in χQSM: $d_3^Q/d_1^Q \sim 0.3$

➔ Use as **systematic uncertainty** in estimating the force/pressure distributions.

Pressure on Quarks in the Proton

M. Polyakov, PL B555 (2003) 57



V.B., L. Elouadrhiri, F.X. Girod, Nature 557 (2018) 7705, 396

Uncertainties from fit to world data prior to CLAS.

Uncertainties for analysis with CLAS data only.

Normal stress (r=0.6fm):

$F_n = 4\pi r^2[2/3\, s^Q(r) + p^Q(r)]$

$\sim(\mathbf{20 \pm 11}) \times \mathbf{10^3\ N}$

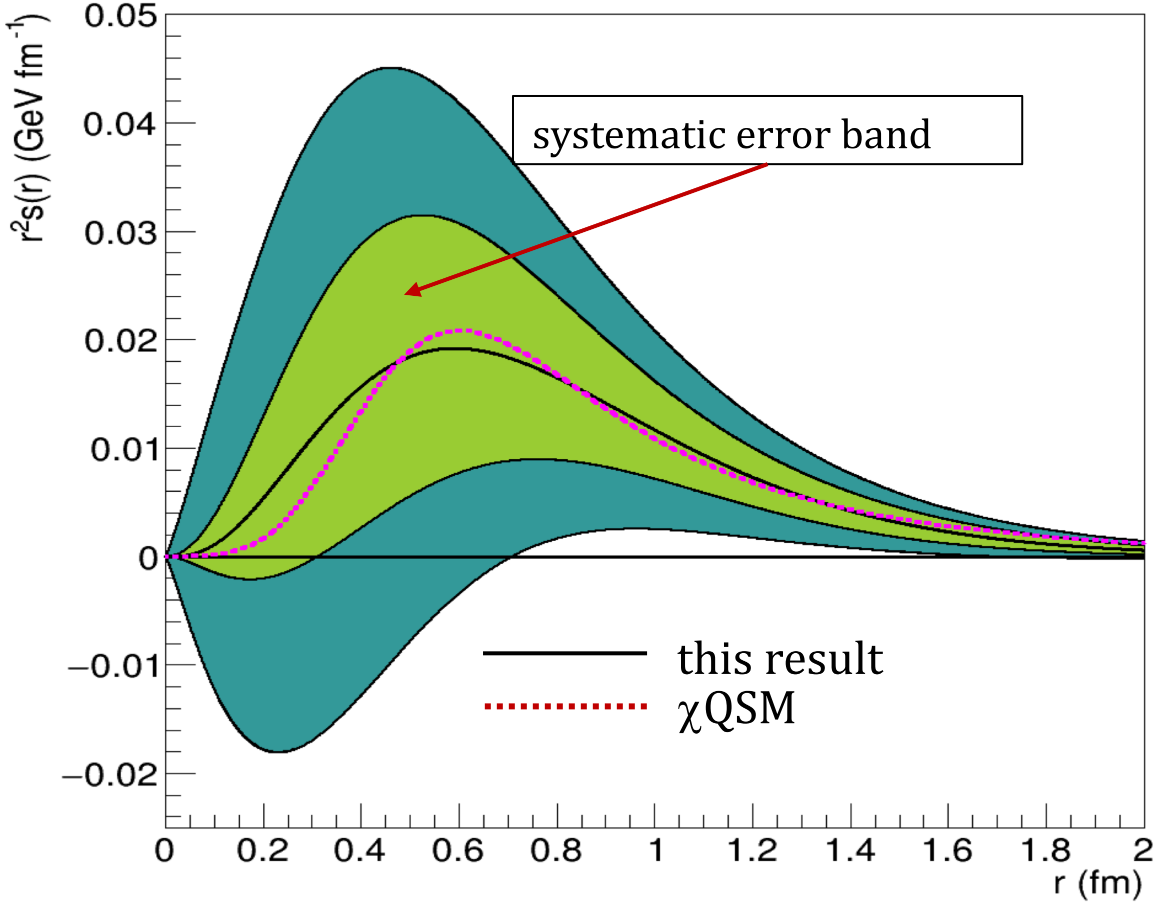
$p^Q(r)$ changes sign @ 0.6 ± 0.1fm

$$\int_0^\infty r^2 p(r)\,dr = 0$$

Pressure distribution for gluons in LQCD: P. Shanahan and W. Detmold, PRL 122 (2019) 7, 072003

Shear Stress on Quarks

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



Uncertainties of fit to world data prior to inclusion of CLAS6.

Uncertainties for analysis with CLAS6 data only.

