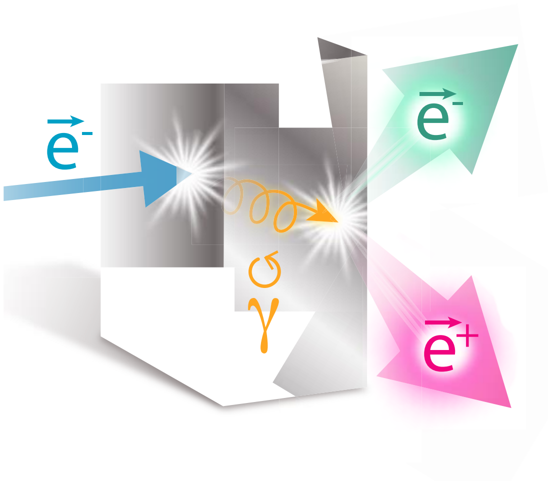
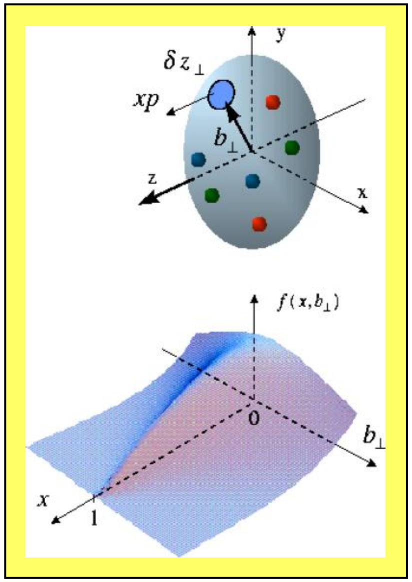
Status of the DVCS proposals

Positron WG Collaboration Meeting

University of Virginia, March 7-8 (2023)

Carlos Muñoz Camacho
IJCLab – CNRS/IN2P3





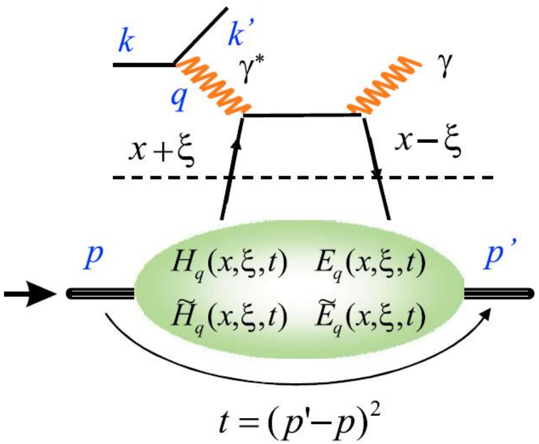
Introduction

- 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

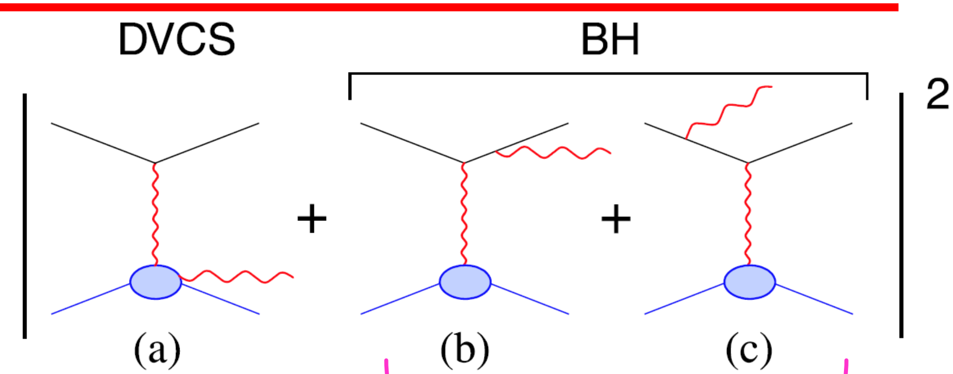
PAC 48 SUMMARY OF RECOMMENDATIONS								
PR12-20-009	E. Voutier	Beam charge asymmetries for Deeply Virtual Compton Scattering on the proton at CLAS12	B	100			**C2**	4
PR12-20-012	C. Munoz Camacho	Deeply Virtual Compton Scattering using a positron beam in Hall C	C	77			**C2**	4

Add C2 definition here!

Motivation



$ep \longrightarrow ep\gamma =$



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

At leading twist:

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

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

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

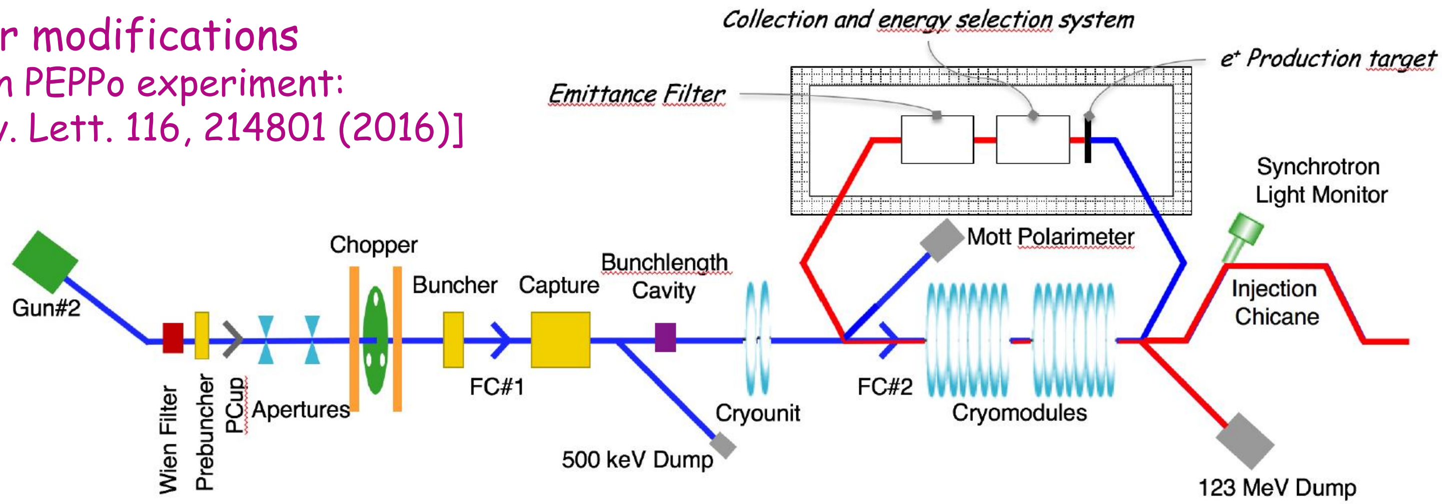
Opposite sign for e- & e+

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

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

Positron production and transport

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



Dominated by damping in the LINACS

Dominated by synchrotron rad. in Arcs

Electrons

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.

