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***12 - 16 May 2008***

# Nucleon structure studies via deeply virtual exclusive reactions at JLab (2)

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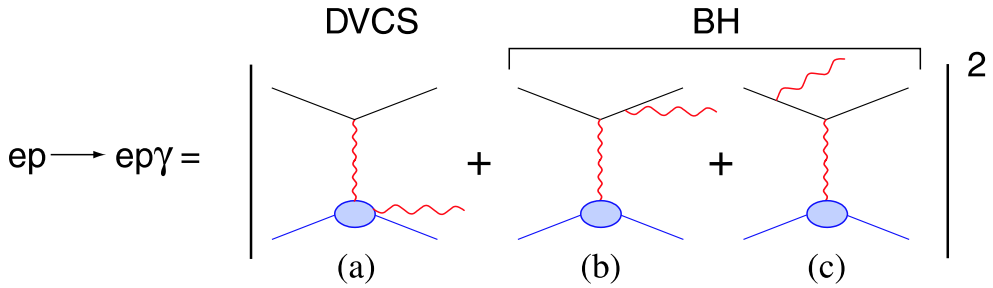
$6^{\text{th}}$ Int. Conference on Perspectives in Hadronic Physics
Trieste, May 12–15 (2008)

# Outline

1. Psedoscalar meson production ($\pi^0$) :
   - Hall B : beam spin asymmetries
   - Hall A : $\pi^0$ preliminary cross sections
2. Upcoming 6 GeV experiments (2009–2010) in Hall A at JLab :
   - E07-007: DVCS/$\pi^0$ on the proton (Rosenbluth-like separation)
   - E08-025: DVCS/$\pi^0$ on the neutron/deuteron

# DVCS experimentally: interference with Bethe-Heitler (BH)




At leading twist:

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

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

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

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

# $\pi^0$ electroproduction ($ep \to ep\pi^0$)

At leading twist:

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

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

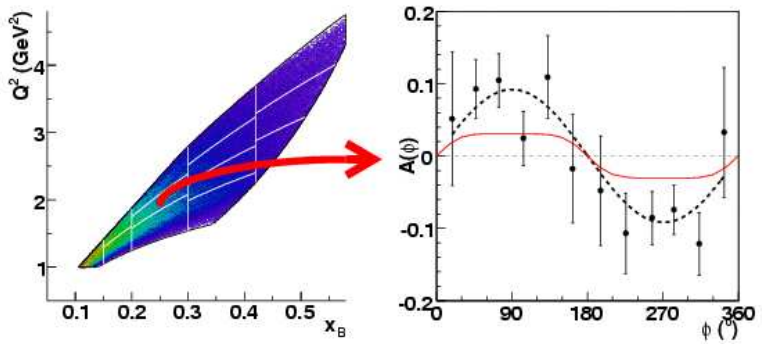
Different quark weights: flavor separation of GPDs

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

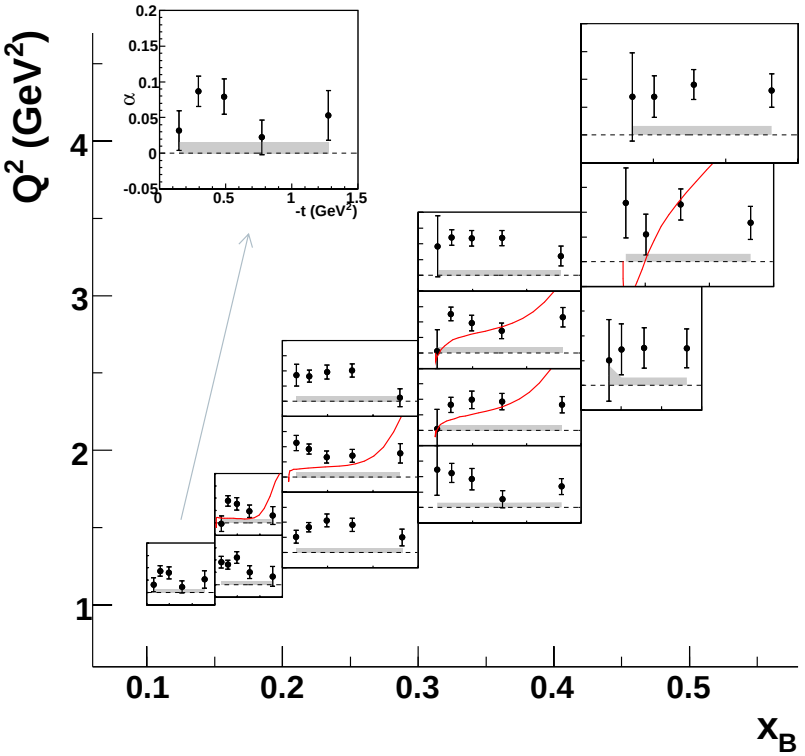
$$|p\rangle = |uud\rangle \qquad H_{DVCS} = \frac{4}{9}H^u + \frac{1}{9}H^d$$

