The NPS Experiments at JLab Hall C

Taiwan EIC Meeting

January 22, 2026

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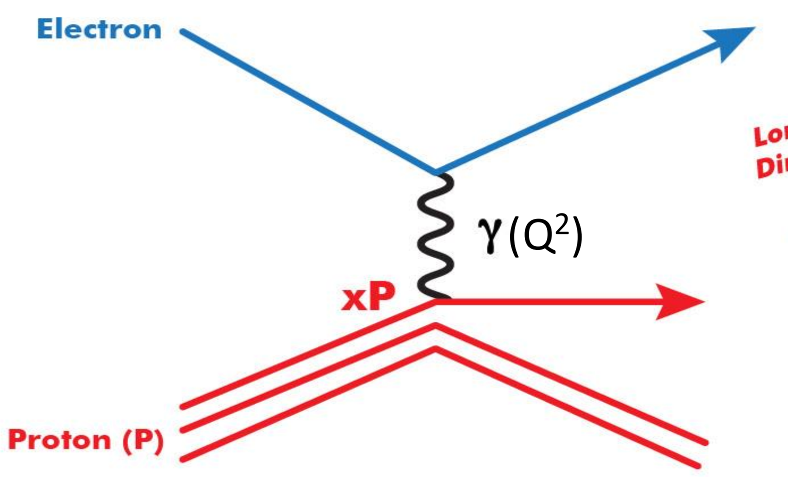
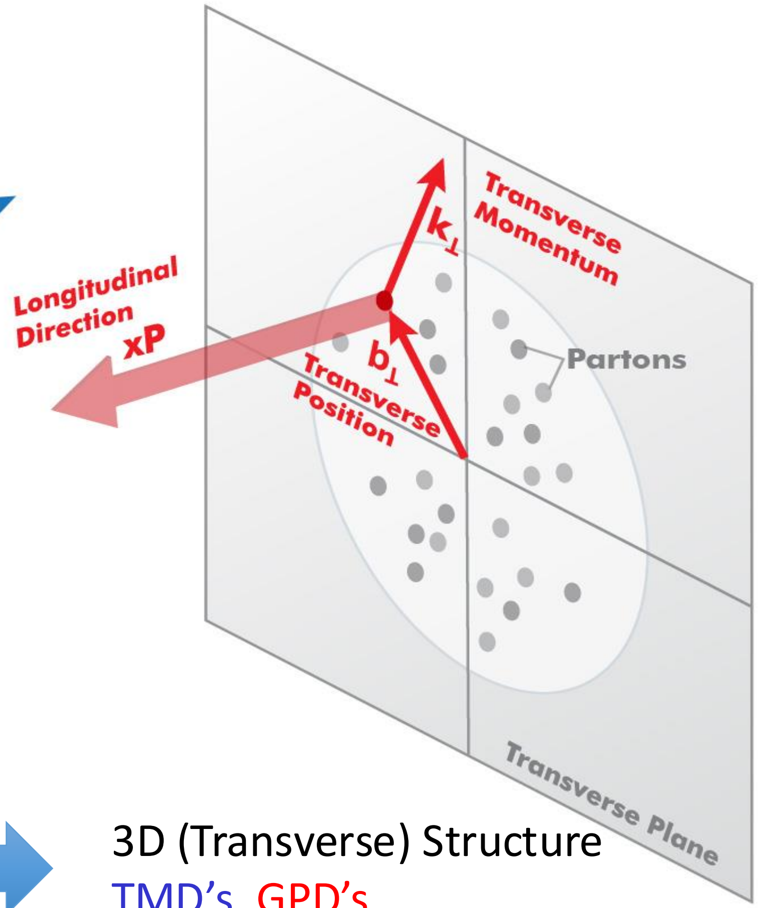
Beyond the Longitudinal Description



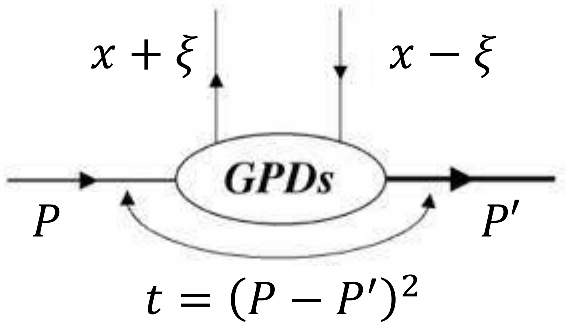


Parton Distribution Functions:
Longitudinal only

3D (Transverse) Structure
TMD's, GPD's

- Transverse Momentum Dependent Distributions (TMD): $k_{\perp}$
- Generalized Parton Distributions (GPD): $b_{\perp}$

Generalized Parton Distributions (GPDs)



- At fixed Q^2, the GPDs depend on the following variables:

  x: average longitudinal momentum fraction

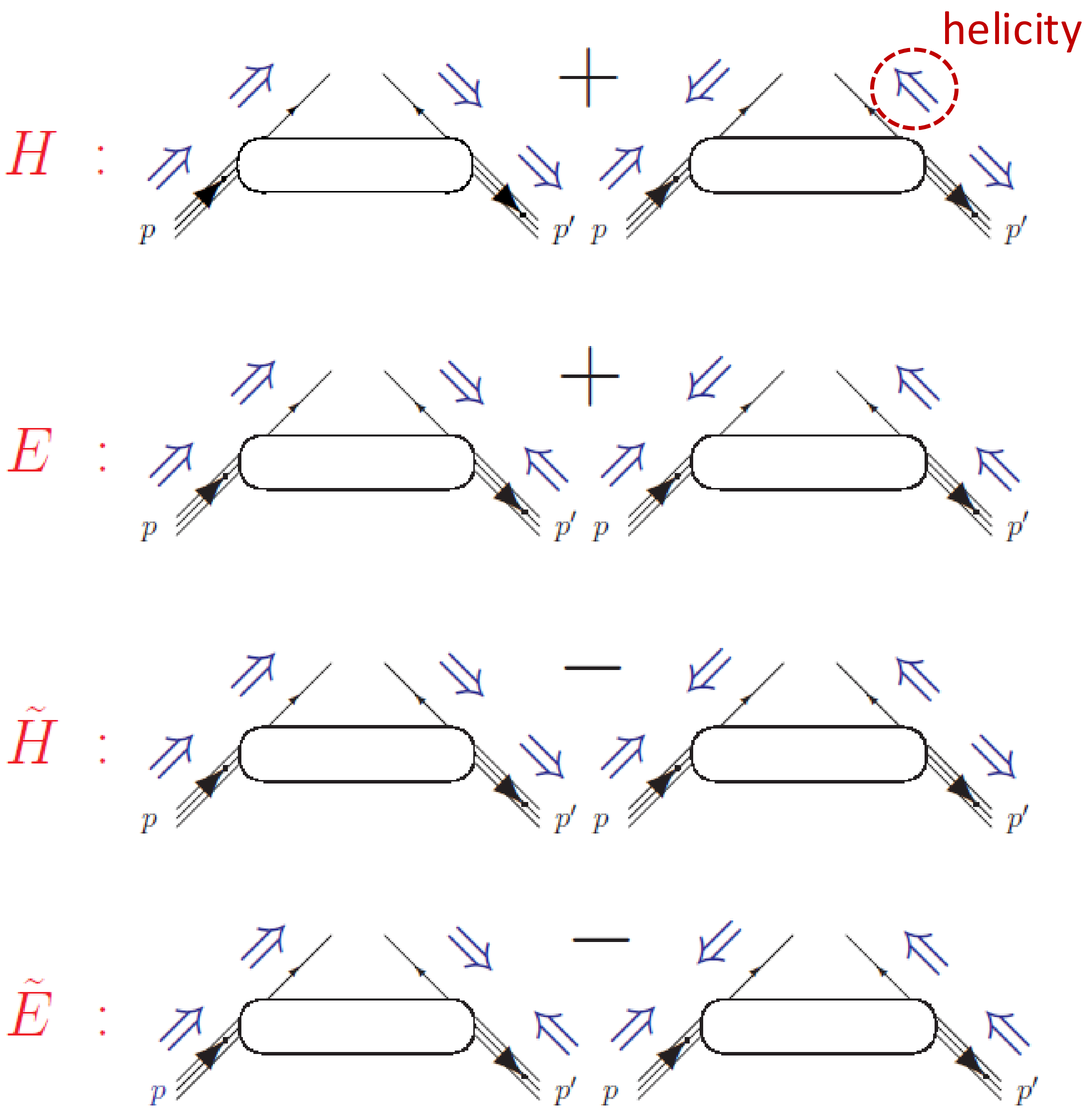
  ξ: longitudinal momentum difference

  t: four momentum transfer
  (correlated to $b_\perp$ via Fourier transform)

- A total of 8 GPDs for a specific parton

4 Chiral-even (parton helicity unchanged): $H, E, \tilde{H}, \tilde{E}$

4 Chiral-odd (parton helicity changed): $H_T, E_T, \tilde{H}_T, \tilde{E}_T$



Generalized Parton Distributions (GPDs)

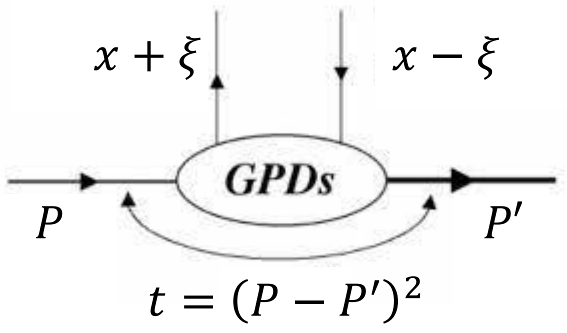
Dirac FF

$$\int H_f(x,\xi,t)dx = F_1^f(t)$$

$$\int E_f(x,\xi,t)dx = F_2^f(t)$$

Pauli FF

First Moment ← Form Factors



$\xi = t = 0$ → PDFs

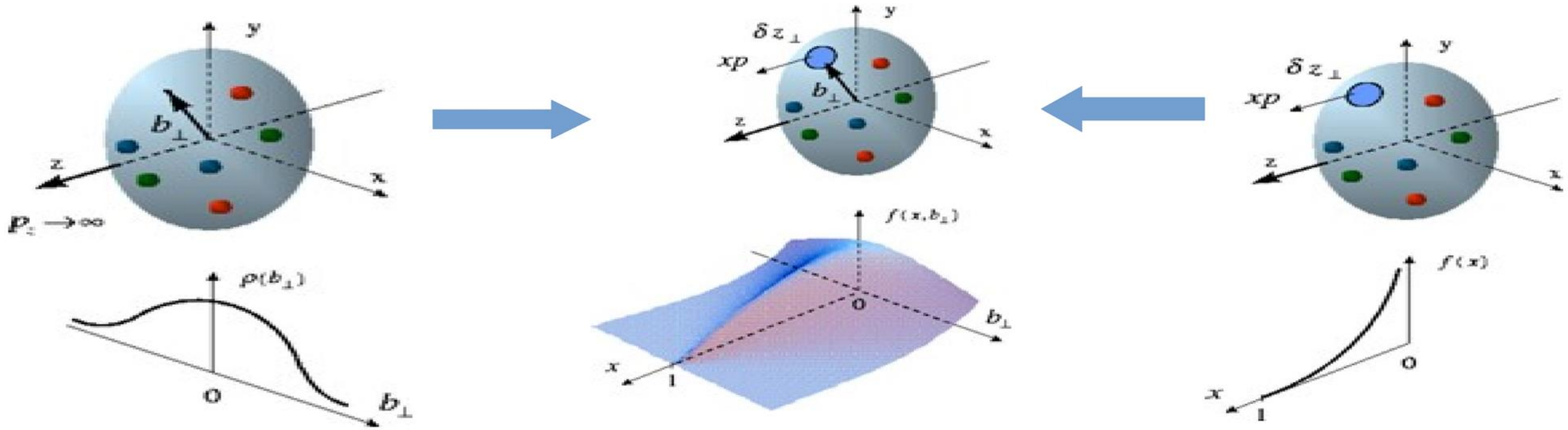
Unpolarized

$$H_f(x,0,0) = q_f(x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x)$$

Polarized

➢ **GPDs embody both PDFs and FFs**



- **Form Factors (FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution
- **G**eneralized **P**arton **D**istributions **(GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution
- **P**arton **D**istribution **F**unctions **(PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

Generalized Parton Distributions (GPDs)

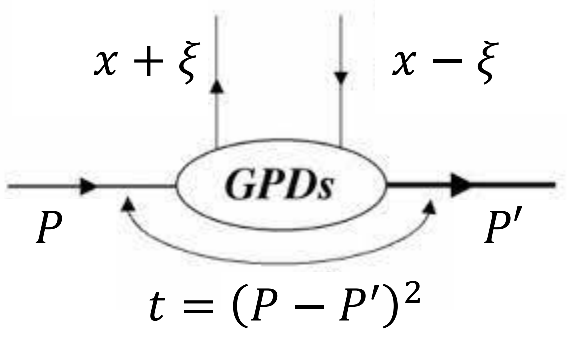
Dirac FF

$\int H_f(x,\xi,t)dx = F_1^f(t)$

$\int E_f(x,\xi,t)dx = F_2^f(t)$

Pauli FF

First Moment ← Form Factors



$\xi = t = 0$ → PDFs

Unpolarized

$H_f(x,0,0) = q_f(x)$

$\tilde{H}_f(x,0,0) = \Delta q_f(x)$

Polarized

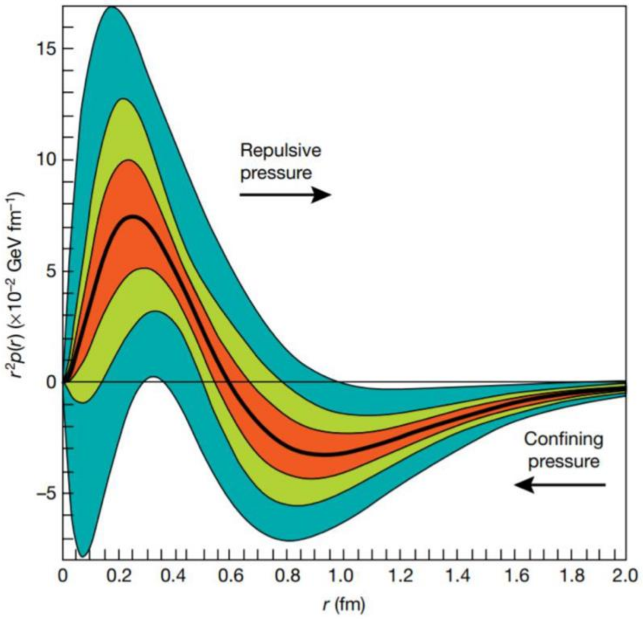
- Access the orbital angular momentum of quarks

