Exclusive Deeply Virtual Compton and π^0 Cross-Sections Measurements in Hall C

Carlos Muñoz Camacho

Institut de Physique Nucléaire, Orsay, France

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NPS Collaboration proposal

A. Camsonne, S. Covrig, R. Ent, D. Gaskell, F.X. Girod, M. Jones,,[1] C. Keppel, P. Nadel-Turoński, A. J. R. Puckett, B. Sawatzky,,[1] P. Solvignon, S.A. Wood, B. Wojtsekhowski,[1] A. Asaturyan, A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan, S. Zhamkochyan,[2] M. Boer, C. Desnault, R. Dupré, B. Garillon, M. Guidal, M. Hattawy, H.S. Jo,,[3] A. Martí Jimenez-Argüello, C. Muñoz Camacho[†*] , S. Niccolai, R. Paremuzyan*,[3] M. Defurne, M. Garçon, F. Sabatié,[4] I. Albayrak, M. Carmignotto, J. Dénes-Couto, N. Hlavin, T. Horn*,,[5] F. Klein, B. Nepal,[5] M. Canan, C. Hyde*, M.N.H. Rashad,[6] P. King, J. Roche*,[7] M. Ben Ali, L. Ghedira, M. Mazouz,,[8] A. Fradi,[9] D. Day, D. Keller, O. Rondon,[10] J.R.M. Annand, D.J. Hamilton,[11] S. Sirca,[12] M. Elaasar,[13] G. Huber,[14] F. Wesselmann,[15] P. E. C. Markowitz,[16] A. Ahmidouch, S. Danagoulian,[17] M. H. Shabestari,[18] D. Androic,[19] C. Chen, Y. Han, P. Gueye, L. Tang,[20] and V. Sulkosky[21]

[1] *Jefferson Lab, Newport News, VA 23606*

[2] *A.I. Alikhanyan National Science Laboratory, Yerevan 0036, Armenia*

[3] *Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France*

[4] *SPhN (Saclay), CEA/DSM/IRFU, Gif-sur-Yvette, France*

[5] *The Catholic University of America, Washington, DC 20064*

[6] *Old Dominion University, Norfolk, Virginia*

[7] *Ohio University, Athens, OH 45701*

[8] *Faculté des Sciences de Monastir, Département de physique, 5000-Monastir, Tunisia*

[9] *Faculty of Sciences of Gabes, Department of Physics, 6072-Gabes, Tunisia*

[10] *University of Virginia, Charlottesville, VA, USA*

[11] *University of Glasgow, Glasgow, Scotland, UK*

[12] *University of Ljubljana, Ljubljana, Slovenia*

[13] *Southern University at New Orleans*

[14] *Univ. of Regina, Regina, SK S4S0A2, Canada*

[15] *Xavier University of Louisiana, New Orleans*

[16] *Florida International University, Miami, FL 33199, USA*

[17] *North Carolina A&T State University, USA*

[18] *Mississippi State University, USA*

[19] *Faculty of Science, University of Zagreb*

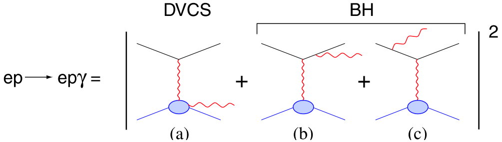
[20] *Hampton University, Hampton, VA 23668, USA*

[21] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

* Co-spokespersons

† Contact person: munoz@ipno.in2p3.fr

DVCS experimentally: interference with Bethe-Heitler



At leading twist:

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

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

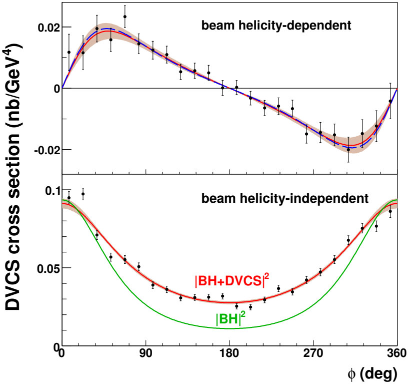
$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

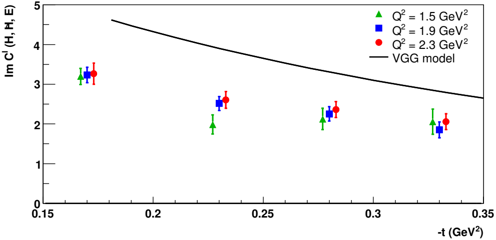
DVCS cross-section measurements

PRL**97**, 262002 (2006)

Accurate measurement of the DVCS:

- helicity-dependent $(d^4\Sigma)$ cross section for $Q^2 = 1.5$, 1.9, 2.3 GeV^2,
- helicity-independent $(d^4\sigma)$ cross section for $Q^2 = 2.3$ GeV^2.





