Neutron DVCS and GPDs

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Polarized light ion physics with EIC
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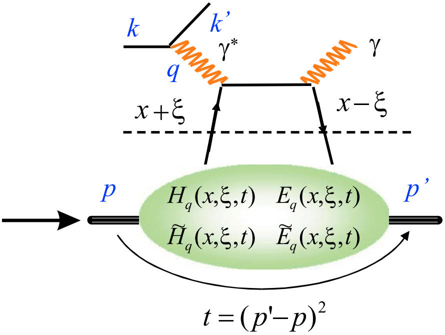
Outline

1. Motivations (GPD E + flavor separation)
2. Hall A nDVCS program of measurements:
    - Early 2007 results
    - Recent (preliminary) results from 2010 run
3. 12 GeV program (CLAS12) and possible extensions (polarized ^{3}He)

Deeply Virtual Compton Scattering (DVCS): $\gamma^* \ p \to \gamma \ p$



Handbag diagram

High Q^2
Perturbative QCD

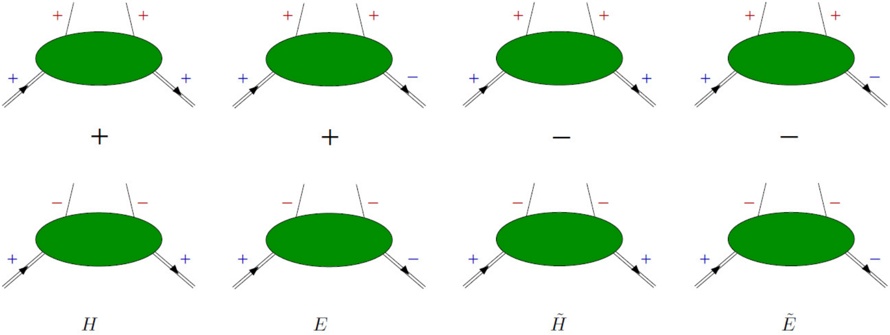
Non-perturbative
GPDs

Bjorken limit:

$$\left.\begin{array}{rcl} Q^2 = & -q^2 \to & \infty \\ & \nu \to & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

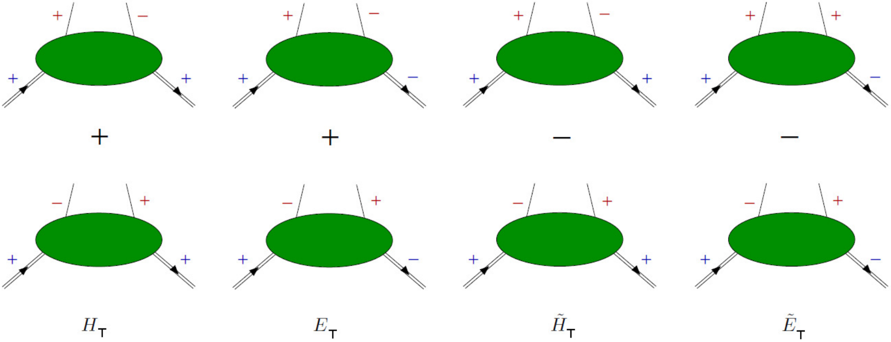


4 chiral-even GPDs: conserve the helicity of the quark

Access through DVCS (and DVMP)

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

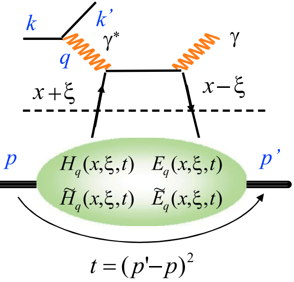


4 chiral-odd GPDs: flip helicity of the quark

"transversity GPDs"

Experimental access more complicated (π^0 electroproduction?)

