清華大學 Tsinghua University

DVCS Experiments at JLab

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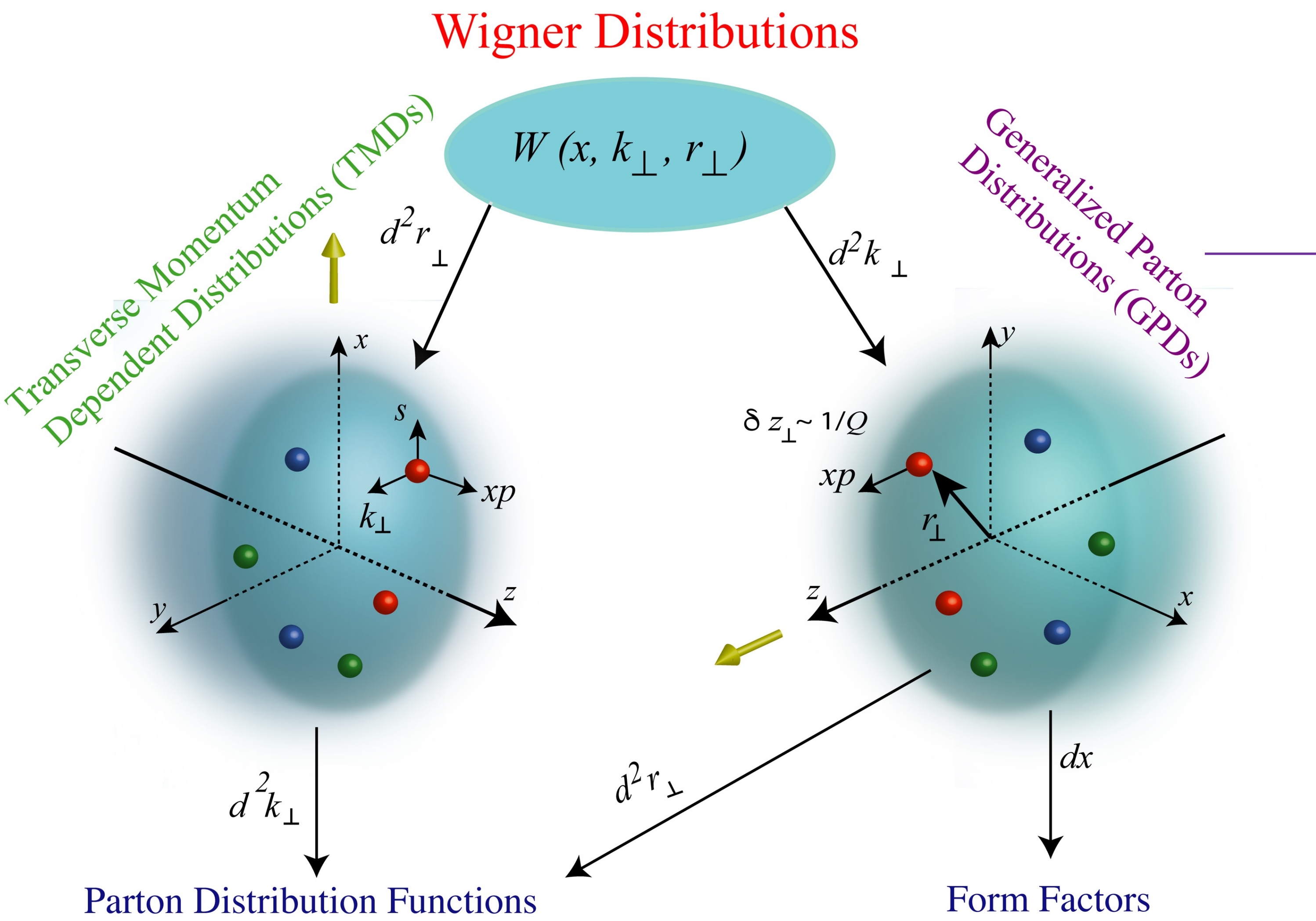
Introduction to DVCS

■ Toward a more complete description of the nucleon

Figure: Dudek et al. Eur. Phys. J. A 48 (2012)



Longitudinal quark distribution in momentum space

Transverse quark distribution in coordinate space

Compton Form Factors

Direct Probe of GPDs

DVCS: Deeply Virtual Compton Scattering

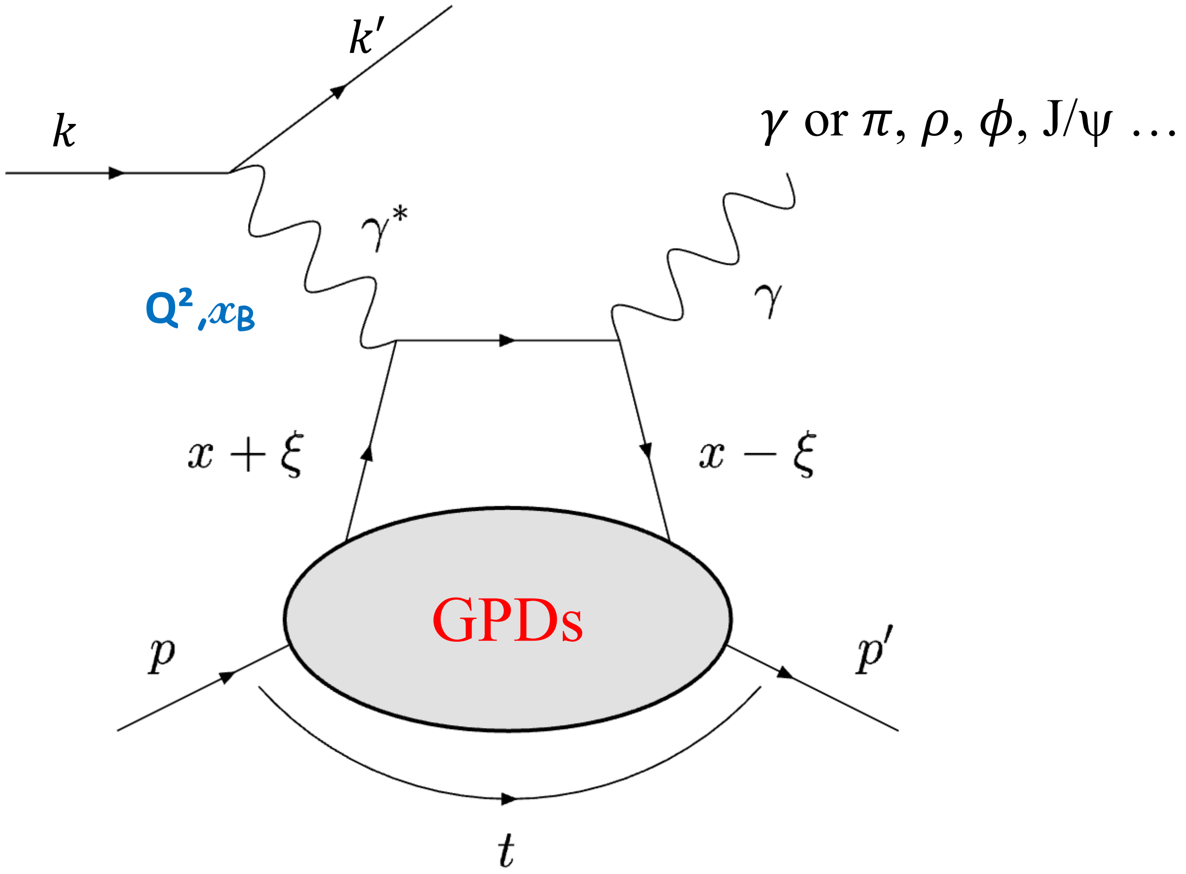
Other Probes:

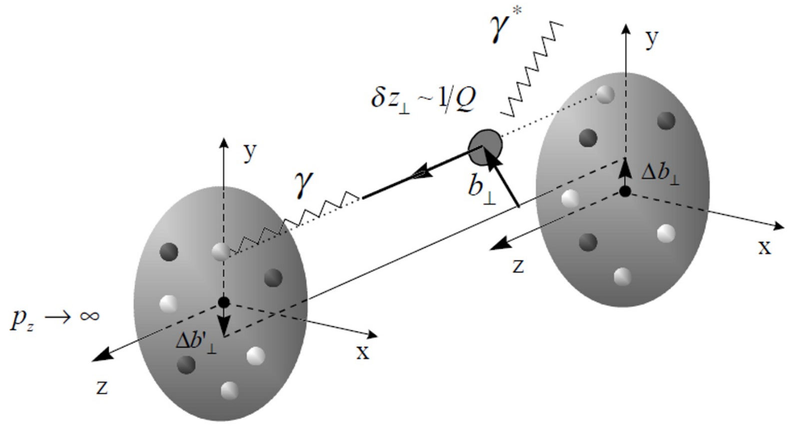
HEMP: Hard Exclusive Meson Production

Introduction to DVCS

■ Exclusive reactions: handbag diagram

DVCS: **ℓp→ ℓ' p' γ** (golden channel)
HEMP: **ℓp→ ℓ' p' π or ρ or ϕ or J/ψ,…**





Definition of variables:

