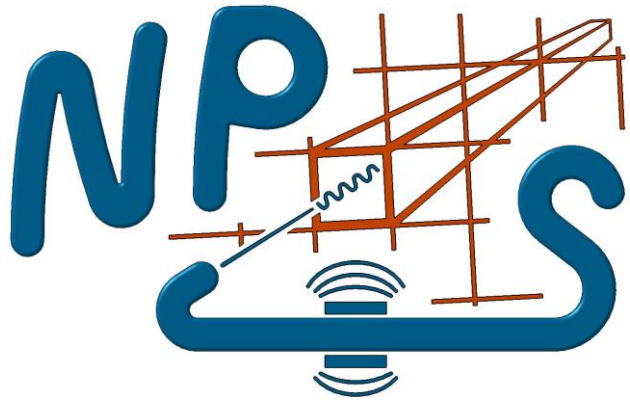


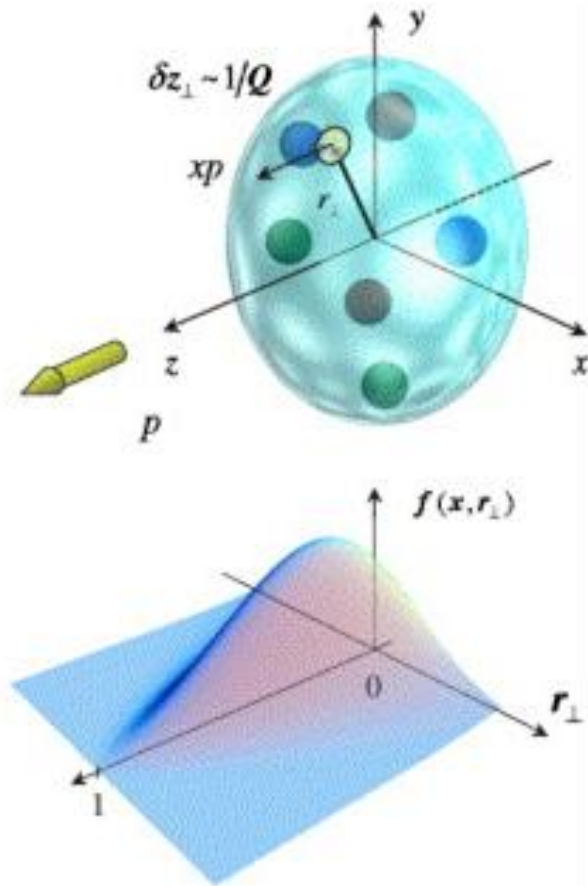


Funded by U.S. National
Science Foundation
Grant PHY-2209199

Nucleon Femtography with NPS Run Group 1a in Jefferson Lab Hall C

Mark Mathison
Ohio University

Moving towards a Multidimensional Picture of the Nucleon



- Form factors and Parton Distribution Functions – well-understood but 1D
- Generalized Parton Distributions (GPDs) – correlated distributions as a function of transverse position and momentum fraction
- GPDs access energy-momentum tensor – encodes mechanical properties, mass distributions
- GPDs extracted from exclusive scattering processes – DVCS, DVMP, etc.

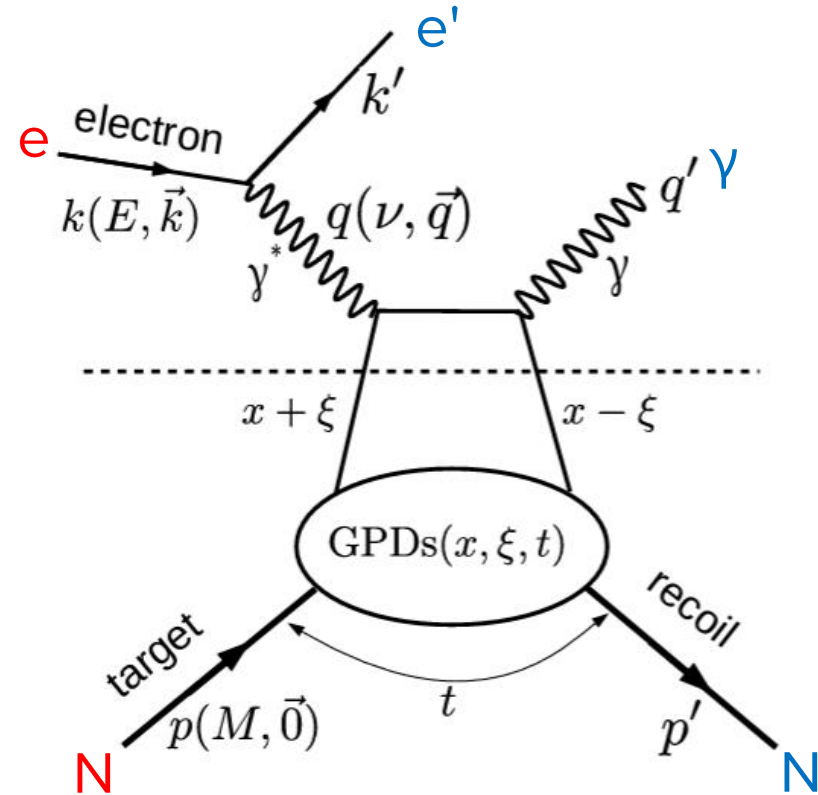
X. Ji, Phys.Rev.Lett. 78 (1997) 610-613

M. Diehl, Phys.Rept.388:41-277,2003

A. Belitsky, A. Radyushkin, Phys.Rept.418:1-387,2005

Probing the Strong Force with Deeply Virtual Compton Scattering (DVCS)

- $eN \rightarrow e'N'\gamma$ process
- Studied for nearly 30 years – HERA (H1 and ZEUS), HERMES, COMPASS, Jefferson Lab
- Cleanest probe for accessing GPDs



Hard processes:
Perturbatively
calculable

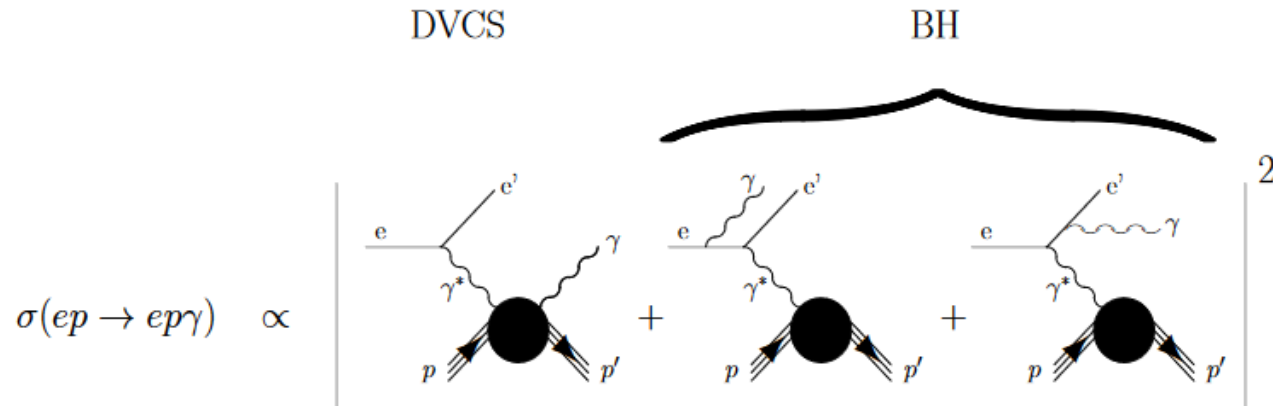
Factorization

Soft processes:
Parametrized by
GPDs

Interference with Bethe-Heitler Process

- Experimentally access GPDs via Compton Form Factors (CFFs)
- $eN \rightarrow e'N'\gamma$ cross section:

$$\frac{d^4\sigma}{dQ^2 dx dt d\phi} (eN \rightarrow e'N'\gamma) \propto \underbrace{|T_{BH}|^2}_{\text{Pure QED process}} + \underbrace{|T_{DVCS}|^2}_{\text{Bilinear combination of CFFs}} + \underbrace{I(BH \cdot DVCS)}_{\text{Linear combination of CFFs and FFs}}$$



T_{BH} and T_{DVCS} – DVCS and BH amplitudes, respectively

I – interference between DVCS and BH

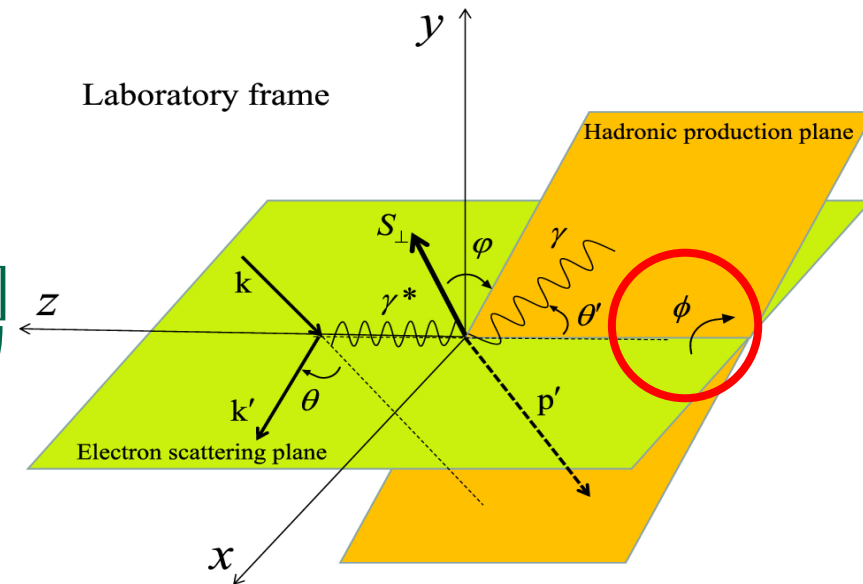
M. Guidal, H. Moutarde, and M. Vanderhaeghen,
Rep. Prog. Phys. **76**, 066202 (2013).

