DVCS using a positron beam in Hall C

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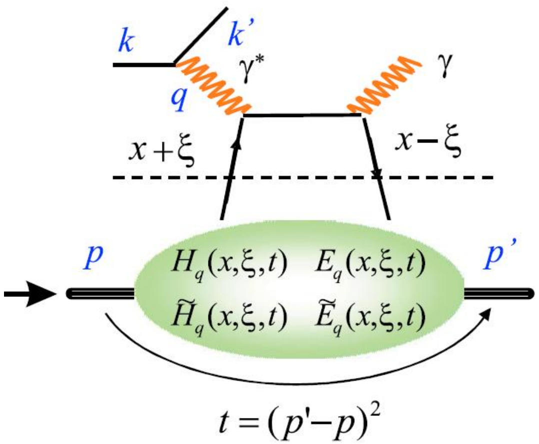
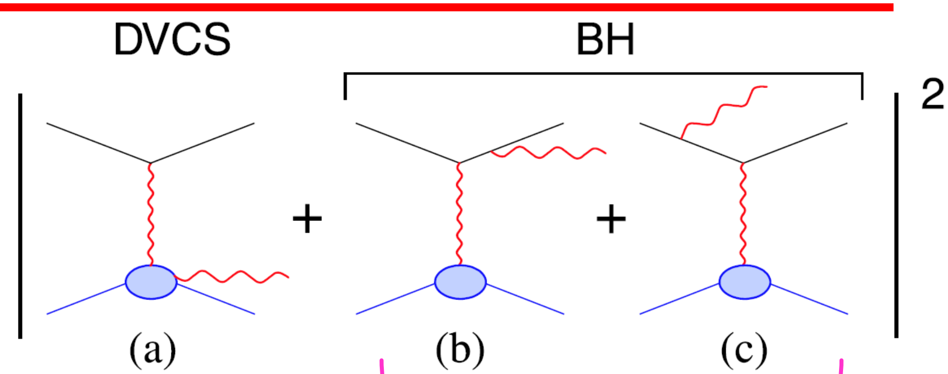
JLab Positron Working Group Proposal
NPS Collaboration Proposal

Motivation



$ep \longrightarrow ep\gamma =$



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

At leading twist:

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

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

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

Opposite sign for e- & e+

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

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

DVCS program at JLab

Two complementary approaches:

- Survey measurements with large acceptance device (CLAS + CLAS12):

Study of many different observables over a wide range of kinematics,

but limited statistical and systematic uncertainties

- Precision measurements in selected kinematic settings (Hall A + Hall C):

test of scaling, higher twist corrections, L/T separations…

Summary document on Halls complementary submitted to PAC40

A few milestones of the precision DVCS program

- First indications of leading twist dominance for DVCS for Q^2 as low as ~2 GeV^2
- Large magnitude of the $DVCS^2$ contribution

Phys. Rev. Lett. **97**, 262002 (2006)
Phys. Rev. **C92**, 055202 (2015)

- Necessity to include corrections $O(t/Q^2)$ & $O(M^2/Q^2)$ to the DVCS cross section
- *Initial separation DVCS2 & BH-DVCS interference (yet ambiguous)*

Nature Communications **8**, 1408 (2017)

- Flavor separation of CFFs combining proton & neutron DVCS data
- DVCS on coherent deuteron ($\rightarrow$ nuclear GPDs)

Phys. Rev. Lett. **99**, 242501 (2007)
Nature Physics **16**, 191 (2020)

- L/T separation of π^0 electroproduction cross section ($\rightarrow$ transversity GPDs)
- Flavor separation of transversity GPDs using π^0 electroproduction & a LD_2 target

Phys. Rev. **C83** 025201 (2011)
Phys. Rev. Lett. **117**, 262001 (2016)
Phys. Rev. Lett. **118**, 222002 (2017)

- High x_B and high Q2 exploration with JLab12

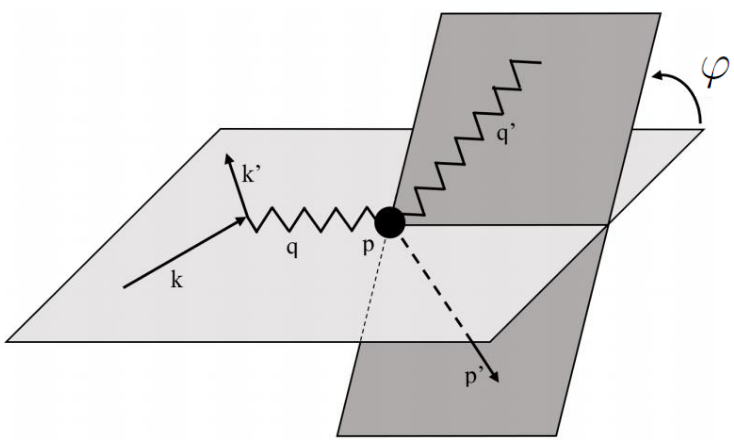
Phys. Rev. Lett. **128**, 252002 (2022)