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g$$

$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

Ji's Sum Rule

- Pressure distribution inside the proton



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

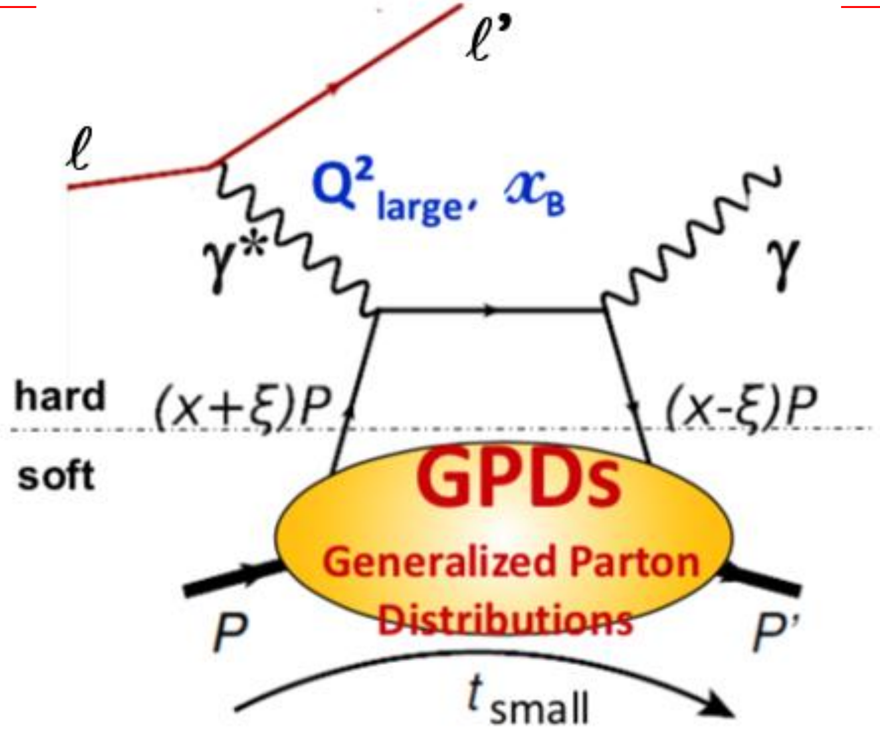
$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r)\mathrm{d}^3r$$

$d_1(t)$: gravitational form factor
$p(r)$: radial pressure distribution

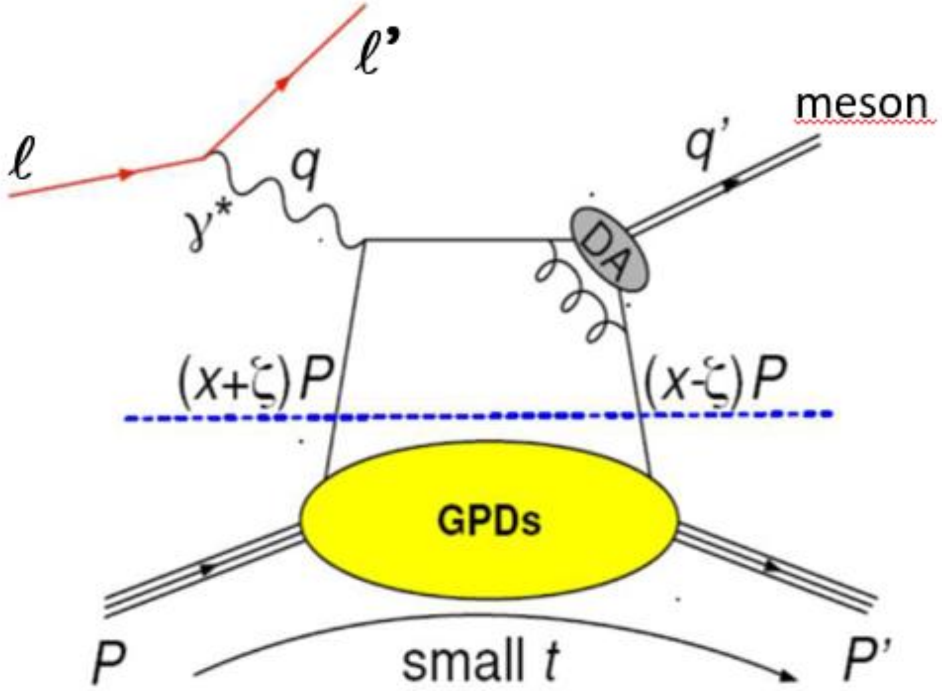
Exclusive Process

➢ Use exclusive processes, where all final state particles are identified, to access the muliti-variable dependence of GPDs, and constrain the GPD parameterization with measurements in various phase space.

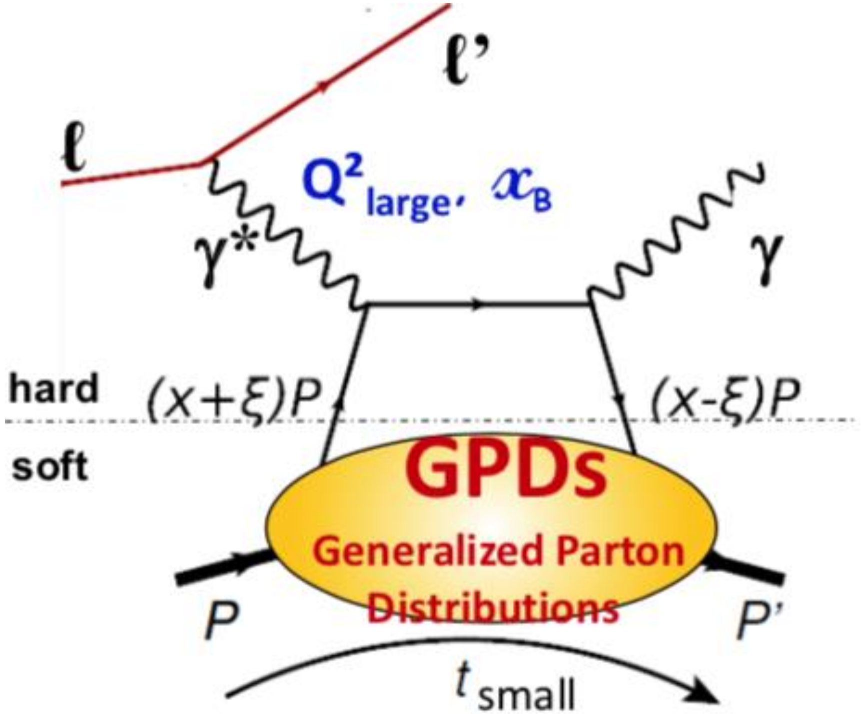
DVCS



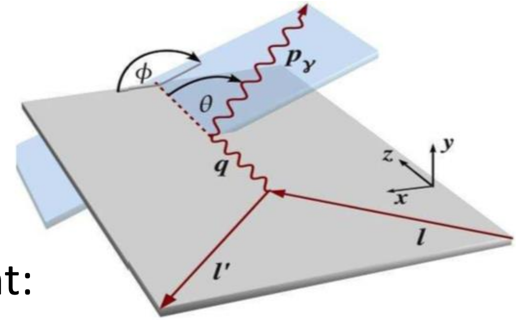
DVMP



DVCS



DVCS: $l + p \rightarrow l' + p' + \gamma$



- The variables measured in the experiment:

  E_ℓ, Q^2, $x_{Bj} \sim 2\xi/(1+\xi)$,

  t (or $\theta_{\gamma^*\gamma}$) and ϕ (ℓℓ' plane/γγ* plane)

CFF → $\mathcal{H}(\xi,t)$; *GPD* → $\mathbf{H}(x,\xi,t)$

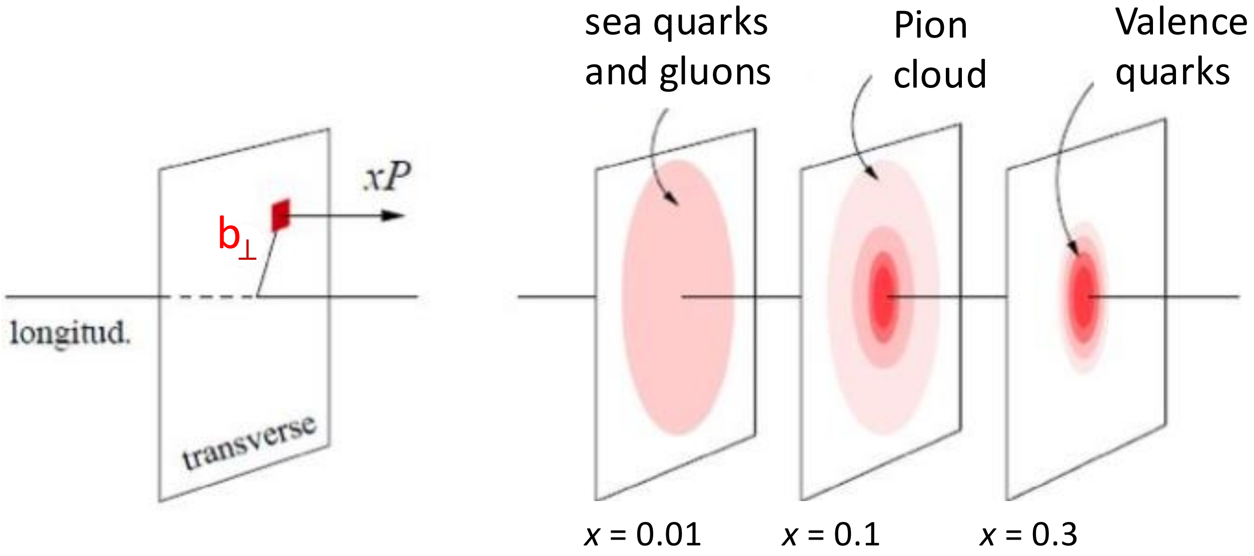
REAL part **Imaginary part**

$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

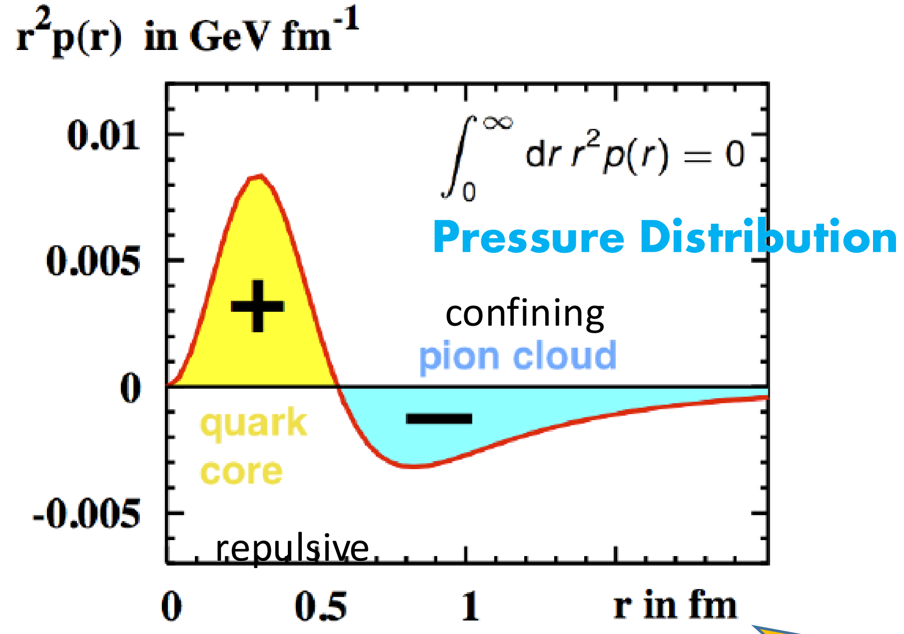
$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

Transverse Imaging and Pressure Distribution

Mapping in the transverse plane



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



FT of H(x, ξ=0,t)

CFF   GPD

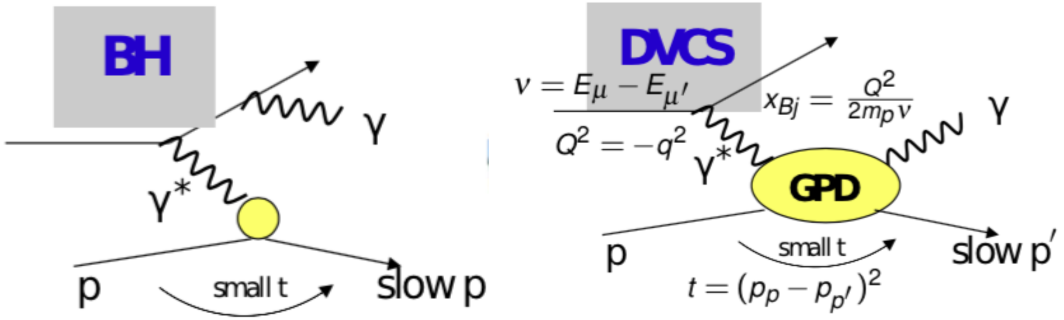
REAL part   Imaginary part

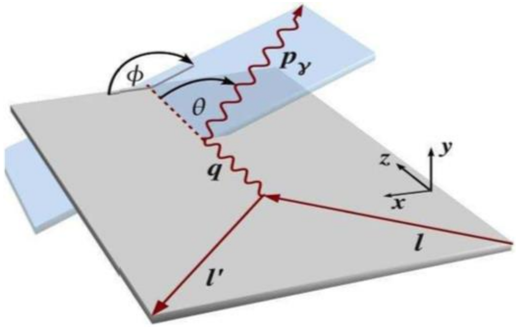
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

D-term $d_1(t)$

Azimuthal Dependence of BH & DVCS





$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = \underbrace{d\sigma^{BH}}_{\text{Well known}} + \left(d\sigma^{DVCS}_{unpol} + P_\ell \, d\sigma^{DVCS}_{pol}\right) + (e_\ell \mathrm{Re}\, I + e_\ell P_\ell \, \mathrm{Im}\, I)$$

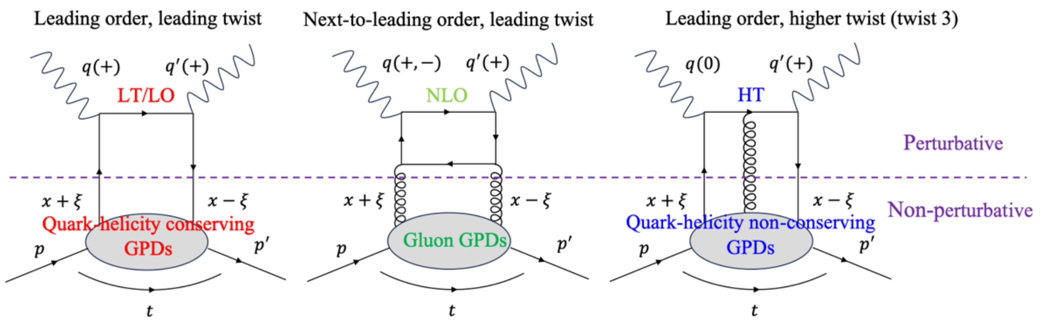
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH} \cos\phi + c_2^{BH} \cos 2\phi$$

