Quark pressure & shear stress at 22 GeV

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Charge: The presentation should be focused on 3 points:

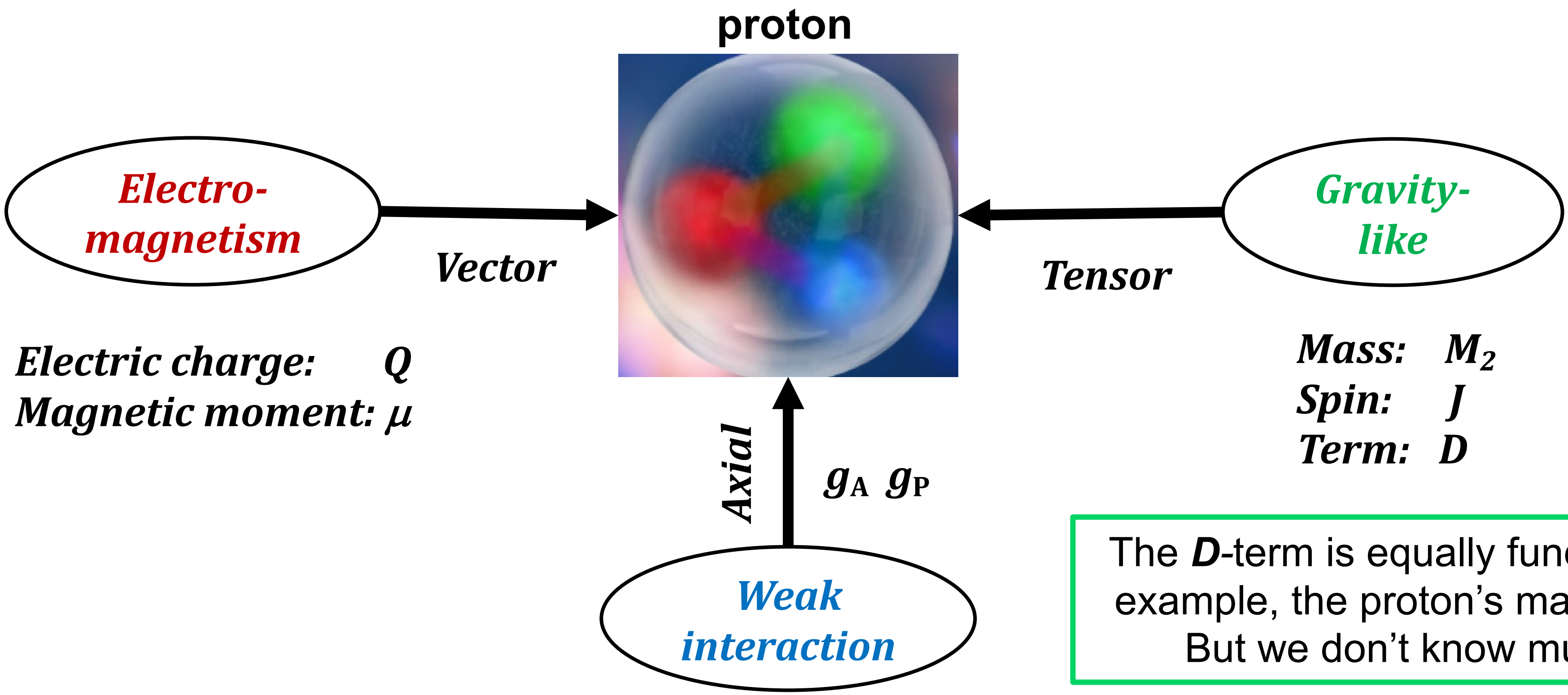
Q1: What fundamental property of nature are we exploring?
Q2: What is being measured and how precisely can it be measured?
Q3: Why are 22 GeV electrons necessary to make the measurement?

Probing novel properties of the strong interaction

Q1

The strong interaction of quarks and gluons in the proton has been studied in its *electromagnetic* *and* *weak* representation.

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



The ***D***-term is equally fundamental as, for example, the proton's magnetic moment. But we don't know much about it.

