DVCS using a positron beam in Hall C

Experiment conditionally approved (C2) by PAC48 (2020)

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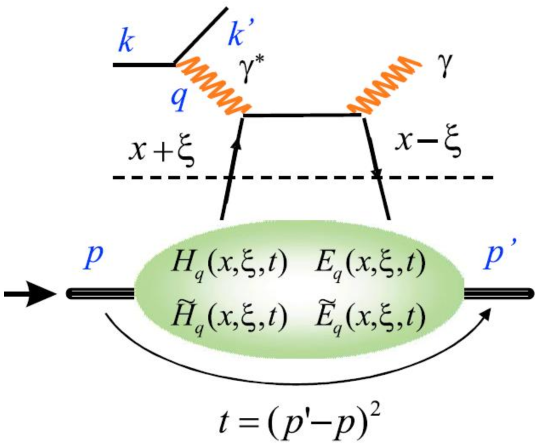
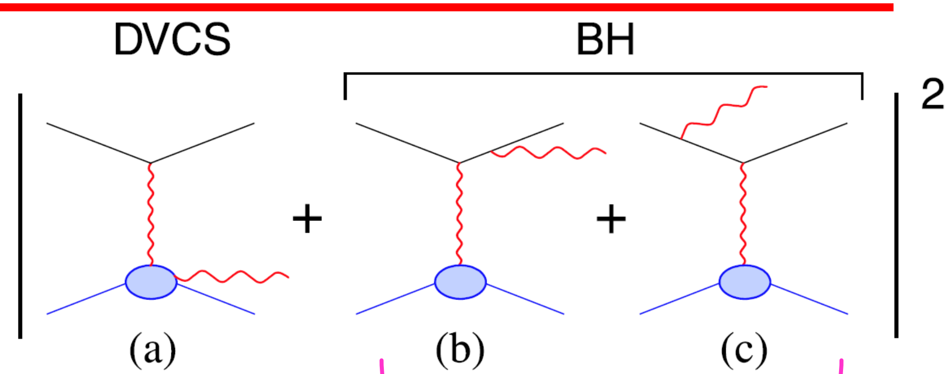
Motivation



$ep \longrightarrow ep\gamma =$



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+

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

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

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…

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

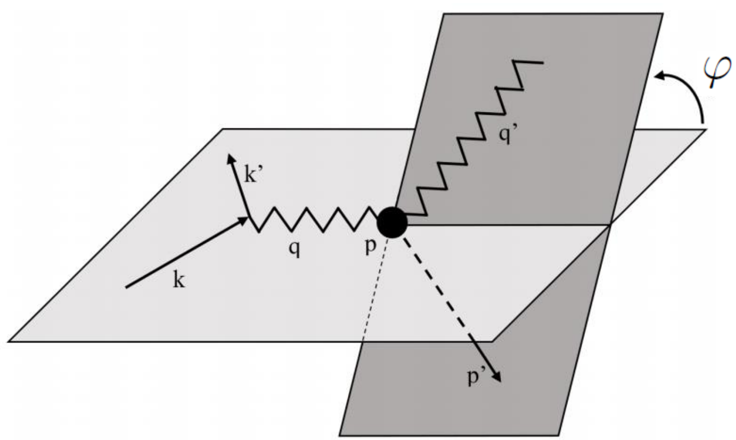
Phys. Rev. **C83** 025201 (2011)
Phys. Rev. Lett. **117**, 262001 (2016)
Phys. Rev. Lett. **118**, 222002 (2017)