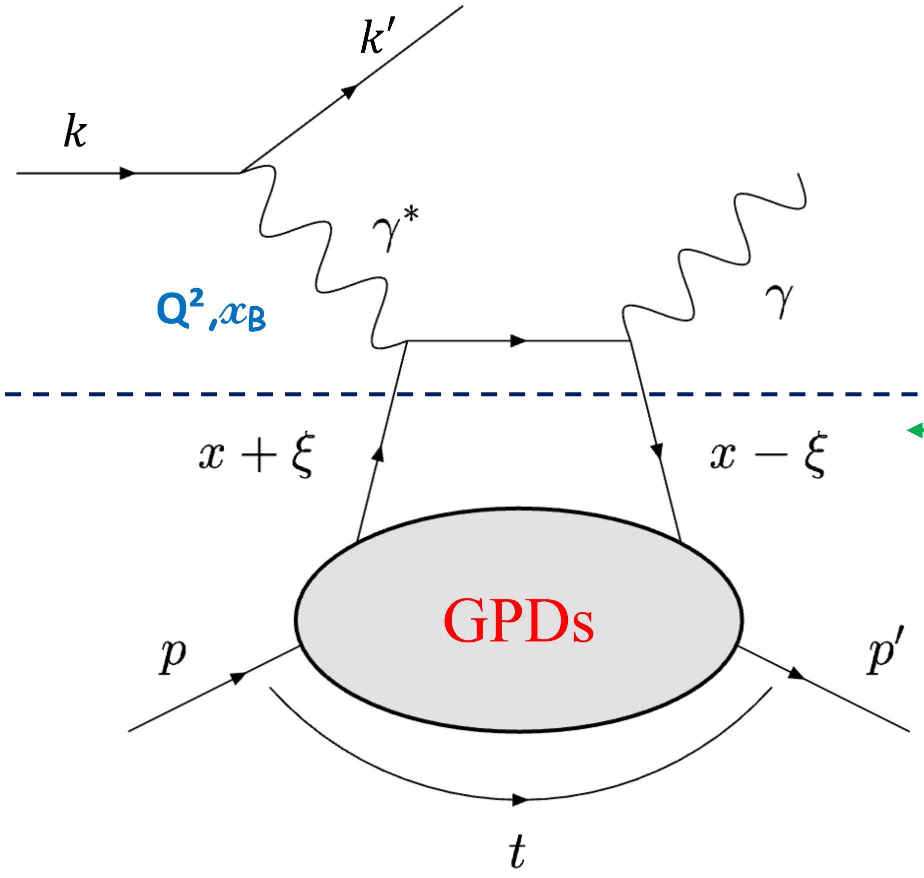
- x: average longitudinal momentum (NOT ACCESSIBLE)
- ξ: longitudinal momentum difference $\simeq x_B/(2-x_B)$
- t: four-momentum transfer

  related to impact parameter $b_\perp$ via Fourier transform
- $Q^2 = -(k - k')^2$
- $x_B = Q^2/2M\nu, \quad \nu = E_e - E_e'$

GPDs and factorization

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

The minimal Q^2 at which the factorization holds must be tested and established by **experiments**



Hard process

QCD perturbative

Soft process

Non perturbative QCD described by GPDs

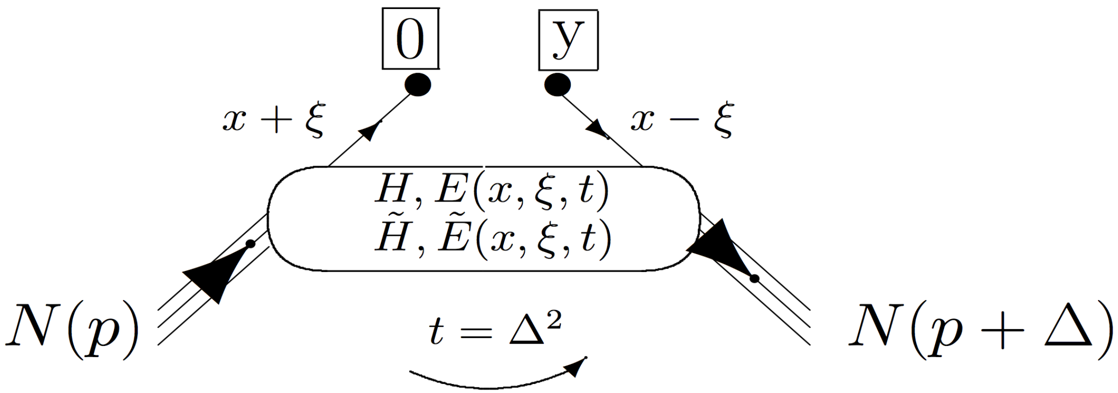
Bjorken limit:

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

One parton per collision

Introduction to DVCS

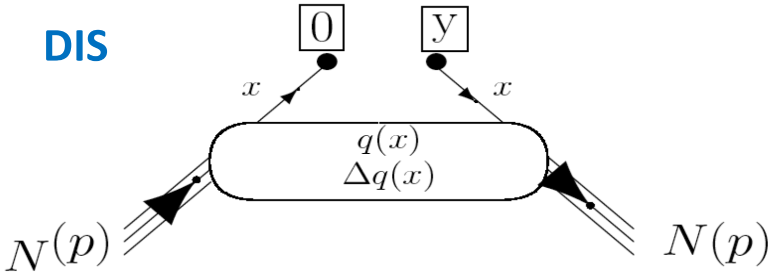
GPDs through DVCS



	Nucleon Helicity conserving	Nucleon Helicity non-conserving
unpolarized GPD	H	E
polarized GPD	$\tilde{\mathrm{H}}$	$\tilde{\mathrm{E}}$

$$\lim_{t\to 0}(GPD) \to PDF$$

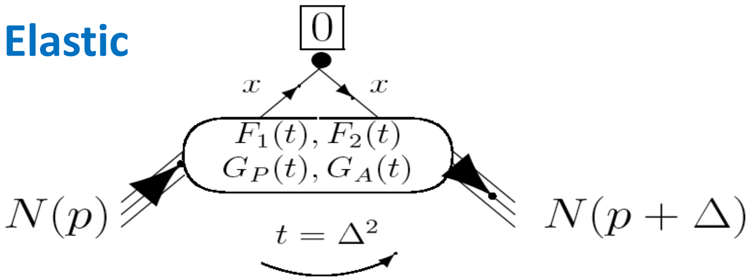
DIS



$$H^i(x,0,0) = q_i(x)$$
$$\tilde{H}^i(x,0,0) = \Delta q_i(x)$$

GPD first moments $\to$ Form Factors

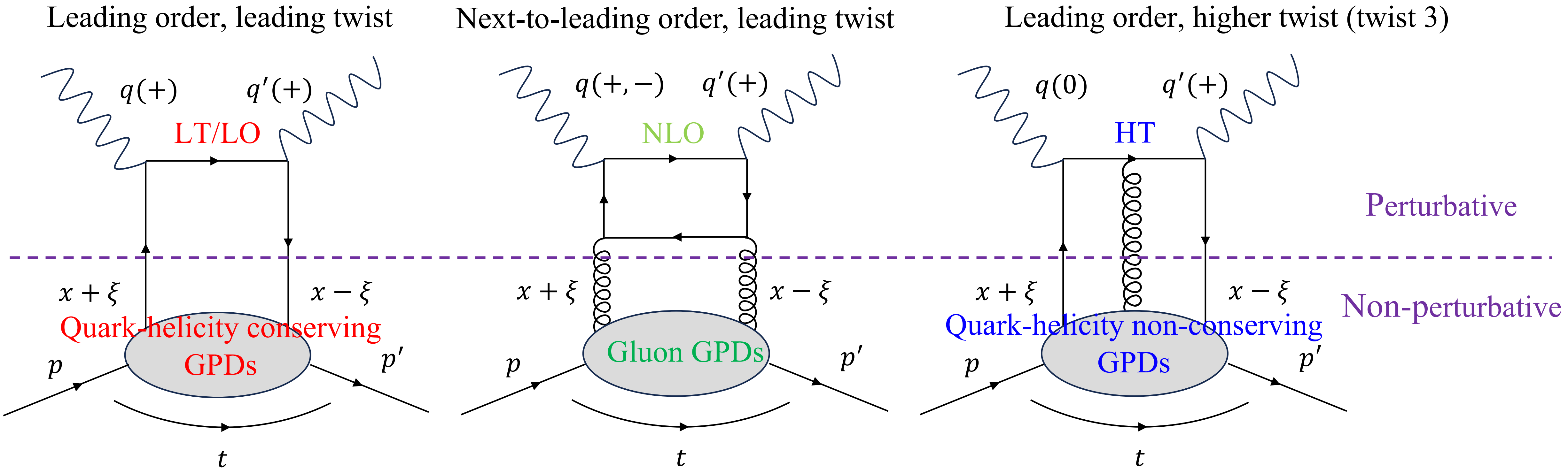
Elastic



$$\int_{-1}^{1} dx H^i(x,\xi,t) = F_1^i(t) \quad \forall\xi$$
$$\int_{-1}^{1} dx E^i(x,\xi,t) = F_2^i(t) \quad \forall\xi$$
$$\int_{-1}^{1} dx \tilde{H}^i(x,\xi,t) = G_A^i(t) \quad \forall\xi$$
$$\int_{-1}^{1} dx \tilde{E}^i(x,\xi,t) = G_p^i(t) \quad \forall\xi$$

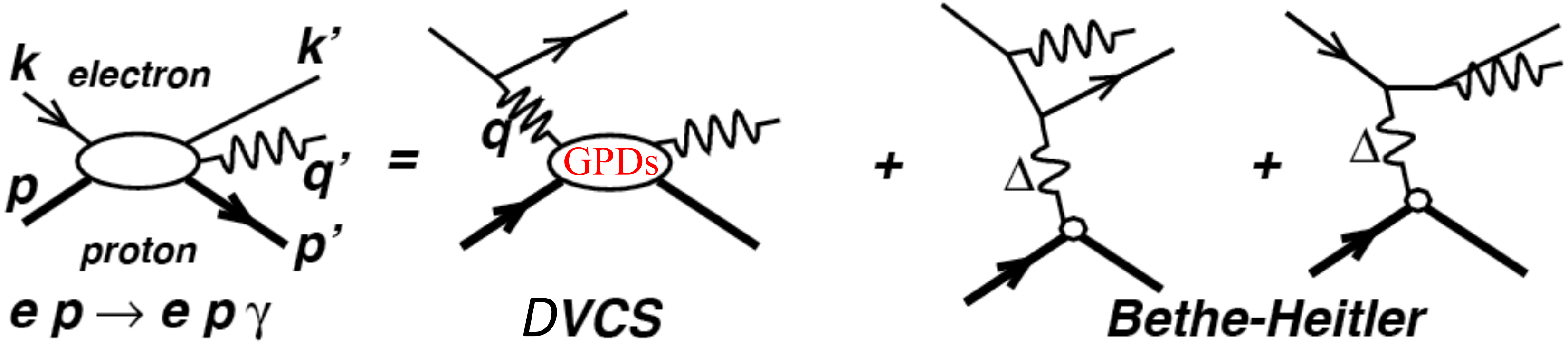
X. Ji, Phys. Rev. Lett. 78, 610 (1997).