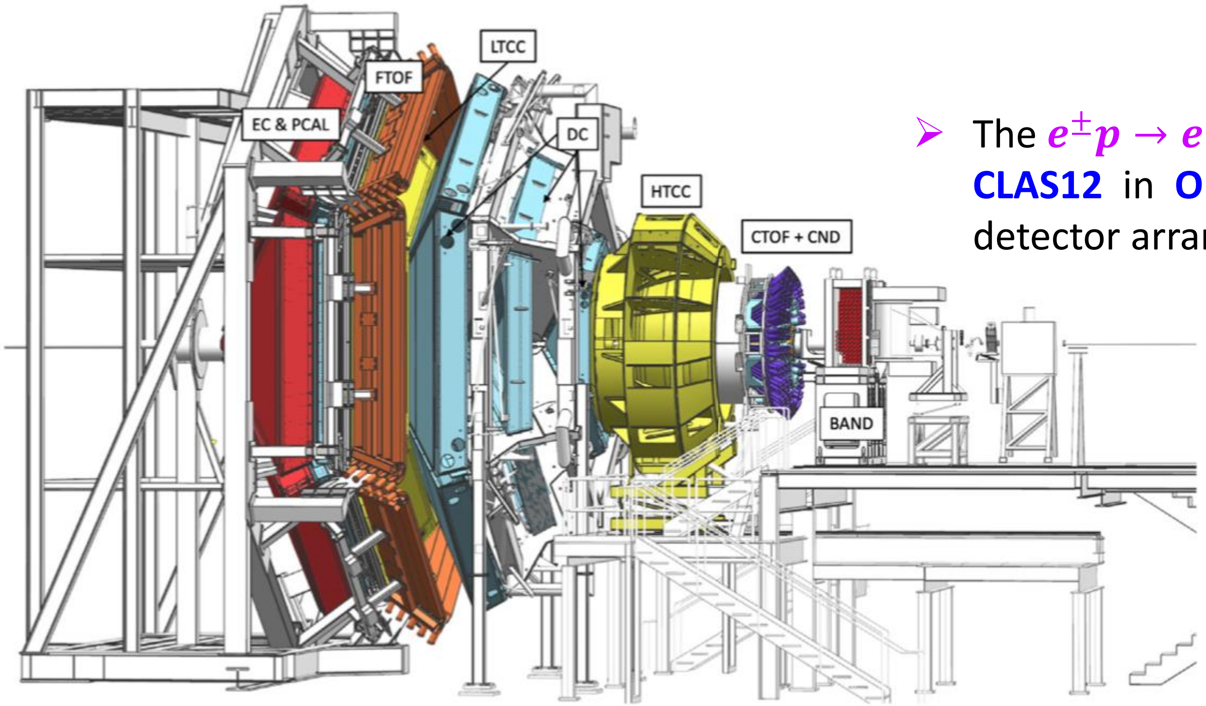
TAC conclusion:

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.

Hall B positron experiment

CLAS12

V. Burkert et al. NIMA 959 (2020) 163419



- The $e^{\pm}p \to e^{\pm}p\gamma$ reaction will be measured with **CLAS12** in **OUT-bending** mode, using the regular detector arrangement.

  - $\mathcal{L} = 0.6 \times 10^{35}\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$
  - New 5 cm LH_2 target cell

- There is **no difference** bewteen **e$^-$** and **e$^+$** beam transport in Hall B beam line, nor in beam related detector background.

- Beam diagnostics are expected to operate similarly with **e$^-$** and **e$^+$** beam.

Hall B beam time request

We are asking for a total of **100 days** of beam, operating **CLAS12** with **45 nA e$^-$** and **e$^+$** beams polarized at **60%**, distributed in :

Purpose	Label	Beam parameters					Target	Sol. Pol.	Tor. Pol.	Time (h)
		q (e)	Nat.	E (GeV)	I (nA)	λ (%)				
$ep \to ep$	Cal.	–	P	2.2	45	0	5 cm LH_2	–	+	24
								+		24
			S					+		24
								–		24
$ep \to ep\gamma$	Phy.			10.6		60		–		480
Background	Cal.							–		48
$ep \to ep\gamma$	Phy.							+		480
Background	Cal.							+		48
Commissioning		+	S	2.2	45	0	5 cm LH_2	+	–	72
$ep \to ep$	Cal.							+		24
								–		24
Commissioning				10.6		60		–		72
$ep \to ep\gamma$	Phy.							–		480
Background	Cal.							–		48
$ep \to ep\gamma$	Phy.							+		480
Background	Cal.							+		48
									Total	**2400**

- **80** days for **physics** data taking;
- **20** days for **commissioning** and **calibration;**

using lepton beams of different nature

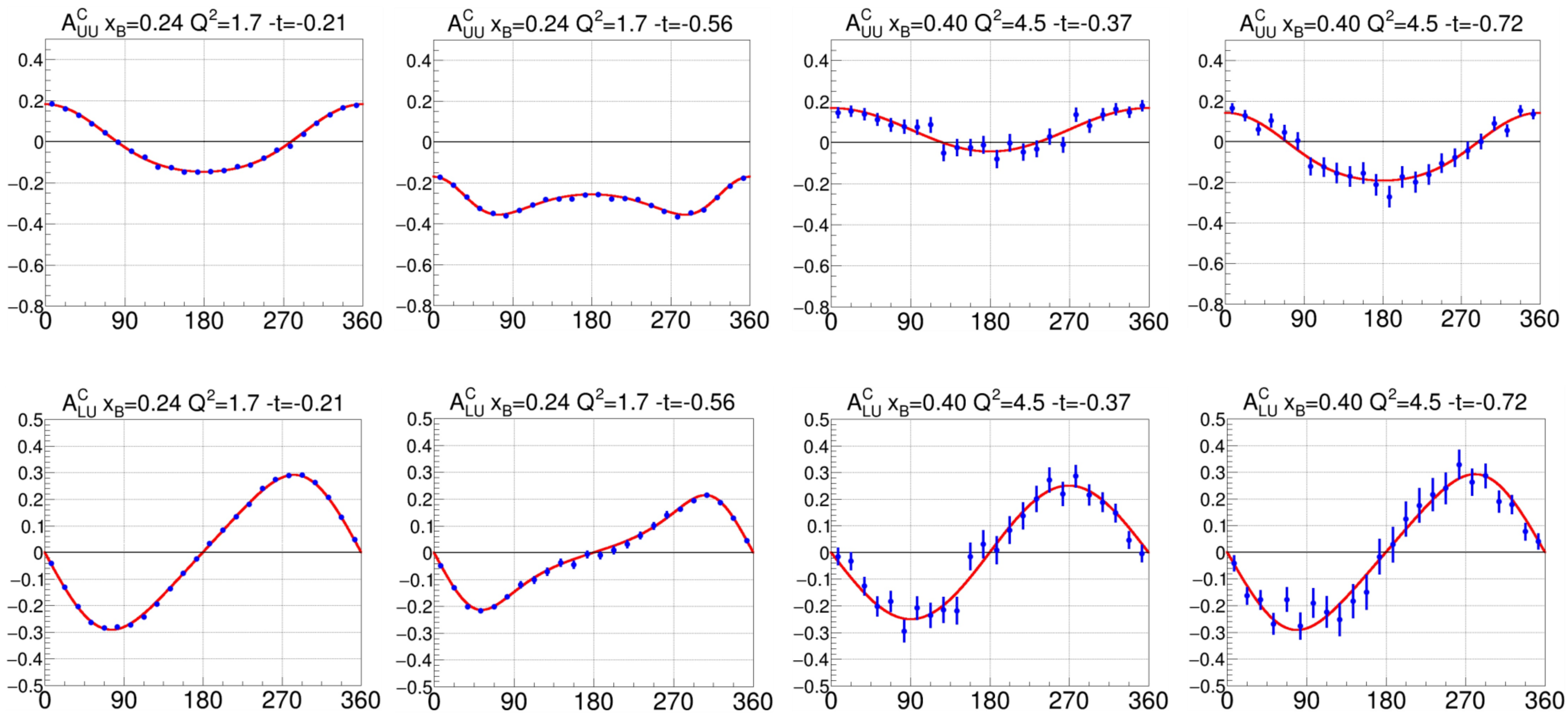
- 2 days with the CEBAF **e$^-$** beam;
- 46 days with the secondary **e$^-$** beam;
- 52 days with the secondary **e$^+$** beam;

and different energies

- 9 days at **2.2** GeV;
- 91 days at **10.6** GeV.