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

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

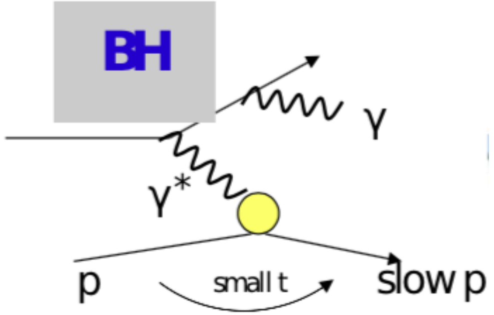
$$\mathrm{Re}\, I \propto c_0^I + c_1^I \cos\phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$$

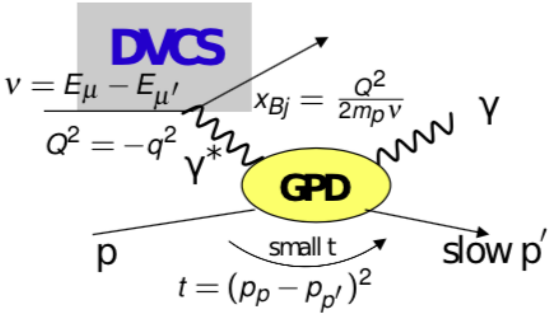
$$\mathrm{Im}\, I \propto s_1^I \sin\phi + s_2^I \sin 2\phi$$

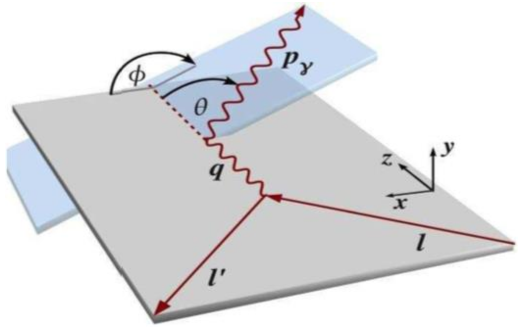


Twist-2 >> ■ Twist-3, ■ Twist-2 - double helicity flip for gluons (NLO)

Azimuthal Dependence of BH & DVCS







$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = \underbrace{d\sigma^{BH}}_{\text{Well known}} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell\, \mathrm{Im}\, I\right)$$

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

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

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

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

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

$C_0^{DVCS} \propto (Im\mathcal{H})^2$

$C_1^I \propto Re\ \mathcal{F}$

$S_1^I \propto Im\ \mathcal{F}$

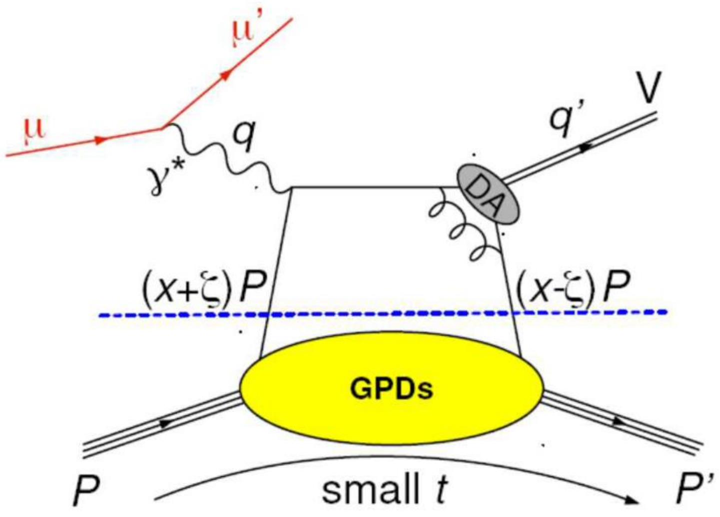
Where

$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} + t/4m^2 F_2\,\mathcal{E}$

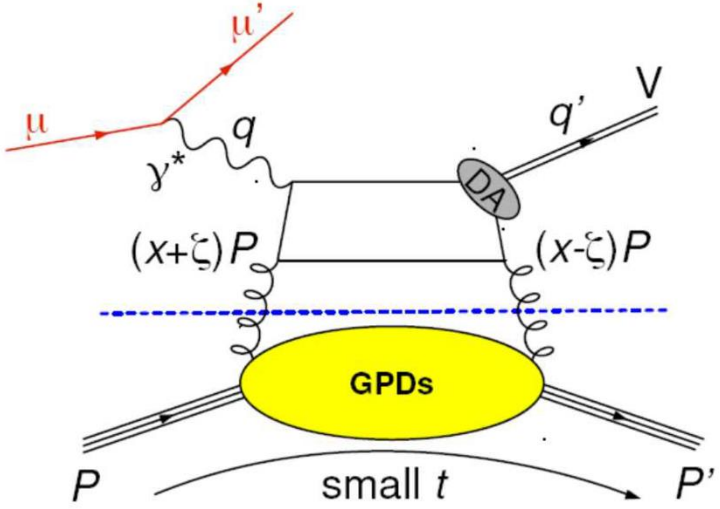
Twist-2 >> ■ Twist-3, ■ Twist-2 - double helicity flip for gluons (NLO)

GPDs in Hard Exclusive Meson Production

quark contribution



gluon contribution



4 chiral-even GPDs: helicity of parton unchanged

$H^q(x, \xi, t)$ $E^q(x, \xi, t)$ → **Vector Meson**

$\tilde{H}^q(x, \xi, t)$ $\tilde{E}^q(x, \xi, t)$ → **Pseudo-Scalar Meson**

+ 4 chiral-odd (transversity) GPDs: helicity of parton changed
(not possible in DVCS)

$H_T^q(x, \xi, t)$ $E_T^q(x, \xi, t)$

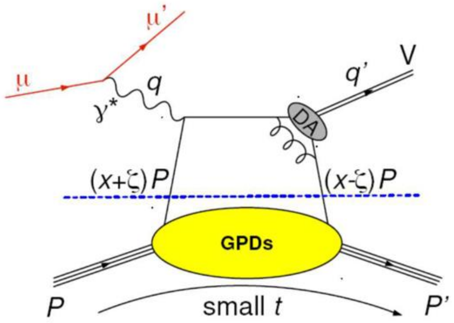
$\tilde{H}_T^q(x, \xi, t)$ $\tilde{E}_T^q(x, \xi, t)$

$$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$$

- Ability to probe the chiral-odd GPDs.
- Universality of GPDs, quark flavor filter
- In addition to nuclear structure, provide insights into reaction mechanism.
- Additional non-perturbative term from meson wave function.

Exclusive π^0 Production on Unpolarized Proton

quark contribution



$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

ϵ : degree of longitudinal polarization

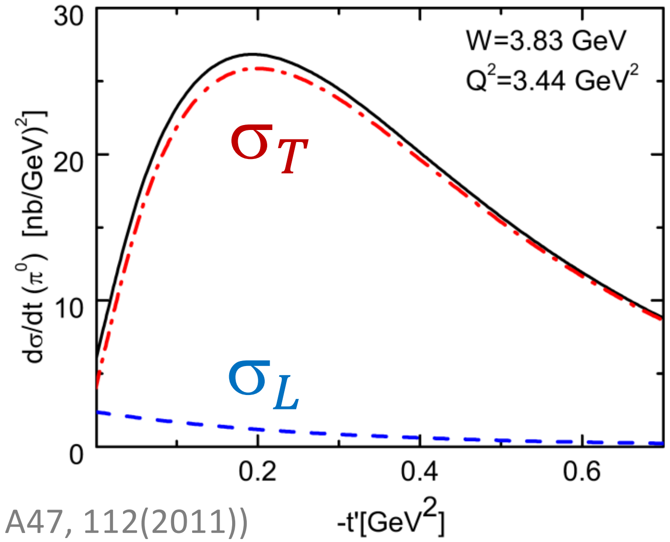
▲ $\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$ Measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

The dominating contributions from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude give access to chiral-odd GPDs

▲ $\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$

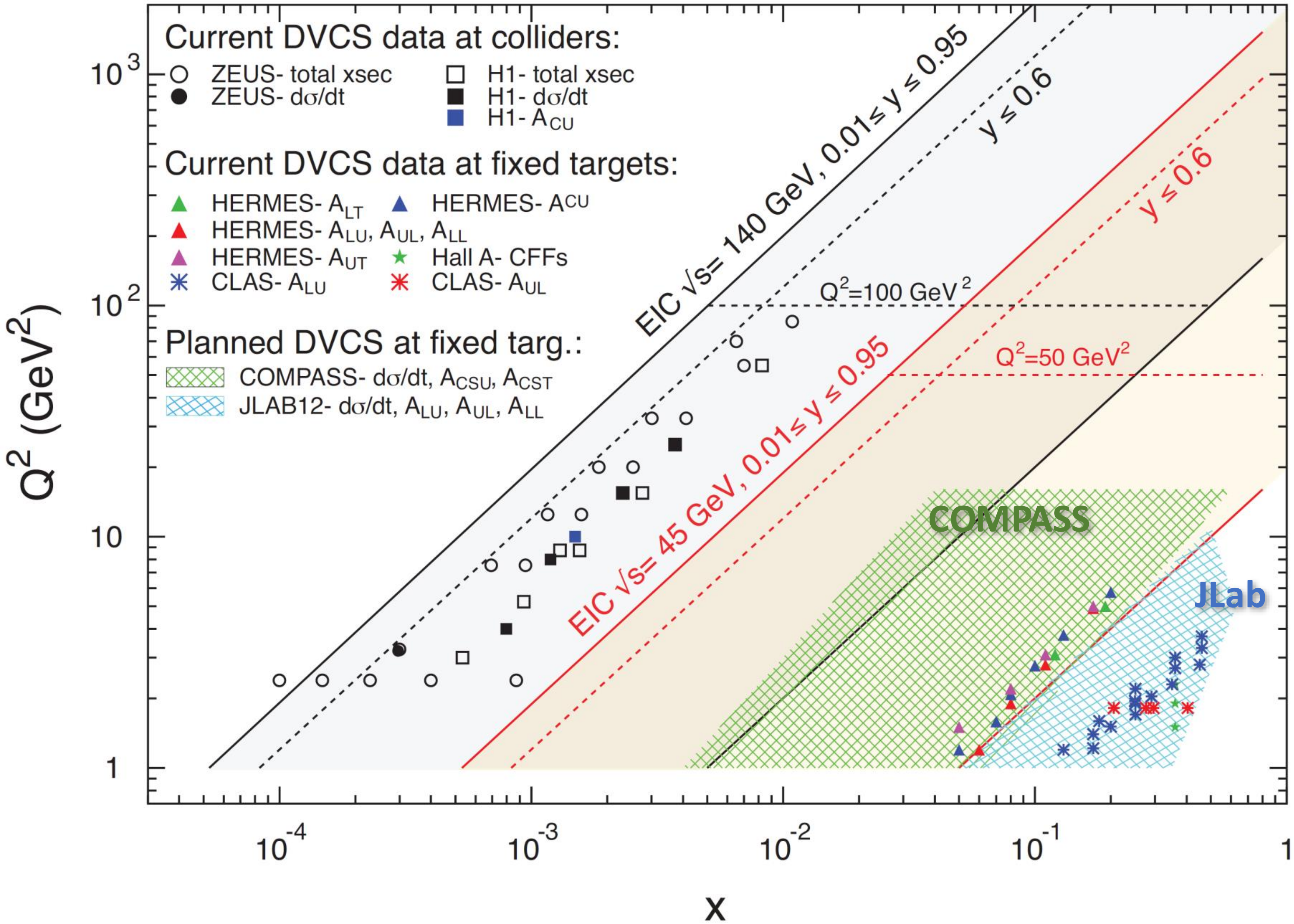
▲ $\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\bar{E}\rangle\right]$

▲ $\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$



S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))