Generalized Parton Distributions



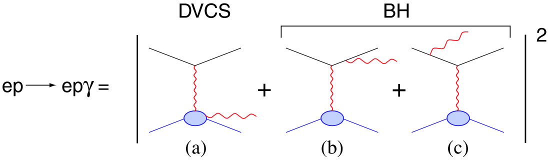
- Correlate between different partonic states
- Correlate momentum and position of partons
- Access to new fundamental properties of the nucleon

Contribution of the **angular momentum of quarks** to proton spin:

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

DVCS cleanest process to access GPDs

DVCS experimentally: interference with Bethe-Heitler



At leading twist:

$$
\begin{aligned}
d^5 \overrightarrow{\sigma} - d^5 \overleftarrow{\sigma} &= \Im m \left(T^{BH} \cdot T^{DVCS} \right) \\
d^5 \overrightarrow{\sigma} + d^5 \overleftarrow{\sigma} &= |BH|^2 + \Re e \left(T^{BH} \cdot T^{DVCS} \right) + |DVCS|^2
\end{aligned}
$$

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

$$
\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}} \quad - \quad \underbrace{i\pi \, H(x=\xi,\xi,t)} \quad + \dots
$$

Access in helicity-independent cross section   Access in helicity-dependent cross-section

Accessing different GDPs

Polarized beam, unpolarized target (BSA)

$$d\sigma_{LU} = \sin\phi \cdot \mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

Unpolarized beam, longitudinal target (lTSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B k F_2\tilde{\mathcal{E}} \ldots\}d\phi$$

Polarized beam, longitudinal target (BlTSA)

$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) \ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

$$d\sigma_{UT} = \cos\phi \cdot \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

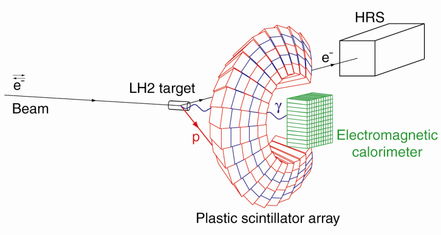
The Hall A DVCS program

1. Accurate cross-section measurements (3–4% uncertainties)
    - Highest sensitivity observable
    - Necessary for disperssion analysis
2. Q^2–dependence of all observables
    - *Only* way to disentangle higher twists
3. Both proton and neutron (deuteron) targets
    - Flavor sensitivity

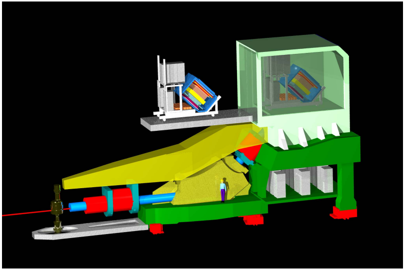
The program:

- First round of experiments in 2004 (published in 2006–2007)
- Second round (Rosenbluth separation) in 2010 (some results published in 2016–2017)
- 12 GeV: Extended kinematic coverage in 2014–2016

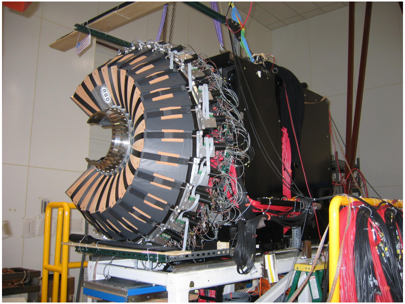
Experimental setup



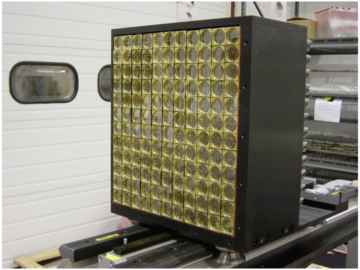
High Resolution Spectrometer



100-channel scintillator array

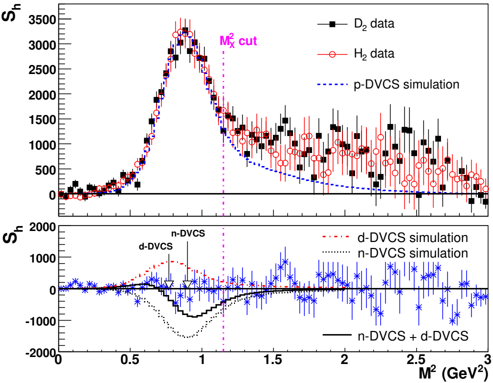


132-block PbF_2 electromagnetic calorimeter

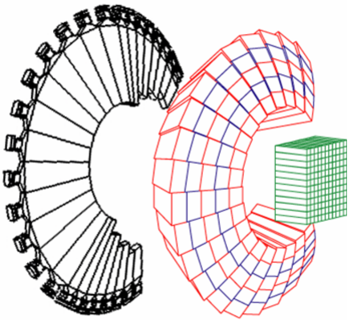


DVCS on the neutron: experiment E03-106 at JLab

LD_2 target ($F_2^n(t) \gg F_1^n(t)$!)