E07-007: Rosenbluth-like separation of DVCS

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

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

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

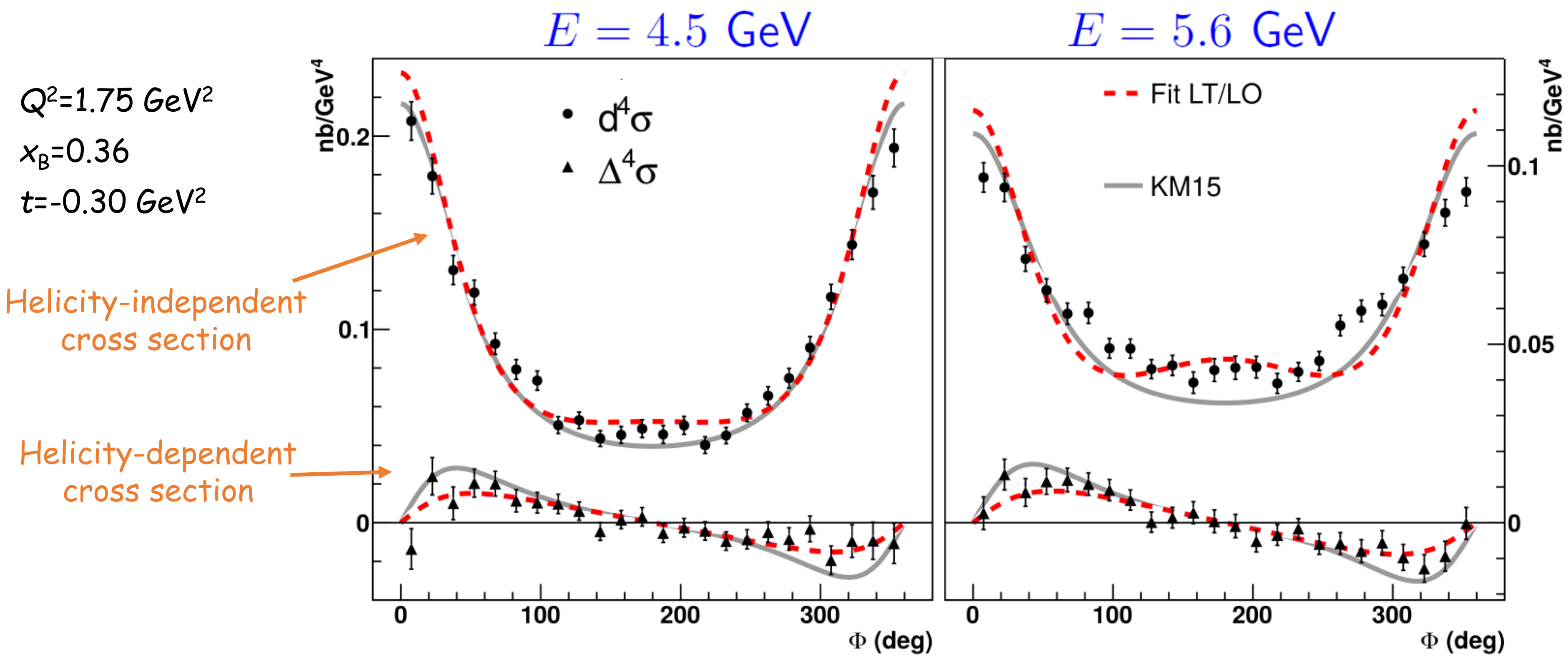


φ-dependence provides 5 independent observables:

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

E07-007: Rosenbluth-like separation of DVCS

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

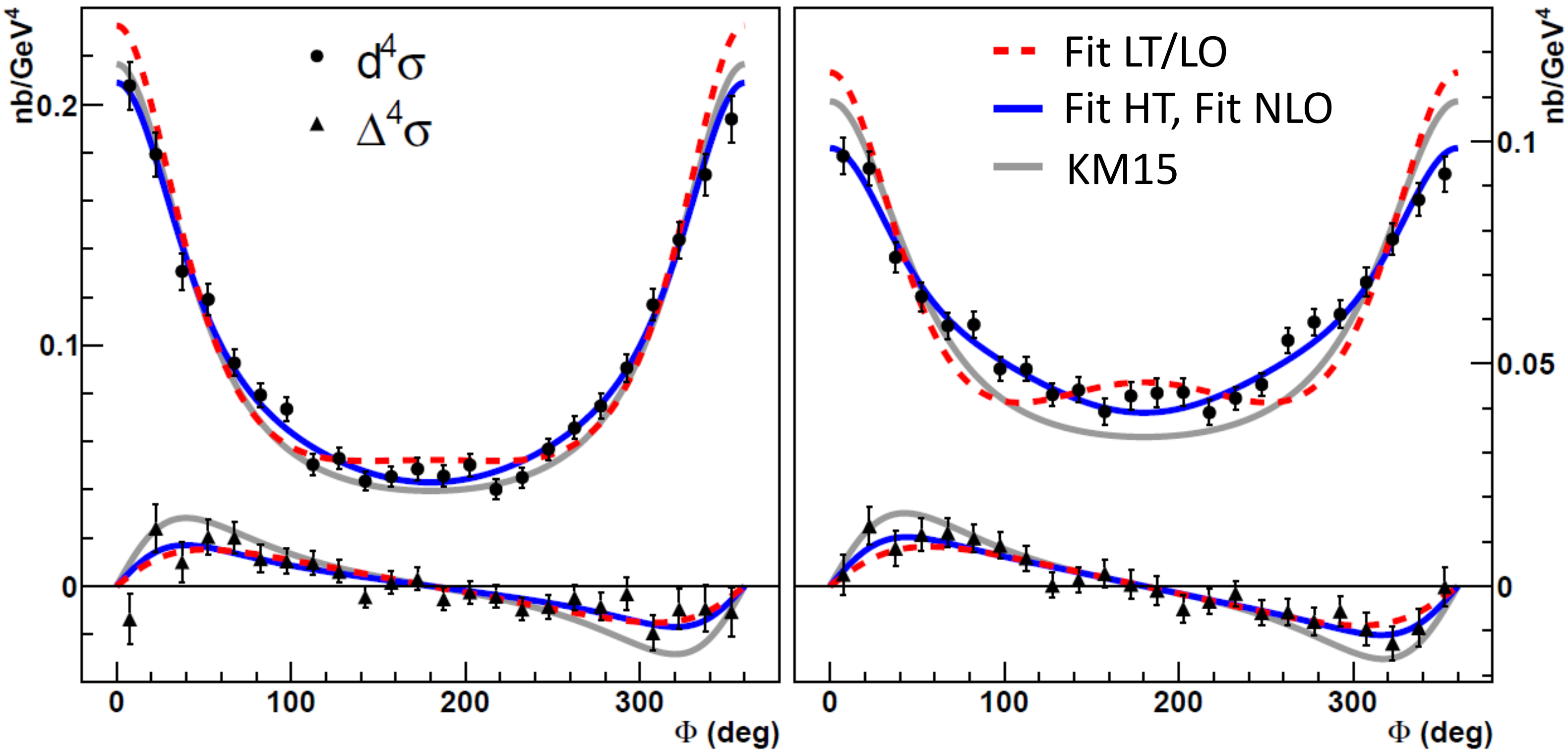


- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

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

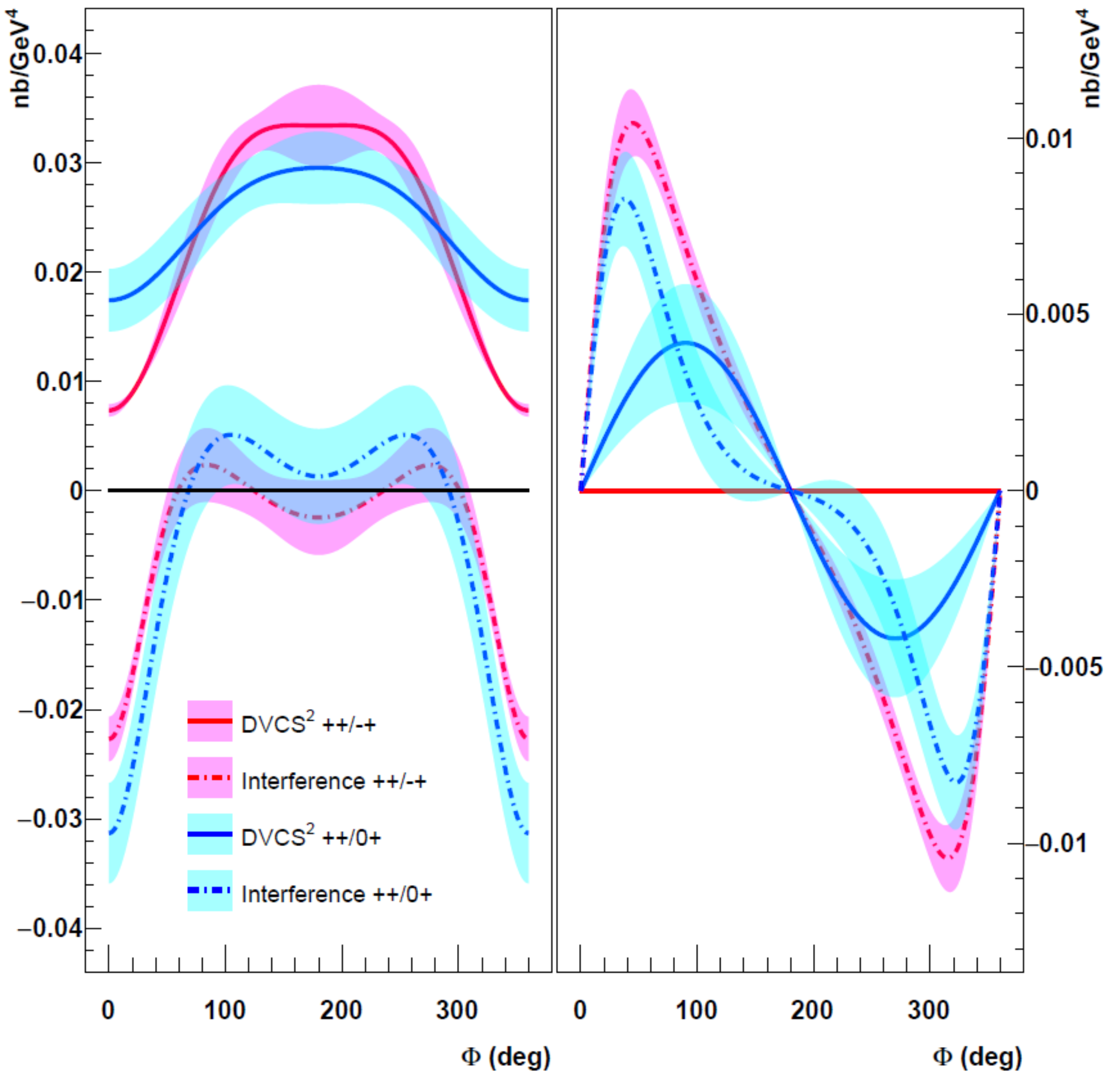
- Cross section measured at 2 beam energies and constant Q^2, x_B, t



- 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 with positrons and NPS (proposal to PAC48)

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

Opposite sign for e- & e+

Physics goals and motivation:

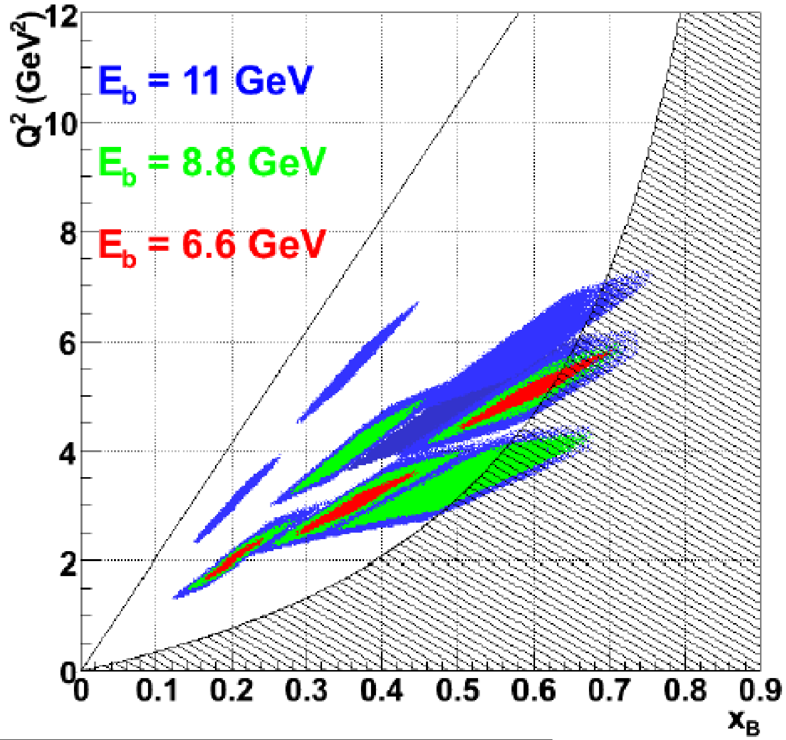
- ✓ Precise determination of the absolute photon electro-production cross section
- ✓ Clean, model-independent separation of $DVCS^2$ and DVCS-BH interference
- ✓ More stringer constraints on CFFs by combining e^- & e^+ data

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

E12-20-012: Kinematic settings

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



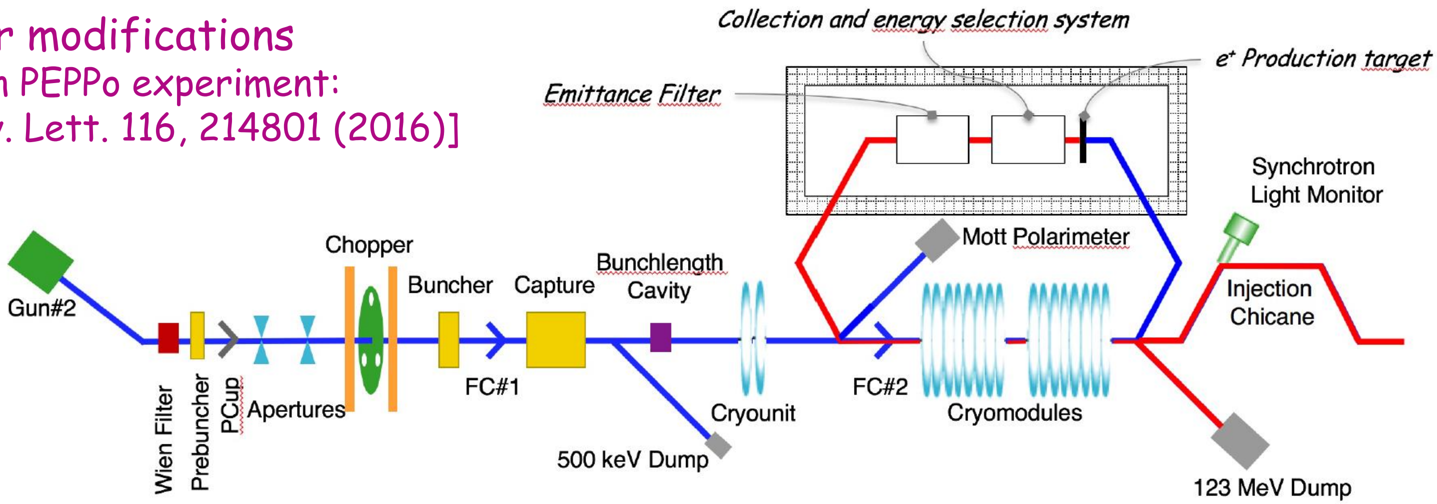
77 days, 5 μA of (unpolarized) positrons assumed

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
k (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																
Days	1	1	3	1	2	3	2	3	4	13	4	3	7	7	2	7	14

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:

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

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

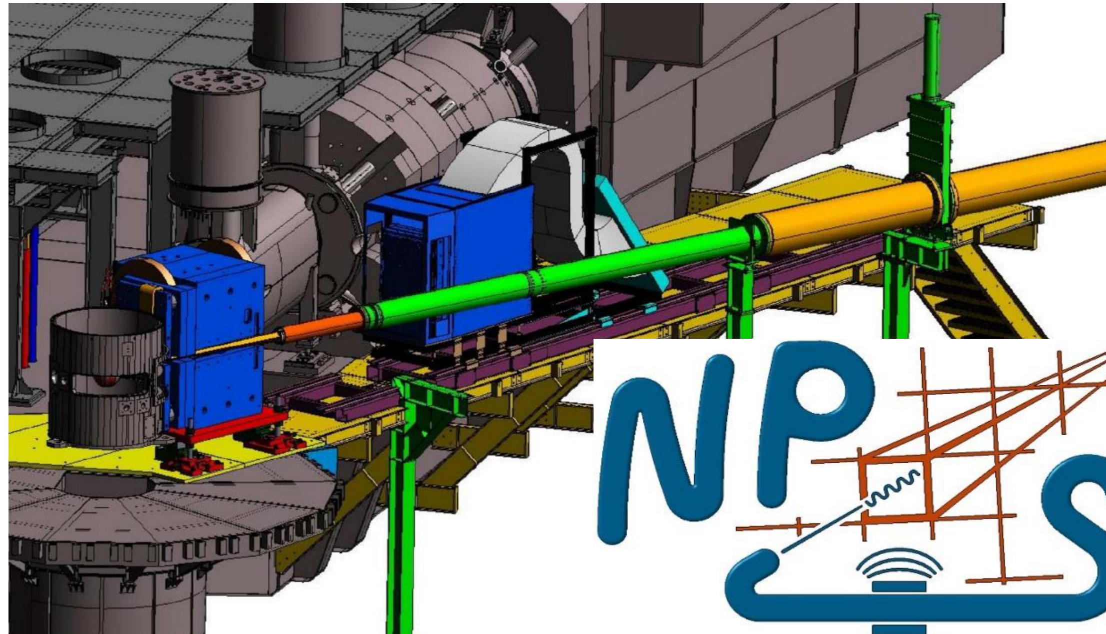
- If the PAC finds our physics program compelling, our collaboration is ready to engage with the Lab to investigate its feasibility.

TAC conclusion:

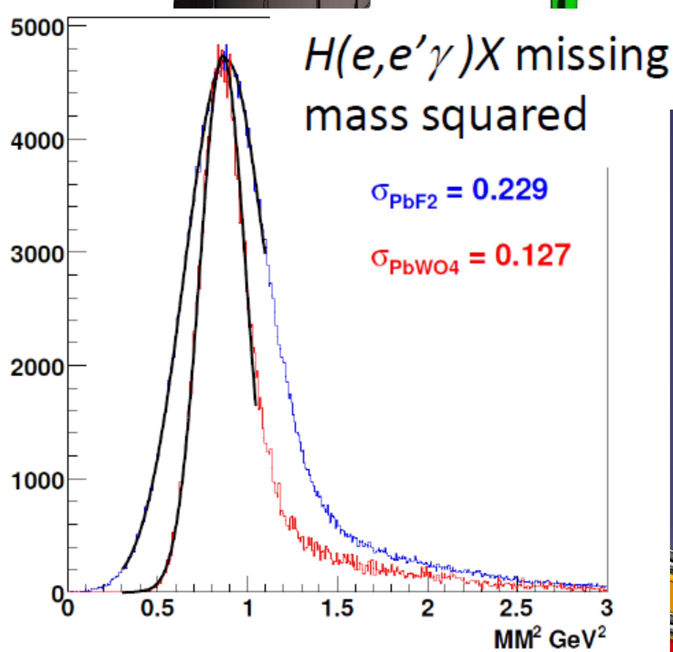
In conclusion, while a positron beam upgrade is a major upgrade which will require substantial accelerator physics development, a detailed cost and implementation plan, and expensive changes to the CEBAF accelerator, a multi-Hall positron beam capability could have great potential for a future JLAB 12-GeV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

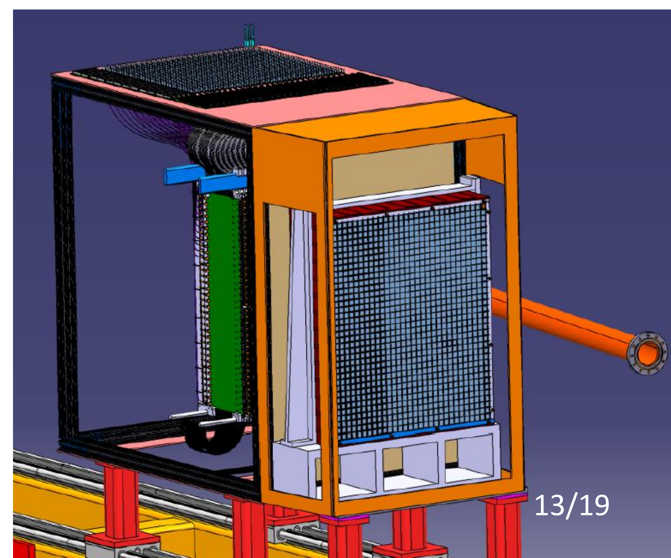
Neutral Particle Spectrometer (NPS)

