

# Near Threshold Pion Electroproduction in CLAS at High Momentum Transfers

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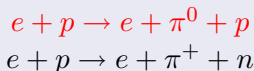
Rensselaer Polytechnic Institute  
Troy, NY

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- Motivation
- Historical background - Recap
- Near threshold cross sections and form factors
- Data availability at Jefferson Lab
  - $e1$ -DVCS (Deeply Virtual Compton Scattering) experiment
  - $e1$ -6 experiment
- Summary

## Processes



- Theoretical

- New extensions of low energy theorems at high  $Q^2$  (Braun *et al*)
- New generalized form factors  $G_1(Q^2)$  and  $G_2(Q^2)$
- Axial form factor  $G_A(Q^2)$ : Fourier transform of the axial charge distribution in the proton that is probed via axial current

$$J_{5\mu}^a \sim \bar{q} \gamma_\mu \gamma_5 \lambda^a q$$

- Experimental

- Previous experiments limited to  $Q^2 < 1 \text{ GeV}^2$
- No data exists for  $Q^2$  between  $1 - 10 \text{ GeV}^2$

# Historical background: @ threshold

For  $Q^2 = 0 \text{ GeV}^2$ :

- LETs and soft pion theorems (Kroll-Ruderman, 1954)
- Using chiral perturbation theory to  $O(m_\pi^2)$   
(Nambu *et al*, '60s; Vainshtein *et al*, '70s; Scherer *et al*, '90s)

For  $Q^2 > 10 \text{ GeV}^2$ :

- pQCD factorization methods
- Separate hard ( $Q^2 \gg \Lambda_{\text{QCD}}^3/m_\pi$ ) and soft ( $k \sim \Lambda_{\text{QCD}}$ ) contributions  
(Brodsky, Lepage, Efremov, Radyushkin, *et al*)

At threshold, for  $Q^2 \sim 1 - 10 \text{ GeV}^2$ :

- Light Cone Sum Rules (LCSR) (Braun *et al*, 2008)
  - Reproduce LET for  $Q^2 \sim 1 \text{ GeV}^2$
  - Reproduce pQCD for  $Q^2 \rightarrow \infty$

These LCSRs are extended for regions near threshold.

# LET Form Factors

At threshold, the differential cross section in terms of S-wave multipoles

$$\left. \frac{d\sigma_{\gamma^*}}{d\Omega_\pi} \right|_{\text{th}} = \frac{2|\vec{k}_f|W}{W^2 - m_N^2} \left[ (E_{0+}^{\pi N})^2 + \epsilon \frac{Q^2}{(\omega_{\gamma^*}^{\text{th}})^2} (L_{0+}^{\pi N})^2 \right]$$

Relate the multipoles to the generalized form factors

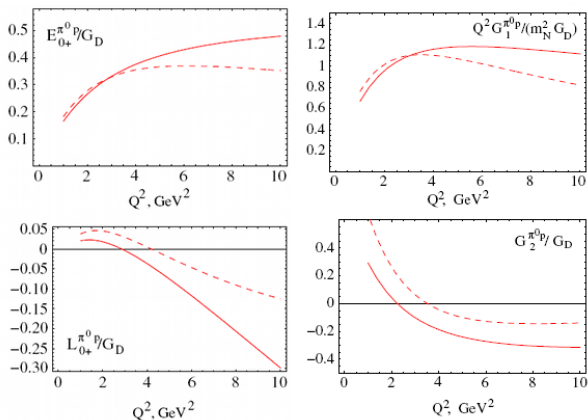
$$E_{0+}^{\pi N} = \frac{\sqrt{4\pi\alpha_{\text{em}}}}{8\pi} \frac{Q^2 \sqrt{Q^2 + 4m_N^2}}{m_N^3 f_\pi} G_1^{\pi N} \quad L_{0+}^{\pi N} = \frac{\sqrt{4\pi\alpha_{\text{em}}}}{32\pi} \frac{Q^2 \sqrt{Q^2 + 4m_N^2}}{m_N^3 f_\pi} G_2^{\pi N}$$

LET expressions for the form factors at threshold can be related to the elastic form factors and the axial form factor:

$$\begin{aligned} \frac{Q^2}{m_N^2} G_1^{\pi^0 p} &= \frac{g_A}{2} \frac{Q^2}{(Q^2 + 2m_N^2)} G_M^p & \frac{Q^2}{m_N^2} G_1^{\pi^+ n} &= \frac{g_A}{\sqrt{2}} \frac{Q^2}{(Q^2 + 2m_N^2)} G_M^n + \frac{G_A}{\sqrt{2}} \\ G_2^{\pi^0 p} &= \frac{2g_A m_N^2}{Q^2 + 2m_N^2} G_E^p & G_2^{\pi^+ n} &= \frac{2\sqrt{2}g_A m_N^2}{Q^2 + 2m_N^2} G_E^n \end{aligned}$$

