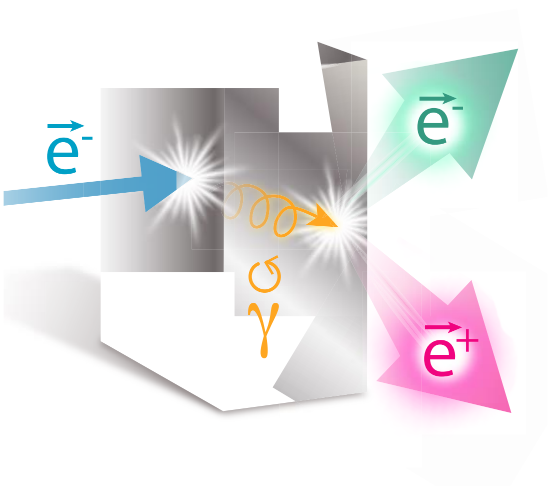
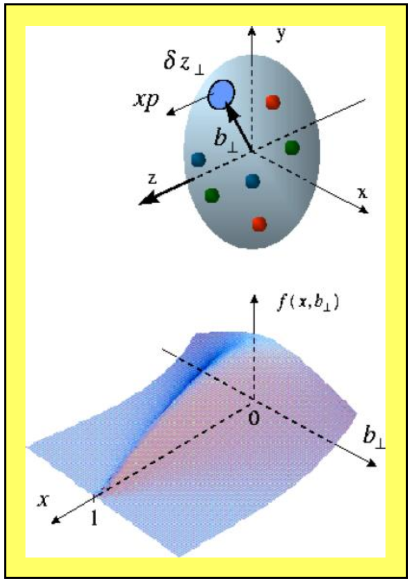
PR12+23-006: Positron DVCS experiment in Hall C using the Neutral Particle Spectrometer (NPS)

Positron WG Workshop

JLab, March 24-26 (2025)



Carlos Muñoz Camacho
IJCLab – CNRS/IN2P3



Introduction

- Two proposals using a positron beam were submitted to PAC48 (2020)
- One experiment proposed to use CLAS12 (Hall B) with a *low current* (≈45 nA) **polarized** beam
- One experiment proposed to use NPS (Hall C) with a *high current* (≈ 5 μA) **unpolarized** beam

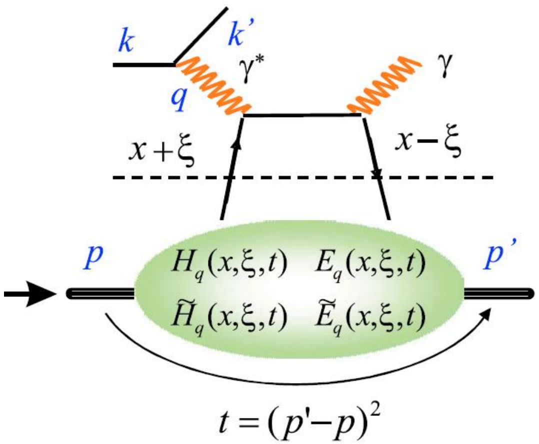
PAC 48 SUMMARY OF RECOMMENDATIONS								
PR12-20-009	E. Voutier	Beam charge asymmetries for Deeply Virtual Compton Scattering on the proton at CLAS12	B	100			C2	4
PR12-20-012	C. Munoz Camacho	Deeply Virtual Compton Scattering using a positron beam in Hall C	C	77			C2	4

- Proposals resubmitted to PAC50 (2023) for scientific grading

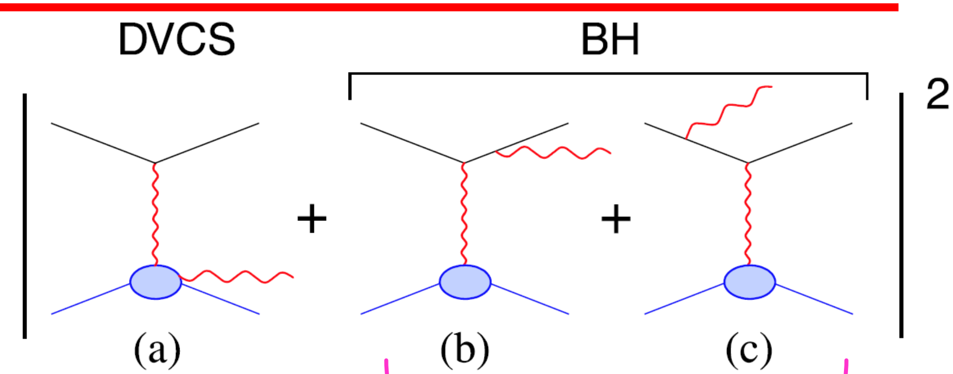
PAC51 Results and Recommendations

PR12+23-006	Carlos Munoz Camacho	Deeply Virtual Compton Scattering using a positron beam in Hall C	C	137	137	A-	C1	4
PR12+23-002	Eric Voutier	Beam Charge Asymmetries for Deeply Virtual Compton Scattering on the Proton at CLAS12	B	100	100	A-	C1	4

Motivation



ep ⟶ epγ =



Calculable in QED with our ~1% knowledge of form factors at low momentum transfer

At leading twist:

$$d^5 \overset{\rightarrow}{\sigma} - d^5 \overset{\leftarrow}{\sigma} = \Im m\,(T^{BH} \cdot T^{DVCS})$$
$$d^5 \overset{\rightarrow}{\sigma} + d^5 \overset{\leftarrow}{\sigma} = |BH|^2 + \Re e\,(T^{BH} \cdot T^{DVCS}) + |DVCS|^2$$

$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

Opposite sign for e- & e+

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

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

DVCS with positrons in Hall C

$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

Opposite sign for e- & e+

Physics goals and motivation:

- ✓ Precise determination of the absolute photon electro-production cross section
- ✓ Clean, model-independent separation of $DVCS^2$ and DVCS-BH interference
- ✓ More stringer constraints on CFFs by combining e^- & e^+ data

In a nutshell:

- Same experimental configuration as approved experiment E12-13-010
- Expected positron beam momentum spread comparable with current electron beam
- Positron beam size larger than current electron beam (twice bigger at 11 GeV according to current simulation)
- No additional systematic uncertainties expected due to the use of positrons

PAC51 report

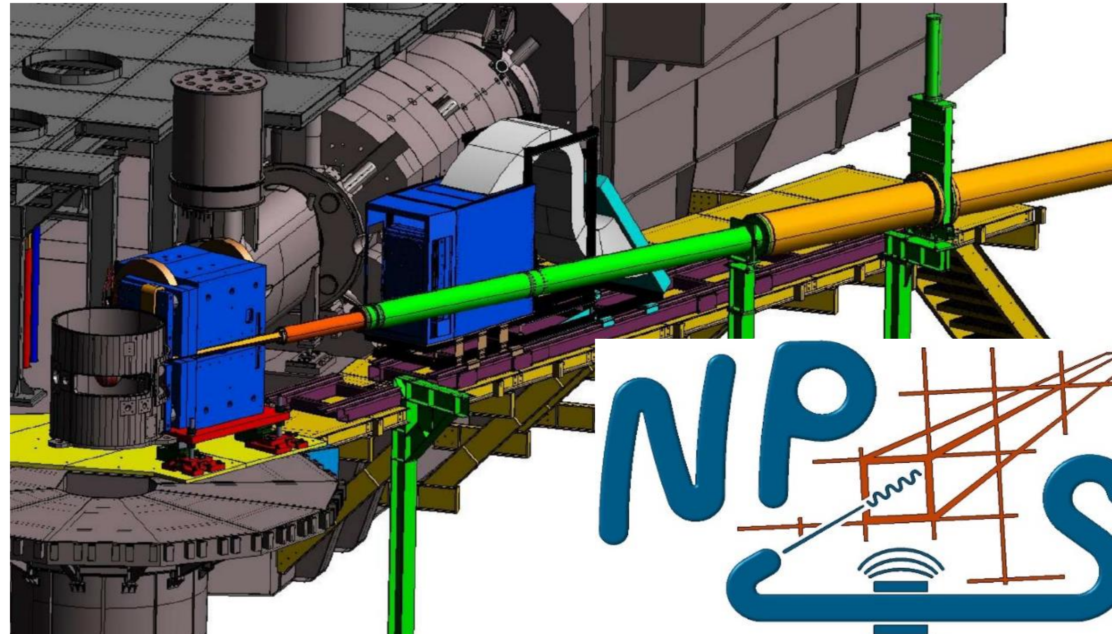
The proponents request 135 days of unpolarized positron beam with a current of 1 μA, plus 2 days of overhead. At the moment when the experiment could run, the experimental setup will have been used in several other experiments and should therefore very well understood. Therefore, there are no concerns about the experimental setup, and the committee is confident that the described measurements can be performed.