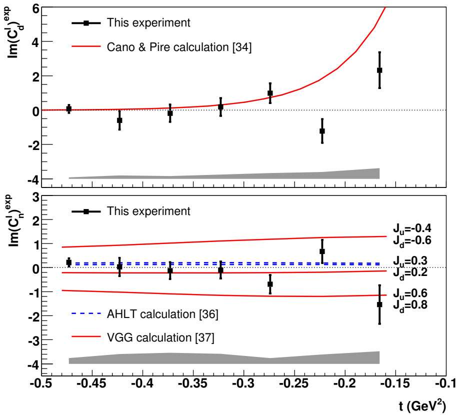
Charged particle veto in front of scintillator array



$$\sigma^{\rightarrow} - \sigma^{\leftarrow} = \Gamma(A \sin\varphi + \dots)$$

$$C^{\mathcal{I}} = F_1(t)\mathcal{H} + \frac{x_B}{2 - x_B}[F_1(t) + F_2(t)]\tilde{\mathcal{H}} - \underbrace{\frac{t}{4M^2} \cdot F_2(t) \cdot \mathcal{E}}_{\text{Main contribution for neutron}}$$

DVCS on the neutron & deuteron



- Small helicity-dependent signal (as expected by models)
- Unpolarized cross section could *not* be extracted
  (experimental calibration issues → next experiment)

Rosenbluth-like separation of the DVCS cross section

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$

$$\left|\mathcal{T}^{DVCS}\right|^2 \propto 1/y^2 = (k/\nu)^2$$

BKM-2010 – at leading twist $\rightarrow$ 7 independent GPD terms:

$$\left\{\Re\text{e}, \Im\text{m}\left[\mathcal{C}^{\mathcal{I}}, \mathcal{C}^{\mathcal{I},V}, \mathcal{C}^{\mathcal{I},A}\right](\mathcal{F})\right\}, \qquad \text{and} \qquad \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}*).$$

φ-dependence provides 5 independent observables:

$$\sim 1, \sim \cos\varphi, \sim \sin\varphi, \sim \cos(2\varphi), \sim \sin(2\varphi)$$

The measurement of the cross section at two or more beam energies for exactly the same Q^2, x_B, t kinematics, provides the additional information in order to extract all leading twist observables independently.

Experimental upgrades and improvements

1. Frequent swap between LH_2 & LD_2 targets

   → **better proton data substraction**

2. Calorimeter upgrade:

   - Larger detector (11×12 → 13×16 3x3 cm^2 PbF_4 crystals)
   - Lower energy threshold

   → **Better π^0 substraction**

LD_2 & LH_2 $ep \to ep\gamma X$ missing mass squared

Impulse approximation:

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

n+d DVCS cross sections (preliminary)

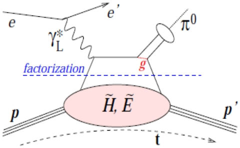
$E_b = 4.5$ GeV

$E_b = 5.6$ GeV

nDVCS & dDVCS cross sections (preliminary)

- First experimental determination of the unpolarized $en \to e\gamma n$ cross section
- $\sigma(en \to e\gamma n) > \sigma(BH_n)$: **Sizeable DVCS off the neutron**

π^0 electroproduction ($ep \to ep\pi^0$)



At leading twist:

$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \qquad \sigma_T \propto \frac{1}{Q^8}$$

$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z}\right] \int_{-1}^{1} dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \times \left\{\Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0}\right\}$$

