The GPD program at Jefferson Lab: recent results and outlook

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Outline

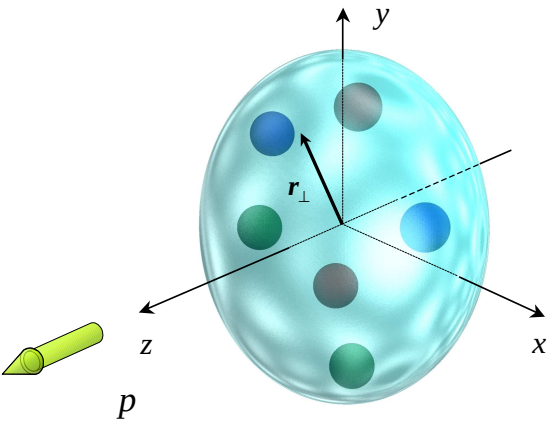
1. Experimental introduction to GPDs
   (how they can be accessed through experiment)

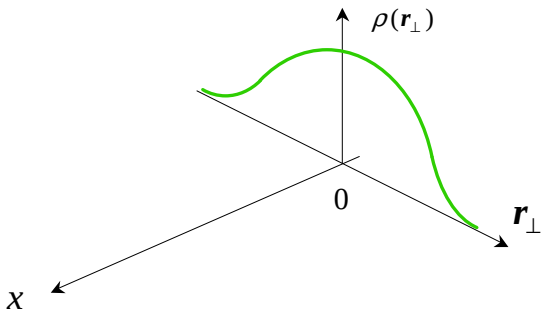
2. Jefferson Lab overview:
   - Complementary programs in Hall A and Hall B

3. Outlook
   - Jefferson Lab at 12 GeV

Studying nucleon structure experimentally

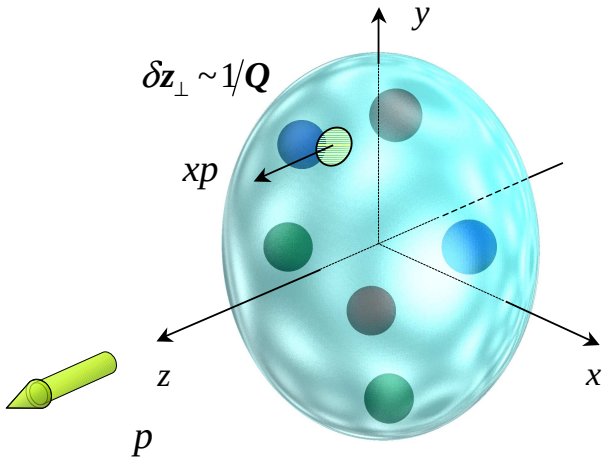
Elastic scattering

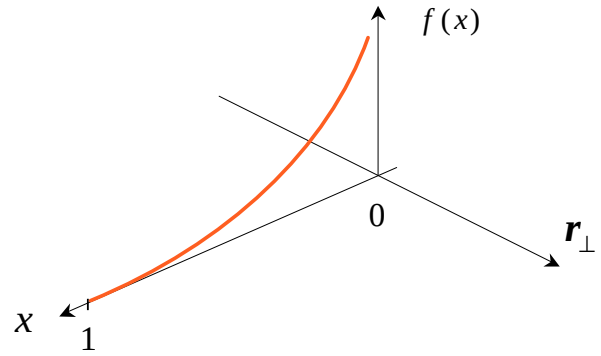




Form factors

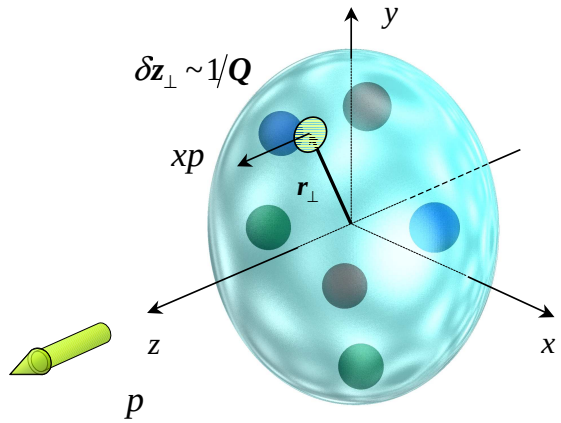
Deep inelastic scattering

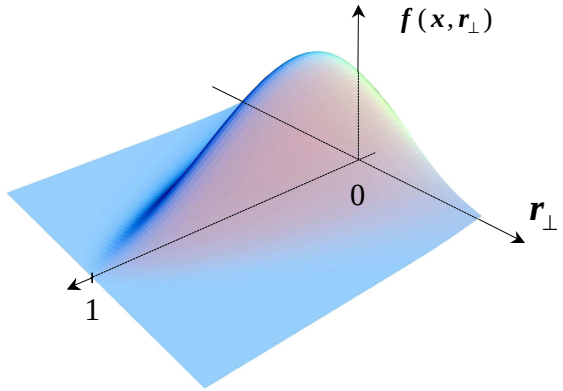




Parton distributions

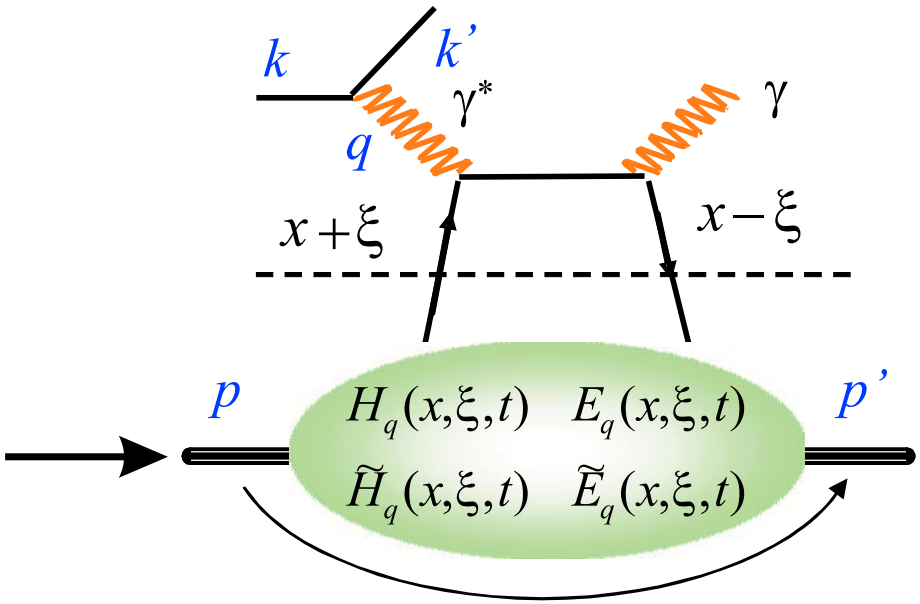
Hard exclusive processes





Generalized Parton Distributions (GPDs)

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



$$t = (p' - p)^2$$

Handbag diagram

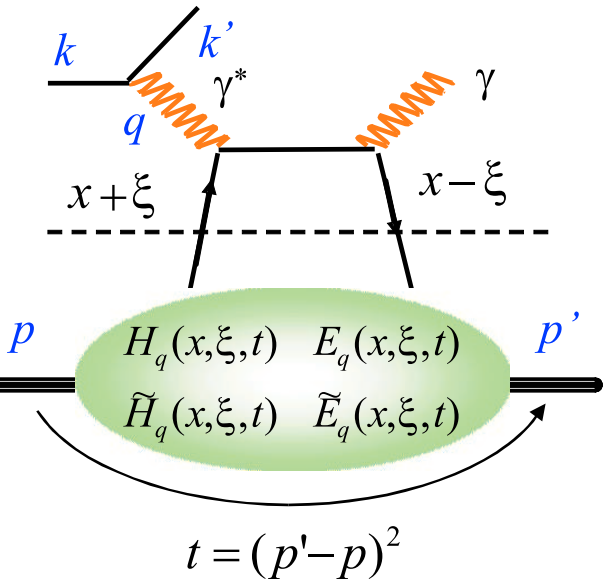
High Q^2
Perturbative QCD

Non-perturbative
GPDs

Bjorken limit:

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

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:

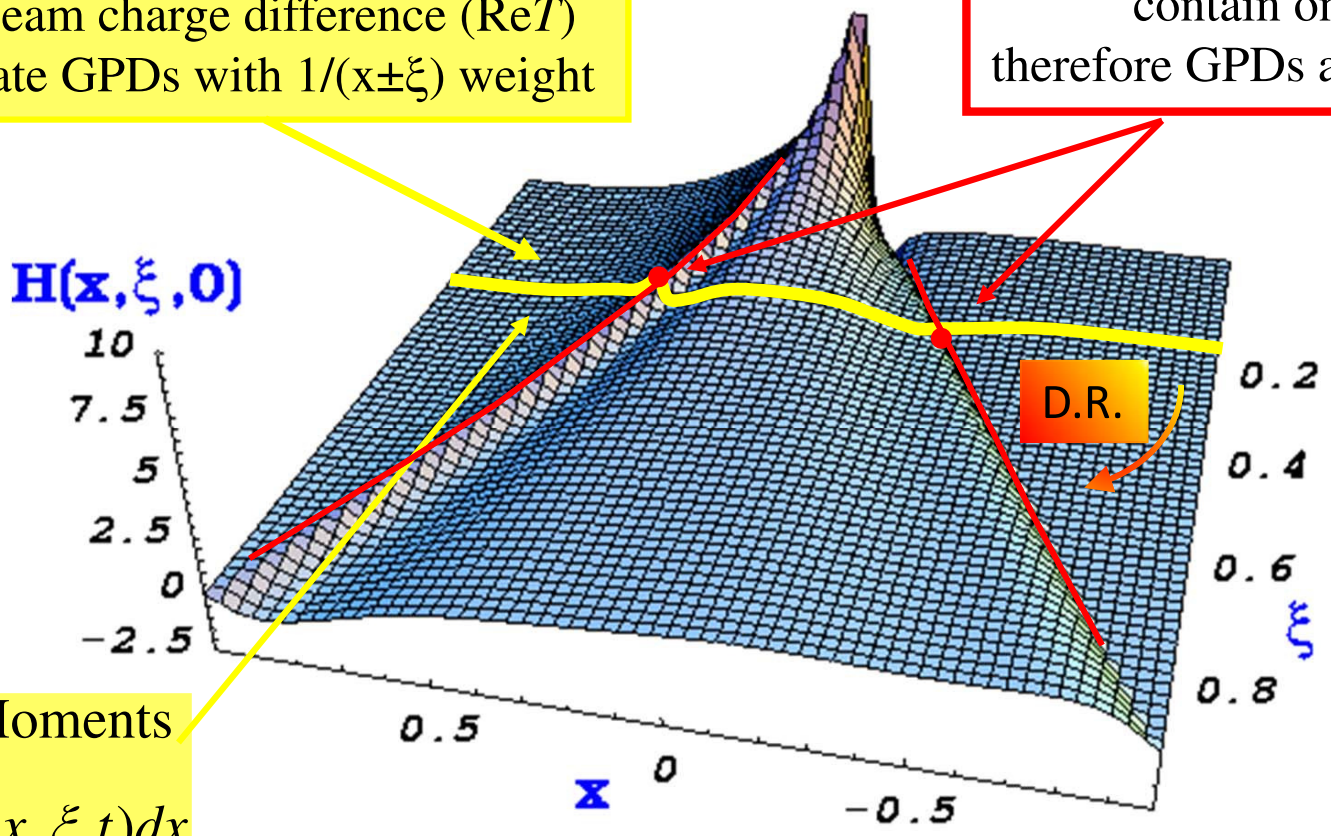
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

DVCS cleanest process to access GPDs

GPD experimentally: Compton Form Factors (CFFs)

Cross-section (σ) measurement and beam charge difference (ReT) integrate GPDs with $1/(x\pm\xi)$ weight