- Obtained in the chiral limit  $m_\pi = 0$
- Only valid at threshold for  $Q^2 \sim 1 \text{ GeV}^2$

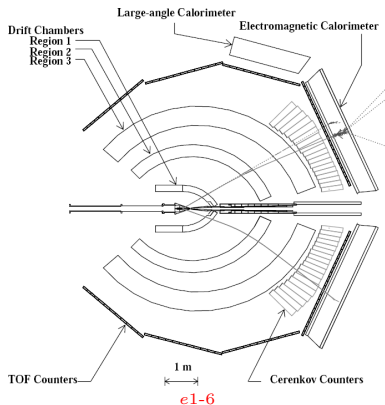
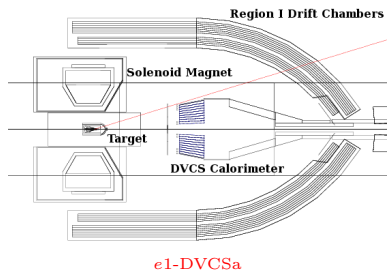
# LCSR Multipoles and Form Factor Predictions



- plots:  $\pi^0$
- $E_{0+}$ ,  $L_{0+}$  in units of  $\text{GeV}^{-1}$
- $G_D(Q^2) = 1/(1 + Q^2/0.71)^2$   
Dipole formula
- Solid curves: LCSR-based model using experimentally measured quantities
- Dashed curves: "pure" LCSR model obtained entirely theoretically

V. M. Braun *et al*, Phys. Rev. D **77**, 034016 (2008)

# Data availability in CLAS



- Expect small cross sections  $\Rightarrow$  low statistics
- Must combine data sets (if possible)
- Analyze data from e1-DVCS *a* and *b* (recent run) experiment, and e1-6 experiment for  $\pi^0$

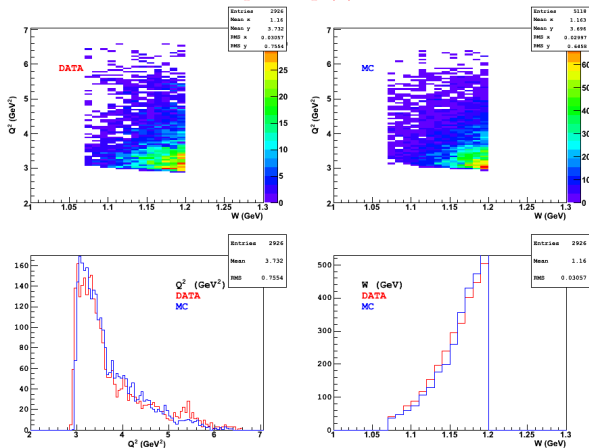
Image courtesy: CLAS

$e1$ -DVCS



- Near threshold:  $W < 1.2$  GeV
- First method:  $ep\pi^0 \rightarrow ep\gamma\gamma$ 
  - Detect electron, proton, and two photons
  - Reconstruct pion from two detected photons
- Second method:  $e\gamma\gamma X$ 
  - Detect electron, two photons and reconstruct pion from photons
  - Construct proton from missing mass
- The second method has more statistics
- Simulation: aao\_rad generator using MAID 2000 model
- Corrections and fiducial cuts
  - Electron  $z$ -vertex corrections
  - DC layer 1 fiducial cuts on electron and proton
  - Energy loss corrections
  - Electron angle and momentum corrections
  - Proton momentum corrections