Hall B projections

➢ *A sample of expected experimental data… 15 bins in (x_B,Q^2) x 6 bins in t =* ***90 azimuthal dependences*** *per observable (A^C_{UU}, A^C_{LU}).*

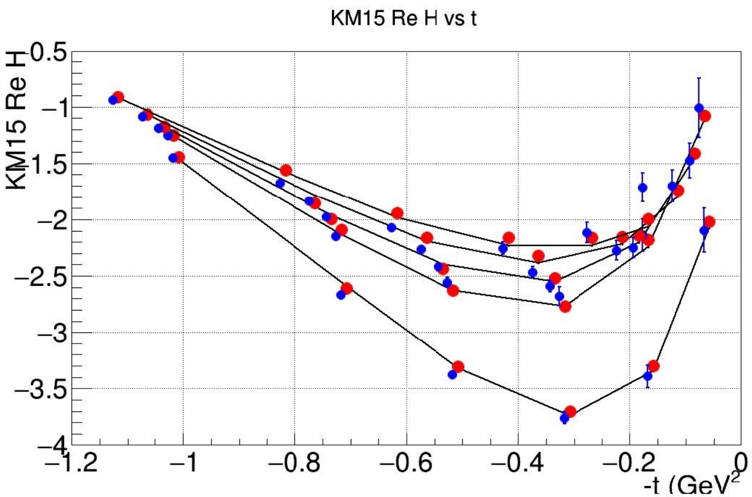


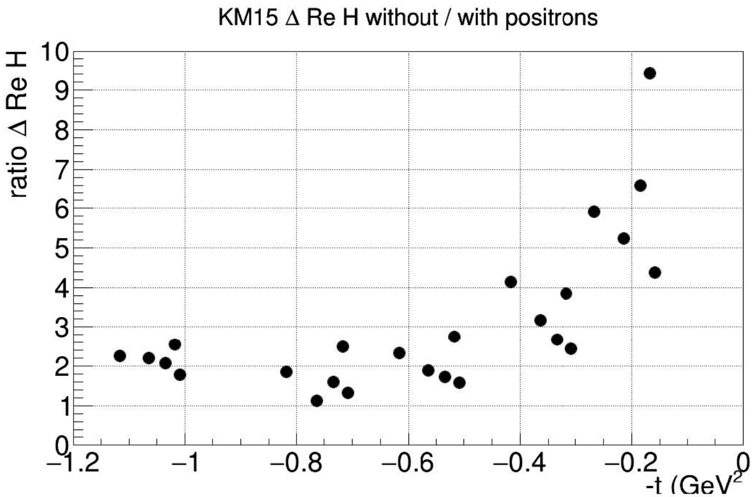
Hall B impact of positrons

- The importance of positron beams for the determination of CFFs can be quantified in a model-dependent way depending on : the cross section model, the GPDs model, and the hypotheses of the fitting approach.

Observable	σ_{UU}	A_{LU}	A_{UL}	A_{LL}	A^C_{UU}	A^C_{LU}
Sytematics (%)	5	3	3	$3 \oplus 3$	3	3

Fitting of $\{\mathcal{H}, \widetilde{\mathcal{H}}\}$ CFFs assuming model values for $\{\mathcal{E}, \tilde{\mathcal{E}}\}$ CFFs.





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:

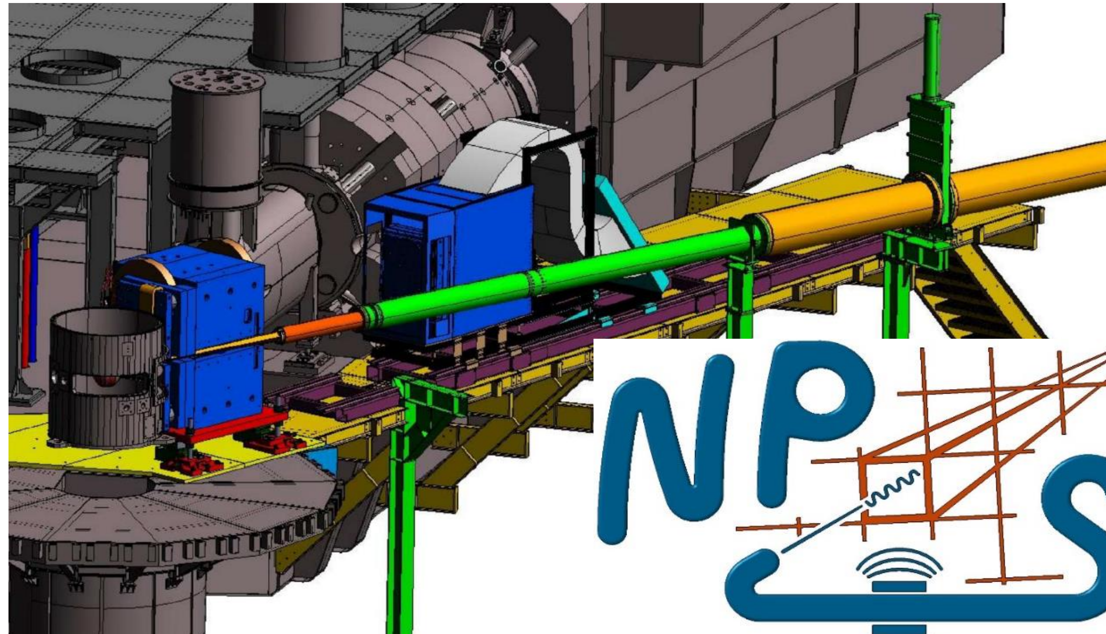
- ✓ Precise determination of the absolute photon electro-production cross section
- ✓ Clean, model-independent separation of DVCS^2 and DVCS-BH interference
- ✓ More stringer constraints on CFFs by combining e^- & e^+ data

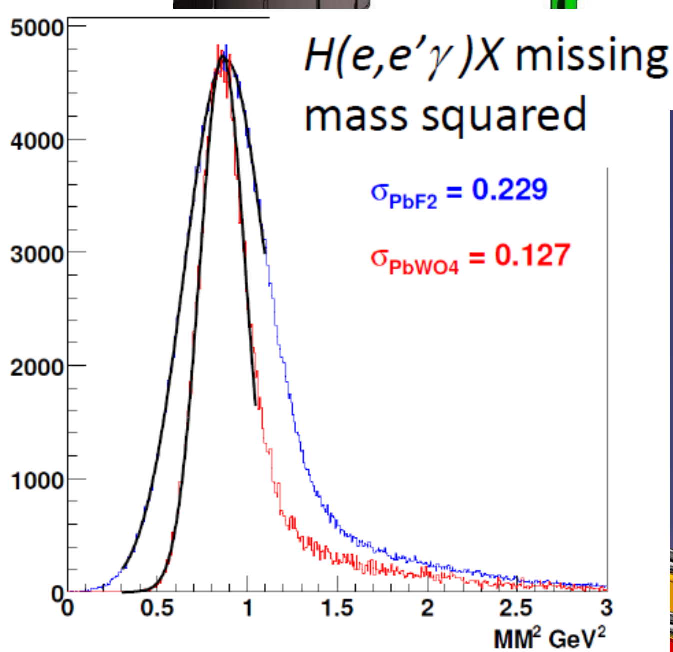
In a nutshell:

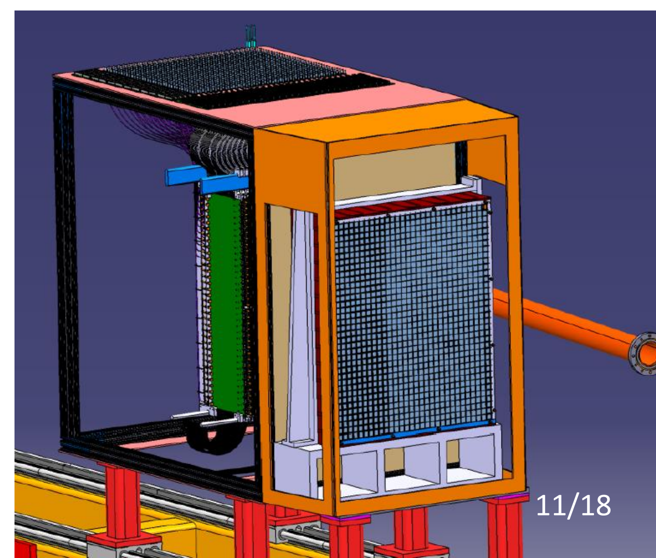
- ➢ Same experimental configuration as approved experiment E12-13-010
- ➢ Expected positron beam momentum spread comparable with current electron beam
- ➢ Positron beam size larger than current electron beam (twice bigger at 11 GeV according to current simulation)
- ➢ No additional systematic uncertainties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

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

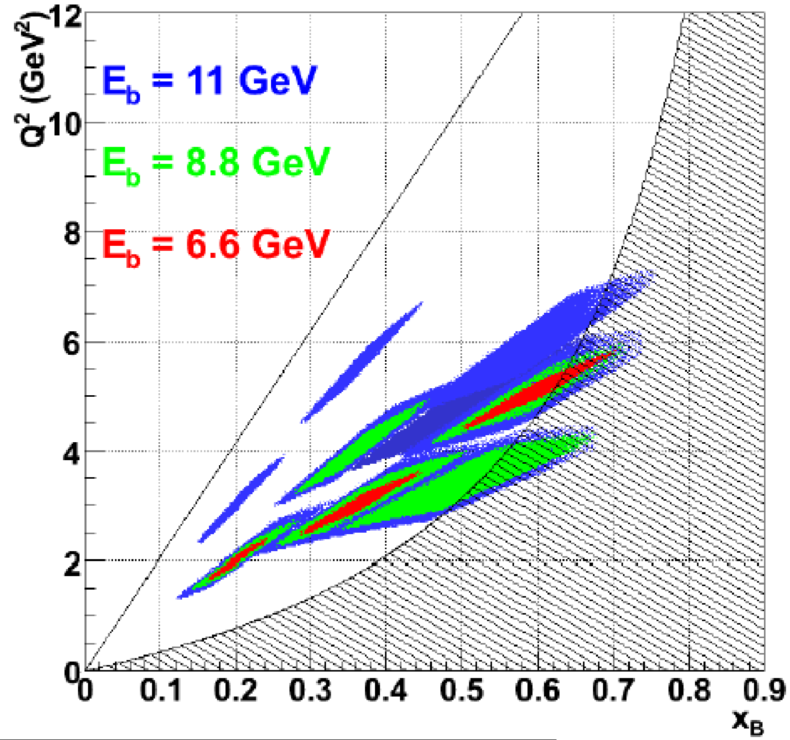






PR12-20-012: Kinematic & beam time request

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



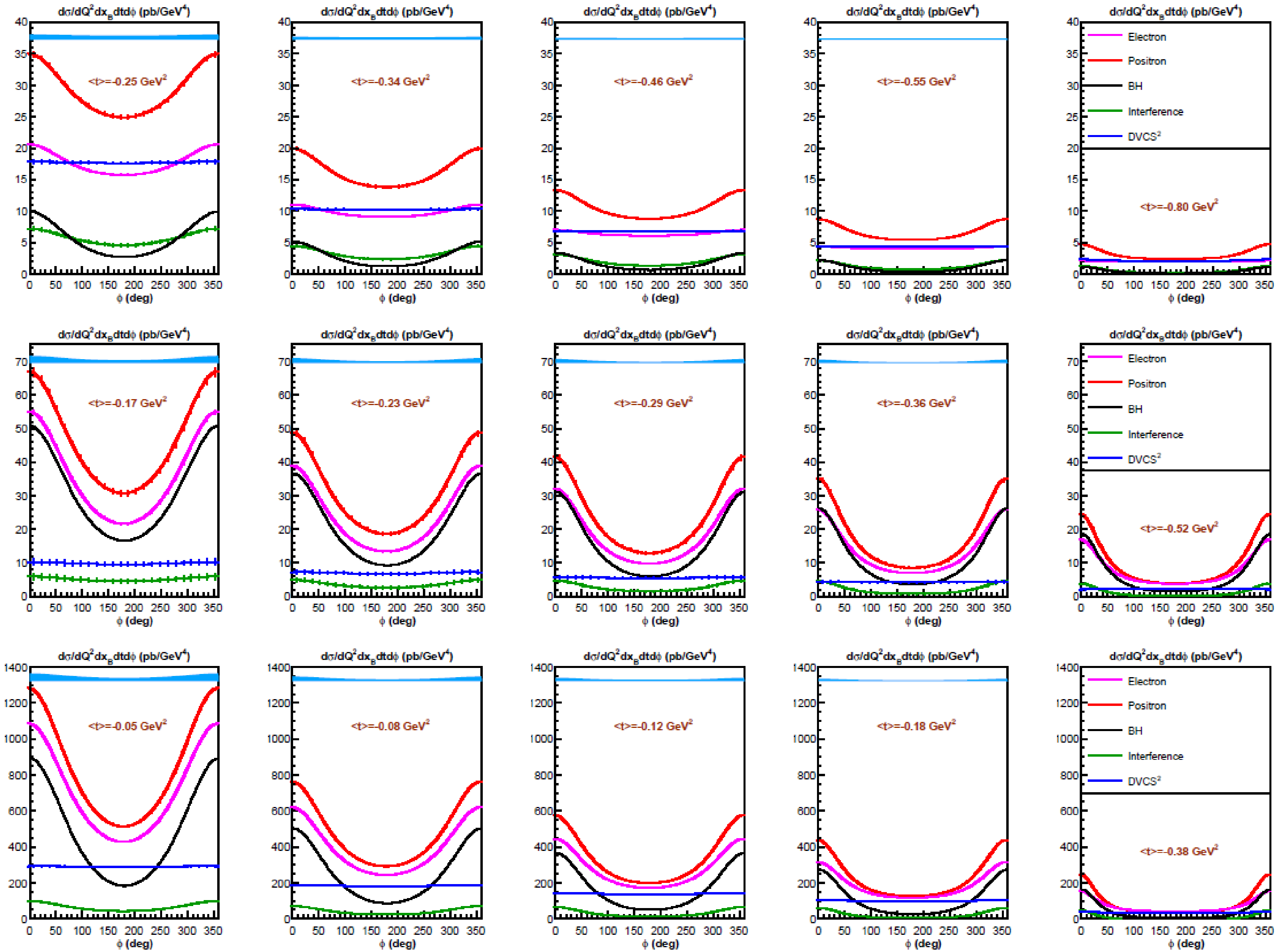
77 days, 5 μA of (unpolarized) positrons assumed