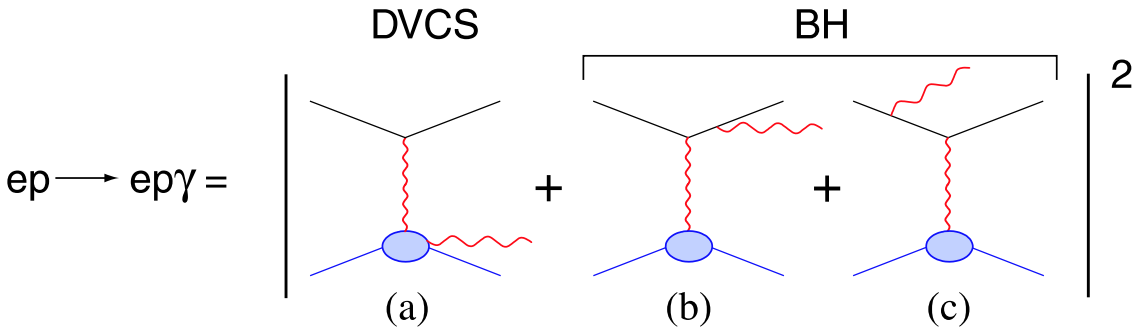
Beam or target spin $\Delta\sigma$ contain only ImT, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

$$= \int x^n H(x,\xi,t)dx$$

DVCS experimentally: interference with Bethe-Heitler (BH)



At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\left(T^{BH}\cdot T^{DVCS}\right)$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\left(T^{BH}\cdot T^{DVCS}\right) + |DVCS|^2$$

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

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

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 (ITSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B kF_2\tilde{\mathcal{E}}\ldots\}d\phi$$

Polarized beam, longitudinal target (BITSA)

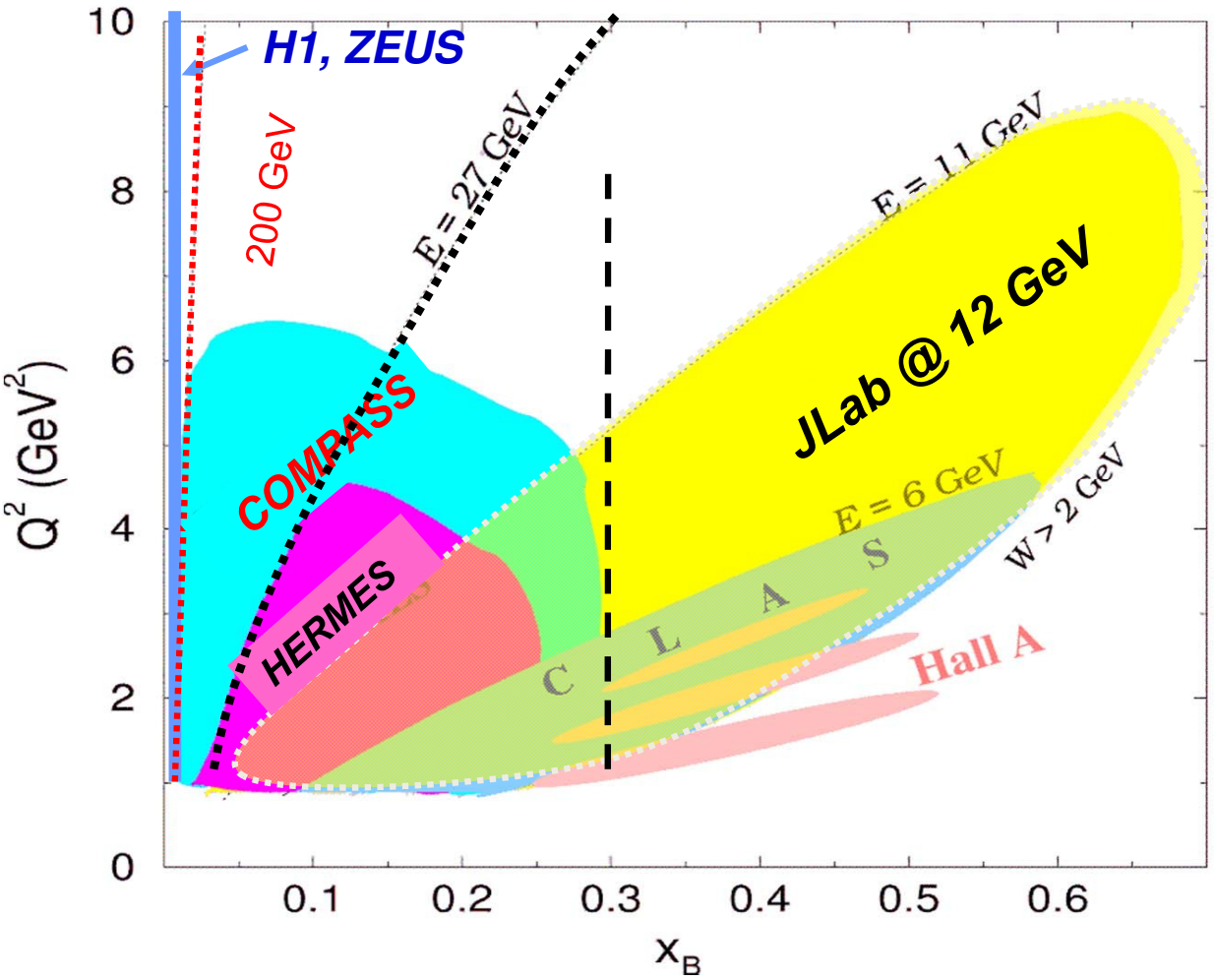
$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

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

Kinematic coverage

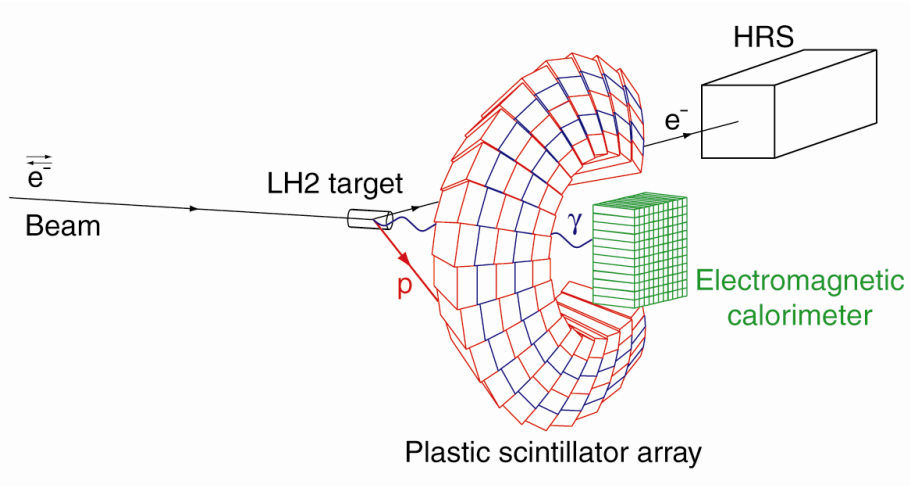
Kinematic complementarity between different facilities:



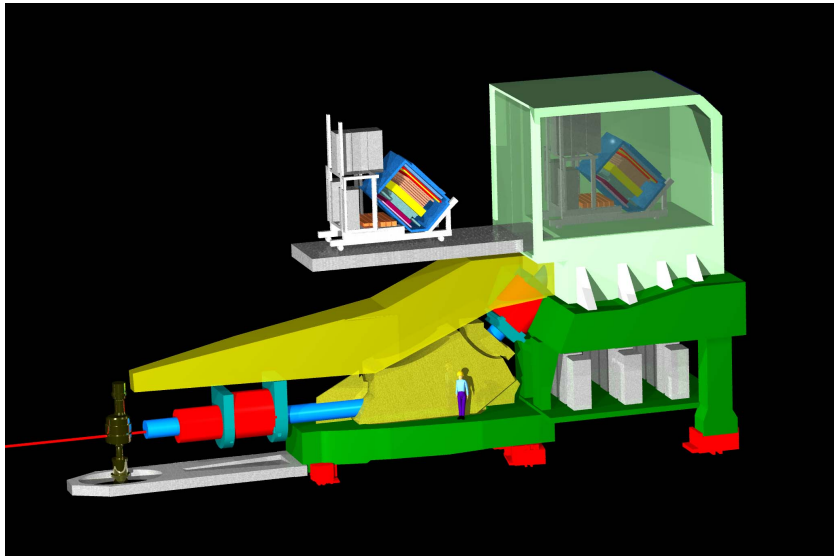
The DVCS program "worldwide"

- HERMES at DESY:
  - Beam (BSA), charge (BCA) and transverse target (TSA) asymetries published
  - Several ongoing analysis + recoil detector installed 1 year before shutdown: results to come...
- Hall A and Hall B partially overlapping, partially complementary, active programs:
  - Hall A: high accuracy, limited kinematics
  - Hall B: wide kinematic range, limited accuracy
  - Very different systematics
- COMPASS at CERN
- The roadmap:
  - Early results (≈ 2001) from non-dedicated exp. (HERMES+CLAS)
  - First round of dedicated experiments in Halls A/B in 2004/5
  - Second round on 2008–2010
  - Compeling DVCS experiments in Halls A/B at 11 GeV (≈2014-16)
  - Exciting program at COMPASS (2015–2016)

