DVCS cross section measurements at JLab

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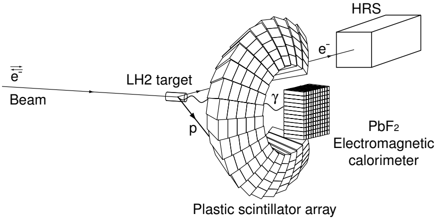
Hard Exclusive Processes at JLab 12 GeV and a Future EIC
Oct 29-30, 2006

E00-110 kinematics



Kin	Q^2 (GeV^2)	x_B	θ_{γ^*} (deg.)	s (GeV^2)
1	**1.5**	0.36	**22.3**	3.5
2	**1.9**	0.36	**18.3**	4.2
3	**2.3**	0.36	**14.8**	4.9

- Measurement of **both** helicity-dependent and helicity-independent DVCS cross sections independently
- Q^2-dependence of helicity-dependent cross section

Goal:

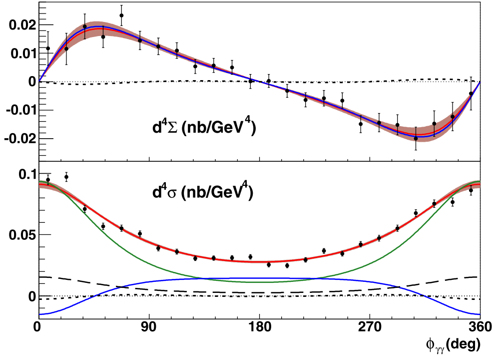
Test **twist-2 dominance** of DVCS at moderate $Q^2 \sim 2$ GeV^2.

. . . and if so, access combinations of **GPDs**.

Helicity-dependent and helicity-independent cross sections

Accurate determination of $\phi_{\gamma\gamma}$ dependence of $d\Sigma = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{2}$ and $d\sigma = \frac{\sigma^{\rightarrow} + \sigma^{\leftarrow}}{2}$

$Q^2 = 2.3\,\mathrm{GeV}^2, \quad \langle t \rangle = -0.28\,\mathrm{GeV}^2, \quad x_{\mathrm{Bj}} = 0.36$



— $\Im\mathrm{m}\, \mathcal{C}^{\mathcal{I},\mathrm{exp}}(\mathcal{F})$
$\cdots$ $\Im\mathrm{m}\, \mathcal{C}^{\mathcal{I}}(\mathcal{F}^{\mathrm{eff}})$
} *1 free parameter each*

— Total fit

— $\Re\mathrm{e}\, \mathcal{C}^{\mathcal{I},\mathrm{exp}}(\mathcal{F})$
- - - $\Re\mathrm{e}\, [\mathcal{C}^{\mathcal{I}} + \Delta\mathcal{C}^{\mathcal{I}}]^{\mathrm{exp}}(\mathcal{F})$
$\cdots$ $\Re\mathrm{e}\, \mathcal{C}^{\mathcal{I}}(\mathcal{F}^{\mathrm{eff}})$
} *1 free parameter each*

— Bethe-Heitler *fixed*

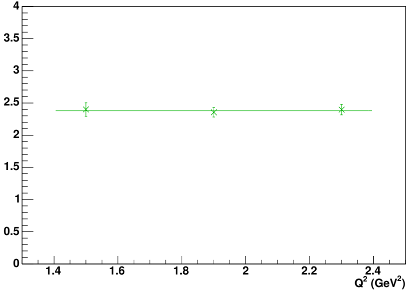
— Total fit

$d\sigma$: - rich and complex $\phi_{\gamma\gamma}$ structure beyond BH
- interesting & complementary GPD information (real part)