Different quark weights: flavor separation of GPDs

$$|\pi^0\rangle = \tfrac{1}{\sqrt{2}}\{|u\bar{u}\rangle - |d\bar{d}\rangle\} \qquad \widetilde{H}_{\pi^0} = \frac{1}{\sqrt{2}}\left\{\frac{2}{3}\widetilde{H}^u + \frac{1}{3}\widetilde{H}^d\right\}$$

$$|p\rangle = |uud\rangle \qquad H_{DVCS} = \frac{4}{9}H^u + \frac{1}{9}H^d$$

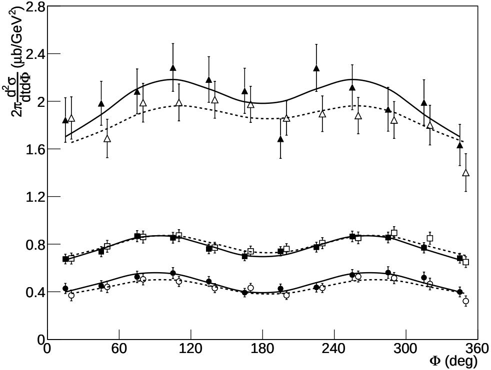
Rosenbluth separation

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi\right]$$

Kinematics

Setting	Q^2 (GeV^2)	x_B	E^{beam} (GeV)	ϵ
Kin1	1.50	0.36	3.355	0.52
			5.55	0.84
Kin2	1.75	0.36	4.455	0.65
			5.55	0.79
Kin3	2.00	0.36	4.455	0.53
			5.55	0.72

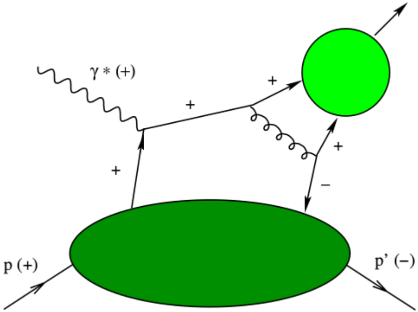
$t_{\text{min}} - t = 0.025$ GeV^2



M. Defurne et al., PRL 117 (2016)

π^0 electroproduction and transversity GPDs

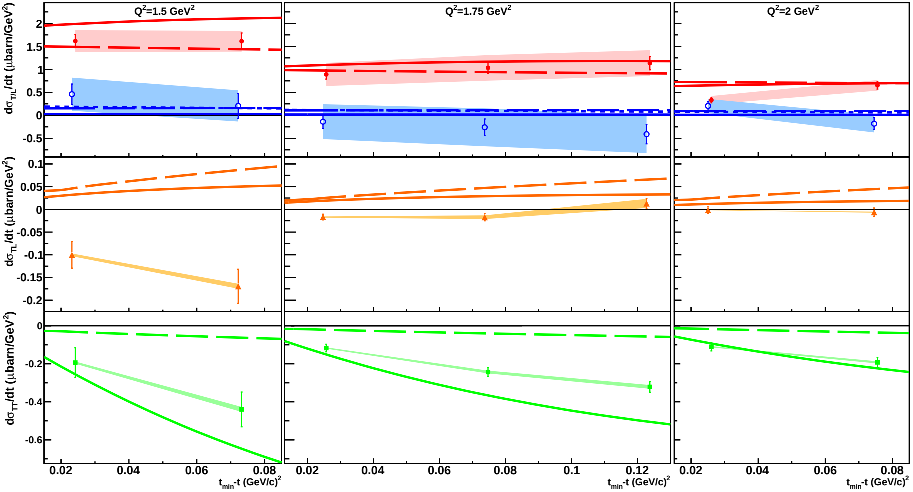
Modified handbag approach (Kroll & Goloskokov):



Divergencies regularized by $k_\perp$ of $q, \bar{q}$ + Sudakov suppression factor:

model of σ_T using transversity GPDs of the nucleon + twist-3 π DA

π^0 separated response functions



Goloskokov, Kroll (2011)

Goldstein, Hernandez, Liuti (2011)

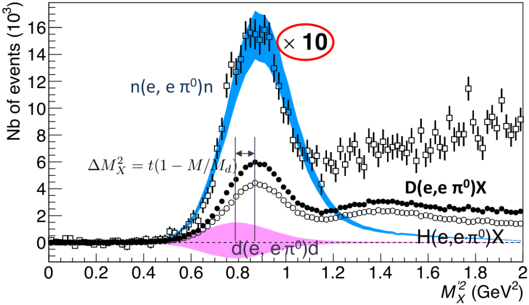
Vanderhaeghen, Guichon, Guidal (1999)