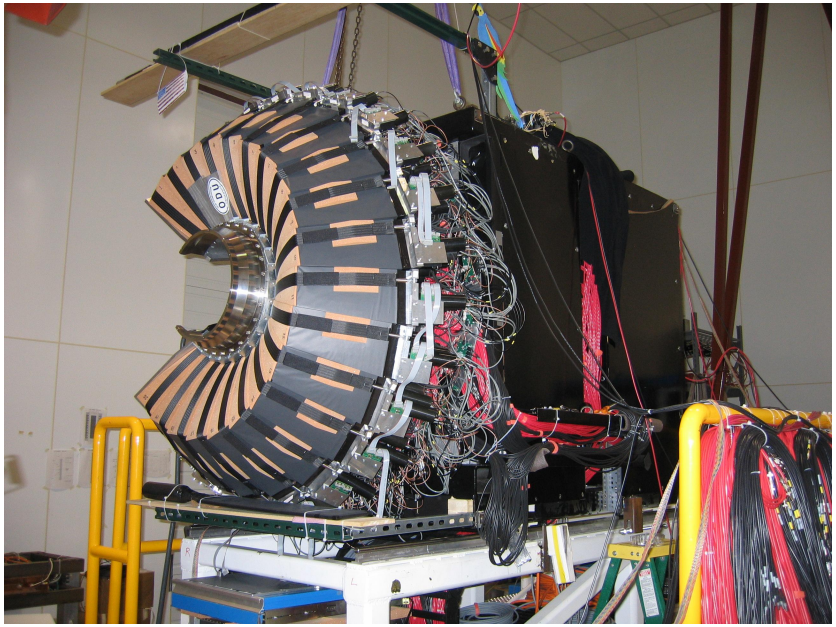
E00-110 experimental setup



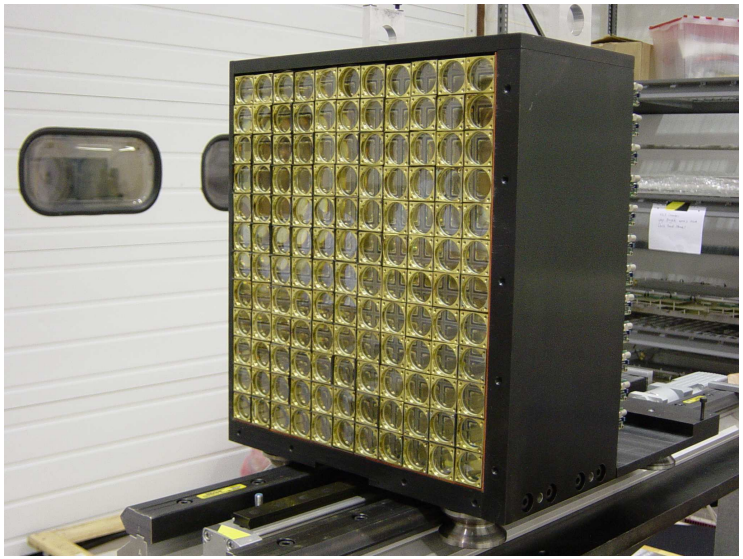
High Resolution Spectrometer



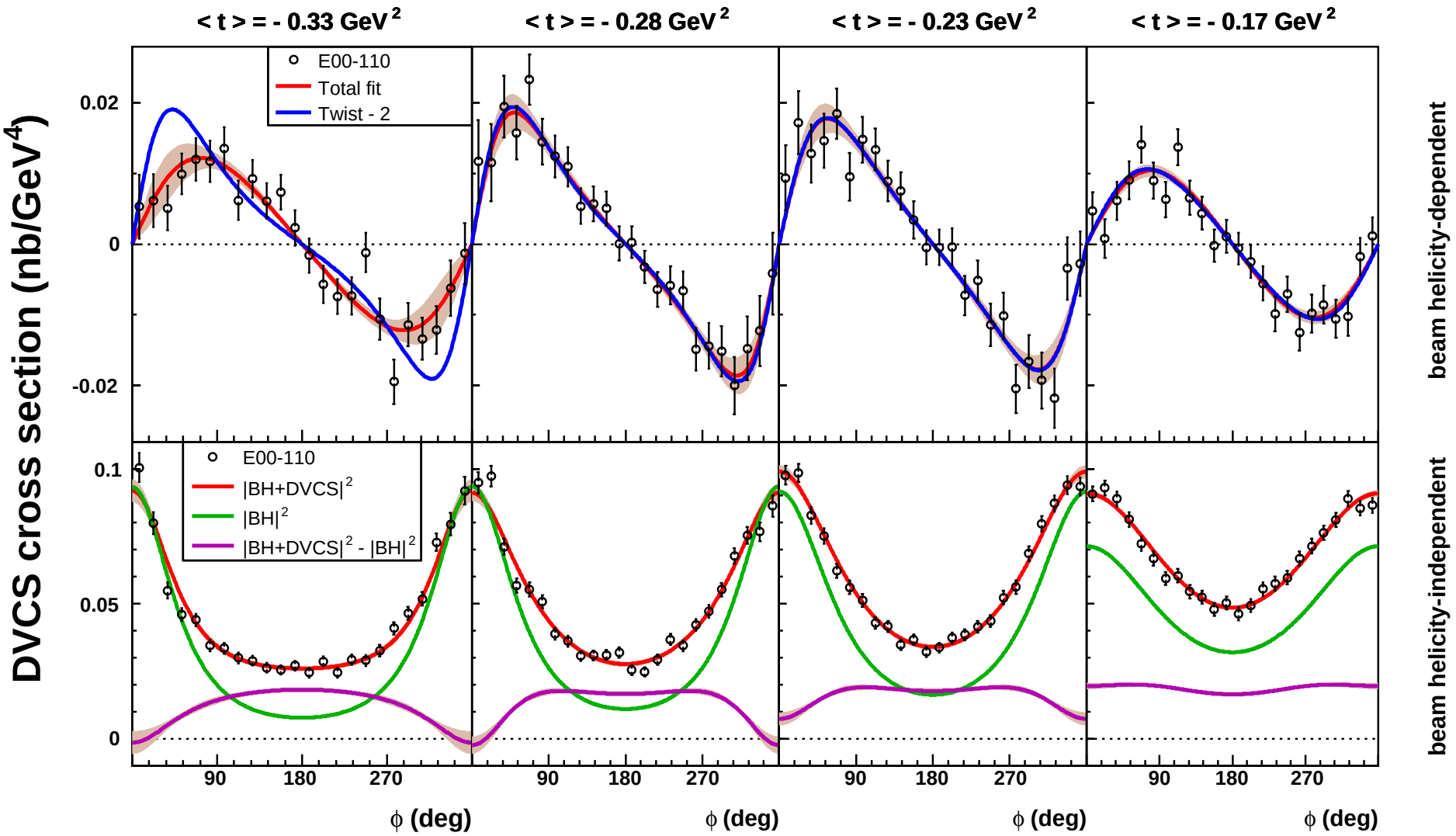
100-channel scintillator array



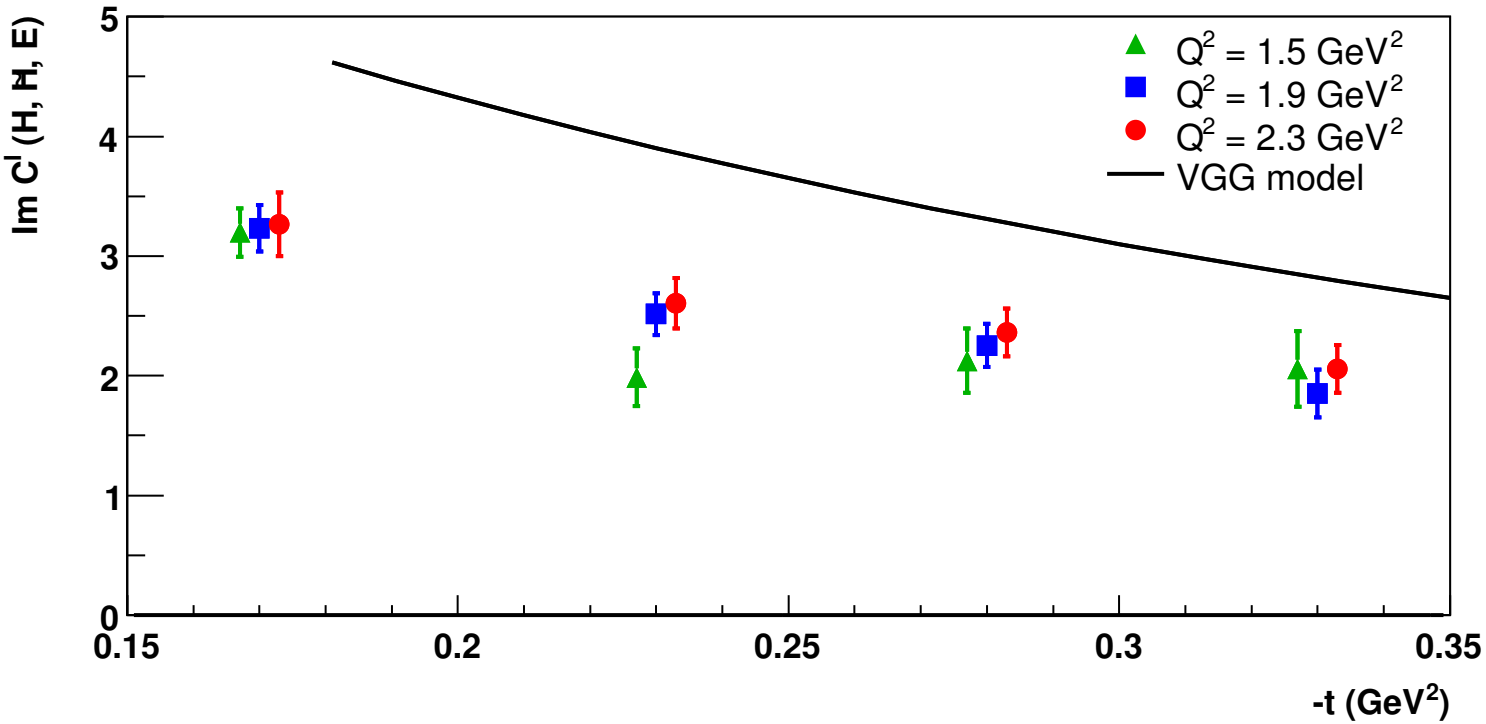
132-block PbF_2 electromagnetic calorimeter



DVCS cross section in the valence region (Hall A: E00-110)



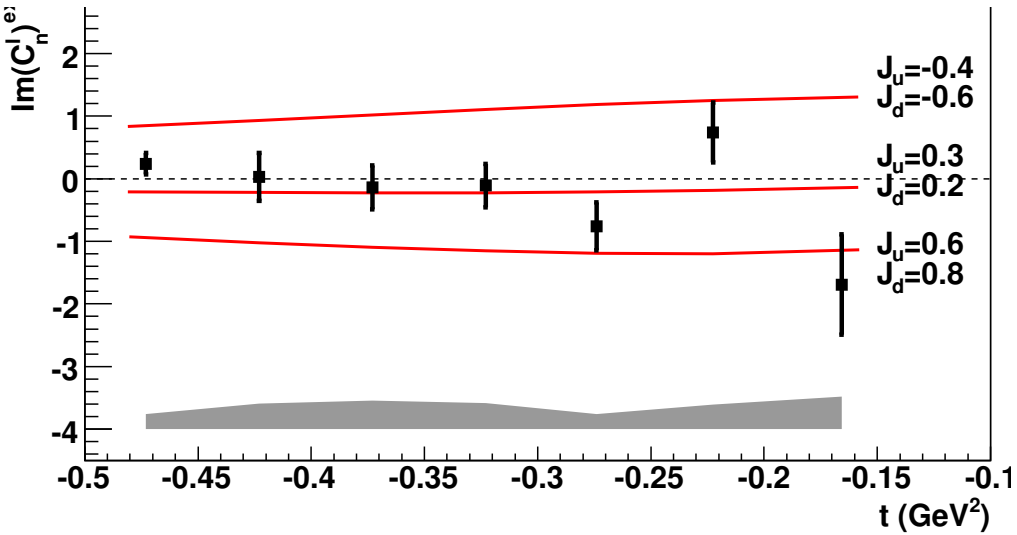
E00-110: Scaling tests



Twist-2: dominant contribution

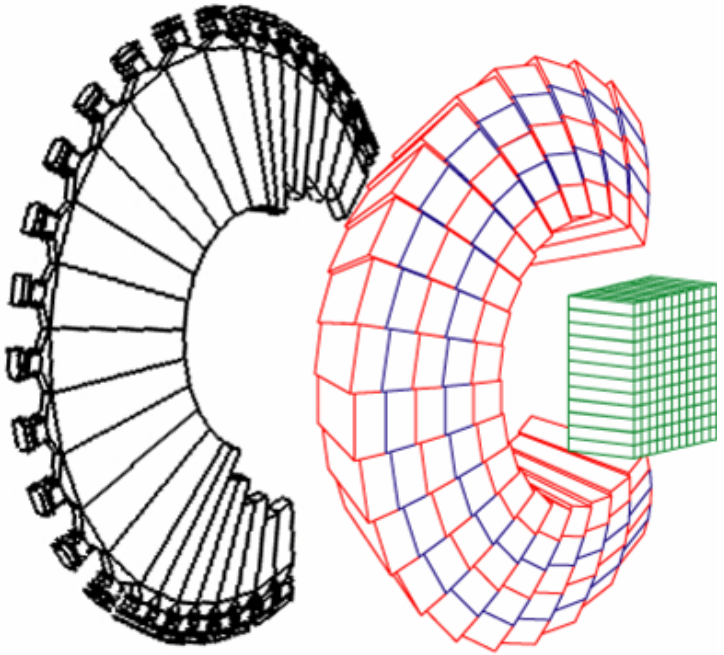
DVCS on the neutron: experiment E03-106 at JLab

LD$_2$ target ($F_2^n(t) \gg F_1^n(t)$!)



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

Charged particle veto
in front of scintillator array

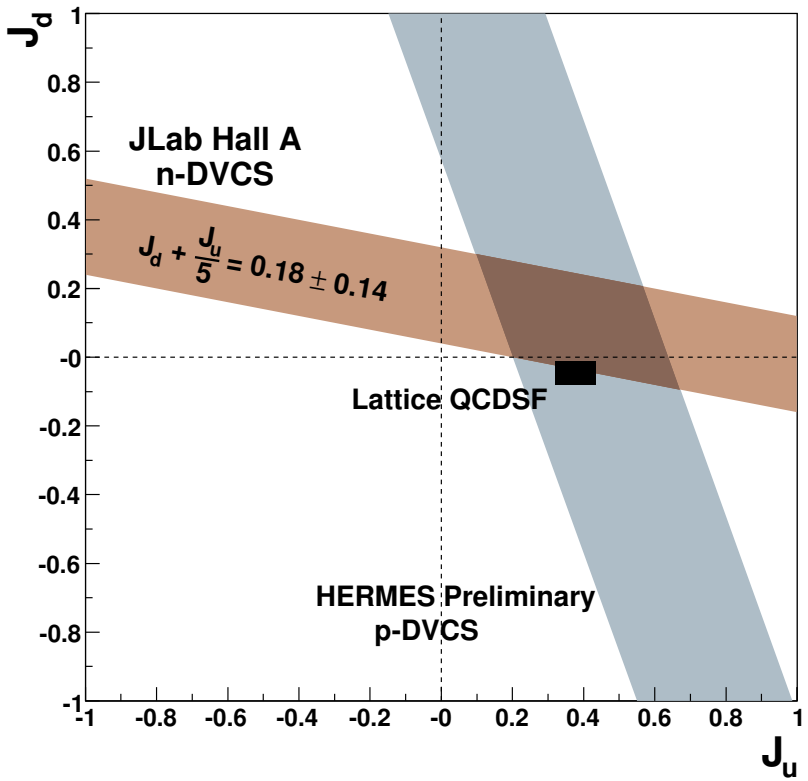


$$A = F_1(t)\mathcal{H} + \frac{x_B}{2 - x_B}[F_1(t) + F_2(t)]\tilde{\mathcal{H}} - \underbrace{\frac{t}{4M^2} \cdot F_2(t) \cdot \mathcal{E}}$$

Main contribution for neutron

DVCS on the neutron: experiment E03-106 at JLab

LD$_2$ target ($F_2^n(t) \gg F_1^n(t)$!)