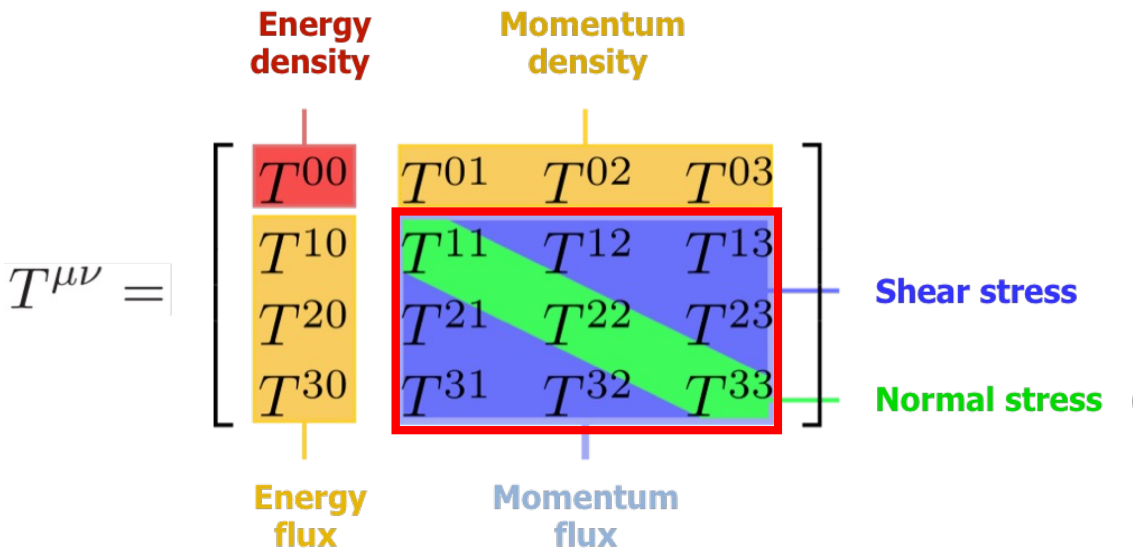
Energy Stress Tensor $T^{\mu\nu}$

Q1

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

Once we have determined the *D*-term we can fill in
The 3x3 matrix $T^{xy}(r)$, x,y =1,2,3

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



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

$$\widetilde{D}(r) = \int \frac{d^3\Delta}{(2\pi)^3}\, e^{-i\vec{\Delta}\cdot\vec{r}} D(-\vec{\Delta}^2)$$

$$s(r) = -\frac{1}{4M_N}\, r\, \frac{d}{dr}\frac{1}{r}\frac{d}{dr}\widetilde{D}(r) \quad \text{Shear stress}$$

$$p(r) = \frac{1}{6M_N}\frac{1}{r^2}\frac{d}{dr} r^2 \frac{d}{dr}\widetilde{D}(r) \quad \text{Pressure}$$

How get to *D*(t)?

"… 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)

Something to remember

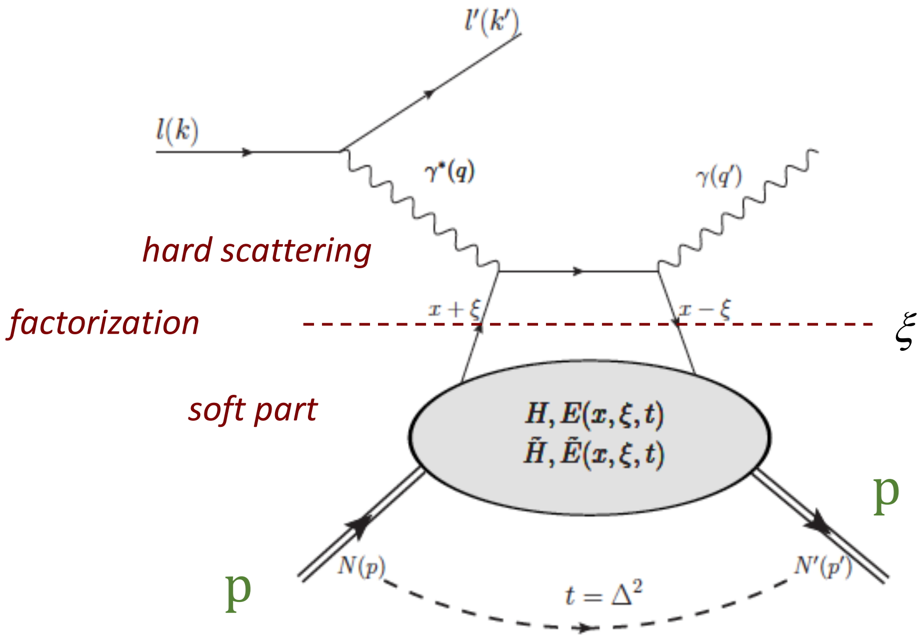
Q1

"It can be shown that any massless **spin-2 field** would give rise to a force indistinguishable[1] from gravitation, because a massless spin-2 field would couple to the stress–energy tensor in the same way gravitational interactions do."[*]

[1] Except for its strength (VB)

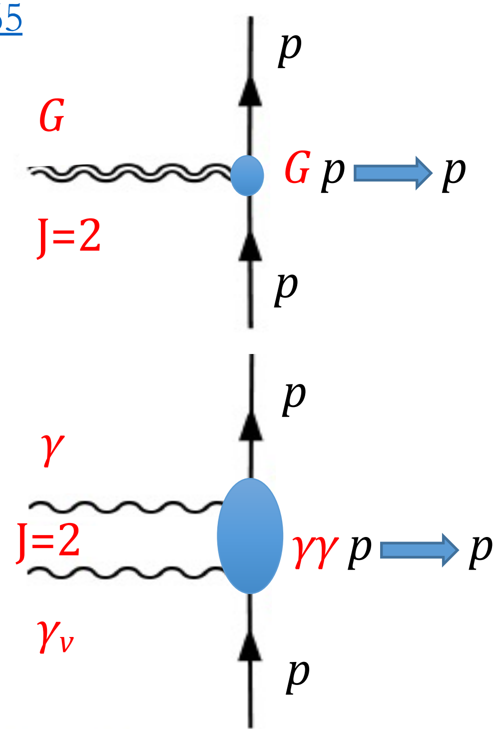
[*] *Misner, C. W.; Thorne, K. S.; Wheeler, J. A. (1973). Gravitation. W. H. Freeman. ISBN 0-7167-0344-0.*