M. Defurne et al., PRL 117 (2016)

E08-025: DVCS and π^0 off quasi-free neutrons

- LD_2 as a target
- Quasi-free *p* evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 $\rightarrow$ minimize uncertainties

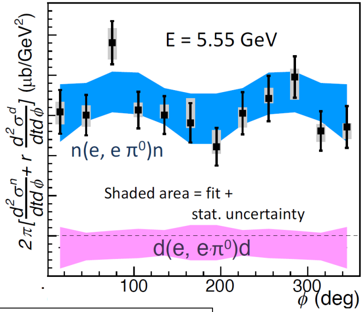
$$D(e, e\,\pi^0)X - p(e, e\,\pi^0)p = n(e, e\,\pi^0)n + d(e, e\,\pi^0)d$$

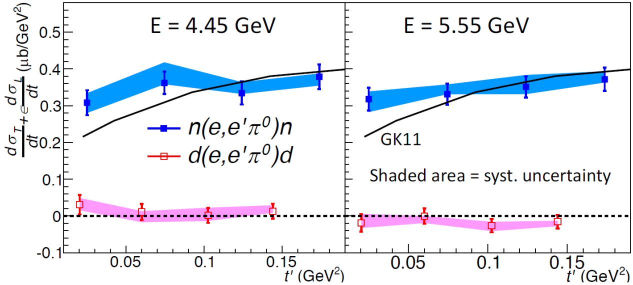


The average momentum transfer to the target is much larger than the *np* relative momentum, justifying this **impulse approximation**

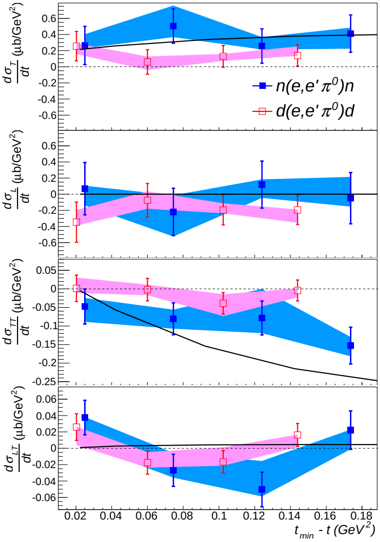
π^0 electroproduction cross section off the neutron

- Cross section off coherent d found negligeable within uncertainties
- Very low E_{beam} dependence of the n cross section → dominance of σ_T





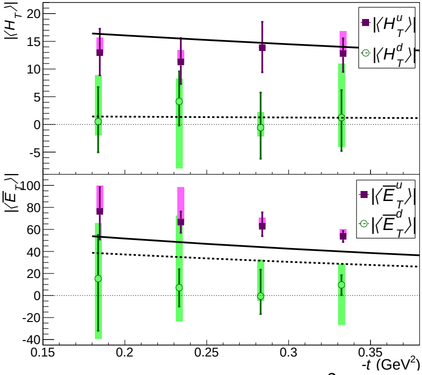
Separated π^0 cross section off the neutron



M. Mazouz et al, Phys.Rev.Lett. 118 (2017)

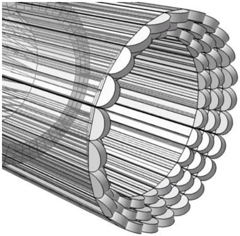
In the modified factorization approach (KG):

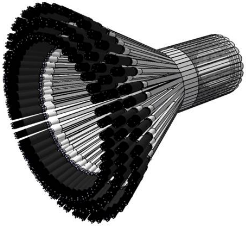
- $d\sigma_T \propto \left[\left(1-\xi^2\right) \left|\langle H_T \rangle\right|^2 - \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2 \right]$
- $d\sigma_{TT} \propto \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2$