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Charged particle veto
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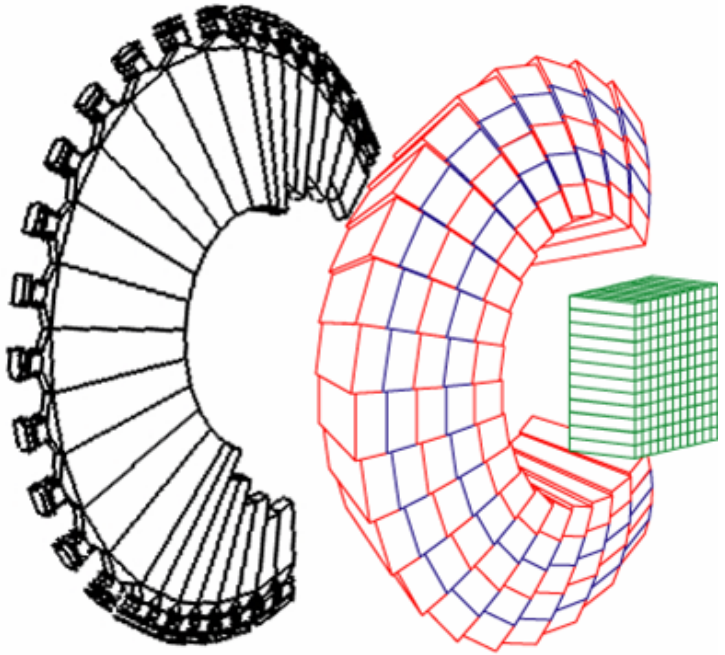

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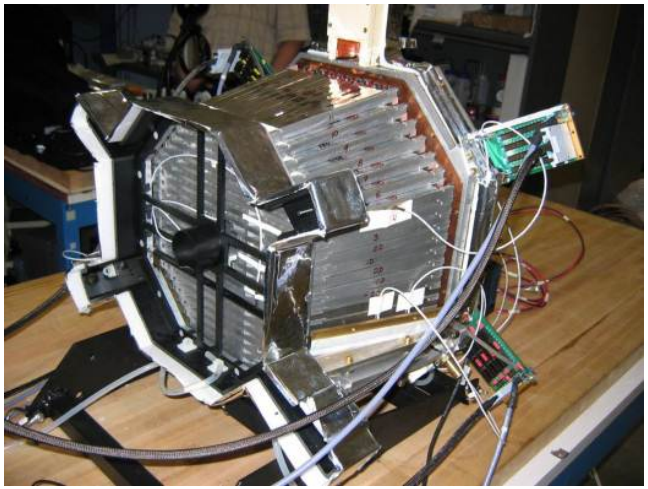
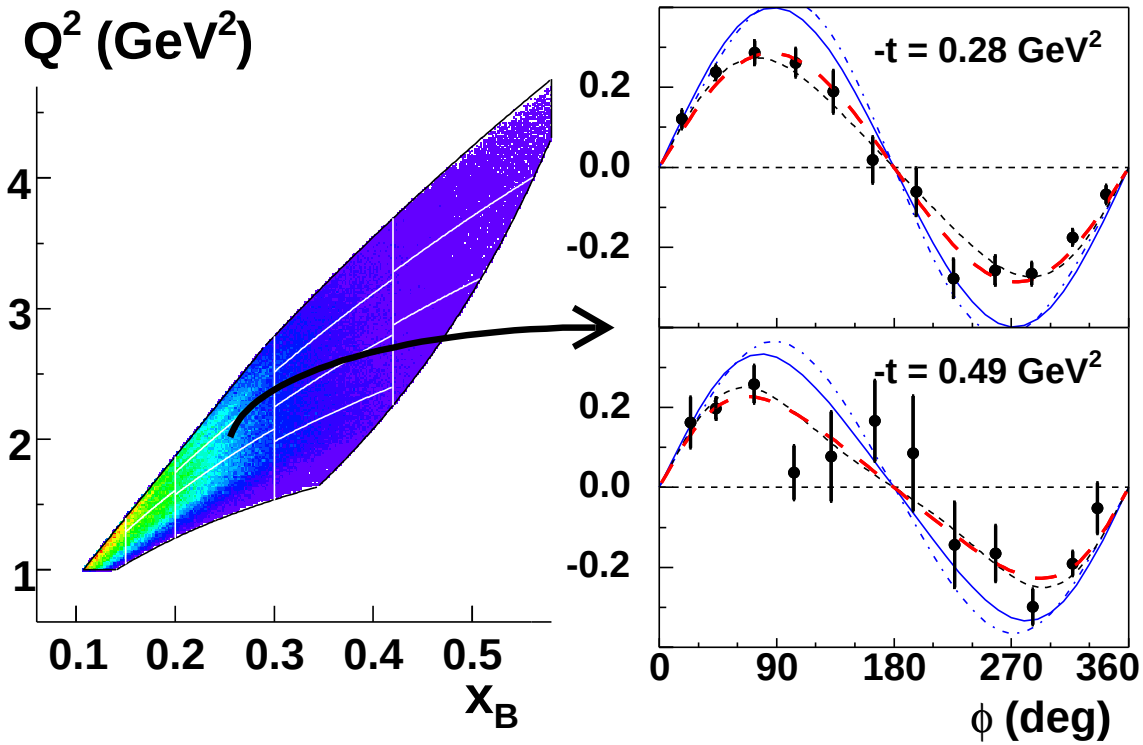
Main contribution for neutron

E01-113: BSA in a large kinematic domain (Hall B)

CLAS+
dedicated calorimeter



$$A = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \approx \frac{\alpha \sin\phi}{1 + \beta \cos\phi}$$



E01-113: BSA in a large kinematic domain (Hall B)

CLAS+
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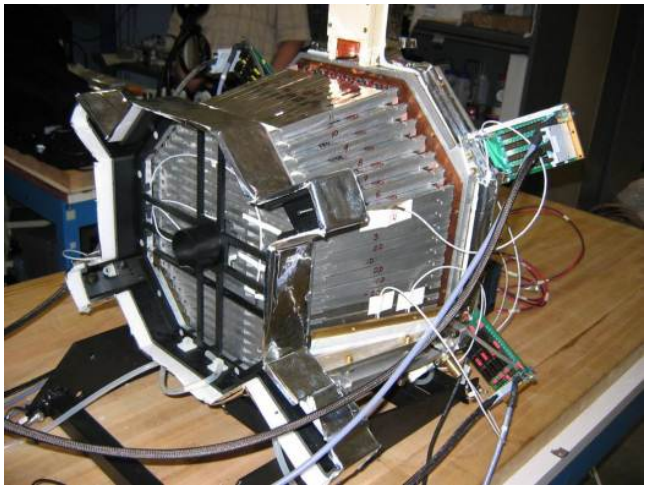
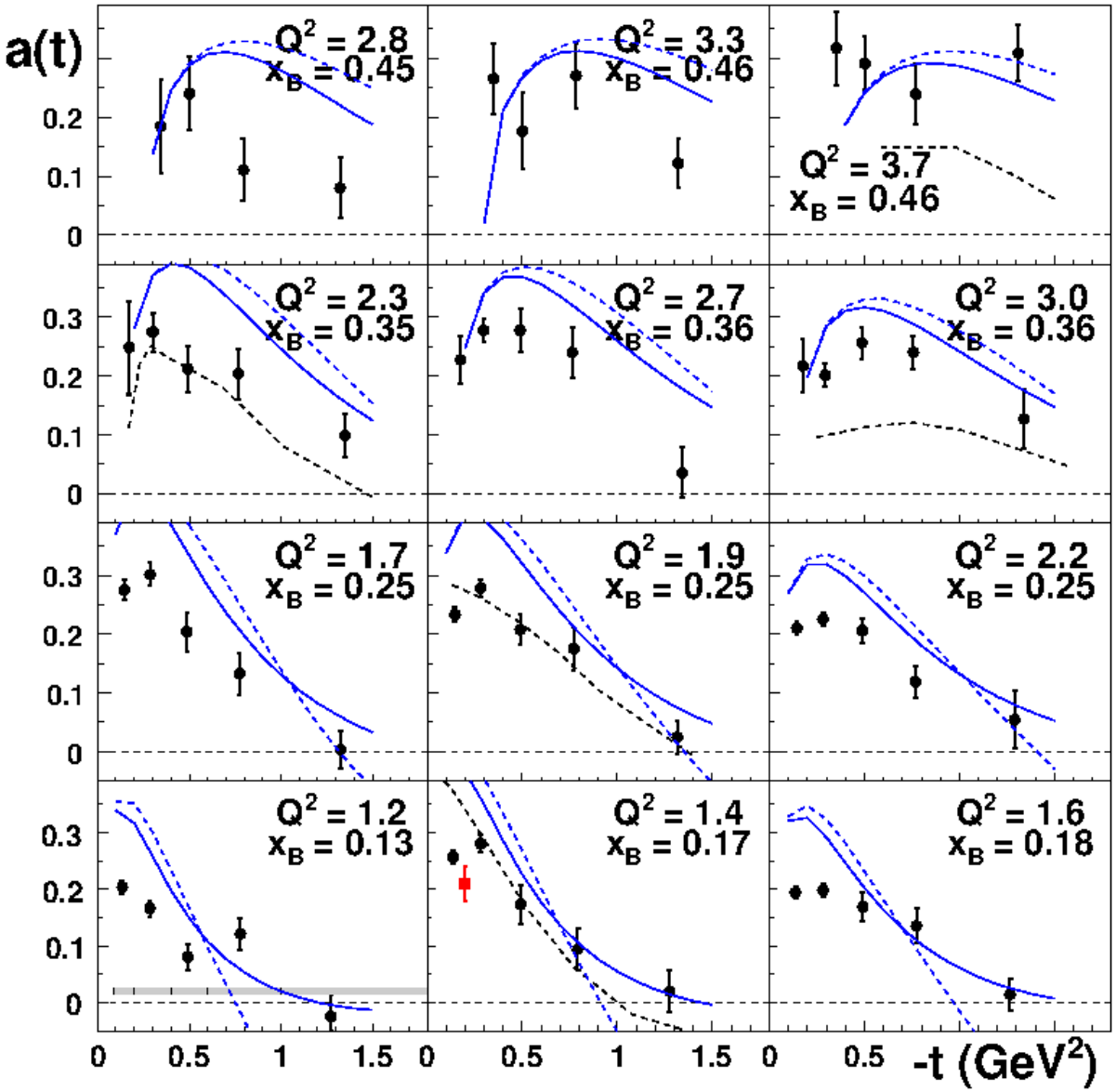