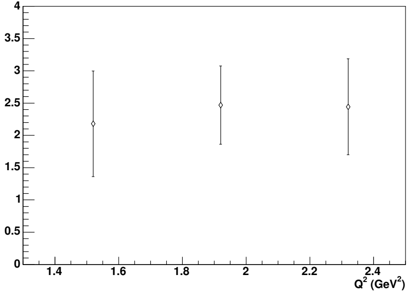
Q^2-dependence: twist-2 dominance

$$0.4 < -t < 0.12 \text{ (GeV}^2\text{)}$$

$\Im\text{m}\, \mathcal{C}^{\mathcal{I}}(\mathcal{F})$

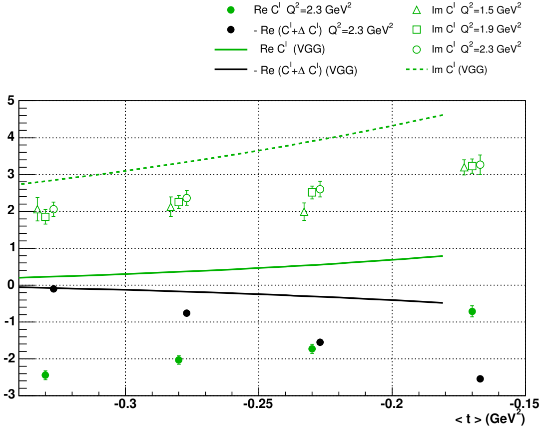


$\Im\text{m}\, \mathcal{C}^{\mathcal{I}}(\mathcal{F}^{\text{eff}})$



- No Q^2-dependence in $\Im\text{m}\, \mathcal{C}^{\mathcal{I}}(\mathcal{F})$ within 3% statistical error bars
- Sets an upper limit for twist-4 and higher $\leq 10\%$

GPD linear combinations and integrals



- Possible (likely) contribution of DVCS^2 terms in these interference results

DVCS^2 contribution

1.- Helicity-correlated cross section: $\Im$maginary part

$$\frac{d^5\Sigma}{d^5\Phi} = \frac{1}{2}\left[\frac{d^5\sigma^+}{d^5\Phi} + \frac{d^5\sigma^-}{d^5\Phi}\right] =$$

$$\underbrace{\sin(\phi_{\gamma\gamma})\Gamma_1^{\Im}\,\Im\mathrm{m}\left[\mathcal{C}^I(\mathcal{F})\right] - \sin(2\phi_{\gamma\gamma})\Gamma_2^{\Im}\,\Im\mathrm{m}\left[\mathcal{C}^I(\mathcal{F}^{\mathrm{eff}})\right]}_{\text{Interference BH-DVCS}} + \underbrace{\sin(\phi_{\gamma\gamma})\Gamma_1^{\Im}\eta_{s1}\Im\mathrm{m}\left[\mathcal{C}^{\mathrm{DVCS}}(\mathcal{F}^{\mathrm{eff}},\mathcal{F}^*)\right]}_{|\mathrm{DVCS}|^2\ \text{(twist-3)}}$$

- Different $\phi_{\gamma\gamma}$ dependence of Twist-2 & Twist-3 interference terms:
  $\Rightarrow$ *independent determination*
- $\sin\phi_{\gamma\gamma}\Gamma_1^{\Im}$ term determines observable $\Im\mathrm{m}\left[\mathcal{C}^{I,\mathrm{exp}}(\mathcal{F})\right]$:

$$\Im\mathrm{m}\left[\mathcal{C}^{I,\mathrm{exp}}(\mathcal{F})\right] = \Im\mathrm{m}\left[\mathcal{C}^I(\mathcal{F})\right] + \langle\eta_{s1}\rangle\Im\mathrm{m}\left[\mathcal{C}^{\mathrm{DVCS}}(\mathcal{F}^{\mathrm{eff}},\mathcal{F}^*)\right] \qquad |\langle\eta_{s1}\rangle|_{E00-110} < 0.01$$

DVCS^2 contribution

$$\frac{d^5\sigma}{d^5\Phi} = \frac{1}{2}\left[\frac{d^5\sigma^+}{d^5\Phi} + \frac{d^5\sigma^-}{d^5\Phi}\right] = \underbrace{\frac{d^5\sigma(|BH|^2)}{d^5\Phi}}_{\text{Known from FF}} + \underbrace{\Gamma\,\eta\;\mathcal{C}^{\text{DVCS}}(\mathcal{F},\mathcal{F}^*)}_{|\text{DVCS}|^2\ \text{(twist-2)}} +$$

$$\underbrace{(\Gamma_0^{\Re} - \cos(\phi_{\gamma\gamma})\Gamma_1^{\Re})\Re\text{e}\left[\mathcal{C}^I(\mathcal{F})\right] + \Gamma_{0,\Delta}^{\Re}\Re\text{e}\left[\mathcal{C}^I + \Delta\mathcal{C}^I\right](\mathcal{F}) + \cos(2\phi_{\gamma\gamma})\Gamma_2^{\Re}\Re\text{e}\left[\mathcal{C}^I(\mathcal{F}^{\text{eff}})\right]}_{\text{Interference BH-DVCS}}$$