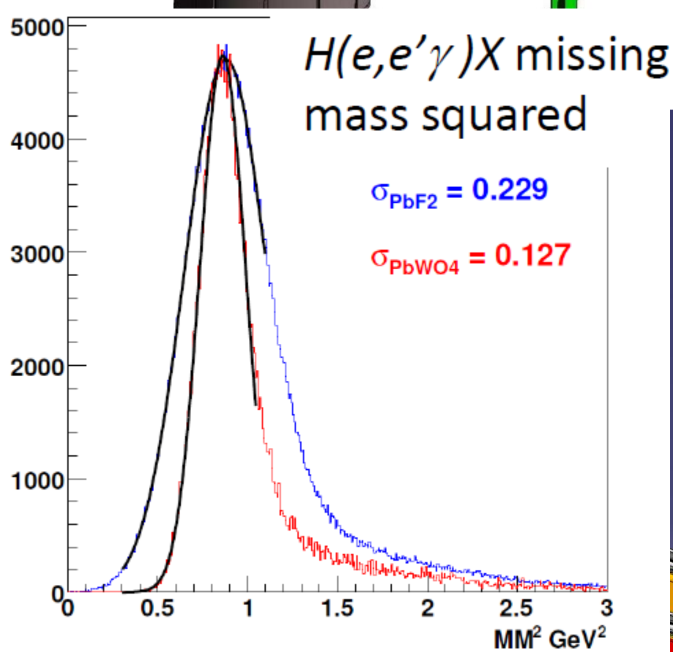
Issues: The committee finds that all issues raised in the PAC48 report on C12-20-012 have been addressed. In particular, the proponents have presented an impact study, and the positron beam required is within the specifications of the positron working group provided to the present PAC.

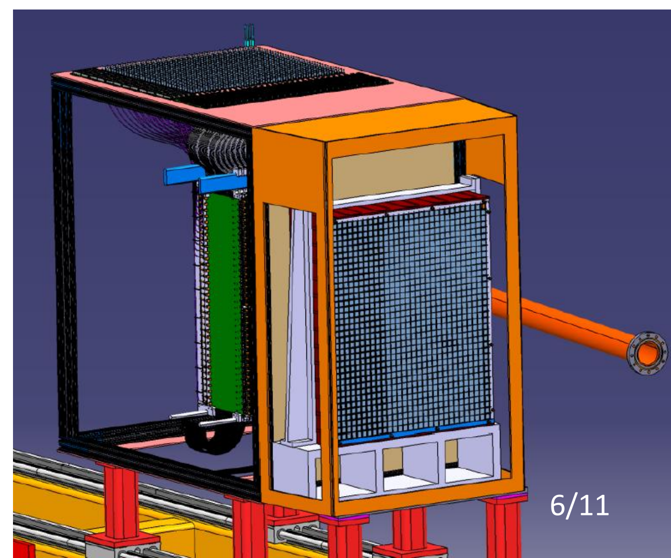
Summary: The PAC recognizes the strong science case of this proposal in constraining the GPDs. It recommends conditional approval (C1) of the requested 137 PAC days. A C1 review by the Lab should be conducted at an appropriate time and verify that positron beams will be available with the parameters required for the experiment.

Hall C positron experiment using NPS

- 1080 $PbWO_4$ crystals
- 0.6 Tm sweeping magnet
- F250ADC sampling electronics
- Large opening angle beam pipe
- SHMS as carriage for rotation



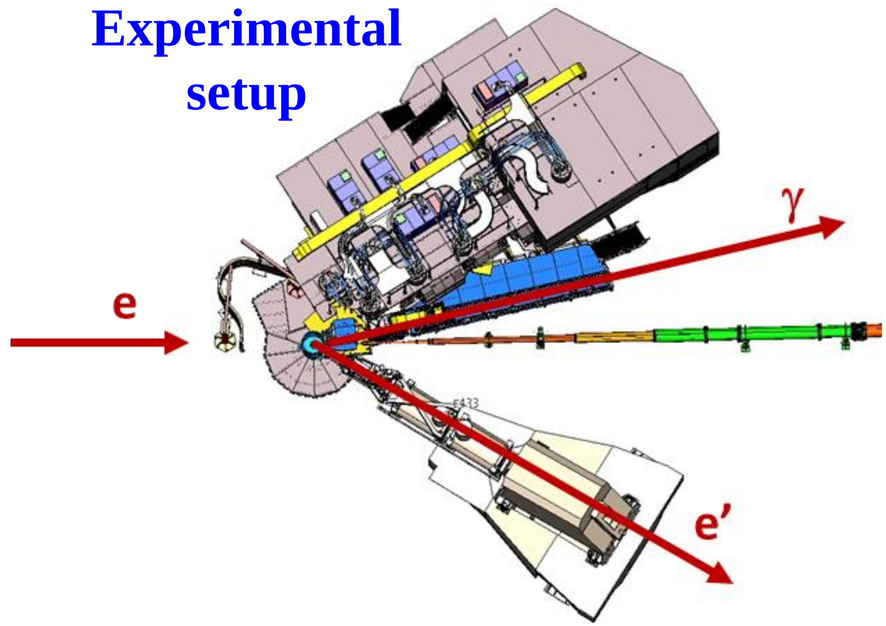


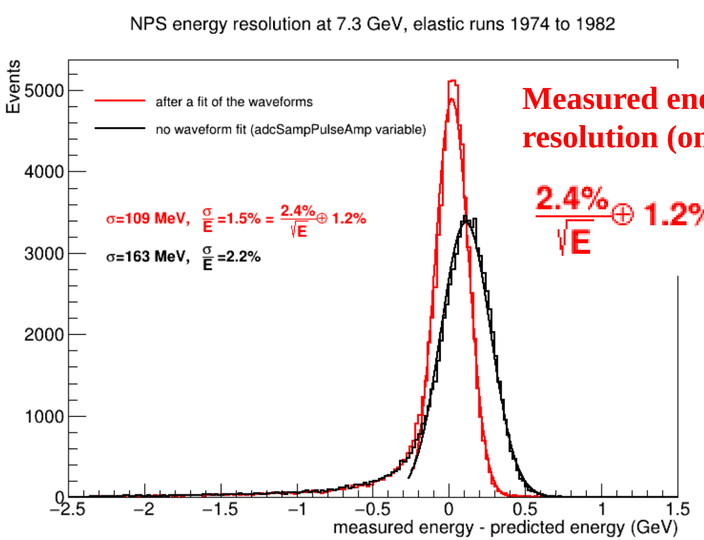


Hall C *electron* experiment using NPS

- Experiment **recently completed**:
  Sep 15 (2023) – May 20 (2024)
- LH2 and LD2 targets
- Energy separation of the DVCS cross section
- Low-x_B coverage