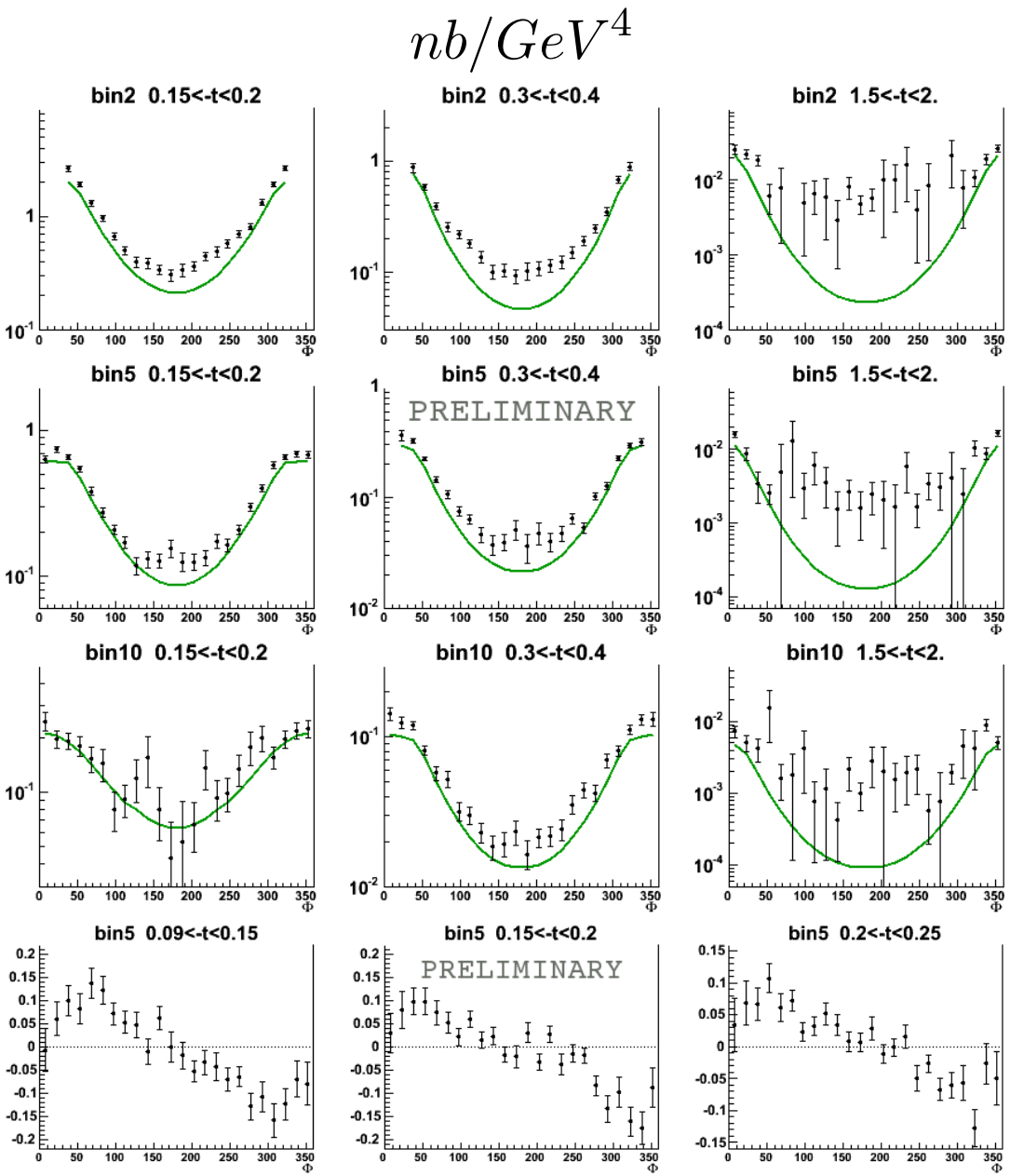
$$A = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \approx \frac{\alpha \sin\phi}{1 + \beta \cos\phi}$$

Simple models do not reproduce the data



Analysis of cross sections underway

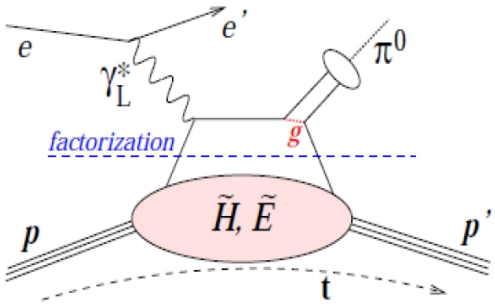
JLab Hall B cross-sections: preliminary



- Large data set under analysis
- Compatible within errors with Hall A in overlap region

arXiv:1207.3709

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



At leading twist:

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

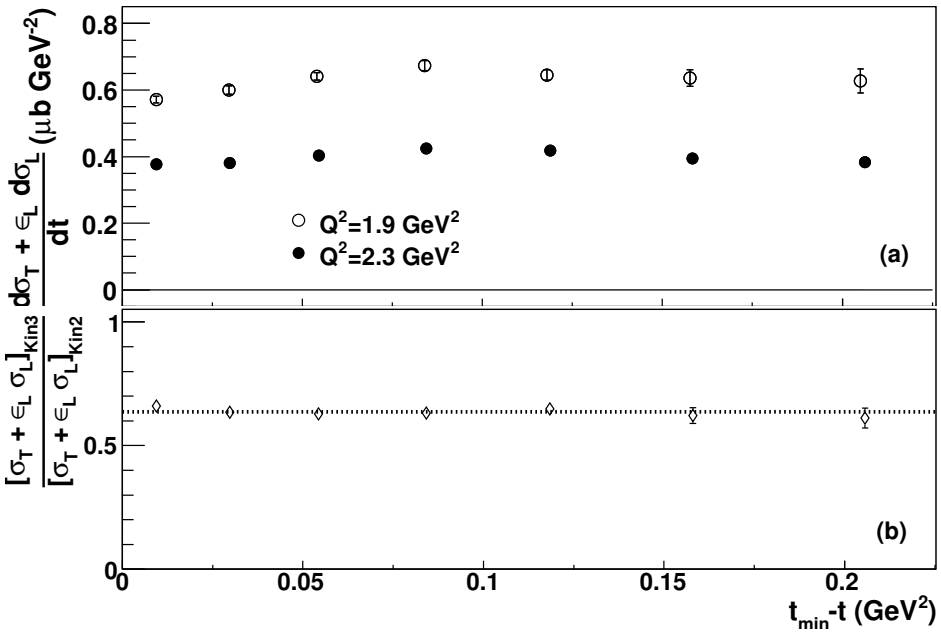
$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z}\right] \int_{-1}^1 dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \times \left\{\Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0}\right\}$$

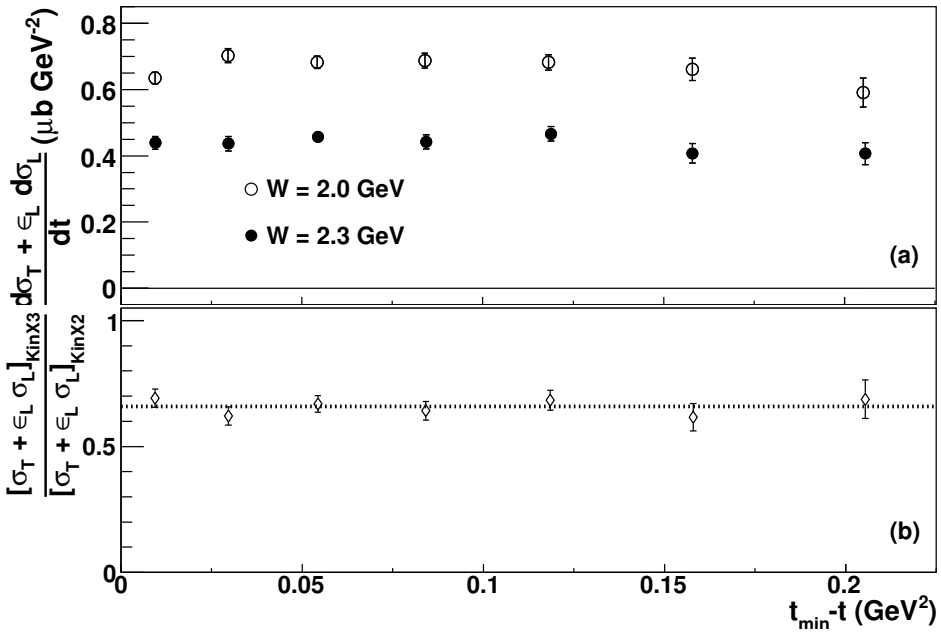
Different quark weights: flavor separation of GPDs

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

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

Exclusive π^0 electroproduction cross-sections

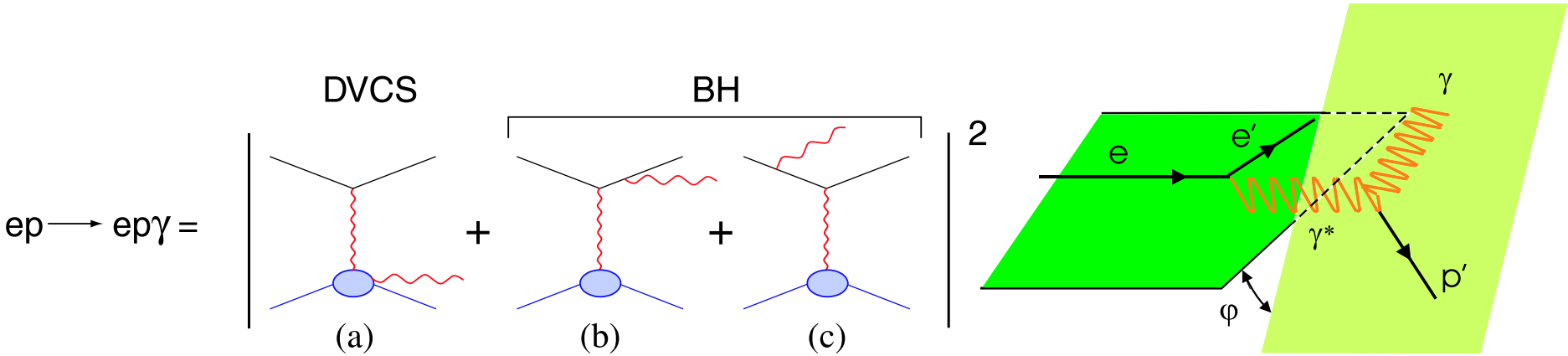




- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$
  (similar to $\sigma_T(ep \to ep\pi^+)$ measured in Hall C)
- GPDs predict $\sigma_L \sim Q^{-6}$
- σ_T likely to dominate at these Q^2,
  but L/T separation necessary ($\to$ new experiment...)

E. Fuchey et al., Phys. Rev. C83 (2011), 025125

E07-007 (Hall A)



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

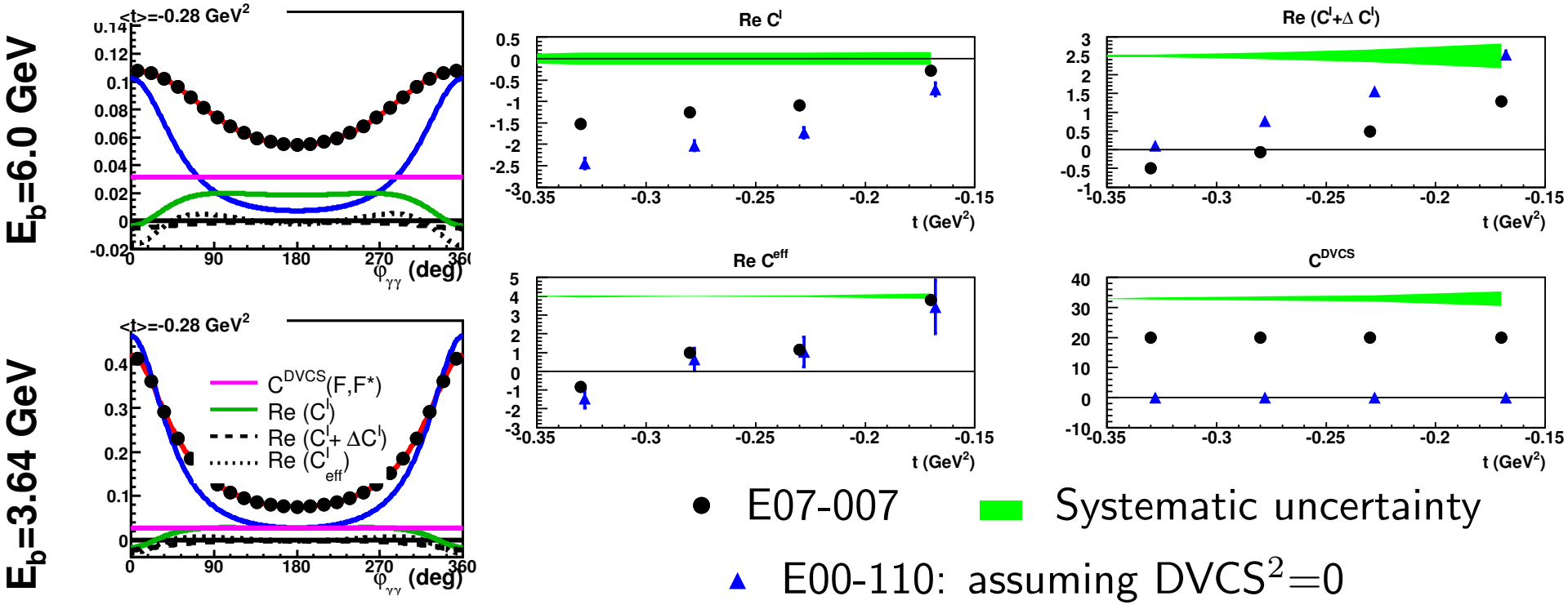
DVCS cross section has a very rich azimuthal structure:

- Azimuthal analysis allows the separation of the different contributions to $\mathcal{I}$ if DVCS^2 is negligeble.
- If DVCS^2 is important, $\mathcal{I}$ and DVCS^2 terms **MIX** in an azimuthal analysis.
- The **different energy dependence** of $\mathcal{I}$ and DVCS^2 allow a full separation.