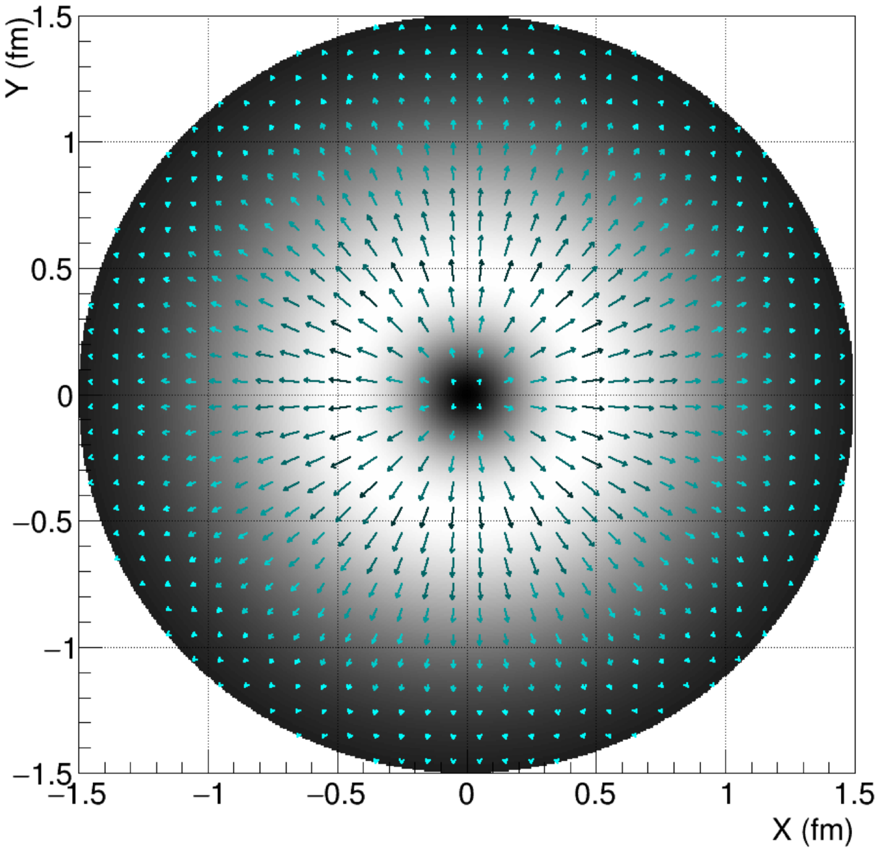
Shear stress near r = 0.6 fm:

$4\pi r^2 s(r) = 0.238$ GeV/fm

$\sim(38 \pm 20)\times 10^3$ N

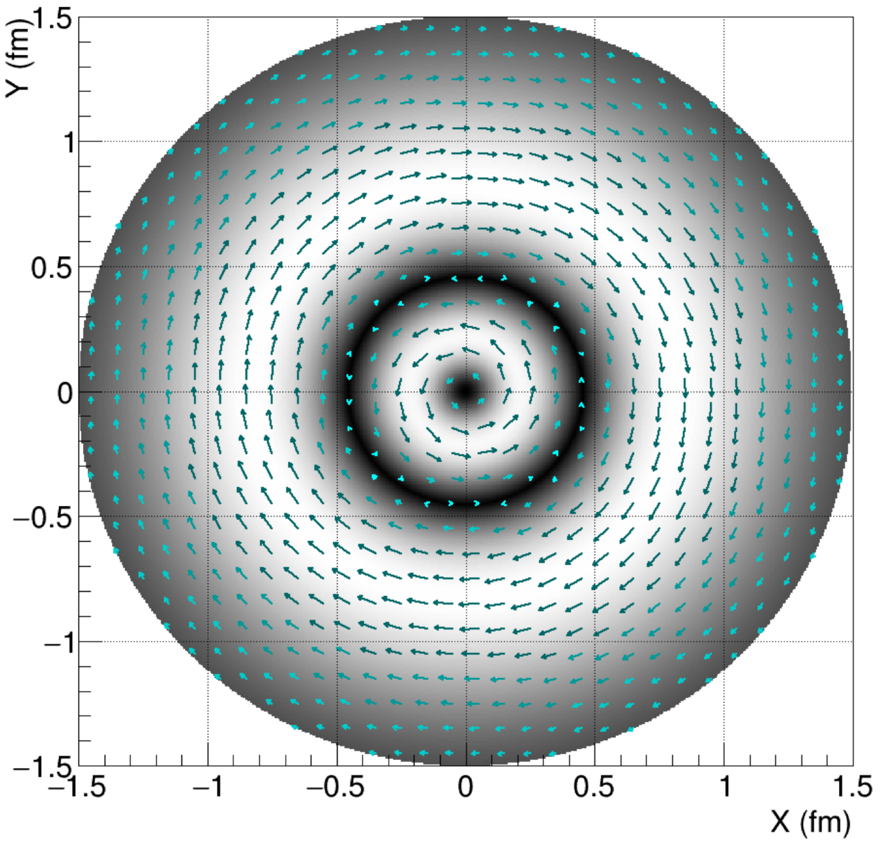
Normal & Tangential Stress on Quarks

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



Normal stress is positive at all r

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



Tangential stress changes direction near r ~ 0.45 fm

Proton mechanical Radius

Physical size is a basic property of the proton, experimentally nothing is known about the proton's **mechanical** radius.

Mechanical mean square radius:

$$\langle r^2 \rangle_{\text{mech}} = \frac{\int d^3r\ r^2\ \left[\frac{2}{3}s(r) + p(r)\right]}{\int d^3r\ \left[\frac{2}{3}s(r) + p(r)\right]} = \frac{6D}{\int_{-\infty}^{0} dt\ D(t)}$$

M. Polyakov and P. Schweitzer, Int. J. Mod. Phys. A33 (2018) 26, 1830025

$$D(t) = D\left[1 + \frac{-t}{M^2}\right]^{-\alpha}$$

For the multipolar form in the fit :

$$\langle r^2 \rangle_{\text{mech}} = 6(\alpha - 1)/M^2$$

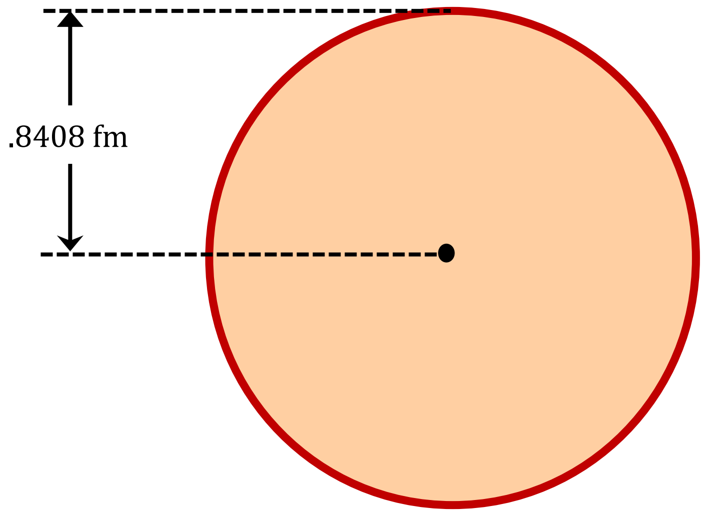
$\sqrt{\boldsymbol{r^2}}_{\textbf{mech}}$ **= 0.63** $\pm$ 0.06(fit) $\pm$ 0.13(sys) fm