Disentangling Interference Term by Kinematics

- Considering beam helicity at leading twist ($\sigma^{\rightarrow}$ & $\sigma^{\leftarrow}$ positive & negative helicity):

$$\frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{2} \propto \Im[I(BH \cdot DVCS)]$$

$$\frac{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}}{2} \propto \underbrace{|T_{BH}|^2}_{\text{Known to 1\%}} + \underbrace{|T_{DVCS}|^2}_{\propto E_{beam}^2 \phi \text{ dependence}} + \underbrace{\Re[I(BH \cdot DVCS)]}_{\propto E_{beam}^3 \phi \text{ dependence}}$$

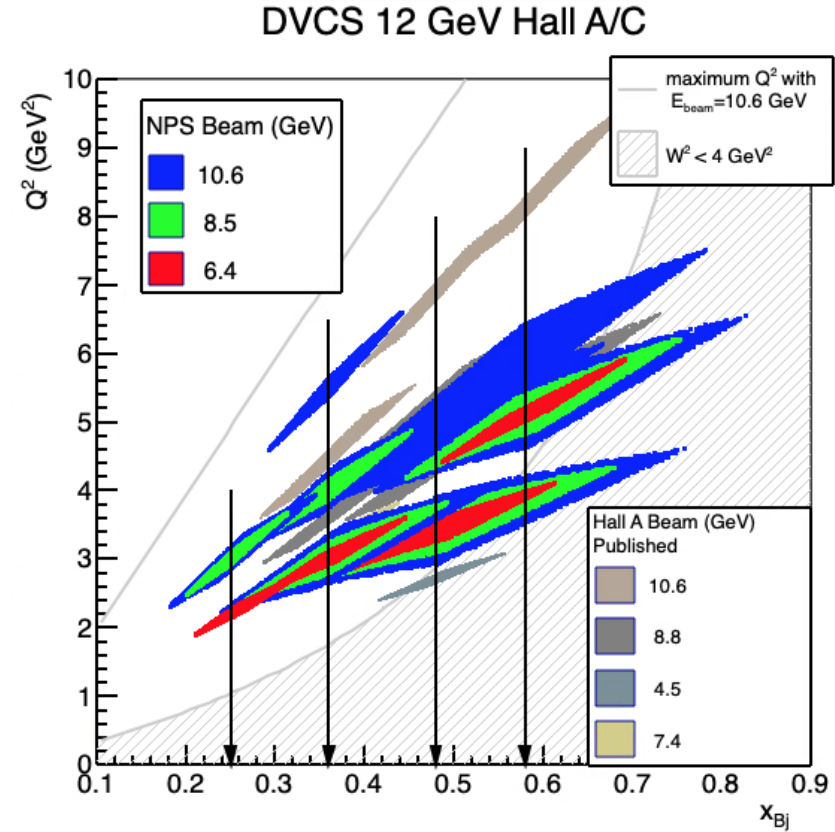
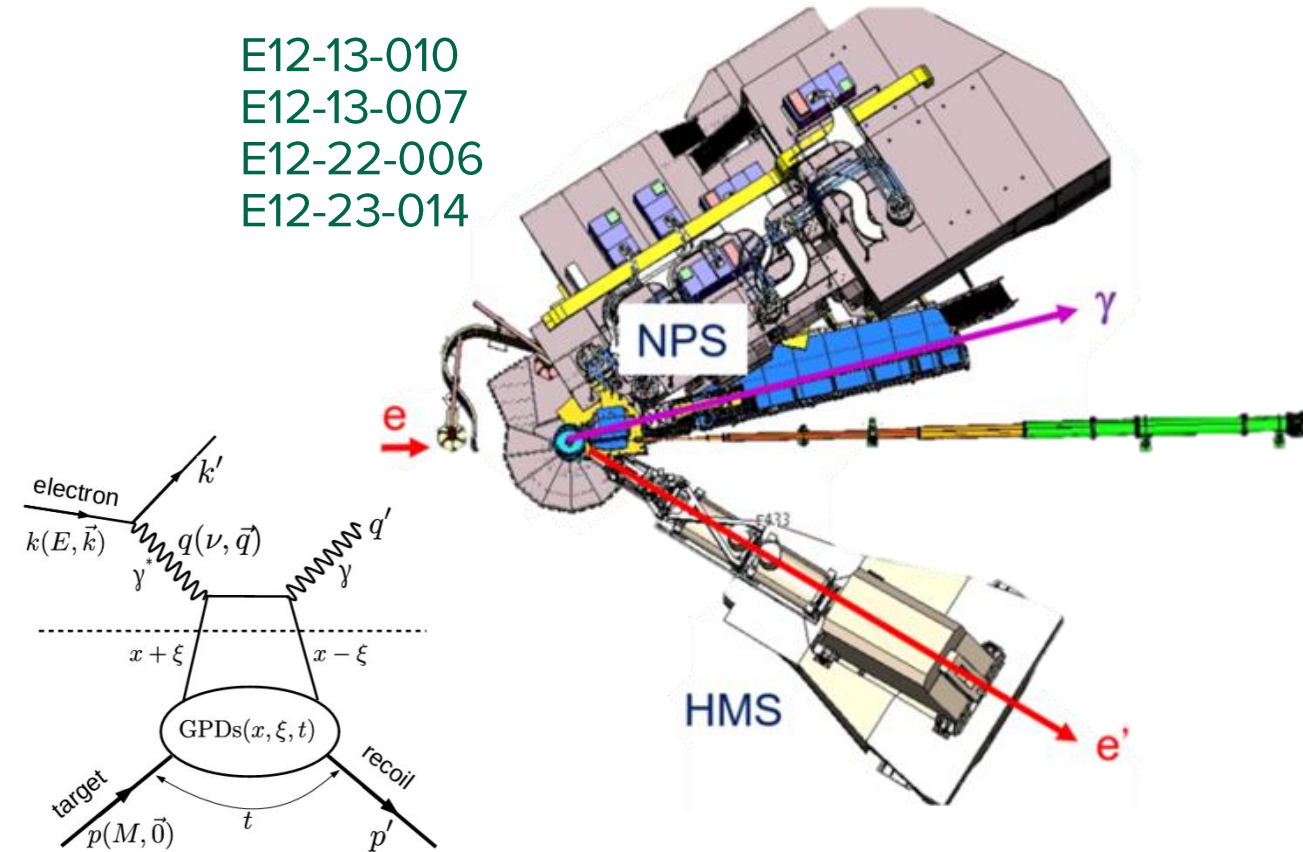


G. Xie *et al.*, Eur. Phys. J. C **83**, 900 (2023).

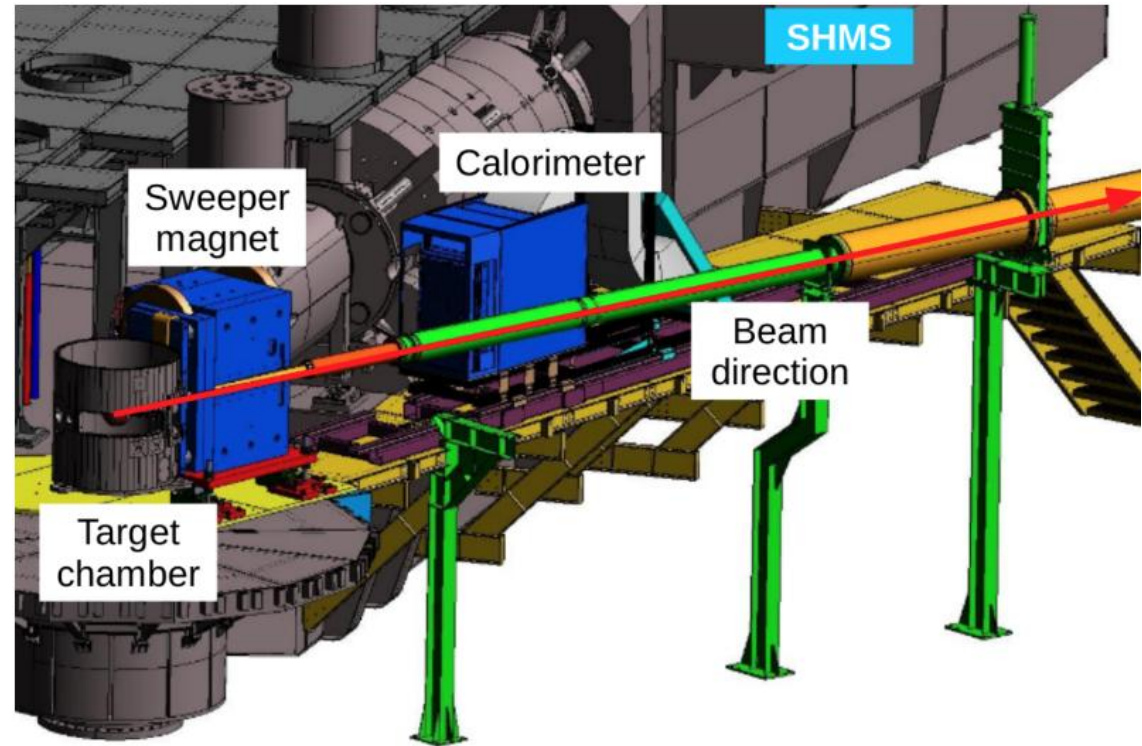
The Neutral Particle Spectrometer (NPS) Experiments

