Studies of the Nucleon Gravitational Form Factors at JLab

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HADRON2025

29th of March 2025

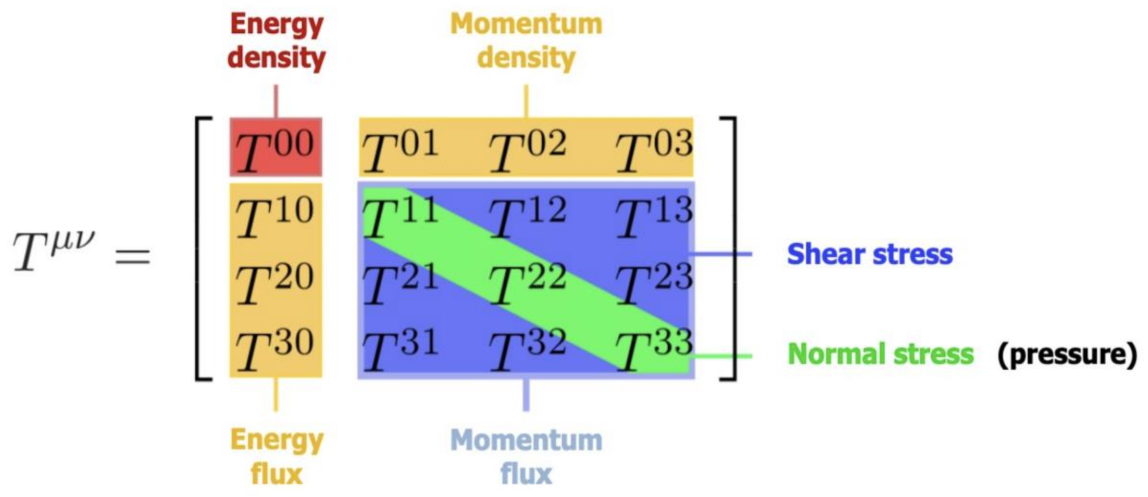
Nucleon Gravitational Form Factors

The mechanical structure of the nucleon is defined by analogy to General Relativity via the QCD energy-momentum tensor (EMT).

The nucleon gravitational form factors (GFFs) encode information about the matrix elements of the QCD energy-momentum tensor.

M(t) : Mass/energy distribution inside the nucleon
J(t) : Angular momentum distribution
d(t) : Forces and pressure distribution

H. Pagels, *Phys. Rev.* **144** (1966).



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

Nucleon Gravitational Form Factors

The mechanical structure of the nucleon is defined by analogy to General Relativity via the QCD energy-momentum tensor (EMT).

The nucleon
information a
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M(t) : Mass/e
J(t) : Angular
d(t) : Forces

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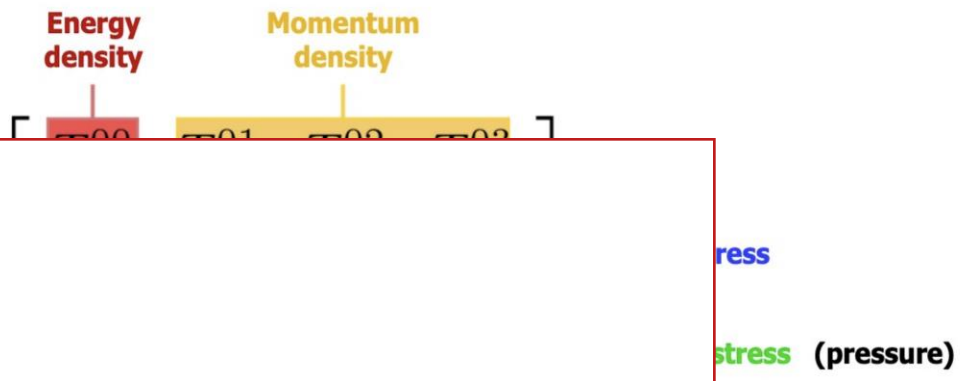


"….. there is very little hope of learning anything about the detailed mechanical structure of a particle, because of the extreme weakness of the gravitational interaction"
H. Pagels c. 1966

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

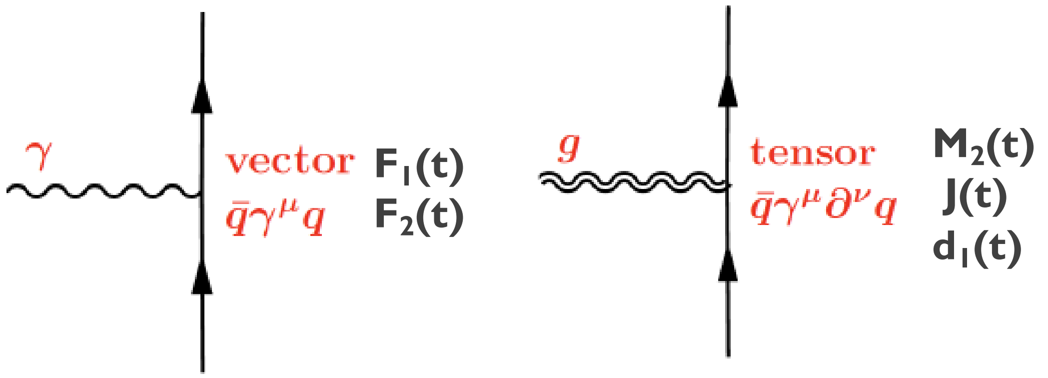
Probing the Mechanical Structure of the Nucleon

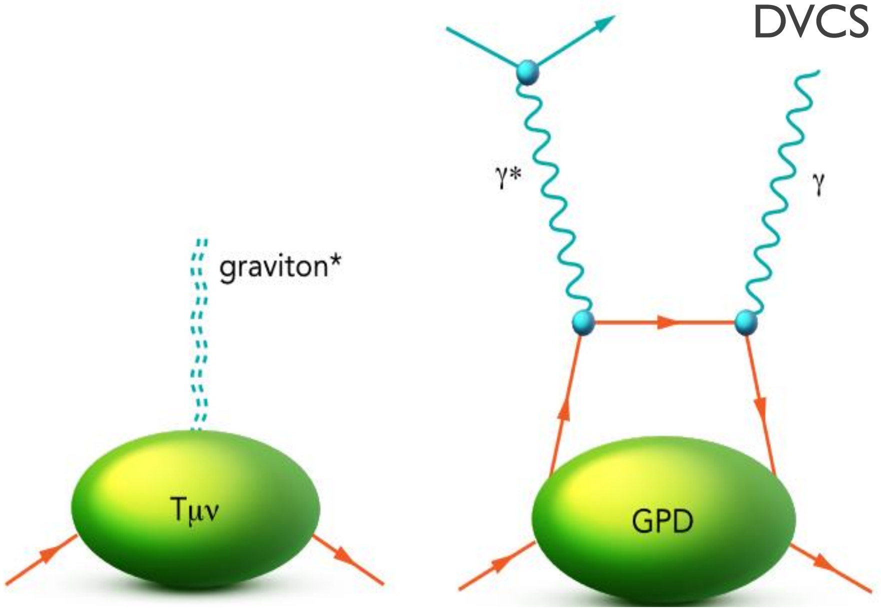
Electromagnetic properties (eg electromagnetic form factors, proton charge radius…) probed with photons.

Gravitational properties are probed with gravitons but graviton beams are currently experimentally unfeasible…

Instead, spin-2 fields couple to the EMT and gives rise to a force indistinguishable from gravity, which allows to probe the nucleon GFFs.

Deeply Virtual Compton Scattering (DVCS) was used to extract the quark GFFs, J/ψ near-threshold photoproduction was used to extract the gluon GFFs.





H. Pagels, *Phys. Rev.* **144** (1966).
C. W. Misner, K.S. Thorne, J.A Wheeler, W. H. Freeman 1973 Box 18.1.
V.D. Burkert, L. Elouadrhiri, F.X. Girod , *Nature* **557** 7705 (2018).
V.D. Burkert, L. Elouadrhiri, F.Girod, arXiv:2104.02031 (2021).

Jefferson Lab clas

Thomas Jefferson National Accelerator Facility (JLab)

JLab is located in Newport News, Virginia, aims to further the global understanding of QCD.

The Continuous Electron Beam Accelerator Facility (CEBAF) produces a 12 GeV electron beam.

Fixed target experiments with a large range of targets & experimental setups.

The High Resolution Spectrometer (HRS) was located in Hall A. Upcoming Solenoidal Large Intensity Device (SoLID) will be located in Hall A.

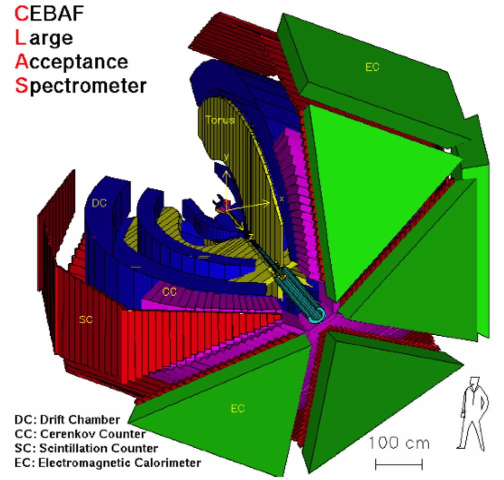
The CEBAF Large Acceptance Spectrometer (CLAS & CLAS12) is located in Hall B.

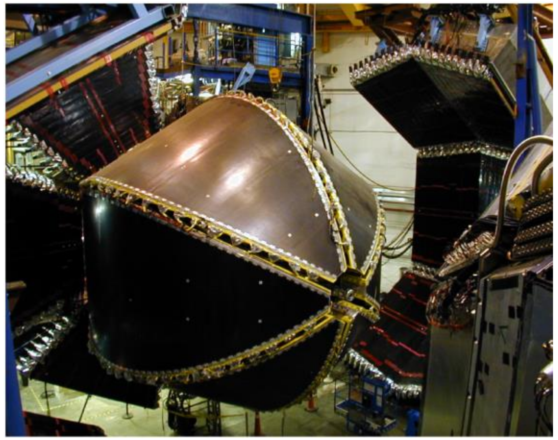
The Super High Momentum Spectrometer (SHMS) & High Momentum Sprectrometer are located in Hall C.

The Gluonic Excitation Experiment (GlueX) is located in Hall D.

P.A. Adderley *et. al., Phys. Rev. Accel. Beams* **27** 084802 (2024).