# CLAS (Hall B) results

$$A = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} = \frac{\alpha \sin\phi}{1 + \beta\cos\phi + \gamma\cos 2\phi}$$

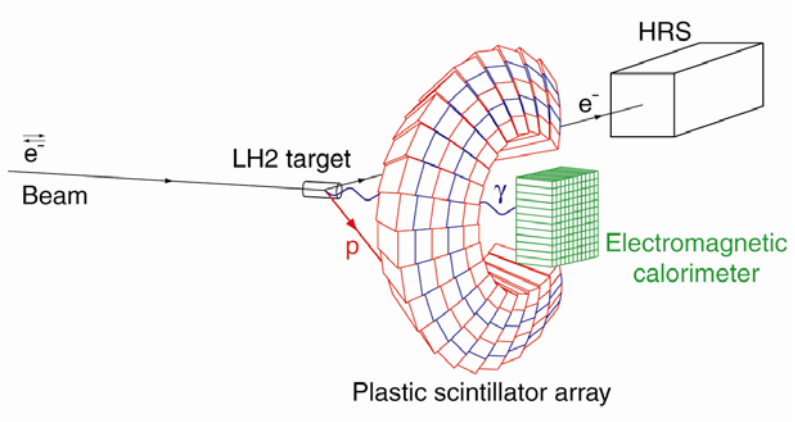



$$\alpha = \frac{\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}}{\sigma_T + \epsilon\sigma_L}$$