From particle tomography to gravitational structure **Q1**



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

M.V. Polyakov, *Phys.Lett.B* 555 (2003) 57-62
GPDs and strong forces inside nucleons and nuclei.
https://arxiv.org/pdf/hep-ph/0210165



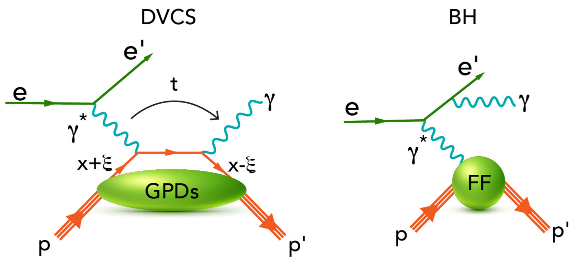
4 chiral even GPDs describe soft part. GPD ***H*** *is* ***essential*** to access gravitational form factor ***D(t)***.

DVCS may be a suitable probe of gravitational properties of particles!

The 2γ J=2 field couples to the EMT the same way gravity does, but with ~10^{38} times greater strength.

Isolating Compton Form Factors in DVCS

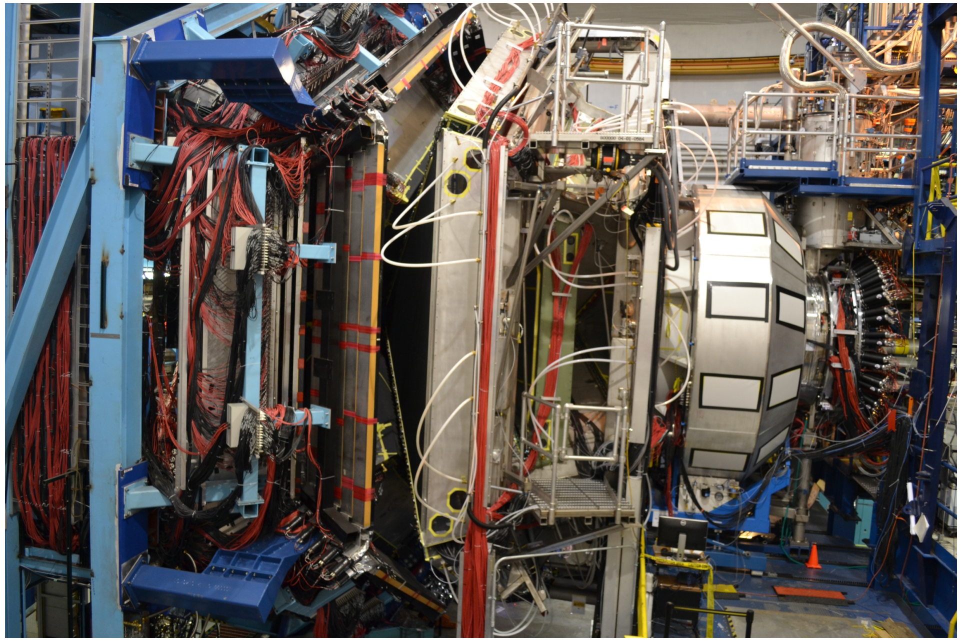
Q2



Probing gravitational structure through DVCS

Polarized beam, **unpolarized** target:

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi$ ⇒ $\mathcal{H}(\xi,t)$



Unpolarized beam, **longitudinal** target:

$\Delta\sigma_{UL} \sim \sin\phi\ \mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \xi/(1+\xi)\mathcal{E})\}d\phi$ ⇒ $\widetilde{\mathcal{H}}(\xi,t)$

Unpolarized beam, **transverse** target:

$\Delta\sigma_{UT} \sim \cos\phi\ \sin(\phi_s-\phi)\mathrm{Im}\{k(F_1\mathcal{E} - F_2\mathcal{H})\}d\phi$ ⇒ $\mathcal{E}(\xi,t)$

Unpolarized cross section:

Re(CFFs), separate h.t. contributions to DVCS ⇒ $\mathcal{R}e(T^{DVCS})$

Gravitational Form Factors & Compton Form Factors

Q2

Gravitational form factor of the EMTs

$$\langle p', \vec{s}' | T_a^{\mu\nu}(0) | p, \vec{s} \rangle = \bar{u}(p', \vec{s}') \Bigg[A_a(t) \frac{P^\mu P^\nu}{M_N} + D_a(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{4M_N} + \bar{C}_a(t) M_N g^{\mu\nu} + J_a(t) \frac{P^{\{\mu} i\sigma^{\nu\}\lambda}\Delta_\lambda}{M_N} - S_a(t) \frac{P^{[\mu} i\sigma^{\nu]\lambda}\Delta_\lambda}{M_N} \Bigg] u(p, \vec{s})$$