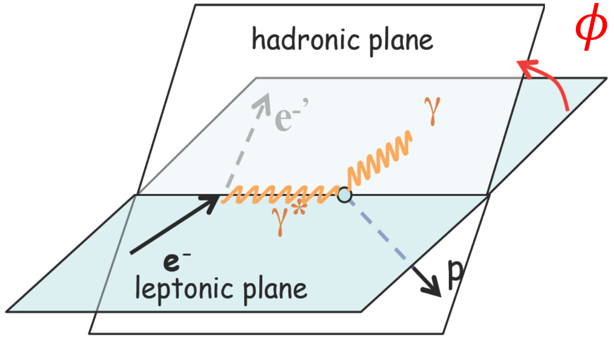
Order, twist: examples for DVCS



- Order appears as powers of α_s
- Twist appears as powers of $1/\sqrt{Q^2}$ in the DVCS amplitude
- General definition of twist of an operator: $\tau = d - s$ (twist, dimension, spin)
- Leading twist: twist = 2

■ Measuring DVCS to access GPDs information





$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol} + e_l \left(Re(I) + P_l Im(I)\right)$$

- $d\sigma^{BH}$ → Known if Nucleon FFs are known
- $d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol}$ → Bilinear combinations of CFFs
- $e_l \left(Re(I) + P_l Im(I)\right)$ → Linear combinations of CFFs and FFs

P_l : polarization target or beam

e_l : charge of the lepton beam

Compton Form Factors:

GPDs

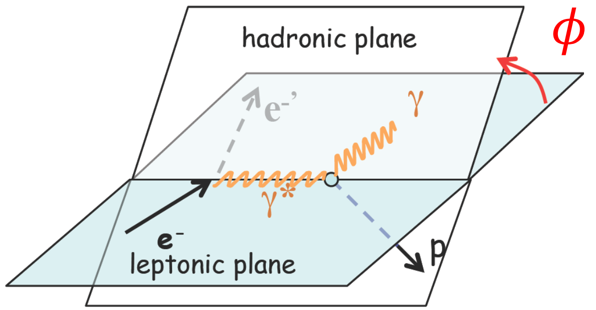
CFFs → $$\mathcal{F}(\xi,t) = \sum_f \left[\frac{e_f}{e}\right]^2 \left\{ i\pi \left[F_f(\xi,\xi,t) \mp F_f(-\xi,\xi,t)\right] + \mathcal{P}\int_{-1}^{+1} dx \left[\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right] F_f(x,\xi,t) \right\}$$

$\xi \simeq x_B/(2 - x_B)$

Introduction to DVCS

■ How to parametrize the measured cross-sections?

$$\frac{\mathbf{d^4\sigma(lp \to lp\gamma)}}{\mathbf{dx_B dQ^2 d|t| d\phi}} = \mathbf{d\sigma^{BH}} + \mathbf{d\sigma^{DVCS}_{unpol}} + \mathbf{P_l} \quad \mathbf{d\sigma^{DVCS}_{pol}} + \mathbf{e_l}\left(\mathbf{Re(I)} + \mathbf{P_l Im(I)}\right)$$



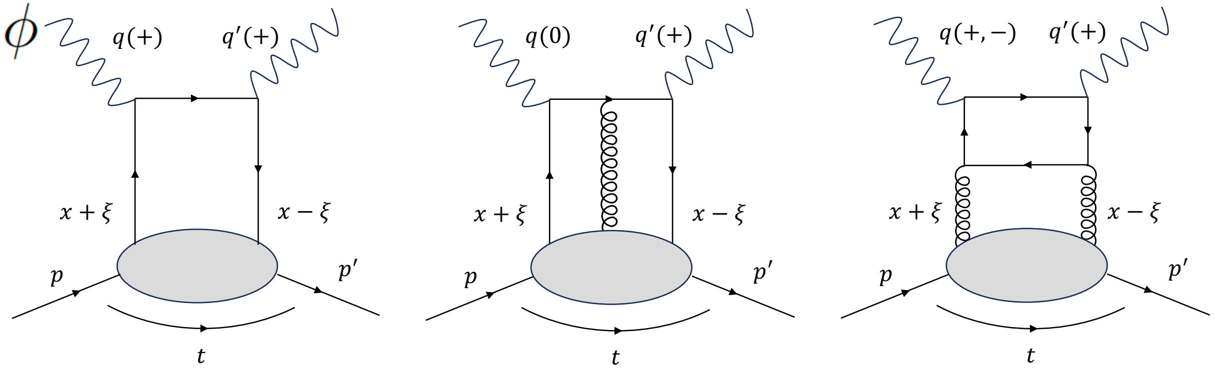
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LT/LO HT NLO

$$s_1^I = F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}$$

$$F \in \{H, E, \tilde{H}, \tilde{E}\} \xrightarrow{dx} \mathcal{F} \in \{\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}\}$$

GPDs CFFs

Cross-sections analysis include more or less terms: both in terms of harmonics (c_i's and s_i's) and In term of GPD/CFFs.

DVCS Experiments at JLab

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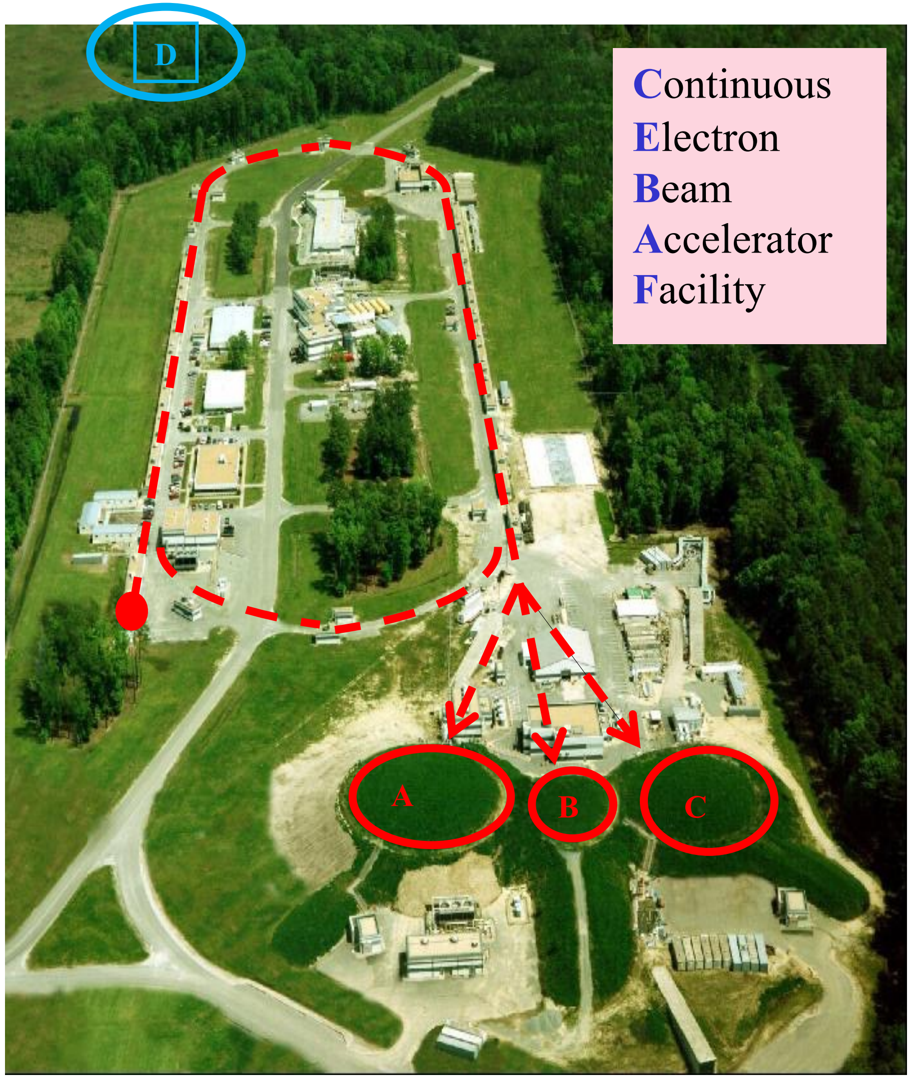
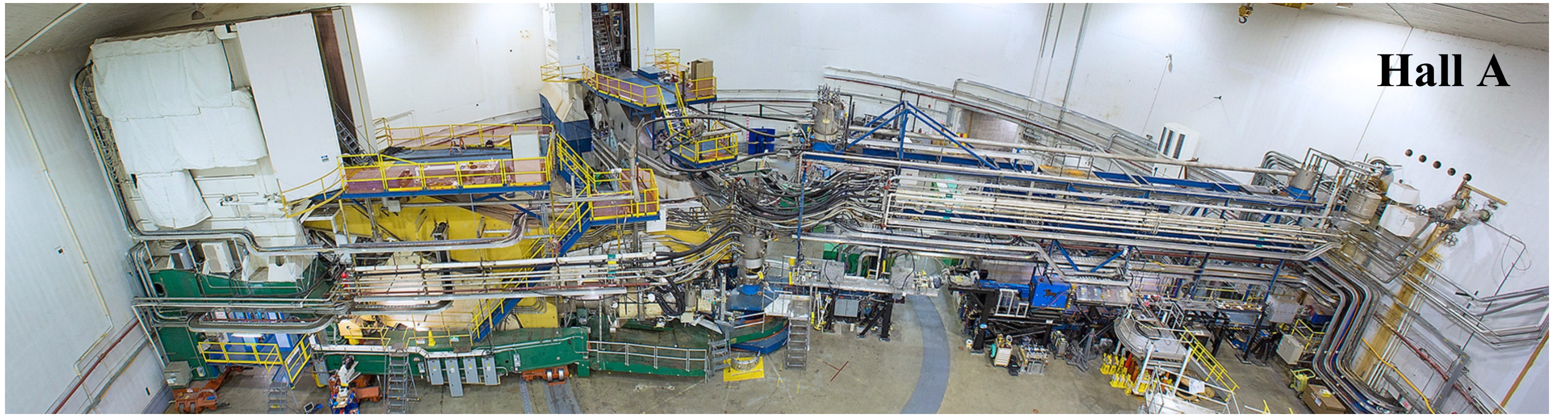
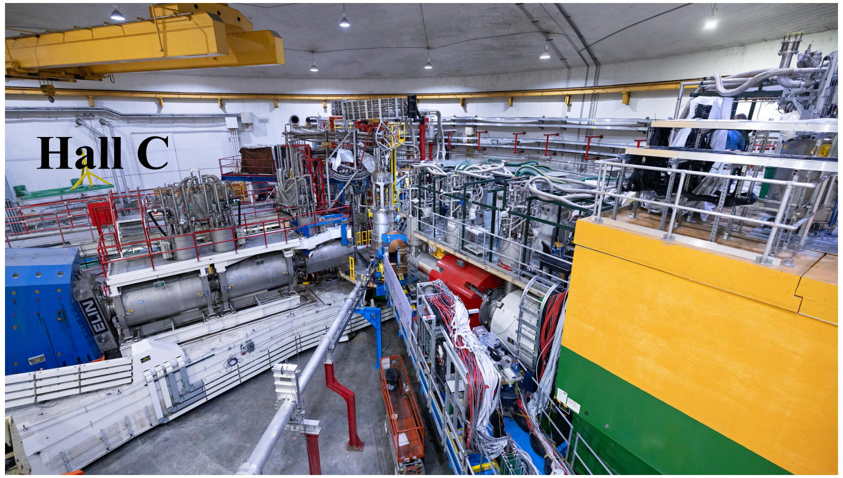
Overview of Hall-A/C and Hall-B