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



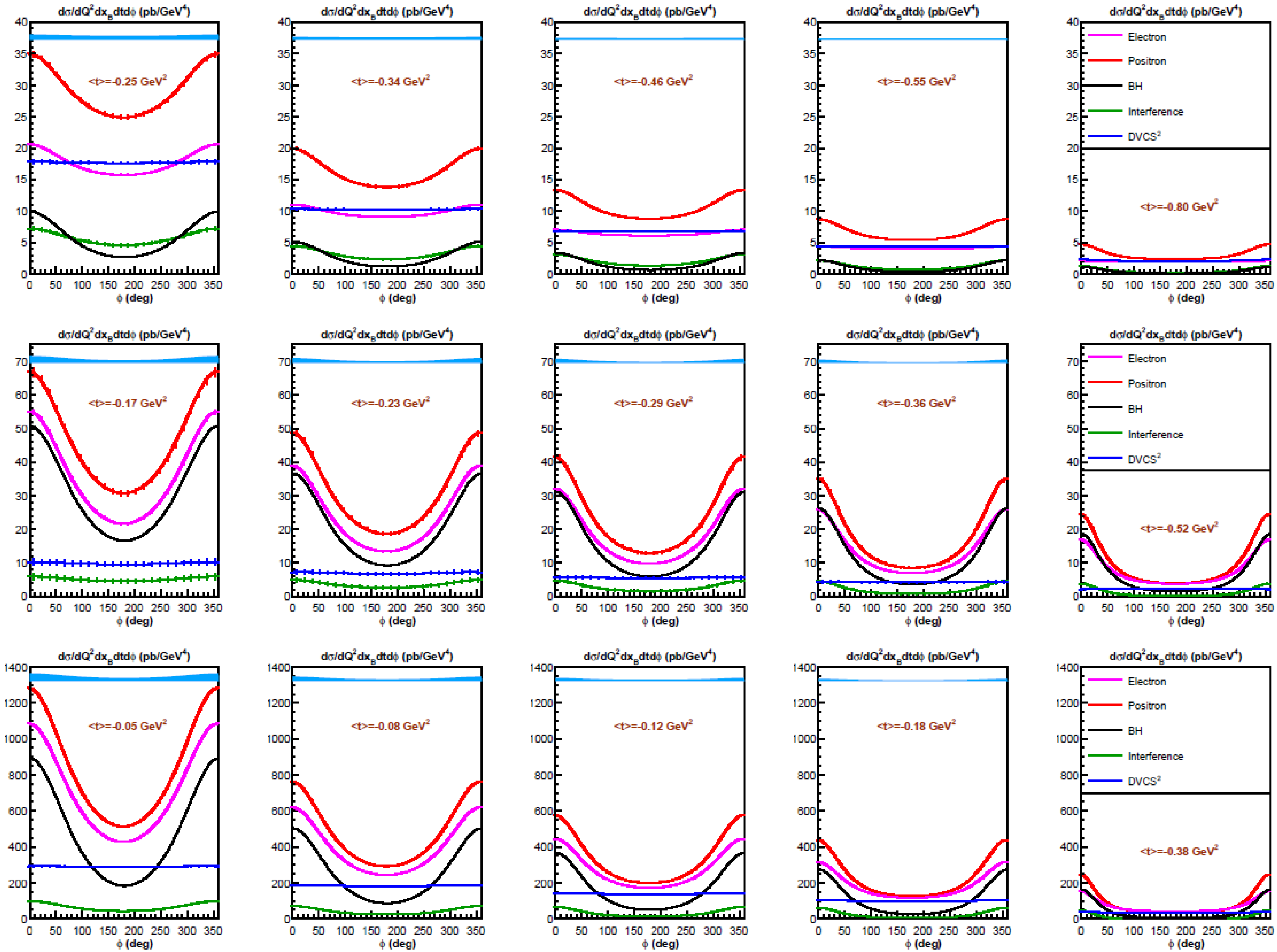
NPS calorimeter assembled in EEL/108





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

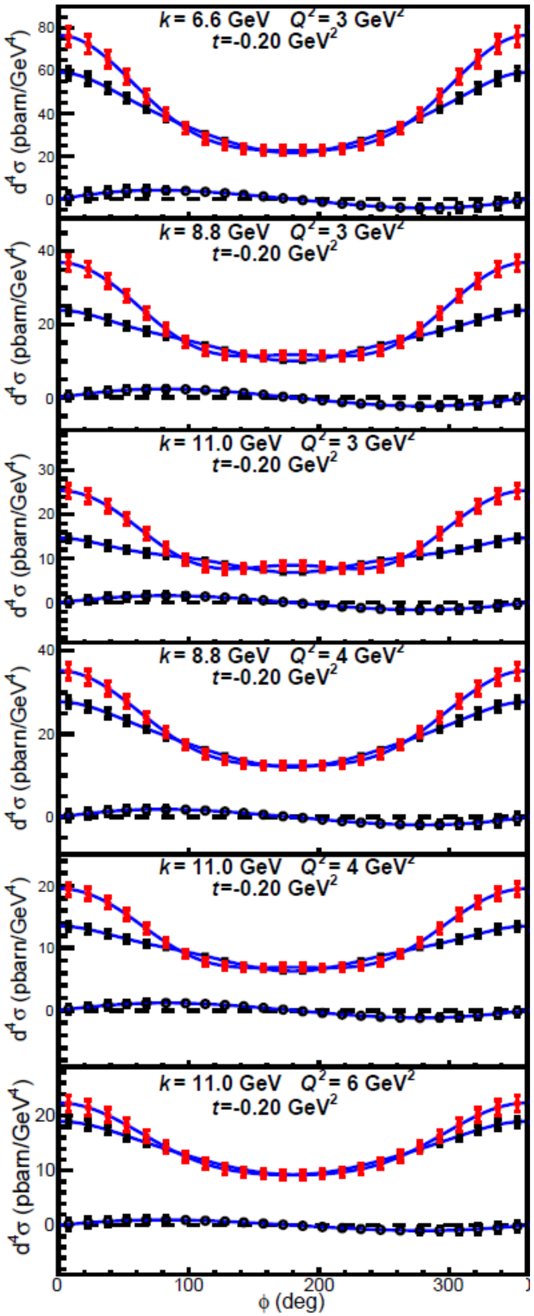
x_B=0.5, Q^2=3.4 GeV^2

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)