Mechanical radius versus charge radius

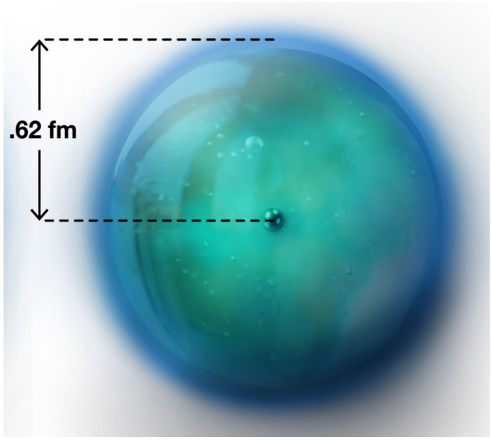
	Mechanical (fm)	Charge (fm)
Proton	**0.63** $\pm$ 0.06(fit) $\pm$ 0.13 (sys)	**0.8408** $\pm$ 0.0004
Neutron	$\mathbf{r_n} \cong \mathbf{r_p}$ (isospin)	$\mathbf{r^2}$ **= - 0.1161** $\pm$ 0.0022 (fm^2)

- **The proton's mechanical radius is significantly smaller than its charge radius.**

Charge radius



Mechanical radius



- The **charge** radius is measured in elastic scattering at **small Q^2** as the slope of the electric charge form factor, which is influenced by the proton's peripheral **pion cloud** .

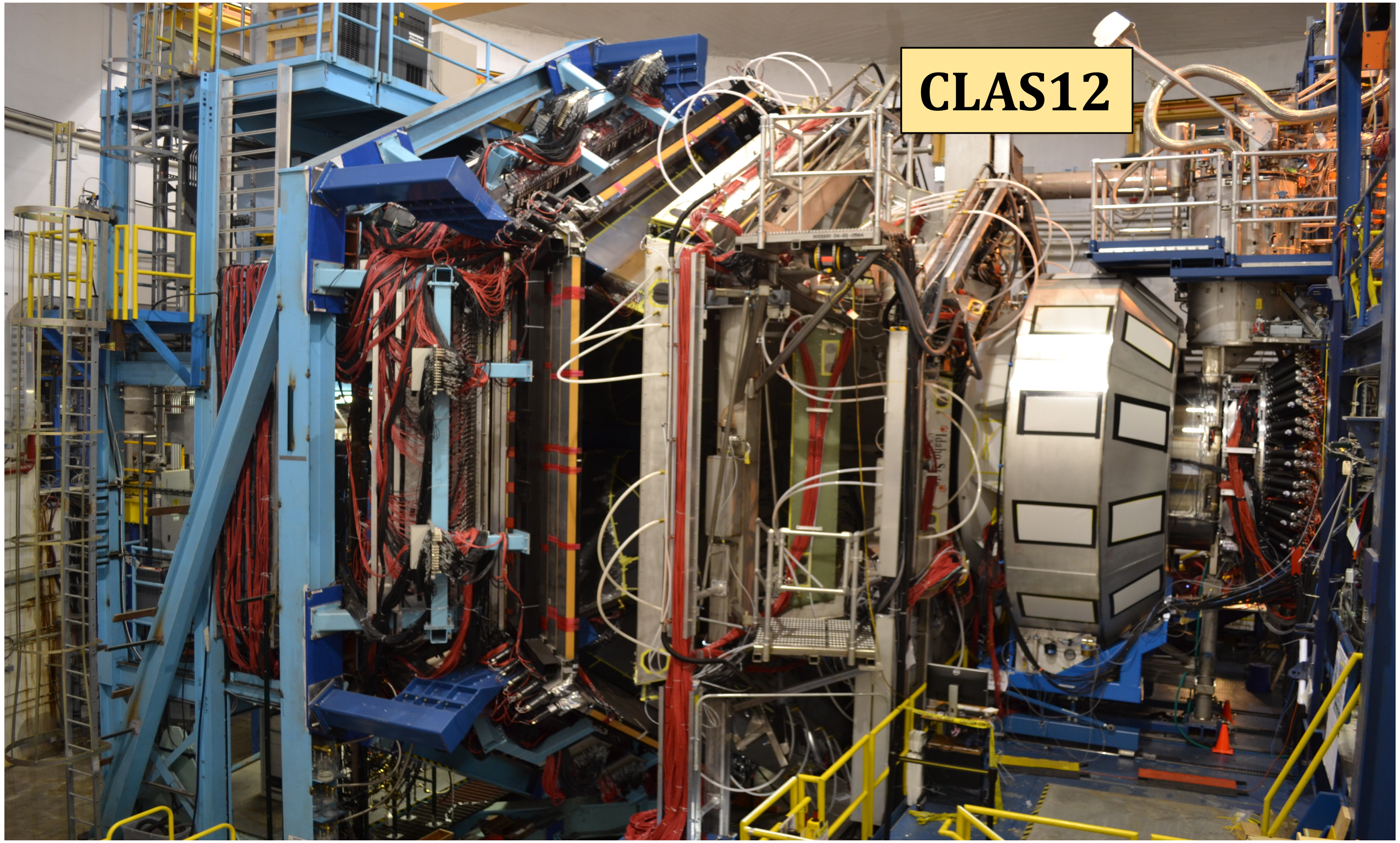
- The **mechanical** radius is measured at **large Q^2**, and is integrated over the entire –t range. The probe couples to **mass and pressure** that are concentrated closer to the proton's center**.**