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

Separation of DVCS^2 and BH-DVCS interference

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

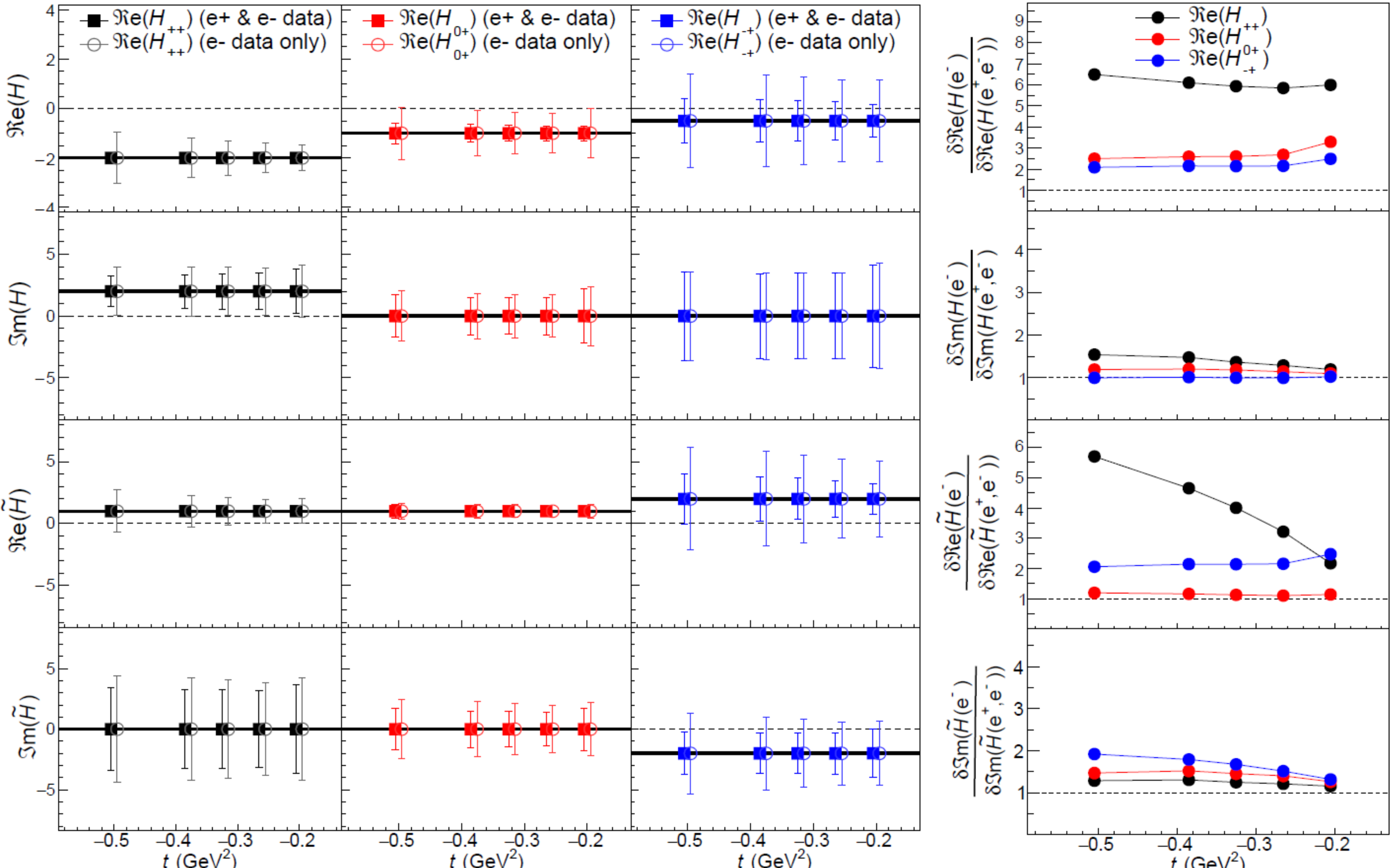


x_B=0.2, Q^2=2.0 GeV^2

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(H̃)

(factor of ~2 for HT and NLO)

PAC48 report

Measurement and Feasibility:

Hall B proposal

As a secondary e^+ beam has a much larger momentum dispersion and emittance than the primary e^- beam currently existing, one has the same δp/p with a spot size 2-3 times larger at the target. Therefore, a target cell with 50% larger (15 mm diameter) entrance and exit windows is needed to avoid any interaction with the target structure frames. This difference in the beam parameters leads the collaboration to require equal statistics of electron and positron data using secondary e^+ *and* e^- beams.

Hall C proposal

Therefore, there are no concerns about the experimental setup, and the committee is confident that the described measurements can be performed.

Common to Hall B and Hall C proposals

Issues: The iTAC report concludes that "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." The PAC fully agrees with this statement.

To clearly show what science would be left unaddressed without having a polarized positron beam available at JLab, the physics impact of positron beam experiments should be demonstrated more rigorously. This should include an impact study with positron beam pseudo-data and all other existing and anticipated future data with an electron beam. One would also like to see which amount of electron data alone would be needed to obtain comparable constrains on the CFFs. Furthermore, to guide the technological development of a positron source, it is important that the experiment determines clear performance requirements for the positron beam.

The PAC notes that proposal PR12-20-012 requires no electron data set with equal beam conditions for an extraction and separation of CFFs with high accuracy. It would be interesting if both groups could come to a common understanding on this issue.

Summary: The PAC recognizes the strong science case of positron beams for the GPD program at JLab. However, it feels that more rigorous simulations are needed to highlight the unique potential of the proposed experiment for constraining Compton Form Factors and eventually GPDs. Moreover, the amount of required beam time with secondary electron beams needs to be justified in a more quantitative way.

(only in Hall B report)