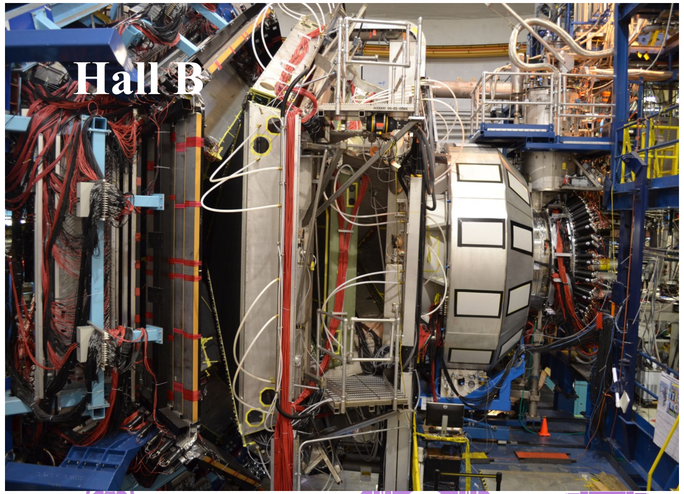


Continuous
Electron
Beam
Accelerator
Facility





- Hall A/C:
  - High accuracy (~5%)
  - High Luminosity (~ $10^{37}/cm^2/s$)
  - Limited kinematic
  - Test the validity of the formalism



- Hall B:
  - Limited accuracy (~15% +)
  - Limited Luminosity (~ $10^{34}/cm^2/s$)
  - Wide kinematic range
  - Map the GPDs

DVCS Experiments at JLab

Hall-B DVCS experiments (CLAS Collaboration)

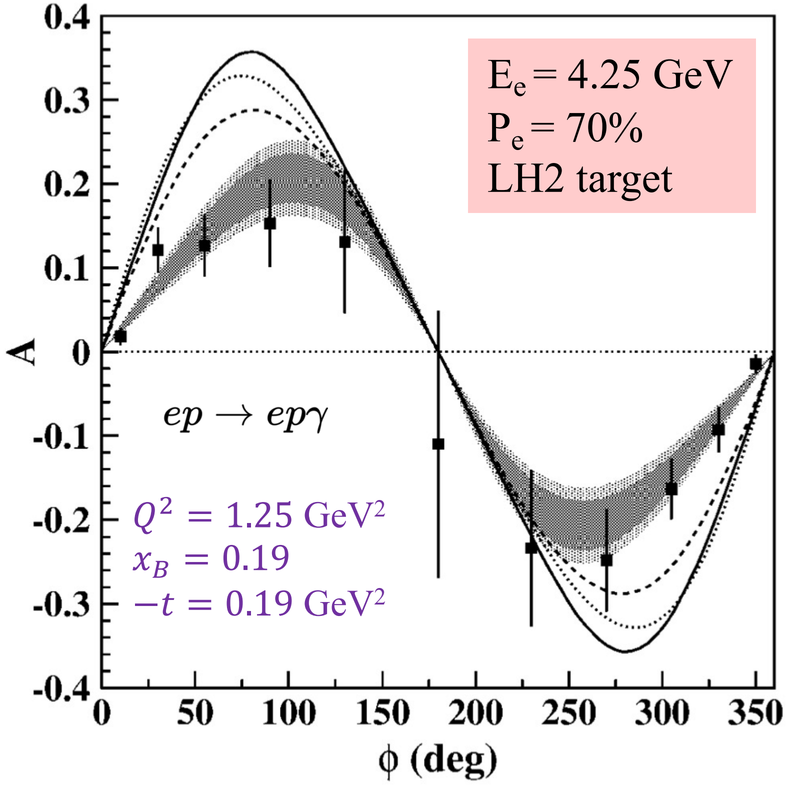
- Main results:

$$A = \frac{1}{P_e}\frac{(N_\gamma^+ - N_\gamma^-)}{(N_\gamma^+ + N_\gamma^-)}$$

  - ✓ DVCS beam spin asymmetries
  - ❑ DVCS cross sections
  - ❑ Fit with GPDs
  - ❑ DVCS longitudinally polarized target asymmetries

- Experimental timeline:
  - ✓ First pioneering result (March 1999)
  - ❑ CLAS e1-DVCS experiment (Spring of 2005)
  - ❑ DVCS on longitudinally polarized target (2009)
  - ❑ CLAS e1-DVCS2 experiment (October 2008 to January 2009)
  - ❑ CLAS with CLAS12 over 10 GeV (fall of 2018 and the spring of 2019)

S. Stepanyan et al., PRL 87



A(ϕ) = αsinϕ + βsin2ϕ

β/α << 1 → twist-2 (handbag) dominance

DVCS Experiments at JLab

■ CLAS e1-DVCS experiment (Spring of 2005)

$E_e = 5.75$ GeV, $P_e = 79.4\%$, LH2 target

➤ Main results:

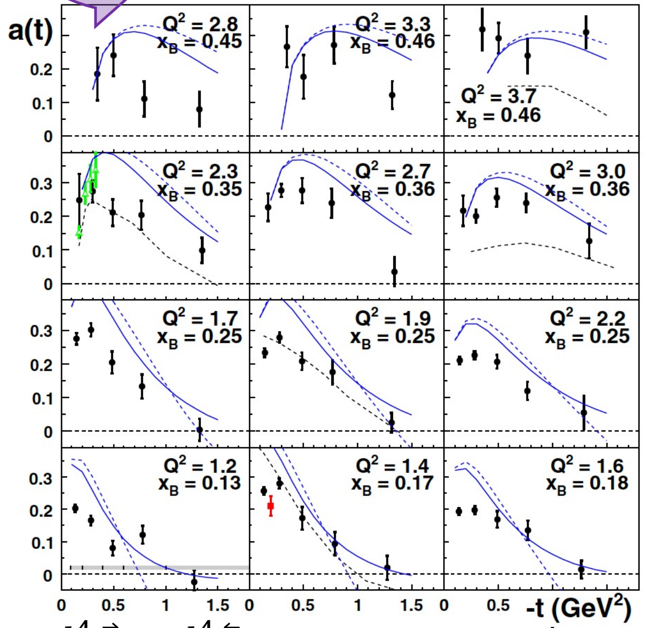
✓ DVCS beam spin asymmetries

✓ DVCS cross sections

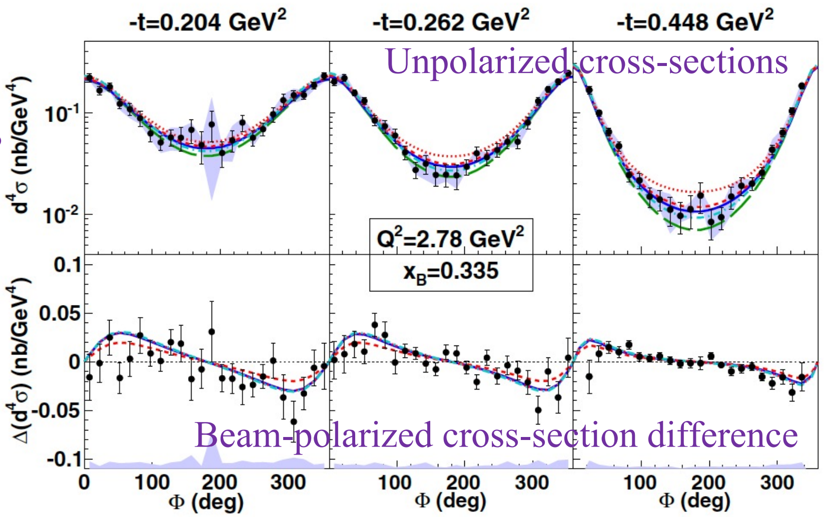
✓ Fit with GPDs

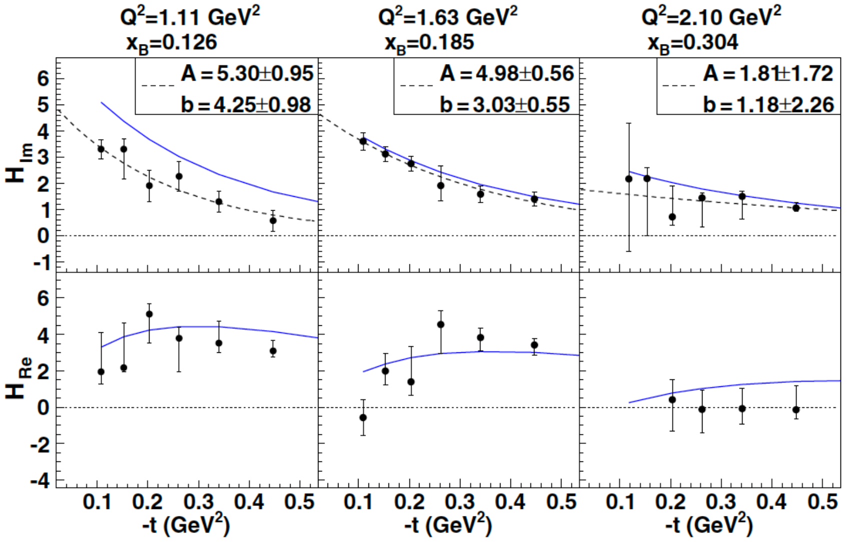
F. X. Girod et al.s Phys. Rev. Lett. 100 (2008)