- **The neutron mechanical radius is expected the same as the proton.**

Current operation of CLAS12 at JLab (Hall B)

In operation since 2018

Hadronic physics at higher energies, and luminosity L= $10^{35}cm^{-2}s^{-1}$, polarized target operation.

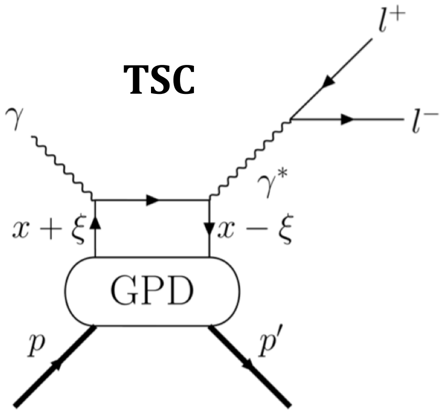


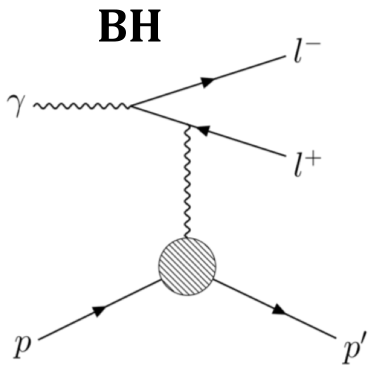
Nuclear Instr. Meth. A959 (2020) 163419

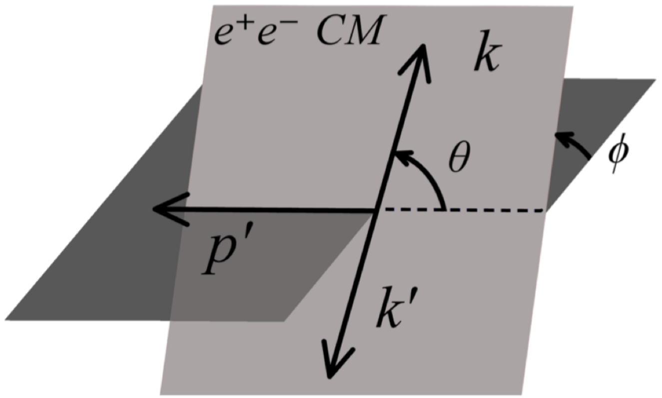
Time-like Compton Scattering

P. Chatagnon et al. (CLAS), PRL 127 (2021) 26, 262501

$\gamma p \rightarrow p e^+ e^-$







The forward-backward asymmetry is **directly** related to the CFF Re$\mathcal{H}(\xi, t)$ through the interference term with BH.

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A\frac{1+\cos^2\theta}{\sin\theta}\left[\cos\phi \, \mathrm{Re}\tilde{M}^{--} - \nu \cdot \sin\phi \, \mathrm{Im}\tilde{M}^{--}\right]$$

$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$

$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

Im$\mathcal{H}(\xi,t)$, Re$\mathcal{H}(\xi,t)$ are projected out through beam polarization ν and the ϕ dependence of σ_{INT}