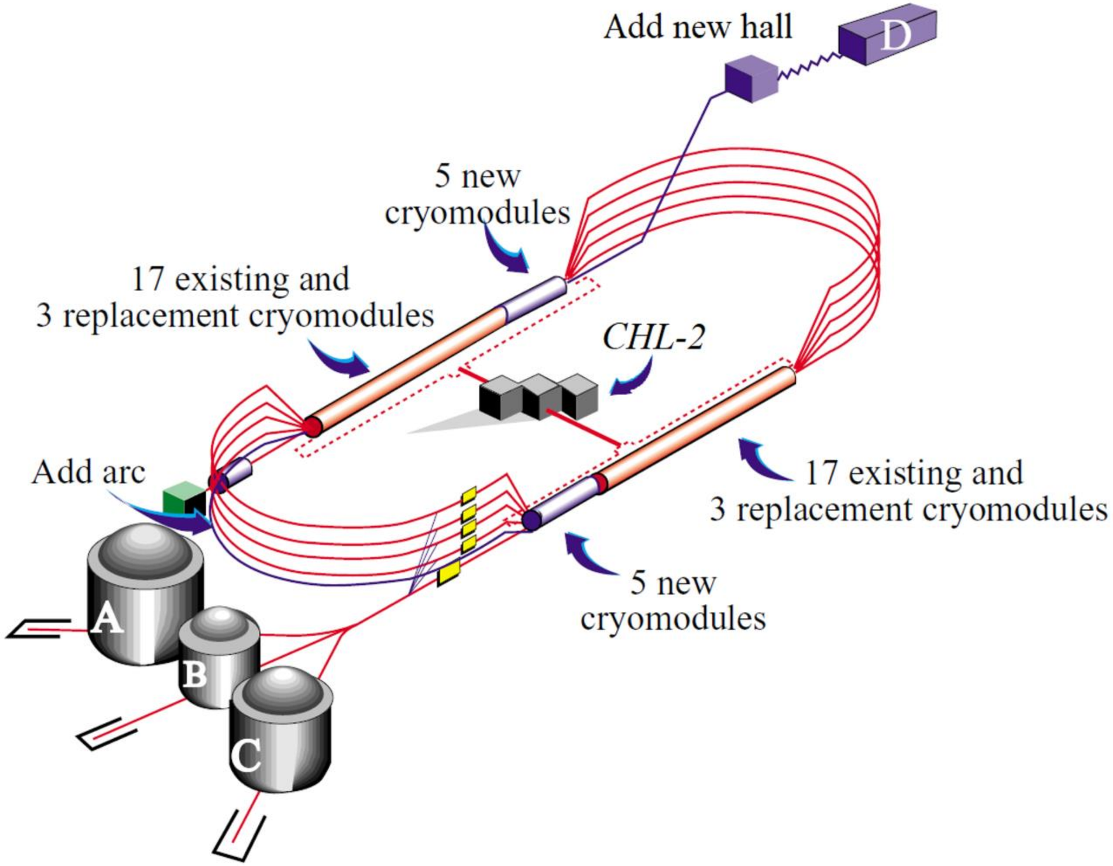
Lanscape – Global Programs of DVCS



Jefferson Lab

Jefferson Lab and Continuous Electron Beam Accelerator Facility

https://www.jlab.org/div_dept/physics_division/GeV/whitepaperv11/index.html

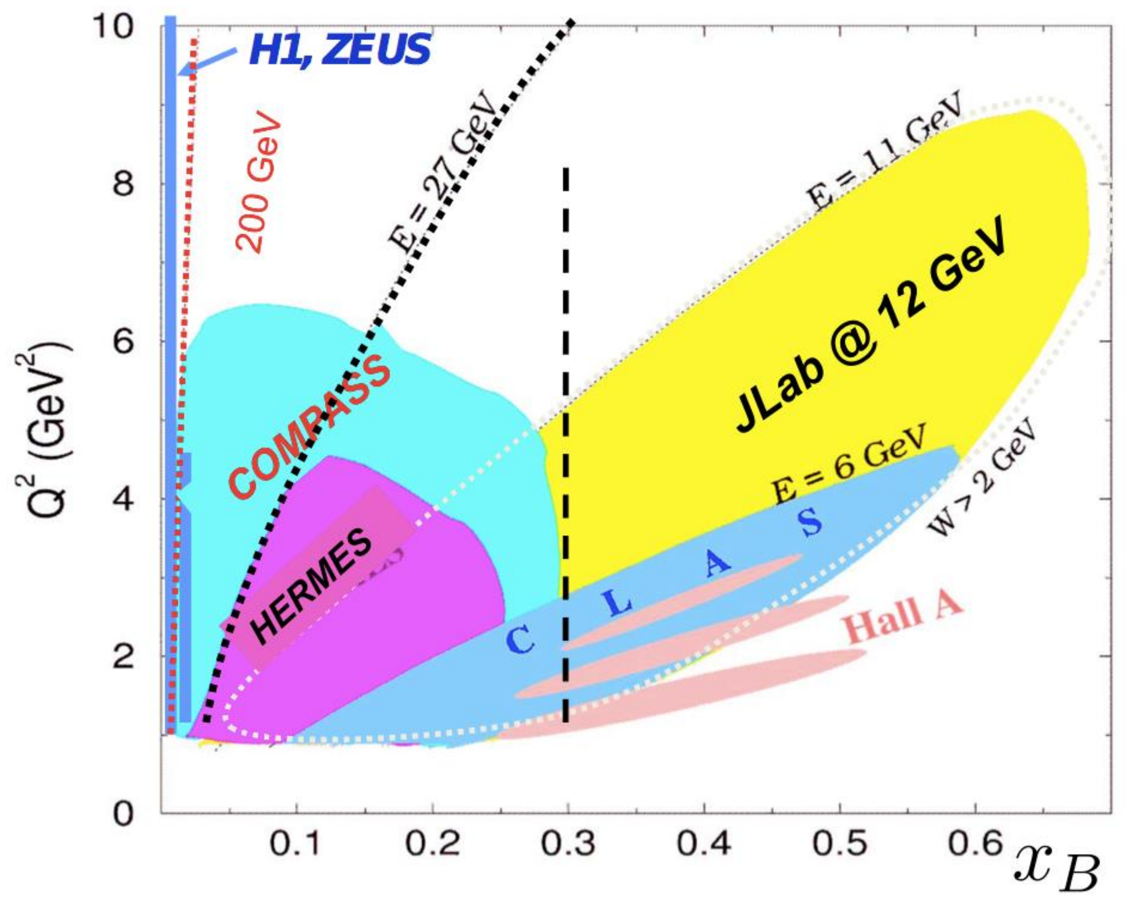


- ➢ Continuous Electron Beam Acclerator Facility (CEBAF)
  - Polarized electrons up to 12 GeV beam energy
  - Simultaneous beam delivery to different halls

JLab Exclusive Reactions for GPDs program

Measurement	Hall
DVCS Polarized beam and/or target	A,B,C
nDVCS Deuterium/He3	B, **C, A(Solid)**
DVCS w/ e+	B, C
TCS	A (Solid), B, C
Excl. π^0	A,B,C
Excl. π^-	A (Solid), (B)
Excl. ϕ, η	B
L/T separation (K, π+)	C
WACS (γ, π^0)	A, C
Backwards π^0	C

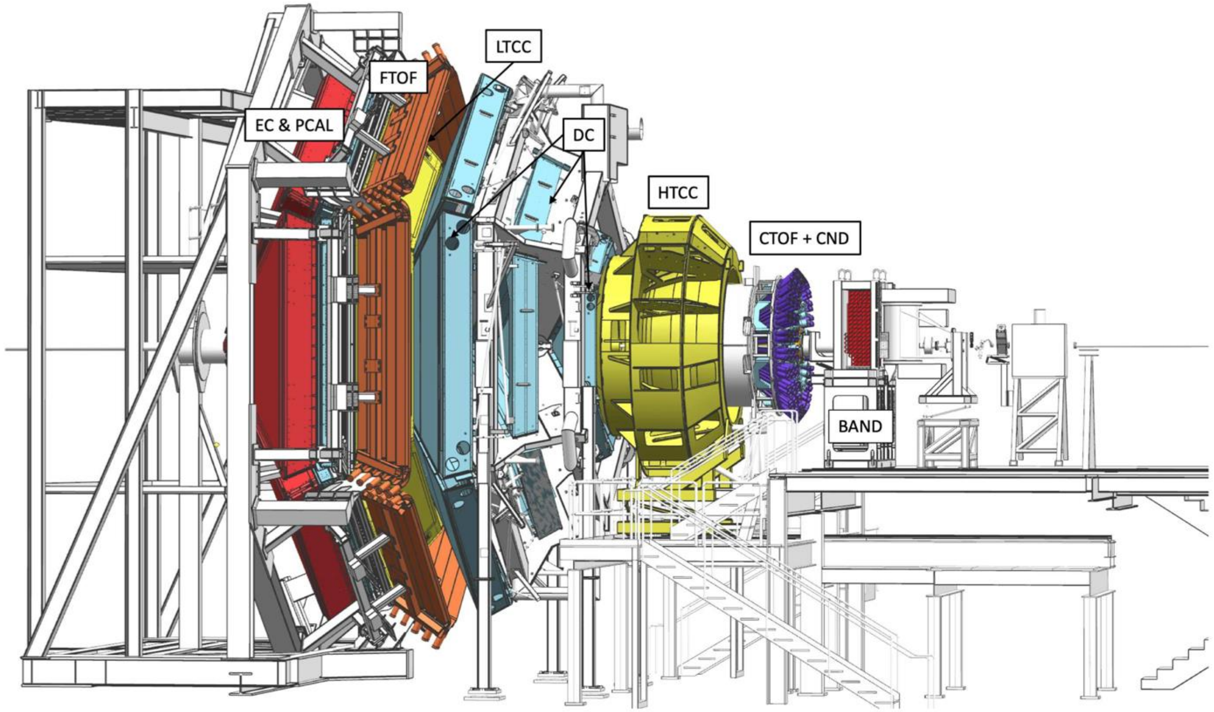
Tables by C. Munoz-Camacho

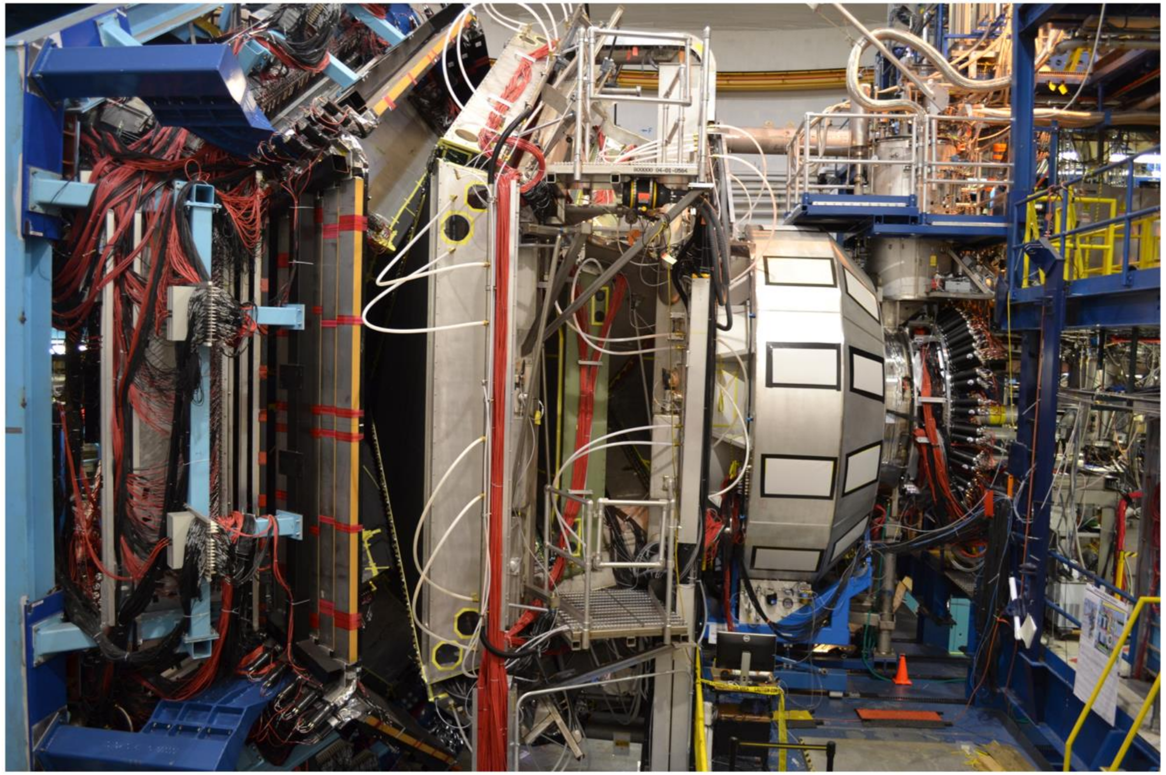


In the valence region (JLab 6 and JLab 12)