E07-007: Rosenbluth-like separation of DVCS

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

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

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



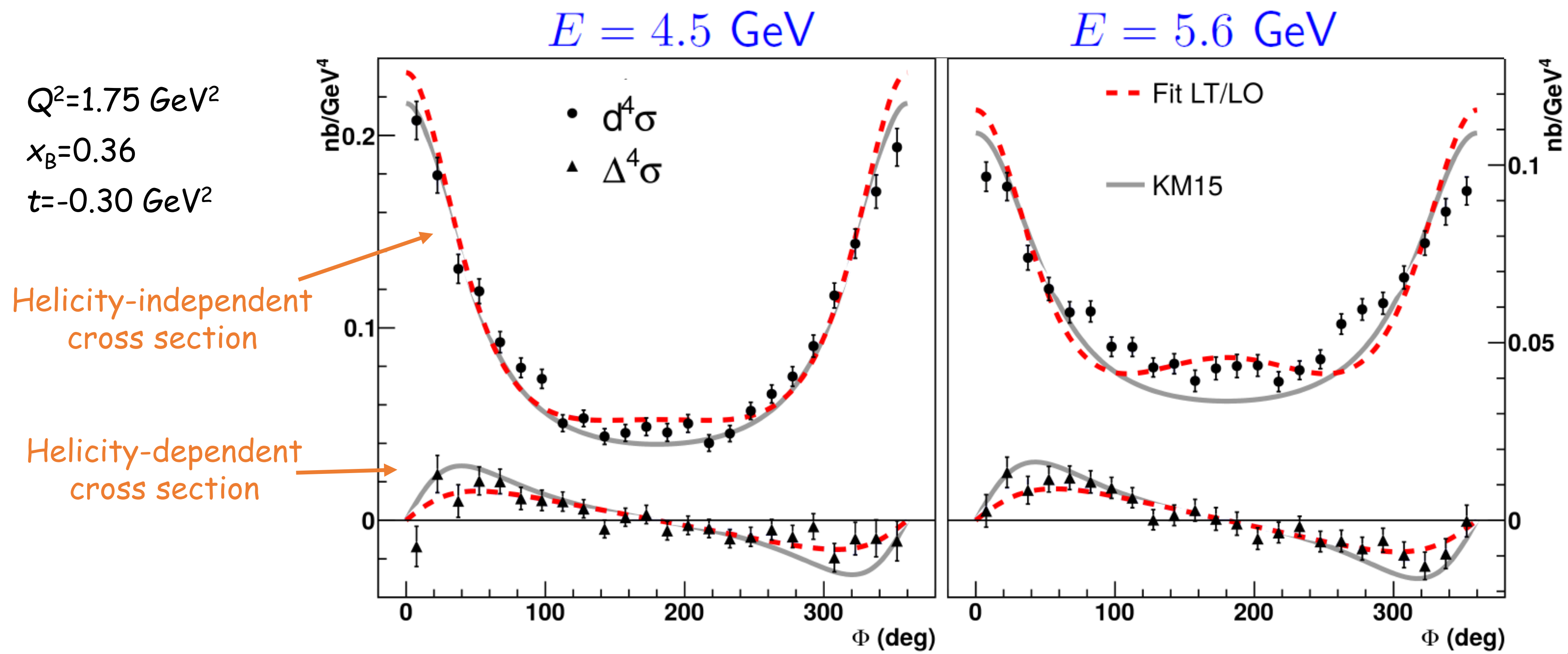
φ-dependence provides 5 independent observables:

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

E07-007: Rosenbluth-like separation of DVCS

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

Q^2=1.75 GeV^2
x_B=0.36
t=-0.30 GeV^2

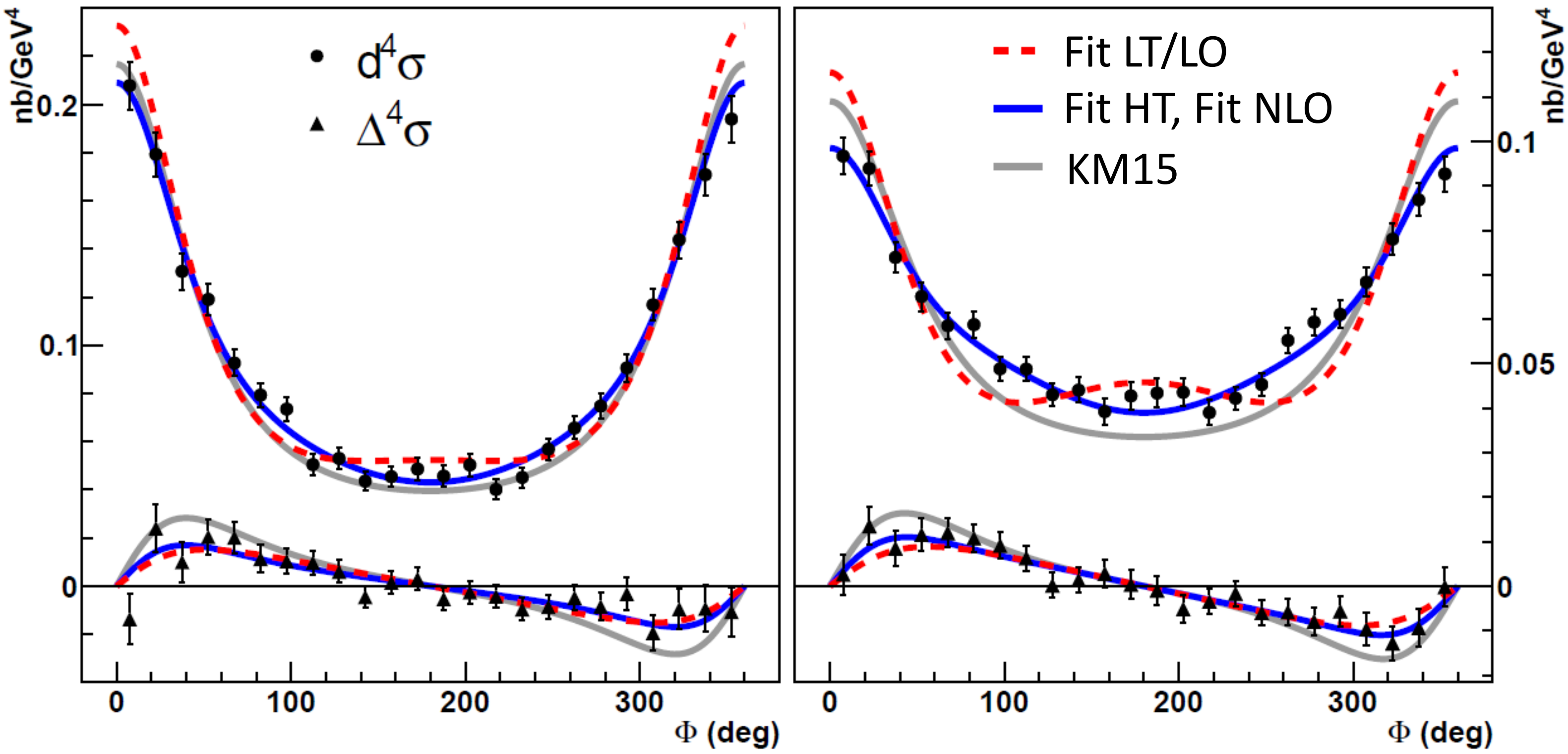


- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

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

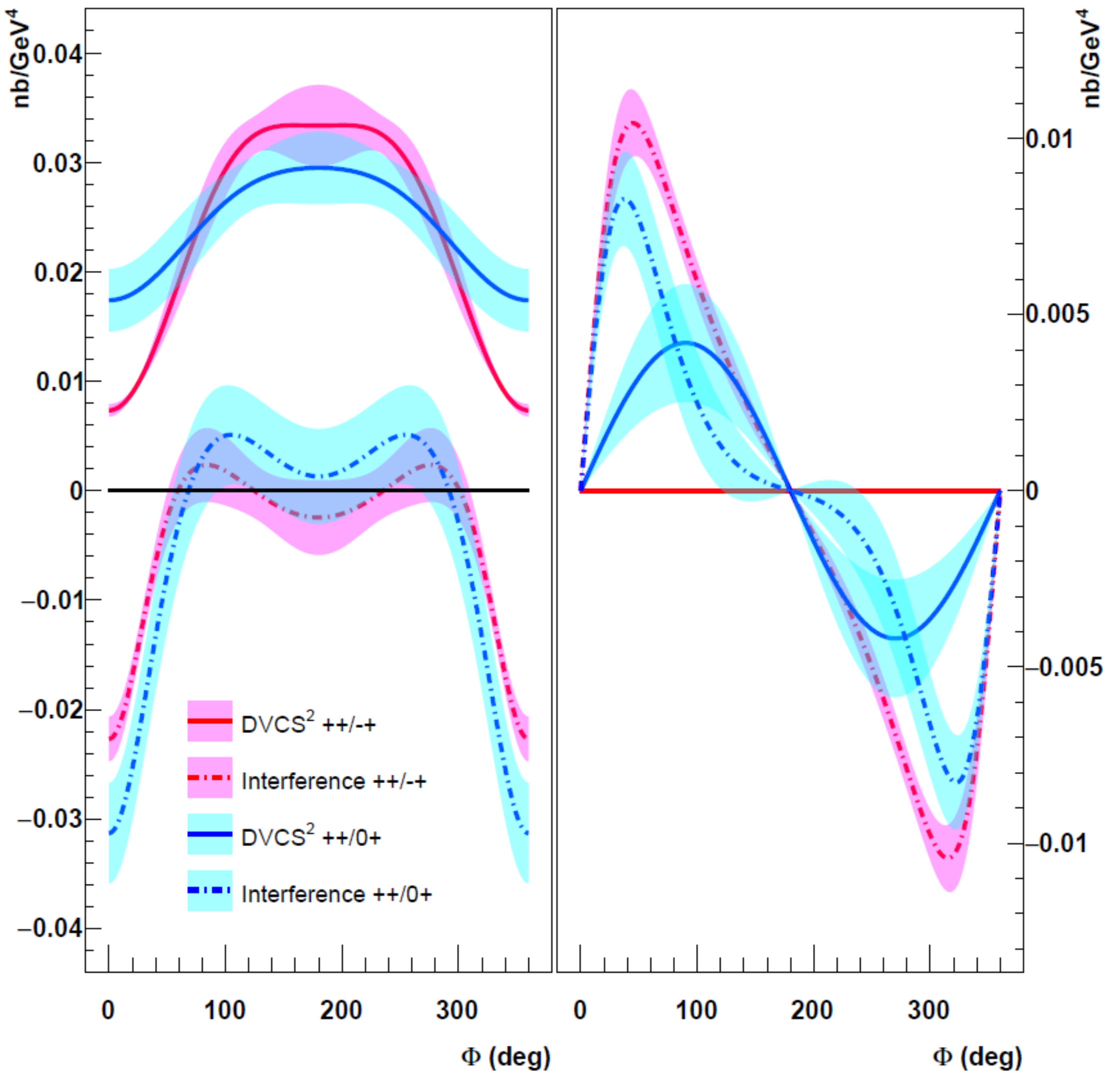
- Cross section measured at 2 beam energies and constant Q^2, x_B, t



- 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 with positrons and NPS (proposal to PAC51)

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

Opposite sign for e- & e+

Physics goals and motivation:

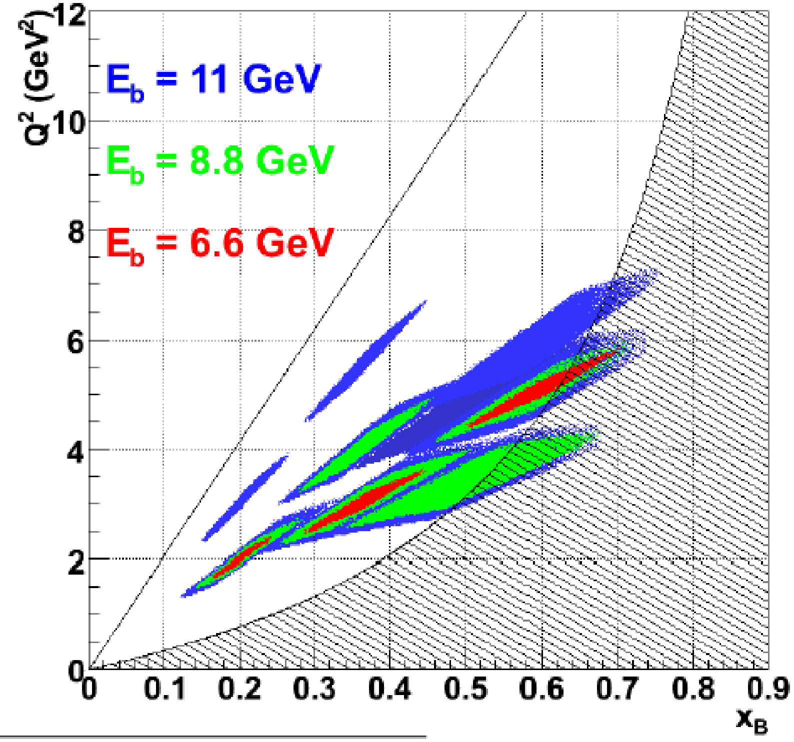
- ✓ Precise determination of the absolute photon electro-production cross section
- ✓ Clean, model-independent separation of $DVCS^2$ and DVCS-BH interference
- ✓ More stringer constraints on CFFs by combining e^- & e^+ data

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

PR12+23-006: Kinematic settings

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
$\theta_{\rm Calo}$ (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
$D_{\rm Calo}$ (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			
$I_{\rm beam}$ (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												

TAC comments on positron

The systematic uncertainty on target length was not accounted and needs to be included. The uncertainty is at the level of 0.7%.