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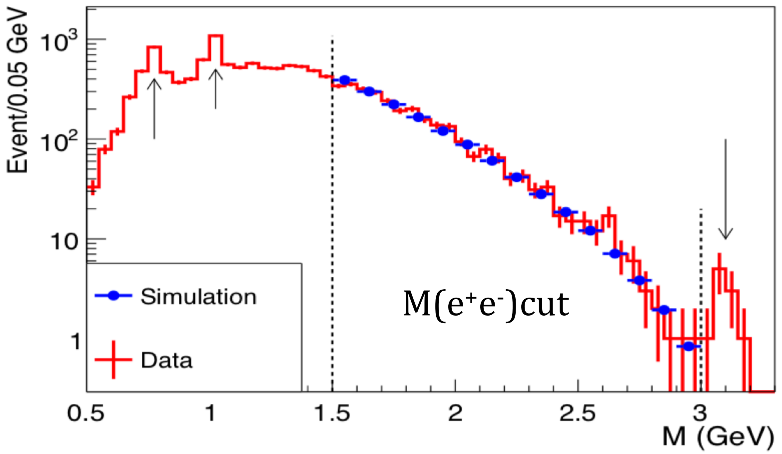
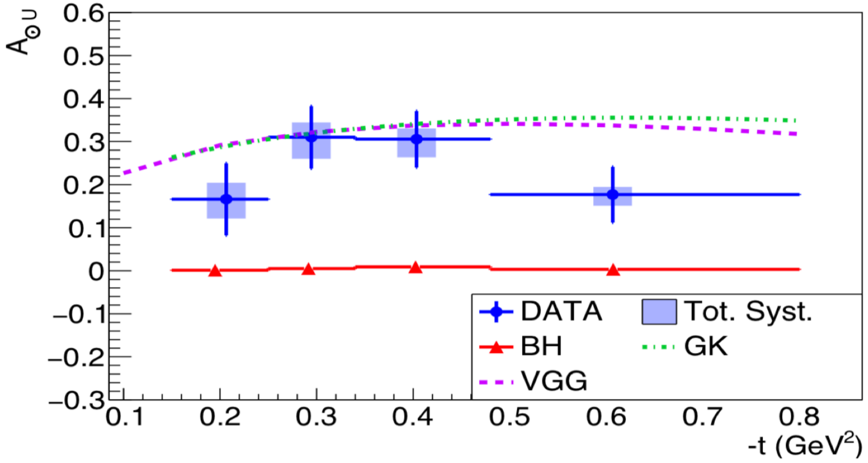
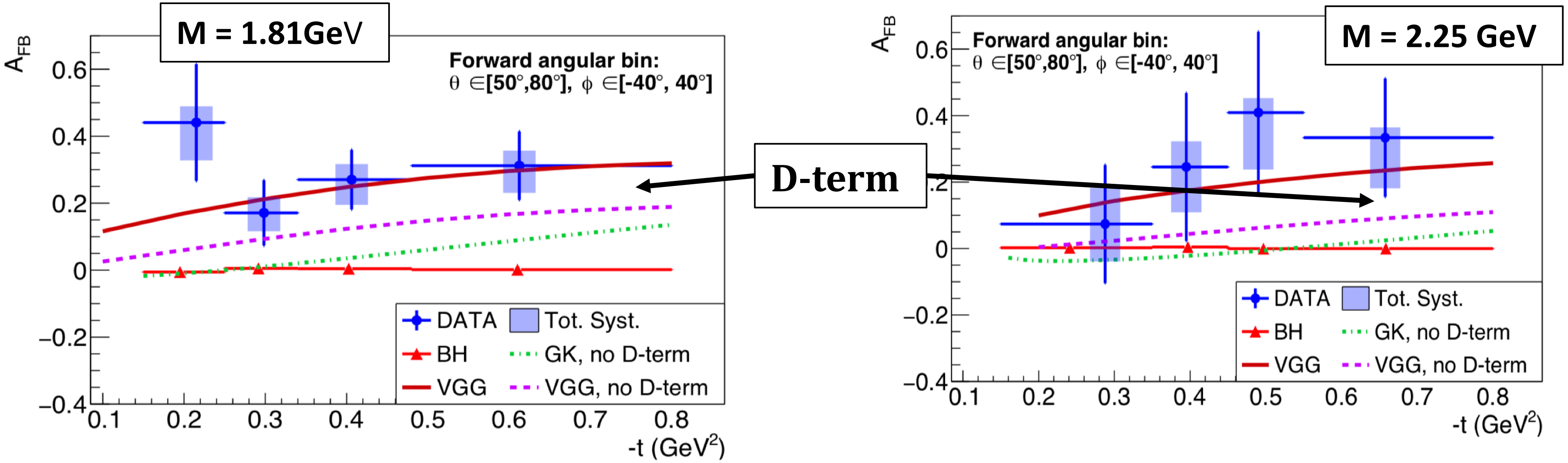
First results on TCS from CLAS12

P. Chatagnon et al. (CLAS), PRL 127 (2021) 26, 262501





TCS-BH BSA is consistent with the DVCS-BH BSA.



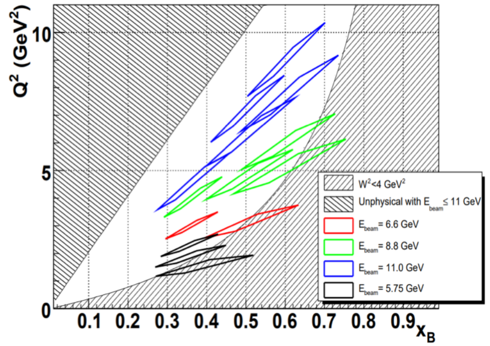
The D-term makes up a large part of the TCS FB-asymmetry.

This is consistent with D-term contributions to the Re(H) in DVCS.

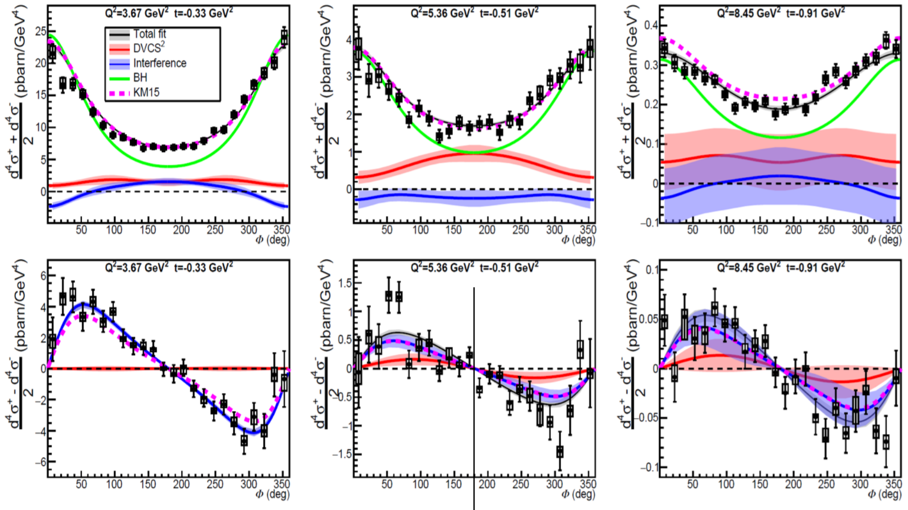
JLab@12 GeV – Hall A, CLAS12 RGA, RGB, RGC

Hall A

High impact for nucleon 3D imaging program
Precision scaling tests of DVCS cross section
Explore high x_B region for the first time