$a = q, G$

Mellin moments

$$\int_{-1}^{1} \mathrm{d}x\, x H_q(x, \xi, t) = A_q(t) + \xi^2 D_q(t)$$

$$\int_{-1}^{1} \mathrm{d}x\, x E_q(x, \xi, t) = B_q(t) - \xi^2 D_q(t)$$

$$B_q(t) = 2J_q(t) - A_q(t)$$

Compton Form Factors (CFFs)

$$\mathrm{Re}\mathcal{H}(\xi, t) + i\,\mathrm{Im}\mathcal{H}(\xi, t) = \sum_q e_q^2 \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right] H_q(x, \xi, t)$$

Fixed-t dispersion relation

$$\mathrm{Re}\mathcal{H}(\xi, t) = \mathcal{C}_\mathcal{H}(t) + \frac{1}{\pi} \mathrm{P.V.} \int_0^1 \mathrm{d}\xi' \left[\frac{1}{\xi - \xi'} - \frac{1}{\xi + \xi'} \right] \mathrm{Im}\mathcal{H}(\xi', t)$$

$\mathcal{C}_\mathcal{H}(t) \rightarrow D_q(t)$

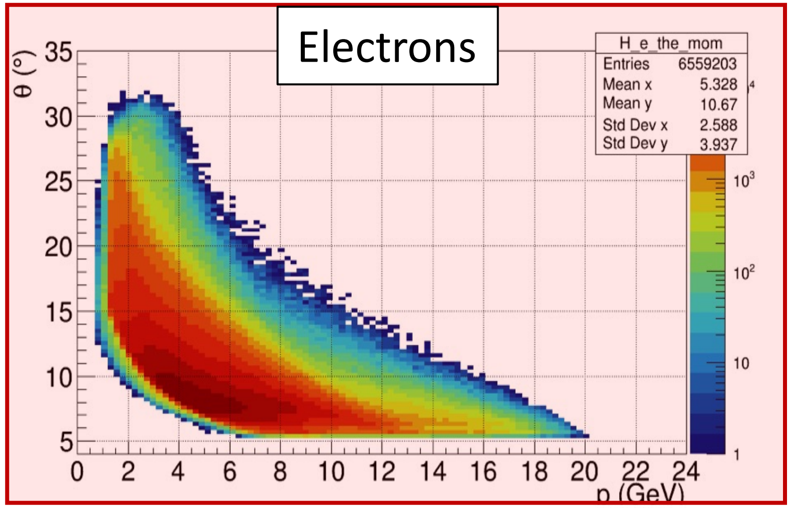
$$\mathcal{C}_\mathcal{H}(t) = \mathcal{C}_\mathcal{H}(0) \left[1 + \frac{(-t)}{M^2} \right]^{-\lambda}$$

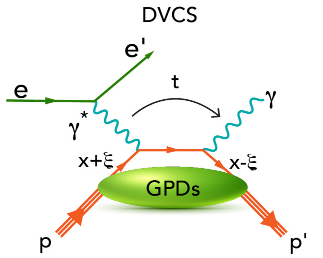
$$\mathcal{C}_\mathcal{H}(t) \approx \frac{10}{9} d_1^{u+d}(t) = \frac{25}{18} D_{u+d}(t)$$