Experimental setup

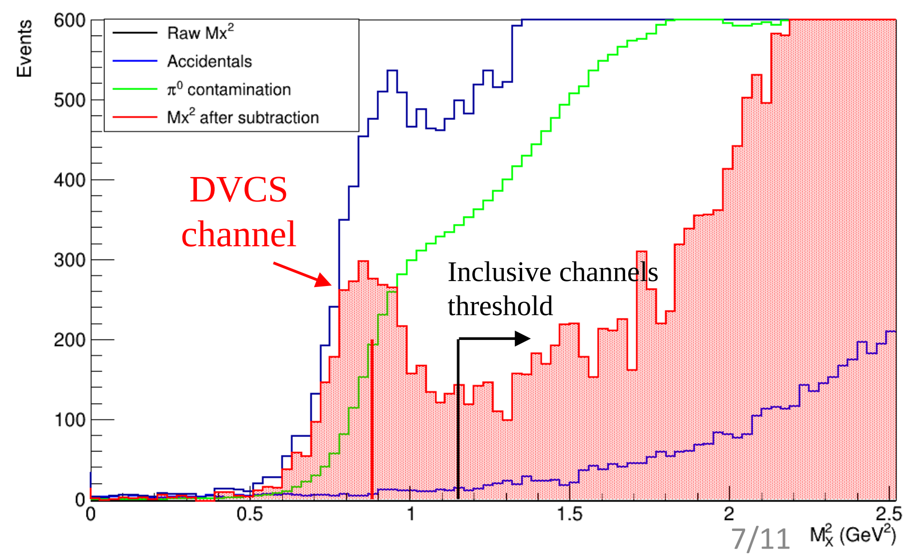




Measured energy resolution (online):

$$\frac{2.4\%}{\sqrt{E}} \oplus 1.2\%$$

DVCS missing mass squared

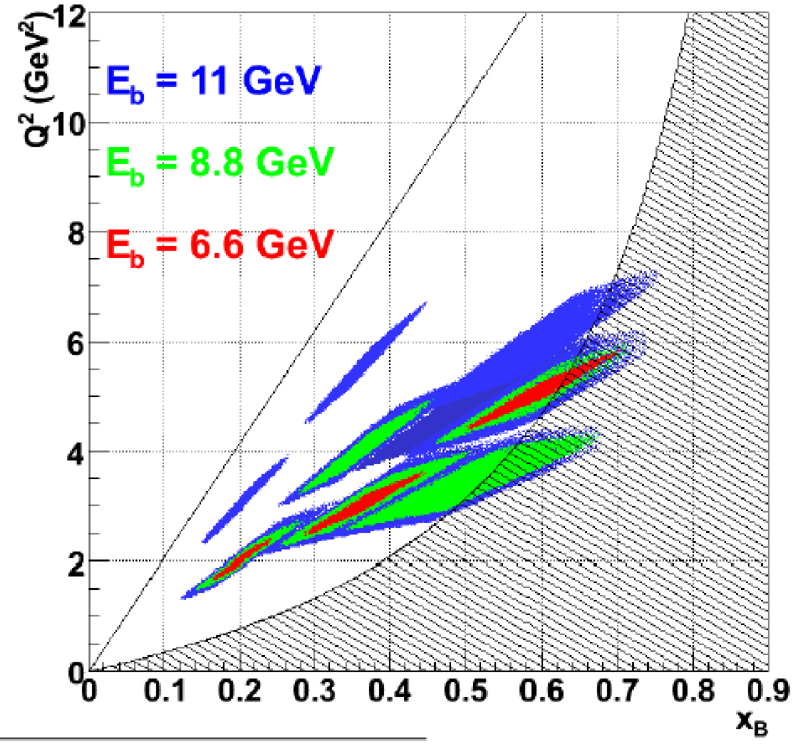


PR12+23-006: Kinematic & beam time request

Same kinematics settings as approved E12—13-010 with electrons

135 days, 1 μA of (unpolarized) positrons assumed

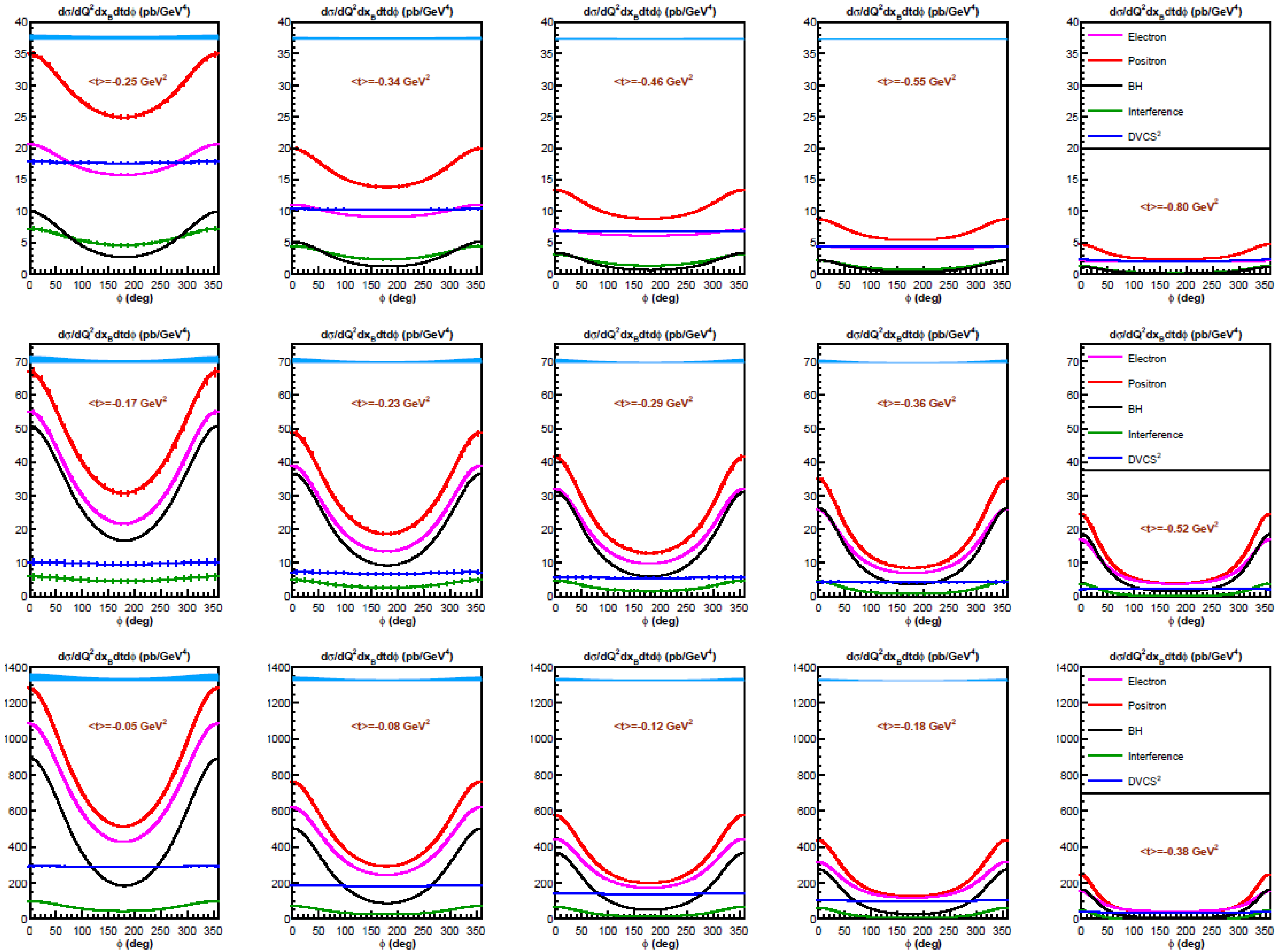
Positron data: 25% of statistics of electron data



x_{Bj}	0.2				0.36						0.5			0.6			
Q^2 (GeV)^2	2.0			3.0	3.0			4.0		5.5	3.4		4.8	5.1			6.0
E_b (GeV)	6.6	8.8	11		6.6	8.8	11	8.8	11		8.8	11		6.6	8.8	11	
k' (GeV)	1.3	3.5	5.7	3.0	2.2	4.4	6.6	2.9	5.1	2.9	5.2	7.4	5.9	2.1	4.3	6.5	5.7
θ_{Calo} (deg)	6.3	9.2	10.6	6.3	11.7	14.7	16.2	10.3	12.4	7.9	20.2	21.7	16.6	13.8	17.8	19.8	17.2
D_{Calo} (m)	6	4		6	3			4	3	4	3						
$\sigma_{M_X^2}$ (GeV^2)	0.17			0.22	0.13		0.12	0.15		0.19	0.09		0.11	0.09			
I_{beam} (μA)	5				1						5						
Days	1	1	3	1	10	15	10	15	20	65	4	3	7	7	2	7	14
					This Proposal: 135 days												