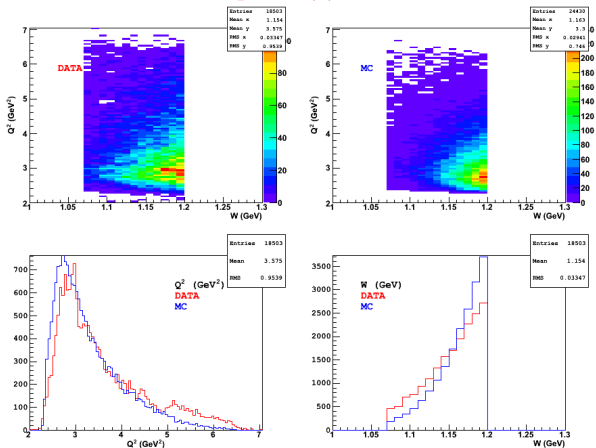
$ep \rightarrow e\pi\gamma\gamma$



$Q^2$  (GeV<sup>2</sup>) vs  $W$  (GeV)  
Preliminary



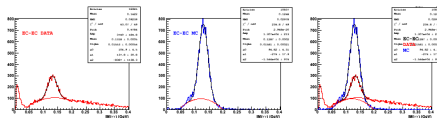
$ep \rightarrow e\gamma\gamma X$



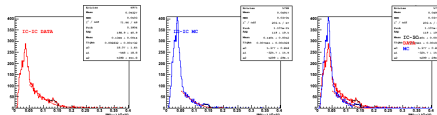
$Q^2$  (GeV<sup>2</sup>) vs  $W$  (GeV)  
Preliminary

$ep \rightarrow e\gamma\gamma X$  (GeV)

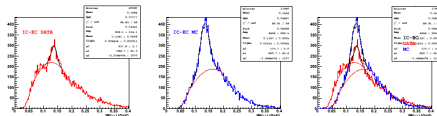
EC-EC



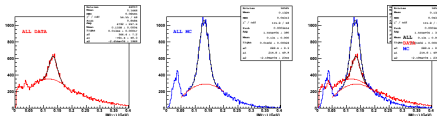
IC-IC



IC-EC



ALL

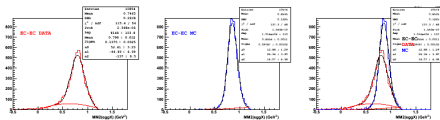


IM( $\gamma\gamma$ ) (GeV)

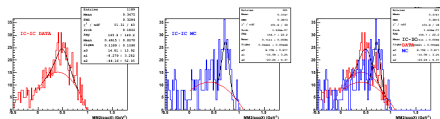
Preliminary

$ep \rightarrow e\gamma\gamma X$

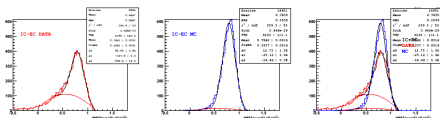
EC-EC



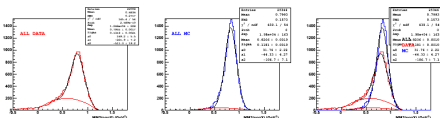
IC-IC



IC-EC



ALL



$MM^2(e\gamma\gamma X)(GeV^2)$

Preliminary

- No cut on missing  $p$  angle
- No cuts to remove radiative tails

EC-EC:  $\sim 8200$  ( $\sim 1000$  1st method)

IC-EC:  $\sim 4800$  ( $\sim 500$  1st method)

Total:  $\sim 13000$  ( $\sim 1500$  1st method)

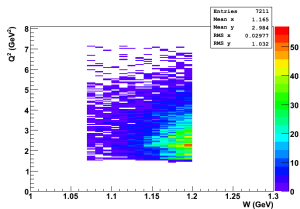
$e1-6$

- Near threshold:  $W < 1.2$  GeV
- First method:  $ep\pi^0 \rightarrow ep\gamma\gamma$ 
  - Detect electron, proton, and two photons
  - Reconstruct pion from two detected photons
- Second method:  $epX$ 
  - Detect electron and proton
  - Construct pion from missing mass
  - Complimentary to  $e1$ -DVCS ( $e\gamma\gamma X$ )
- Note: used two-thirds of the available statistics

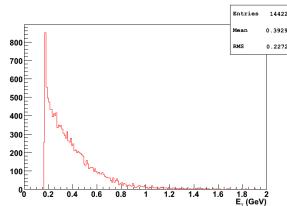


# e1-6: First method ( $ep\gamma\gamma$ ) [Preliminary]

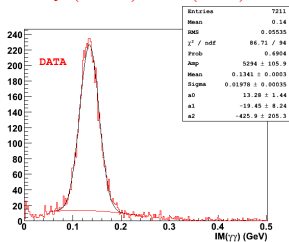
$ep \rightarrow ep\gamma\gamma$



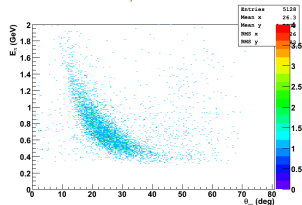
$Q^2(\text{GeV}^2)$  vs  $W(\text{GeV})$



$E_\gamma$  (GeV)