Run Group 1a – DVCS, exclusive and inclusive π^0 production

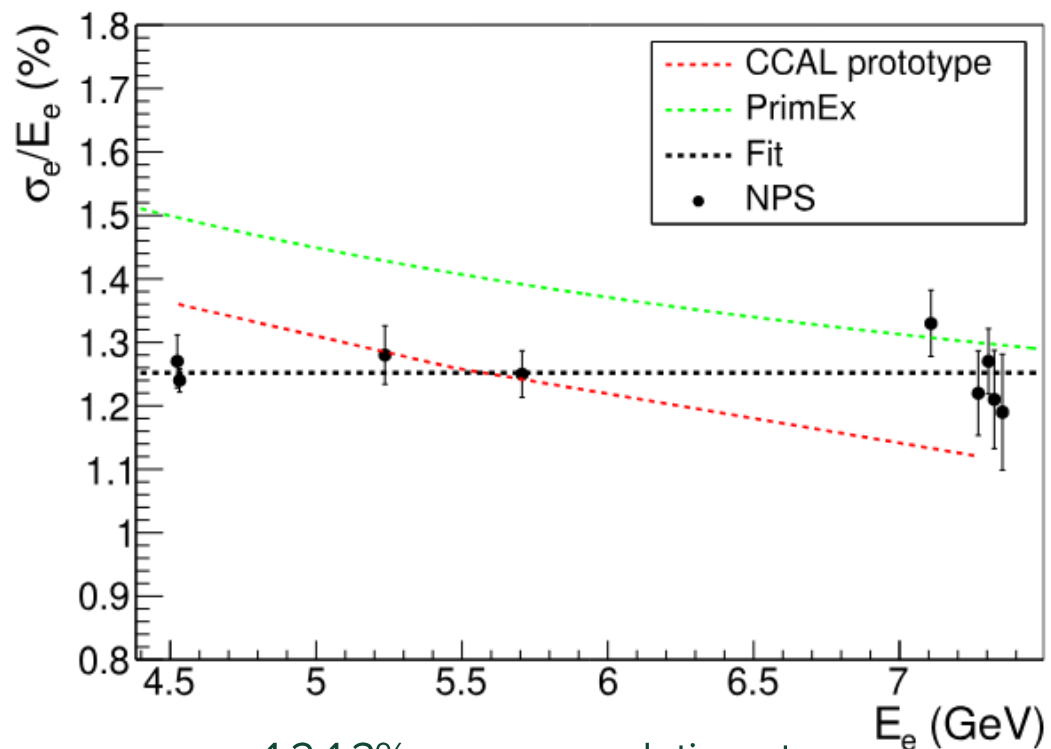
E12-13-010
E12-13-007
E12-22-006
E12-23-014



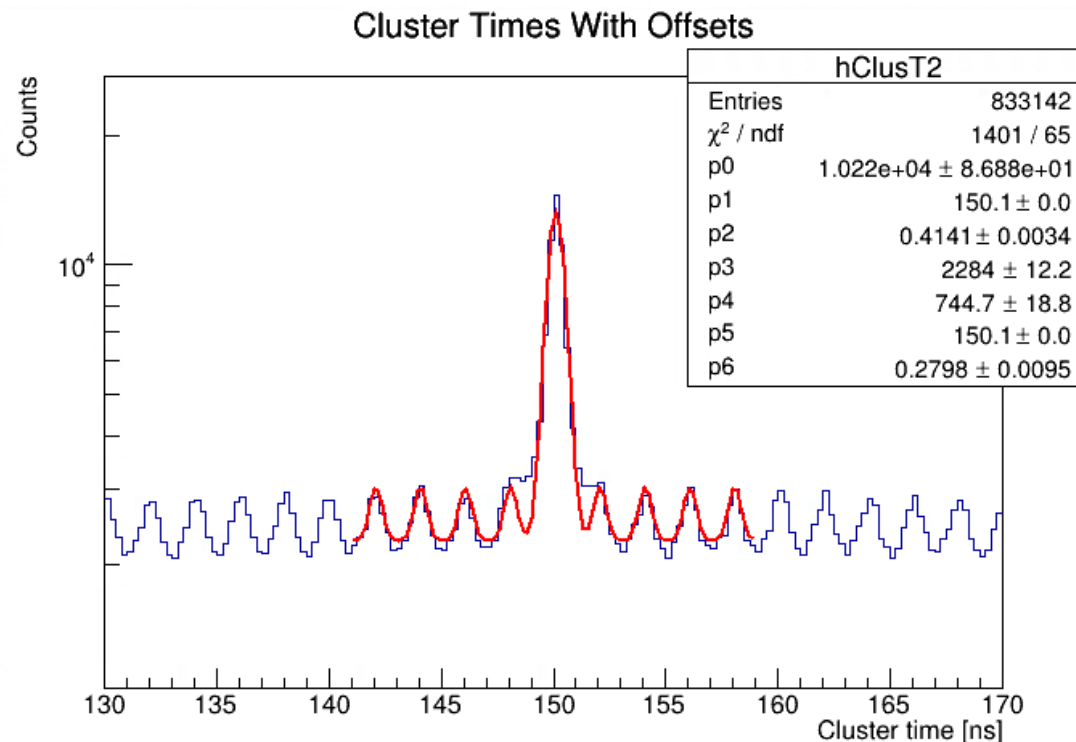
The Neutral Particle Spectrometer (NPS)



The NPS: a High-Resolution, High-Luminosity Calorimeter



1.2-1.3% energy resolution at
4.5-7.3GeV



<0.42ns time resolution
Blue – data; red – fit

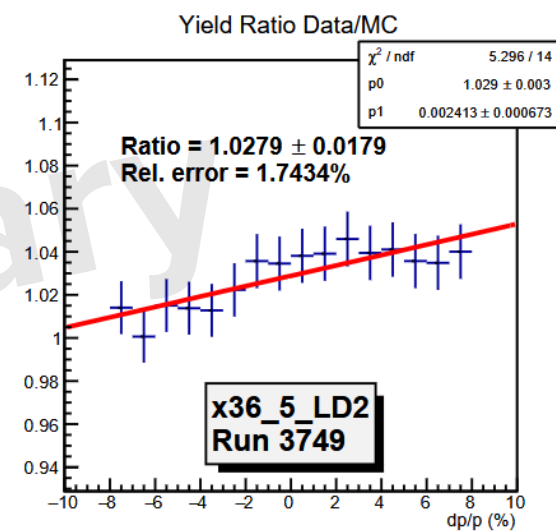
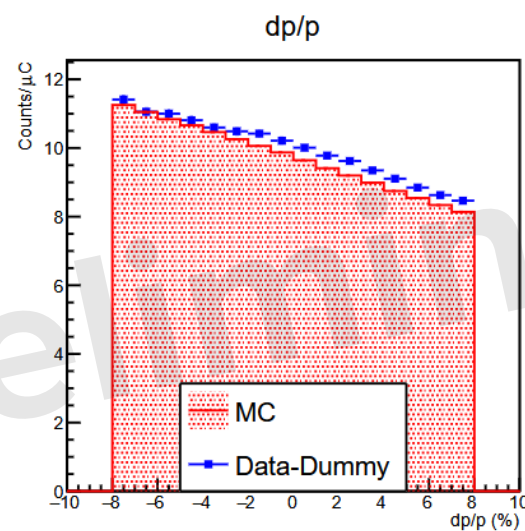
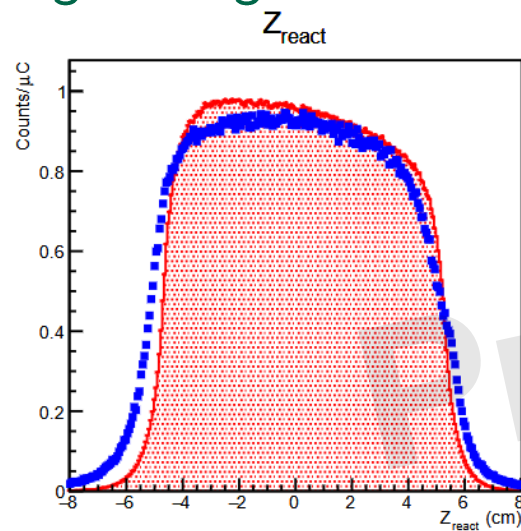
W. Hamdi *et al.*, NIM A **1086**, 171323 (2026).