$a(t) = A(90°)$



$$A = \frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{d^4\vec{\sigma} + d^4\overleftarrow{\sigma}} = \frac{a \sin\phi}{1 + c\cos\phi + d\cos 2\phi}$$





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

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$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

➤ Use LO and LT decomposition (red terms)

➤ Fit with 8 GPDs but only gets well defined results for $\mathfrak{Re}(\mathcal{H})$ and $\mathfrak{Im}(\mathcal{H})$

DVCS Experiments at JLab

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Hall-B DVCS experiments on polarized target

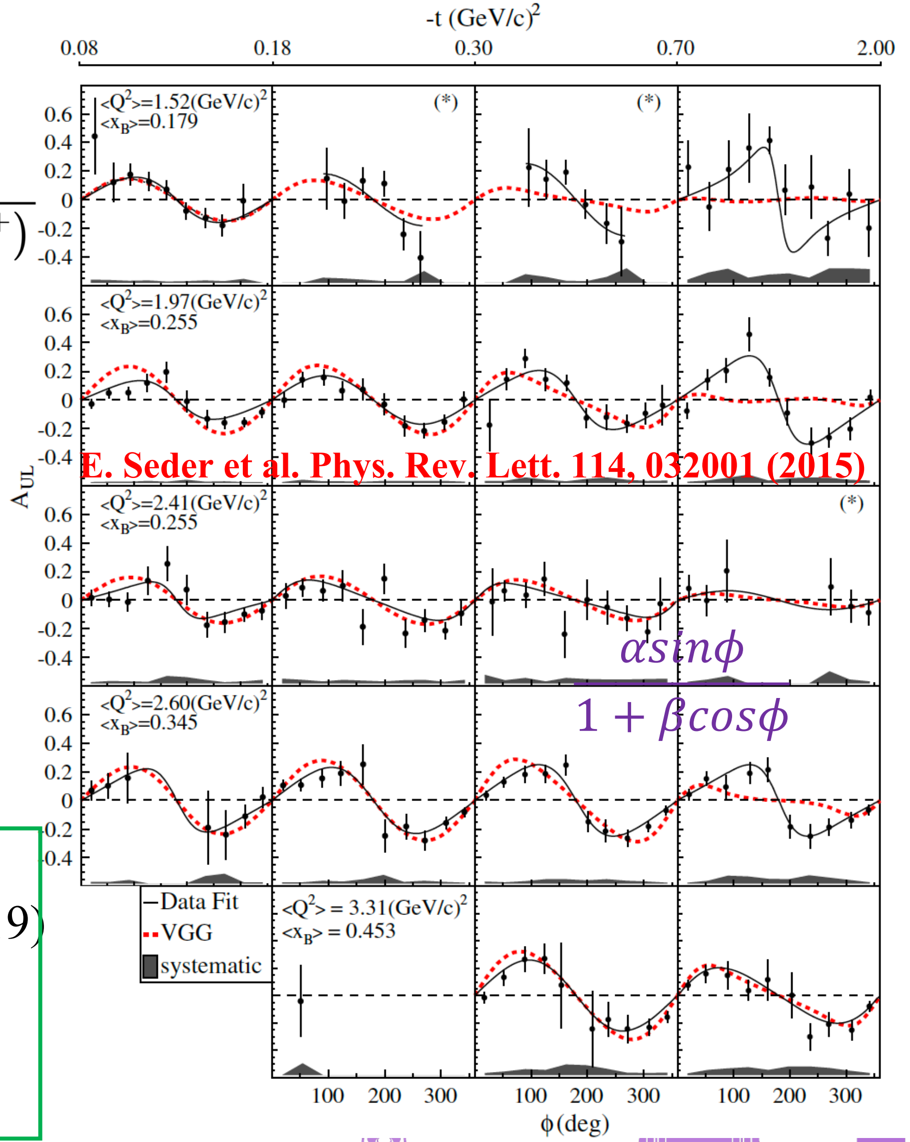
$E_e = 5.9$ GeV, $P_e = 84\%$, $P_t^+ = 79\%$, $P_t^- = 74\%$, $^{14}NH_3$ target

- Main results:
  - DVCS beam spin asymmetries
  - DVCS cross sections
  - Fit with GPDs
  - ✓ DVCS longitudinally polarized target asymmetries

Target-spin asymmetry:

$$A_{UL} = \frac{1}{D_f} \frac{(N_+ - N_-)}{(N_+ P_t^- + N_- P_t^+)}$$

dilution factor



E. Seder et al. Phys. Rev. Lett. 114, 032001 (2015)

$\frac{\alpha \sin\phi}{1 + \beta \cos\phi}$

- Experimental timeline:
  - First pioneering results (March 1999)
  - CLAS e1-DVCS experiment (Spring of 2005)
  - ✓ DVCS on longitudinally polarized target (2009)
  - CLAS e1-DVCS2 experiment (October 2008 to January 2009)
  - CLAS with CLAS12 over 10 GeV (fall of 2018 and the spring of 2019)

Cross sections over broad kinematics:

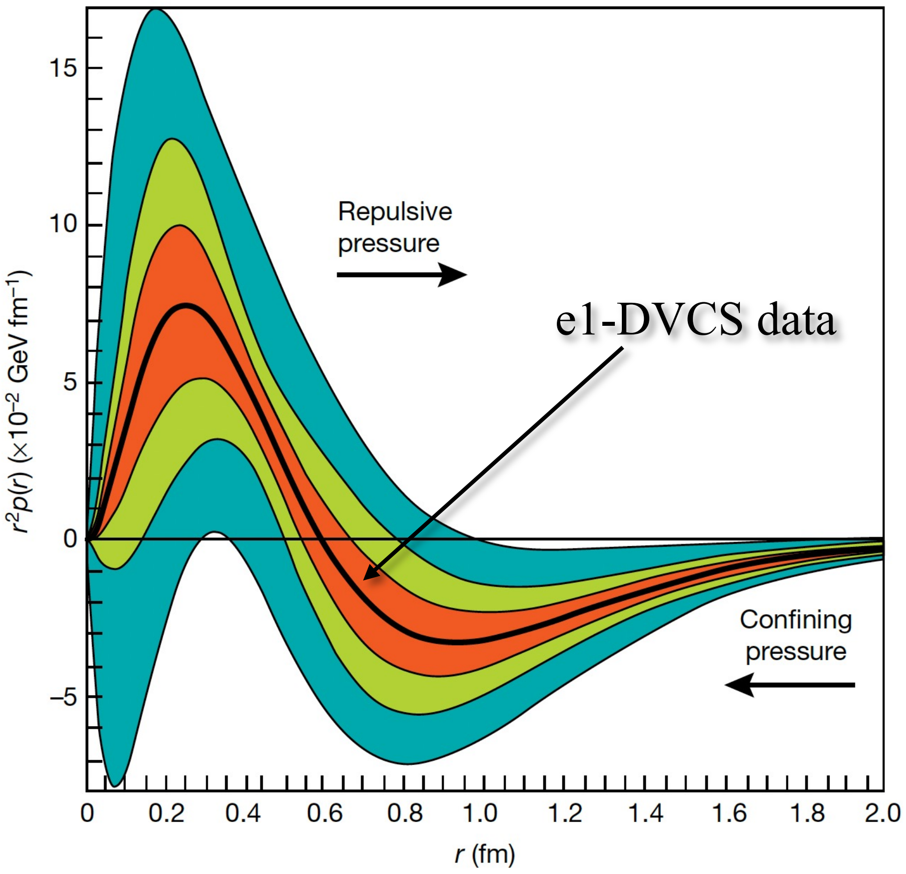
$0.1 < x_B < 0.58, 1.0 < Q^2 < 4.8$ GeV^2, $0.09 < -t < 2$ GeV^2

10GeV beam greatly extend the Q^2 and x_B phase space

DVCS Experiments at JLab

■ CLAS DVCS experiment: physics insights

➢ Radial pressure distribution in the proton



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

The sum rules:

Ji, X. D. Phys. Rev. D 55 (1997)

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

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

Gravitational Form Factors (GFFs)

❖ $d_1(t)$: shear forces and pressure distribution

❖ $M_2(t)$: mass distributions

❖ $J(t)$: angular momentum distributions

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t}\,p(r)\mathrm{d}^3r$$

DVCS Experiments at JLab

CLAS DVCS experiment: physics insights

Dupré, Raphaël, et al. The European Physical Journal A 53 (2017)