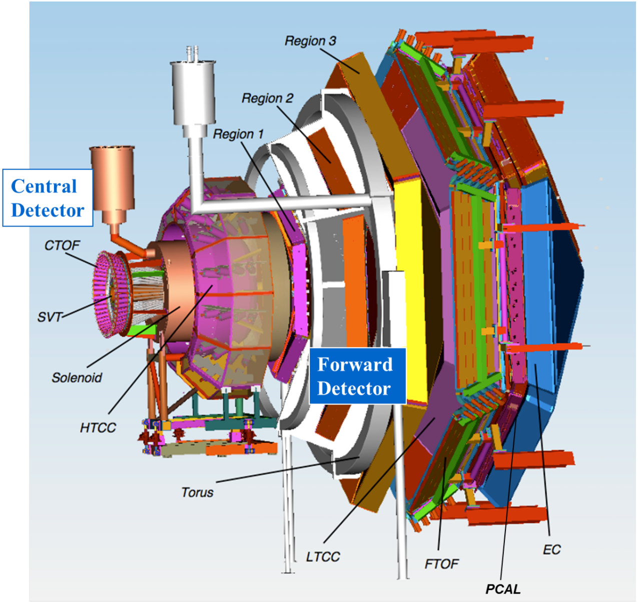
$$\left|\langle H_T^{p,n} \rangle\right|^2 = \frac{1}{2} \left| \frac{2}{3} \left\langle H_T^{u,d} \right\rangle + \frac{1}{3} \left\langle H_T^{d,u} \right\rangle \right|^2$$

E12-11-003: DVCS on the neutron with CLAS12

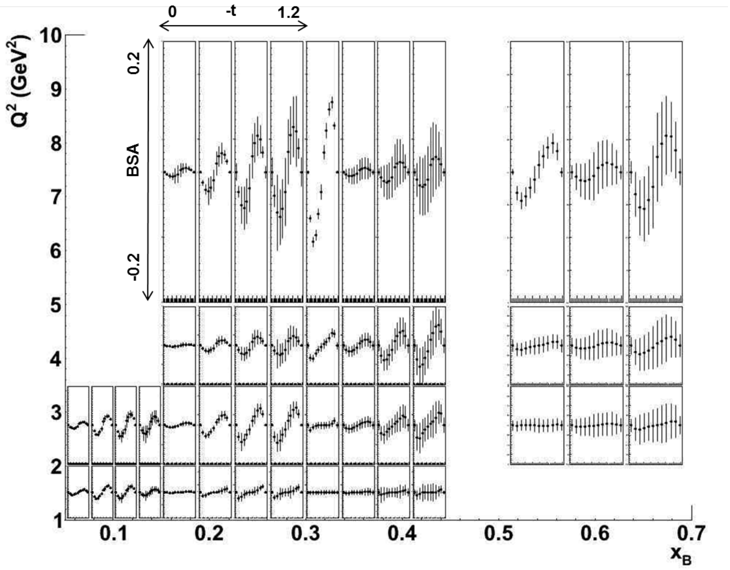




High impact experiment:
(expected to run $\sim$ 2019)

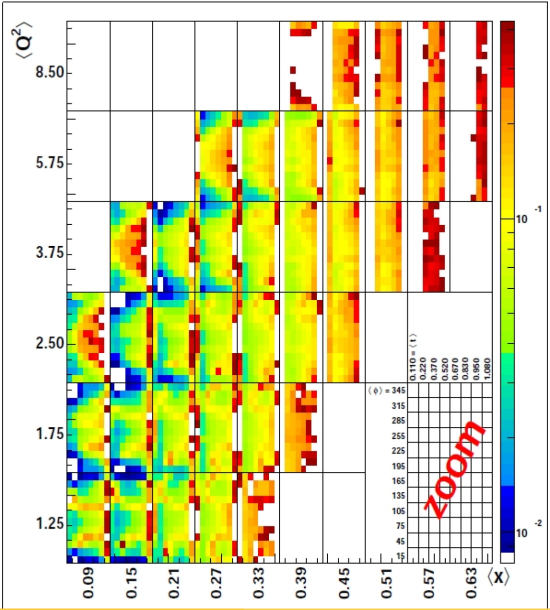


E12-11-003: projections



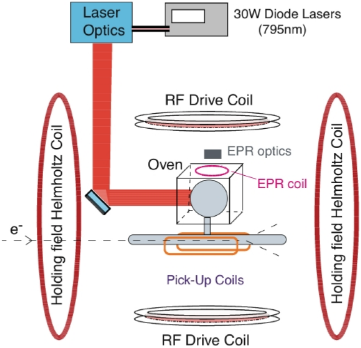
DVCS with transversally polarized target