Overview of DVCS program at JLab[1]

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): test of scaling, higher twist corrections, L/T separation...

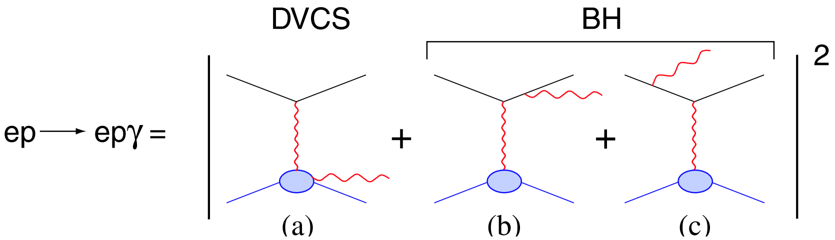
At 12 GeV the Hall A program is limited to the kinematics of approved experiment E12-06-114 (HRS: p <4 GeV) :

Hall C (with the addition of a photon detector) is perfectly suited to carry out the DVCS/π^0 precision program

[1] Summary document on exclusive program submitted to PAC40

Motivation #1

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



The $\mathcal{I}$ and DVCS^2 terms mix as a function of the azimuthal angle φ, but:

- $\mathcal{R}e(\mathcal{I}) \propto 1/y^3 = (E_b/\nu)^3$
- $\mathcal{D}VCS^2 \propto 1/y^2 = (E_b/\nu)^2$

PR12-13-010 physics goals

1. Beam energy dependence of cross section:
   - Separation of the $|\text{DVCS}|^2$ and $\mathcal{I}(\text{BH}\cdot\text{DVCS})$ from DVCS cross section
   - L/T separation of π^0 cross section

Unique to Hall C

Proposed at 6 GeV in Hall A (E07-007) –*preliminary results will be shown*–, but at 12 GeV the high momentum reach of Hall C HMS is essential

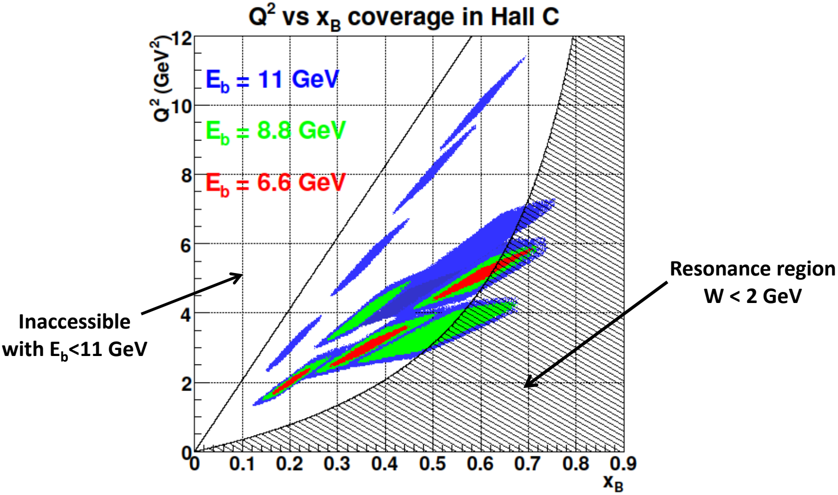
2. Increase the Q^2 reach to even higher values at fixed x_B