Source	pt-to-pt (%)	scale (%)
Acceptance	0.4	1.0
Electron/positron PID	<0.1	<0.1
Efficiency	0.5	1.0
Electron/positron tracking efficiency	0.1	0.5
Charge	0.5	2.0
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	3.8–3.9

Proposal, page 15

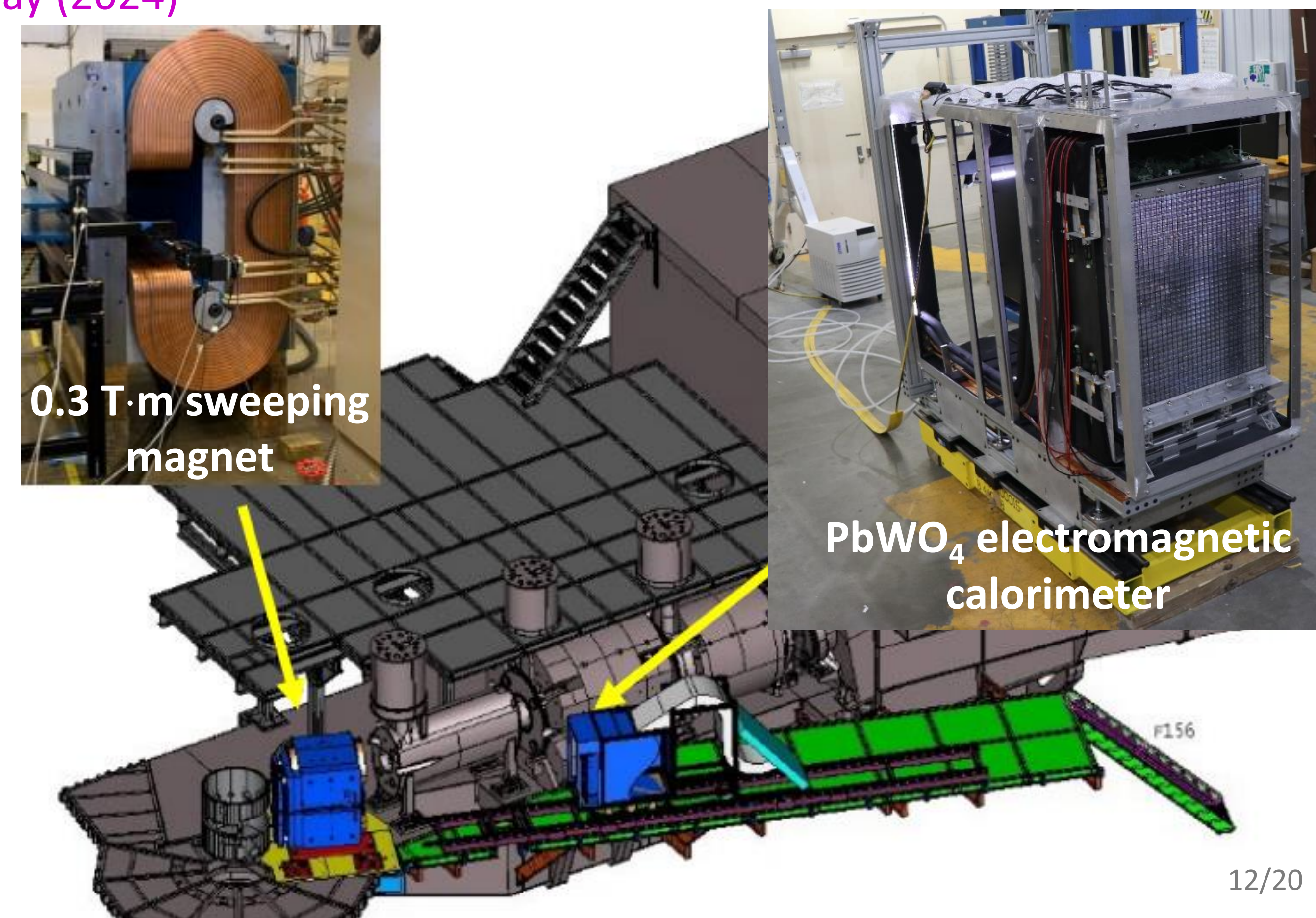
The proposal does not provide any information whether the days requested include the time needed for setting up the experiment (optics, calibrations, etc).
It also doesn't mention whether Al dummy data taking is needed.