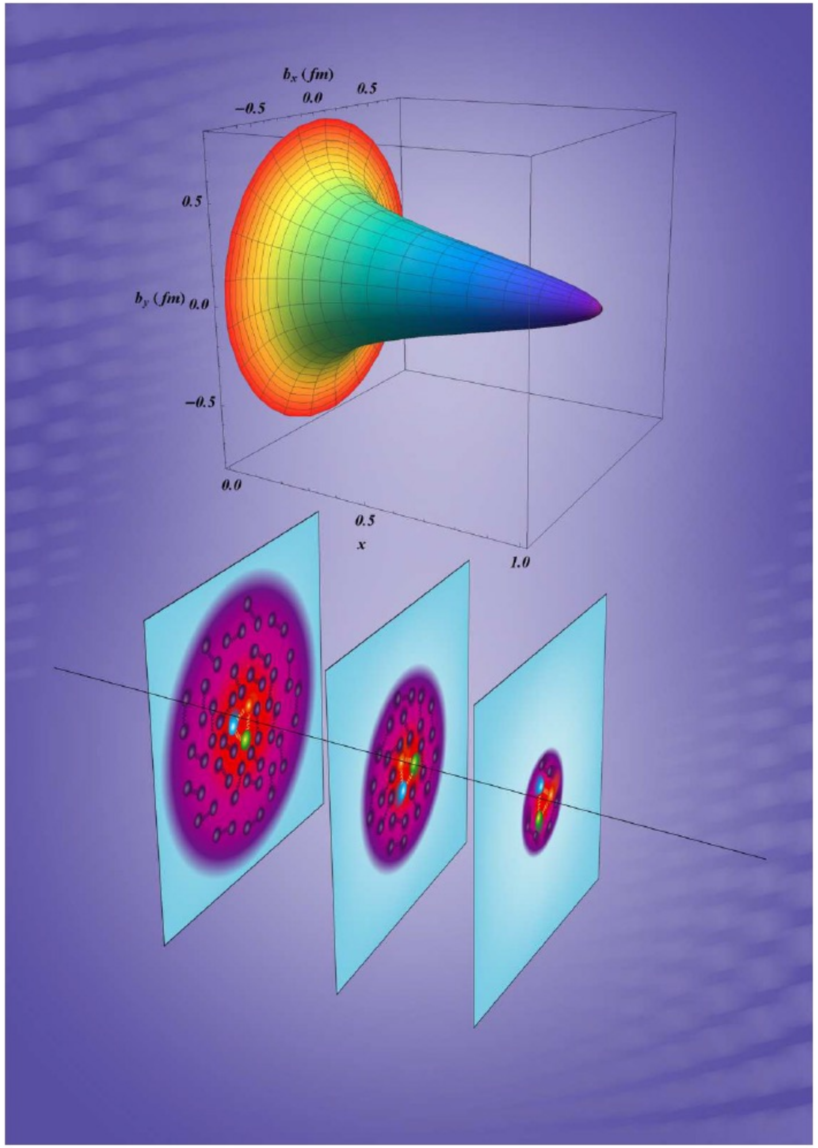
- Impact parameter results: Proton Tomography
- x dependence of the radius of the transverse charge distribution
- Used Hall-B and Hall-A data

$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \boldsymbol{\Delta}_\perp} H_-^q(x, 0, -\boldsymbol{\Delta}_\perp{}^2)$$

$$H_-^q(x, 0, t) \equiv H^q(x, 0, t) + H^q(-x, 0, t)$$

❖ Squared radius of the quark density in the transverse plane:

$$\langle b_\perp^2 \rangle^q(x) = \frac{\int d^2\,\mathbf{b}_\perp \mathbf{b}_\perp^2 \rho^q(x, \mathbf{b}_\perp)}{\int d^2\,\mathbf{b}_\perp \rho^q(x, \mathbf{b}_\perp)}$$



DVCS Experiments at JLab

Hall-A DVCS experiments

Target: LH2 and LD2

- 1st Generation (2004, 5.75 GeV)

C. Muñoz Camacho et al., Phys. Rev. Lett. 97(2006) and M. Mazouz et al. Phys. Rev. Lett. 99 (2007)

- ✓ Q^2 dependence study (of red terms)
- ✓ 1st neutron DVCS experiment
  - ❑ constraint band on quark angular momenta J_u, J_d (proof of principle)

$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

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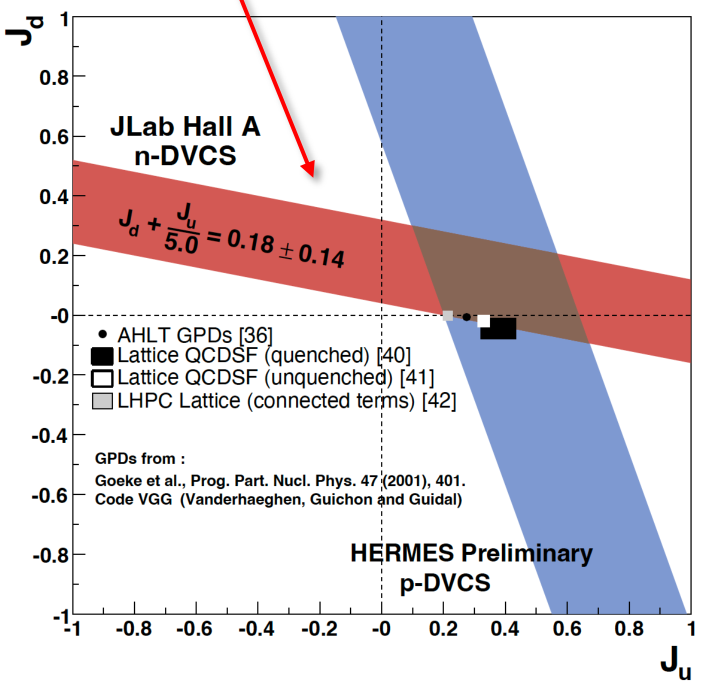

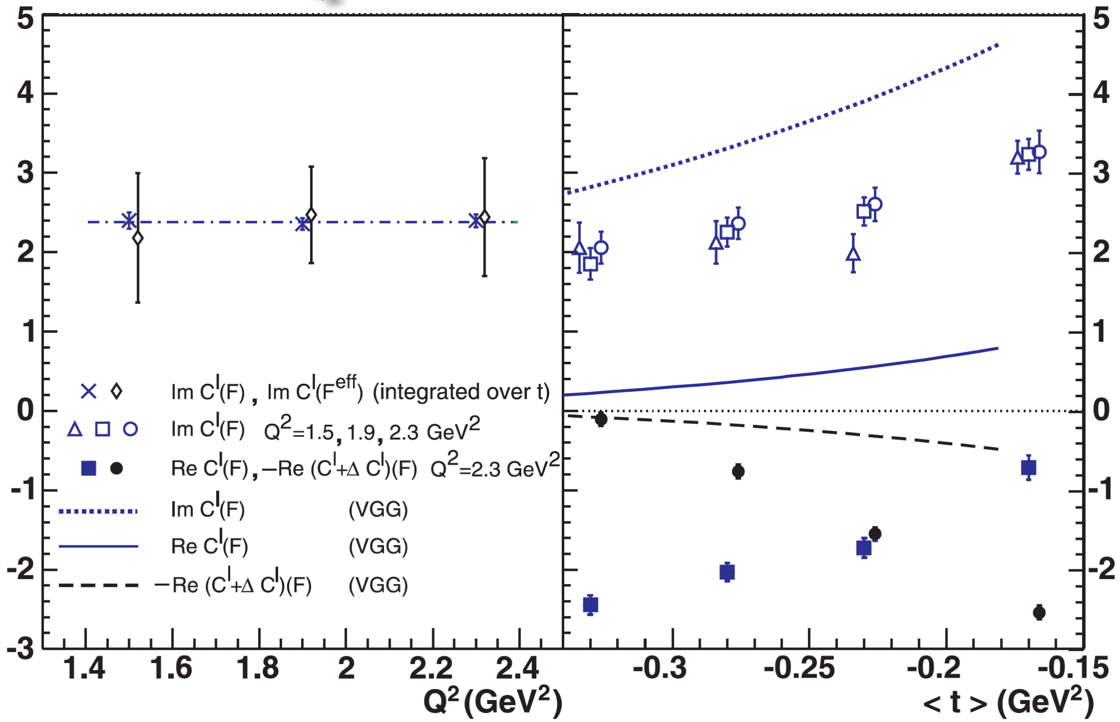

DVCS Experiments at JLab

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Hall-A DVCS experiments

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  - ✓ Q^2 dependence study (of red terms)
  - ✓ 1st neutron DVCS experiment
    - ❑ constraint band on quark angular momenta J_u, J_d

- 2nd Generation (2010, 4.45 and 5.55 GeV)

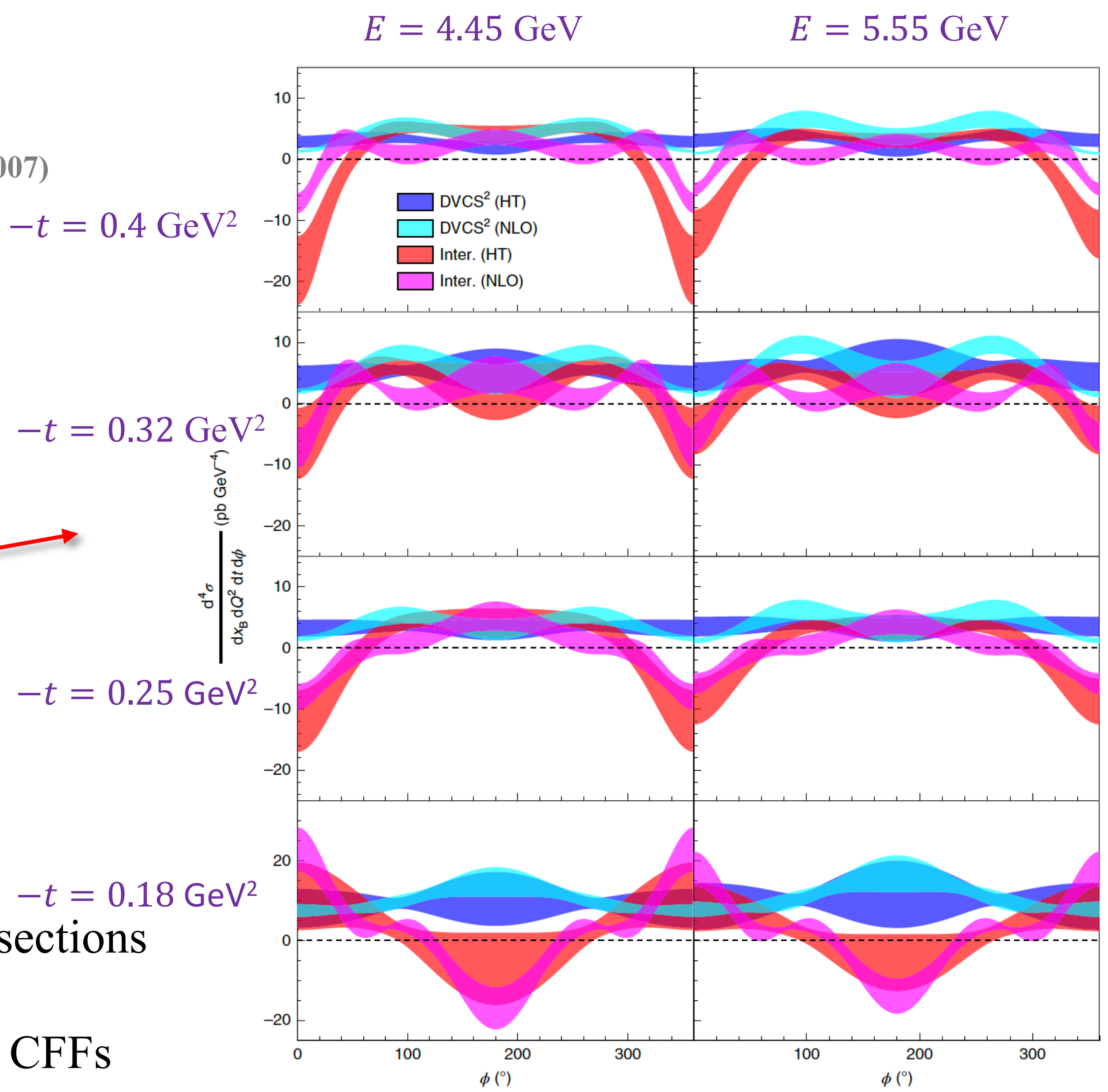
Defurne, M. et al. Nat Commun 8 (2017) and Benali, M. et al. Nat. Phys. 16 (2020)