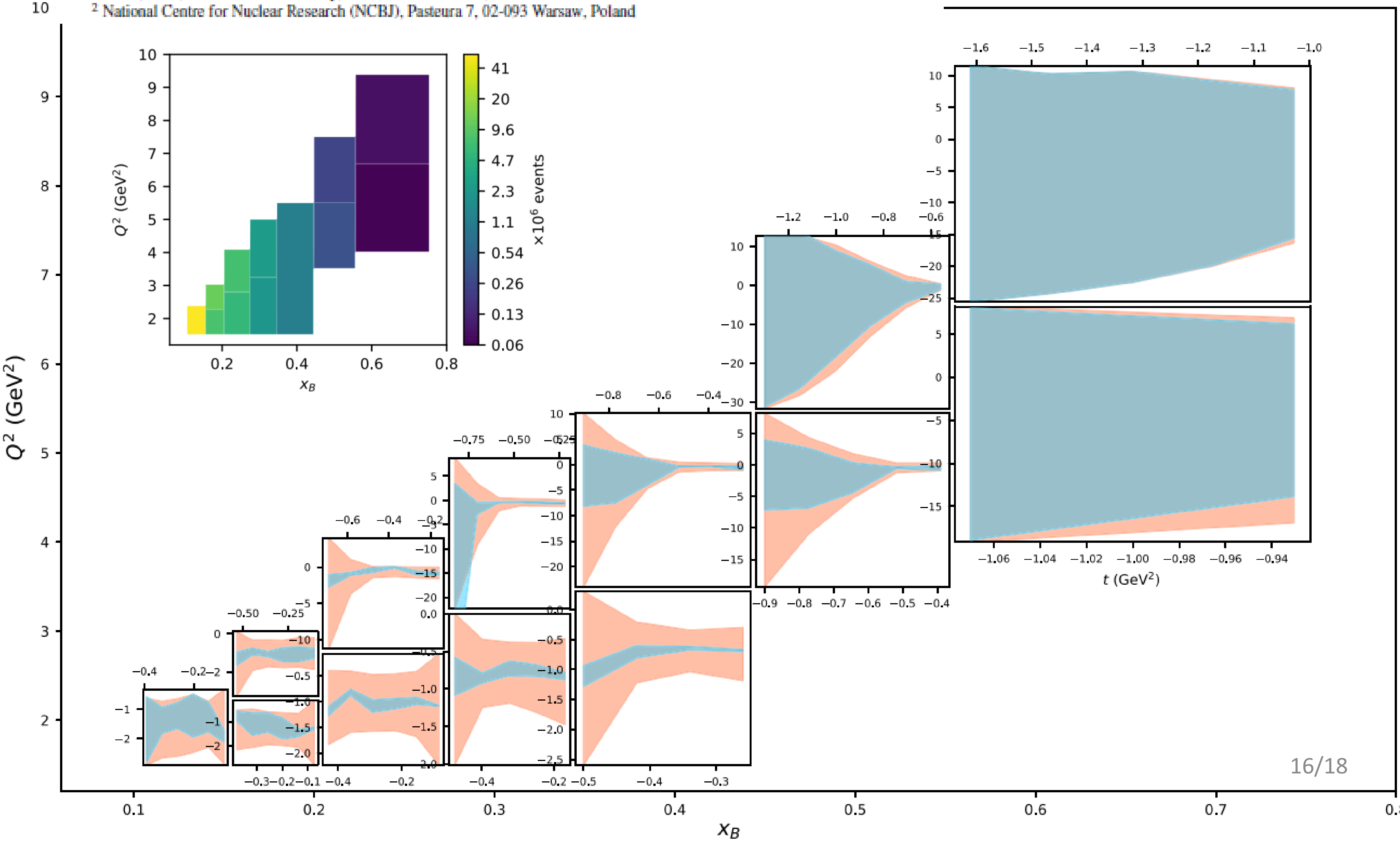
EPJA paper (Pawel et al.)

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

H. Dutrieux[1,a], **V. Bertone**[1,b], **H. Moutarde**[1,c], **P. Sznajder**[2,d]

[1] IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[2] National Centre for Nuclear Research (NCBJ), Pasteura 7, 02-093 Warsaw, Poland

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



Gepard (K. Kumericki's code)