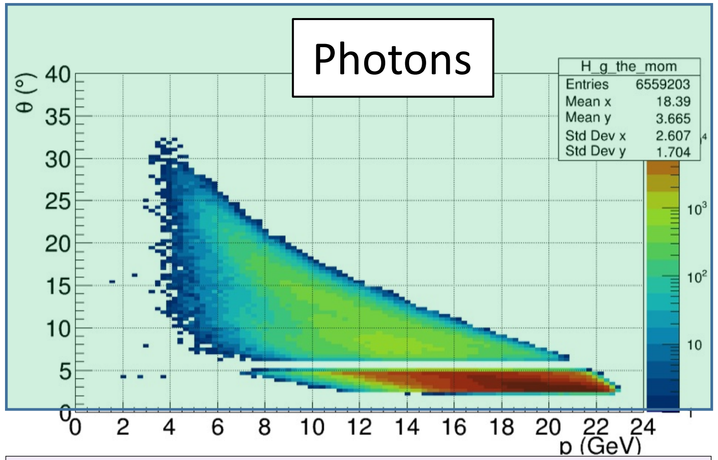
Exclusive DVCS @ 24 GeV with CLAS12

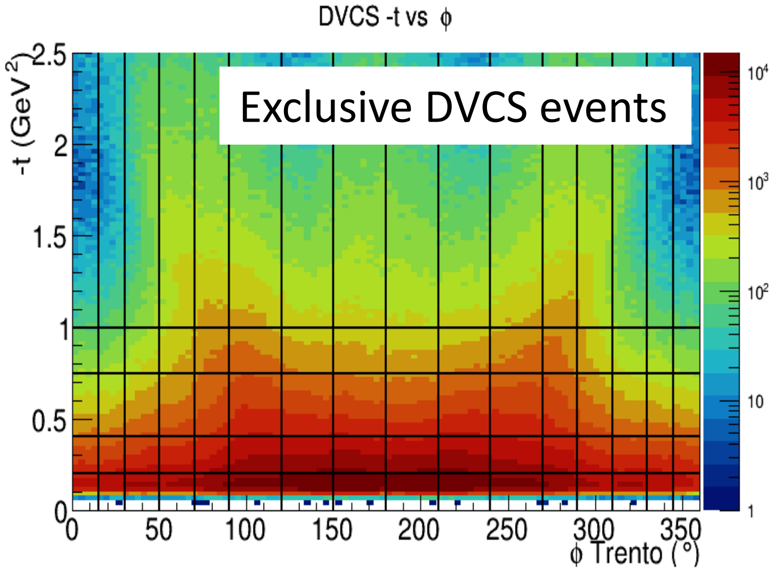
Q2

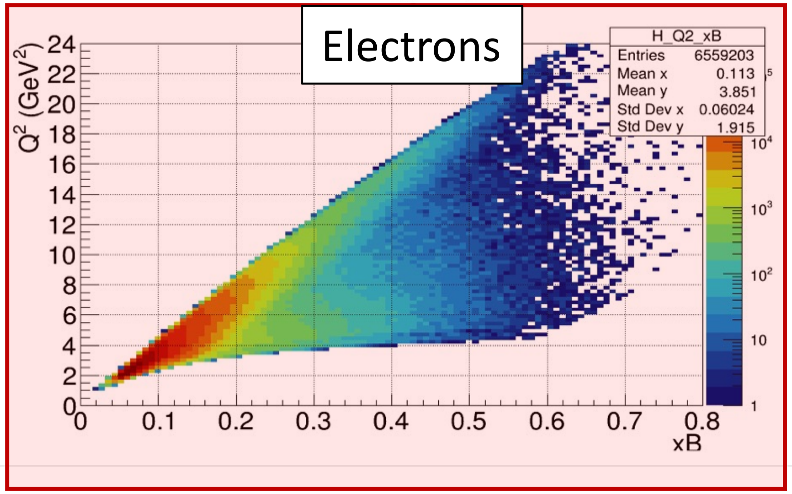
F.X. Girod

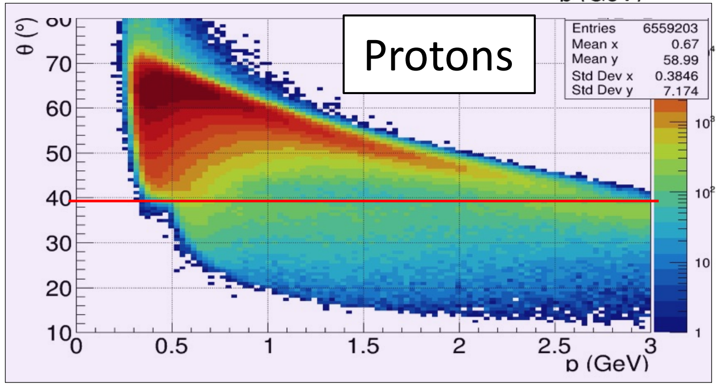


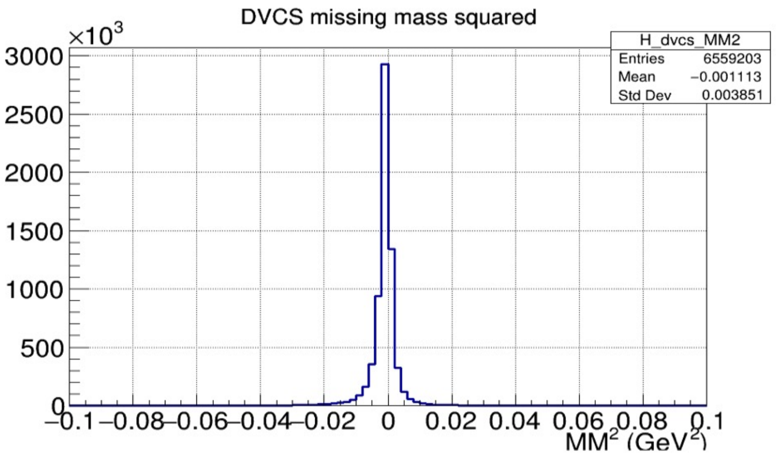












Beam spin asymmetry A_{LU} (E=24GeV)