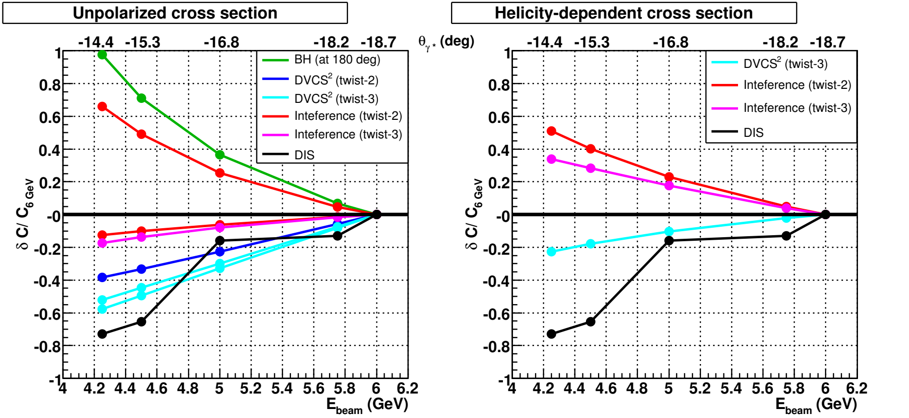
- $$\Re\text{e}\left[\mathcal{C}^{I,\,\text{exp}}(\mathcal{F})\right] = \Re\text{e}\left[\mathcal{C}^I(\mathcal{F})\right] + \langle\eta_{c1}\rangle\,\mathcal{C}^{\text{DVCS}}(\mathcal{F},\mathcal{F}^*)$$
- $$\Re\text{e}\left[\mathcal{C}^{I,\,\text{exp}} + \Delta\mathcal{C}^{I,\,\text{exp}}\right](\mathcal{F}) = \Re\text{e}\left[\mathcal{C}^I + \Delta\mathcal{C}^I\right](\mathcal{F}) + \langle\eta_0\rangle\,\mathcal{C}^{\text{DVCS}}(\mathcal{F},\mathcal{F}^*)$$

$$|\langle\eta_{0,c1}\rangle|_{E00-110} < 0.05$$

η_{c1} and η_0 depend on beam energy ! $\Longrightarrow$

DVCS^2: proposed separation (with JLab 6 GeV!)

$$Q^2 = 1.9\,\text{GeV}^2,\ x_B = 0.36,\ s = 4.9\ \text{GeV}^2$$

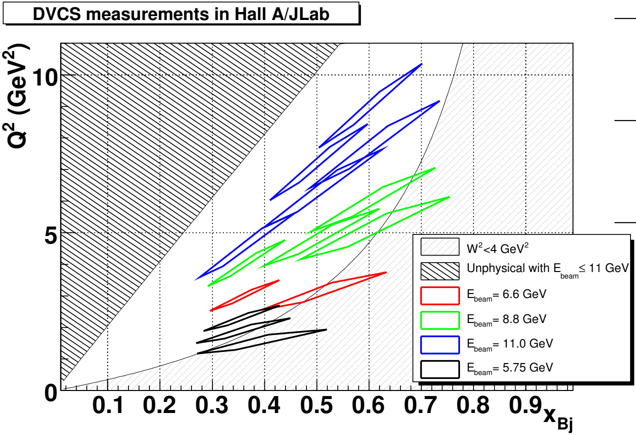


Possible DVCS^2 separation by changing beam energy

Kinematic coverage

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)



Beam time (days)

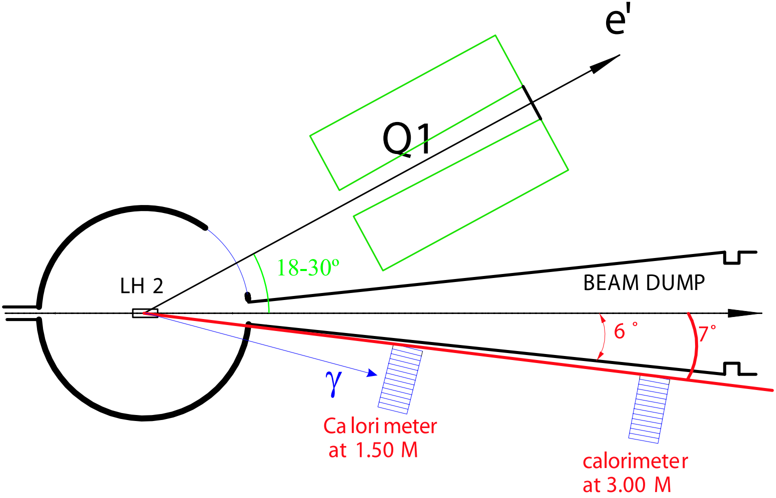
Q^2 (GeV^2)	x_{Bj} 0.36	0.50	0.60
3.0	3		
4.0	2		
4.55	1		
3.1		5	
4.8		4	
6.3		4	
7.2		7	
5.1			13
6.0			16
7.7			13
9.0			20
Total	6	20	62

1 GeV^2 range in $t_{min} - t$

88 days

250k events/setting

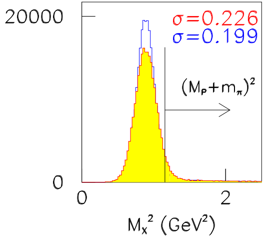
Experimental configuration $(e\,p \to e\,\gamma\,X)$