  - ✓ Beam energy dependence study
  - ✓ Extraction of the 3 helicity-conserving CFFs
  - ✓ DVCS Rosenbluth-like separation:
    - ❑ Separate C_0^{DVCS} from C_0^I
    - ❑ Seprate HT and NLO coefficients

- 3rd Generation (2014-2016, 4.5 to 11 GeV)

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

  - ✓ Helicity-independent and helicity-dependent DVCS cross sections for multiple x_B and Q^2
  - ✓ 1st Experimental extraction of all the 4 helicity-conserving CFFs



DVCS Experiments at JLab

■ First Hall-C DVCS experiment (September 2023 - May 2024)

➢ The Goal for the latest DVCS experiment in hall-C

❑ Higher Q^2 and x_B

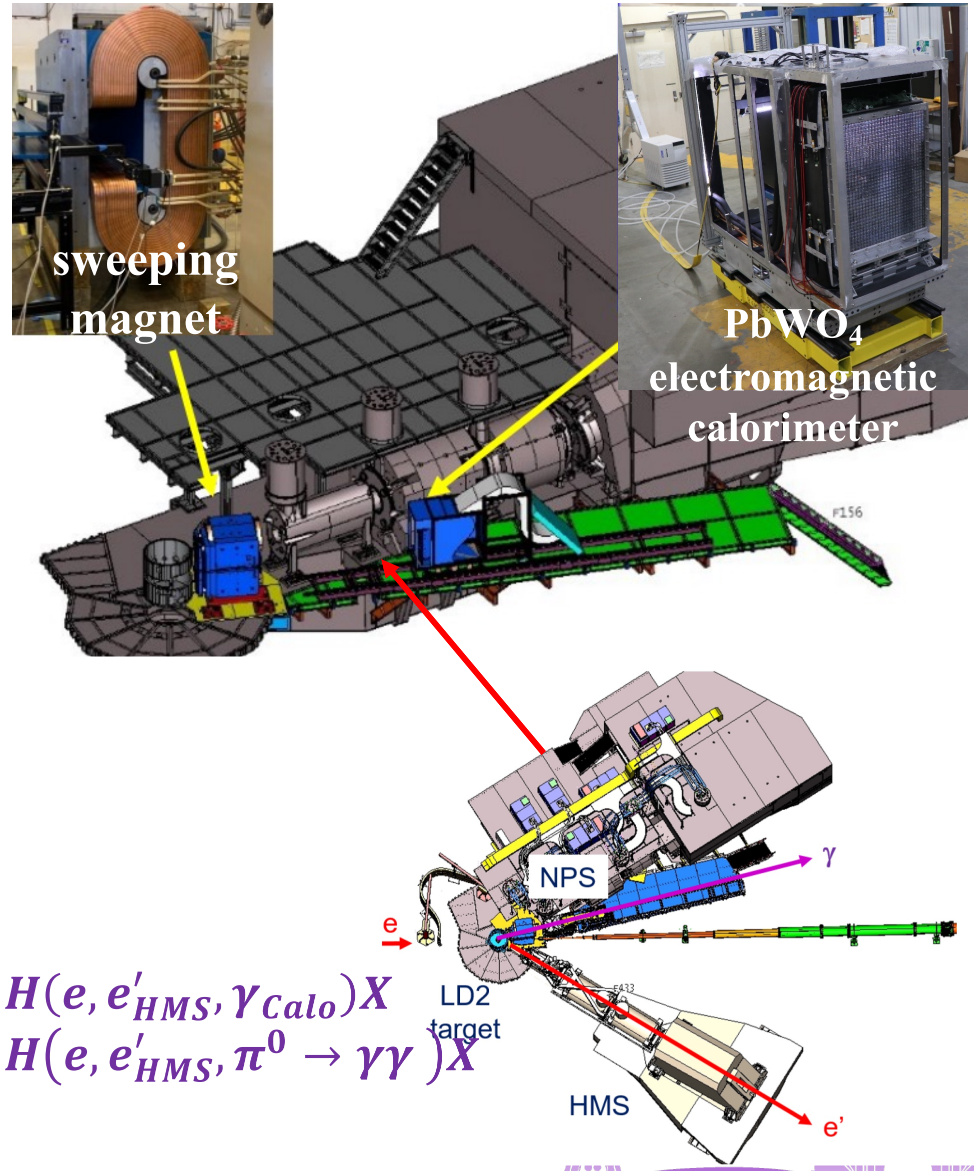
1. It helps to verify factorization
2. Study NLO coefficients

❑ Multiple beam energies for most kinematics

1. Study beam energy dependence
2. Better DVCS and interference separation

❑ New Calorimeter: **Neutral Particle Spectrometer (NPS)**

1. Good spatial resolution (2x2cm²)
2. Good energy resolution (1.3% at 7.3 GeV)
3. Precise cross section measurement

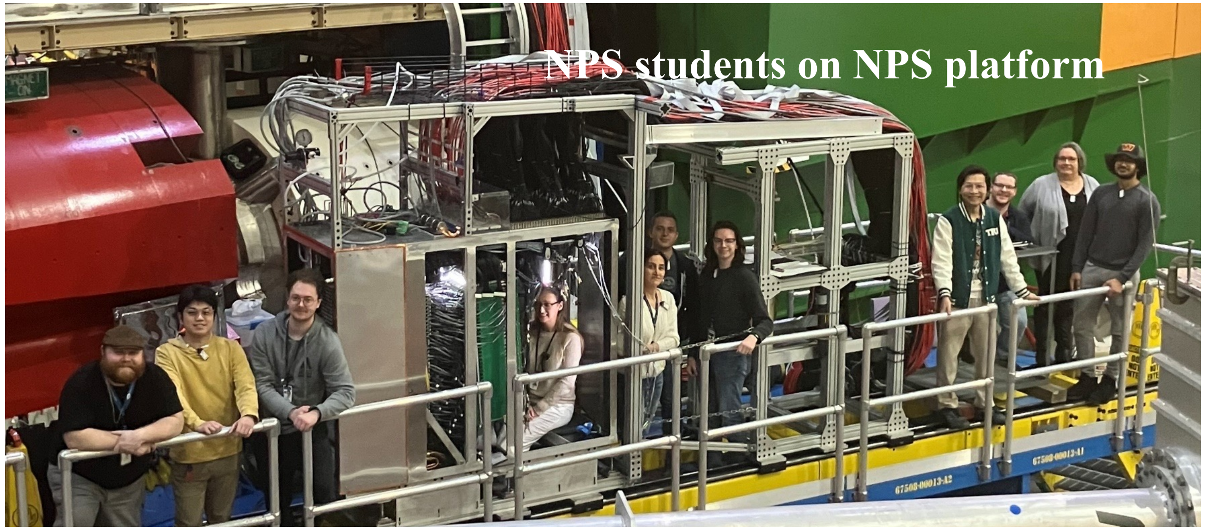


$$H(e, e'_{HMS}, \gamma_{Calo})X$$
$$H(e, e'_{HMS}, \pi^0 \to \gamma\gamma)X$$

DVCS Experiments at JLab

■ NPS Calorimeter

- 1,080 $PbWO_4$ ($2x2cm^2$) blocks in 30x36 array
- 0.5mm carbon fiber grid to hold crystals
- 0.6 T·m sweeping magnet
- F250ADC sampling electronics for high data rate