Allowed by the use of a sweeping magnet: smaller calorimeter θ permitted

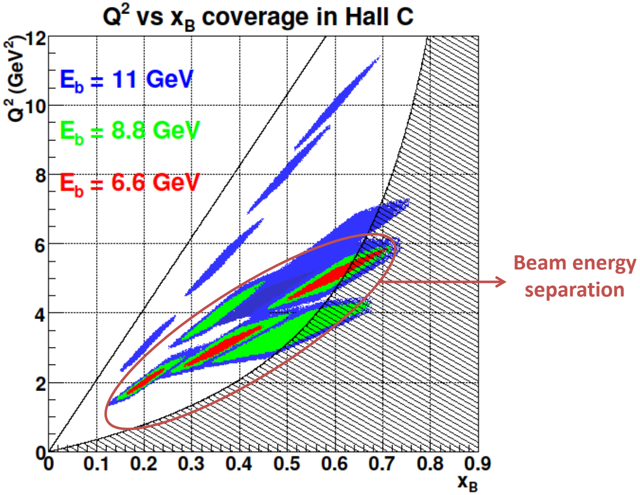
3. Expand the kinematic coverage at smaller values of x_B

Allowed by the use of a sweeping magnet: smaller calorimeter θ permitted

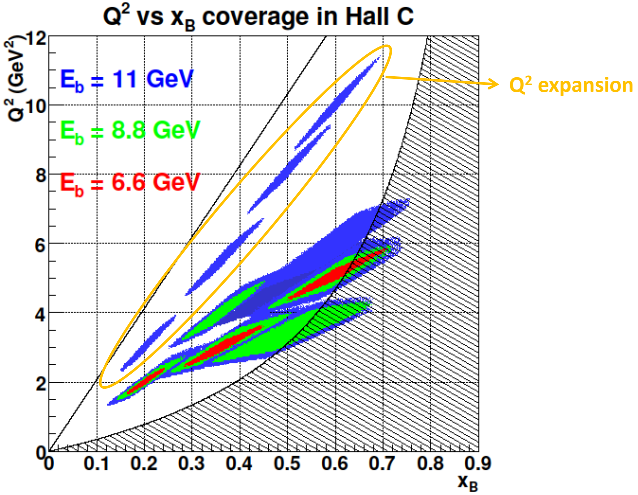
Kinematics coverage



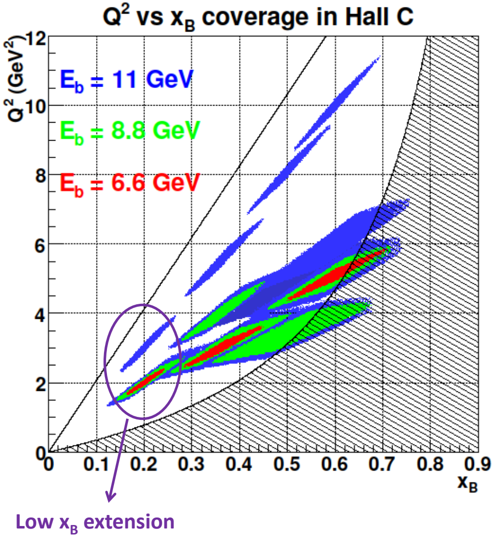
Kinematics coverage



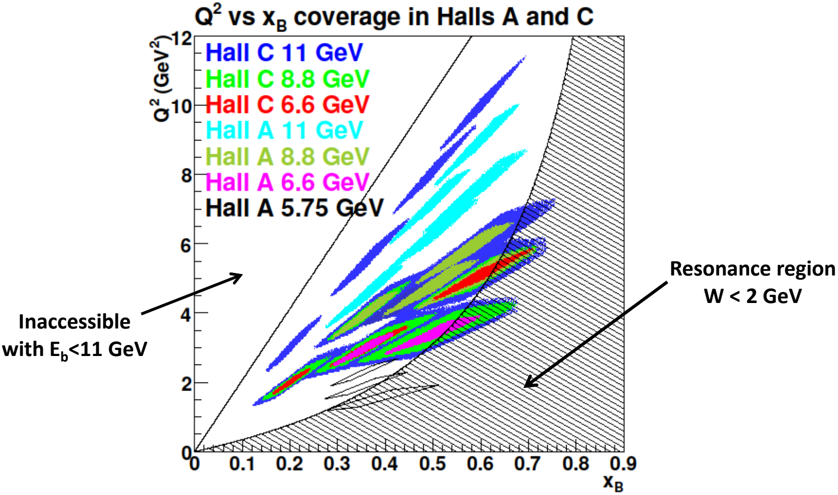
Kinematics coverage



Kinematics coverage

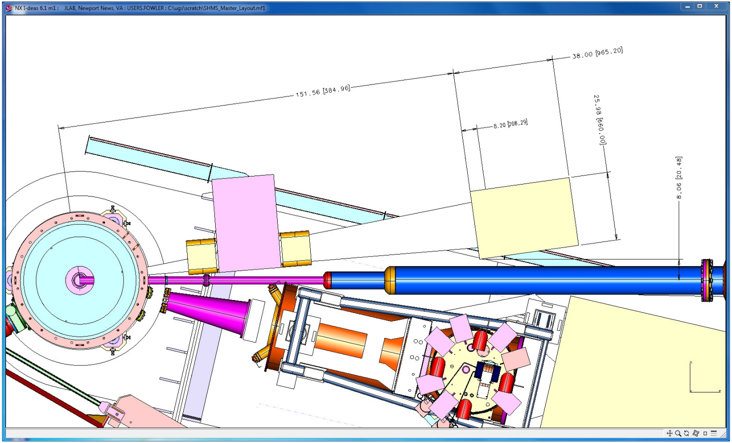


Kinematics: combined Hall A and Hall C coverages



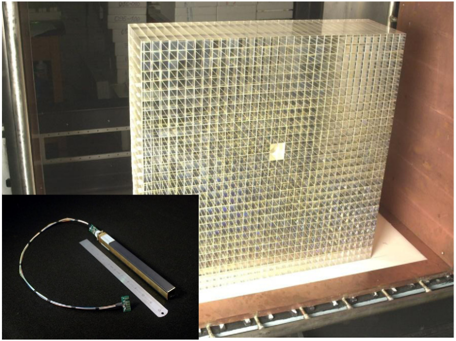
Experimental setup

- HMS ($p < 7.3$ GeV): scattered electron
- $PbWO_4$ calorimeter: γ/π^0 detection
- Sweeping magnet



$PbWO_4$ electromagnetic calorimeter

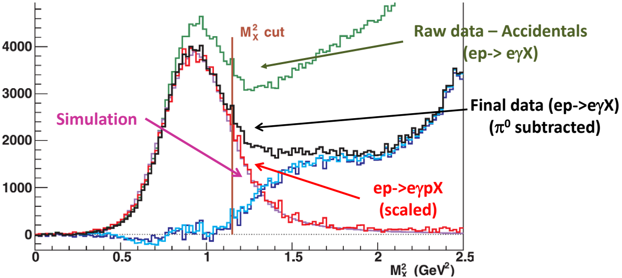
Design *based on* HYCAL detector



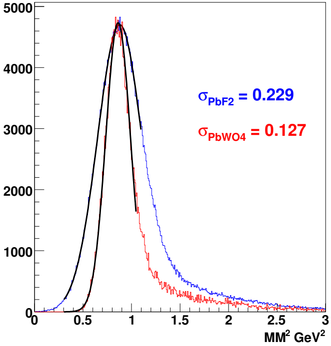
- 58×70 cm^2 detector: 1116 $PbWO_4$ crystals (2×2 cm^2 each)
- Temperature controlled frame
- "Hall-D" 250 MHz flash ADC to record PMT waveforms