gepard.phy.hr/index.html

gepard

Search docs

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

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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)
```

Summary and outlook

- Both Hall B and Hall C proposals are C2 from PAC48 (3 years ago)

- To address the report, a better, more comprehensive way to show the impact of positrons for DVCS and CFF extraction needs to be presented:

  Two possibilities:

  - Extend EPJA paper to all DVCS data (present and future) using PARTONS

  - Develop a global fit using the GEPARD code

- The Hall B proposal needs to clarify (or justify better) the need of electron new/additional electron data for the BCA measurement

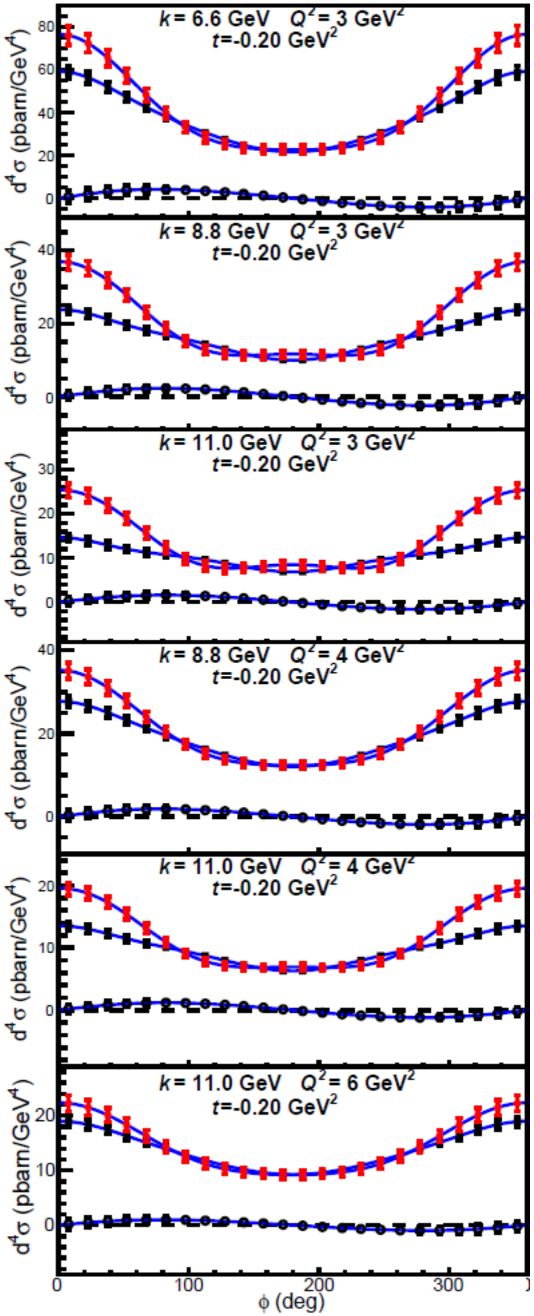
BACK-UP

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**

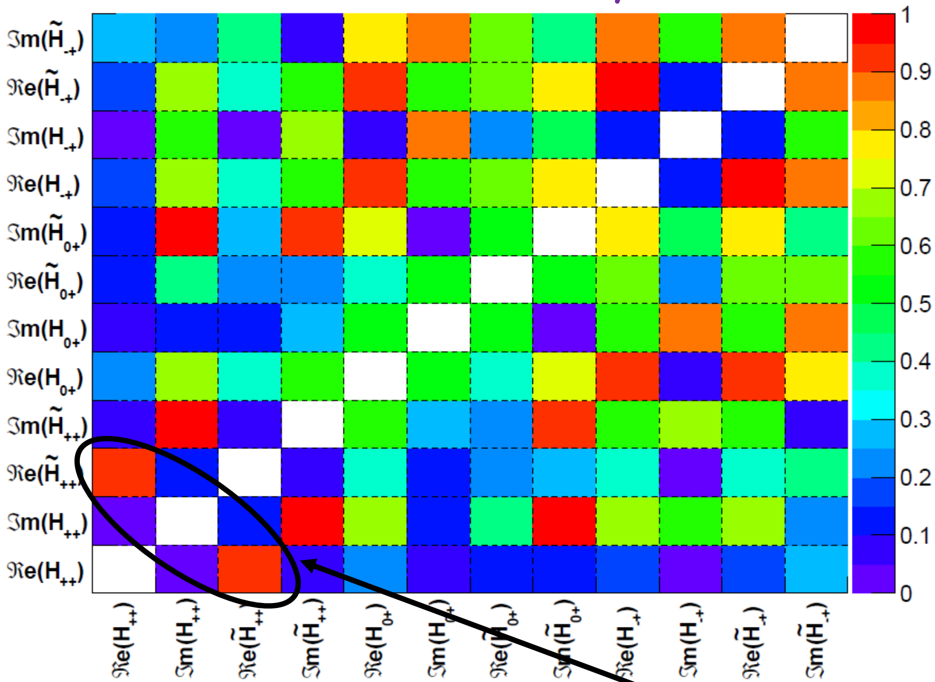
of the DVCS cross section

Correlation coefficients

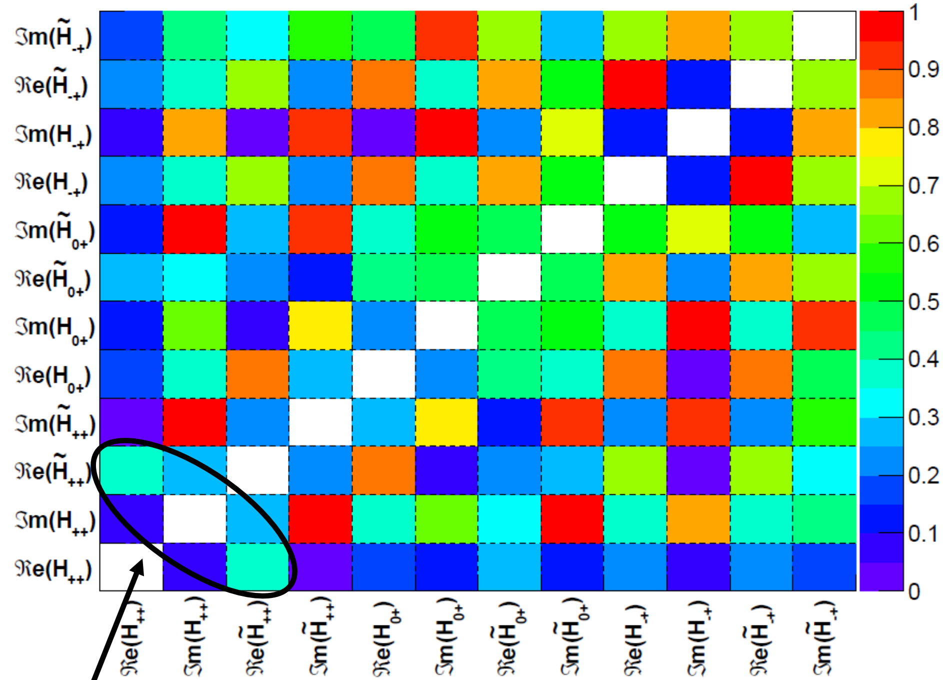
Correlations between different CFFs are significantly improved by a combined fit with positrons

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

Electrons only