- Beamtime request does not include calibrations or Al dummy running
- Calibrations in our previous DVCS experiments required 3 calendar days (1.5 PAC days) and dummy running 1 calendar day (0.5 PAC)
- A total overhead of 2 additional PAC days should be added to our request to account for this

Neutral Particle Spectrometer (NPS)

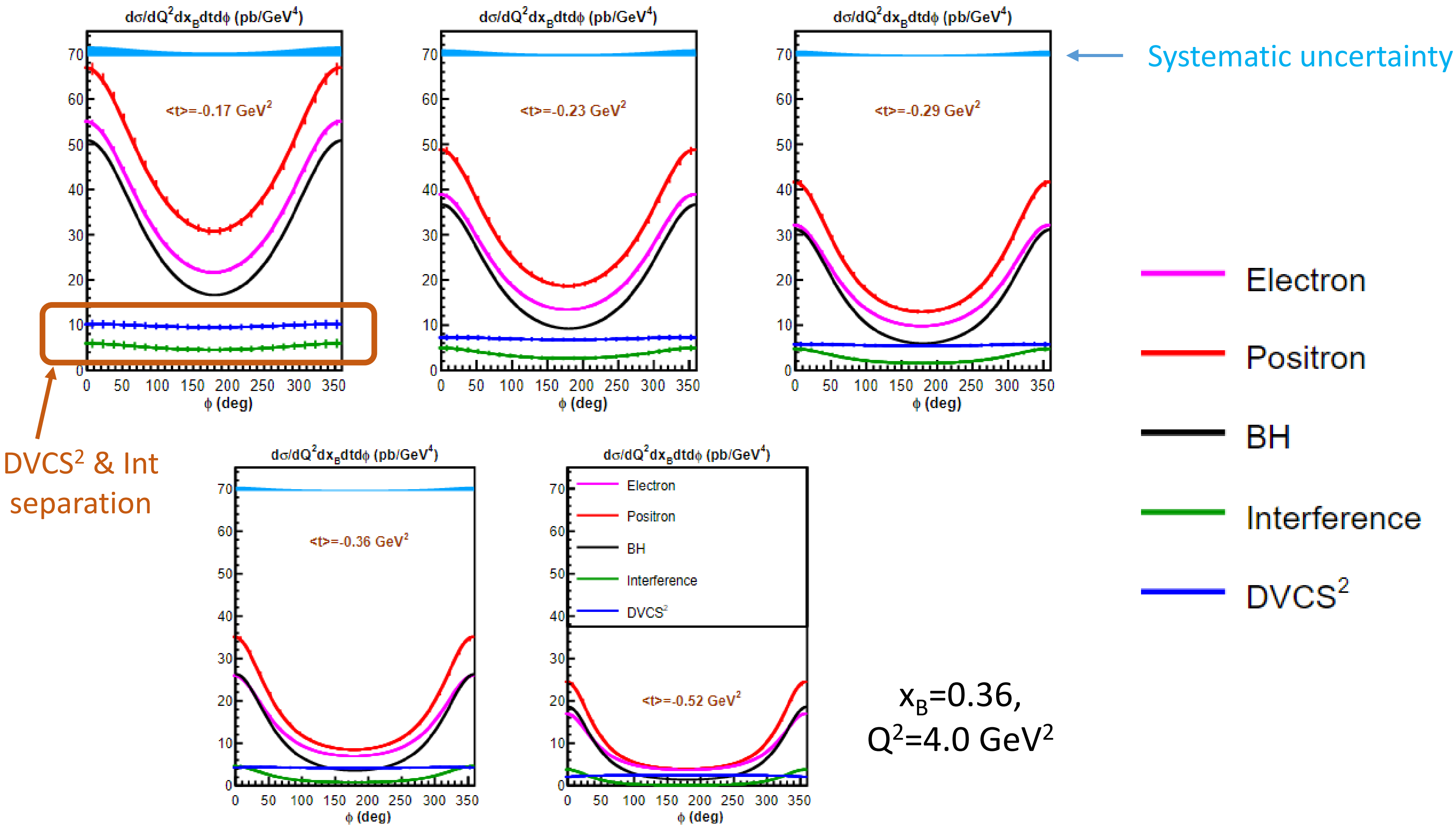
- **NPS (Neutral Particle Spectrometer)** experiment is on the floor !
- Equipment (calorimeter and sweeping magnet) ready and being tested
- NPS run (E12-13-010 & E12-22-006) scheduled from Sep (2023) to May (2024)

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



Separation of DVCS^2 and BH-DVCS interference

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



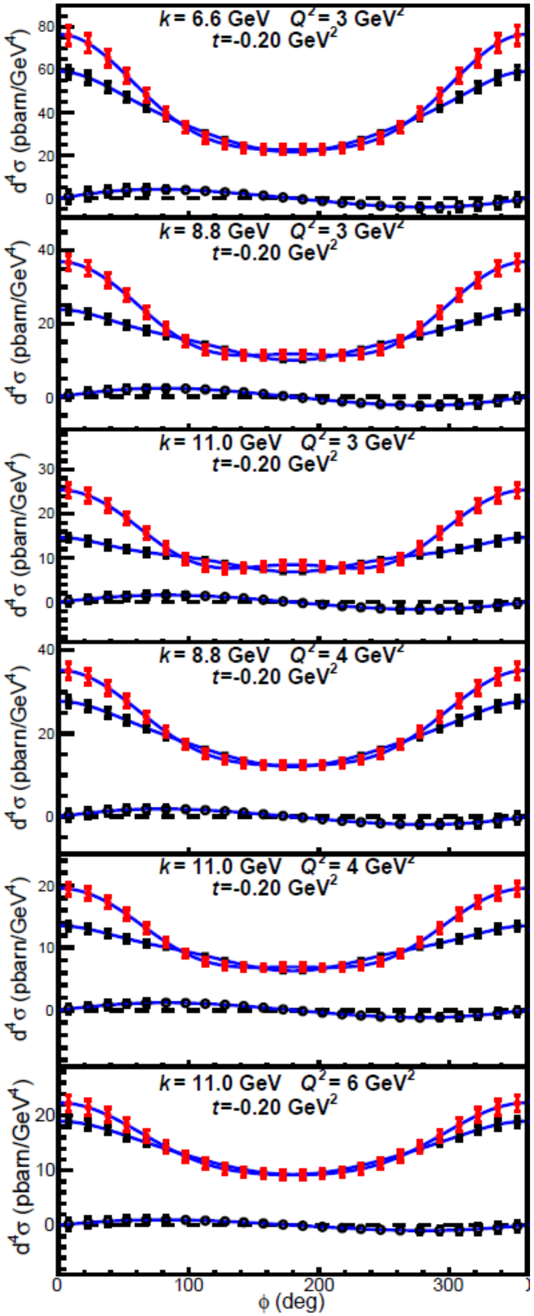
x_B=0.36,
Q^2=4.0 GeV^2

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)