Validating Luminosity and HMS Acceptance via Analysis of DIS Yield

- DIS cross section is well-known at our kinematics of interest
- Comparing the measured DIS cross section to MC simulation with cross section model serves to benchmark experimental setup and analysis w.r.t. HMS performance, luminosity
- LD2 target – good agreement

Deuterium
(1/21/24):
 $102.8 \pm 1.8\%$

(Systematic +
statistical
error bars)



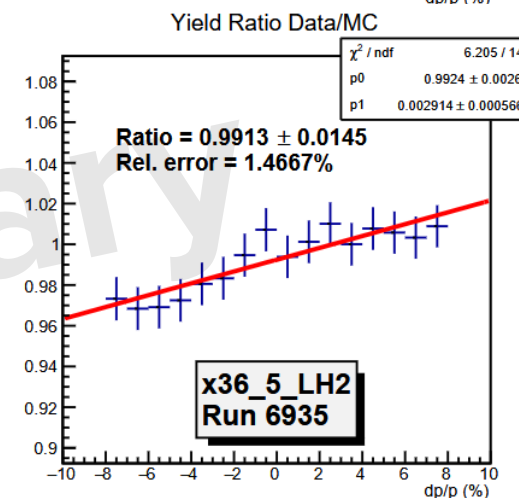
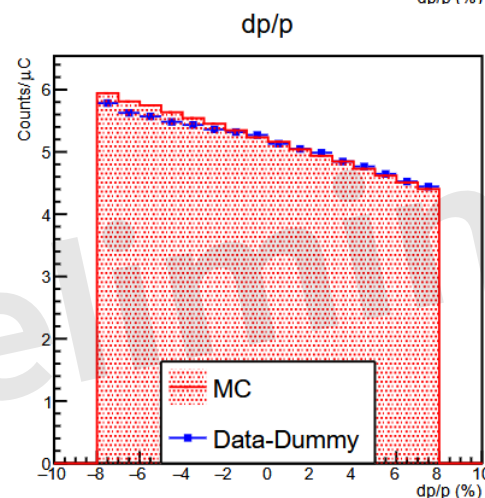
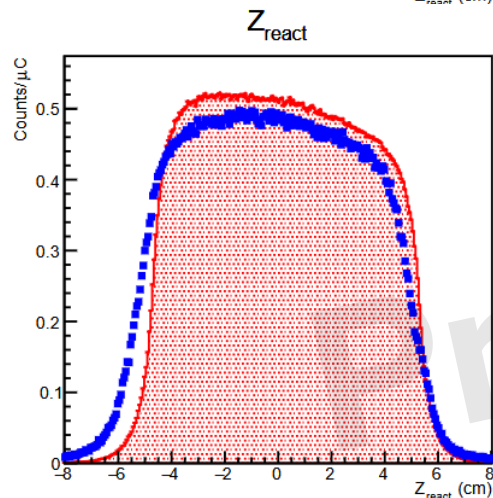
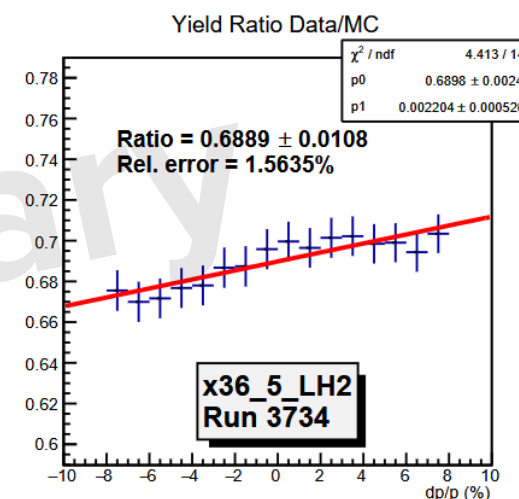
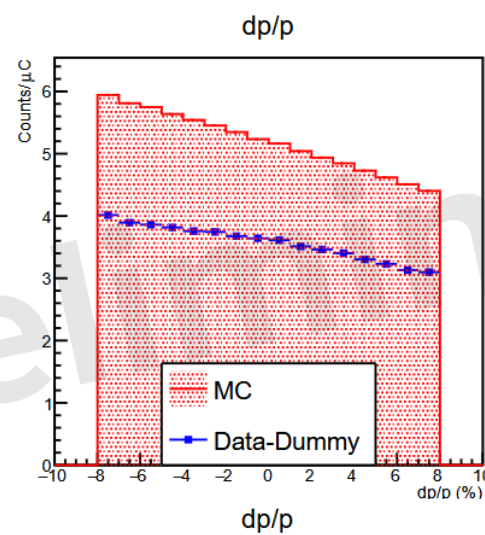
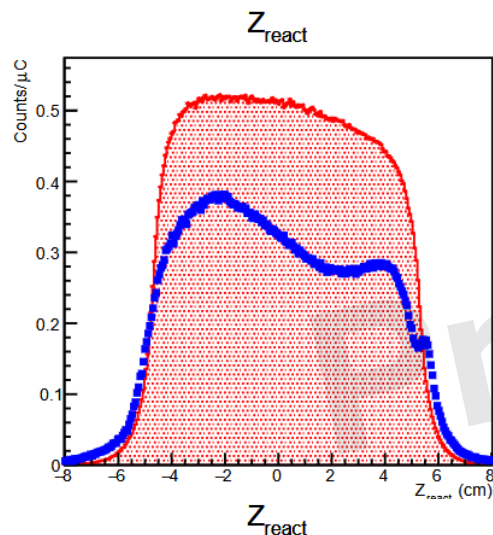
DIS Yield: Hydrogen Target

Hydrogen
(1/20/24):
 $68.9 \pm 1.1\%$

Adjust fan
speed, increase
pressure, new
target cell

Hydrogen
(5/16/24):
 $99.1 \pm 1.5\%$

(Sys. + stat.
errors)



DIS Yield: Conclusions

- Helium contamination in hydrogen target
- Comparison of DIS yield to simulation over course of experiment allows extraction of target density correction factor as function of time to be used in exclusive channel analysis
- Good agreement of LD2 data and LH2 data after improving target conditions with simulation points towards reliability of correction

DVCS Analysis Procedure

On behalf of Hao Huang

Kinematics: $\langle Q^2 \rangle = 4 \text{ GeV}^2$, $\langle x_{Bj} \rangle = 0.36$, $E_{\text{beam}} = 10.54 \text{ GeV}$

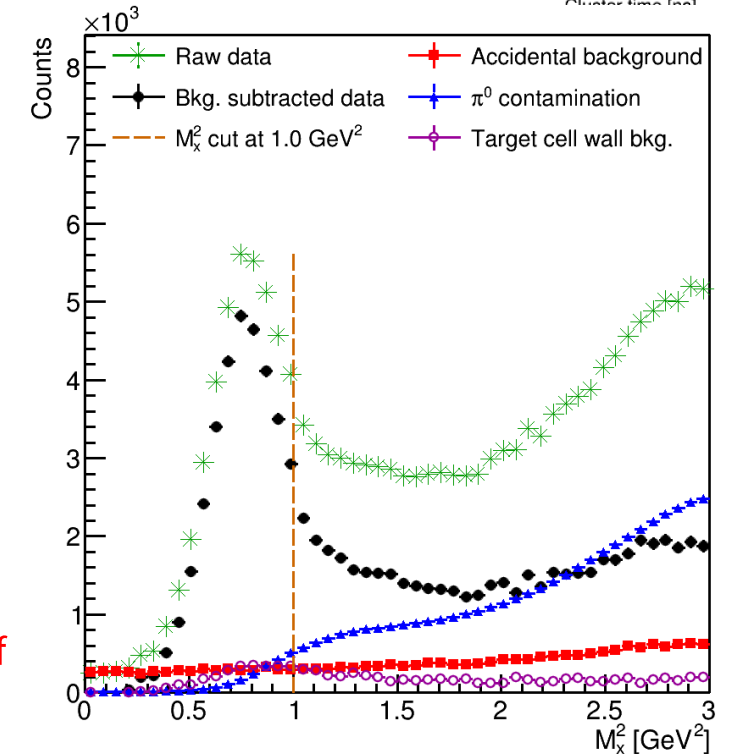
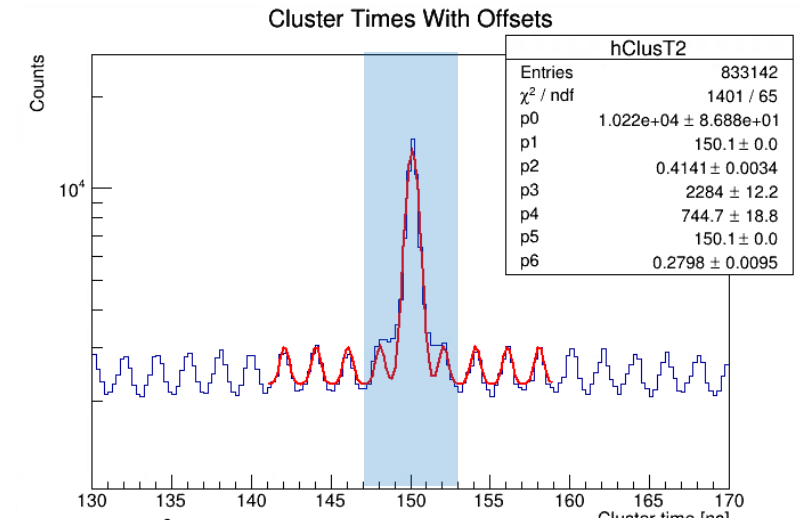
1. Select electrons in standard HMS acceptance
2. Select events with only 1 photon detected in NPS
 - a. Apply coincidence time cut $[-3, +3] \text{ ns}$.
 - b. Reconstruct DVCS photons from multiple NPS calorimeter blocks
3. Apply missing mass cut of recoil proton (undetected)

$$M_x^2 = (k_e + p_P - k'_e - q_\gamma)^2 < 1.0 \text{ GeV}^2$$

Subtracting backgrounds from:

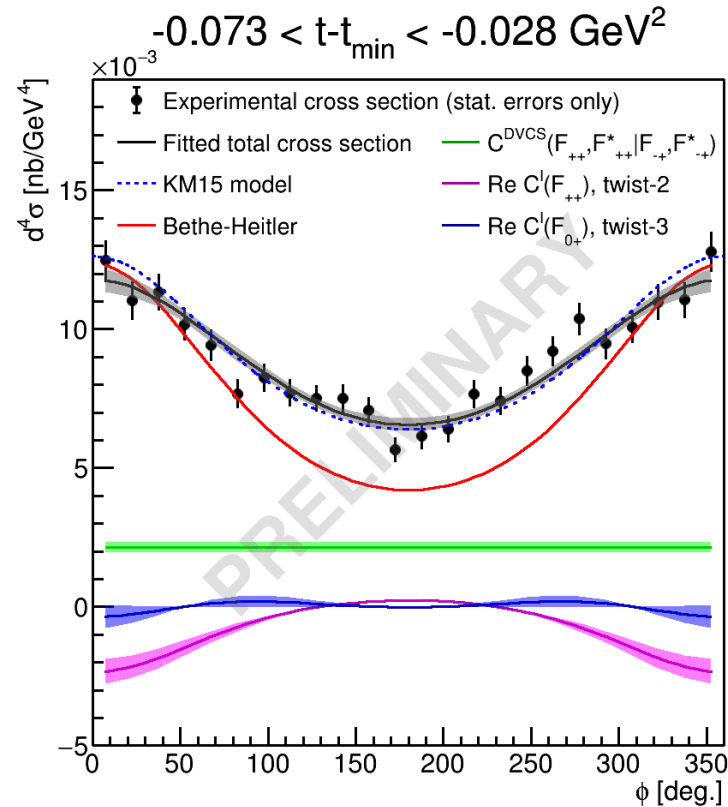
- a. Accidental events
 - b. π^0 contamination
 - c. Aluminum target cell wall
 - d. SIDIS background
4. Unfolding procedure
 5. Fit CFF combinations to data

Plot courtesy of
H. Huang



Preliminary cross sections (helicity independent)

- Proton data, statistical errors only
- Systematic uncertainties are under evaluation
- Good agreement with the KM15 model (parametrization of CFFs fitted to previous DVCS data) and prior Hall A results

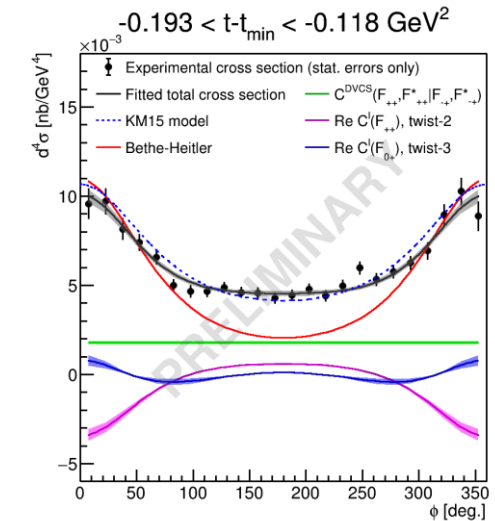
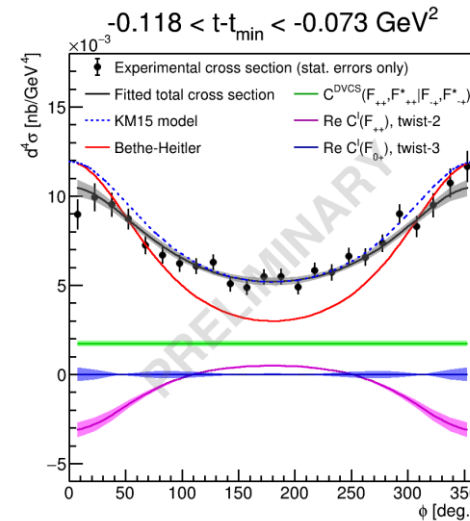
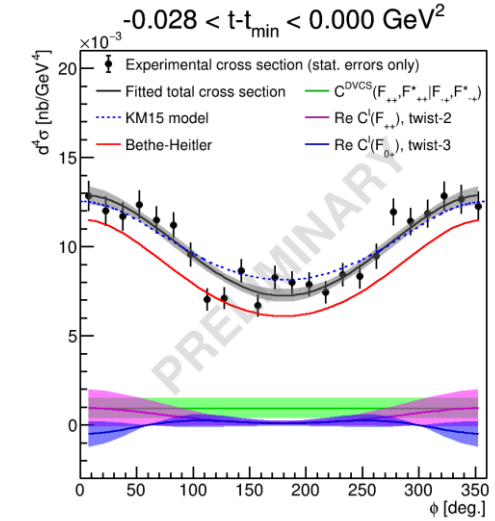


$$\langle Q^2 \rangle = 4 \text{ GeV}^2,$$

$$\langle x_{\text{Bj}} \rangle = 0.36,$$

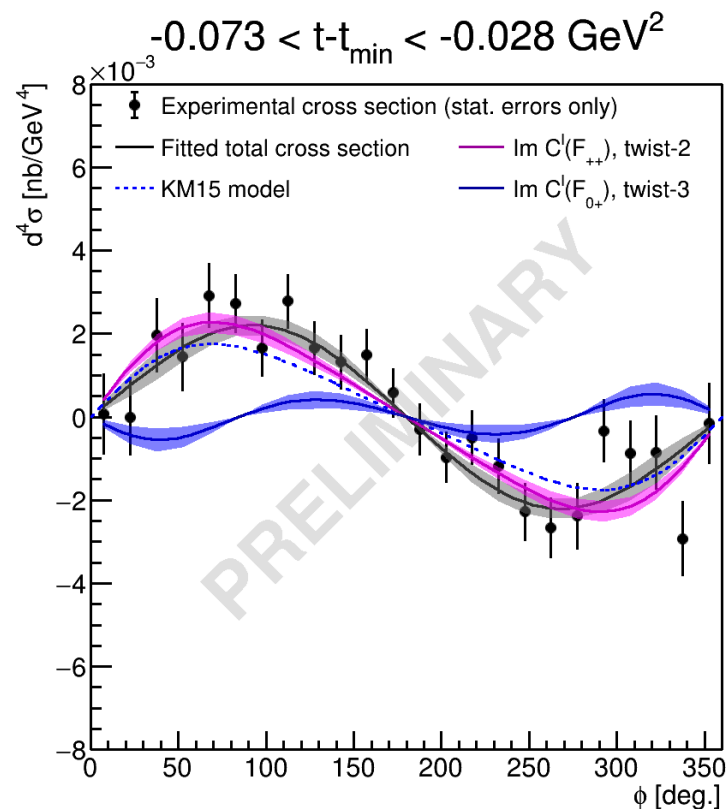
$$E_{\text{beam}} = 10.54 \text{ GeV}$$

Plots courtesy of
H. Huang



Preliminary cross sections (helicity dependent)

- Proton data, statistical errors only
- Systematic uncertainties are under evaluation
- Good agreement with the KM15 model (parametrization of CFFs fitted to previous DVCS data) and prior Hall A results