Electrons & Positrons



LT/LO HT NLO

(t = -0.26 GeV^2)

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

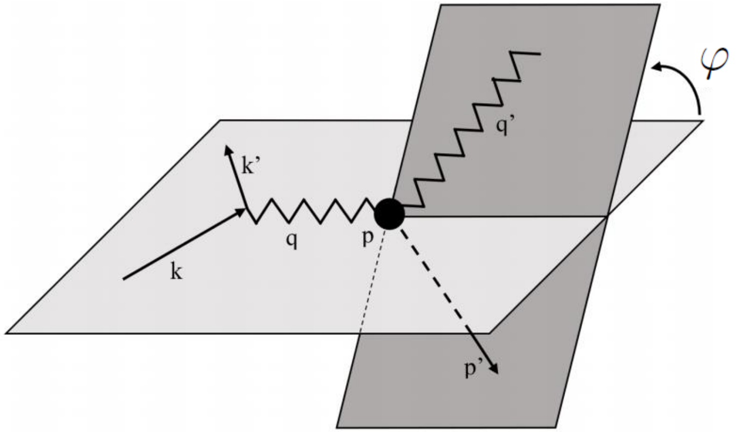
(from -94% without positrons to -39% when electron and positrons are combined, in this t-bin)

E07-007: Rosenbluth-like separation of DVCS

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

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

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

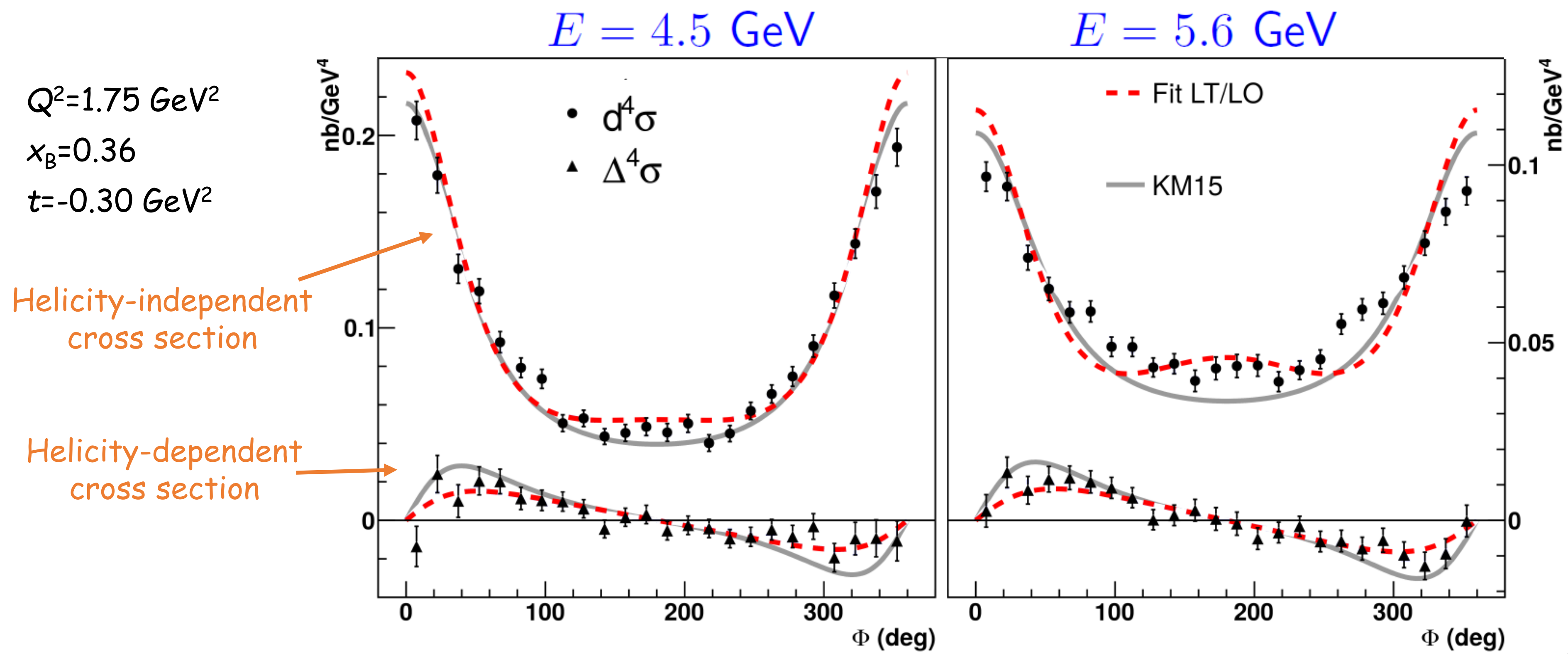


φ-dependence provides 5 independent observables:

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

E07-007: Rosenbluth-like separation of DVCS

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

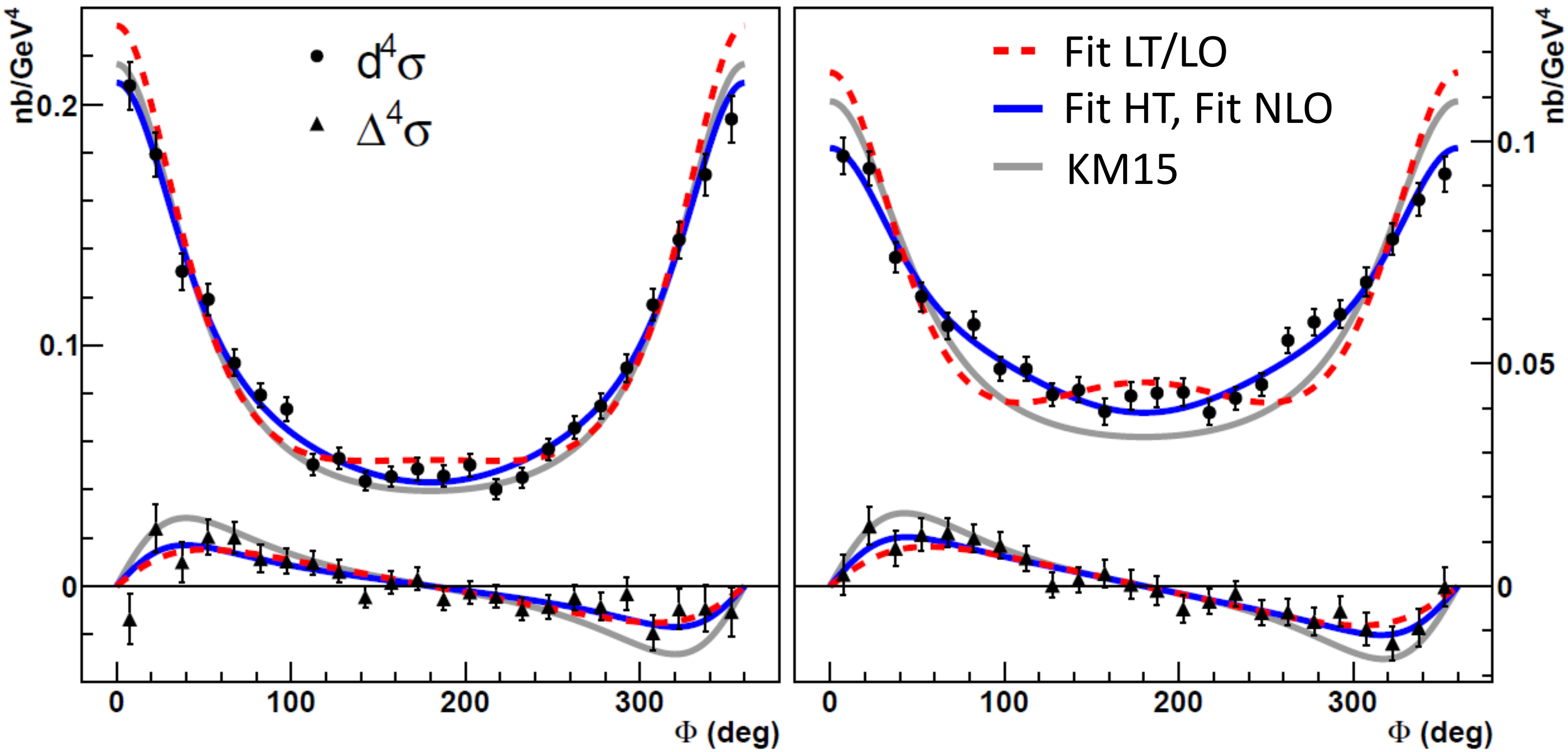


- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

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

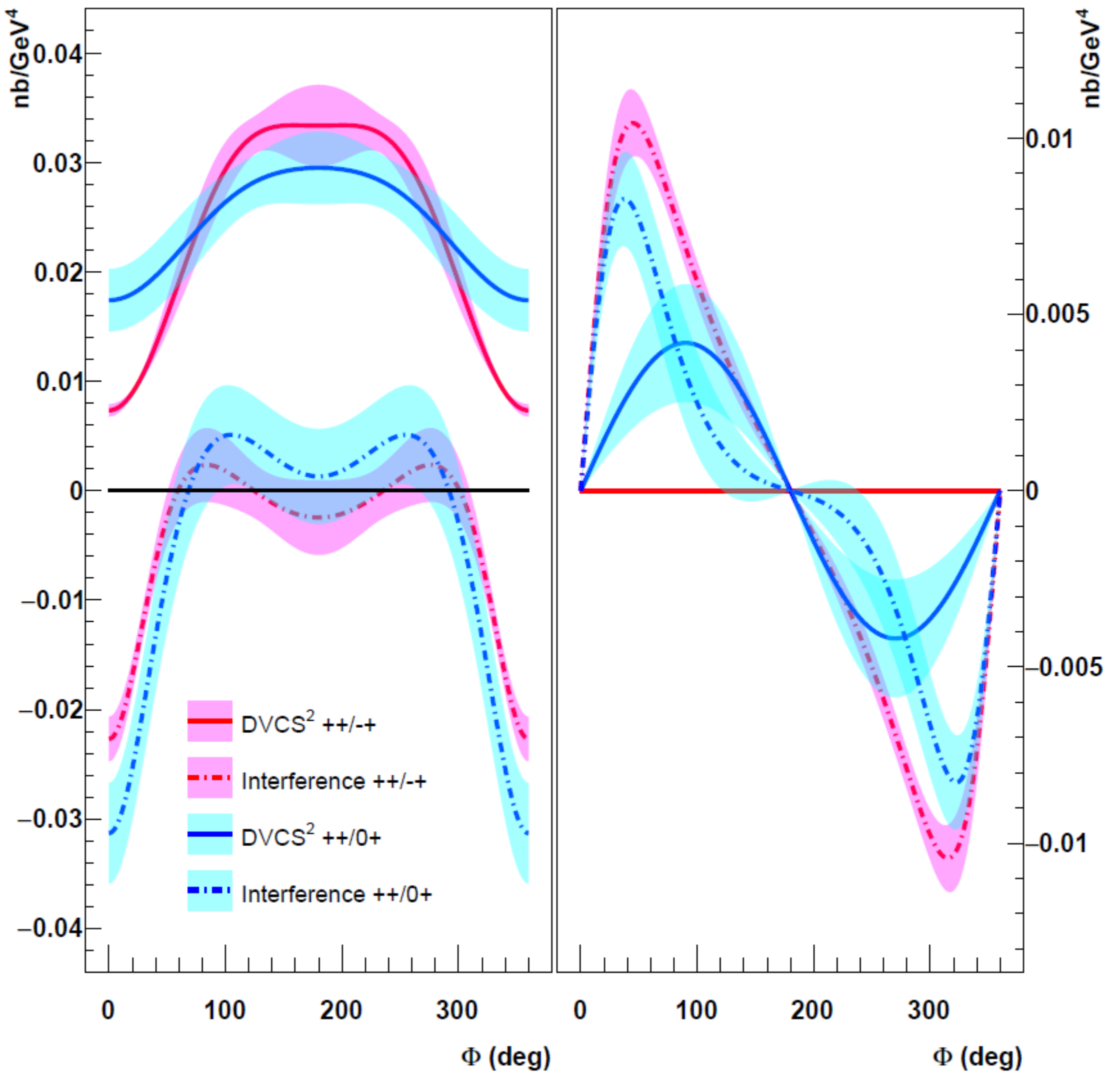
- Cross section measured at 2 beam energies and constant Q^2, x_B, t



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

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

(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