Partially complimentary, overlapping

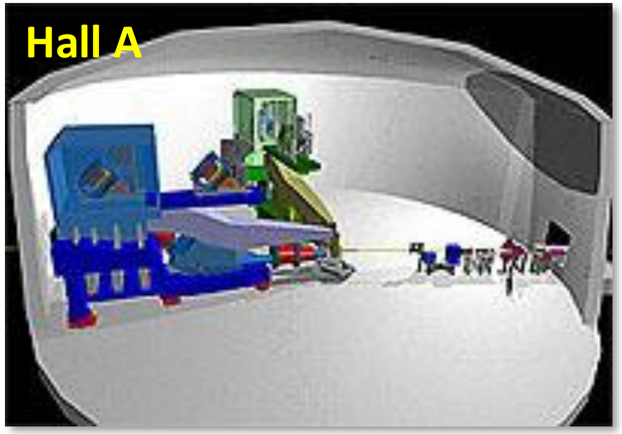
Hall B – CLAS 12

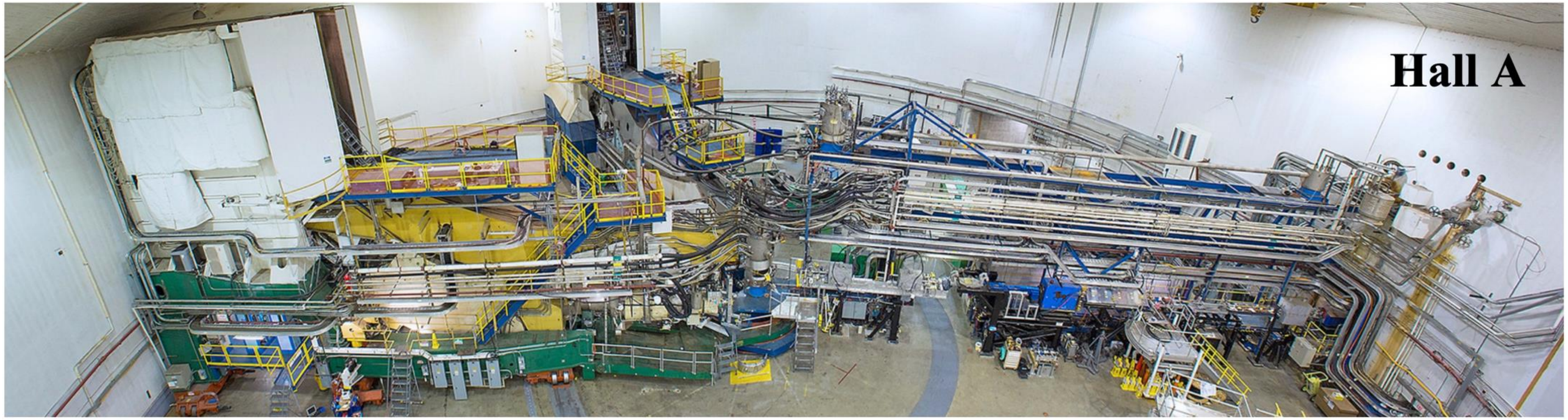


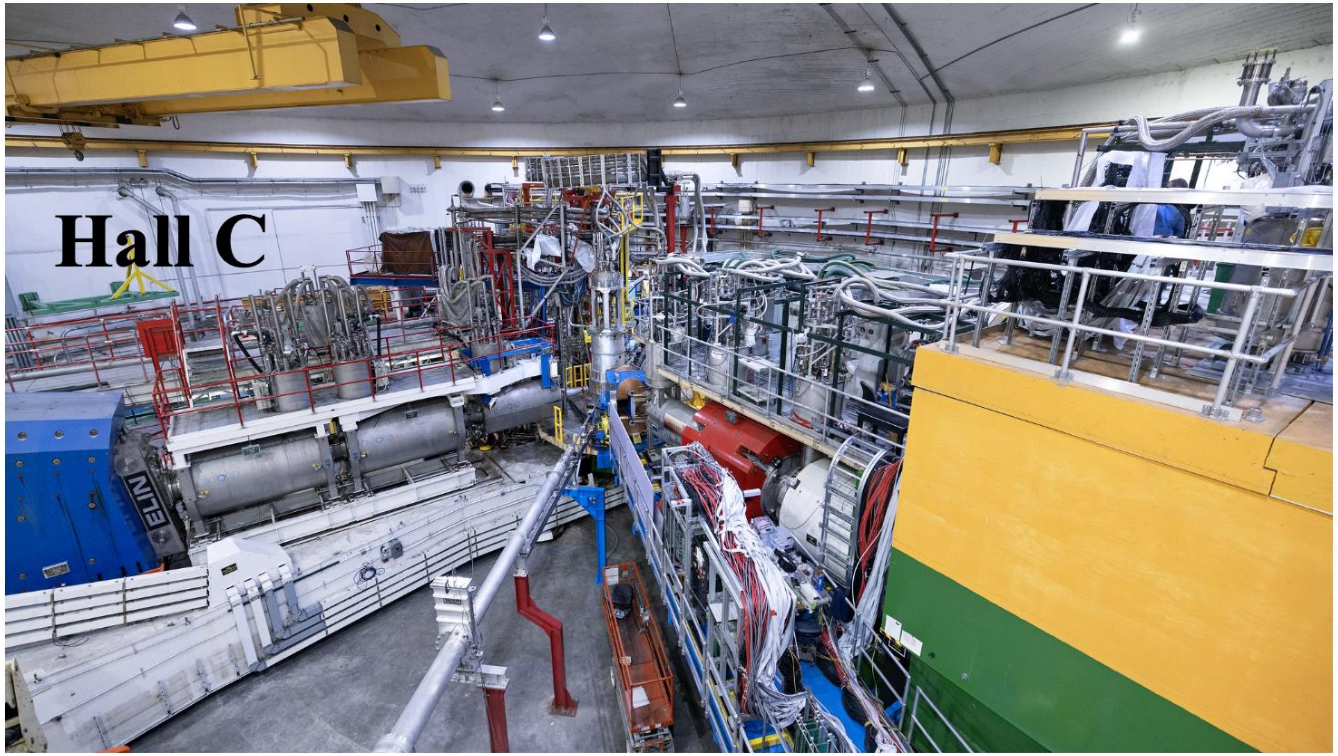


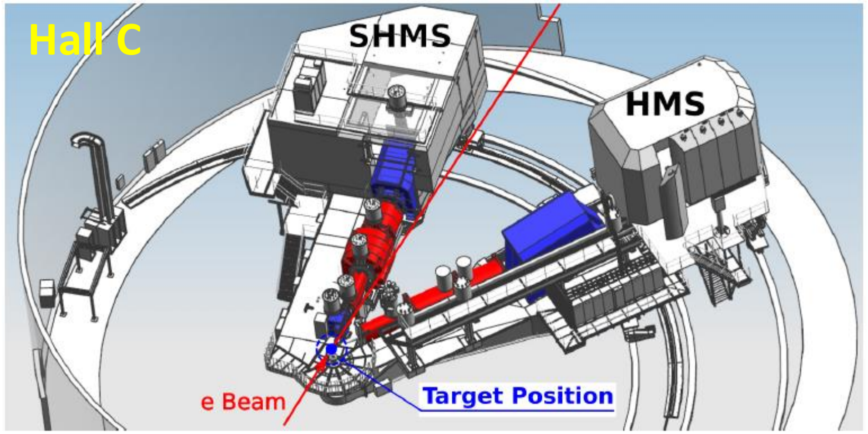
- ➢ Lower luminosity → approximately 10^{34} /(cm^{2} s)
- ➢ Wide kinematic coverage
  → Map the GPDs

Hall A/C









- Limited kinematic coverage
- High luminosity → about 10^{37} /(cm^2 s)
  → Test validity of formalism

JLab Exclusive Reactions for GPDs program

The DVCS and DVMP- π^0 using the Hall A/C scheme

	Experiment	PAC	Goal	Results
6 GeV	E00-110	PAC18	1st dedicated DVCS experiment at JLab	PRL97 (2006), PRC83 (2011), PRC92 (2015)
6 GeV	E03-106	PAC24	1st neutron DVCS experiment	PRL99 (2007)
6 GeV	E07-007	PAC31	DVCS Rosenbluth-like separation (proton)	PRL117 (2016), Nature Commun. 8 (2017)
6 GeV	E08-025	PAC33	DVCS Rosenbluth-like separation (neutron)	PRL118 (2017), Nature Physics 16 (2020)
12 GeV	E12-06-114	PAC30+38+41+47	1st 12 GeV experiment	PRL127 (2021), PRL128 (2022)
12 GeV	E12-13-010	PAC40	DVCS Rosenbluth-like separation (proton)	**NPS Experiments**

1st Generation (2004)

Q^2 dependence study (of leading terms)

2nd Generation (2010)

Beam energy dependence study at fixed x_B and Q^2

- Separate C_0^{DVCS} from C_0^I
- Separate HT and NLO from LT/LO coefficients

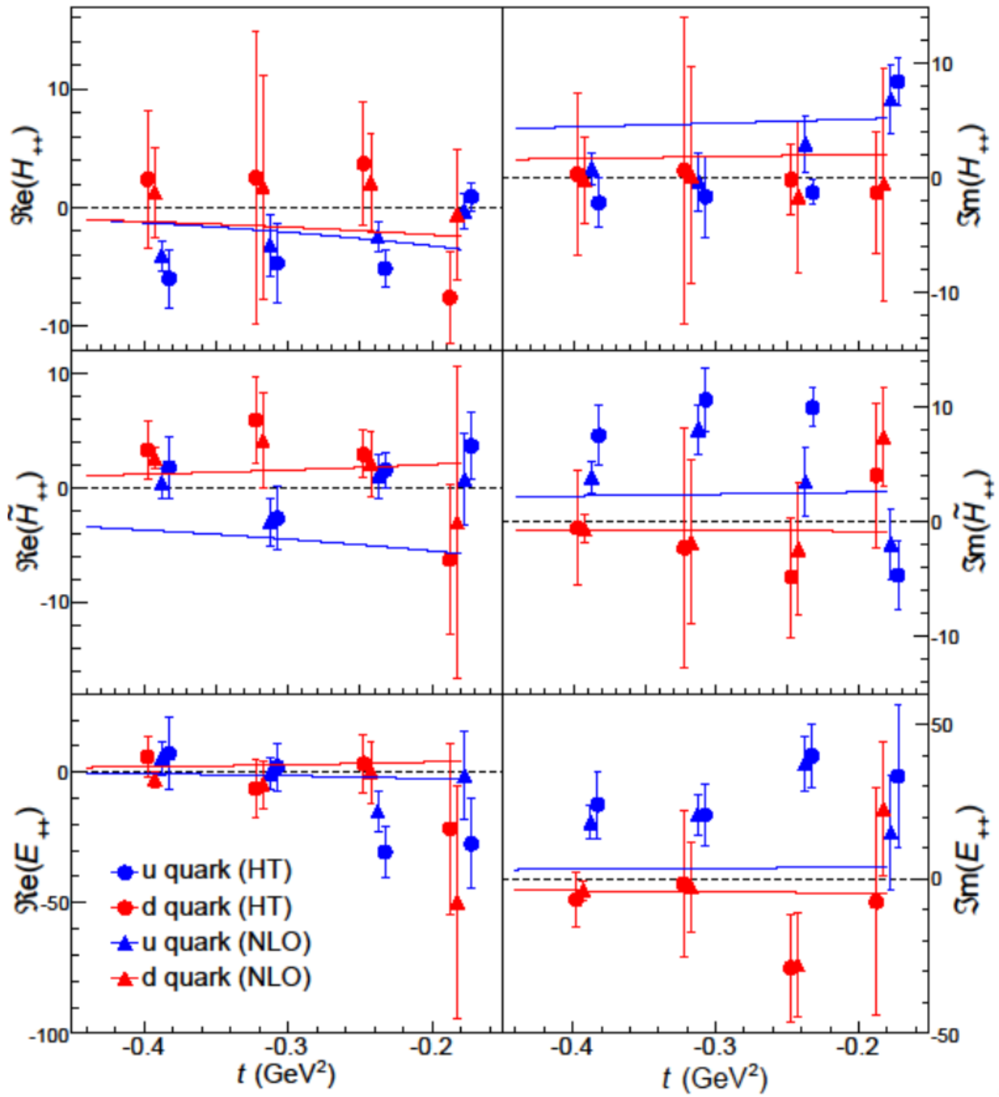
3rd Generation (2014-2016)

Multiple x_B and Q^2 measurements

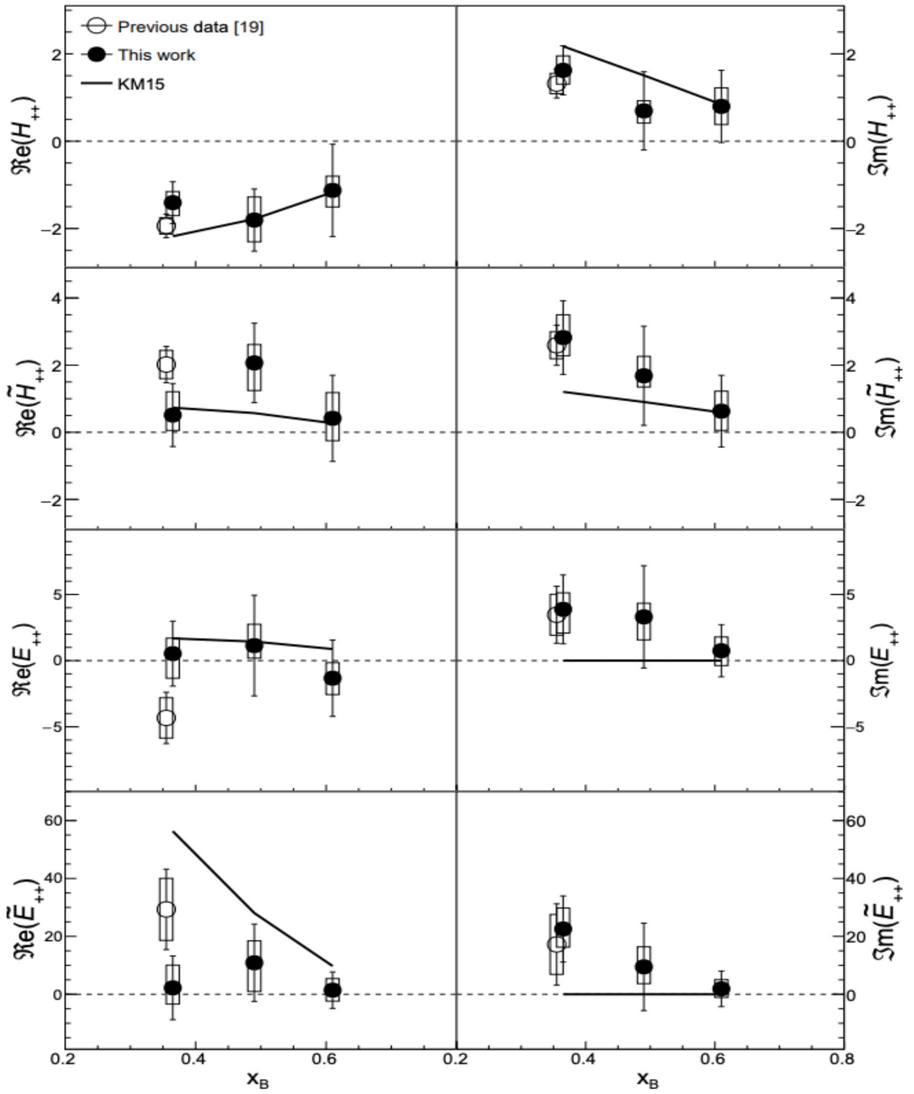
- Experimental extraction of the CFFs as a function of x_B
- Importance of considering all CFFs when extracting CFFs

Hall A Results - DVCS

Neutron data



Proton data



- ➢ Flavor separation of Compton Form Factors

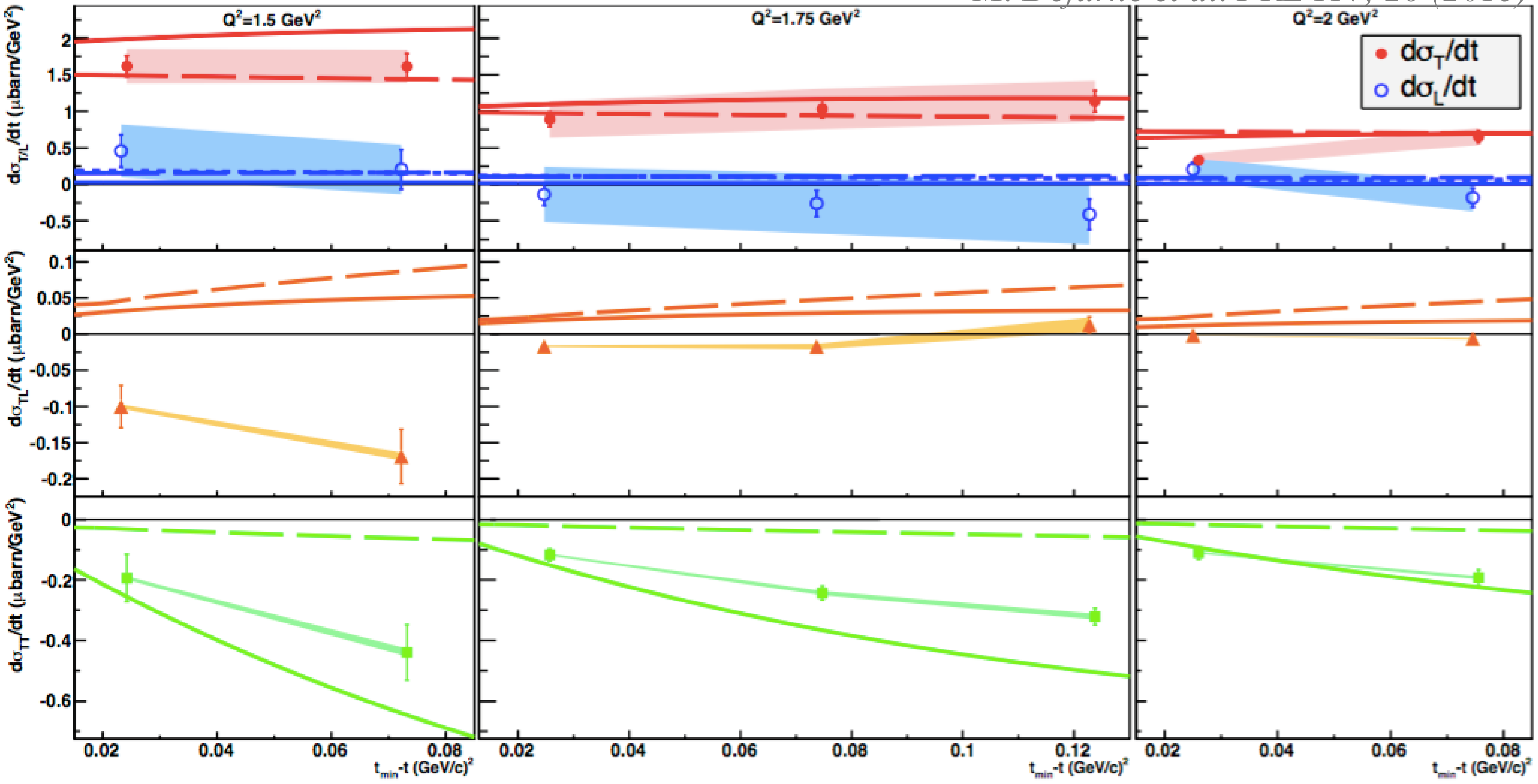
Benali et al, Nature Phys. 16, 191 (2020)