Proton target



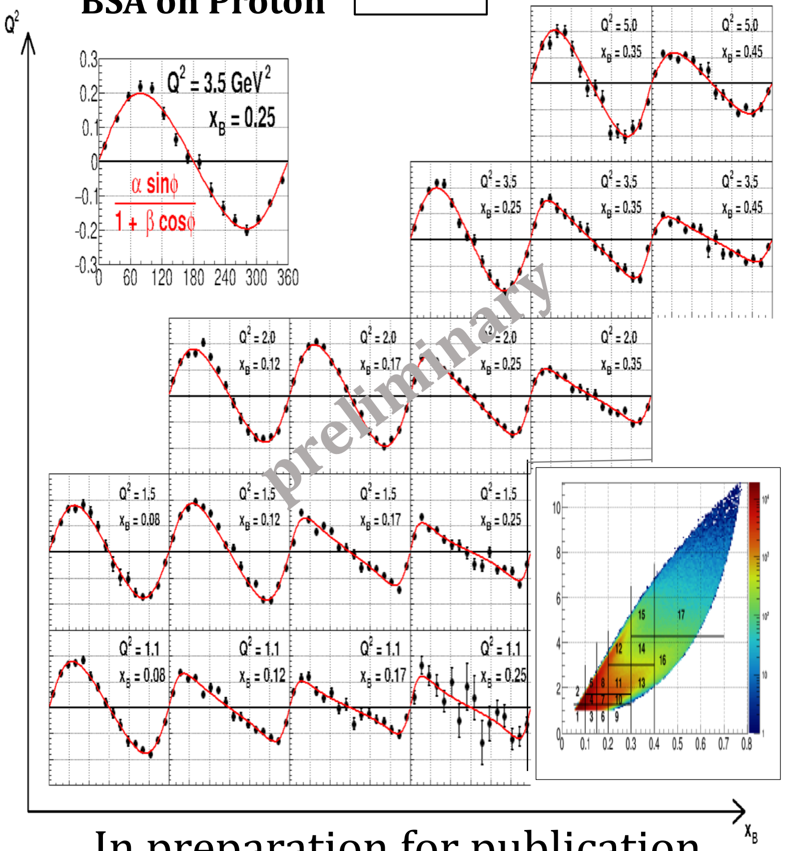
F. Georges et al, Phys. Rev. Lett. 128 (2022) 25, 252002

Hall B/CLAS12

Contiguous coverage in wide Q^2, x_B, t range enables 3D imaging and study of mechanical structure with controlled systematics.

RGA

BSA on Proton



In preparation for publication

RGB

Polarized electron beam at 10.6 GeV. Measure BSA on protons and neutrons in D_2.

Analysis in progress.

RGC

Polarized electron beam at 10.6 GeV on polarized proton (NH_3) and polarized deuterium (ND_3). Sensitivity to GPD $\widetilde{\mathcal{H}}$.

Experiment has started, scheduled to run until March 14, 2023.

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 access to the 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.

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

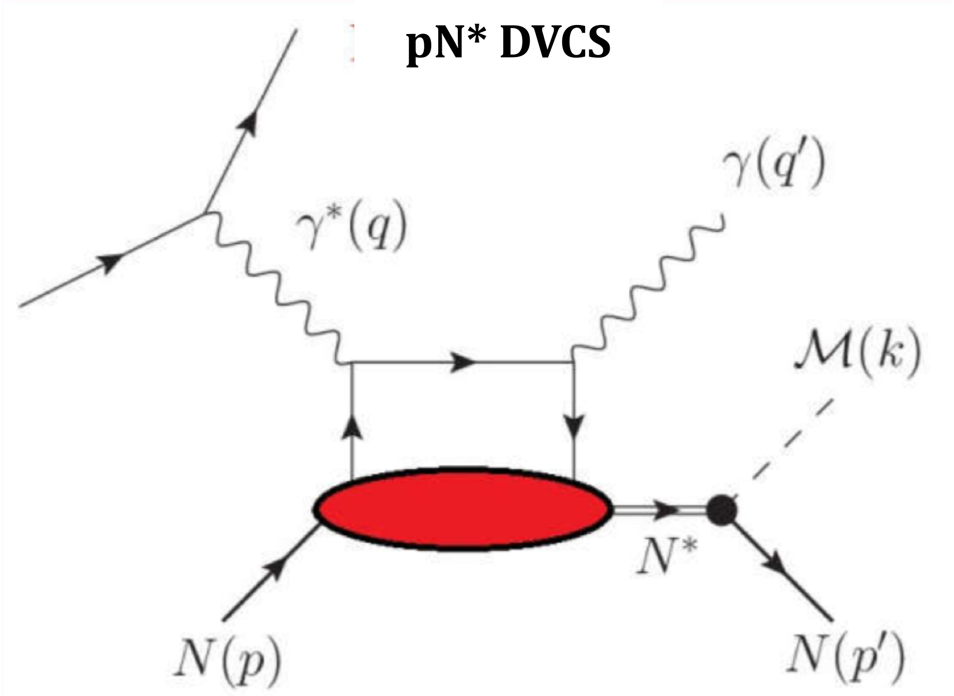
With CFF Im$\mathcal{H}$ known, determination of Im$\mathcal{E}$ requires DVCS measurements on transversely polarized proton target.