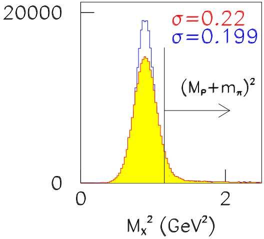
Missing mass resolution

(Cf. Table V for all kinematic settings)

6.6 GeV setting



11 GeV setting



E00-110 **This proposal**

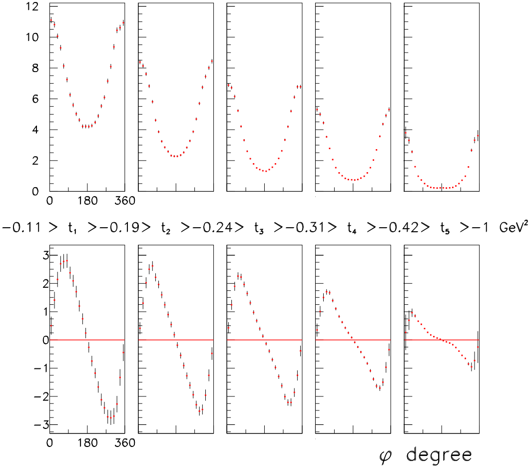
Very similar M_X^2 resolution $\Rightarrow$ same exclusivity with $e\ \gamma$ *detection only*.

Cross sections

- Model by Vanderhaeghen, Guichon & Guidal (VGG), with factorized $t-$dependence
- 250k events/setting or 40k events per $t-$bin
- Similar statistical accuracy as E00-110

Helicity-independent cross sections (pb/GeV^4)

6.6 GeV setting $Q^2 = 3.0\,\mathrm{GeV}^2$, $x_{\mathrm{Bj}} = 0.36$

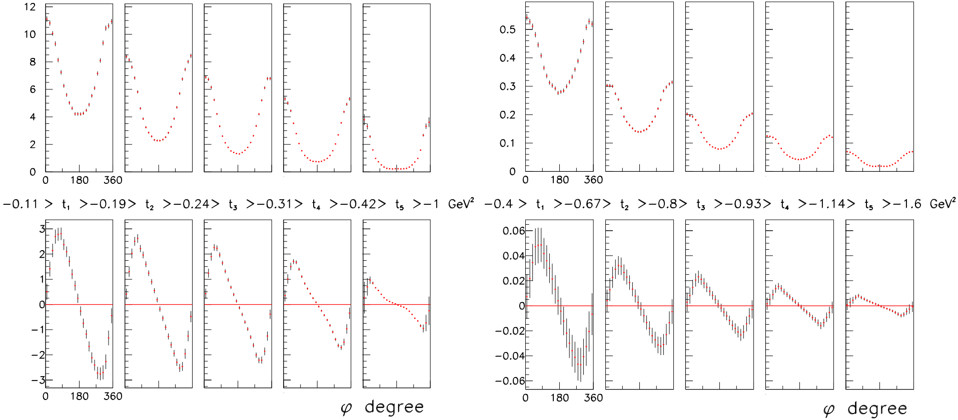


Helicity-dependent cross sections (pb/GeV^4)

Cross sections

Helicity-independent cross sections (pb/GeV^4)

8.8 GeV setting $Q^2 = 4.8$ GeV^2, $x_{\rm Bj} = 0.50$ 11 GeV setting $Q^2 = 9.0$ GeV^2, $x_{\rm Bj} = 0.60$



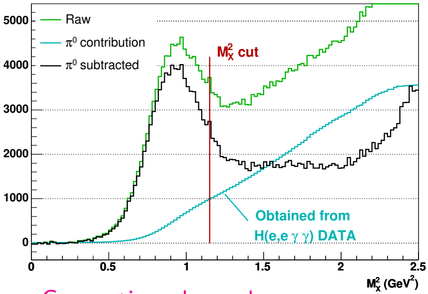
Helicity-dependent cross sections (pb/GeV^4)

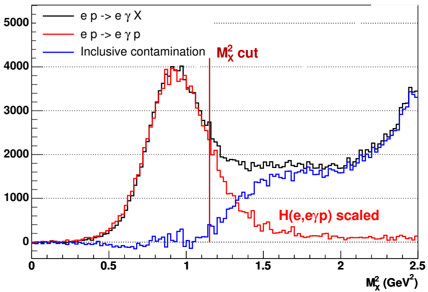
Systematic errors

Type		Relative errors (%) E00-110	Relative errors (%) proposed
Luminosity	target length and beam charge	1	1
HRS-Calorimeter	Drift chamber multi-tracks	1.5	1
	Acceptance	2	2
	Trigger dead-time	0.1	0.1
DVCS selection	π^0 subtraction	3	1
	e(p,e'γ)πN contamination	2	3
	radiative corrections	2	1
Total cross section sum		4.9	4.1
Beam	Polarization $\Delta P/P$	2	1
Total cross section difference		5.3	4.2