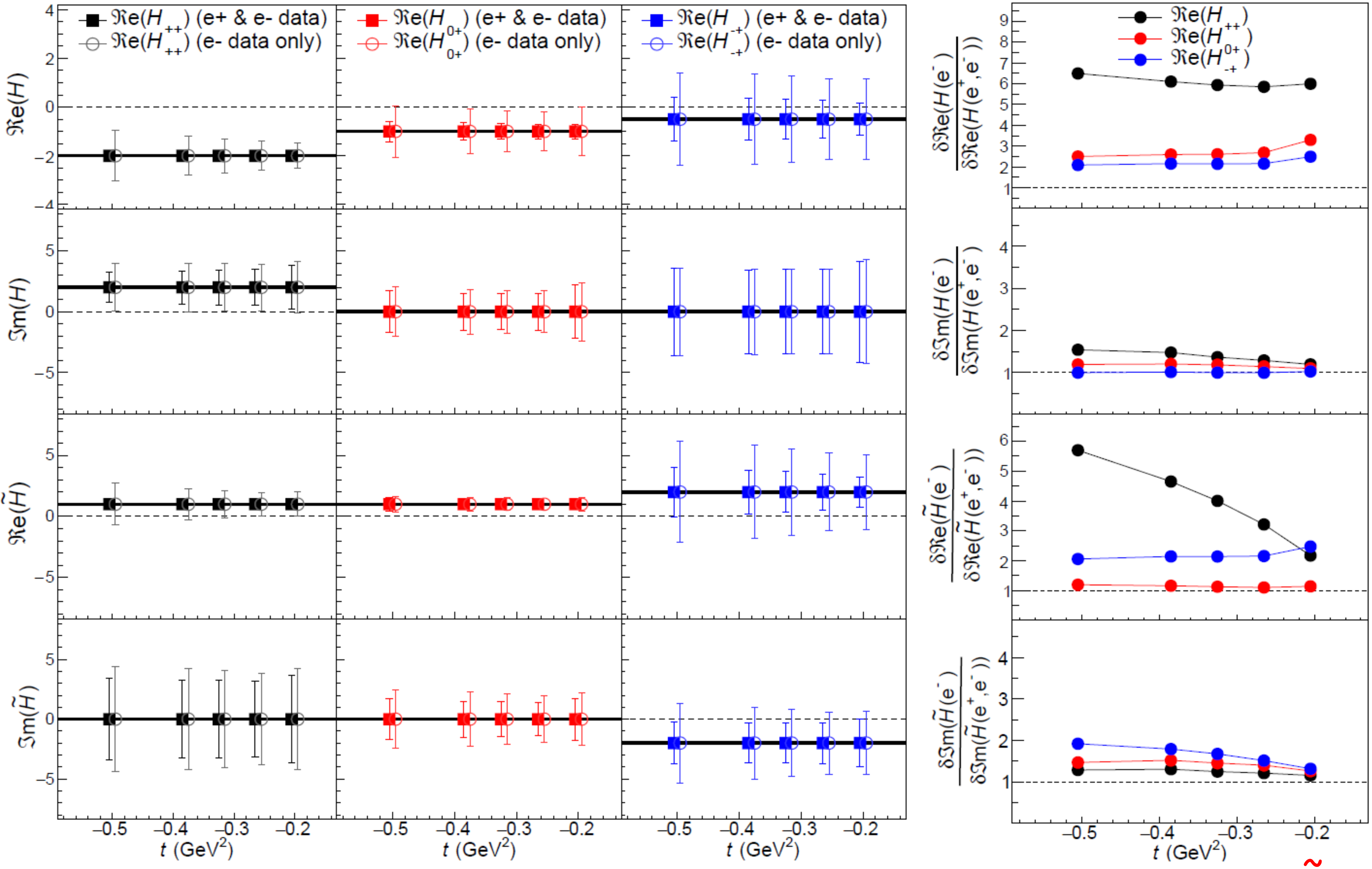
- ✓ Fits with and without the proposed positron data
- ✓ Fits include helicity-conserving CFFs, but also +1 helicity-flip CFFs ("HT") and +2 helicity-flip CFFs ("NLO")
- ✓ Cross sections generated with CFFs values fitted to 6 GeV data

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

Impact on Compton Form Factors (CFFs) extraction



A factor or 4-6 improvement in the extraction of LO/LT CFFs Re(H) and Re(H̃)

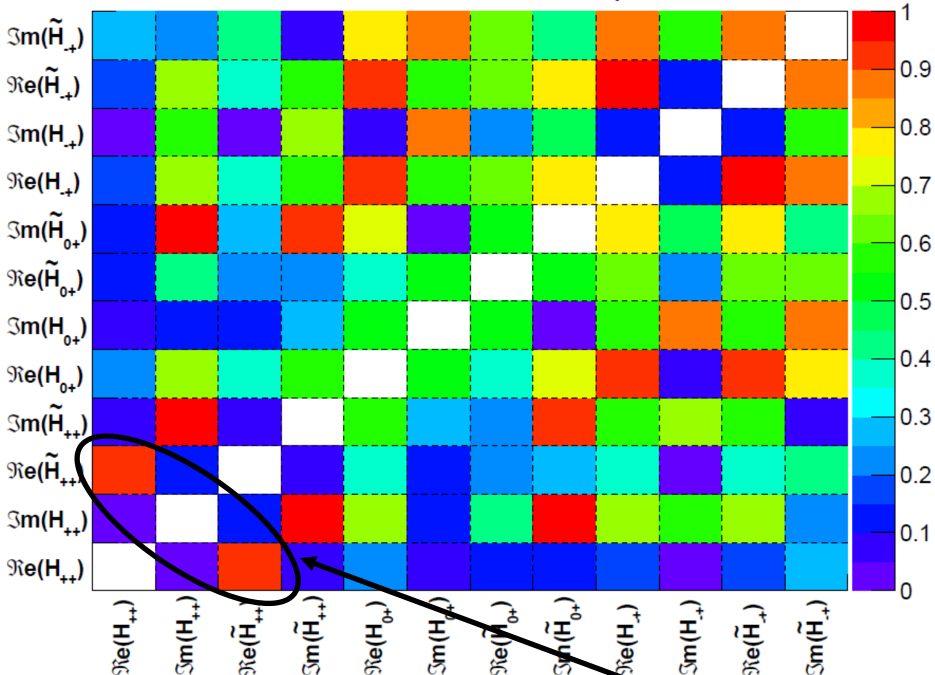
(factor of ~2 for HT and NLO)