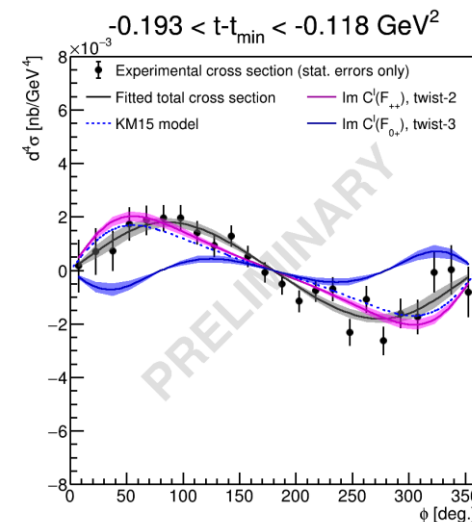
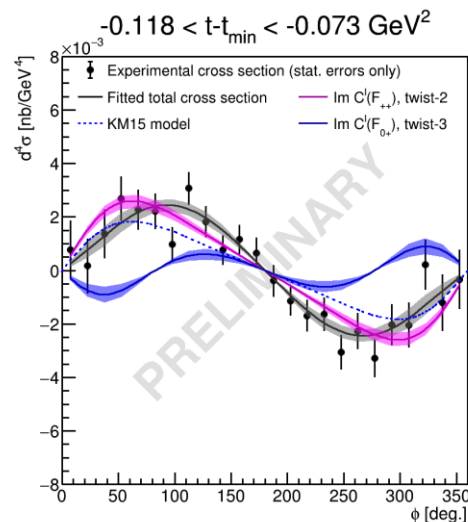
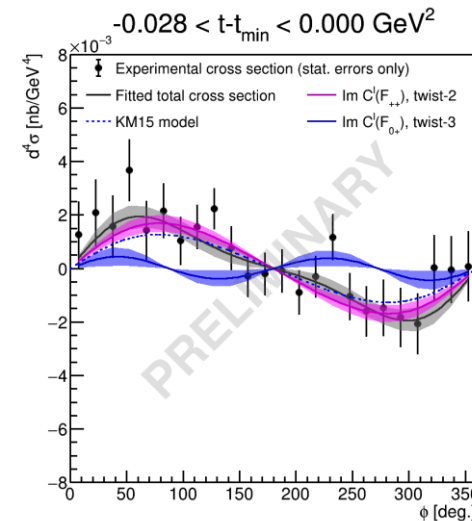


$$\langle Q^2 \rangle = 4 \text{ GeV}^2,$$

$$\langle x_{\text{Bj}} \rangle = 0.36,$$

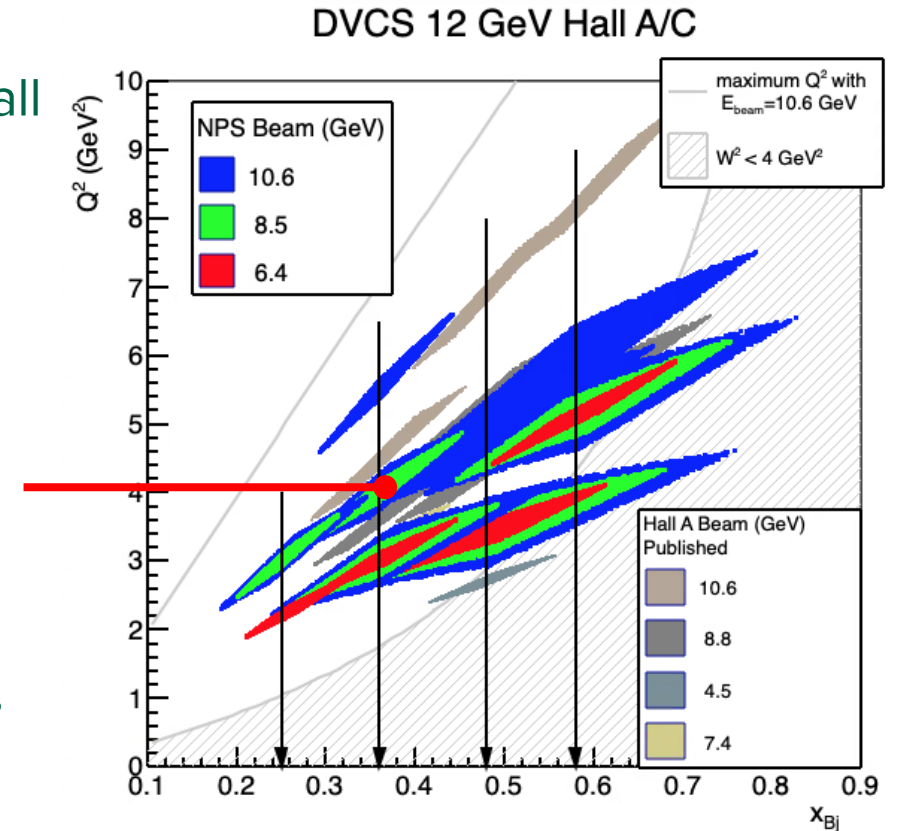
$$E_{\text{beam}} = 10.54 \text{ GeV}$$

Plots courtesy of
H. Huang



Summary and Outlook

- The NPS Run Group 1a experiments in Jefferson Lab's Hall C aim to precisely measure DVCS cross sections, the cleanest probe of GPDs
- Several beam energies at the same (x_B, Q^2) points allow separation of DVCS and interference terms. Kinematics extend those of prior Hall A DVCS experiments
- Preliminary DVCS cross section measurements on first analyzed kinematic are compatible with KM15 model and prior Hall A results
- Future work: quantifying systematics on DVCS cross sections, continuing analysis on other kinematic settings, LD2 data for neutron DVCS
- π^0 analysis channels as well! (See Avnish's talk)

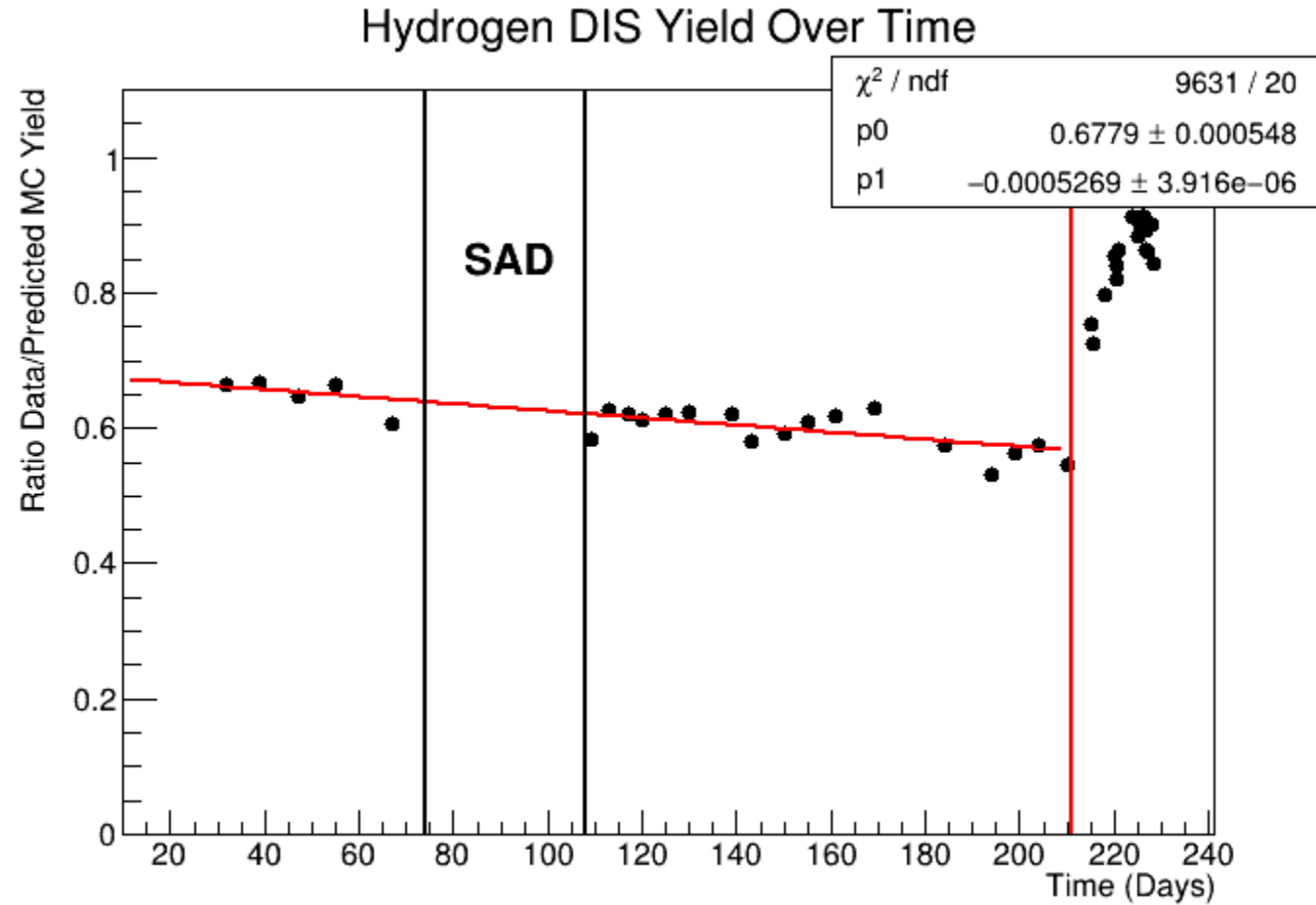


Thank you for your time and attention!