Backup slides

Missing mass squared $e\ p \rightarrow e\ \gamma\ X$ (E00-110)

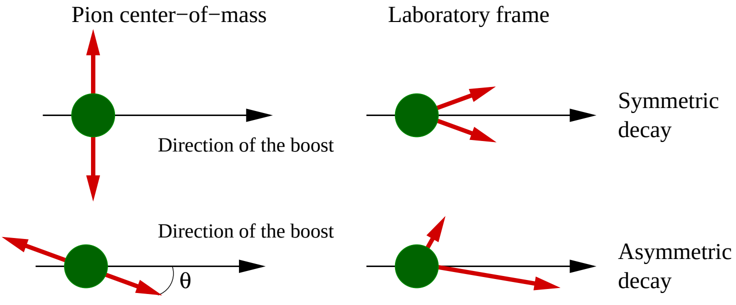




Competing channels:

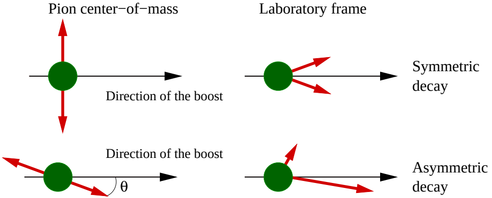
- π^0 electroproduction: $e\ p \rightarrow e\ p\ \pi^0 X \rightarrow e\ p\ \gamma\ \gamma\ X$
- Associated DVCS: $e\ p \rightarrow e\ N\ \pi\ \gamma$
  - Non-resonant: $e\ p \rightarrow e\ N\ \pi\ \gamma$ $\quad M_X^2 > (M + m_{\pi^0})^2$
  - Resonant: $e\ p \rightarrow e\ (\Delta$ or $N^*)\gamma$ $\quad m_\Delta^2 = 1.52$ GeV^2

π^0 substraction ($\pi^0 \to \gamma\gamma$)



- Symmetric decay: minimum angle in lab of 4.4° for $E_{\pi^0}^{\text{max}} = 3.5\,\text{GeV}$
  $\Rightarrow$ **Clusters separation**
- Asymmetric decay: sometimes only 1-cluster
  $\Rightarrow$ **Mistaken for DVCS event**

π^0 substraction ($\pi^0 \rightarrow \gamma\gamma$)

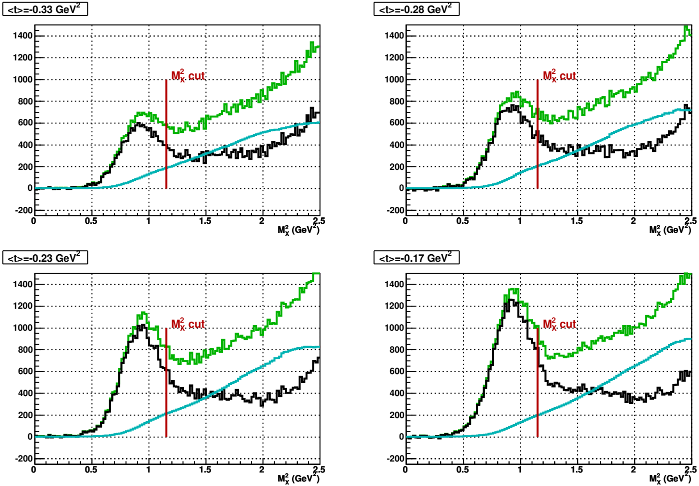


Substraction procedure:

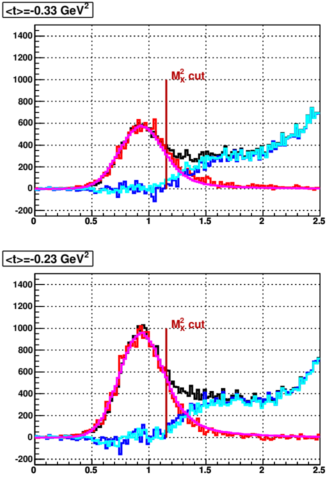
1. Compute kinematics of each *detected* π^0 (2 clusters in calorimeter).
2. Randomize the decay : sample $\cos\theta$ randomly between [-1,1] a big number of times (~ 5000).
3. Compute the ratio of 2-cluster/1-cluster events generated by this π^0 ($\sim$30% in average).

Repeating this procedure for *each* detected π^0 provides an automatic normalization of the contamination as a function of Q^2, t, φ, ...