Correlation coefficients

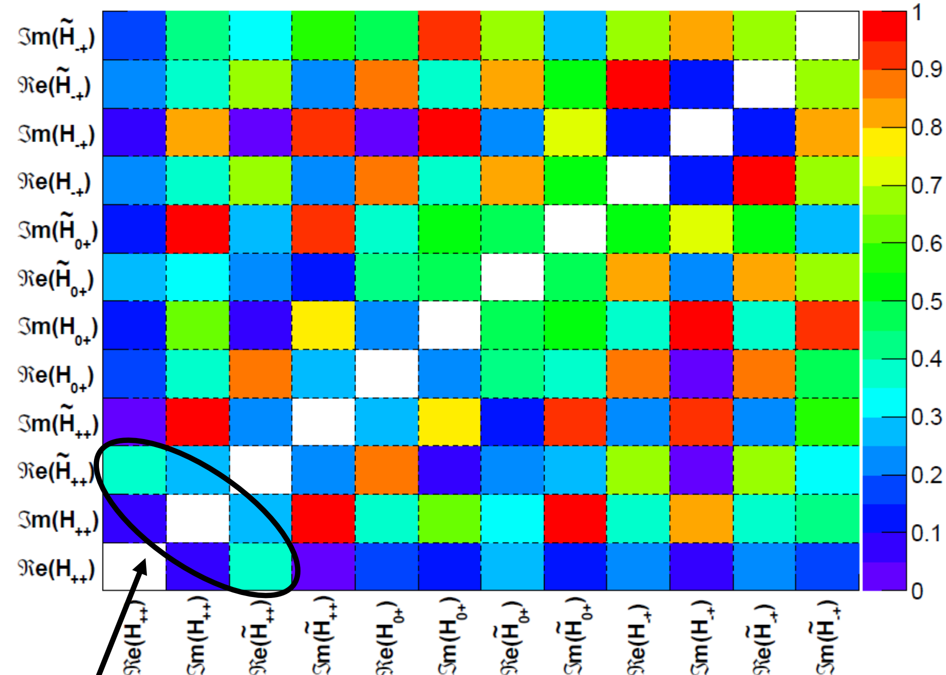
Correlations between different CFFs are significantly improved by a combined fit with positrons

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

Electrons only



Electrons & Positrons



LT/LO HT NLO

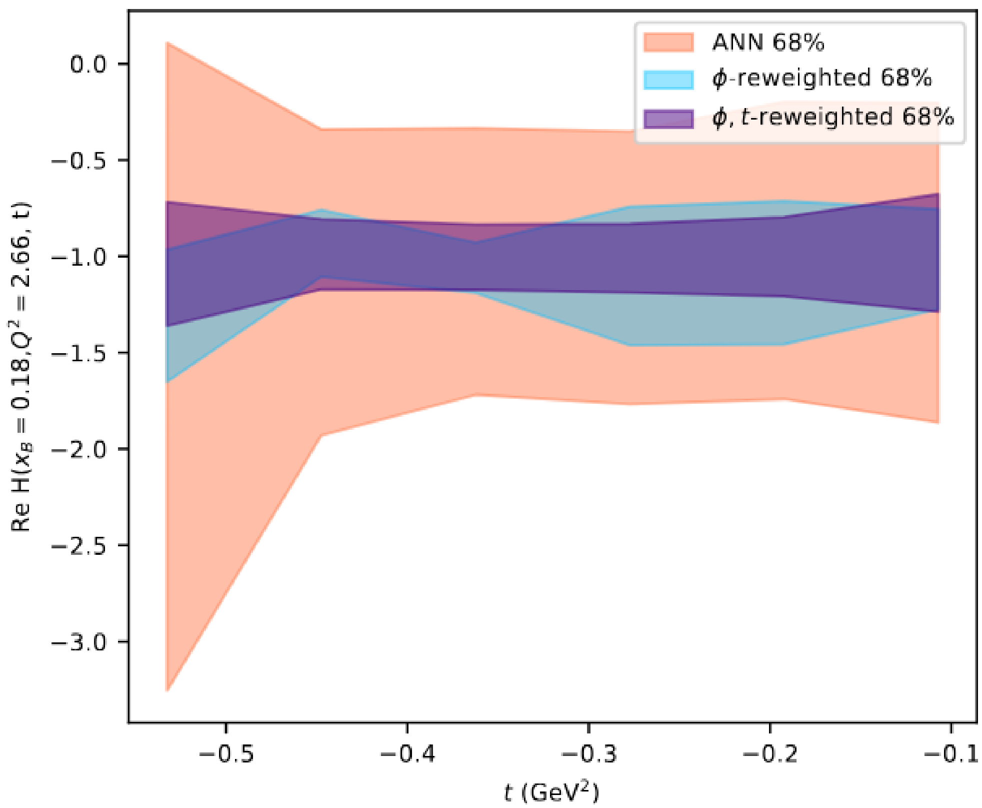
(t = -0.26 GeV^2)

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)

Other impact studies of positron data on DVCS

- Recent Baysian reweighting analysis by H. Dutrieux et al. (2022)
- CFF input provided by a global fit to existing DVCS data from JLab Hall A, CLAS, HERMES, COMPASS, ZEUS and H1 experiments.
- Demonstrates that the addition of positron data to the existing DVCS electron data reduces the uncertainties in the real part of CFF H by a factor of ~3