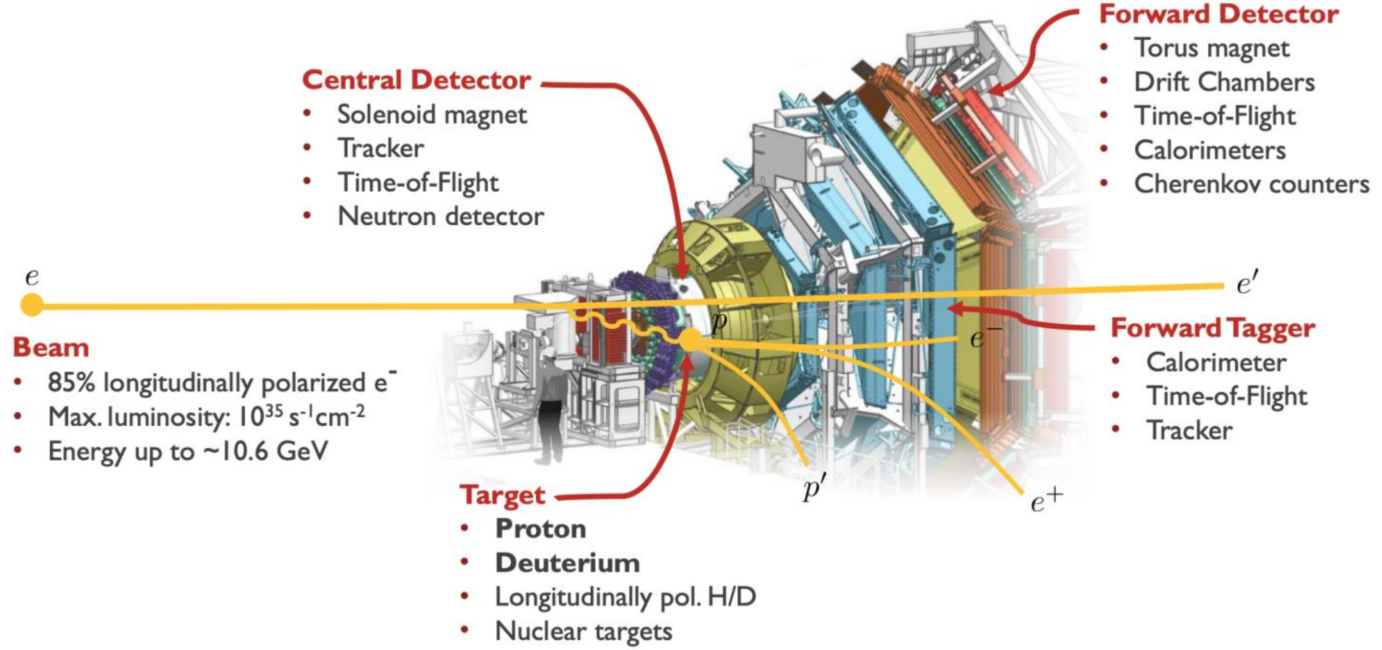
CEBAF Large Acceptance Spectrometer - Hall B (CLAS & CLAS12)





CLAS12 is the successor of CLAS in the 12 GeV JLab era.

Large angular coverage enables measurements of many reactions over wide kinematic range.

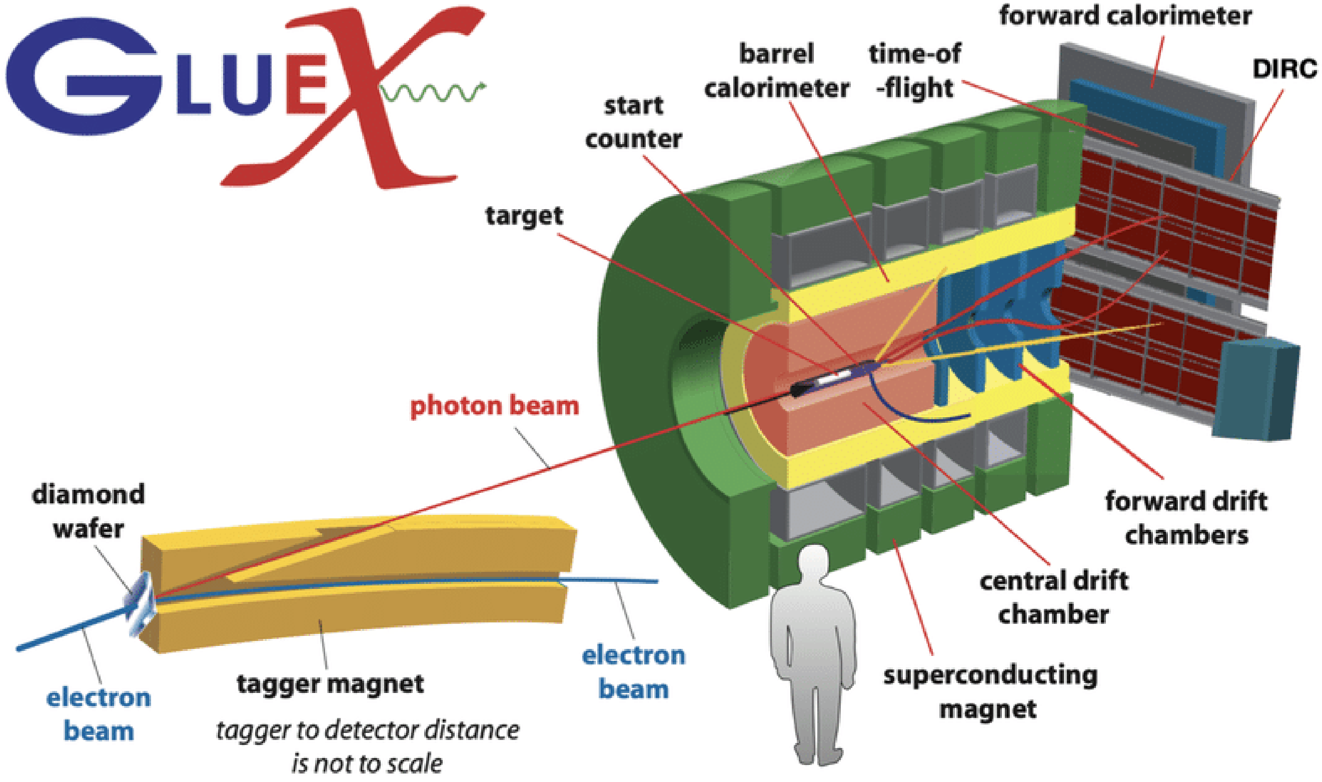


B.A. Mecking *et. al.*, *NIM A* **503** 3 513-553 (2003).
V.D. Burkert *et. al.*, *NIM A* **959** 163419 (2020).

GlueX - Hall D

GlueX produces a bremsstrahlung photon beam using the diamond wafer. Electrons are tagged to determine the photon energy.

Large angular coverage enables measurements of many reactions over wide kinematic range.



S. Adhikari *et. al.*, *NIM A*, **987** 164807 (2021).

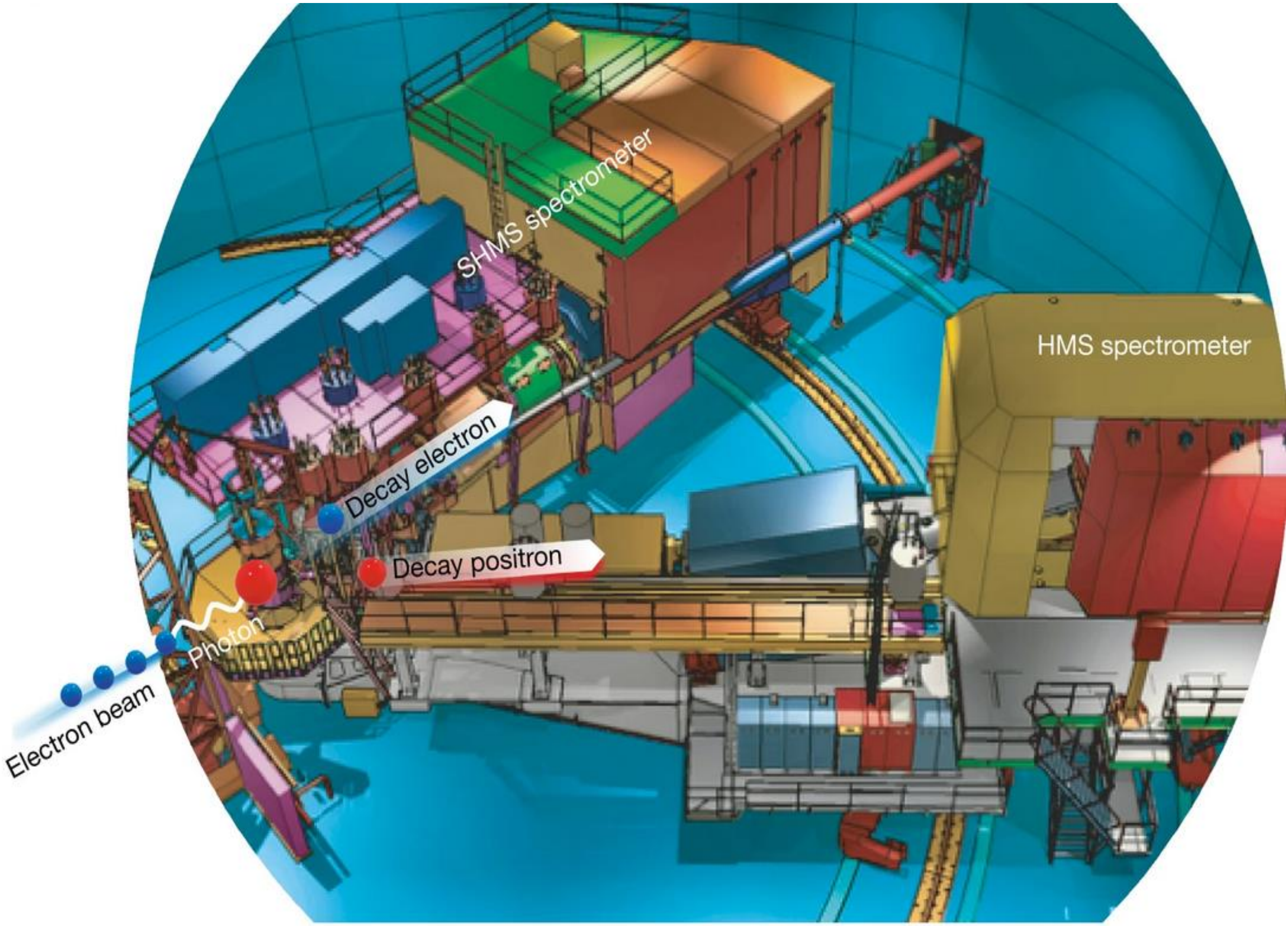
HRS – Hall A
SHMS & HMS - Hall C

Hall A employed two identical high resolution spectrometer (HRS) arms.

Hall C employs two high precision spectrometer (SHMS & HMS).

Small acceptance allows to run at high beam intensities.

Tuning the position of the spectrometer arms provides precise measurements of specific reactions with low background at specific kinematic points.



J. Alcorn *et. Al.*, *NIM A* 522 **3** 294-346 (2024).
S. Ali, *et. al.*, arXiv:2503.08706 (2025).

Deeply Virtual & Timelike Compton Scattering

GFFs can be extracted from the Mellin moments of Generalized Parton Distributions (GPDs).

GPDs are determined from the Compton Form Factors (CFFs) through an integral over the quark longitudinal momentum fraction x.