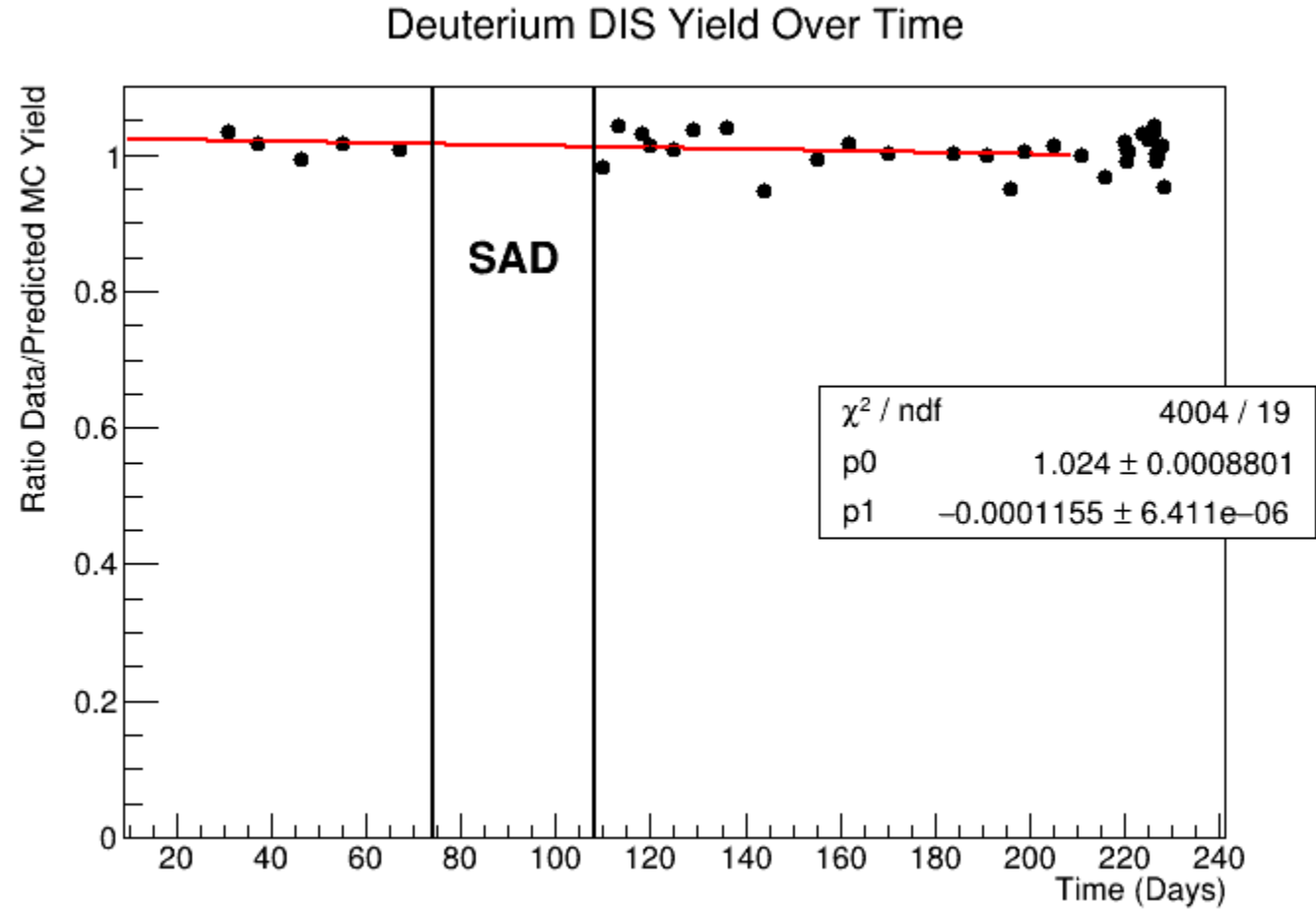


Backup slides

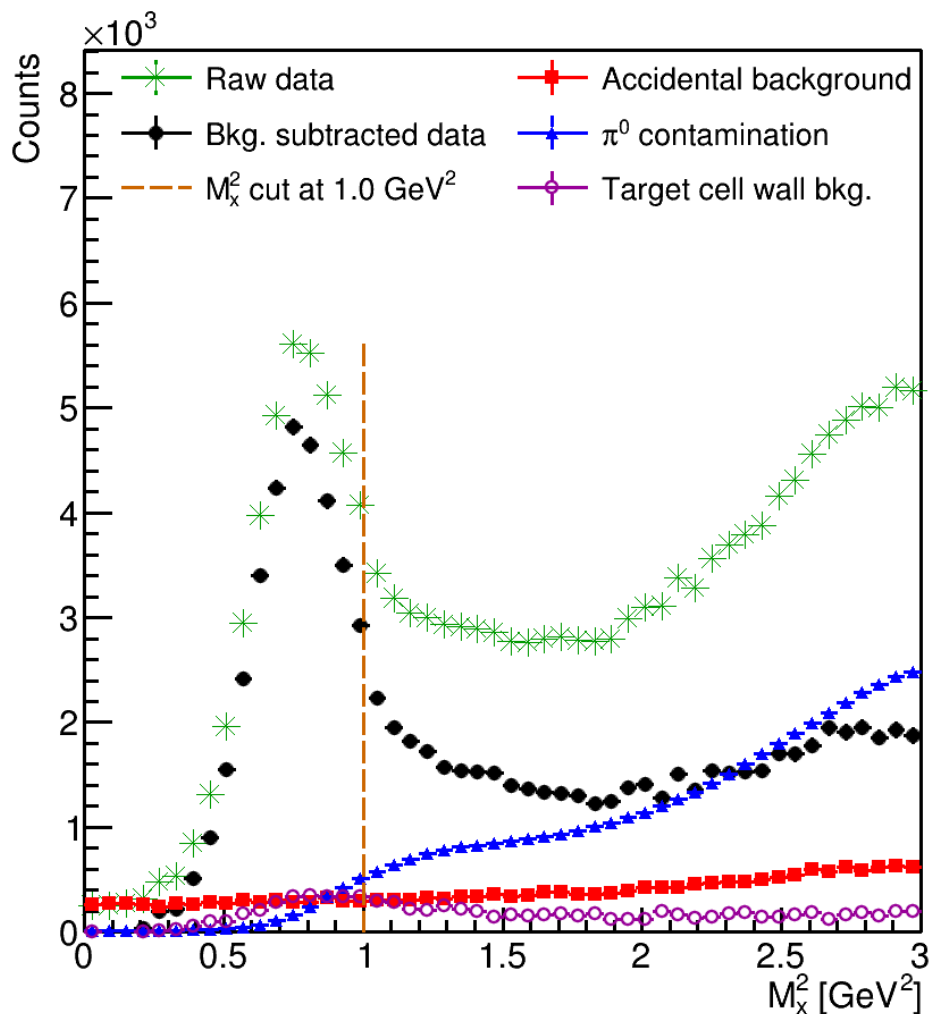
DIS Yield: Hydrogen Target



DIS Yield: Deuterium Target



➤ Missing mass square $M_x^2 = (k_e + p_P - k'_e - q_\gamma)^2$ of recoil proton (undetected)



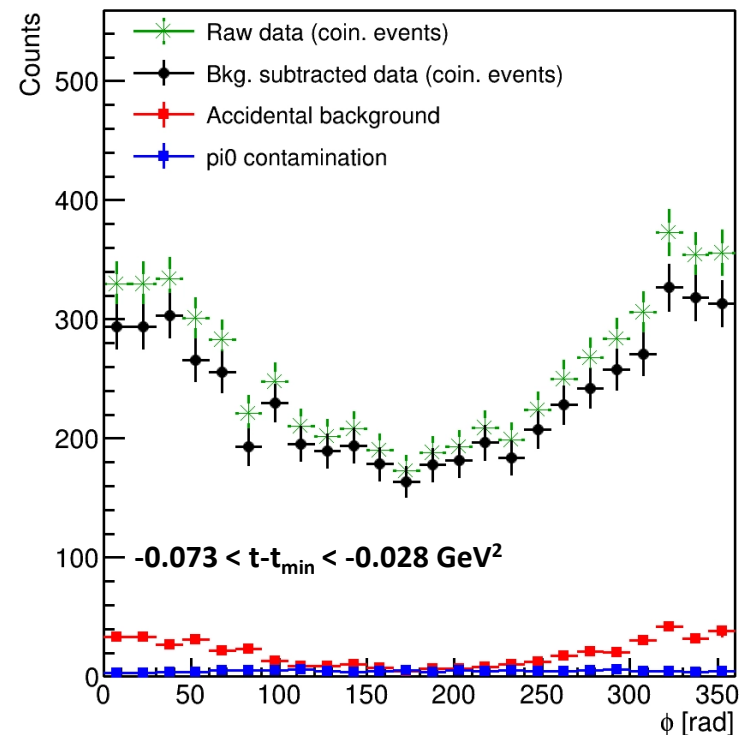
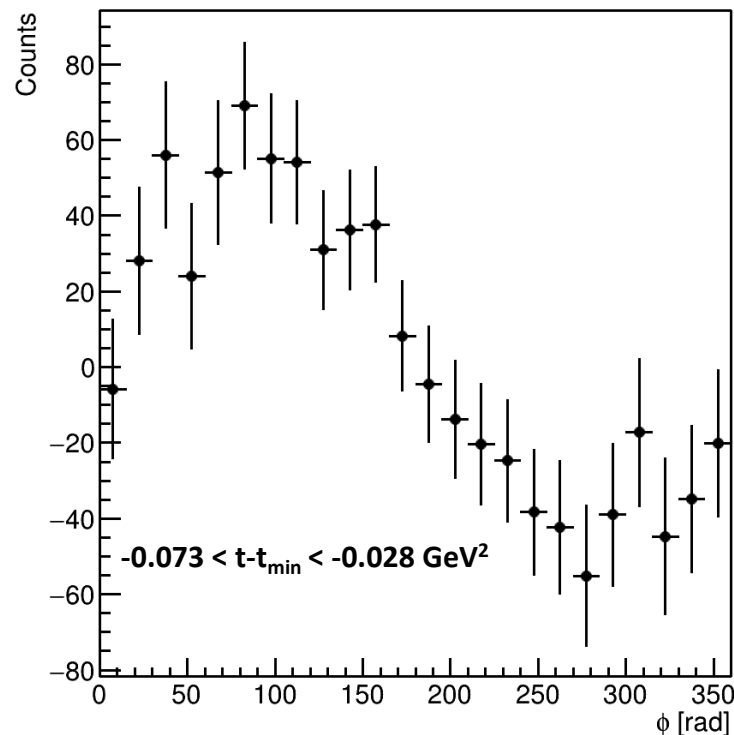
Raw M_x^2