Exclusivity: $ep \to e\gamma X$ missing mass squared (M_X^2)

Experimental M_X^2 resolution (Hall A)



Simulated M_X^2 resolution



Higher light yield of $PbWO_4$ (compared to PbF_2) significantly improves the M_X^2 resolution

Kinematics

	Energy Dependence at fixed (Q^2, x_B)												Low-x_B				High-Q^2		
x_B	0.36					0.50			0.60				0.2				0.36	0.50	0.60
Q^2 (GeV)^2	3.0			4.0		3.4		4.8	5.1			6.0	2.0			3.0	5.5	8.1	10
k (GeV)	6.6*	8.8	11	8.8*	11	8.8	11	11	6.6	8.8*	11	11	6.6	8.8	11	11	11		
k' (GeV)	2.2	4.4	6.6	2.9	5.1	5.2	7.4	5.9	2.1	4.3	6.5	5.7	1.3	3.5	5.7	3.0	2.9	2.4	2.1
θ_{Calo} (deg)	11.7	14.7	16.2	10.3	12.4	20.2	21.7	16.6	13.8	17.8	19.8	17.2	6.3	9.2	10.6	6.3	7.9	8.0	8.0
D_{Calo} (m)	3	3	3	4	3	3	3	3	3	3	3	3	6	4	4	6	4	4	4
I_{beam} (μA)	28	28	28	50	28	28	28	28	28	28	28	28	11	5	50	11	50	50	50
N_{evt} (10^5)	1.5	8.8	8.2	2.1	7.9	7.3	11	5.1	0.2	0.2	2.7	2.6	3.5	3.6	64	3.4	6.1	0.8	0.4
$\sigma_{M_X^2}$ (GeV^2)	0.13	0.13	0.12	0.15	0.15	0.09	0.09	0.11	0.09	0.09	0.09	0.09	0.17	0.17	0.17	0.22	0.19	0.15	0.13
Days	1	2	1	1	3	3	2	5	5	1	5	10	1	1	1	1	5	5	12