Exploit the interference of the Deeply Virtual Compton Scattering (DVCS) and Timelike Compton Scattering (TCS) amplitudes with the Bethe-Heitler amplitude that results in a polarized beam spin asymmetry to estimate CFFs.

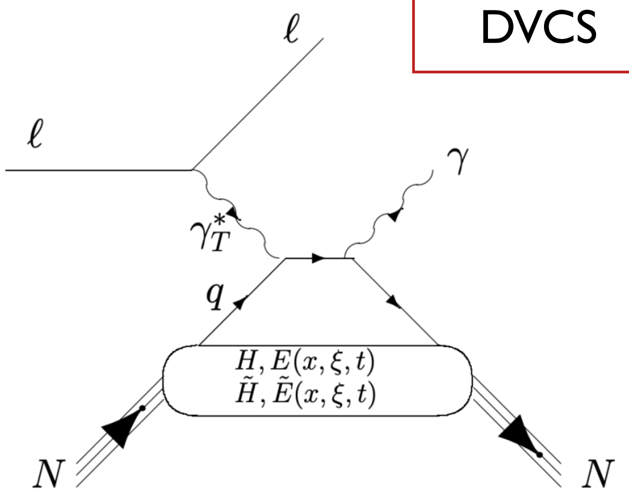
$$\int dx\, x\, [H(x,\xi,t) + E(x,\xi,t)] = 2J(t)$$

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

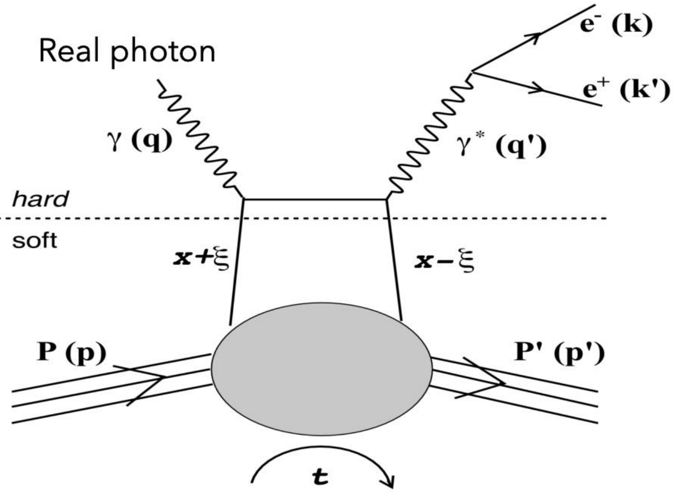
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx H(x,\xi,t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right)$$

D. Müller et al., *F.Phys.* **42** (1994).
X. Ji, *PRL* **78** 610 (1997).
A. Radyushkin, *PLB* **380** (1996).
M, Boer et. al., *Eur. Phys. J. A* **51** 103 (2015).
X. Ji, *Phys. Rev. D* **55** 7114 (1997).
M. Polyakov, *Phys. Lett. B* **555** 57 (2003).

DVCS



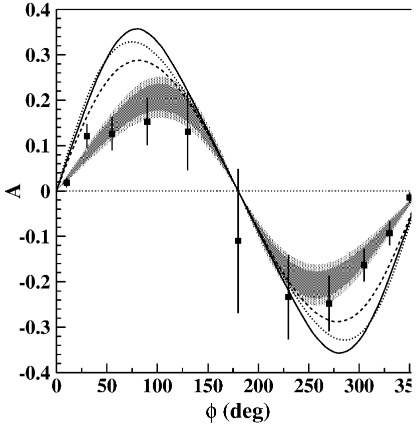
TCS

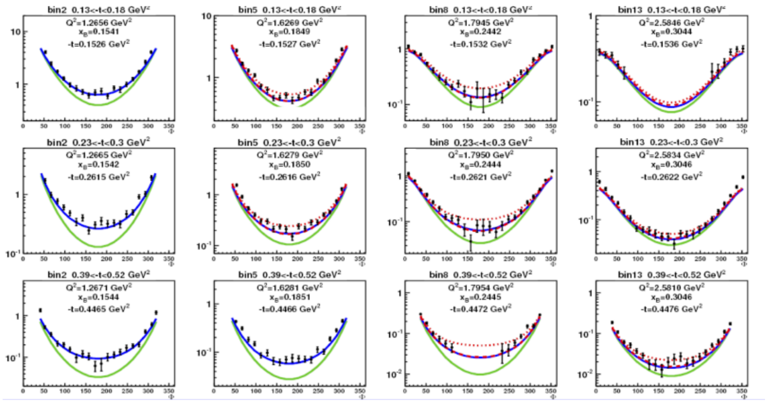


DVCS Measurements at JLab

CLAS – Hall B

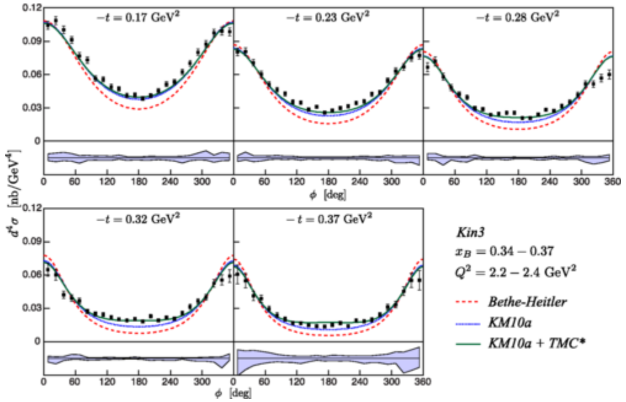
First observation of a DVCS signal at CLAS and HERMES in 2001.
Soon followed by additional measurements including of the cross section.

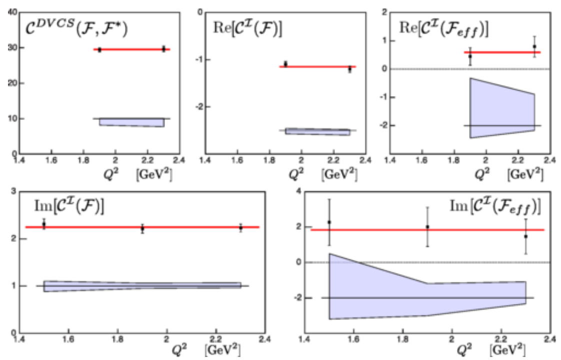




Hall A

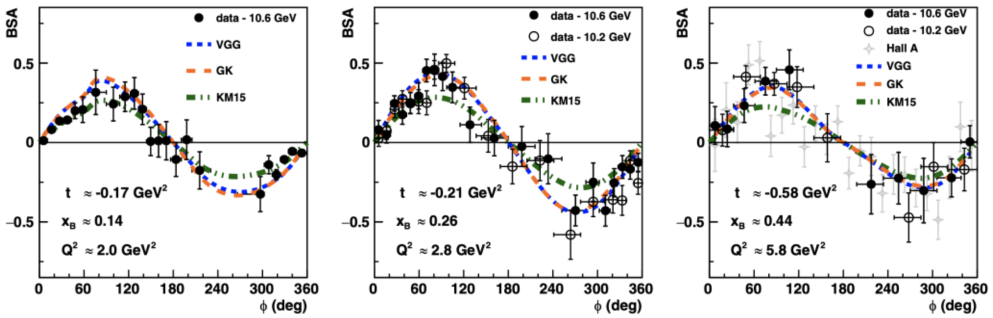
Performed precision measurements of the cross section and extraction of Compton Form Factors.





CLAS12 - Hall B

Extended the kinematic coverage in the 12 GeV JLab era for the asymmetry measurement. Cross section measurements expected soon.



S. Stepanyan *et. al.* (CLAS Collaboration), *Phys. Rev. Lett.* 87 182002 (2001).

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

C. Muñoz Camacho *et. al.* (Hall A Collaboration), *Phys. Rev. Lett.* **97** 262002 (2006).

M. Defurne *et. al.* (Hall A Collaboration), *Phys. Rev. C* **92**, 055202 (2015).

F. Georges *et al.* (Hall A Collaboration), *Phys. Rev. Lett.* **128**, 252002 (2022).

G. Christiaens *et. al* (CLAS Collaboration), *Phys. Rev. Lett.* **130**, 211902 (2023).

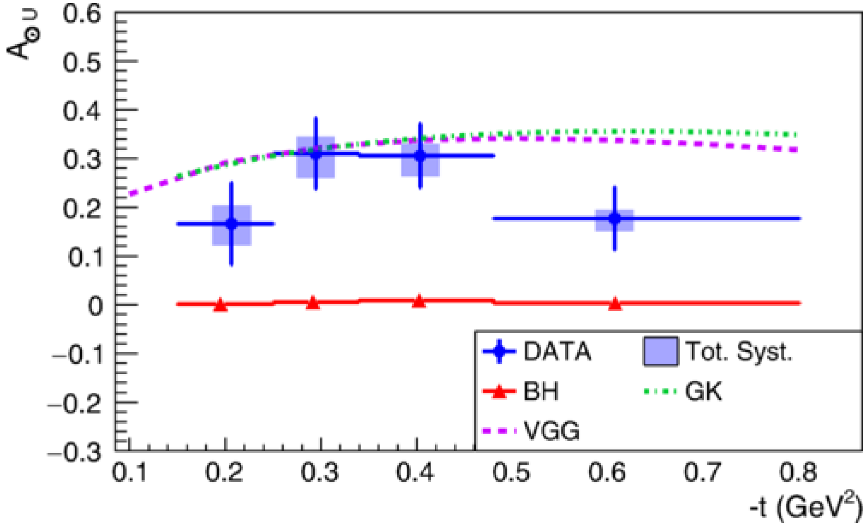
Timelike Compton Scattering at JLab

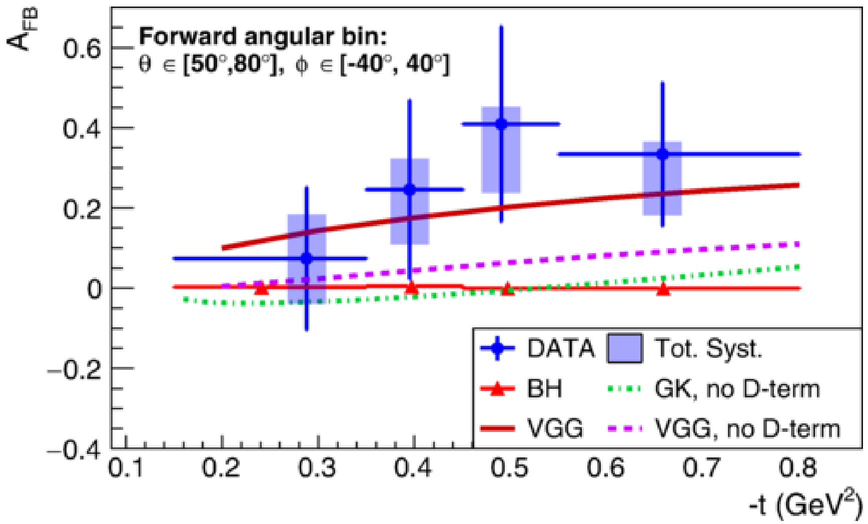
CLAS12 - Hall B

First measurement of Timelike Compton Scattering with limited statistics.