Q2

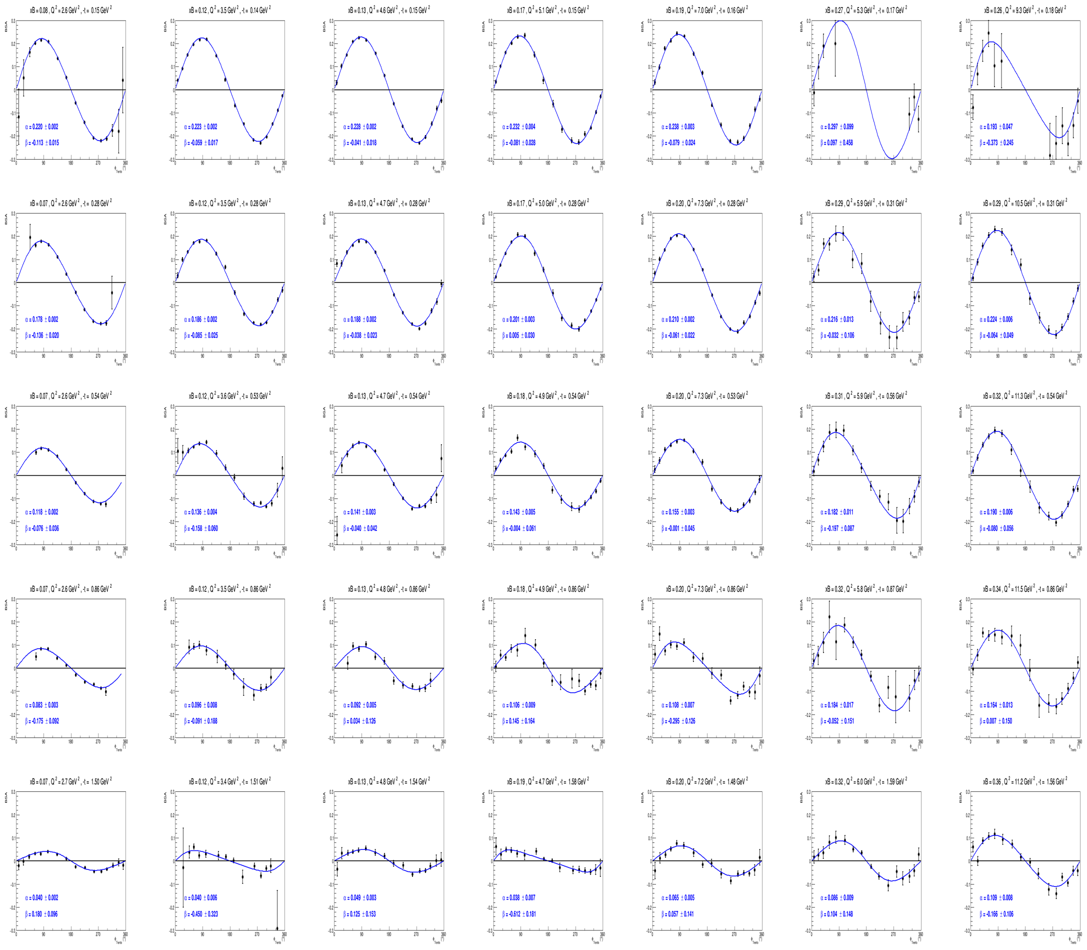
From full simulations & reconstructions

F.X. Girod

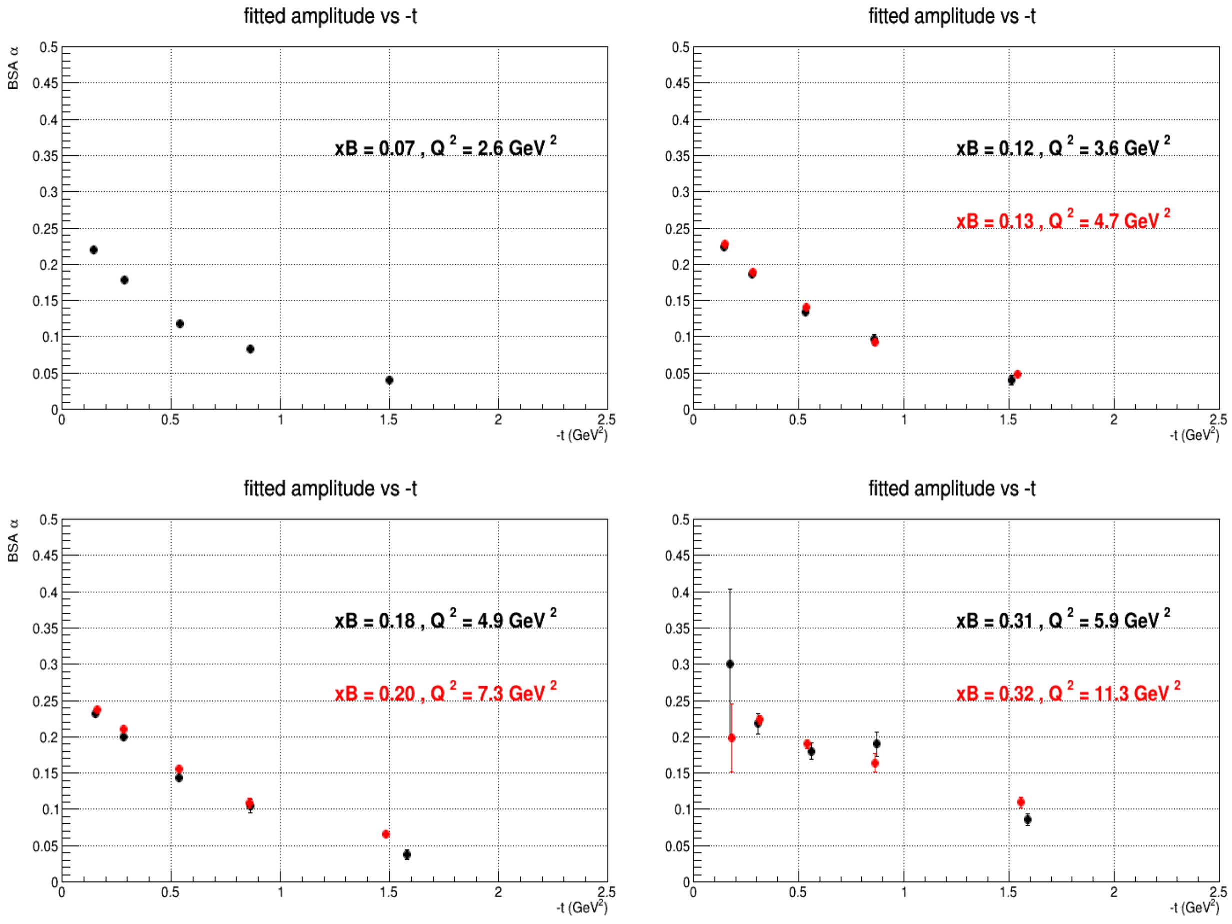
$A_{LU} = \alpha \sin\phi / (1 + \beta \cos 2\phi)$