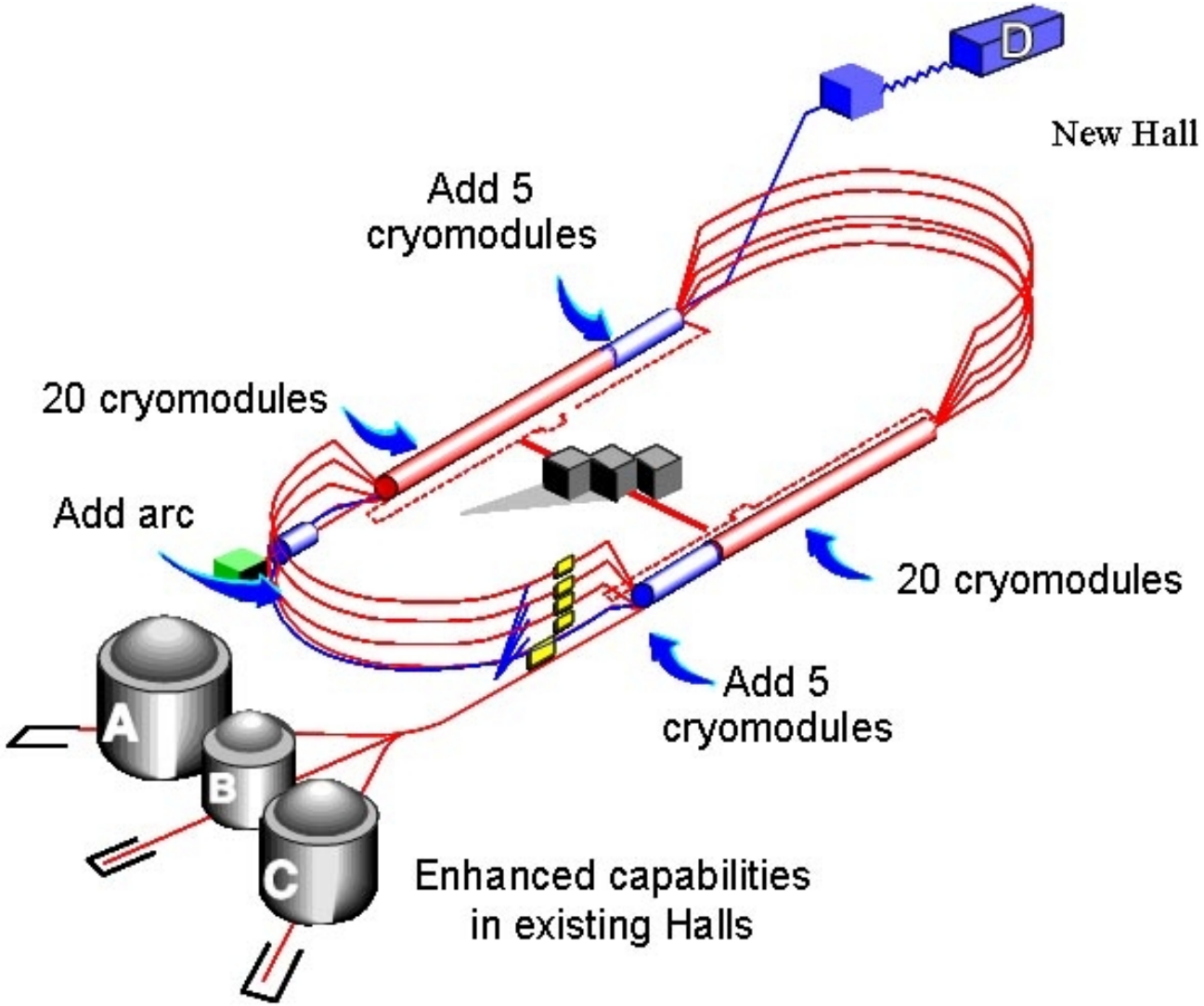
E07-007: Rosenbluth-like DVCS^2–$\mathcal{I}$ separation in Hall A

- Clean separation of BH-DVCS intereference term from pure DVCS^2
- Scaling test on the real part of the DVCS amplitude
- Rosenbluth separation of σ_L/σ_T for $ep \to ep\pi^0$

$d^4\sigma$ (nb/GeV^4)



Upgrade of Jefferson Lab to 12 GeV



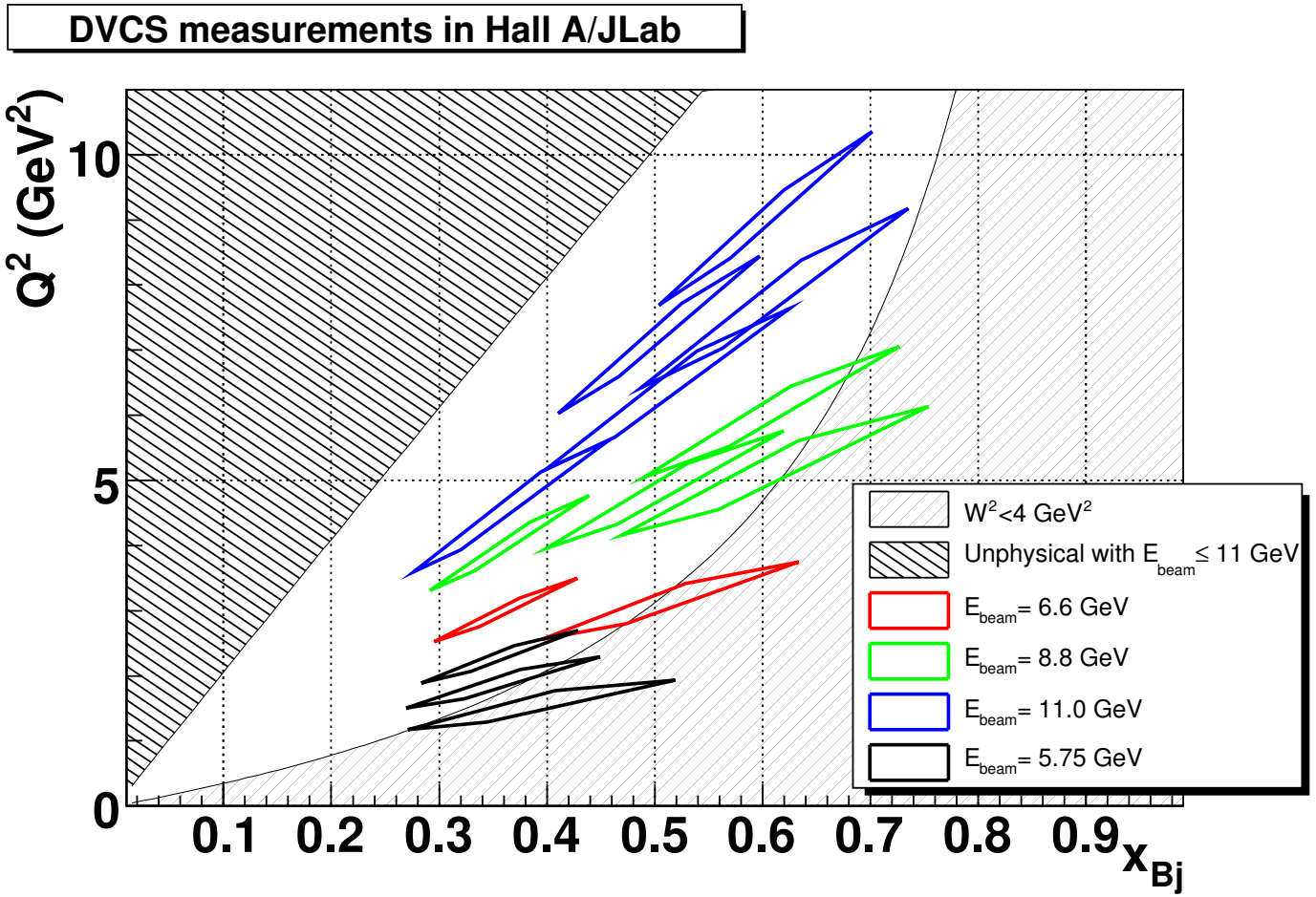
JLab 12 GeV DVCS experiments

- E12-06-114: Hall A unpolarized protons
- E12-06-119: Hall B unpolarized protons
- E12-11-003: Hall B unpolarized neutrons
- E12-06-119: Hall B long polarized protons
- E12-12-010: Hall B tran polarized protons

E12-06-114: JLab Hall A at 11 GeV

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)