More data is now available, and will be taken in the future.

Several Halls at JLab are considering new experimental apparatus for additional measurements.





P. Chatagnon *et. al.* (CLAS Collaboration), *Phys. Rev. Lett.* **127**, 262501 (2021).

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

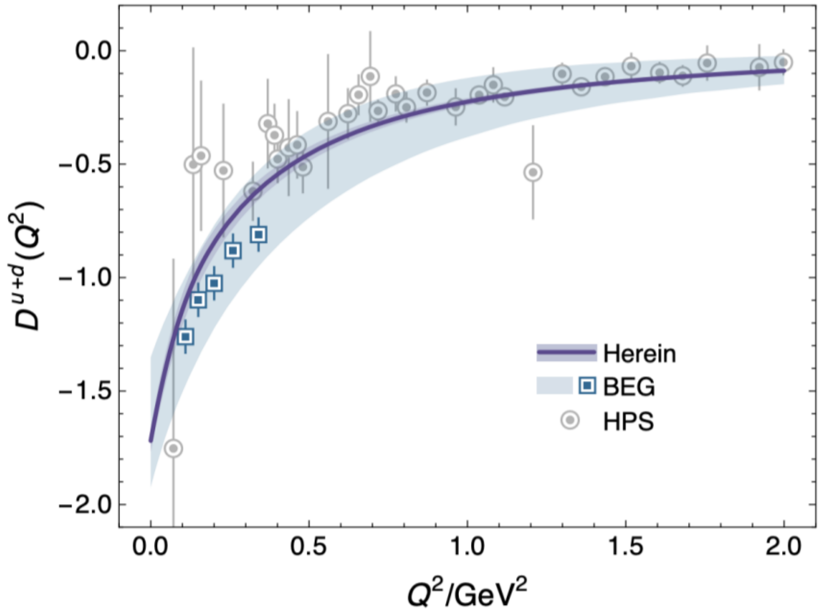
Jefferson Lab clas

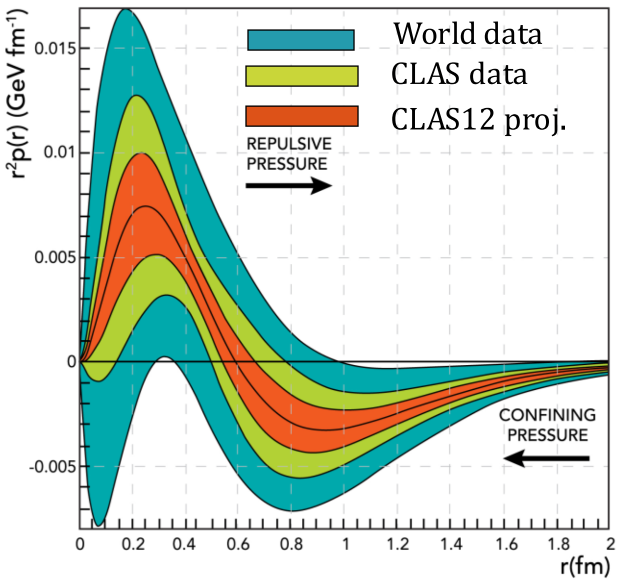
Quark Gravitational Form Factors

The quark D GFF has been extracted from DVCS data using the GPD framework. This allows to estimate the pressure and shear stress distributions of quarks inside the proton.

The extraction of the D GFF agrees well with predictions from continuum Schwinger function methods (CSM) and lattice QCD.

The quark D GFF from experiment (BEG), CSM (herein) and lattice QCD (HPS)





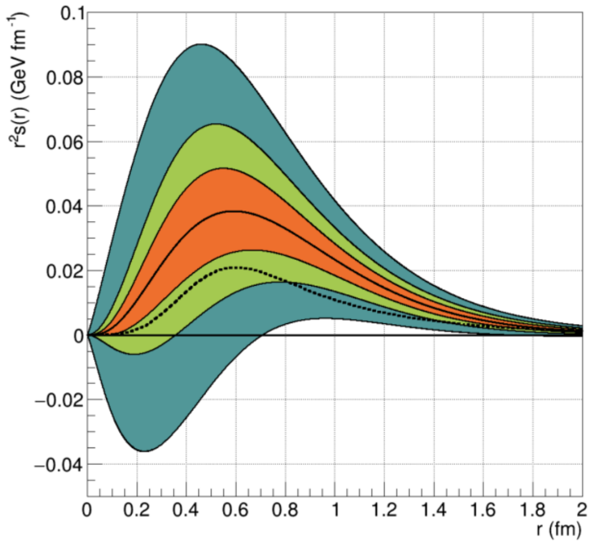
V.D. Burkert, L. Elouadrhiri, F.X. Girod , *Nature* **557** 7705 (2018).

V.D. Burkert, L. Elouadrhiri, F.Girod, arXiv:2104.02031 (2021).

Z.-Q. Yao *et. al.* arXiv:2409.15547v3 (2024).

D. C. Hackett, D. A. Pefkou, P. E. Shanahan, *Phys. Rev. Lett.* **132** (25) 251904 (2024).

Pressure and shear stress distributions of quarks inside the proton.



J/ψ Near Threshold Photoproduction

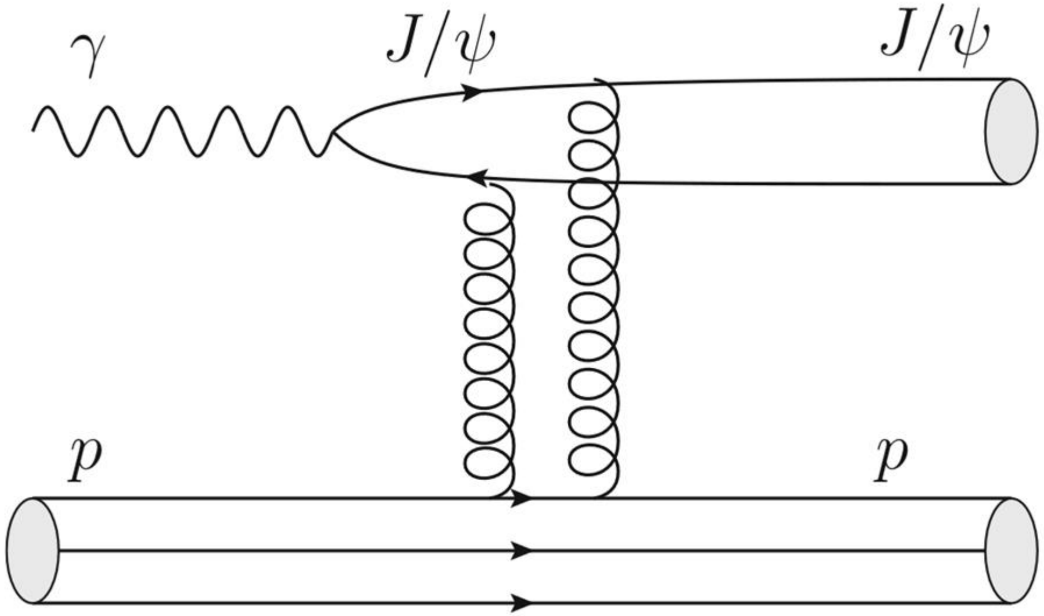
Close to the 8.2 GeV threshold, J/ψ photoproduction is mediated by the exchange of two gluons.

J/ψ then allows to probe the gluonic GFFs via the two-gluon exchange which is a spin-2 field coupling to the EMT.

We are interested in measuring the process:

$$\gamma N \to J/\psi N \to l^+ l^- N$$

At CLAS12 further measure quasi-real photoproduction with a quasi-real photon interacting with our target.

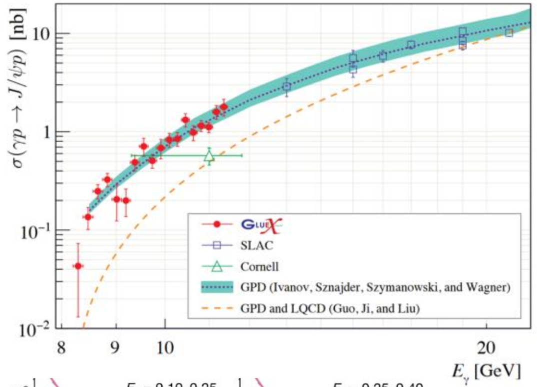


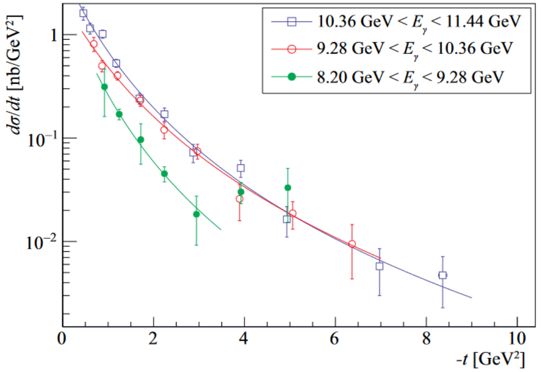
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovev, *Nucl.Phys. A* **661** 568 (1999).
L. Frankfurt, M. Strikman, *Phys. Rev. D.* **66** 031502 (2002).
Y. Hatta, D.-L. Yang, *Phys. Rev. D* **98** 074003 (2018).
Y. Guo, X. Ji, Y. Liu, *Phys. Rev. D* **103**, 096010 (2021).
S.J. Brodsky, E. Chudakov, P. Hoyer, J.M. Laget, *Phys.Lett. B* **498** 23 (2001).

J/ψ Photoproduction Measurements at JLab

GlueX – Hall D

The GlueX Collaboration has made measurements of the total and differential cross section over the full near-threshold range.