Separation of DVCS^2 and BH-DVCS interference

Projections based on the KM15 model (Kumericki and Mueller, 2015)

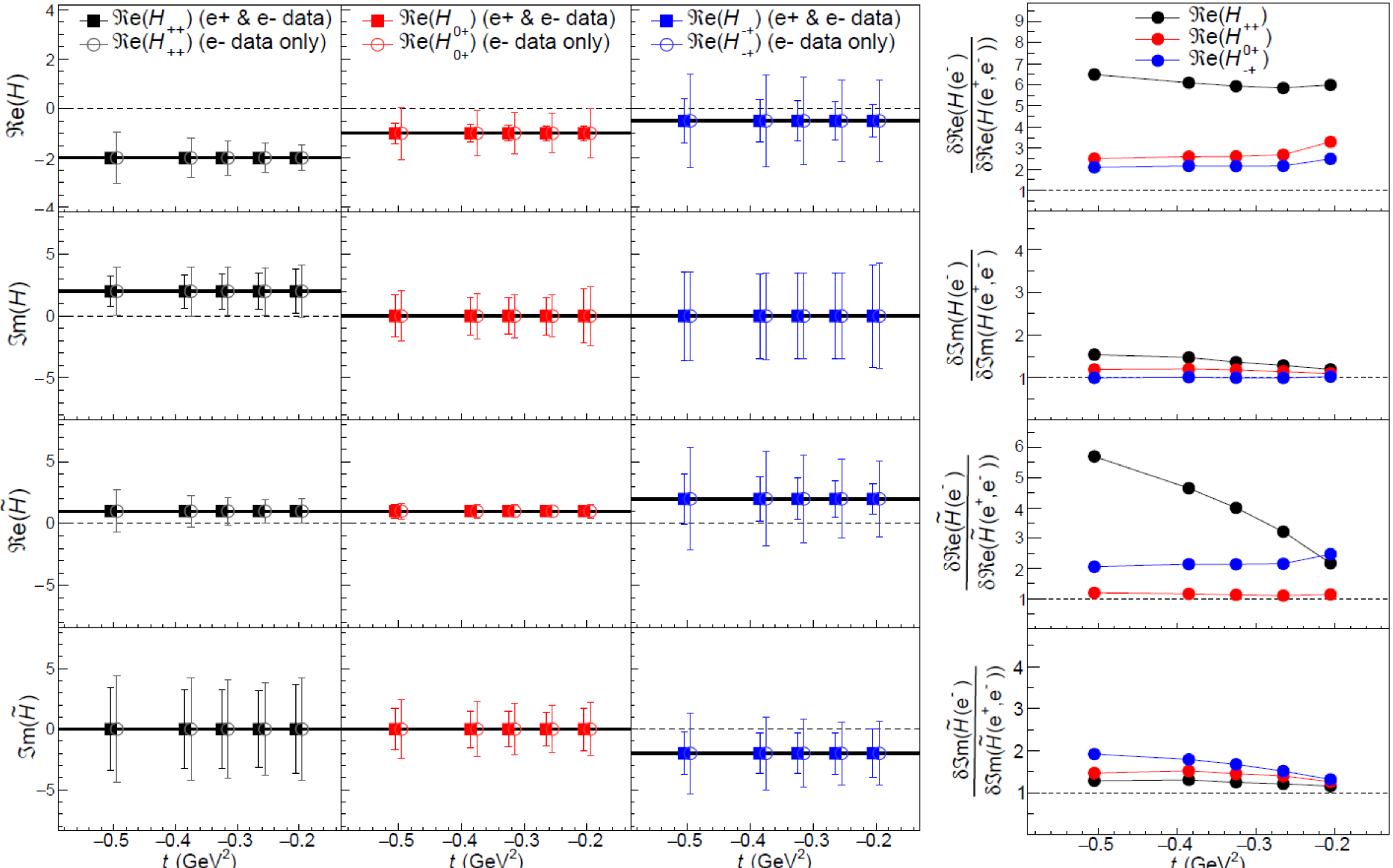


x_B=0.2, Q^2=2.0 GeV^2

x_B=0.3, Q^2=4.0 GeV^2

x_B=0.5, Q^2=3.4 GeV^2

Impact on Compton Form Factors (CFFs) extraction



A factor or 4-6 improvement in the extraction of LO/LT CFFs Re(H) and Re($\tilde{H}$)

(factor of ~2 for HT and NLO)

Summary and outlook

- Proposal approved (C1) for 137 days in Hall C
- Electron part of the experiment is completed (NPS run 2023-2024)
- All equipment is ready and operational
- Low current (~1 uA) measurement will require the development of a Faraday cup in Hall C (plans already exist)

BACK-UP

EPJA paper (Pawel et al.)

Impact of a positron beam at JLab on an unbiased determination of DVCS Compton form factors

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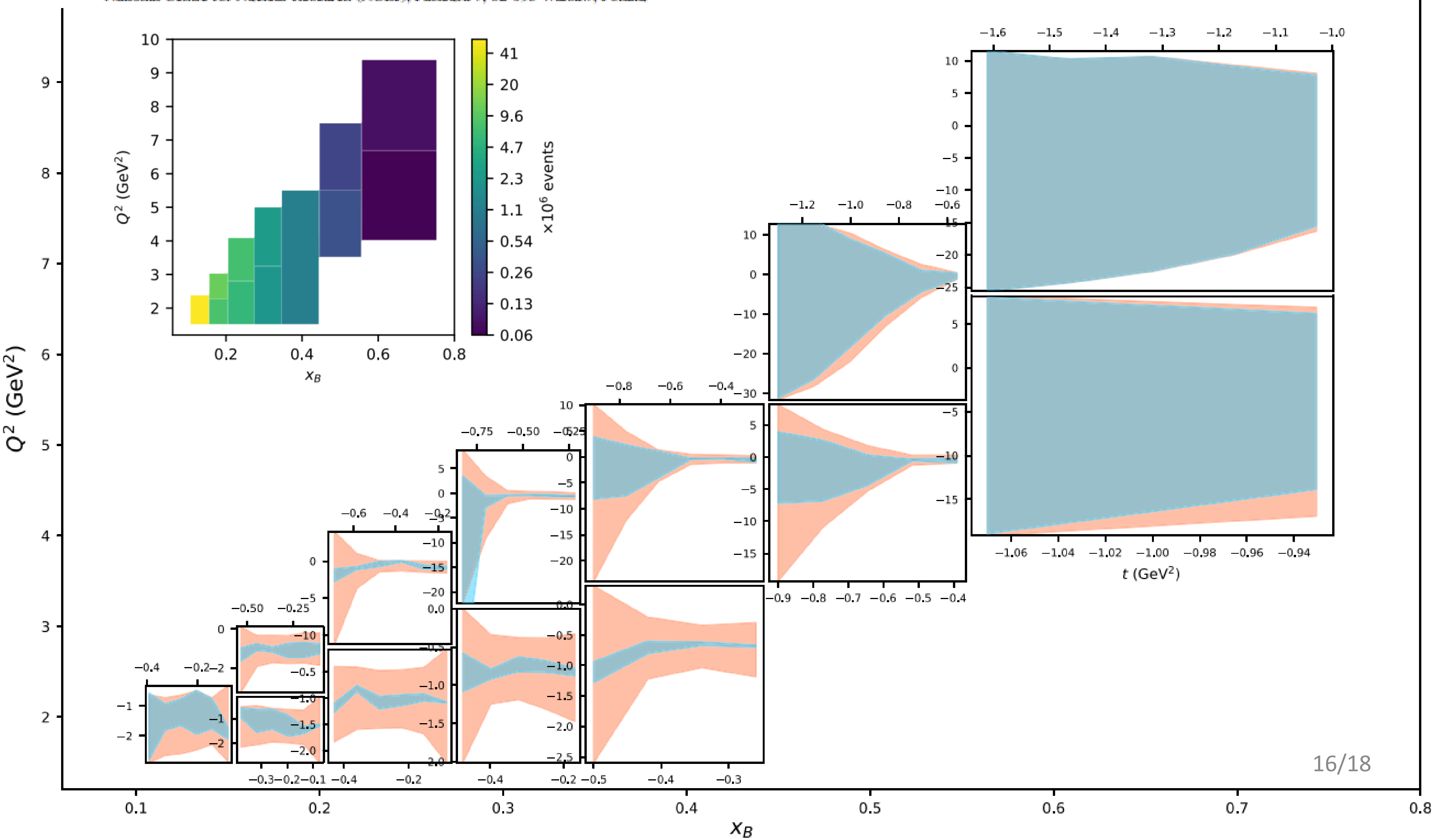
CLAS12 data
(unpolarized target): e- & e+



Gepard (K. Kumericki's code)

gepard.phy.hr/index.html

gepard

Search docs

CONTENTS:

Tool for studying the 3D quark and gluon distributions in the nucleon

Fitting theory to data

At the moment, only the standard least-squares fitting is implemented, and it uses the iminuit Python interface for the Minuit2 C++ library.