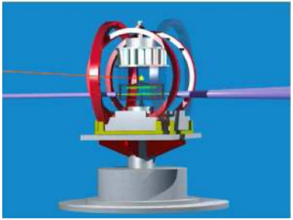
- Conditionally approved (pending target feasibility)
- $d\sigma_{UT} \propto \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$



Polarized ^3He target

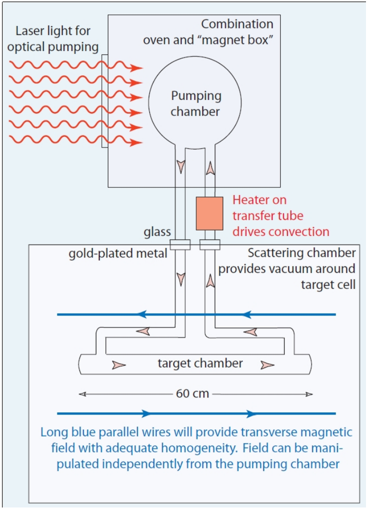
- n lum. of $10^{36}/\text{cm}^2/\text{s}$ (14 atm$\times$40 cm)
- Background luminosity:
  - p in ^3He + entrance/exit windows
  - $10^{37}/\text{cm}^2$ total luminosity
- Polarization: 50%
  - Nuclear physics dilution factor 0.86 (d-state)
  - -2.8% p polarization
  - Long. & Trans.





^{3}He target upgrade

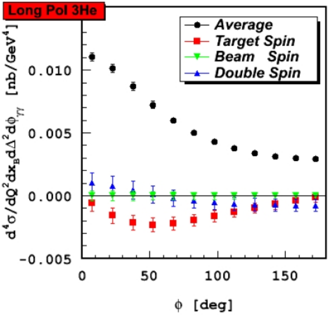
- R&D ongoing for an upgraded target
- Neutron luminosity of $10^{37}/\text{cm}^2/\text{s}$
  - Proton luminosity $2 \cdot 10^{37}/\text{cm}^2/\text{s}$
  - Endcaps $\leq 10^{37}/\text{cm}^2/\text{s}$
- Target polarization: $0.5 \cdot (0.86n - 0.028p)$



Cross section projections (at 10^{37} cm^{-2}s^{-1})

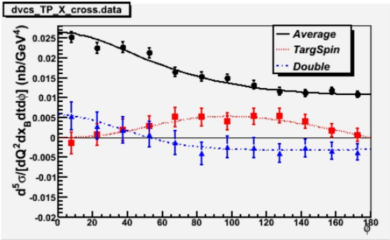
$Q^2 = 4$ GeV^2, $x_B = 0.36$, $k = 8.8$ GeV,

$t_{min} - t = 0.15$ GeV^2, 20 days

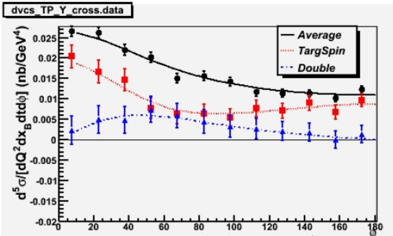


- 50%×80% polarization

$Q^2 = 2.3$ GeV^2, $x_B = 0.36$, $k = 8.8$ GeV, $t = -0.26$ GeV^2, 10 days



Polarization sideways ($\|$) to (e, e') plane



Polarization normal ($\perp$) to (e, e') plane

Figures by C. Hyde

Summary

- Recent DVCS cross sections off a LD_2 target in Hall A at JLab
- Sizeable signal from nDVCS beyond BH
- Analysis underway on impact in GPD E & flavor separation for DVCS
- L/T separation of π^0 electroproduction cross section off neutron: dominance of σ_T measured
- Flavor separation of transversity GPD convolutions within the modified factorization approach
- Posibilities of polarized target observables (long. & trans.) with polarized ^{3}He target