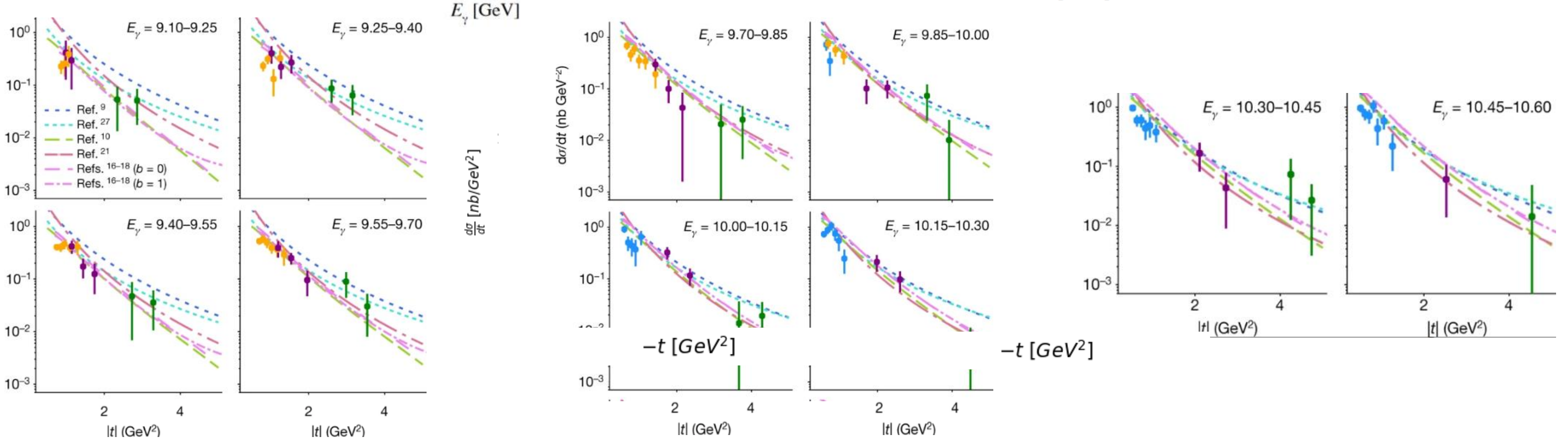




A. Ali, et. al. (GlueX Collaboration), *Phys. Rev. Lett.* **123**, 072001 (2019).
S. Adhikari et al. (GlueX Collaboration) *Phys. Rev. C* **108**, 025201 (2023).
D. Duran, et al. (J/ψ-007 Collaboration), *Nature* **615** (2023).

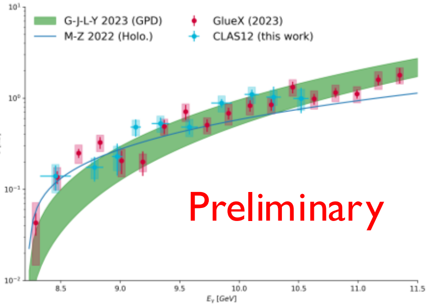
J/ψ 007 – Hall C

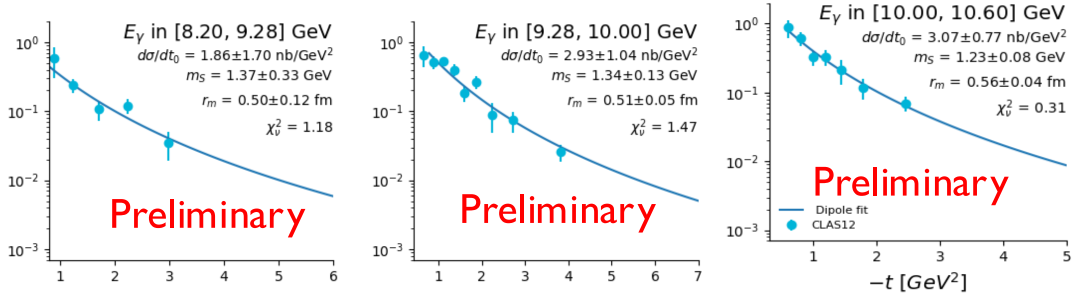
The J/ψ – 007 Collaboration has made precision measurements of the differential cross section as a function of t in 10 bins of E_γ.



CLAS 12 – Hall B (*P. Chatagnon*)

Measurements of the total and differential cross section produced on the free proton are currently undergoing internal CLAS collaboration review.



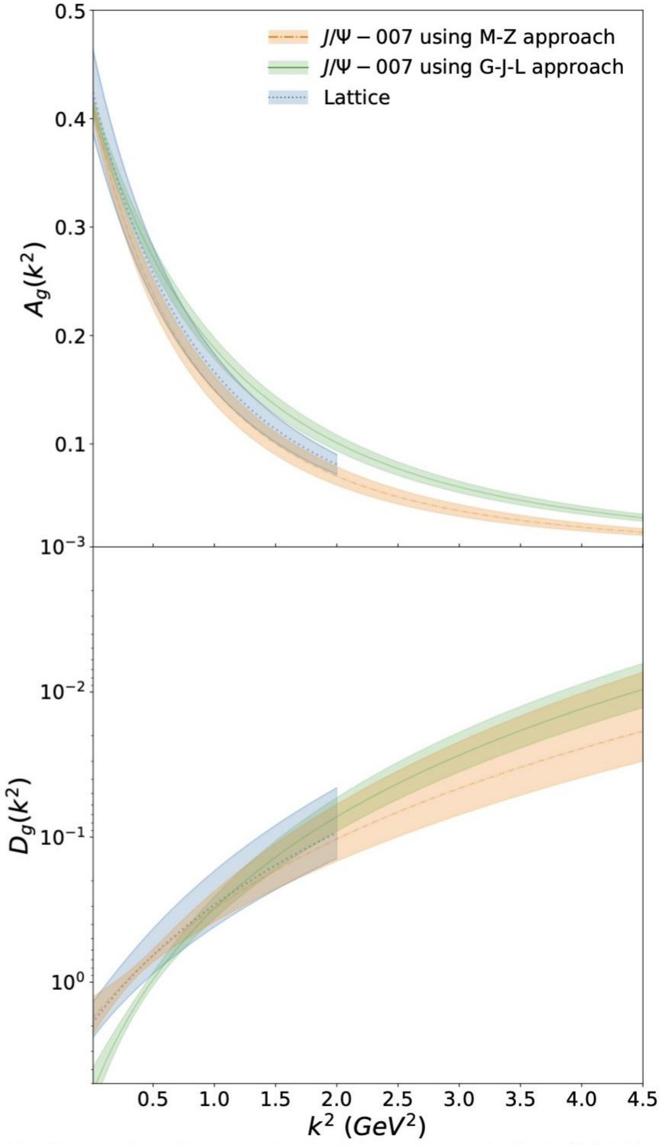


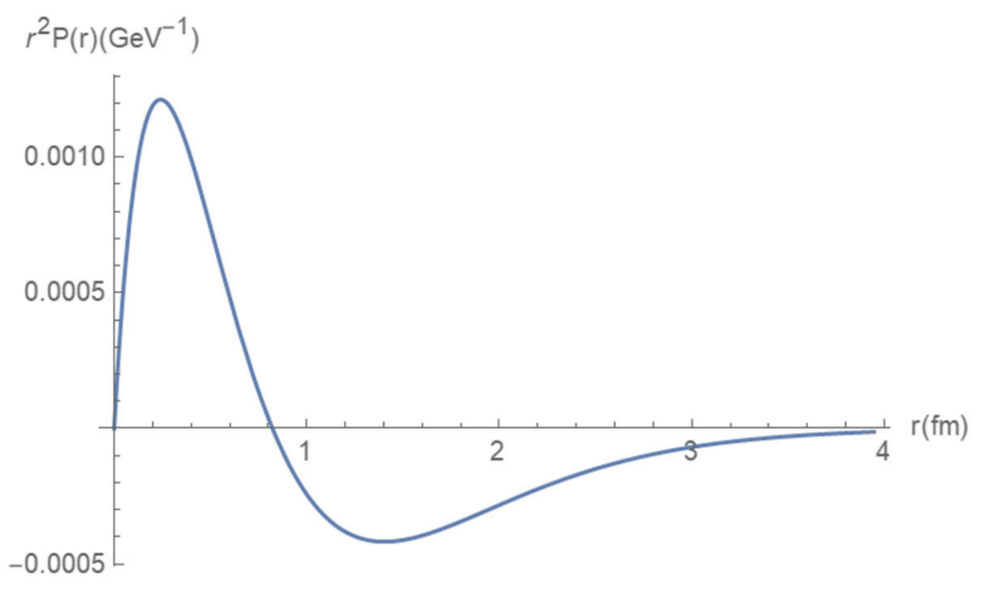
Gluon Gravitational Form Factors

In holographic QCD a higher dimensional duality relates spin-2 fields to gravity. J/ψ is produced by the exchange of gravitons (tensor 2++glueballs) and scalar (0++) glueballs.

In the GPD framework, large skewness at threshold allows to relate the scattering amplitude to gluon GPDs. The GFFs are extracted from the first moments of the GPDs.

The $A_g(t)$ and $D_g(t)$ GFFs estimated using holographic QCD (orange) and GPD (green) models compared to lattice QCD predictions (blue). ($k^2 \equiv |t|$)





The gluon contribution to the pressure distribution inside the proton.

D. Duran, et al. (J/ψ-007 Collaboration), *Nature* **615** (2023).
Y. Hatta, D.-L. Yang, *Phys. Rev. D* **98** 074003 (2018).
Y. Guo, X. Ji, Y. Liu, *Phys. Rev. D* **103**, 096010 (2021).
K. A. Mamo and I. Zahed *Phys. Rev. D* **106**, 086004 (2022).
Y. Guo, X. Ji, Y. Liu, J. Yang, *Phys. Rev. D* **108**, 034003 (2023).
Y. Guo, X. Ji, F. Yuan, *Phys. Rev. D* **109** 014014 (2024).
D. A. Pefkou, D. C. Hackett, P. E. Shanahan, *Phys. Rev. D* **105** 054509 (2022).

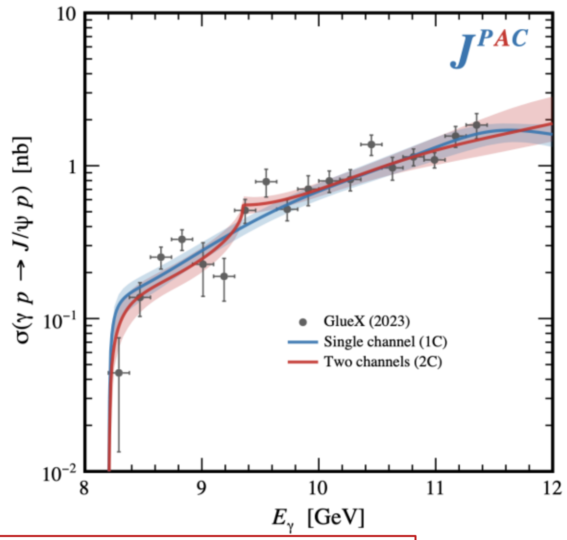
The Near-Threshold J/ψ Photoproduction Production Mechanism

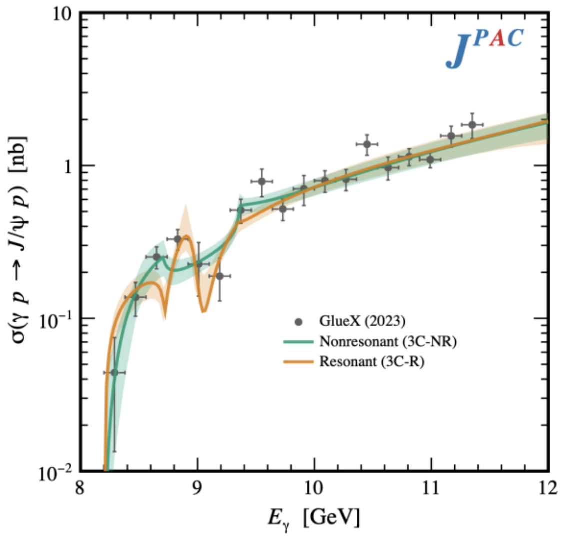
Suggestions that J/ψ near-threshold could be dominated by the contribution from open-charm intermediate state.