- ➢ First experimental extraction of all four helicity-conserving CFFs

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

Hall A Results – Exclusive π^0

M. Defurne et al. PRL 117, 26 (2015)



- **Experimental Support for the large contribution from $d\sigma_T$, rather than $d\sigma_L$**

Science Programs of NPS at Hall C

Run Group 1a (NPS at small angles and HMS - SHMS used as carriage for NPS):

- **E12-13-010** (Run status: complete): Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C Link
- **E12-13-007** (Run Status: complete): Measurement of Semi-Inclusive pi0 Production as Validation of Factorization Link
- **E12-22-006** (Run status: complete): Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C Link
- **E12-23-014** (Run status: complete): Measurements of the Ratio R = sigmaL/sigmaT p/d ratios, Pt dependence, and azimuthal asymmetries in Semi-Inclusive DIS pi0 production form proton and deuteron targets using the NPS in Hall C Link

Run Group 1b (NPS at small angles and HMS - SHMS used as carriage for NPS):

- **E12-06-114** (35 days moved to Hall C): Measurements of the electron-helicity dependent cross-sections of deeply virtual Compton scattering

Run Group 2 (NPS at large angles and HMS - SHMS used as carriage for NPS):

- **E12-14-003**: Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies Link
- **E12-14-005**: Wide Angle Exclusive Photoproduction of pi-zero Mesons Link

Run Group 3 (NPS+CPS - SHMS used as carriage for NPS)

- **E12-17-008**: Polarization Observables in Wide-Angle Compton Scattering at large s, t, and u Link

Run Group 4 (NPS reconfigured as part of an ECAL+HCAL system downstream from target)

- **E12-23-004**: A Search for a Nonzero Strange Form Factor of the Proton at 2.5 (GeV/c)^2 Link

Run Group 5 (NPS+Positrons)

- **C12-20-012** (status C2): Deeply Virtual Compton Scattering using a positron beam in Hall C Link

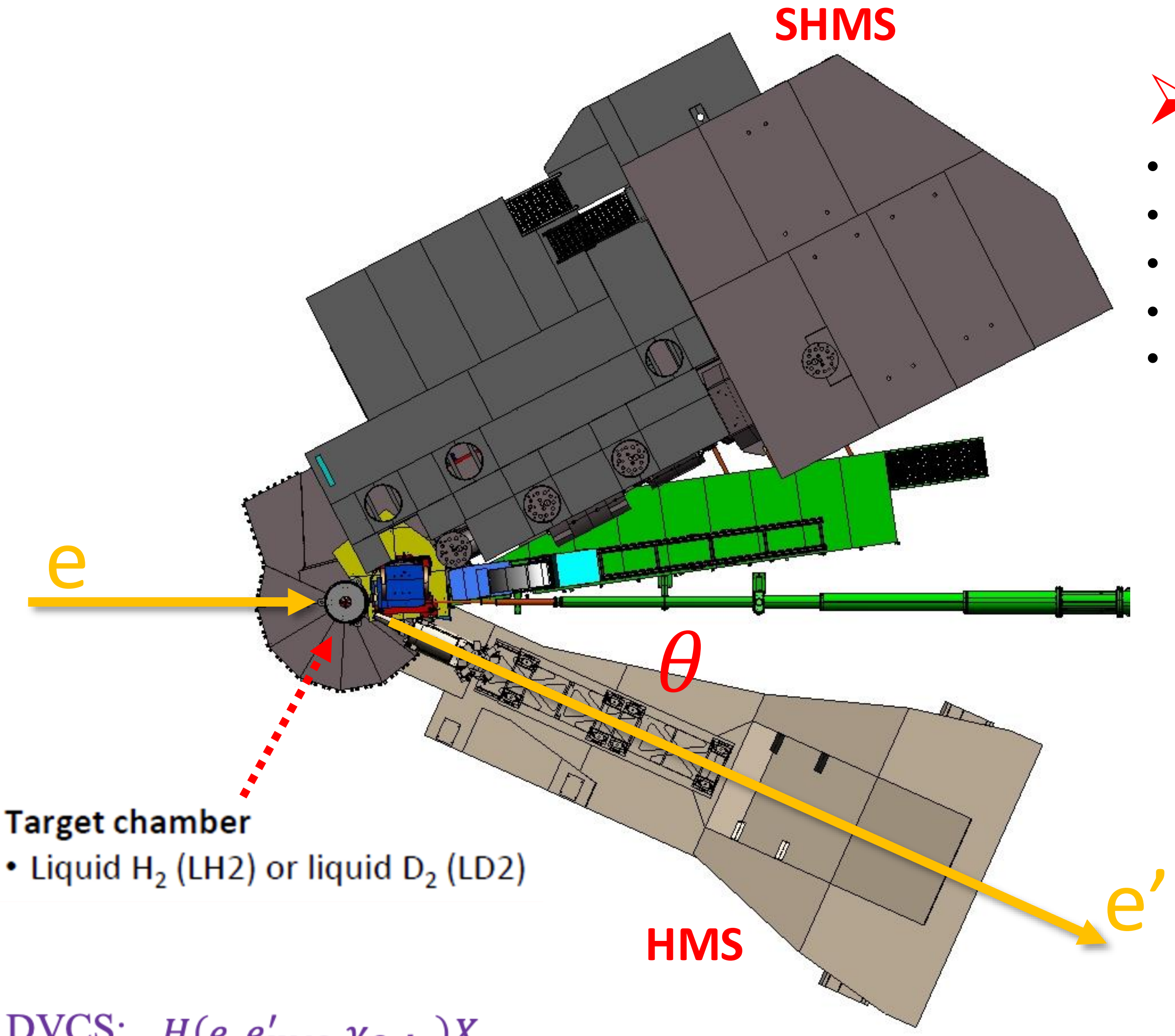
LOIs and proposal being developed

- LOI12-23-003: GluToNY: Gluon tomography in nucleons by gamma-polarimetry
- LOI12-23-014: Recoil Nucleon Polarization in Deeply Virtual Compton Scattering and Neutral Pion Electroproduction in Hall C
- C12-18-005: Timelike Compton Scattering Off a Transversely Polarized Proton Link (requires NPS + CPS)

NPS Run Group 1a: NPS at small angle

- Simultaneous data taking with measurements of exclusive and semi-exclusive processes.
- Complete, data analysis starting

NPS Experimental Setup at Hall C



Target chamber

- Liquid H_2 (LH2) or liquid D_2 (LD2)

DVCS: $H(e, e'_{HMS}, \gamma_{Calo})X$

DVMP: $H(e, e'_{HMS}, \pi^0 \rightarrow \gamma\gamma)X$

➢ High Momentum Spectrometer (HMS)

- Momentum Range: 0.4 to 7.4 GeV/c.
- Momentum Acceptance: ±10%.
- Momentum Resolution: 0.1% – 0.15%.
- Scattering Angle Range: 10.5° to 90° relative to the beam.
- Angular Acceptance: ±32 mr (in-plane) by ±85 mr (out-of-plane).

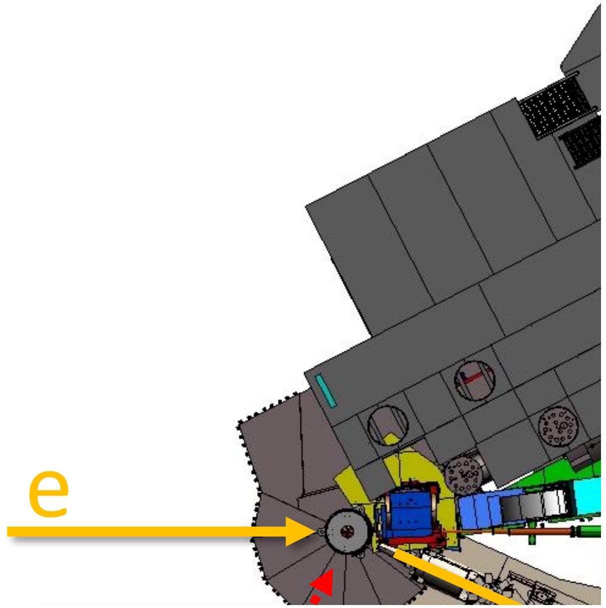
→Detection of the Scattered electron e'

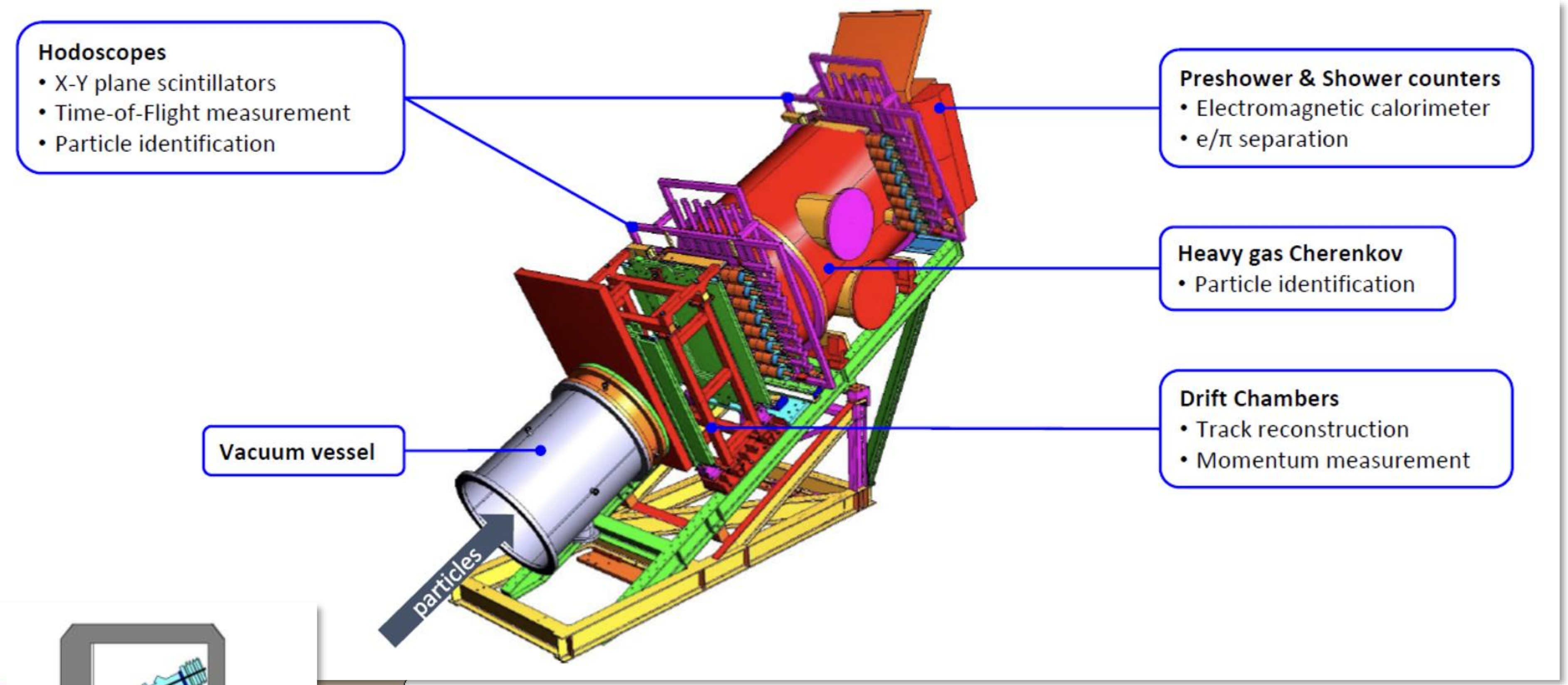
$$Q^2 = 2E_e \cdot E_{e'}(1 - \cos\theta)$$

$$x_B = \frac{Q^2}{2M_p(E_e - E_{e'})}$$

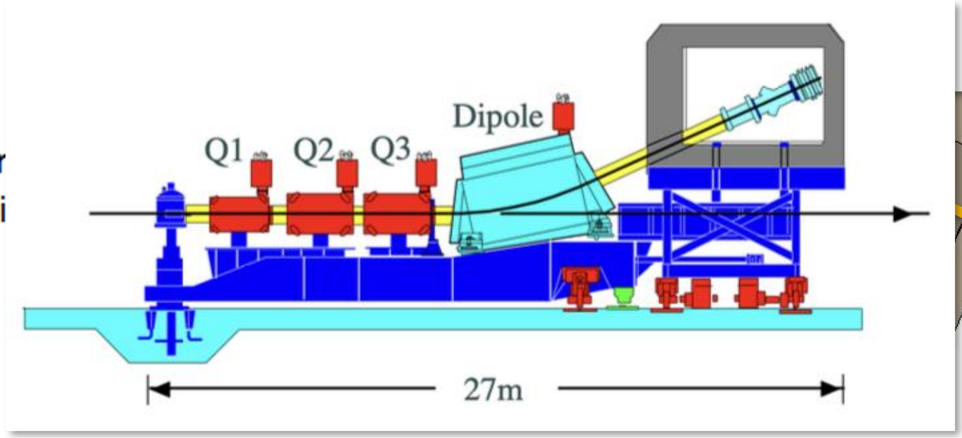
Set θ, E_e and $E_{e'}$ → set Q^2 and x_B

NPS Experimental Setup at Hall C





Tar
• Li

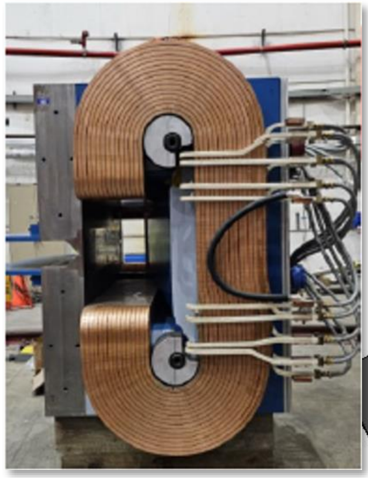


•**Optical Configuration:** QQQD (Three Quadrupoles, one Dipole).