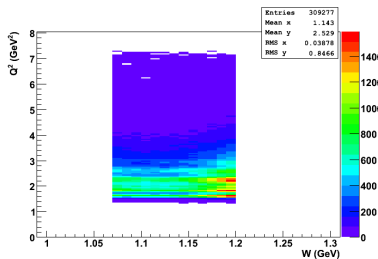
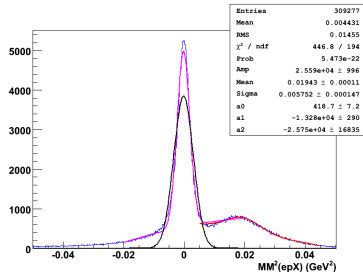
$IM(\gamma\gamma)$  (GeV)



$E_\gamma$  (GeV) vs  $\theta_{\gamma\gamma}$  (deg)

Preliminary

Total:  $\sim 5300$

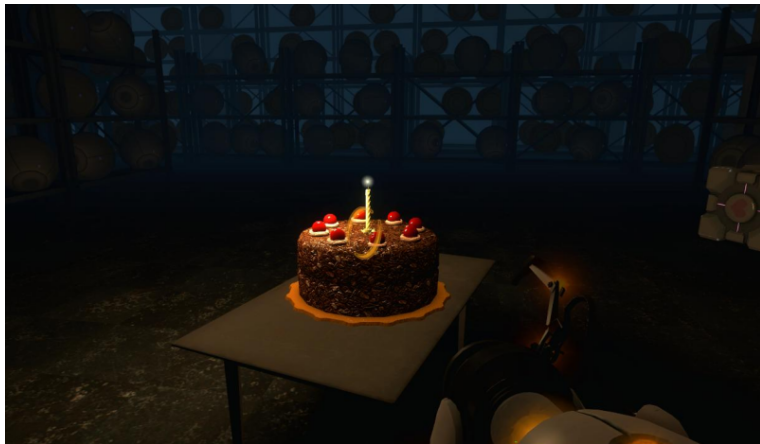
$ep \rightarrow epX$  $Q^2$  (GeV<sup>2</sup>) vs  $W$  (GeV) $MM^2(epX)$  (GeV<sup>2</sup>)

Preliminary

- Total:  $\sim 25K$
- Radiative tail cleanup not performed

- $e1$ -DVCSa:
  - Clean up background for  $e\gamma\gamma X$  channel
  - Obtain acceptances and cross sections
- $e1$ -DVCSb: Everything
- $e1$ -6:
  - Simulation
  - Corrections and Fiducial Cuts
  - Obtain acceptances and cross sections
- Try to combine datasets if possible
- Extract generalized form factors:  $G_1$  and  $G_2$

- Studying pion electroproduction near threshold  $W \approx m_N + m_\pi$
- Test the applicability of LETs in  $Q^2 \sim 1 - 10 \text{ GeV}^2$
- $e1$ -DVCSa and b;  $e1$ -6 datasets
  - Low statistics
  - Small cross sections
  - Large radiative tail from proton
- Combination of the data sets will give us good statistics (hope)
- Use existing data from CLAS for neutral pion analysis
- Use these data sets to study generalized form factors,  $G_1^{\pi N}$  and  $G_2^{\pi N}$ , near threshold

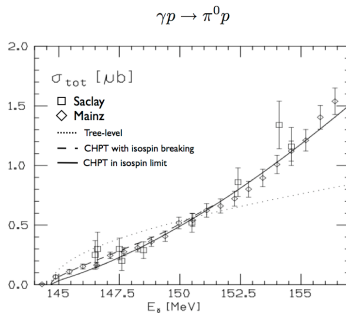
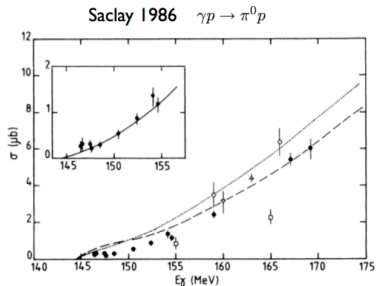


“The cake is a lie.” - *Portal*

Backup slides

# Historical background: @ threshold (continued)

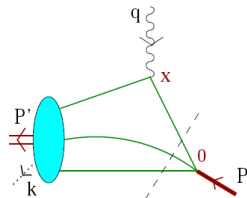
Bernard *et al.* Int. J. Mod. Phys. E4 (1995) 193-346



- rederived low energy theorems to  $O(m_\pi^2)$
- used chiral perturbation theory
- yields better results at  $Q^2 = 0$   
(Vainshtein, Zakharov, 1970s; Scherer, Koch, 1990s)