There also exists predictions that the higher twist 3-gluon exchange dominates close to threshold, or that J/ψ photoproduction may be mediated via Pomeron and meson exchange.

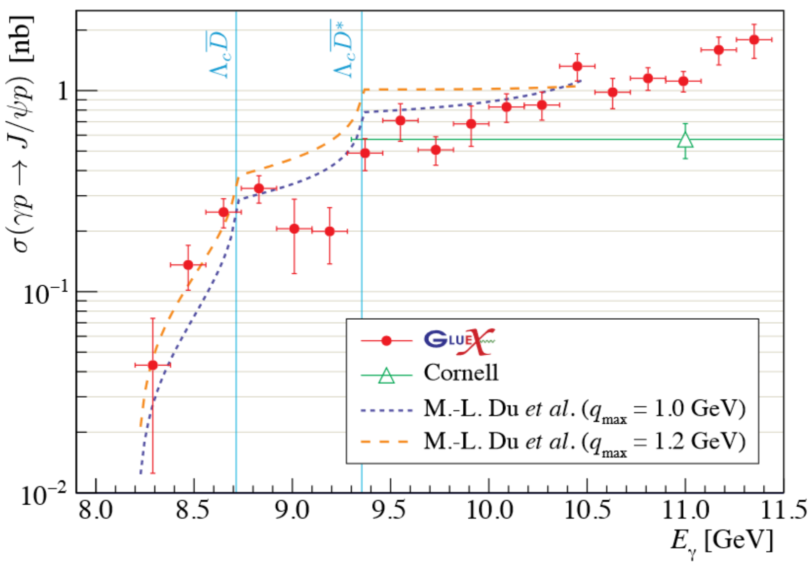
In general, need higher statistical precision. Also need to determine polarization observables such as Spin Density Matrix Elements (SDMEs).

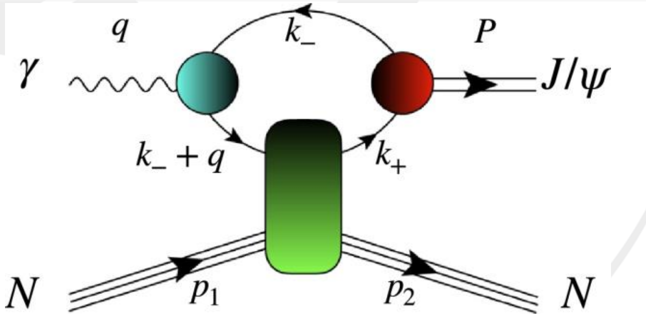
GlueX is investigating upper limits for the photoproduction of open charm states. Letter of Intent submitted for CLAS12.





Estimating the contribution to the J/ψ cross section from intermediate open charm production.





M.-L. Du, *et. al., Eur. Phys. J. C* **80** 1053 (2020).
D. Winney, *et. al.* (Joint Physics Analysis Center), *Phys. Rev. D* **108** 054018 (2023).
L.Tang, Y.-X. Yang, Z.-F. Cui, C. D. Roberts, *Phys. Lett. B* **856** 138904 (2024).
S.H. Kim arXiv:2503.09995v1 (2025).
S.J. Brodsky, E. Chudakov, P. Hoyer, J.M. Laget, *Phys.Lett. B* **498** 23 (2001).

ϕ Photo- & Electro-production Measurements

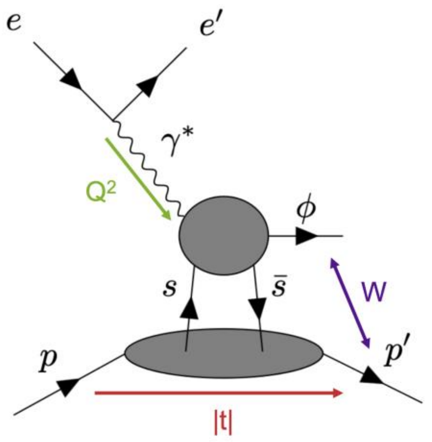
ϕ near-threshold photoproduction (at Q^2=0) has been predicted to be mediated by the exchange of two gluons. More theoretical uncertainty for ϕ due to lower mass compared to J/ψ.

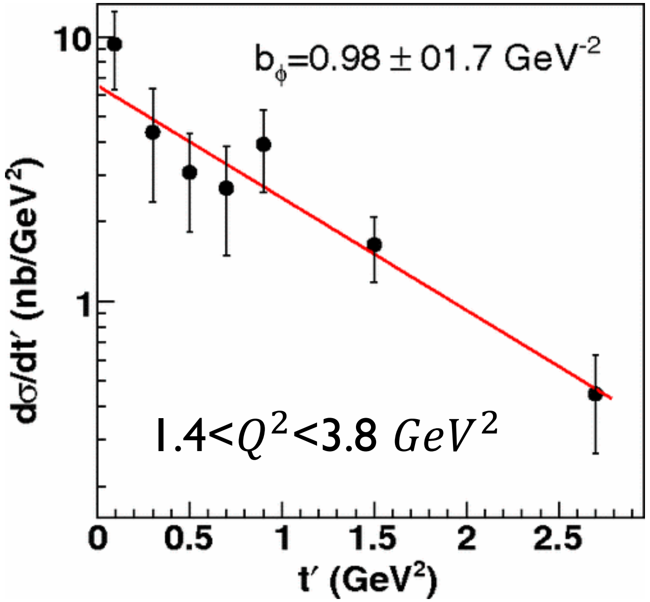
At larger Q^2, ϕ electroproduction is predicted to give access to the strangeness content of the nucleon and therefore the strange quarks GFFs.

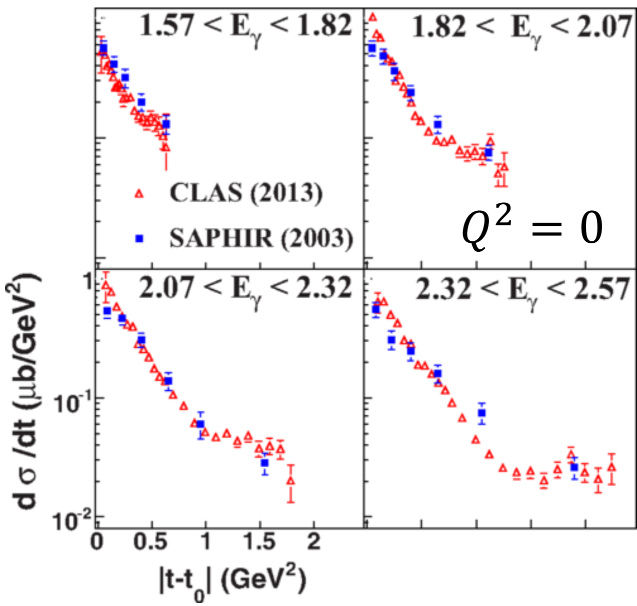
CLAS has measured during the six GeV era ϕ photo- and electroproduction, including measurements of the ϕ SDMEs.

Unfortunately the extraction of the strangeness GFFs requires binning in t and Q^2 which is not available.

New data is expected from CLAS12.







L. Frankfurt, M. Strikman, *Phys. Rev. D.* **66** 031502 (2002).
Y. Hatta, M. Strikman, *Phys.Lett. B* **817** 136295 (2021).
B. Dey *et. al* (CLAS Collaboration), *Phys. Rev. C* **89**, 055208 (2014).
J.P. Santoro *et. al* (CLAS Collaboration), *Phys. Rev. C* **78**, 025210 (2008).

Quark and Gluon Radius

Mechanical Radius: root-mean-square radius of the longitudinal force density $F_i^{||}(r)$.

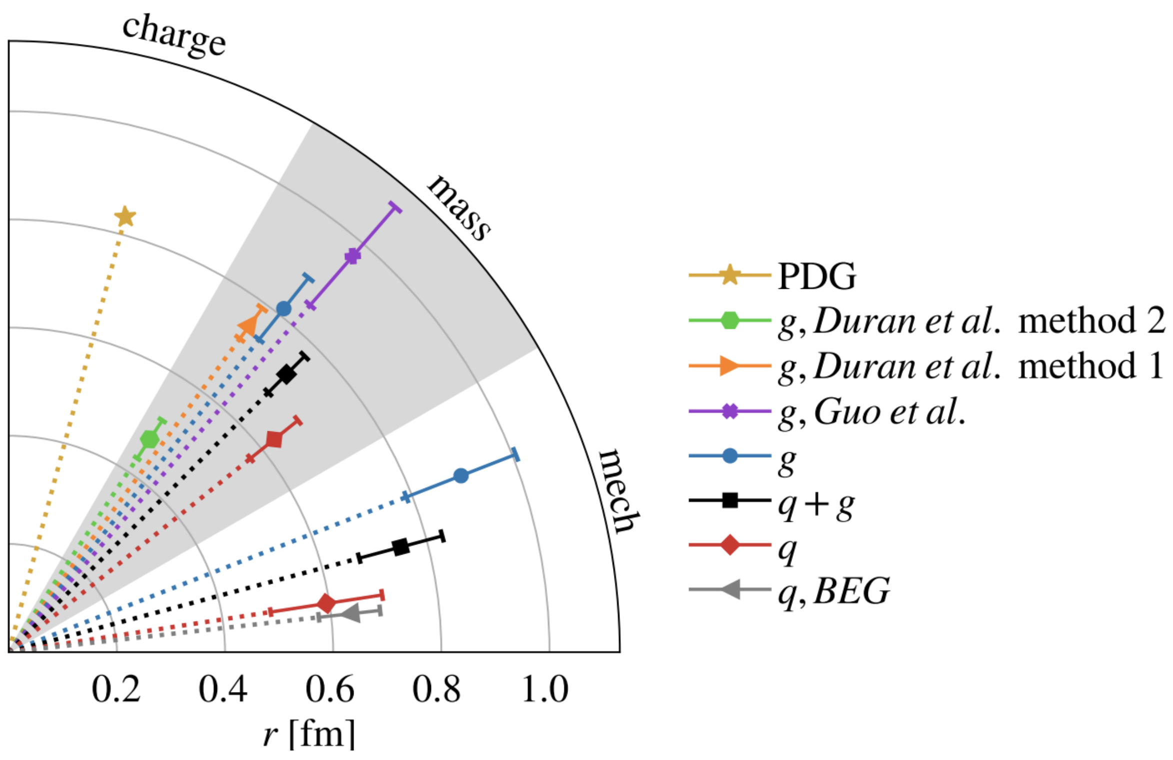
Mass radius: root-mean-square radius of the energy density $\varepsilon_i(r)$.

Can be decomposed into contributions from quark and gluons components ($i \in \{q, g, q+g\}$).