- Events with only 1 photon detected in NPS
- Photon timing in $[-3, 3]$ (ns) compared to the timing of electron

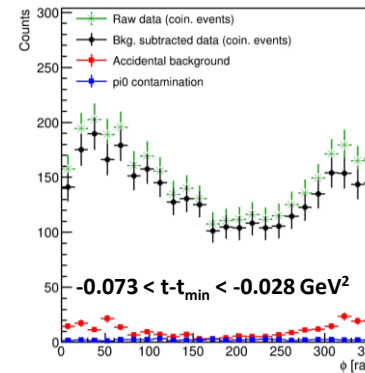
Background subtraction

1. Accidental background: γ and e' from different events
2. π^0 contamination: photons from $\pi^0 \rightarrow \gamma\gamma$ asymmetric decay
3. Target cell wall contribution: estimated using Al. foil (dummy) target
4. SIDIS background
 - Lowest M_x^2 : $ep \rightarrow e'\gamma p'\pi^0 \sim 1.15 \text{ GeV}^2$
 - Remove by a cut on missing mass
 - Correction using simulation data

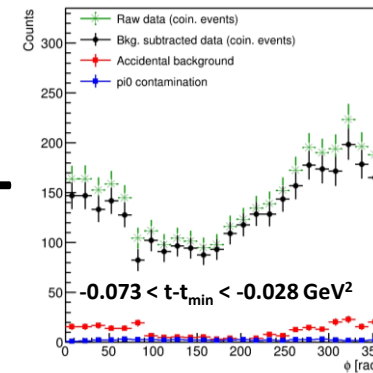
- Kinematics: $\langle Q^2 \rangle = 4 \text{ GeV}^2$, $\langle x_{Bj} \rangle = 0.36$, $E_{\text{beam}} = 10.54 \text{ GeV}$
- 5 bins of $t-t_{\text{min}}$ between 0 and -0.35 GeV^2 (M_x^2 cut: 0 to 1 GeV^2)
- Background subtracted & detector efficiency corrected (tracking, electron PID)

Helicity **independent** distributionHelicity **dependent** distribution

Positive helicity



Negative helicity



- The cross section is the summation of **CFF combinations** multiplied by **kinematics pre-factors**

$$\frac{d^4\sigma^{\rightarrow} \pm d^4\sigma^{\leftarrow}}{2} = \sum_{n=1}^N \Gamma^n(x) F^n(\text{CFFs})$$

- F^n (CFFs): the n^{th} CFF combination
- $\Gamma^n(x)$: the corresponding pre-factor
- x : kinematic point ($Q^2, x_{\text{Bj}}, t, \phi$)

- In a vertex bin v , the number of events N_v can be calculated:

$$N_v = \mathcal{L}_{\text{int}} \int_{x_v \in \text{bin}(v)} \left[\sum_{n=1}^N \Gamma^n(x_v) F_v^n \right] dx_v$$

- N_v cannot be measured directly, but in the generated level of the simulation

- In a reconstructed bin r , the number of events N_r is

$$N_r = \sum_{v=1}^V N_v K(x_r | x_v)$$

- $K(x_r | x_v)$: migration matrix, taking care of bin migration and detector acceptance
- N_r can be measured experimentally, and also in the reconstructed level of the simulation

- Minimizing $\chi^2(\langle F^n \rangle_v) = \sum_{i=1}^R \frac{(N_r^{\text{exp}} - N_r^{\text{sim}})^2}{(\sigma_r^{\text{exp}})^2}$ to extract $\langle F^n \rangle_v$
- N_r^{sim} : number of simulated events
 - N_r^{exp} : experimental data
 - σ_r^{exp} : experimental uncertainty (statistics)

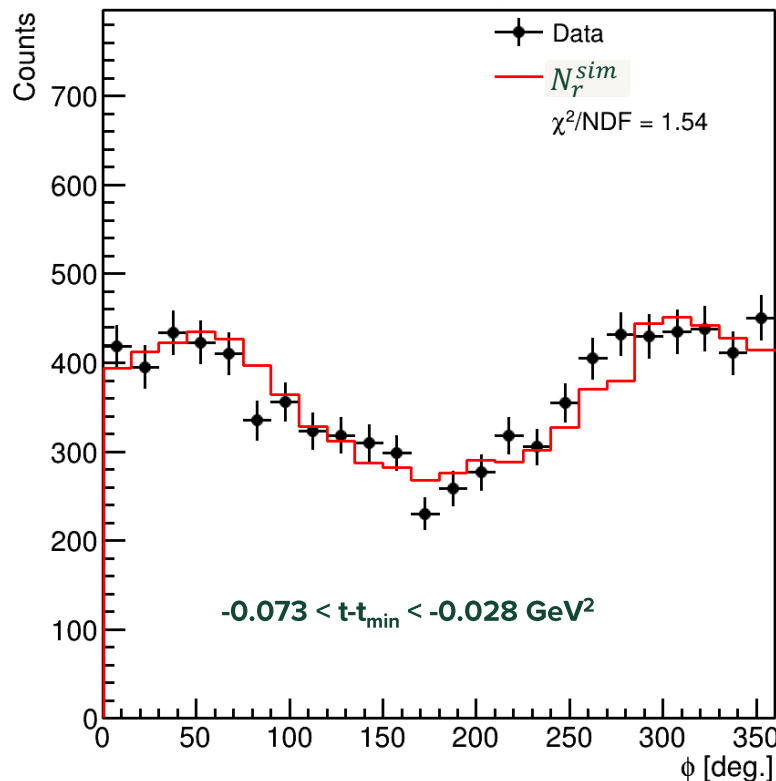
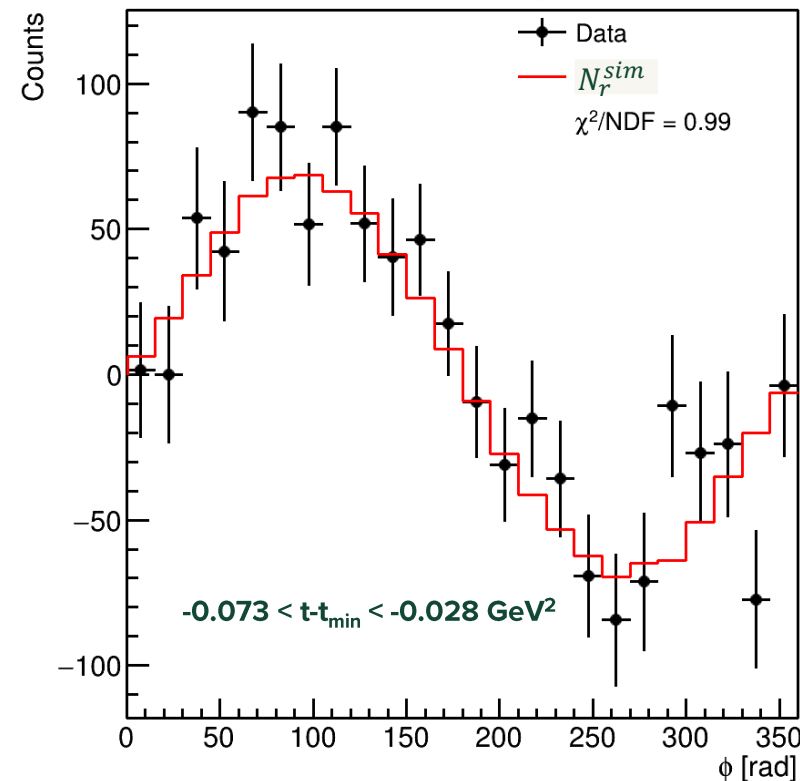
Fitted CFF combinations:

➤ Helicity independent

- twist-2 DVCS term
+ twist-2 Re{interference}
+ twist-3 Re{interference}

➤ Helicity dependent

- twist-2 Im{interference}
+ twist-3 Im{interference}

Fitted result (helicity **independent**)Fitted result (helicity **dependent**)

$$\frac{d^4\sigma_r^{exp}}{dQ^2 dx_{Bj} dt d\phi} = \frac{N_r^{exp}}{N_r^{sim}} \underbrace{\frac{d^4\sigma_r^{fit}}{dQ^2 dx_{Bj} dt d\phi}}_{\text{total fitted cross section, calculated using fitted } \langle F^n \rangle_v}$$