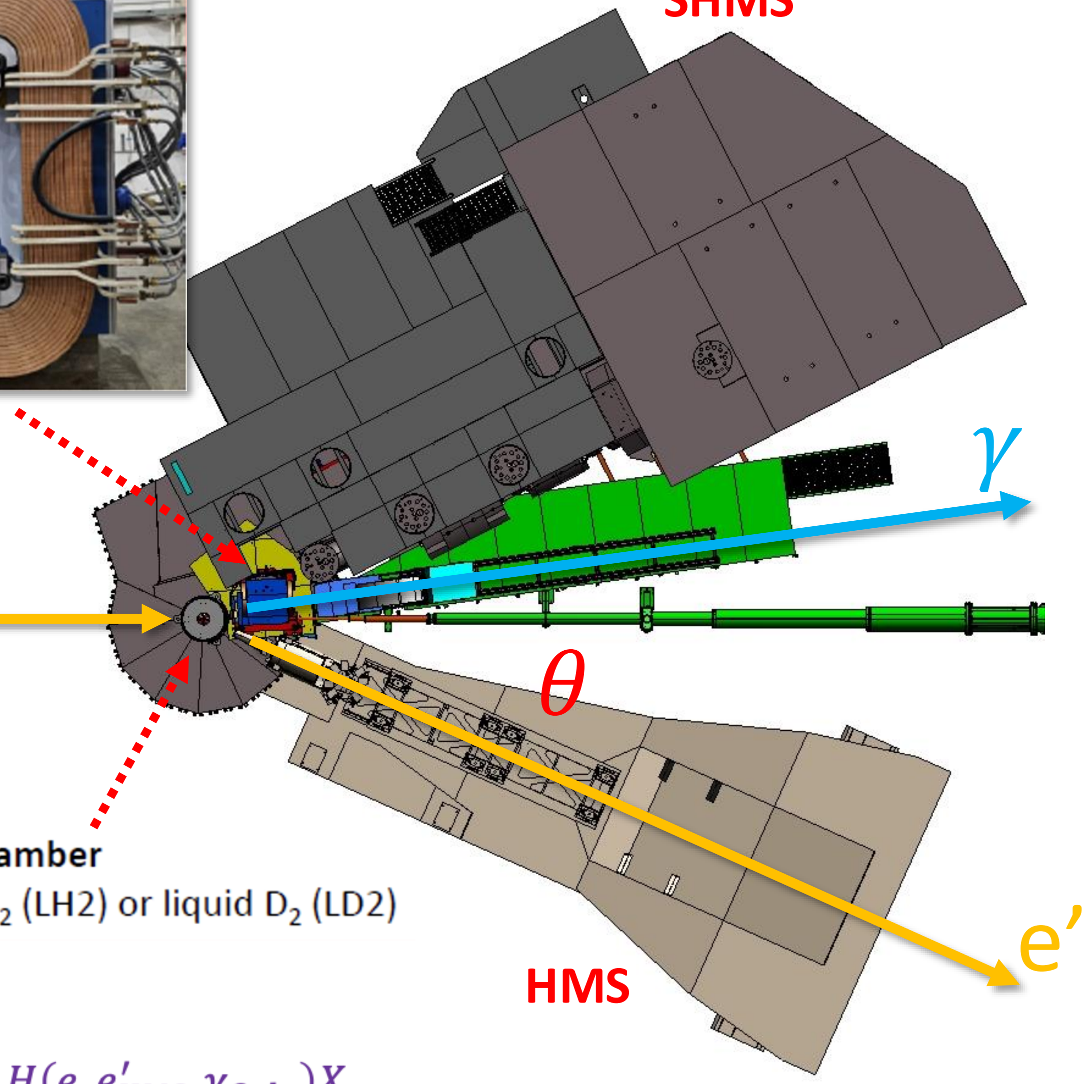
•**Detection Efficiency:** >99%.

•**Electron/Pion Separation:** >1000:1

NPS Experimental Setup at Hall C



Sweep magnet



DVCS: $H(e, e'_{HMS}, \gamma_{Calo})X$

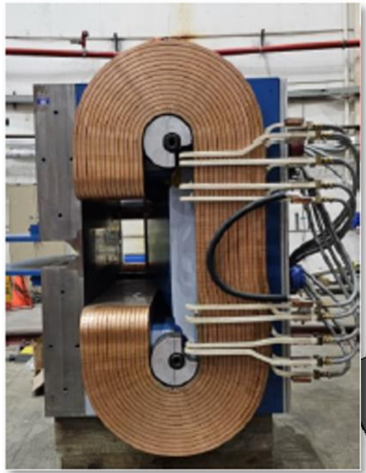
DVMP: $H(e, e'_{HMS}, \pi^0 \rightarrow \gamma\gamma\ )X$

- Neutral Particle Spectrometer (NPS):
  - Photon detection
  - A total of 30 × 36 (1080) PbWO4 crystals
  - PbWO4 crystals size 2×2×20 cm^3

- Sweep magnet:
  - 0.3 T magnetic field
  - Reduce low-energy electron background

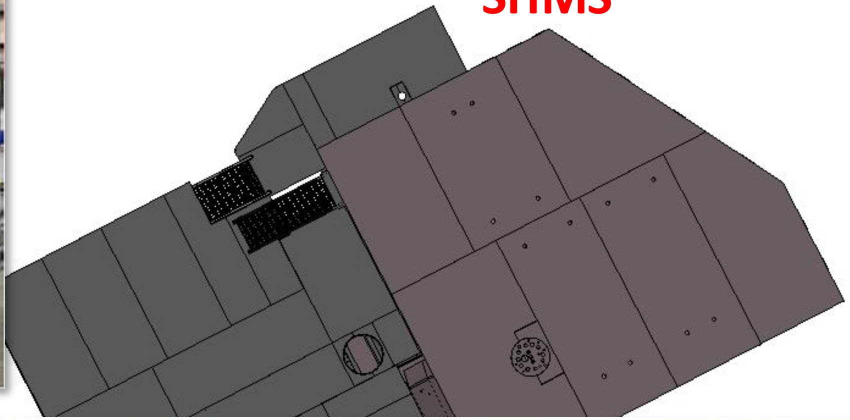
- Super High Momentum Spectrometer (SHMS) used as the NPS carriage

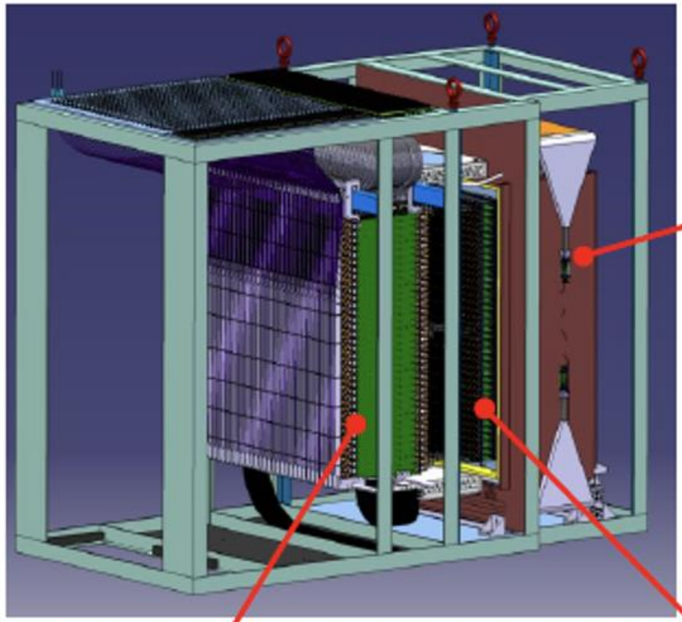
NPS Experimental Setup at Hall C



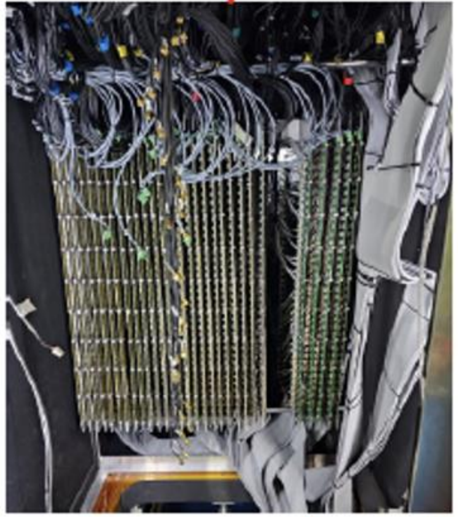
Sweep magnet

SHMS





Front view of 30x36 NPS crystal array

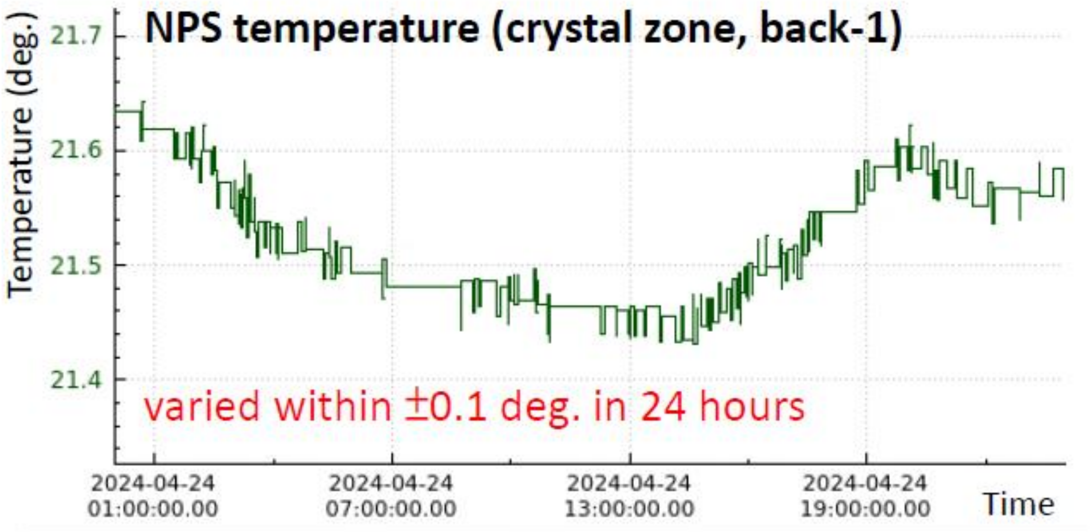


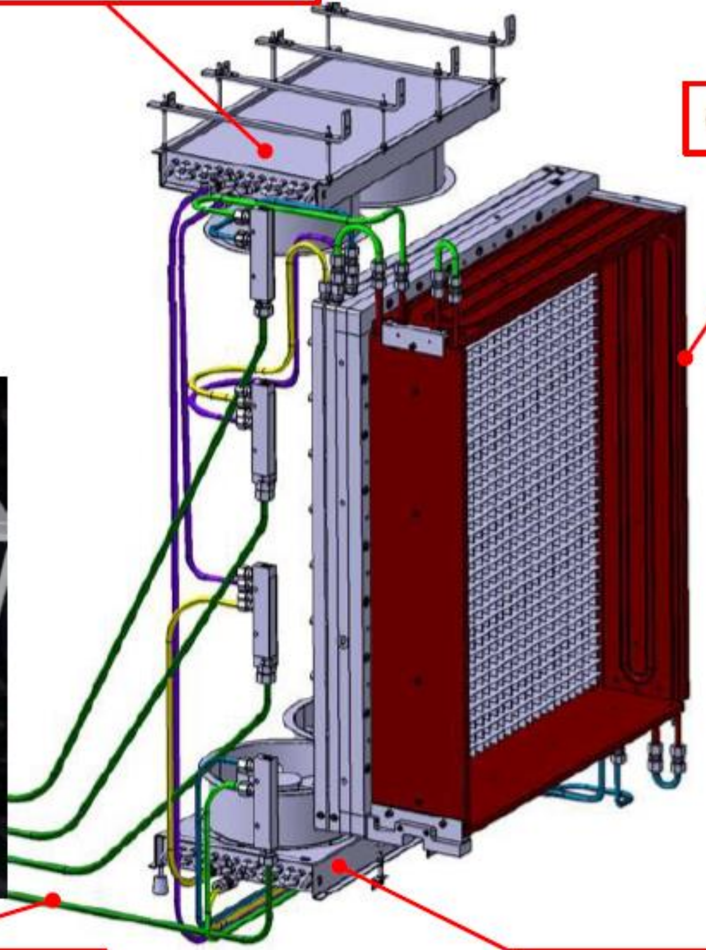
Signal and high voltage (HV) distribution boards

Photomultipliers (PMTs) and HV divider base

Temperature Control System

- Heat generate by PMTs and electronics
- Light yield in $PbWO_4$ crystals are sensitive to their temperature (-2% / °C at 20°C)
- Keep the temperature as stable as possible
- 56 sensors on the back and front of crystals for temperature monitoring

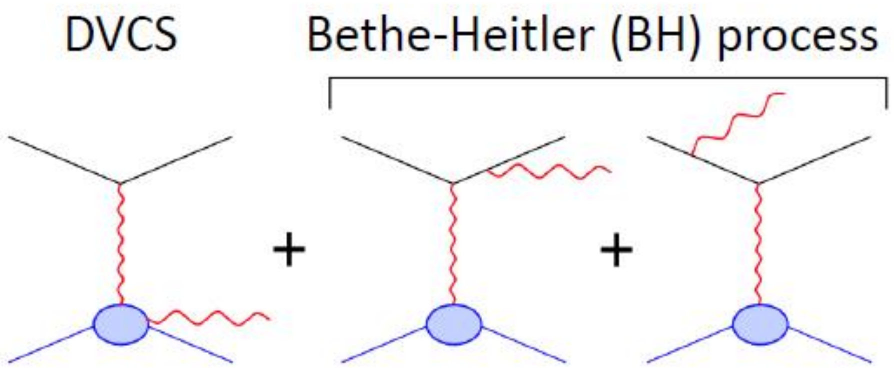




Extended Measurements at Hall C

- **Expanded kinematic coverage compared to Hall A**
- **Multiple beam energies for most kinematic settings (6.4, 8.5, 10.5 GeV)**