Generally good agreement between lattice and experimental extractions.

$$\langle r_i^2 \rangle^{\text{mass}} = \frac{\int d^3\mathbf{r} r^2 \varepsilon_i(r)}{\int d^3\mathbf{r} \varepsilon_i(r)},$$

$$\langle r_i^2 \rangle^{\text{mech}} = \frac{\int d^3\mathbf{r} r^2 F_i^{||}(r)}{\int d^3\mathbf{r} F_i^{||}(r)}.$$



M. V. Polyakov and P. Schweitzer, *Int. J. Mod. Phys. A* **33** 1830025 (2018).
V.D. Burkert, L. Elouadrhiri, F.X. Girod , *Nature* **557** 7705 (2018).
V.D. Burkert, L. Elouadrhiri, F.Girod, arXiv:2104.02031 (2021).
D. C. Hackett, D. A. Pefkou, P. E. Shanahan, *Phys. Rev. Lett.* **132** (25) 251904 (2024).
D. Duran, et al. (J/ψ-007 Collaboration), *Nature* **615** (2023).
Y. Guo, X. Ji, F. Yuan, *Phys. Rev. D* **109** 014014 (2024).

What About the Neutron?

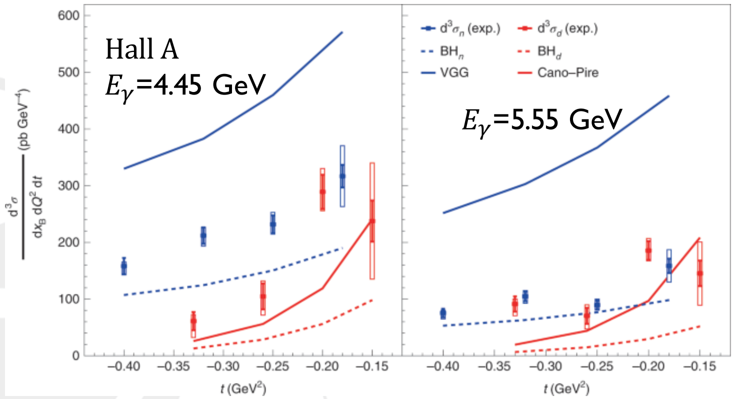
Deeply Virtual Compton Scattering

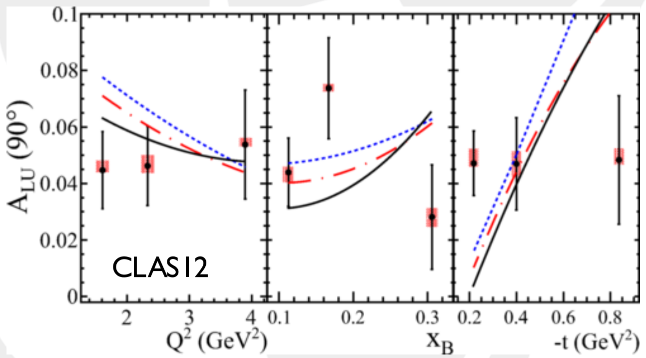
Measurements of DVCS on the neutron in Hall A and at CLAS12.
Allows for a separation of the contribution of the up and down quarks to the Compton Form Factors.

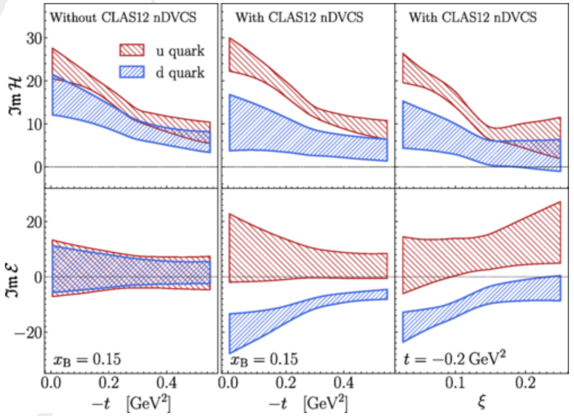
J/ψ Photoproduction *(RT)*

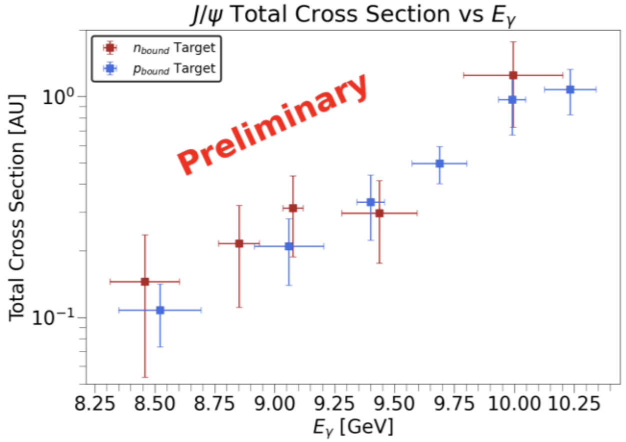
Preliminary measurements at CLAS12 of the J/ψ cross section on bound neutron.
Comparison to bound proton allows to test isospin invariance of the J/ψ production mechanism.

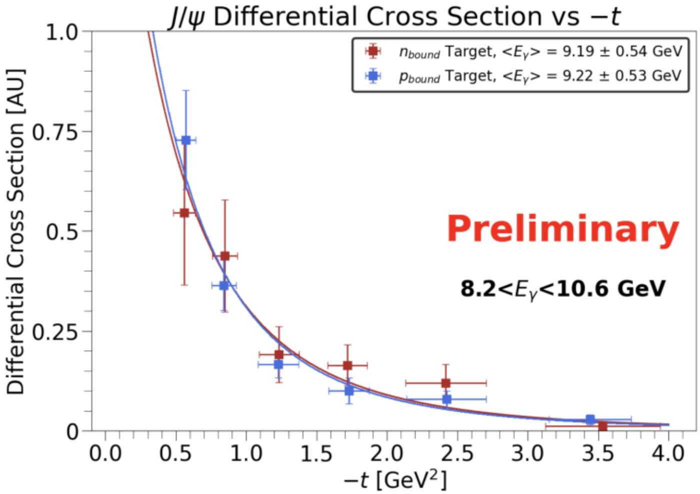
M. Mazouz *et. al.* (Hall A Collaboration), *Phys. Rev. Lett.* **99** 242501 (2007).
M. Benali *et. al.* (Hall A Collaboration), *Nature Physics* **16** 191–198 (2020)
A. Hobart *et. al.* (CLAS Collaboration), *Phys. Rev. Lett.* **133** 211903 (2024).









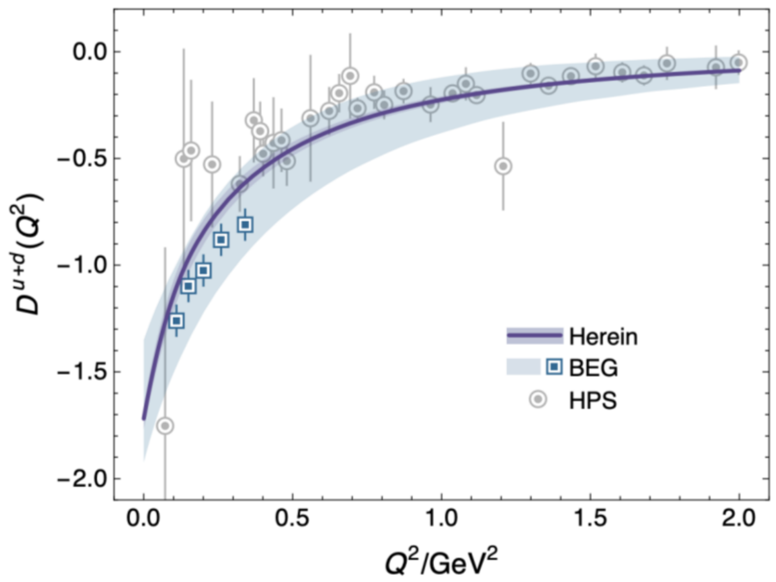


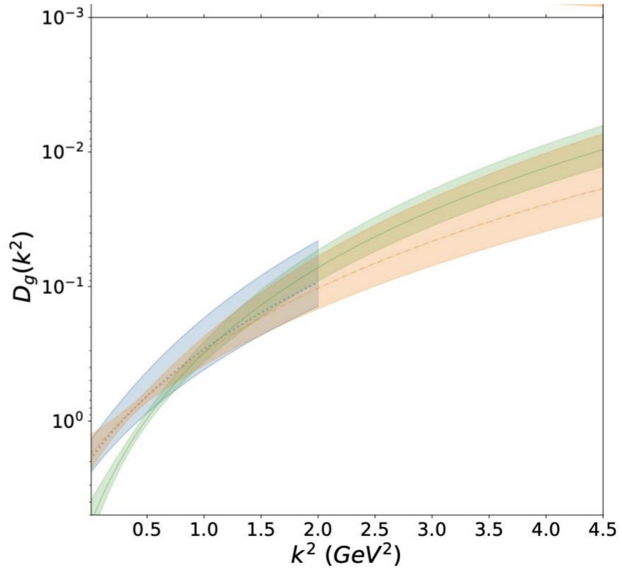
Conclusion

The study of the Nucleon Gravitational Form Factors is an active area of research at JLab.

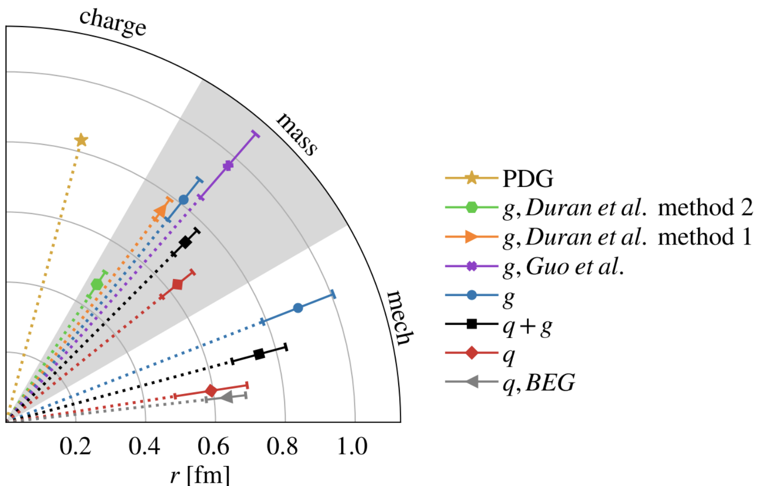
All four halls have made measurements of either Deeply Virtual Compton Scattering or J/ψ data that have been used to extract the quark and gluonic GFFs of the proton.

Many additional experiments have been proposed, are already scheduled, are under analysis or are planned in the long term to increase the statistical precision and kinematic reach for higher precision determination of GFFs - *Stay tuned!*





The proton quark and gluon D GFF and a comparison of quark and gluon mass and mechanical radii from JLab data, lattice QCD and CSM.