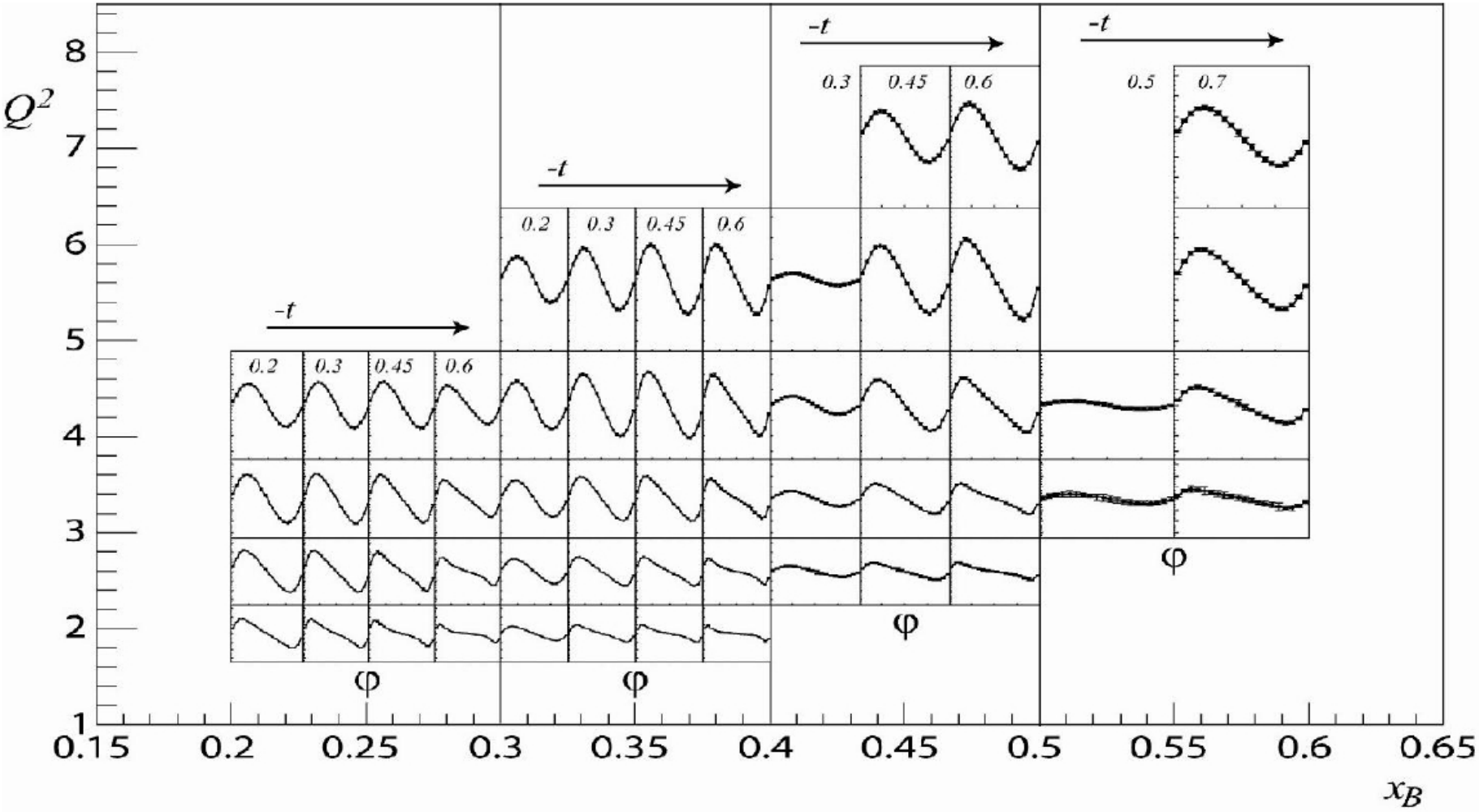


88 days

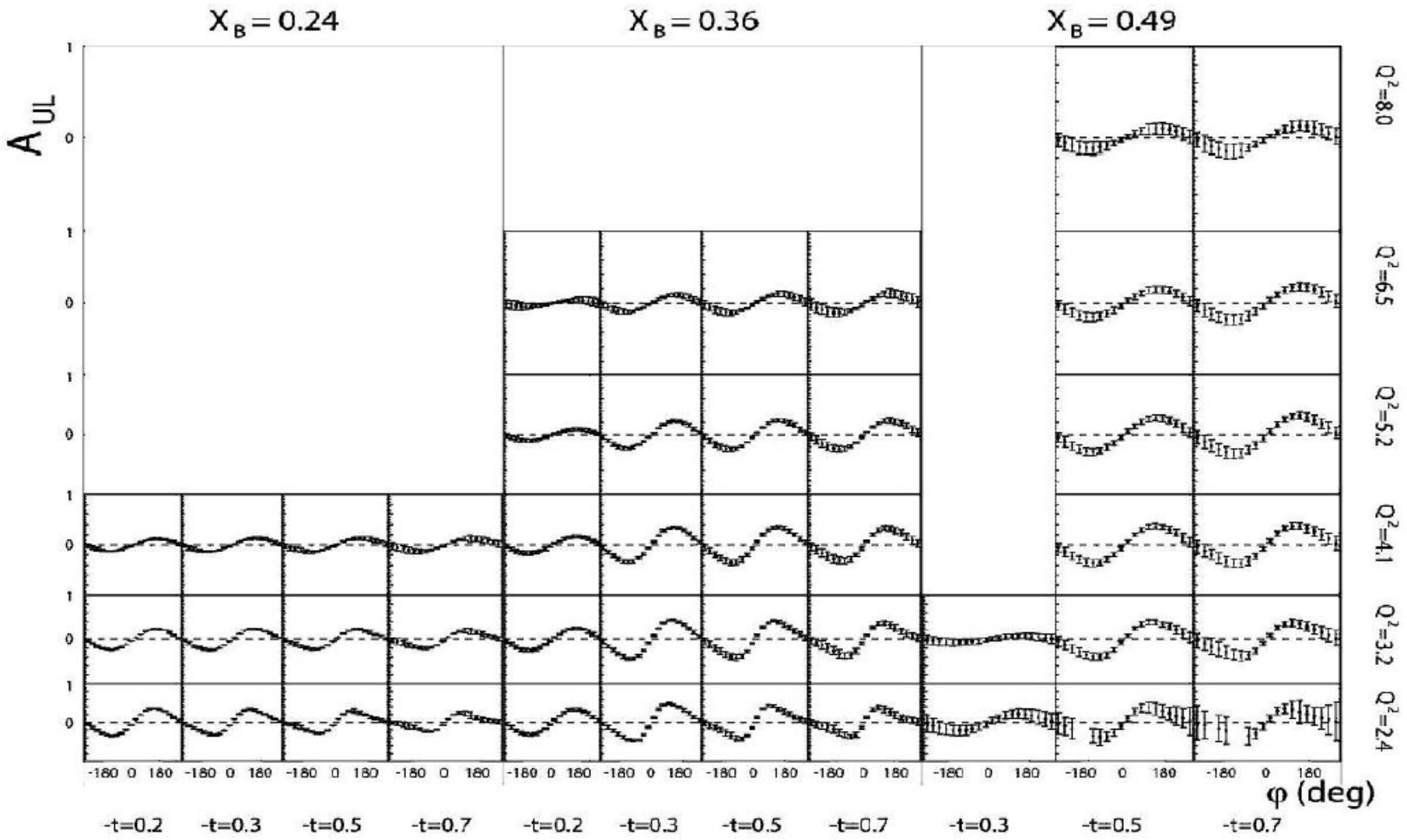
250k events/setting

1 year of operations in JLab/Hall A

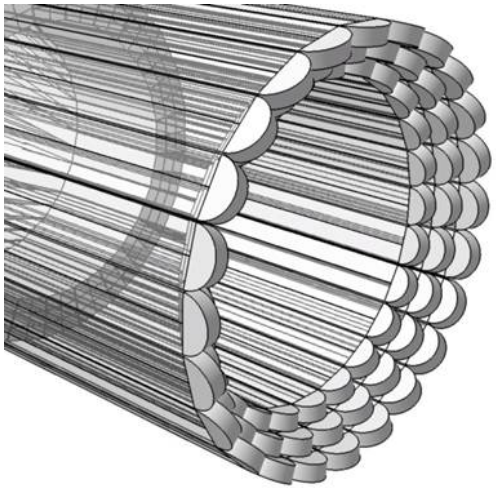
E12-06-119: DVCS on the proton with CLAS12

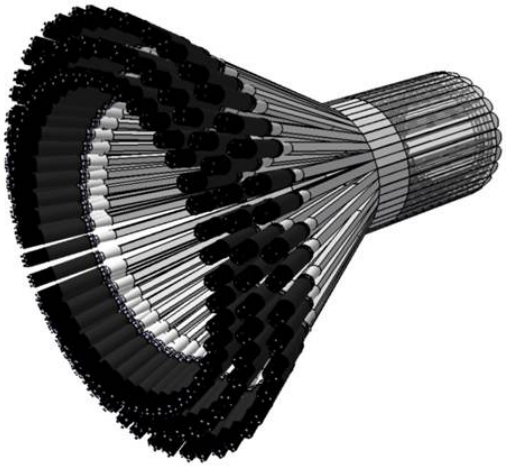


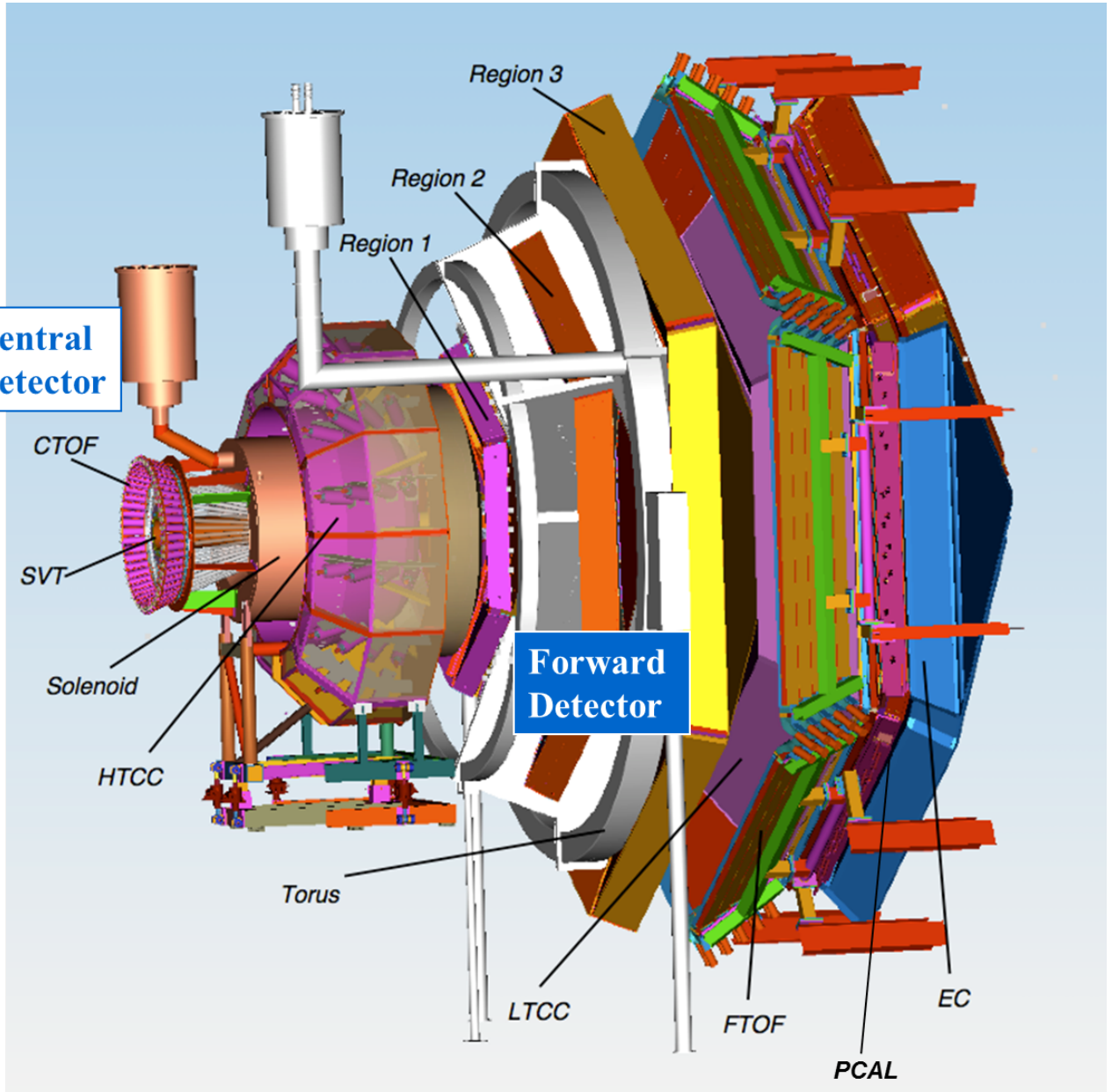
E12-06-119: DVCS on the proton with CLAS12



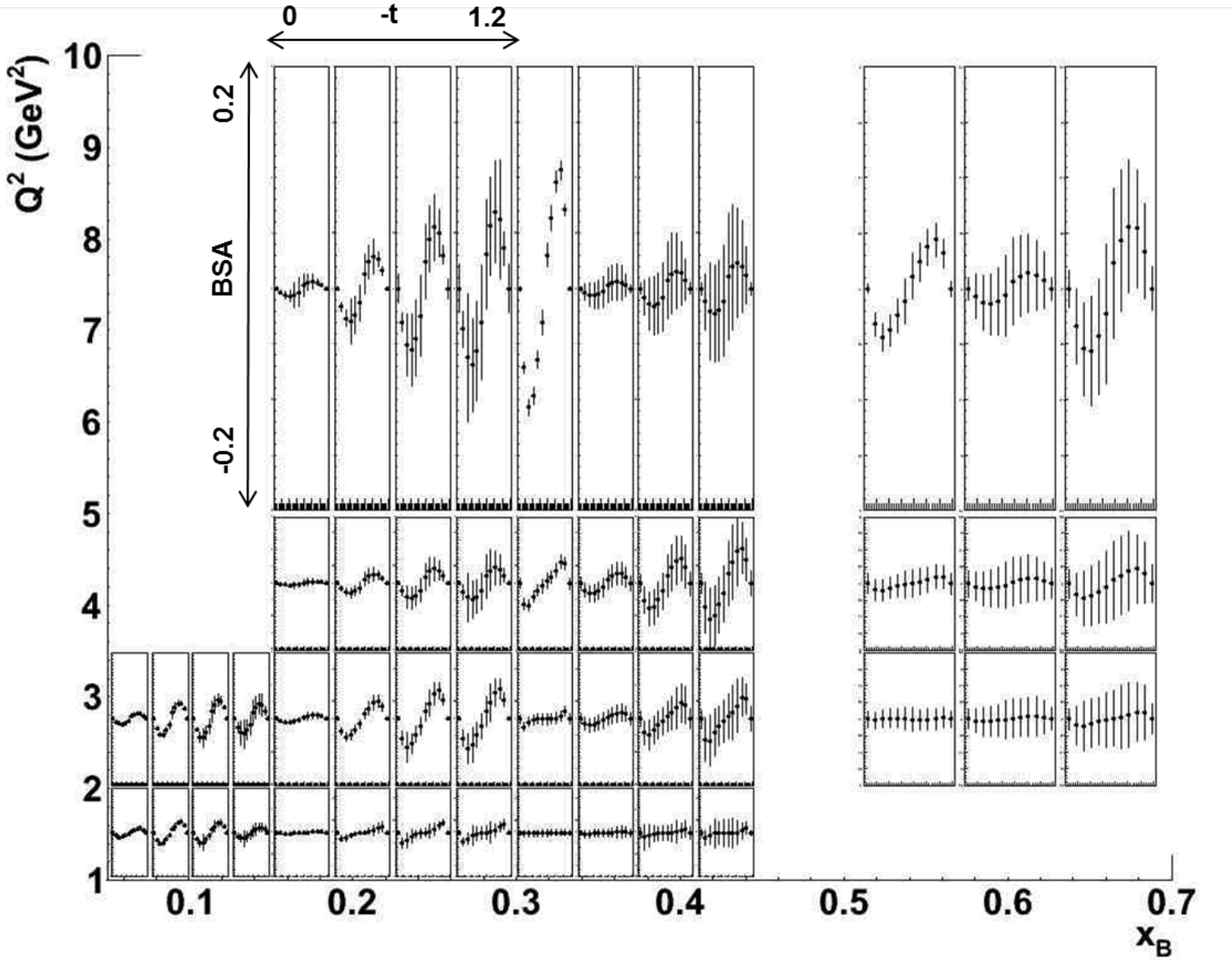
E12-11-003: DVCS on the neutron with CLAS12