Correlation function:

$$\int dx e^{-iqx} \langle N(P') \pi(k) | j_\mu^{\text{em}}(0) | p(P) \rangle$$



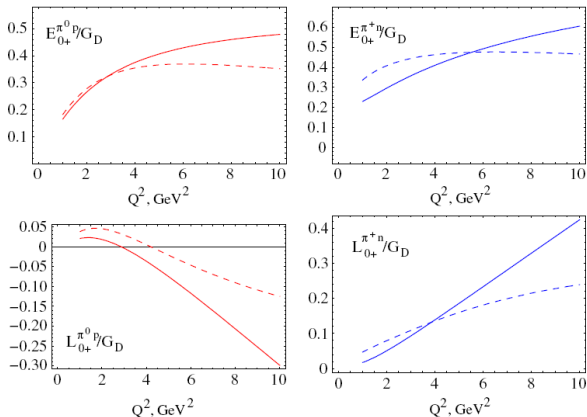
Near threshold,

$$\begin{aligned} \langle N(P') \pi(k) | j_\mu^{\text{em}}(0) | p(P) \rangle = & -\frac{i}{f_\pi} \bar{N}(P') \gamma_5 \left\{ \left( \gamma_\mu q^2 - q_\mu \not{q} \right) \frac{1}{m_N^2} G_1^{\pi N}(Q^2) - \frac{i \sigma_{\mu\nu} q^\nu}{2m_N} G_2^{\pi N}(Q^2) \right\} p(P) \\ & + \frac{ic\pi g_A}{2f_\pi [(P'+k)^2 - m_N^2]} \bar{N}(P') \not{k} \gamma_5 (\not{P}' + m_N) \left\{ F_1^P(Q^2) \left( \gamma_\mu - \frac{q_\mu \not{q}}{q^2} \right) + \frac{i \sigma_{\mu\nu} q^\nu}{2m_N} F_2^P(Q^2) \right\} p(P) \end{aligned}$$

- S-wave: generalized form factors from LCSR ( $G_1^{\pi N}$  and  $G_2^{\pi N}$ )
- P-wave: pion emission from final state nucleon



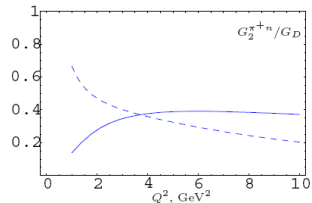
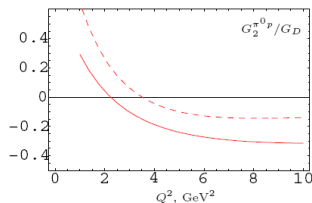
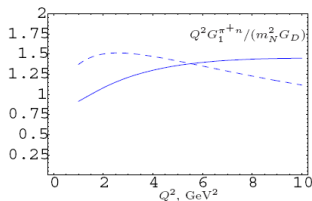
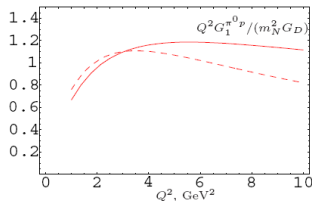
# LCSR S-Wave Multipoles



- Red plots:  $\pi^0$ , Blue plots:  $\pi^+$
- units of  $\text{GeV}^{-1}$
- $G_D(Q^2) = 1/(1 + Q^2/0.71)^2$   
Dipole formula

- Solid curves: LCSR-based model using experimentally measured quantities
- Dashed curves: “pure” LCSR model obtained entirely theoretically

# LCSR Form Factors



- Red plots:  $\pi^0$ , Blue plots:  $\pi^+$
- $G_D(Q^2) = 1/(1 + Q^2/0.71)^2$   
Dipole formula

- Solid curves: LCSR-based model using experimentally measured quantities
- Dashed curves: “pure” LCSR model obtained entirely theoretically

$$\frac{d\sigma_{\gamma^*}}{d\Omega_\pi} = \sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT} \cos(\phi_\pi) + \epsilon\sigma_{TT} \cos(2\phi_\pi) + \lambda\sqrt{2\epsilon(1-\epsilon)}\sigma'_{LT} \sin(\phi_\pi)$$

$$\sigma_T \rightarrow G_1^{\pi N}, G_M^2$$

$$\sigma_L \rightarrow G_2^{\pi N}, G_E^2$$

$$\sigma_{LT} \rightarrow G_M, G_E, \text{Re}G_1^{\pi N}, \text{Re}G_2^{\pi N}$$

$$\sigma_{TT} = 0$$

$$\sigma'_{LT} \rightarrow G_M, G_E, \text{Im}G_1^{\pi N}, \text{Im}G_2^{\pi N}$$

- $\sigma_{TT} = 0$ : D-wave contribution neglected
- $\sigma'_{LT}$ : related to single-spin symmetry