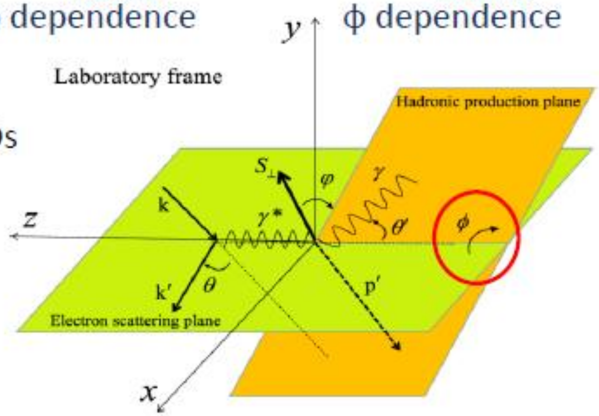
$ep \rightarrow e'p'\gamma$ =

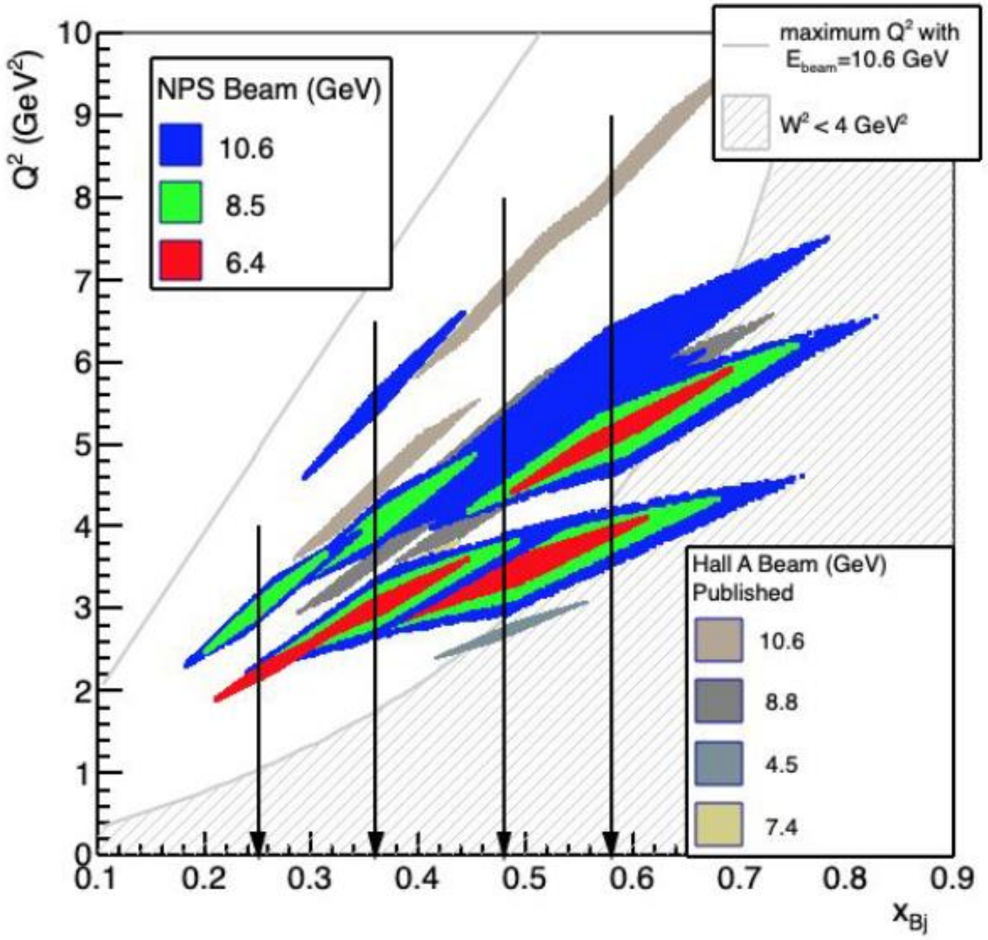


- $\sigma(ep \rightarrow e'p'\gamma) \propto \underbrace{|T_{BH}|^2}_{\text{pure QED process}} + \underbrace{|T_{DVCS}|^2}_{\propto E_{beam}^2,\ \phi \text{ dependence}} + \underbrace{I(BH \cdot DVCS)}_{\propto E_{beam}^3,\ \phi \text{ dependence}}$

pure QED process | $\propto E_{beam}^2$ ϕ dependence | $\propto E_{beam}^3$ ϕ dependence

T_{BH}: Amplitude of Bethe-Heitler process
T_{DVCS}: DVCS amplitude, bi-linear combination of GPDs
I: interference term, linear combination if GPDs





Extended Measurements at Hall C

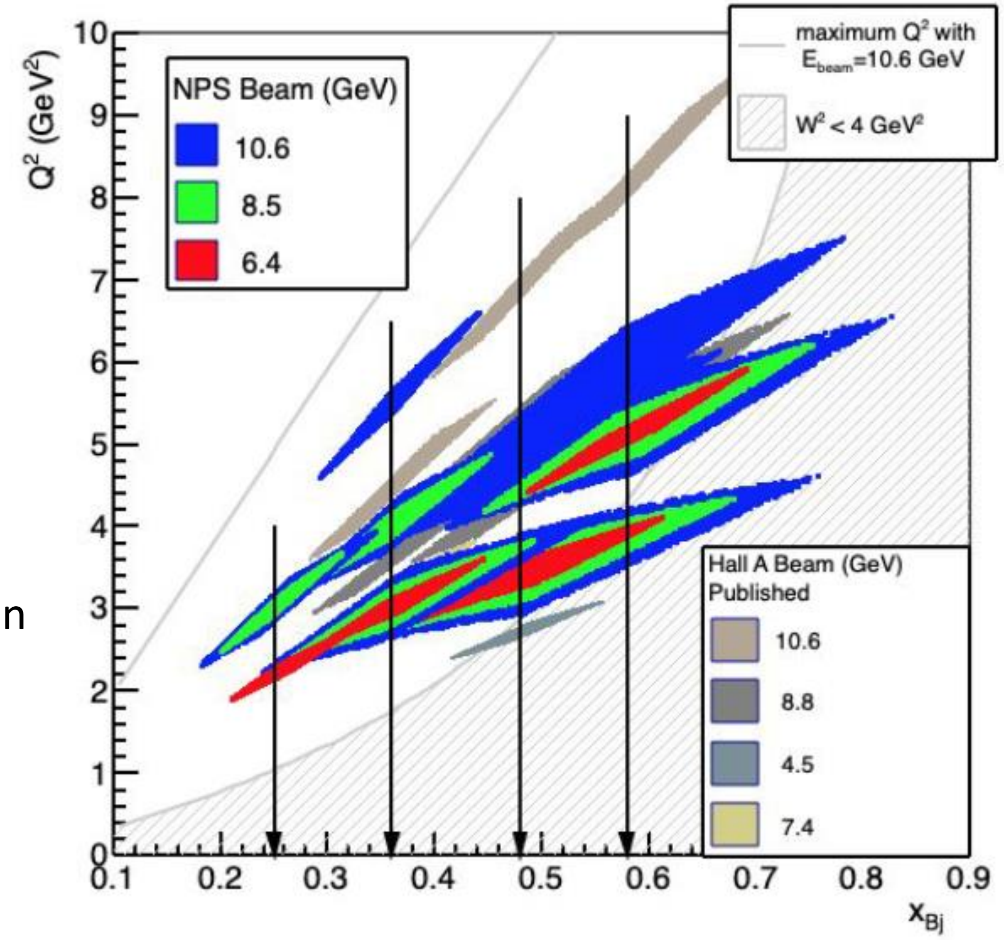
- **Expanded kinematic coverage compared to Hall A**
- **Multiple beam energies for most kinematic settings (6.4, 8.5, 10.5 GeV)**

DVCS:

- Disentangle all Fourier moments of the cross-section
  → E and ϕ dependence
- Quantify the size of higher-twist corrections
  → Q^2 dependence
- Disentangle the imaginary and real part of the DVCS amplitude
  → helicity dependence

Exclusive π^0 electroprdution:

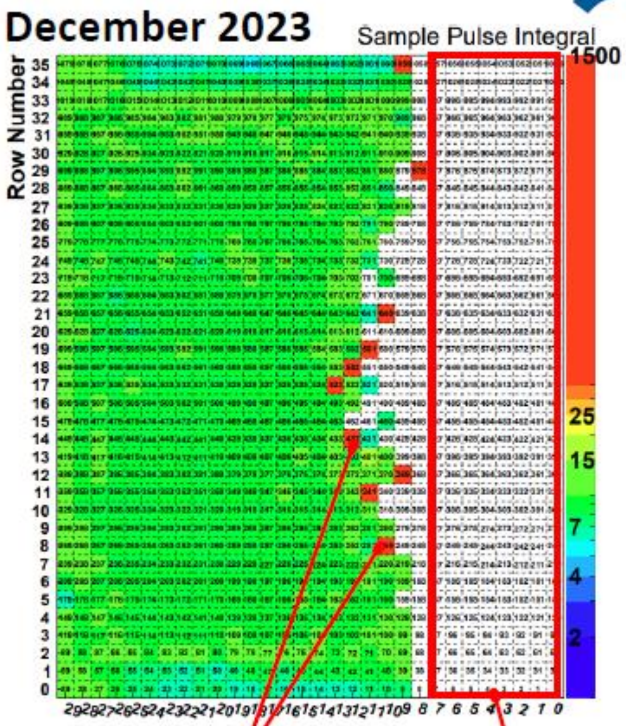
- Disentangle the longitudinal/transverse contribution to the cross section
  → E dependence
- Measure the Q^2 evolution of σ_L and σ_T
  → Q^2 dependence



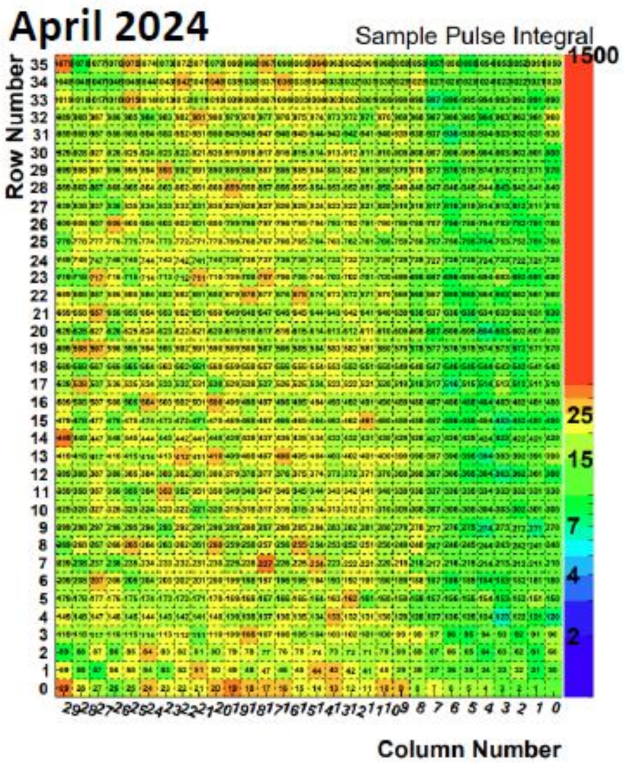
Refurbishment of Radiation Damaged Bases

- Data taking from September 2023 to May 2024
- Radiation damage to the LV regulators on the PMT base pre-amps
- LV regulators were bypassed and re-installed from Dec. 2023 – March 2024

Divider base boards were removed for bypassing



No major problems with the bases till the end of experiment

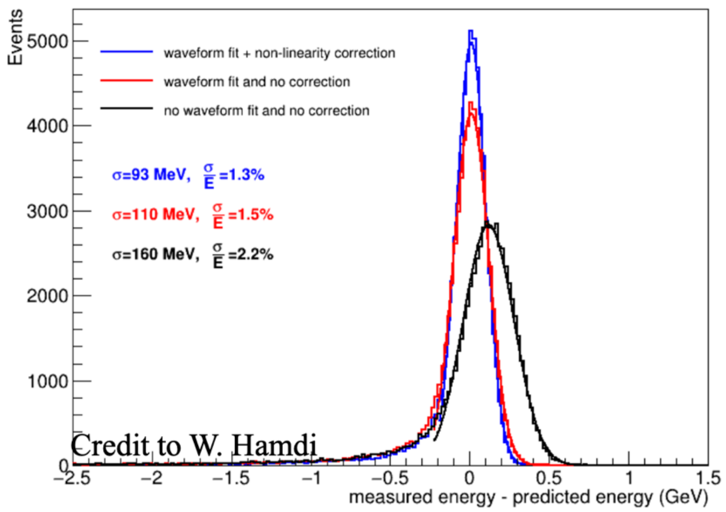


Preliminary Results of DVCS Extraction

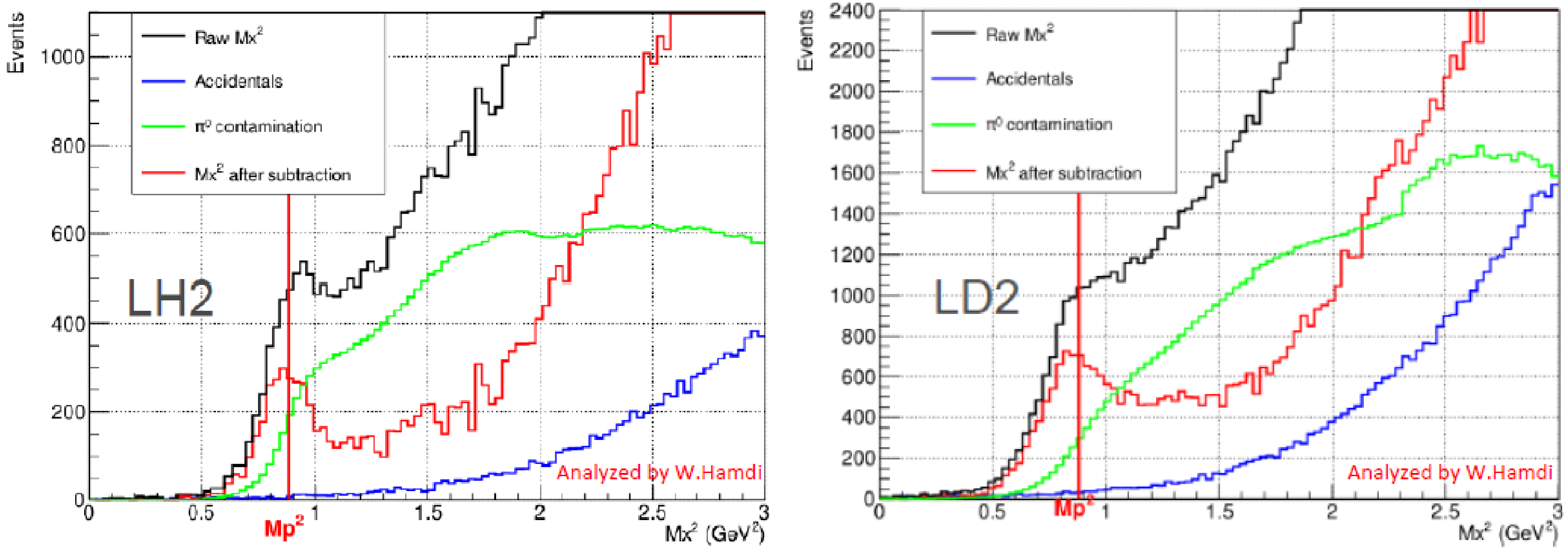
DVCS: $H(e, e'_{HMS}, \gamma_{Calo})X$ DVMP: $H(e, e'_{HMS}, \pi^0 \rightarrow \gamma\gamma)X$

- Recoil proton not detected
  - → Determine the exclusivity of an event by the missing mass technique
  - → Decent photon energy resolution required
  - → 1.3% @ 7.3 GeV observed

NPS Energy Resolution



Missing mass square from data with different target



- Mass peak of the recoil proton can be observed

- On-going calibration work on the data collected. Preliminary physics analysis started.

Summary

- **GPD study can provide interesting insights into the nucleon properties.**

- **The experimental extraction of GPDs via exclusive processes is quite challenging.**

- **GPD Measurements at JLab Hall C NPS experiments**
  - Run group 1a of NPS has finished data taking.
  - DVCS on proton/neutron and exclusve production of π^0
  - Intense calibration work on the data collected
  - Physics analysis initiated