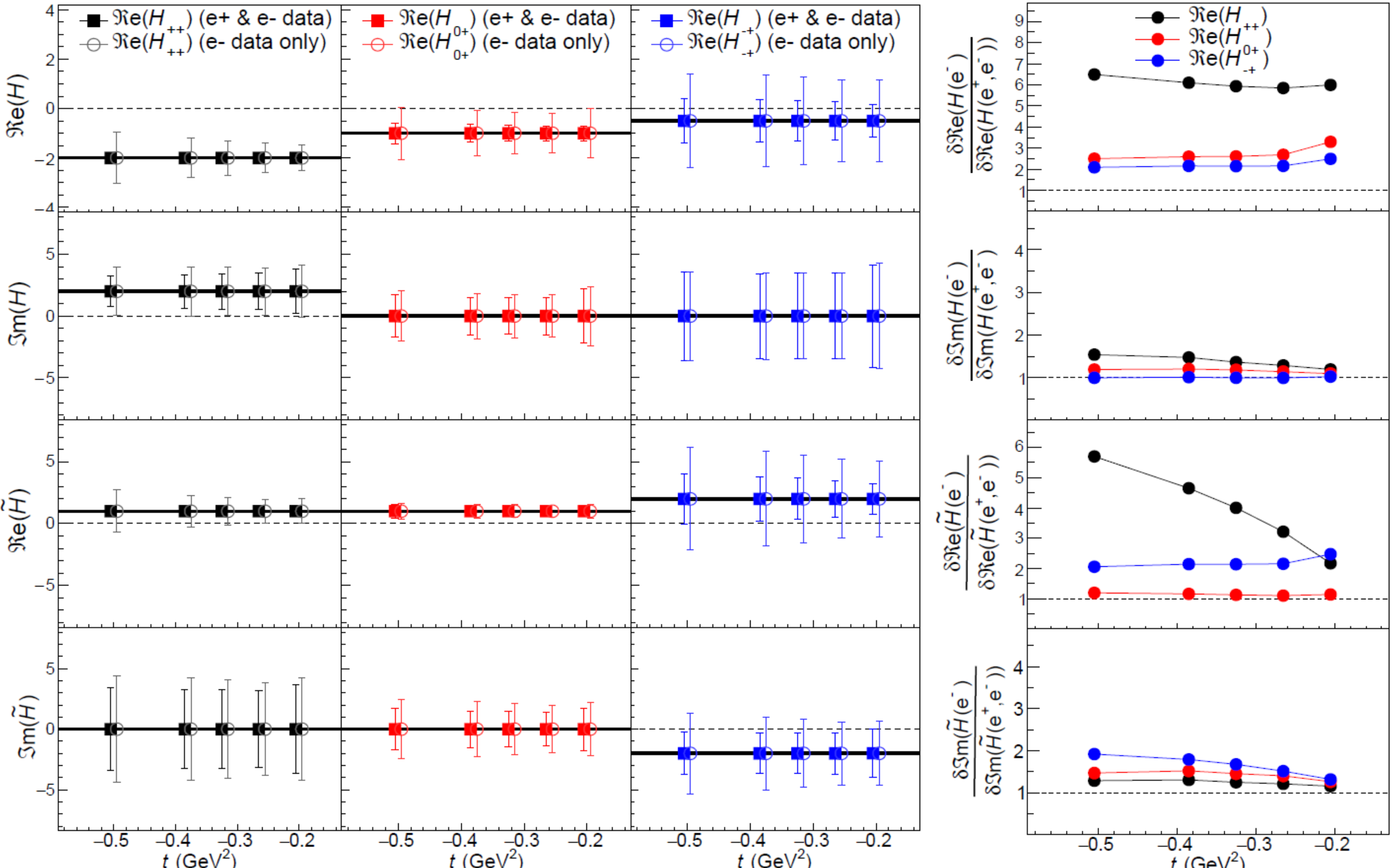
- ✓ Fits with and without the proposed positron data
- ✓ Fits include helicity-conserving CFFs, but also +1 helicity-flip CFFs ("HT") and +2 helicity-flip CFFs ("NLO")
- ✓ Cross sections generated with CFFs values fitted to 6 GeV data