Gepard user creates a `MinuitFitter` object, where first argument is a dataset (collection of `DataPoint` objects), and second argument is a `Theory` object. Then `fit()` method of this `MinuitFitter` objects starts the fit (by calling `migrad` optimizer of Minuit). Before this, user should release some parameters of the `Theory` because all parameters are by default fixed at the moment of the creation of `Theory` object.

So, the minimal example of fitting is:

```
>>> import gepard as g
>>> pts = g.dset[36]     # 12 H1 DVCS measurements
>>> class FitTest(g.gpd.PWNormGPD, g.cff.MellinBarnesCFF, g.dvcs.BMK):
...     pass
>>> th = FitTest()
>>> f = g.MinuitFitter(pts, th)
>>> f.release_parameters('ns', 'ms2', 'secs')
>>> f.fit()
```

Final values of chi-square and of parameters are available as

```
>>> f.minuit.fval
8.411
>>> f.print_parameters()
ns    =    1.46 +- 0.45
ms2   =    0.93 +- 0.07
secs  =   -0.32 +- 0.01
```

After successful fit of theory object `th`, user can access parameter uncertainties as `th.parameters_errors` dictionary, and full covariance matrix (inverse of the chi-square Hessian matrix) as `th.covariance` dictionary.

Covariance matrix can then be used to propagate uncertainty to prediction of observables, like this:

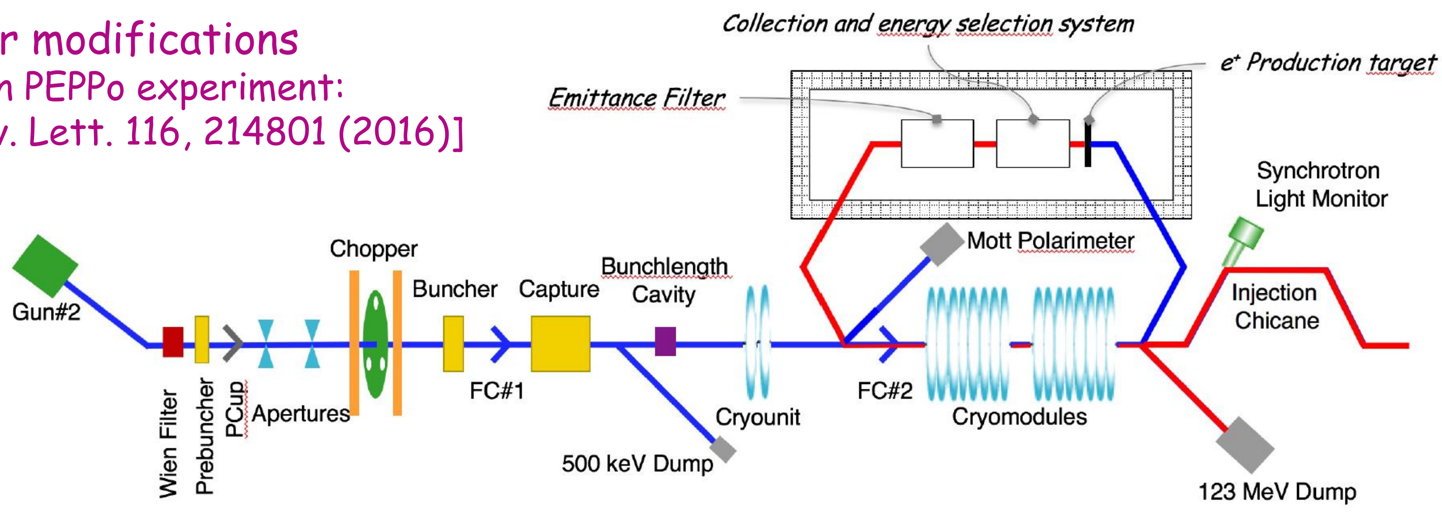
```
>>> th.predict(pts[0], uncertainty=True)
(13.25, 1.62)
```

where parameter-dependent form factors (such as CFFs) can also be "predicted", i. e., calculated together with their uncertainty:

```
>>> pt = g.DataPoint(xB=0.01, t=-0.2, Q2=10)
>>> th.predict(pt, observable='ImH', uncertainty=True)
(273.2, 25.8)
```

Positron production and transport

Injector modifications
[based on PEPPo experiment:
Phys. Rev. Lett. 116, 214801 (2016)]



Electrons

Dominated by damping in the LINACS

Dominated by synchrotron rad. in Arcs

Area	δp/p [x10⁻³]	ε_x [nm]	ε_y [nm]
Chicane	0.5	4.00	4.00
Arc 1	0.05	0.41	0.41
Arc 2	0.03	0.26	0.23
Arc 3	0.035	0.22	0.21
Arc 4	0.044	0.21	0.24
Arc 5	0.060	0.33	0.25
Arc 6	0.090	0.58	0.31
Arc 7	0.104	0.79	0.44
Arc 8	0.133	1.21	0.57
Arc 9	0.167	2.09	0.64
Arc 10	0.194	2.97	0.95
Hall D	0.18	2.70	1.03

Positrons

Area	δp/p [x10⁻³]	ε_x [nm]	ε_y [nm]
Chicane	10	500	500
Arc 1	1	50	50
Arc 2	0.53	26.8	26.6
Arc 3	0.36	19	18.6
Arc 4	0.27	14.5	13.8
Arc 5	0.22	12	11.2
Arc 6	0.19	10	9.5
Arc 7	0.17	8.9	8.35
Arc 8	0.16	8.36	7.38
Arc 9	0.16	8.4	6.8
MYAAT01	0.18	9.13	6.19

At 11 GeV, after Arc9, e+ beam size ~twice bigger than e- beam

Averaging εx and ε_y:

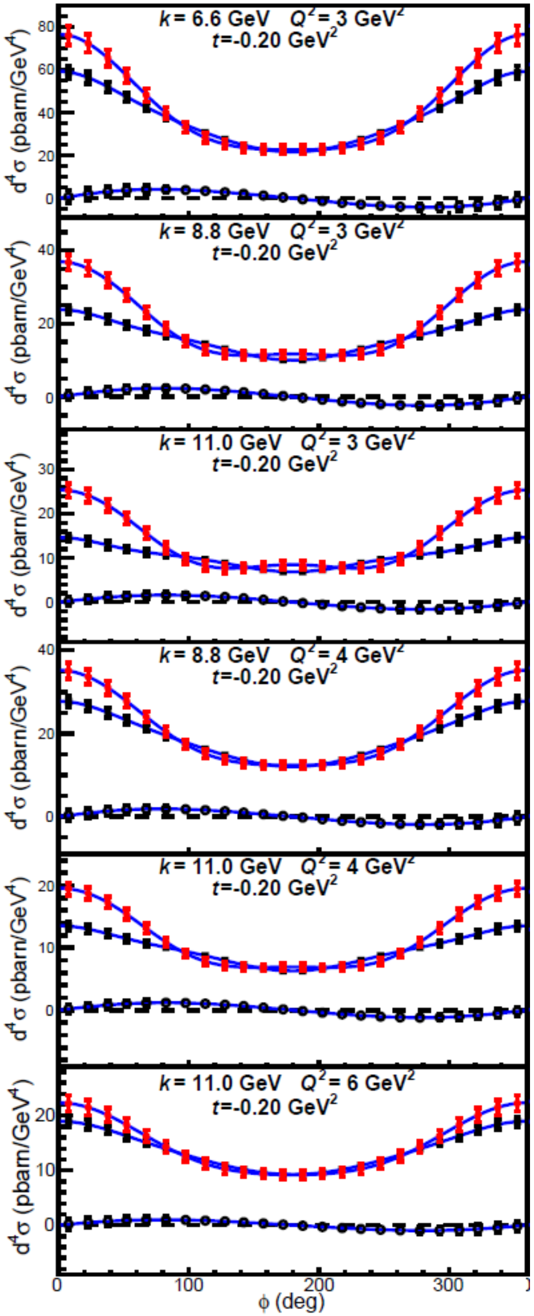
$$\sqrt{7.6/1.4} \sim 2.3$$

Systematic uncertainties

Source	pt-to-pt (%)	scale (%)
Acceptance	0.4	1.0
Electron PID	<0.1	<0.1
Efficiency	0.5	1.0
Electron tracking	0.1	0.5
Charge	0.5	1.0
Target thickness	0.2	0.5
Kinematics	0.4	<0.1
Exclusivity	1.0	2.0
π^0 subtraction	0.5	1.0
Radiative corrections	1.2	2.0
Total	**1.8-1.9**	**3.4-3.5**

The π^0 electroproduction cross section would be measured concurrently with DVCS with both electrons and positrons, and would allow to monitor the systematics of the e- and e+ runs

Impact on Compton Form Factors (CFFs) extraction



✓ Combined fit of all electron data from approved experiment E12-13-010

(helicity-dependent AND helicity-independent cross sections)

✓ Fits with and without the proposed positron data

✓ Fits include helicity-conserving CFFs, but also +1 helicity-flip CFFs ("HT") and +2 helicity-flip CFFs ("NLO")

✓ Cross sections generated with CFFs values fitted to 6 GeV data

In order to extract the CFFs we exploit the combined

- Azimuthal dependence (ϕ)
- Beam-energy dependence
- Q^2-dependence
- Helicity dependence (for E12-13-010 data)
- **Beam-charge dependence**

of the DVCS cross section

TAC comments on positron

- The implementation of a multi-Hall, high current, high polarization positron beam at CEBAF raises multiple and complex challenges, as detailed in the TAC report

- If the PAC finds our physics program compelling, our collaboration is ready to engage with the Lab to investigate its feasibility.

TAC conclusion:

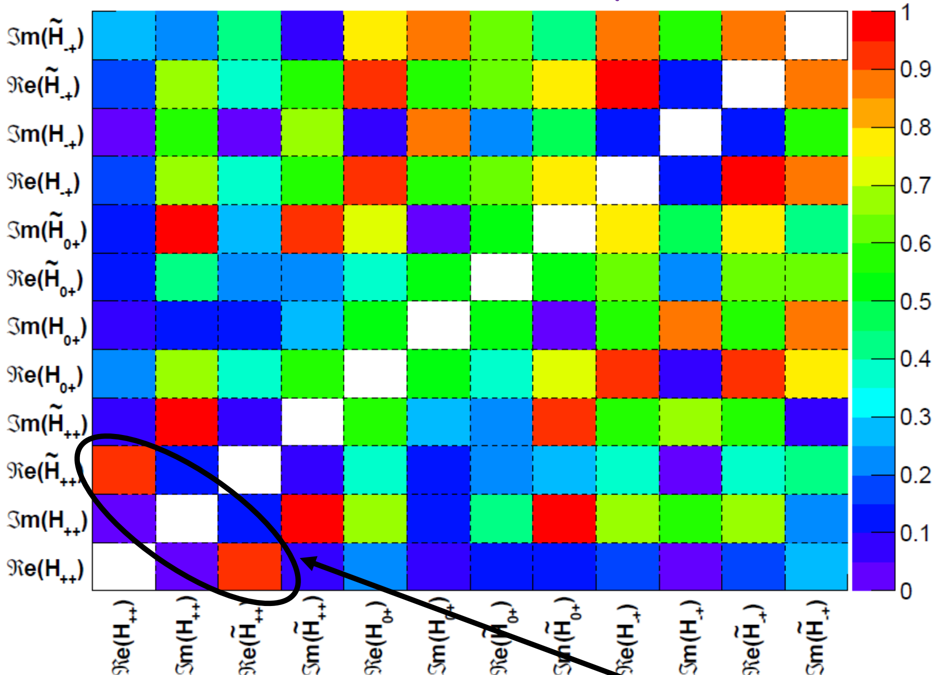
In conclusion, while a positron beam upgrade is a major upgrade which will require substantial accelerator physics development, a detailed cost and implementation plan, and expensive changes to the CEBAF accelerator, a multi-Hall positron beam capability could have great potential for a future JLAB 12-GeV science program.

Correlation coefficients

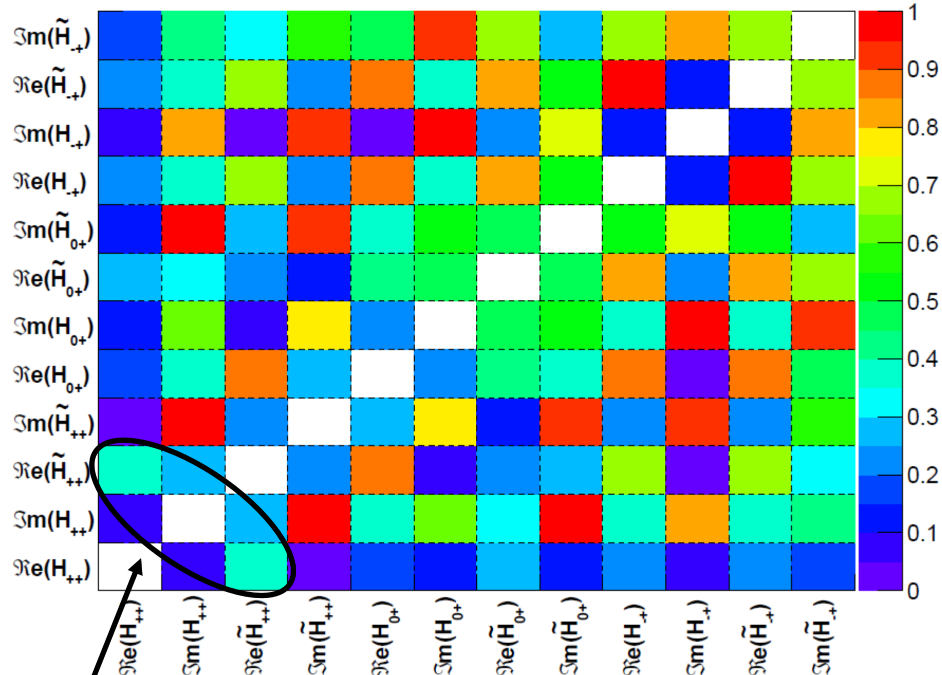
Correlations between different CFFs are significantly improved by a combined fit with positrons

$$|\rho_{i,j}| = \left|\mathrm{cov}[\mathbb{F}_i, \mathbb{F}_j]/(\sigma_i \sigma_j)\right|$$

Electrons only



Electrons & Positrons



LT/LO HT NLO

(t = -0.26 GeV^2)