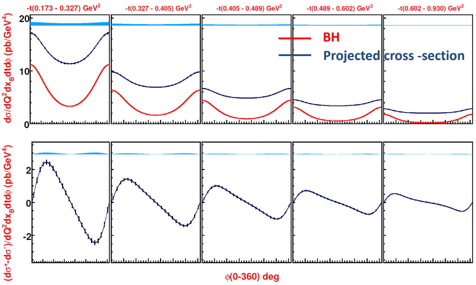
- $\sim 3 - 10 \cdot 10^5$ counts in a 0.01 GeV^2 bin in $t \Rightarrow$ 1-2% statistical precision per ϕ-bin.
- Less statistics are needed in cross-check points (DIS cross section)
- Compromise at high Q^2/x_B to obtain valuable physics results, despite being statistically limited

Total request: 65 days of beam

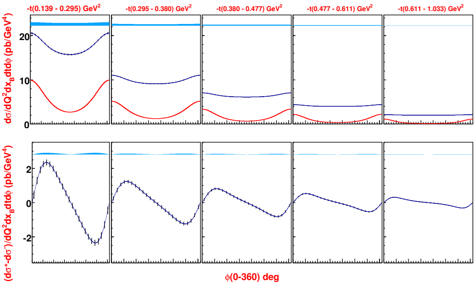
* 3 cross-checks with Hall-A kinematics (3 days total)

DVCS: Energy separation setting ($Q^2 = 3.4$ GeV^2, $x_B = 0.5$)

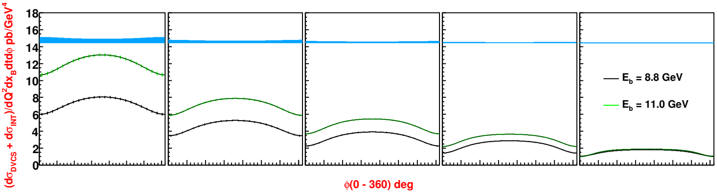
$E_b = 8.8$ GeV



$E_b = 11$ GeV



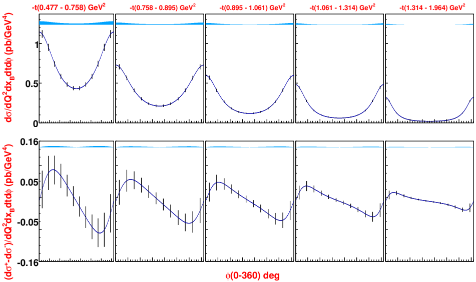
Cross section as a function of ϕ for different bins in t