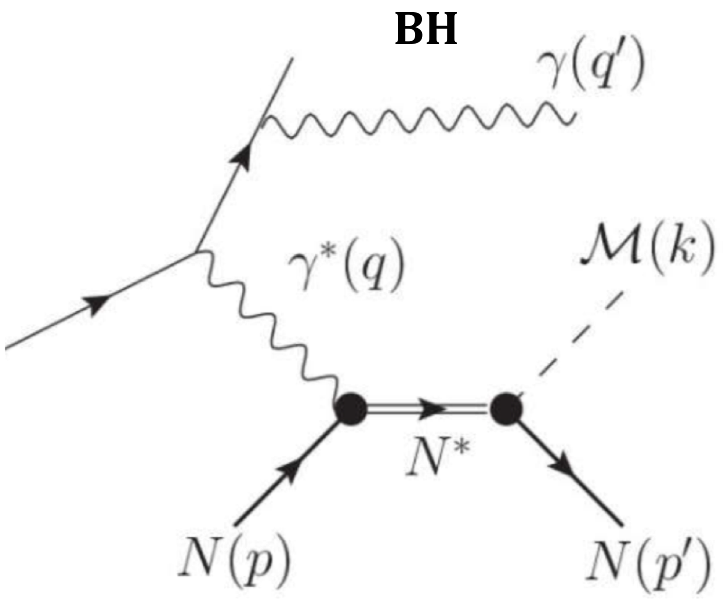
CLAS12 GPD program

Number	Title	Contact	Days	Energy	Target	Data status
E12-06-108	Hard Exclusive Electroproduction of π^0 and η	Kubarovski	80	11	lH_2	50%
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	80	11	lH_2	45%
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	120	11	NH_3	currently running
E12-11-003	DVCS on Neutron Target	Niccolai	90	11	lD_2	45%
E12-12-001	Timelike Compton Scat. & J/Ψ prod. in e^+e^-	Nadel-Turonski	120	11	lH_2	35%
E12-12-007	Exclusive ϕ meson electroproduction	Girod	60	11	lH_2	60%
C12-12-010	DVCS with a transverse target	Elouadrhiri	110	11	NH_3	in prep.
E12-16-010	DVCS with CLAS12 at 6.6 GeV and 8.8 GeV	D'Angelo	50+50	6.6 & 8.8	lH_2	scheduled 2023/24

From proton ground state to pN* transition GPDs

ep → eN*γ → eNMγ



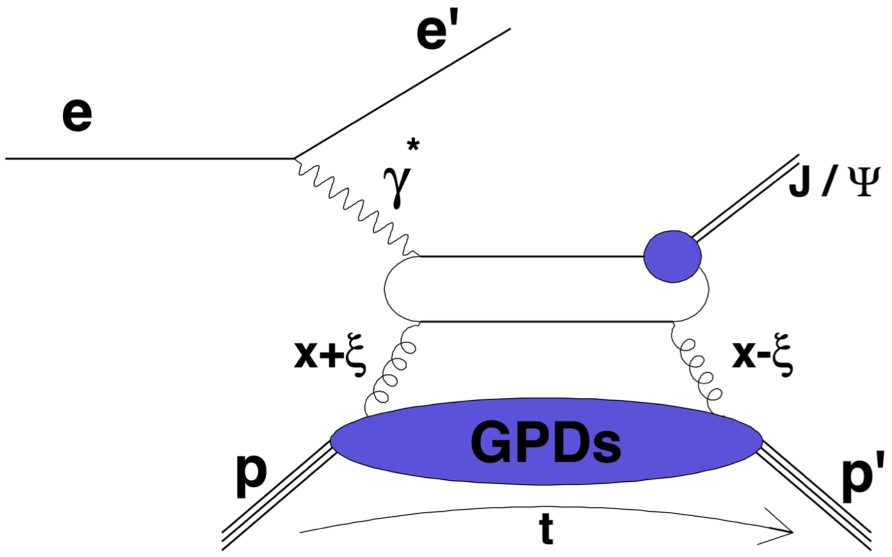


See talk by Kyungseon JOO

J/ψ as probe of mechanical properties of glue

Use J/ψ production at threshold
to probe gluon GPDs of the proton.

GlueX, CLAS12 upgrade, SOLID

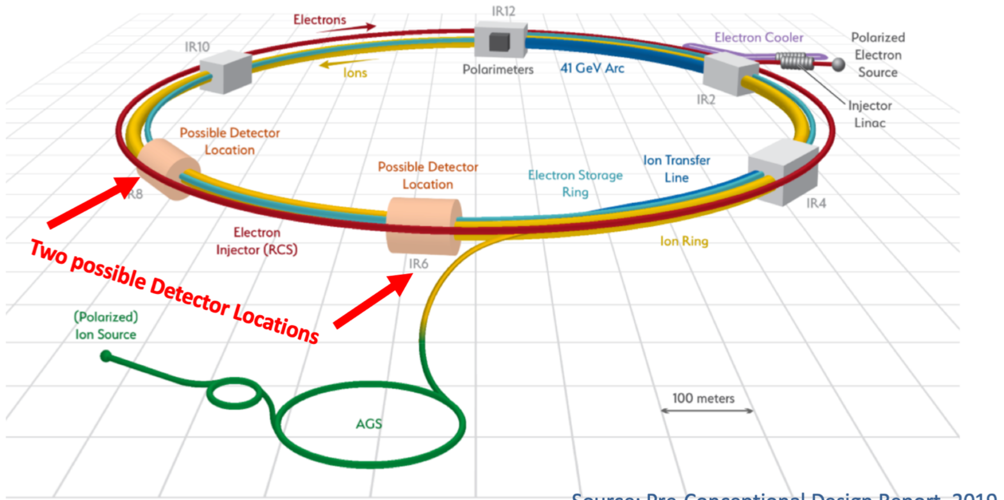


J/ψ mass provides short distance coupling to proton GPDs via 2-gluon exchange.