Much better separation of
H & Ht CFFs at LT/LO

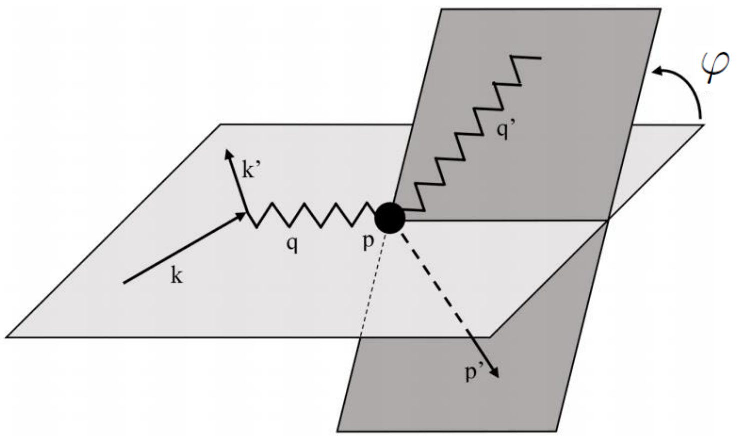
(from -94% without positrons to -39% when electron and positrons are combined, in this t-bin)

E07-007: Rosenbluth-like separation of DVCS

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

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

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

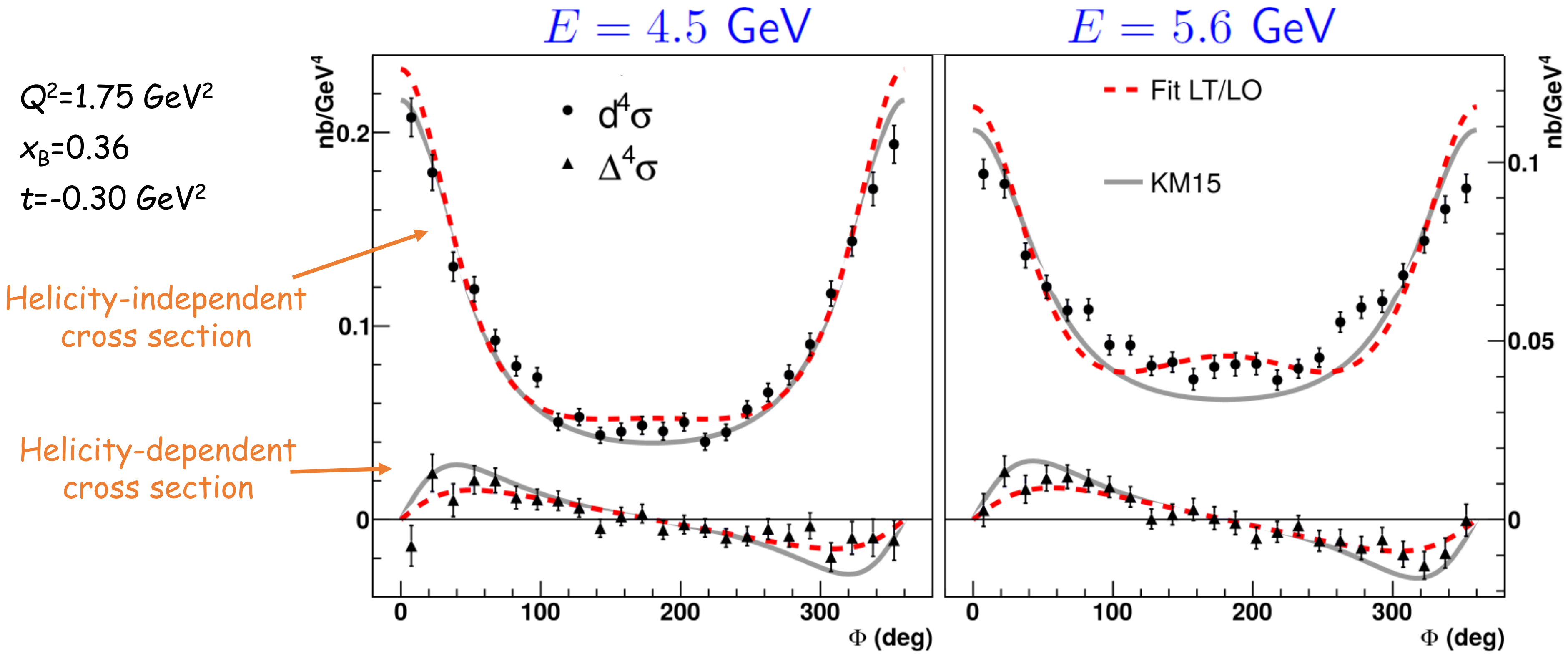


φ-dependence provides 5 independent observables:

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

E07-007: Rosenbluth-like separation of DVCS

- Cross section measured at 2 beam energies and constant Q^2, x_B, t

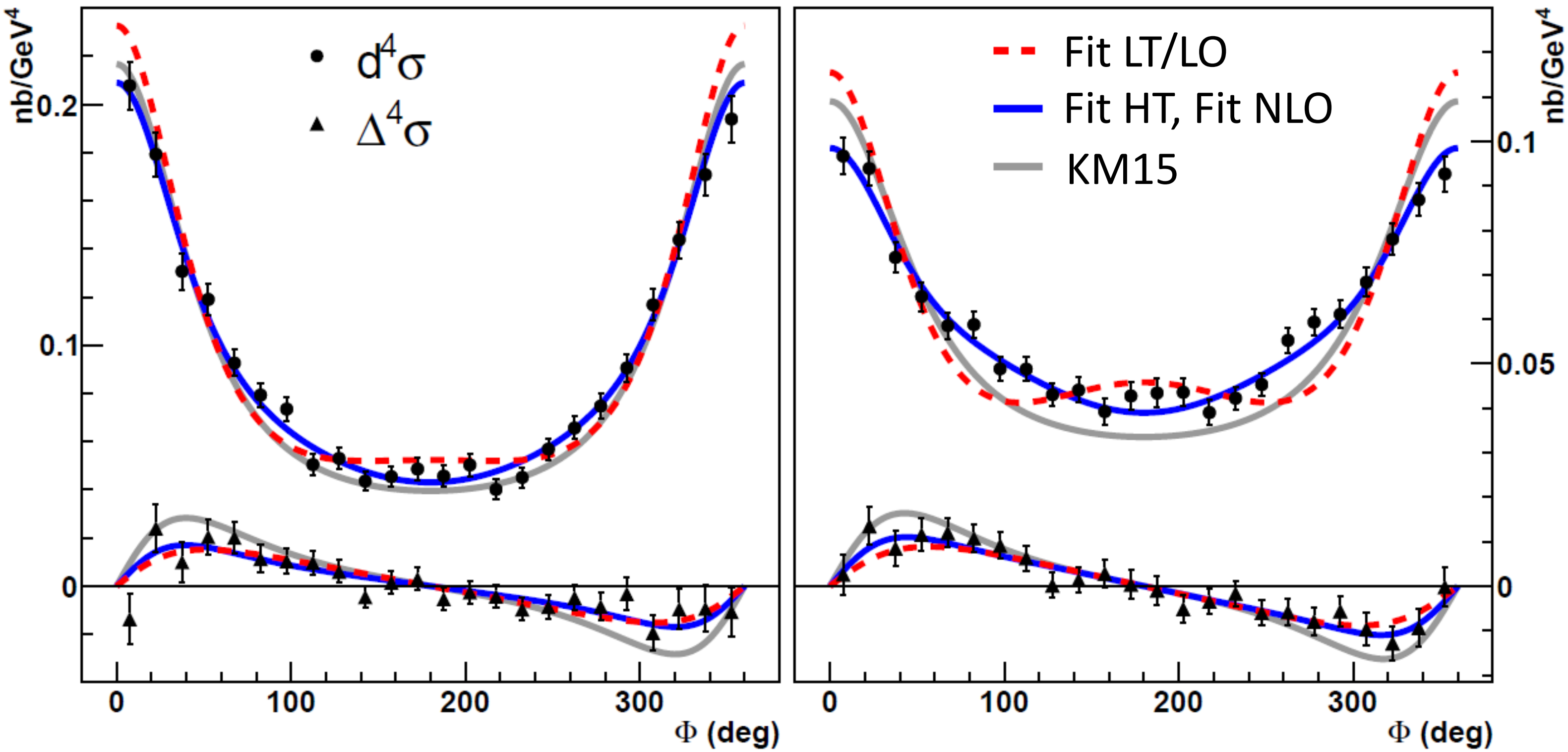


- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

Light-cone axis in the (q, q') plane (Braun et al.): $\mathbb{H}_{++}$, $\widetilde{\mathbb{H}}_{++}$, $\mathbb{E}_{++}$, $\widetilde{\mathbb{E}}_{++}$