Collaboration track record

	Experiment	PAC	Goal	Results
6 GeV	E00-110	PAC18	1st dedicated DVCS experiment at JLab	PRL97 (2006), PRC83 (2011), PRC92 (2015)
	E03-106	PAC24	1st neutron DVCS experiment	PRL99 (2007)
	E07-007	PAC31	DVCS Rosenbluth-like separation (proton)	PRL117 (2016), Nature Commun. 8 (2017)
	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)
	E12-13-010	PAC40	DVCS Rosenbluth-like separation (proton)	*Scheduled 2023-2024*
	E12-22-006	PAC50	DVCS Rosenbluth-like separation (neutron)	*Scheduled 2023-2024*

Summary and conclusion

- Positrons are the unique way to unambiguously separate the $DVCS^2$ and the BH-DVCS interference

- They will have a strong impact on GPD CFFs fits and extraction, and the 3D-imaging program of the nucleon

- We request **135 (+2) PAC days** of (unpolarized) positrons at $I \geq 1\ \mu A$

- Same setup (HMS+NPS) and kinematics of approved experiment E12-13-010

BACK-UP

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 $\sim \mathcal{O}(M^2/Q^2)$, $\sim \mathcal{O}(t/Q^2)$

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

(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:

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

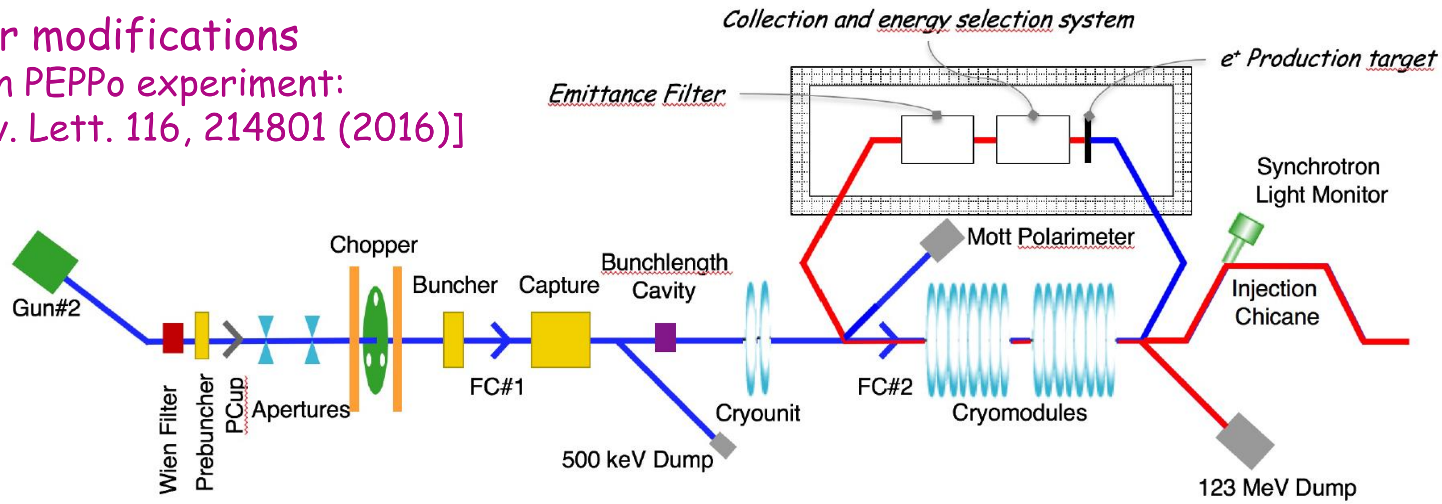
Reducing to a common denominator ($\times\mathcal{P}_1\mathcal{P}_2$), one obtains:

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

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

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

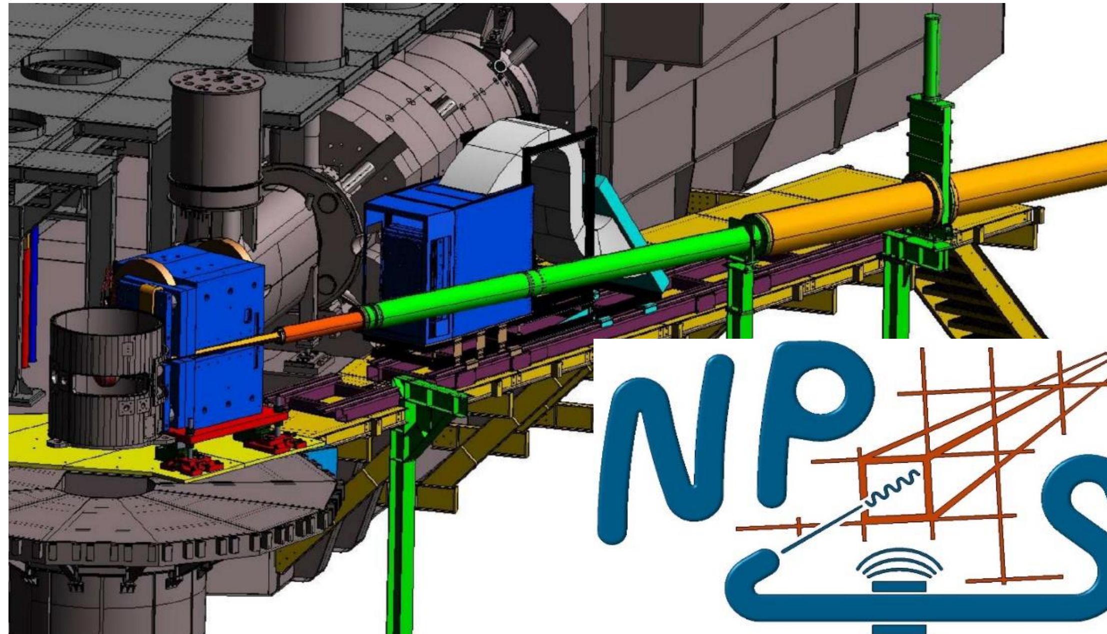
At 11 GeV, after Arc9, e+ beam size ~twice bigger than e- beam

Averaging εx and ε_y:

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

Neutral Particle Spectrometer (NPS)

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



Calorimeter frame being assembled