Backup Slides

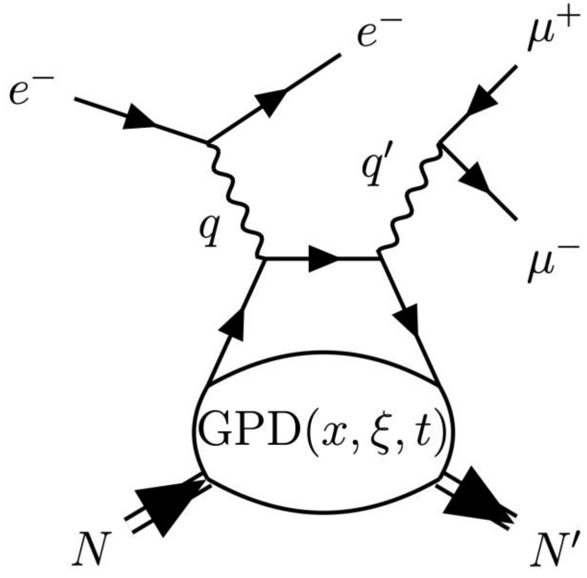
Double Deeply Virtual Compton Scattering

Double Deeply Virtual Compton Scattering (DDVCS) differs from DVCS & TCS in that it sees the scattering of a spacelike virtual photon from the nucleon with the production of a virtual photon in the final state.

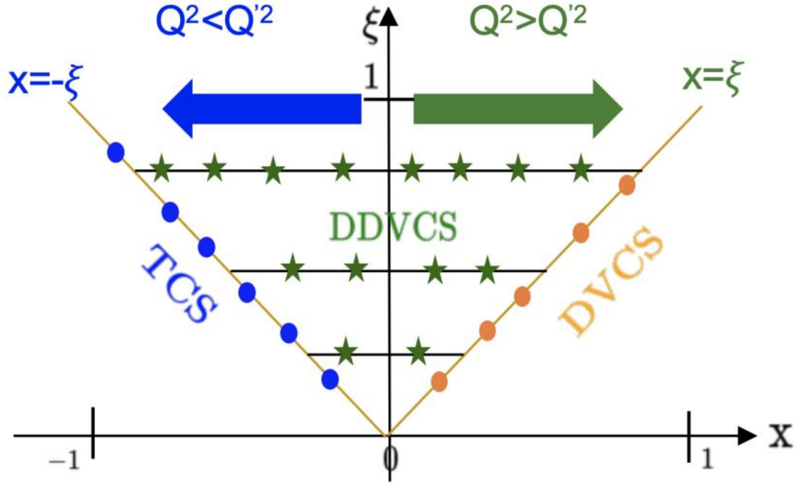
Virtual photons in both the initial and final state means DDVCS gives access to the nucleon GPDS over a wider kinematic range than DVCS or TCS.

The cross section for DDVCS is much smaller than for DVCS and so DDVCS has not yet been measured.

Several experiments are being proposed/planned for DDVCS in Halls A, B and C.



M. Guidal and M. Vanderhaeghen, *Phys. Rev. Lett.* **90** 012001 (2003).
K. Deja *et. al.*, *Phys. Rev.* **D** 107 094035 (2023).



The Future

GlueX & CLAS12 will take more data, increasing their statistics for J/ψ photoproduction and TCS. They will also aim for measurements of ϕ production. GlueX will aim for measurements of higher mass charmonium states.

Cross section measurements of DVCS are being prepared at CLAS12.

GlueX is investigating upper limits for the photoproduction of open charm states. A Letter of Intent has been submitted for such a measurement at CLAS12.

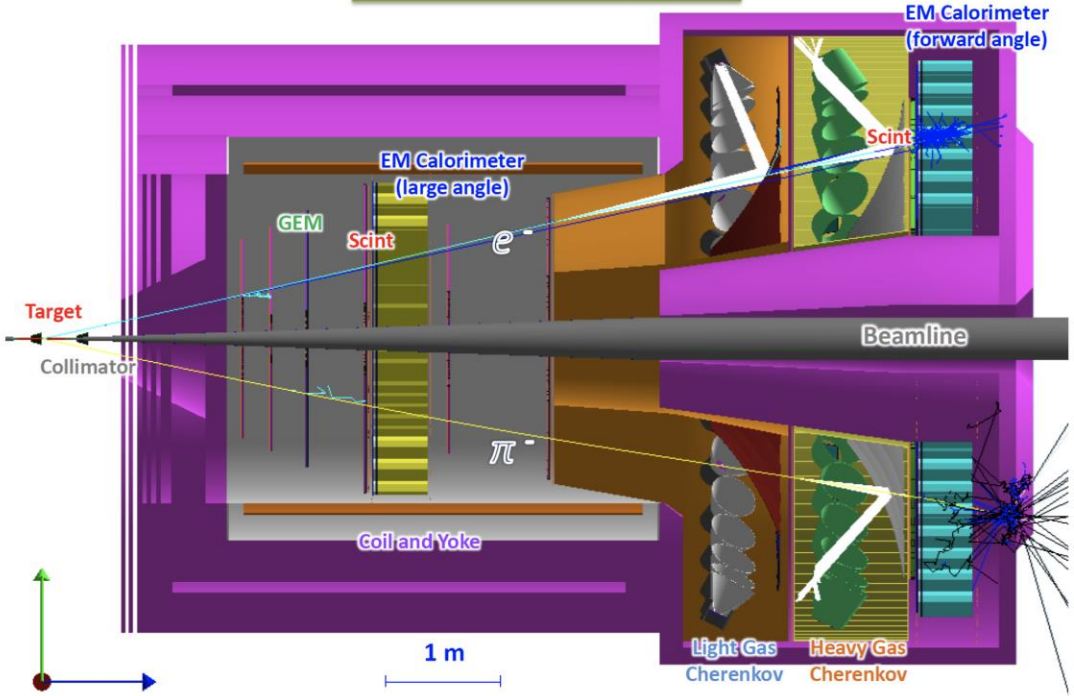
The Solenoidal Large Intensity Device will aim to measure DDVCS, TCS, J/ψ and ϕ photo- & electro-production with a very high intensity electron beam and high statistical precision.

A proposal will soon be submitted for a μCLAS12 allowing for measurements of DDVCS, TCS, J/ψ and ϕ with higher statistical precision.

Proposals for a muon detector in Hall C capable of measuring DDVCS & TCS have/will be submitted.

The proposed CEBAF upgrade to 22 GeV would allow for a better kinematic reach allowing to constrain the extraction of GFFs from JLab data.

SoLID (SIDIS and J/ψ)



J. Arrington *et. al.*, *J. Phys. G: Nucl. Part. Phys.* **50** 110501 (2023).
A. Accardi *et. al.*, *Eur. Phys. J. A* **60** 173 (2024).

Vector Meson Dominance Framework

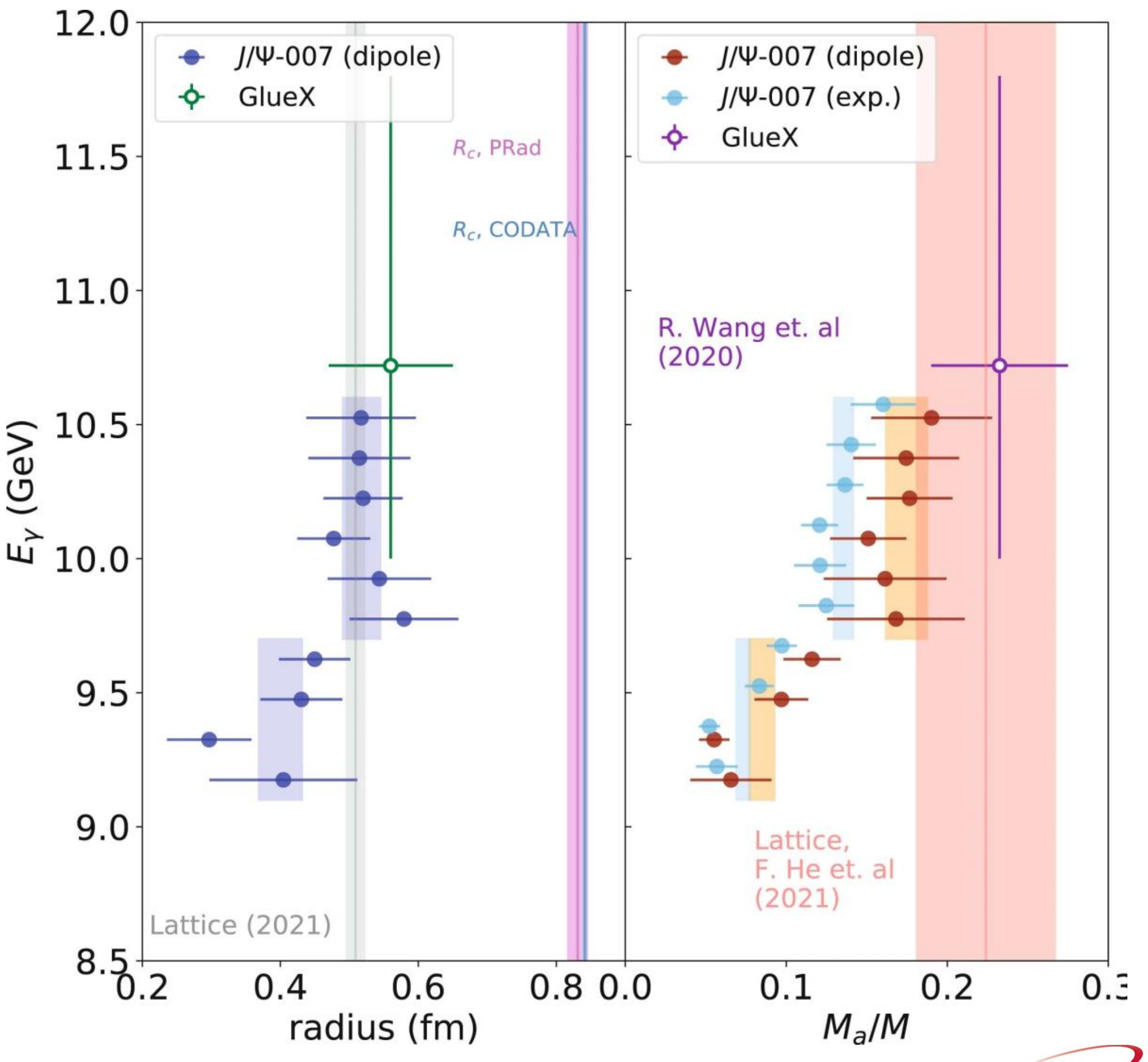
The nucleon mass can be decomposed into the contributions from the quark masses, the energy of quarks and gluons and the trace anomaly contribution.

A scalar gravitational form factor $G(t)$ gives access to the mass radius of the nucleon. Assuming a dipole form for $G(t)$:

$$\frac{d\sigma}{dt} = G(t)^2 = \left(\frac{M_p}{(1-\frac{t}{m_s^2})^2}\right)^2$$

The mass radius r_m is calculated from the free parameter m_s :

$$r_m = \frac{\sqrt{12}\hbar c}{m_s}$$



D. Duran, et al. (J/ψ-007 Collaboration), *Nature* **615** (2023).

R. Wang, X. Chen, J. Evslin, *Eur. Phys. J. C* **80** 507 (2020).

D. Kharzeev, *Phys. Rev. D* 104 054015 (2021).

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