$2.6 < Q^2 < 11.5\ GeV^2$

$0.15 < -t < 1.6\ GeV^2$



$0.07 < x_B < 0.36$



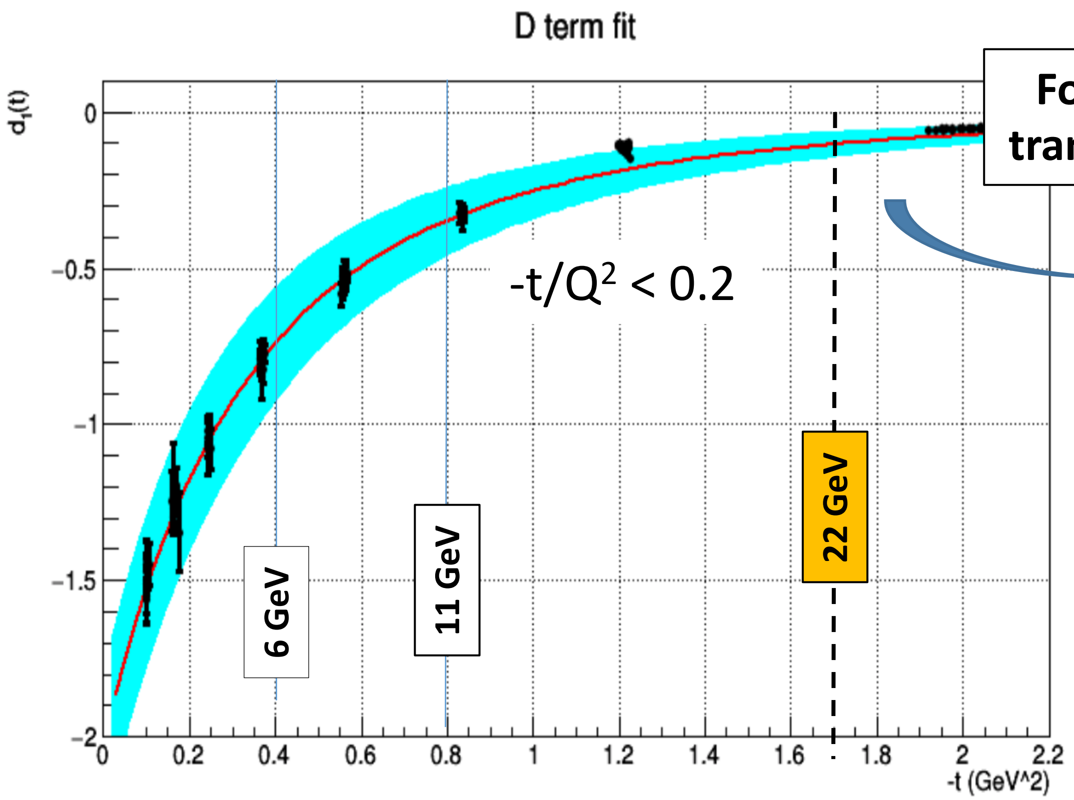
Answer to Q2

The proton's D(t) and pressure at 22 GeV

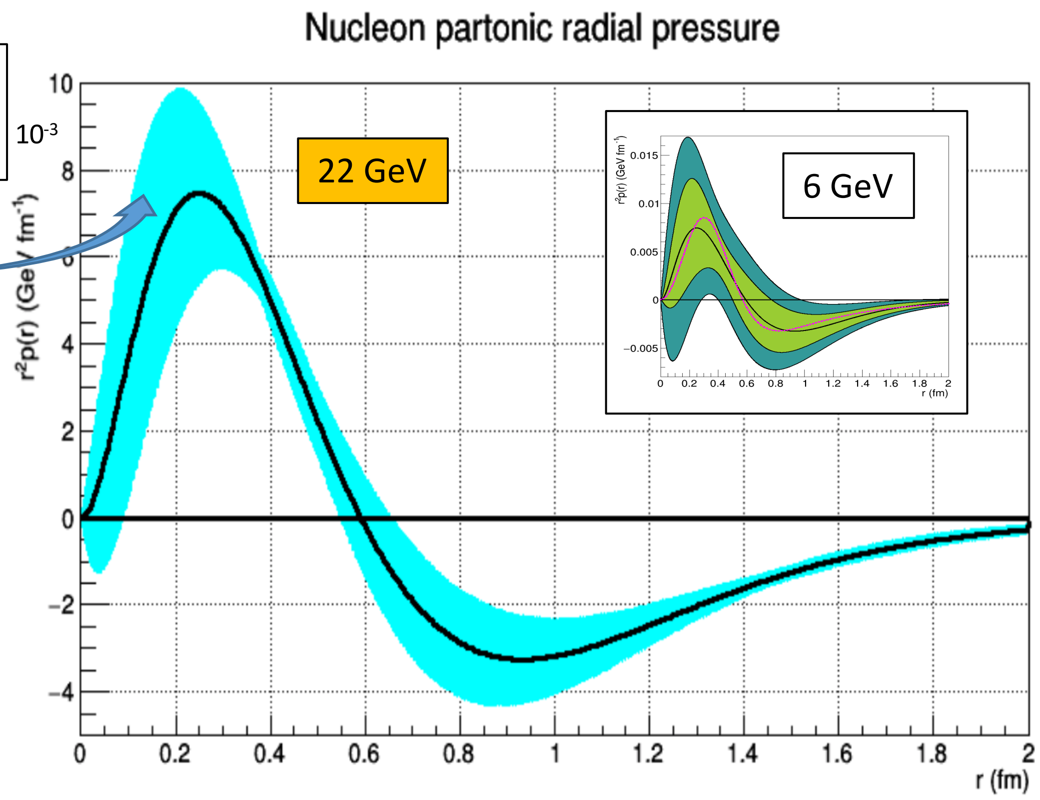
Q3

Fitting the dispersion relation to Im$\mathcal{H}$, Re$\mathcal{H}$

$-t/Q^2 < 0.2$



Fourier transform



22 GeV will cover a large range in -t and may discover existence of pressure domains.

References to GPDs, DVCS, GFF, Stress/Forces

Q3

15 references out of 60 total to the White Paper

- Bridging Electromagnetic and Gravitational Form Factors: Insights from LFHQCD
- Gravitational form factors of charmonia
- Exploring Baryon Resonances with Transition Generalized Parton Distributions: Status and Perspectives
- Stress out of charmonia
- Understanding Gravitational Form Factors with the Weizsäcker-Williams Method
- Systematic description of hadron's response to nonlocal QCD probes: Froissart-Gribov projections in analysis of deeply virtual Compton scattering
- Pion and kaon electromagnetic and gravitational form factors
- One-loop evolution of twist-2 generalized parton distributions
- Generalized parton distributions for the lowest-lying octet baryons
- Proton's gluon GPDs at large skewness and gravitational form factors from near threshold heavy quarkonium photoproduction
- Forces inside a strongly-coupled scalar nucleon
- Gravitational form factors of the proton from near-threshold vector meson photoproduction*
- Deeply virtual Compton process e-N→e-γπN to study nucleon to resonance transitions
- Fresh look at the generalized parton distributions of light pseudoscalar mesons

Why 22 GeV?

Q3

- The extension of data to **22 GeV** will very significantly reduce limitations from using 6 GeV and 10.6 GeV data
  - Much increased range in –t to probe the short distance behavior
  - Extended range to lower $x_B > 0.05$ limit.
  - Availability of corrections from higher Gegenbauer moments.

- This is the first time that the subject of *Gravitational Form Factors* is part of the NSAC LRP (2023). It should be viewed as a comprehensive program that will be more complete the wider the ranges in available energies and in luminosities are.
- Other gravitational form factors of the proton will be accessible A(t), J(t) accessing mass distribution and angular momentum distributions in protons, neutrons, other baryons, mesons, and nuclei. Every hadron/nucleus has its specific *D*-term for the quark and gluon content.
- Further opening a broad, novel program of mechanical properties of particles.