Cross section after BH subtraction: large variation with E_b

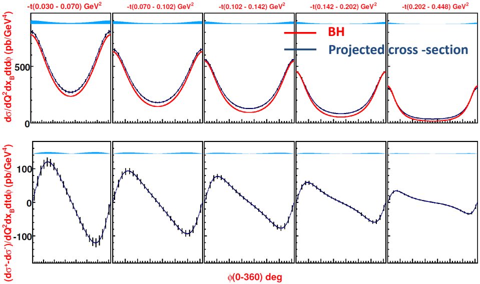
DVCS: high-Q^2 and low-x_B extension

$Q^2 = 10$ GeV^2, $x_B = 0.6$



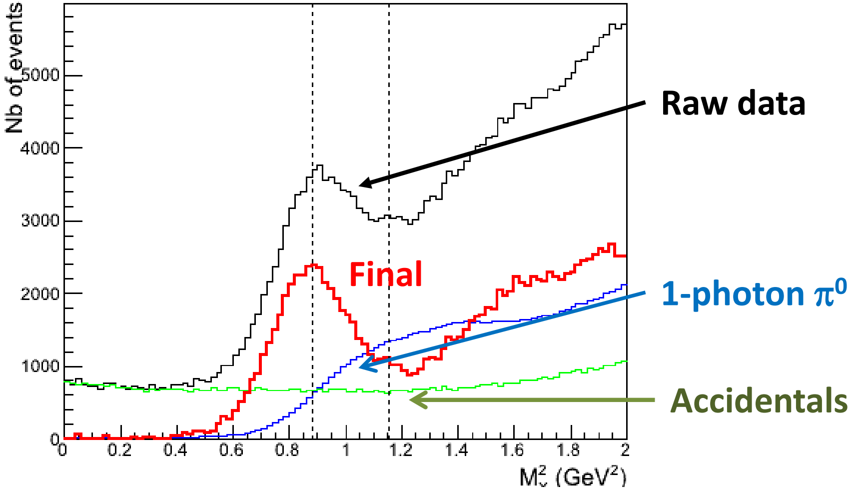
12 days

$Q^2 = 3$ GeV^2, $x_B = 0.2$

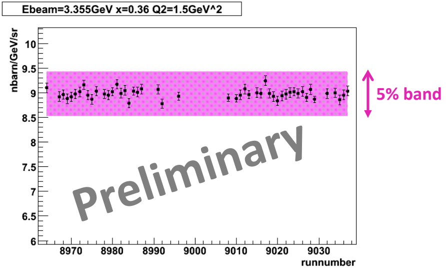


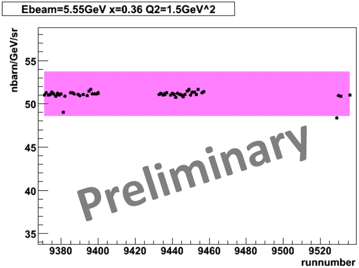
1 day

E07-007 missing mass



E07-007: DIS normalization check





E_b (GeV)	Q^2 (GeV^2)	DIS parametrization (nb/GeV/sr)	Exp. data (nb/GeV/sr)	Relative difference (%)
3.3	1.5	$9.16^{+0.61\%}_{-3.87\%}$	8.98	-2.0
5.6	1.5	$56.07^{+0.66\%}_{-3.81\%}$	51.14	-8.8
4.5	1.75	$13.41^{+0.85\%}_{-3.58\%}$	12.86	-4.1
5.6	1.75	$29.39^{+0.88\%}_{-3.6\%}$	27.14	-7.7
4.5	2	$6.7^{+1\%}_{-3.43\%}$	6.79	1.3
5.6	2	$16.14^{+1.05\%}_{-3.4\%}$	14.9	-7.7

Still preliminary: studying multi-track, dead-time, radiative... corrections

But overall normalization correct to $< 10\%$ at this stage of the analysis

E07-007 preliminary results

$Q^2 = 1.5$ GeV^2, $x_B = 0.36$

$E_b = 5.552$ GeV

- Large contribution of DVCS^2 to the total cross section
- Significant relative variation with E_b

Preliminary results not shown in online version

$E_b = 3.355$ GeV

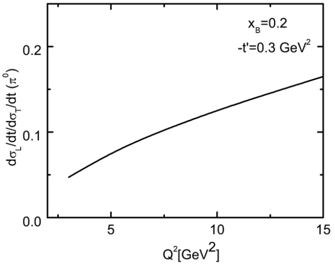
- Final normalization checks ongoing
- Other Q^2 settings under analysis

The energy dependence of the cross section is an essential and powerful tool for the DVCS program

π^0 electroproduction cross section

Data taken concurrently with DVCS

- Current data hint to a significant contribution of the transverse part
- No L/T separated cross section available

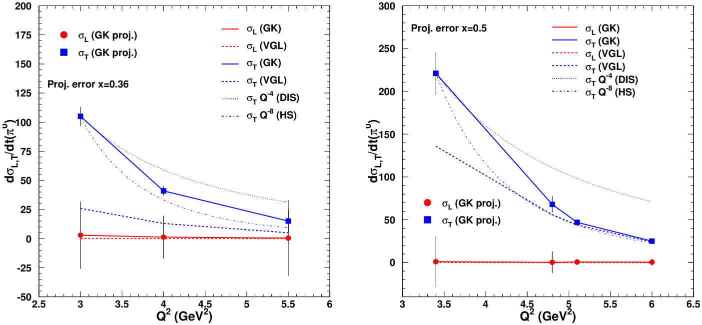


- If σ_L is large: access to ordinary GPDs
- If σ_T is large: access to transversity GPDs

It is crucial to have σ_T and σ_L measured !