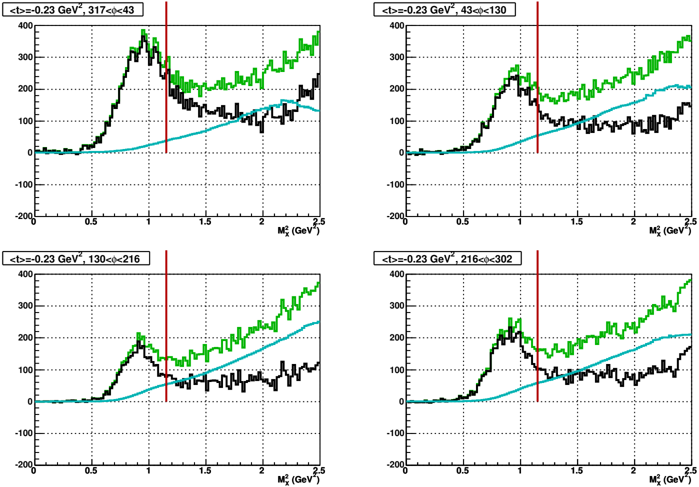
π^0 subtraction results for different $(t, \phi_{\gamma\gamma})$ bins



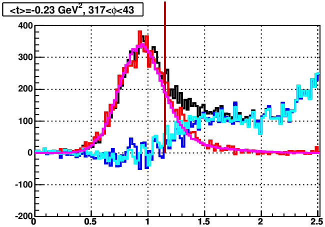
π^0 subtraction results for different $(t, \phi_{\gamma\gamma})$ bins

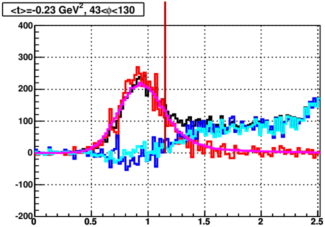


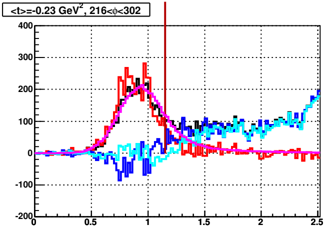
π^0 subtraction results for different $(t,\, \phi_{\gamma\gamma})$ bins



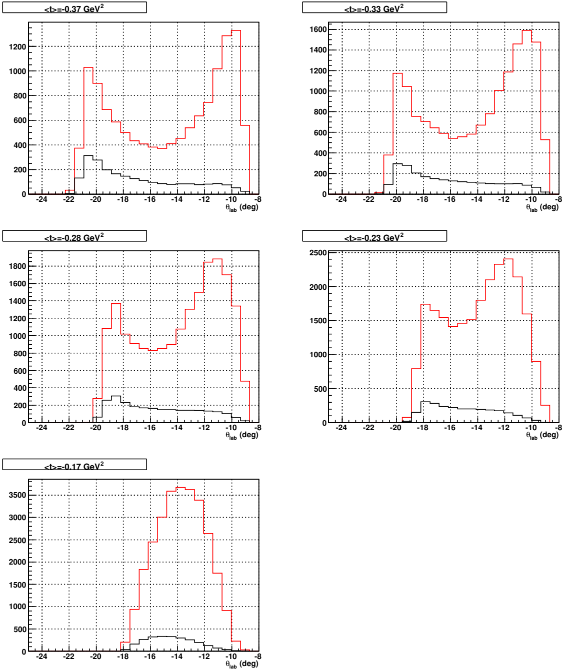
π^0 subtraction results for different $(t,\, \phi_{\gamma\gamma})$ bins