DVCS Experiments at JLab

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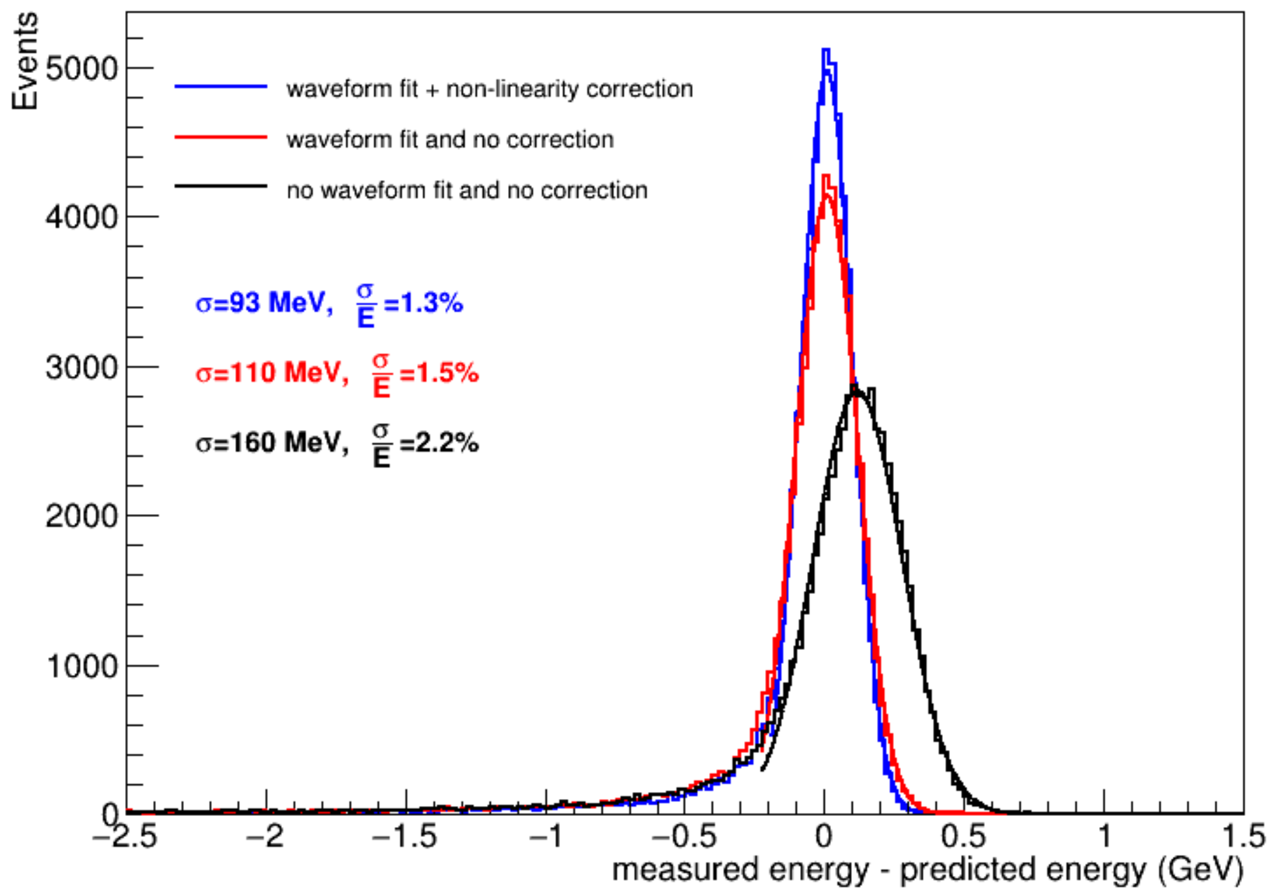
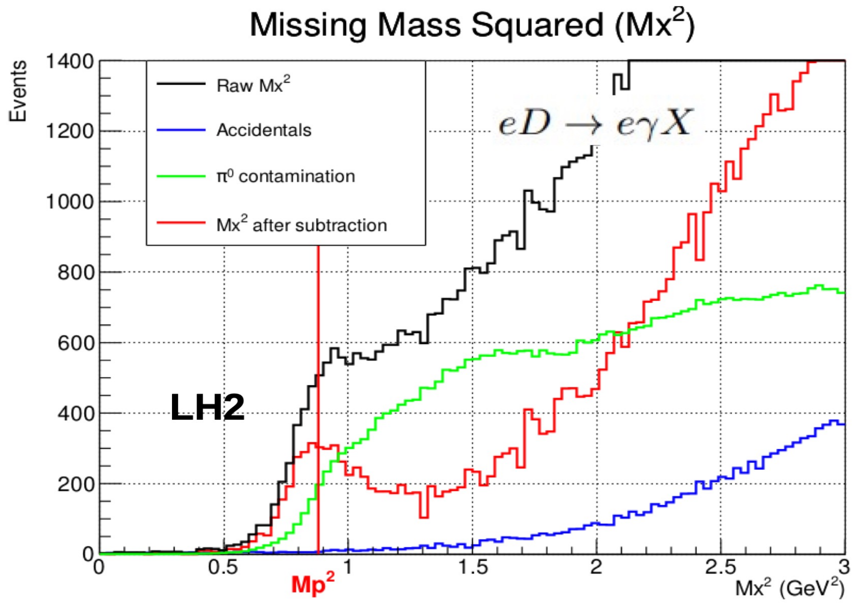
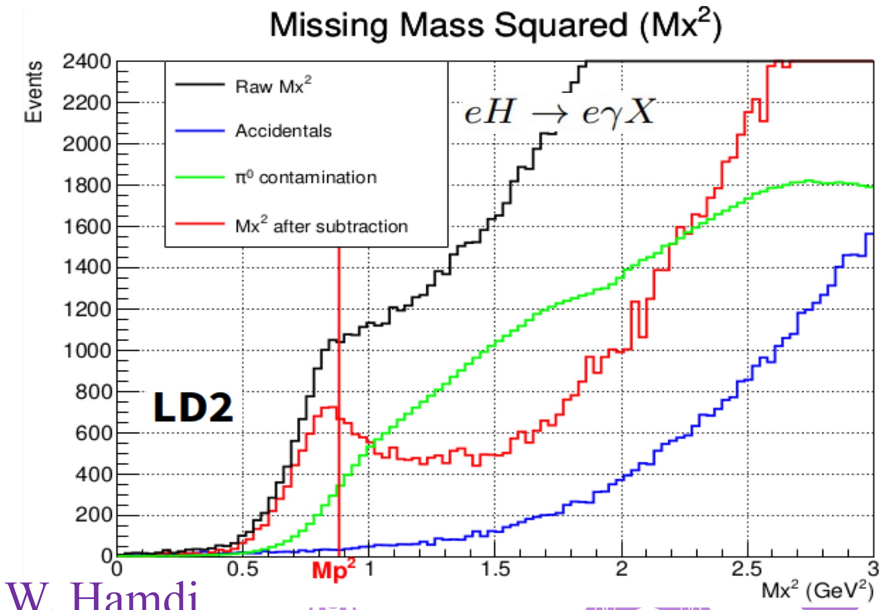
NPS performance and preliminary results

- After waveform analysis and calorimeter calibration

NPS Energy Resolution





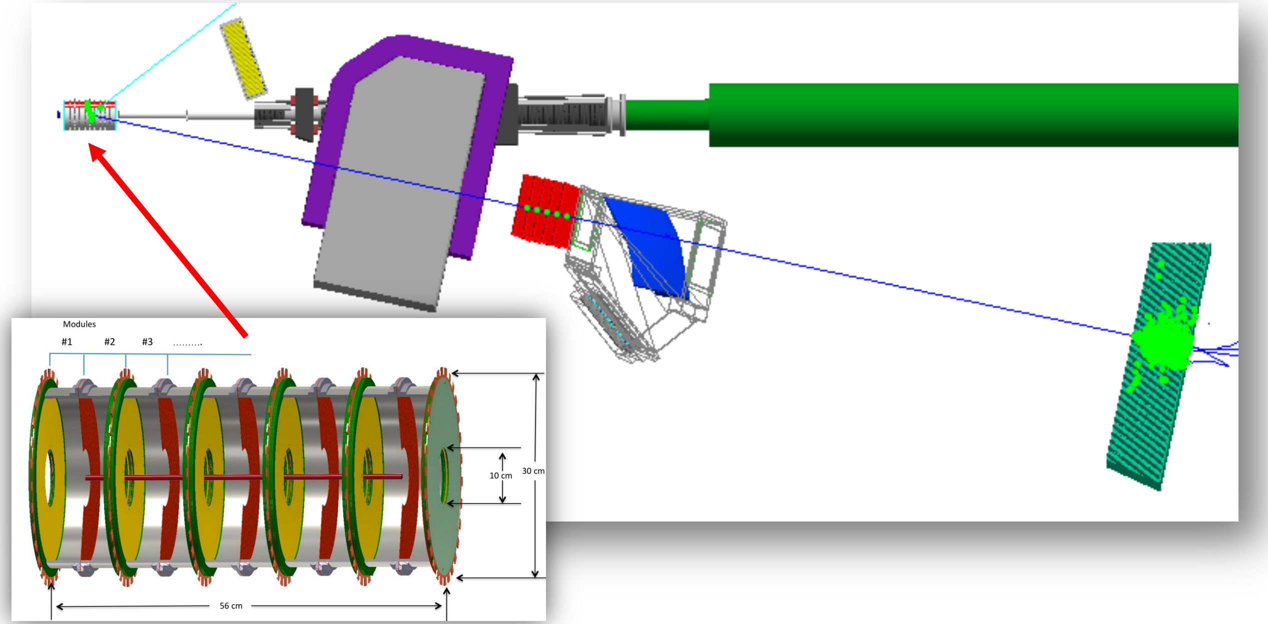


Credit to W. Hamdi

Future JLab DVCS Experiments

Hall-A and Hall-C

- Hall-C NPS DVCS experiments
  - ✓ Run Group 1a: E12-13-010 and E12-22-006 (Complete)
  - ❑ Run Group 1b: E12-06-114 (like RG1a but on the kinematic missed in RG1a)
  - ❑ Run Group 2: E12-14-003 (Wide-angle Compton Scattering)
  - ❑ …
- Hall-A neutron-DVCS experiment
  - ❑ Neutron-DVCS with SBS+NPS+TDIS recoil detector



A Letter Of Intent Submitted to PAC 52

Deeply Virtual Compton Scattering using the Tagged Deeply Inelastic Scattering Experimental Setup

Spokesperson: A. Camsonne, E. Fuchey*, R. Montgomery, Z.H. Ye, Z.Y. Ye

Summary

Tsinghua University

Introduction to DVCS

- Handbag diagram and factorization
- How GPDs enter the DVCS cross sections

Past DVCS experiments at JLab

- Hall-B experiments: e1-DVCS, e1-DVCS2, …
- Hall-A experiments: 3 generations
- Hall-C NPS experiment: latest DVCS program

Future JLab DVCS Experiments

- Hall-C: Run Group 1b, Run Group 2, …
- Hall-A neutron-DVCS proposal, SoLID-DVCS, …

THANKS!

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Backup

Hall-C NPS DVCS Experiment Kinematics

- Data taken in 2023

x_Bj	Kinematic Setting	Pass	Q2 (GeV^2)
0.36	KinC_x36_3	5	3.0
	KinC_x36_5	5	4.0
	KinC_x36_2	4	3.0
0.50	KinC_x50_2	5	3.4
	KinC_x50_3	5	4.8
	KinC_x50_1	4	3.4
0.6	KinC_x60_3	5	5.1
	KinC_x60_2	4	5.1

- Data taken in 2024

x_Bj	Kinematic Setting	Pass	Q2 (GeV^2)
0.25	KinC_x25_1	5	2.1
	KinC_x25_2	5	2.4
	KinC_x25_3	4	2.4
	KinC_x25_4	3	3.0
0.36	KinC_x36_6	5	5.5
	KinC_x36_4	4	4.0
	KinC_x36_1	3	3.0
0.5	KinC_x50_0	3	3.4
0.6	KinC_x60_4	5	6.0
	KinC_x60_1	3	5.1