L/T separation projections

Projections assuming the GK model predictions



- Hard scattering $R = \sigma_L/\sigma_T \sim Q^2$
- DIS $R = \sigma_L/\sigma_T \sim 1/Q^2$
- GK: Goloskokov & Kroll predictions (handbag)
- VGL: Vanderhaeghen, Guidal, Laget predictions (Regge)

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 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 (for DVCS)	0.5	1.0
Radiative corrections	1.2	2.0
Total	1.8–1.9	3.8–3.9

Summary

- Precision measurements of DVCS and deep π^0 cross sections
- Energy separation of the DVCS cross section
- L/T separation of the π^0 cross section
- High–Q^2 and low–x_B extension

Every observable measured as a function of Q^2:

- Test of scaling
- Study of higher twist corrections

We request 65 days of beam,
excluding set-up and detector check-out

Back-up

DVCS cross-section: φ & Q^2

$$\begin{aligned}
\mathcal{I} &= \frac{i_0/Q^2 + i_1\cos\varphi/Q + i_2\cos 2\varphi/Q^2 + i_3\cos 3\varphi/Q}{\mathcal{P}_1\mathcal{P}_2} \\
\text{DVCS}^2 &= d_0/Q^2 + d_1\cos\varphi/Q^3 + d_2\cos 2\varphi/Q^4 \,.
\end{aligned}$$

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:

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

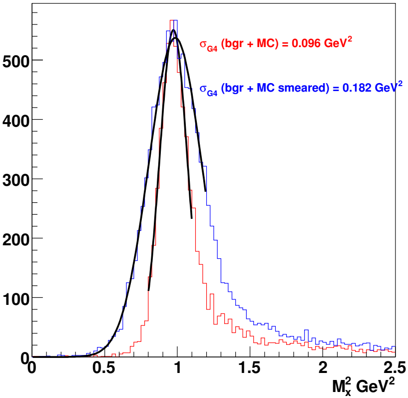
The $\mathcal{I}$ and DVCS^2 terms **mix at leading order in 1/Q** in the φ expansion

Single and random rates

E_b (GeV)	Q^2 (GeV^2)	x_B	HMS (kHz)	$PbWO_4$ (MHz) E_{th} =300 MeV	$PbWO_4$(MHz) E_{th} =1 GeV	Random coinc. E_{th} =1 GeV
6.6	3	0.36	0.73	115	27	0.03
8.8	3	0.36	4.40	68	11	0.01
11	3	0.36	13.0	52	7	0.008
8.8	4	0.36	1.20	145	41	0.05
11	4	0.36	2.90	100	22	0.02
8.8	3.4	0.50	3.30	26	2	0.002
11	3.4	0.50	9.00	20	1.3	0.001
11	4.8	0.50	1.70	48	6	0.007
6.6	5.1	0.60	0.053	79	14	0.01
8.8	5.1	0.60	0.34	39	4.2	0.005
11	5.1	0.60	1.10	27	2.2	0.002
11	6	0.60	0.45	43	5	0.006
6.6	2	0.20	0.26	30	14	0.02
8.8	2	0.20	1.30	18	6	0.007
11	2	0.20	47.0	28	8	0.009
11	3	0.20	0.70	30	14	0.02
11	5.5	0.36	0.53	222	86	0.1
11	8.1	0.50	0.072	220	84	0.09
11	10	0.60	0.017	220	85	0.1

Table: Single rates in HMS and $PbWO_4$ calorimeter for each kinematic setting. Random rates in calorimeter are calculated assuming a coincidence window of 50 ns and a solid angle of 25 blocks.

Effect of background in the missing mass resolution



Simulation of the missing mass resolution of PbF_2 with *real* background measured in Hall A experiment E07-007 (red). In order to match the resolution of the data, the simulation needs to be smeared assuming 175 photons/GeV were collected by PMTs (blue).