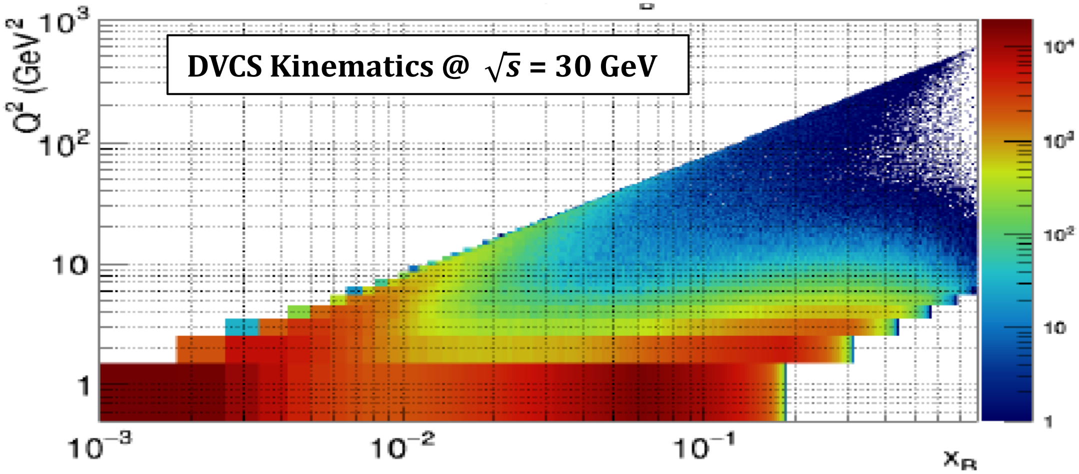
Electroproduction probes gluon CFF $\mathcal{H}_g$, $\mathcal{E}_g$, to measure gluonic contribution to shear, pressure, and J_g.

See discussion by Harry Lee on Monday

Precision studies of QCD@EIC

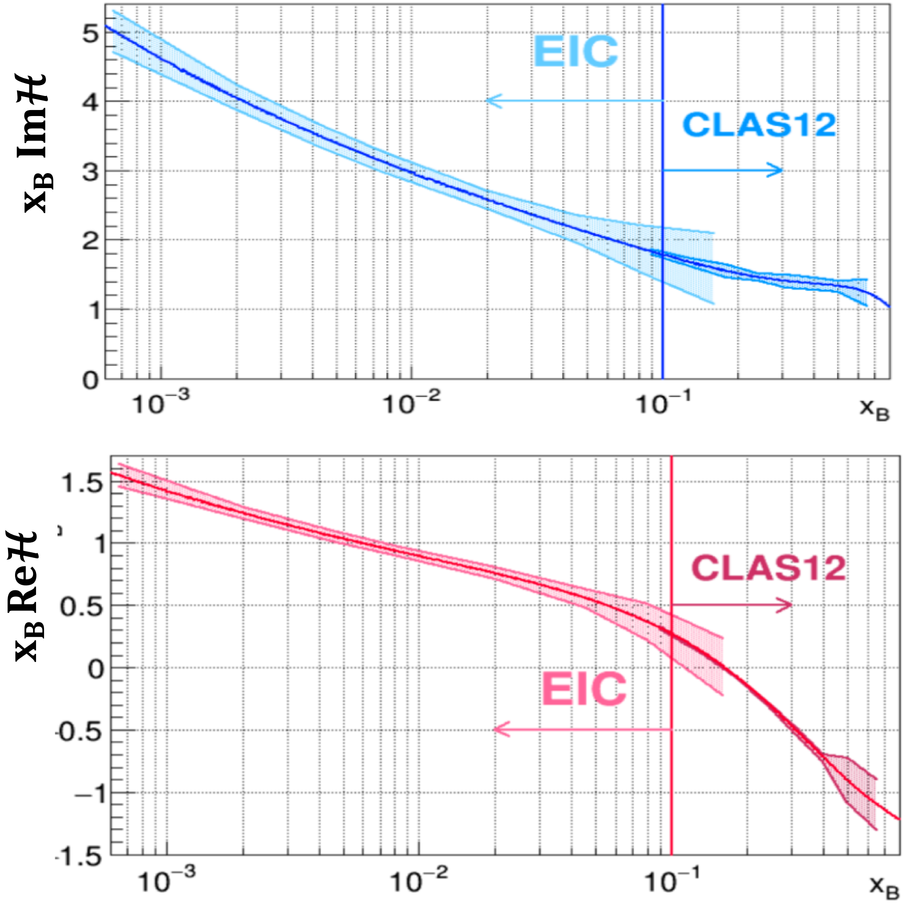


Source: Pre-Conceptional Design Report, 2019



Source: 2021 Workshops PSQ@EIC and IR2@EIC

CFF $\mathcal{H}$(x,t) extraction at EIC kinematics after L = 200 fb^{-1} w/ polarized electrons and protons.



Polarized electrons, polarized protons, with no dilution.

Credit: F.X. Girod

Summary and Outlook

- First data-based estimate of the stress and pressure on quarks in the proton
- Determination of the mechanical radius of the proton.
- First results on TCS in the 12 GeV era confirm large contributions of the D-term extracted from DVCS at lower energies.
- New 12 GeV data extend the kinematic reach and precision with higher luminosity experiments.
- DVCS experiments with positron beam are planned with different sensitivity to gravitational form factors.
- Longer term plans to employ DDVCS to directly access GPDs in DVCS with luminosity upgraded CLAS12 and SOLID (Hall A).
- The proposed JLab energy upgrade will further extend kinematics reach to sea quarks. (Pohang workshop next week)
- The Electron Ion Collider can provide large increase in kinematic reach to low x, and probe the gluon contributions.