E07-007: Rosenbluth-like separation of DVCS

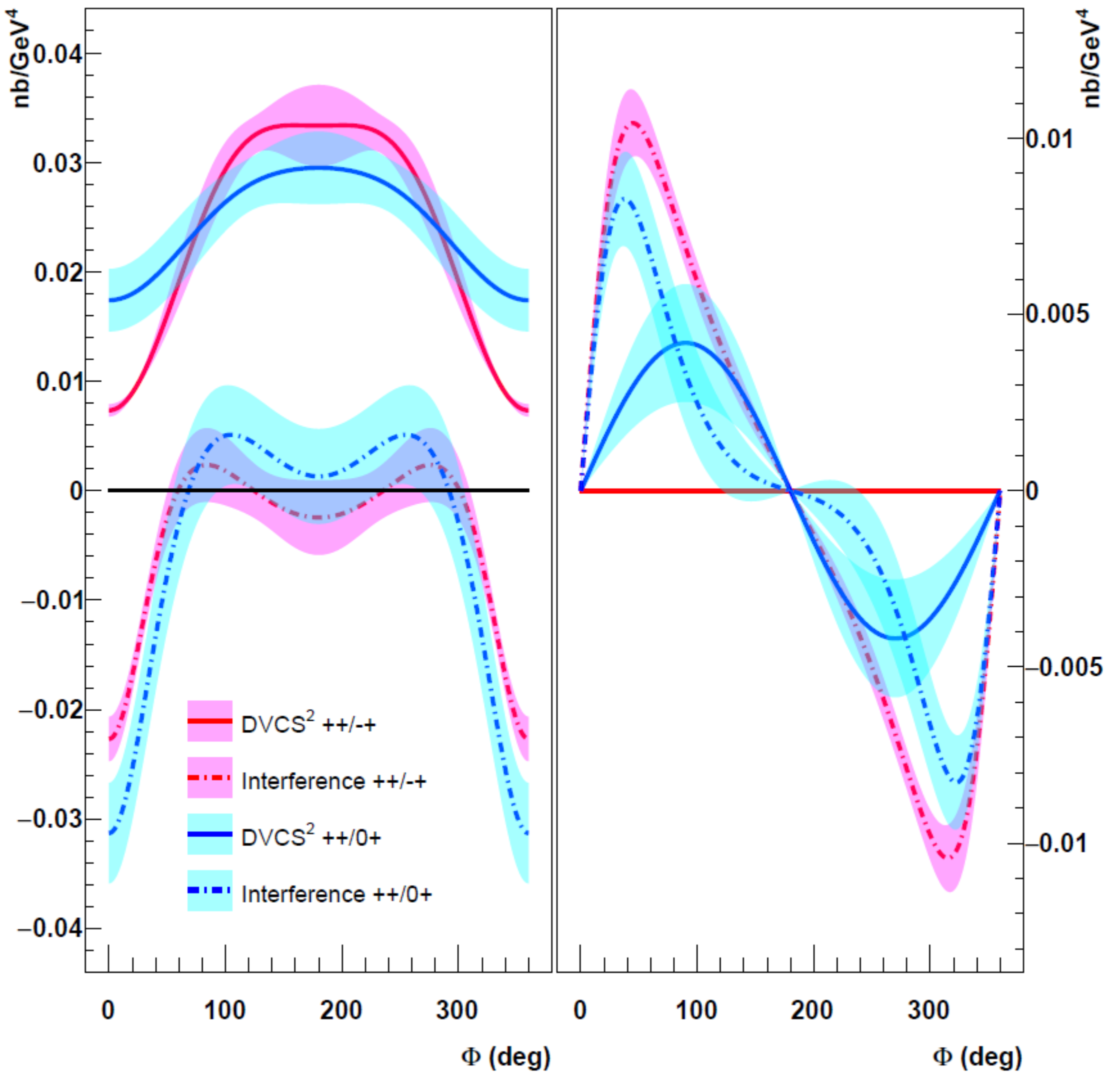
- Cross section measured at 2 beam energies and constant Q^2, x_B, t



- Using only helicity-conserving CFFs ("LT/LO") the fit of both beam energies (dashed line) does not reproduce the data
- Including helicity-flip CFFs, either single-helicity flip ("HT") or double-helicity flip ("NLO") satisfactorily reproduce the angular dependence (blue solid line)

E07-007: Rosenbluth-like separation of DVCS

DVCS^2 and $\mathcal{I}$(DVCS·BH) separated in NLO and higher-twist scenarios



Helicity-independent cross section

Helicity-dependent cross section

- DVCS^2 & $\mathcal{I}$ significantly different in each scenario
- Sizeable DVCS^2 contribution in the higher-twist scenario in the helicity-dependent cross section

Nature Commun. 8, 1408 (2017)

DVCS process: leading twist ambiguity

- DVCS defines a preferred axis: light-cone axis
- At finite Q^2 and non-zero t, there is an ambiguity:
  1. Belitsky et al. ("BKM", 2002–2010): light-cone axis in plane (q,P)
  2. Braun et al. ("BMP", 2014): light-cone axis in plane (q,q')
     easier to account for kin. corrections $\sim \mathcal{O}(M^2/Q^2)$, $\sim \mathcal{O}(t/Q^2)$

$$\left.\begin{array}{ll} \mathcal{F}_{++} = & \mathbb{F}_{++} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+} \\ \mathcal{F}_{-+} = & \mathbb{F}_{-+} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+} \\ \mathcal{F}_{0+} = & -(1+\chi)\mathbb{F}_{0+} + \chi_0\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] \end{array}\right\} \xrightarrow[\mathbb{F}_{0+}=0]{\mathbb{F}_{-+}=0} \left\{\begin{array}{ll} \mathcal{F}_{++} & = (1+\frac{\chi}{2})\mathbb{F}_{++} \\ \mathcal{F}_{-+} & = \frac{\chi}{2}\mathbb{F}_{++} \\ \mathcal{F}_{0+} & = \chi_0 \mathbb{F}_{++} \end{array}\right.$$

(eg. $\chi_0 = 0.25$, $\chi = 0.06$ for $Q^2 = 2$ GeV^2, $x_B = 0.36$, $t = -0.24$ GeV^2)

DVCS cross-section: φ & Q^2

$$\mathcal{I} = \frac{i_0/Q^2 + i_1 \cos\varphi/Q + i_2 \cos 2\varphi/Q^2 + i_3 \cos 3\varphi/Q}{\mathcal{P}_1\mathcal{P}_2}$$

$$\text{DVCS}^2 = d_0/Q^2 + d_1 \cos\varphi/Q^3 + d_2 \cos 2\varphi/Q^4 \,.$$

The product of the BH propagators reads:

$$\mathcal{P}_1\mathcal{P}_2 = 1 + \frac{p_1}{Q}\cos\varphi + \frac{p_2}{Q^2}\cos 2\varphi \,.$$

Reducing to a common denominator ($\times\mathcal{P}_1\mathcal{P}_2$), one obtains:

$$\begin{aligned}
\mathcal{P}_1\mathcal{P}_2\mathcal{I} + \mathcal{P}_1\mathcal{P}_2\text{DVCS}^2 = & \boxed{(i_0 + d_0)/Q^2} + d_1 p_1/2/Q^4 + p_2 d_2/2/Q^6 \\
& + [i_1/Q + (p_1 d_0 + d_1)/Q^3 + (p_1 d_2 + p_2 d_1)/2/Q^5]\cos\varphi \\
& + [i_2/Q^2 + (p_2 d_0 + p_1 d_1/2 + d_2)/Q^4]\cos 2\varphi \\
& + [i_3/Q + (p_1 d_2 + p_2 d_1)/2/Q^5]\cos 3\varphi \\
& + [p_2 d_2/4/Q^6]\cos 4\varphi \,.
\end{aligned}$$

The $\mathcal{I}$ and DVCS^2 terms **mix at leading order in 1/Q** in the φ expansion