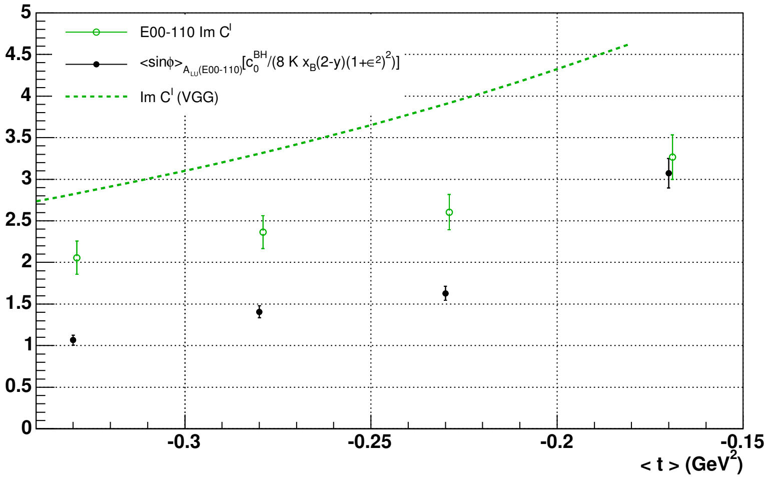




π^0 subtraction *vs.* θ_{lab}



GPDs from cross sections *vs.* GPDs from asymmetries

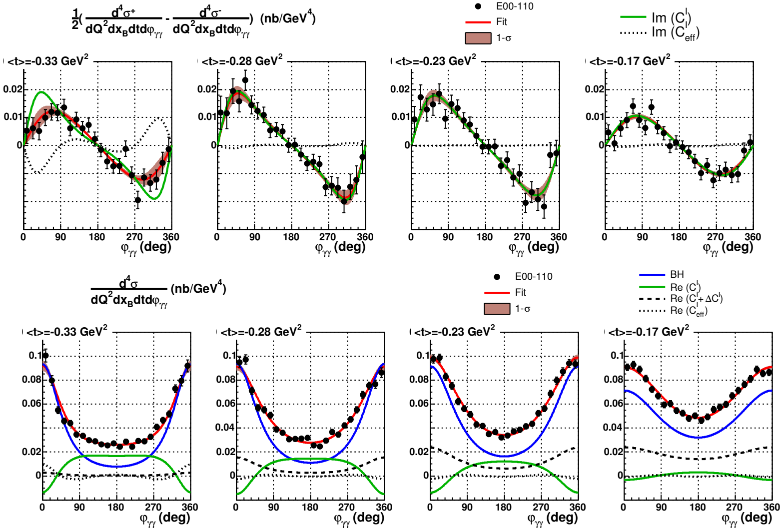


GPDs from cross sections *vs.* GPDs from asymmetries

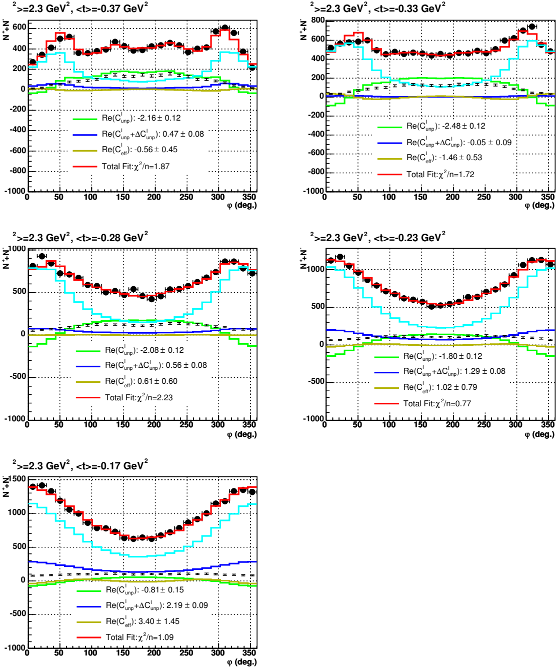
Even within a model (VGG). . . :

-t(GeV^2)	$\Im m\mathcal{C}^{\mathcal{I}}$	$\langle\sin\phi\rangle[c_0^{BH}/8Kx_B(2-y)(1+\epsilon^2)^2]$	Error
0.19	7.22	4.65	36%
0.30	4.47	2.40	46%
0.46	2.22	0.92	59%

Cross sections for each t bin ($\langle Q^2\rangle$=2.3 GeV^2)



Counts


2>=2.3 GeV2, <t>=-0.37 GeV2
N+N-
φ (deg.)
Re(CIunp): -2.16 ± 0.12
Re(CIunp+ΔCIunp): 0.47 ± 0.08
Re(CIeff): -0.56 ± 0.45
Total Fit:χ2/n=1.87
2>=2.3 GeV2, <t>=-0.33 GeV2
N+N-
φ (deg.)
Re(CIunp): -2.48 ± 0.12
Re(CIunp+ΔCIunp): -0.05 ± 0.09
Re(CIeff): -1.46 ± 0.53
Total Fit:χ2/n=1.72
2>=2.3 GeV2, <t>=-0.28 GeV2
N+N-
φ (deg.)
Re(CIunp): -2.08 ± 0.12
Re(CIunp+ΔCIunp): 0.56 ± 0.08
Re(CIeff): 0.61 ± 0.60
Total Fit:χ2/n=2.23
2>=2.3 GeV2, <t>=-0.23 GeV2
N+N-
φ (deg.)
Re(CIunp): -1.80 ± 0.12
Re(CIunp+ΔCIunp): 1.29 ± 0.08
Re(CIeff): 1.02 ± 0.79
Total Fit:χ2/n=0.77
2>=2.3 GeV2, <t>=-0.17 GeV2
N+N-
φ (deg.)
Re(CIunp): -0.81 ± 0.15
Re(CIunp+ΔCIunp): 2.19 ± 0.09
Re(CIeff): 3.40 ± 1.45
Total Fit:χ2/n=1.09