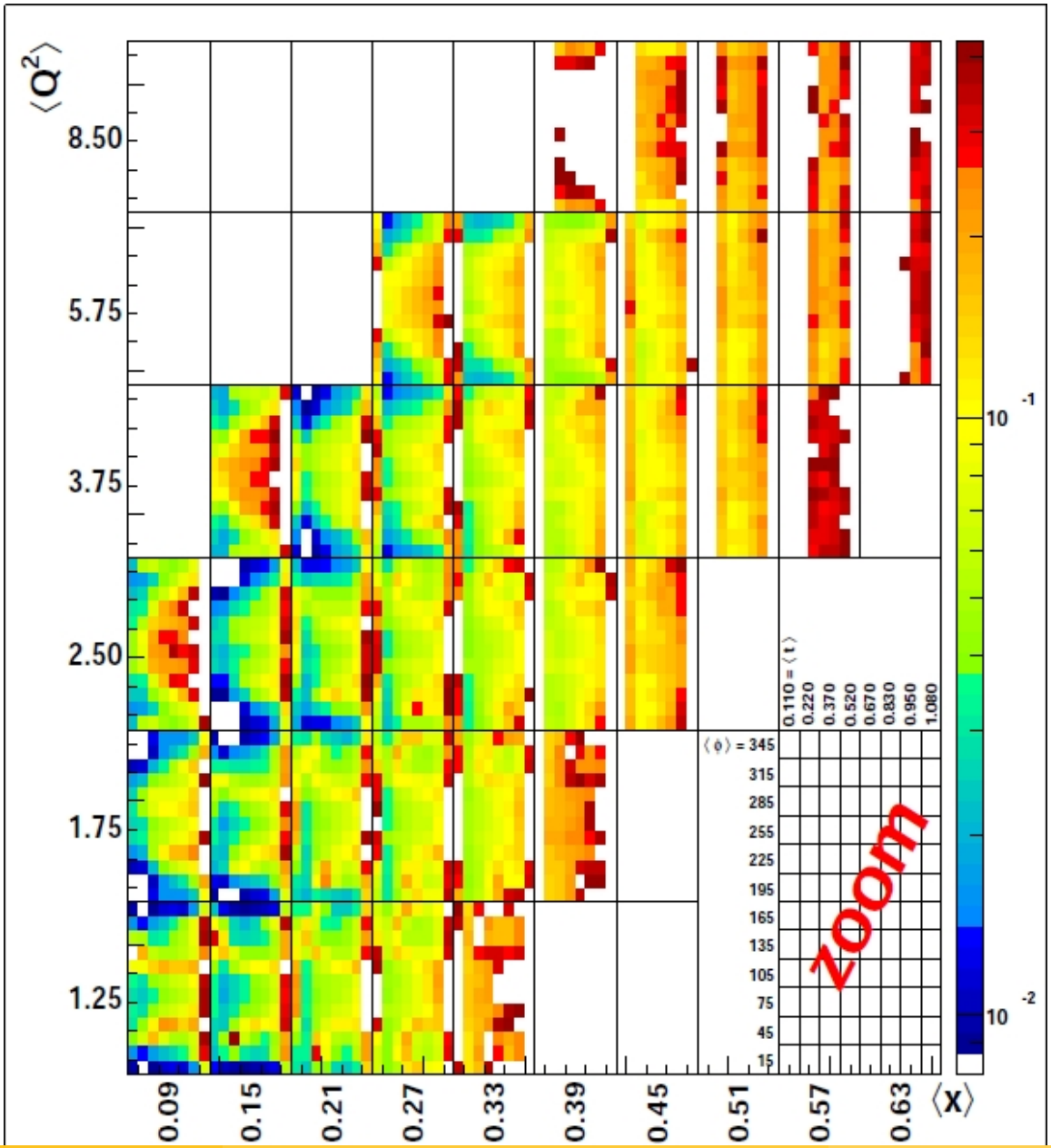




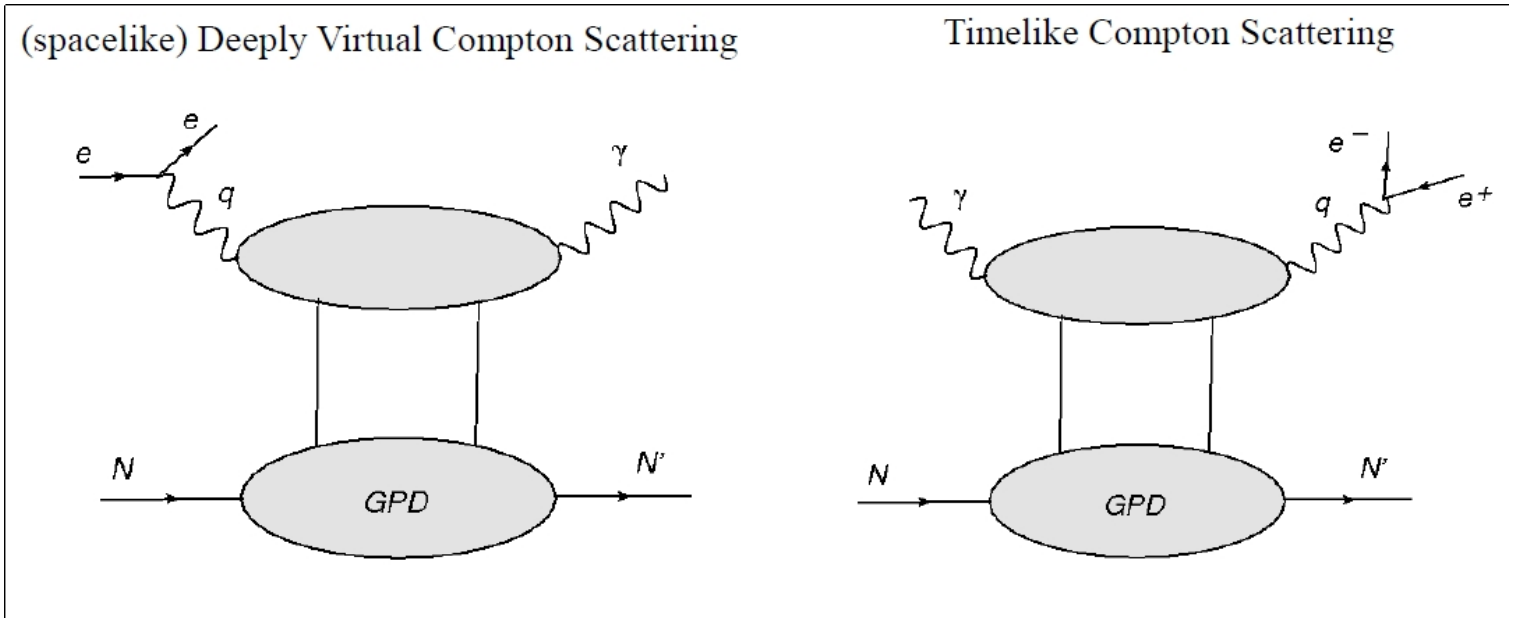
E12-11-003: projections



DVCS with transversally polarized target



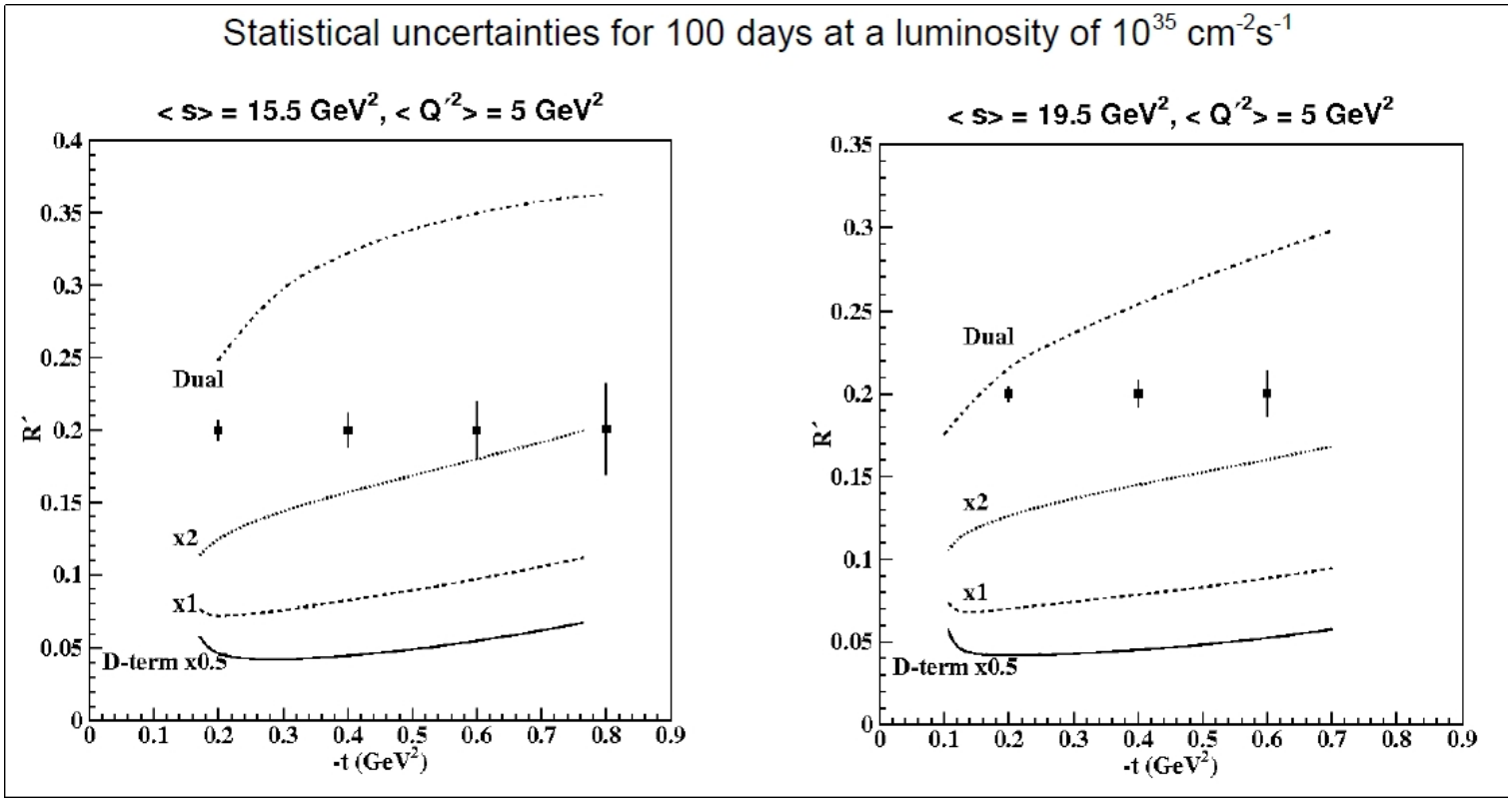
Time-like DVCS: Time-like Compton Scattering (TCS)



- TCS: Same factorization as in DVCS
- Test of universality of GPDs (like DIS vs Drell-Yann)

TCS experiment E12-12-001: projections

$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{d\sigma}{dQ'^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{d\sigma}{dQ'^2 dt d\varphi}} \sim Re\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}$$



Summary

- DVCS golden channel for GPDs, but also accessible in:
  - Time-like Compton Scattering (JLab proposal recently approved)
  - Deep meson production (but higher Q^2 are needed...)
- Large set of data (cross-sections and asymmetries) is now available
- Compeling GPD program in the future at Jefferson Lab 12 GeV