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($\tilde{H}$)

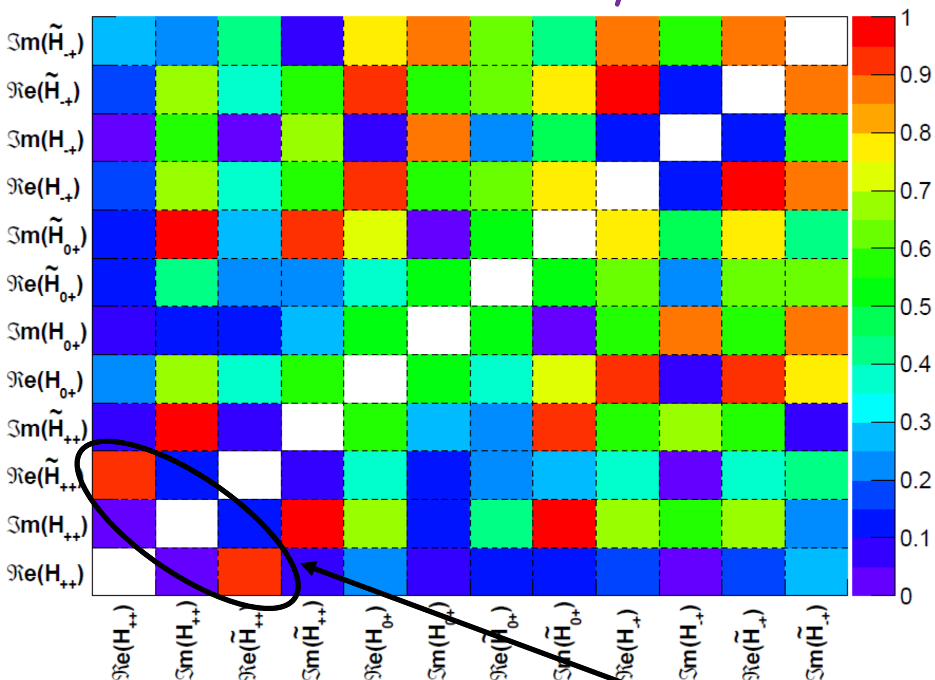
(factor of ~2 for HT and NLO)

Correlation coefficients

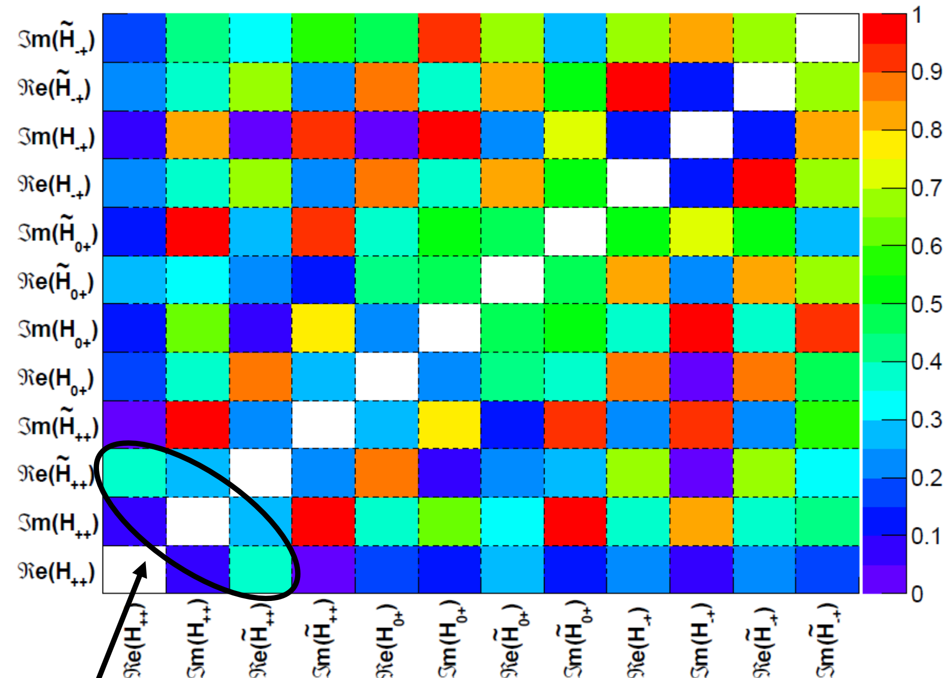
Correlations between different CFFs are significantly improved by a combined fit with positrons

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

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)

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

- **77 PAC days** of (unpolarized) positrons at I ≥ 5 mA requested to PAC48
  (C2 conditionally approved)

- 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