Calorimeter radiation damage

E00-110 experience:

- Dose dominated by e and π^0 above 15° and Møller below 10°
- Dose grows a factor 5 from 11.5° to 7.5°
- 20% gain loss without loss in M_X^2/energy resolution

New experiment strategies:

- Minimum angle of the closest block: 7°
- Luminosity equal to the peak luminosity in E00-110 taking into account the distance to the target: $\mathcal{L} = 4 \cdot 10^{37} (D/110\,\mathrm{cm})^2\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Blue light curing (MAMI-A4): 17 h to cure a transparency loss of 25%

Curing every 6$^{\text{th}}$ day of running at the minimum angle

Total of 12 curing days for 88 beam days

Physics reach

1. Q^2 variation:
   - 2:1 range at each x_{Bj}
   - Accurate measurement of twist-2 dominance
2. x_{Bj} variation (ξ dependence):
   - Precision data on variation of $t-$dependence with x
   - Study of transverse correlations
3. t variation:
   - 5 bins in $0 < t_{min} - t < 1$ GeV^2
   - Fourier-conjugate to the spatial distributions of quarks as a function of their momentum fraction x
4. π^0 electroproduction cross section:
   - Dominance of Twist-2 (isolation of leading twist)
   - Sensitive to nucleon GPDs $\widetilde{H}$ and $\widetilde{E}$ ($\times$ the π DA)

π^0 electroproduction: $\sigma_L + \sigma_T/\epsilon$

At leading twist:

$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \qquad \sigma_T \propto \frac{1}{Q^8}$$

$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z} \right] \int_{-1}^{1} dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi} \right] \times \left\{ \Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0} \right\}$$

Different quark weights: flavor separation of GPDs

$$|\pi^0\rangle = \frac{1}{\sqrt{2}} \{ |u\bar{u}\rangle - |d\bar{d}\rangle \} \qquad \widetilde{H}_{\pi^0} = \frac{1}{\sqrt{2}} \left\{ \frac{2}{3} \widetilde{H}^u + \frac{1}{3} \widetilde{H}^d \right\}$$

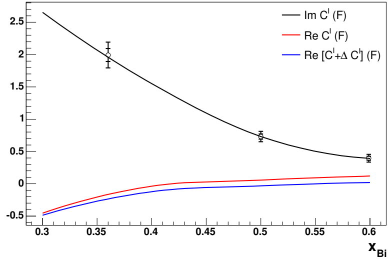
$$|p\rangle = |uud\rangle \qquad H_{DVCS} = \frac{4}{9} H^u + \frac{1}{9} H^d$$

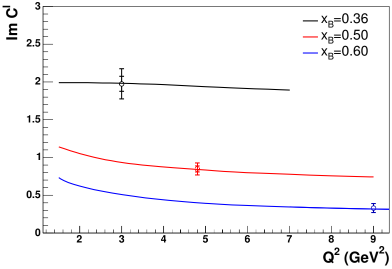
Upgrades (from E00-110)

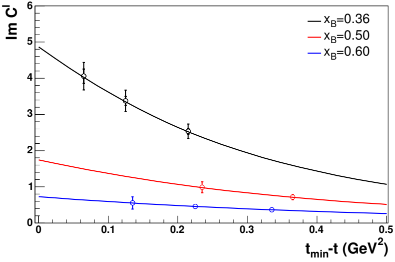
1. Expanded PbF_2 calorimeter: $11 \times 12 + \underline{76}$ blocks.
   - Higher acceptance for π^0 measurements/subtraction.
   - Increased $t-$acceptance: $\Delta(t_{min} - t) = 1\,\text{GeV}^2$.
2. Electronics:
   - ARS system (as E00-110) + Upgraded calorimeter trigger (2 thresholds to increase $ep \to ep\pi^0$ statistics).
   - FPGA & VME upgrades to increase livetime & bandwidth.
3. No proton detection: calorimeter can handle $4\times$ E00-110 rate
4. Flared beam pipe to minimize secondary background in calorimeter.
   (Background dominated by Møller and $\pi^0 \to \gamma\gamma$ from target)

Model prediction for Q^2, x_{Bj} and t dependencies

- **Sample** of statistical & systematic errors on coefficients
- Total of 55 data points
- Full $t-$dependence at each (Q^2,x_{Bj}) point







Summary

- **Absolute** DVCS cross sections in almost the complete kinematic region of JLab12
- **Precision** determination of Twist-2 and Twist-3 observables: ξ, t (and Q^2) scan
- π^0 electroproduction **cross sections**

. . . using the successful experimental technique of E00-110 (nucl-ex/0607029)

This experiment requires 88 days of beam + 12 days for calorimeter curing

Future extentions: DVCS on the neutron, recoil polarimetry. . .