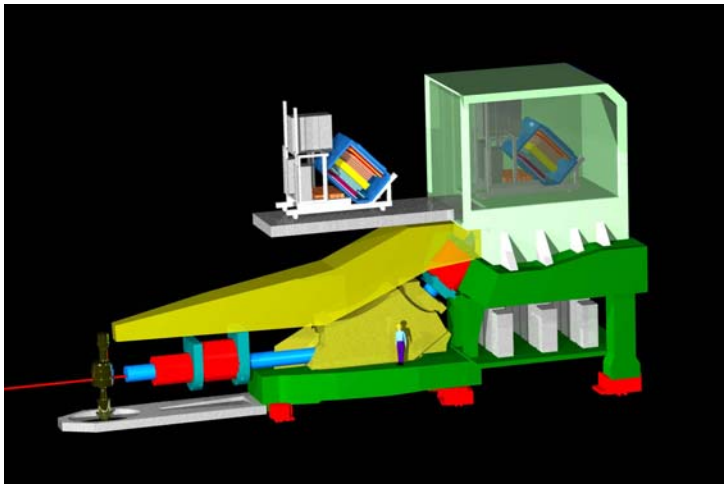



- Evidence for non-zero $\sigma_{LT'}$
- For GPDs we need $\sigma_L$

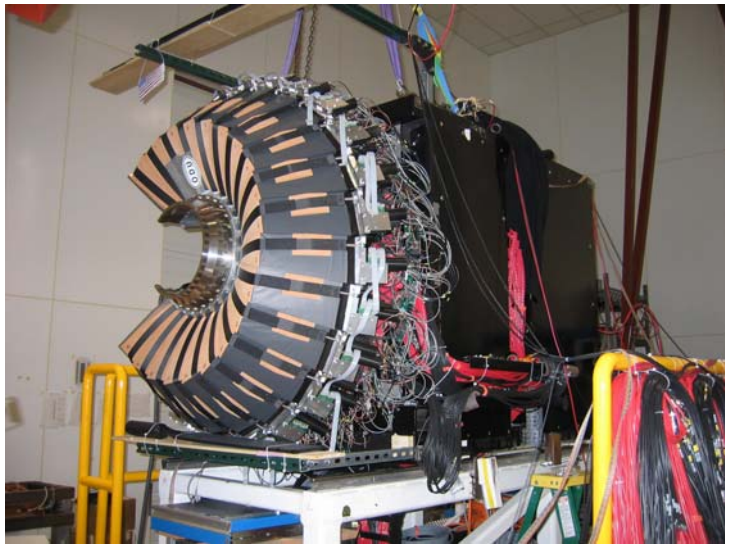
# Hall A experimental setup



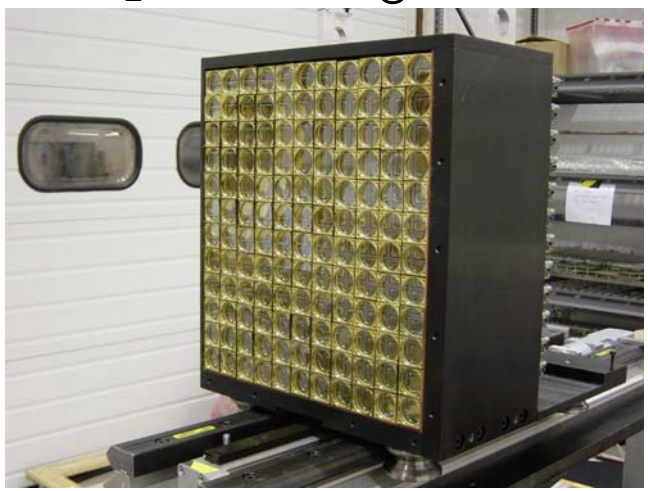

High Resolution Spectrometer



100-channel scintillator array

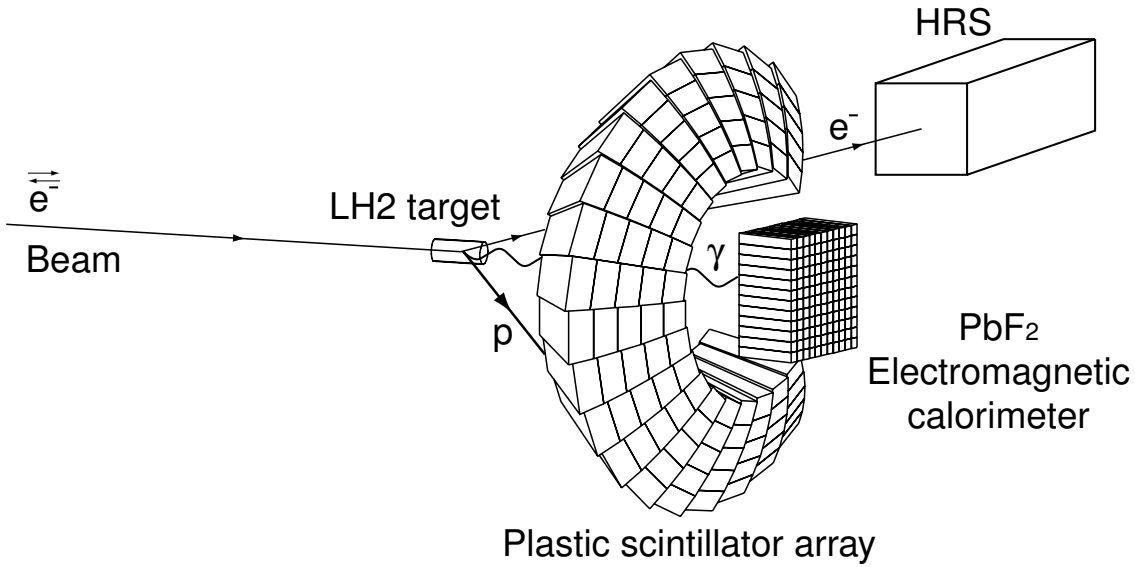


132-block $PbF_2$ electromagnetic calorimeter



# $\pi^0$ cross-section measurements

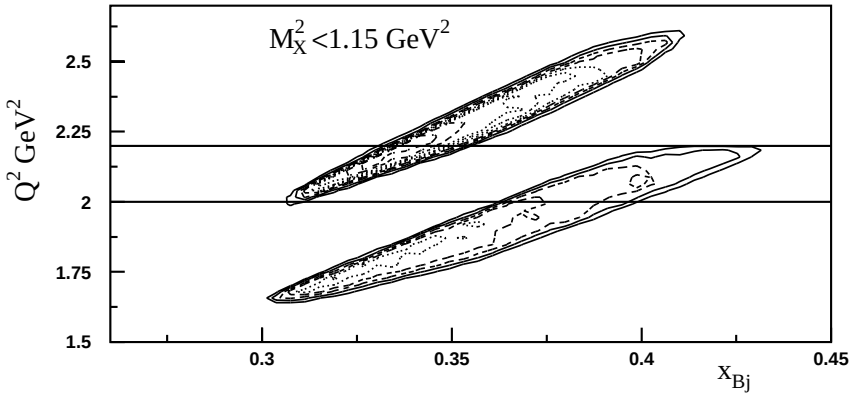
## Data taken concurrently with E00-110 (Hall A – DVCS)

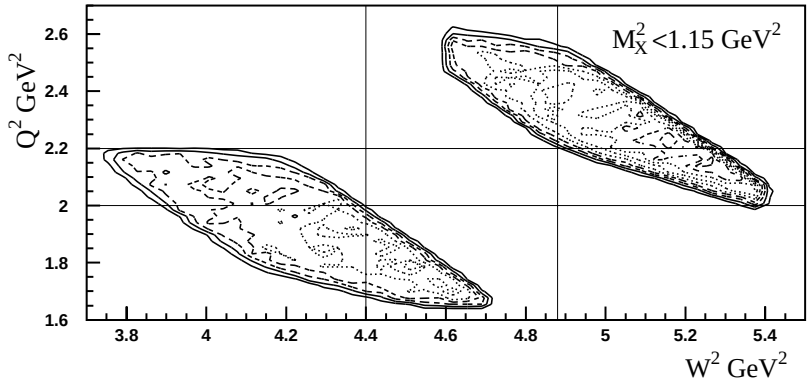



Event sample for $\pi^0$ analysis:

- Scattered electron $e'$ in Left High Resolution Spectrometer (HRS)
- 2 photons $\gamma$ $\gamma$ in electromagnetic calorimeter
- No recoil proton detection (missing mass and invariant mass cuts)

# Kinematics




Small lever arm, but very high accuracy

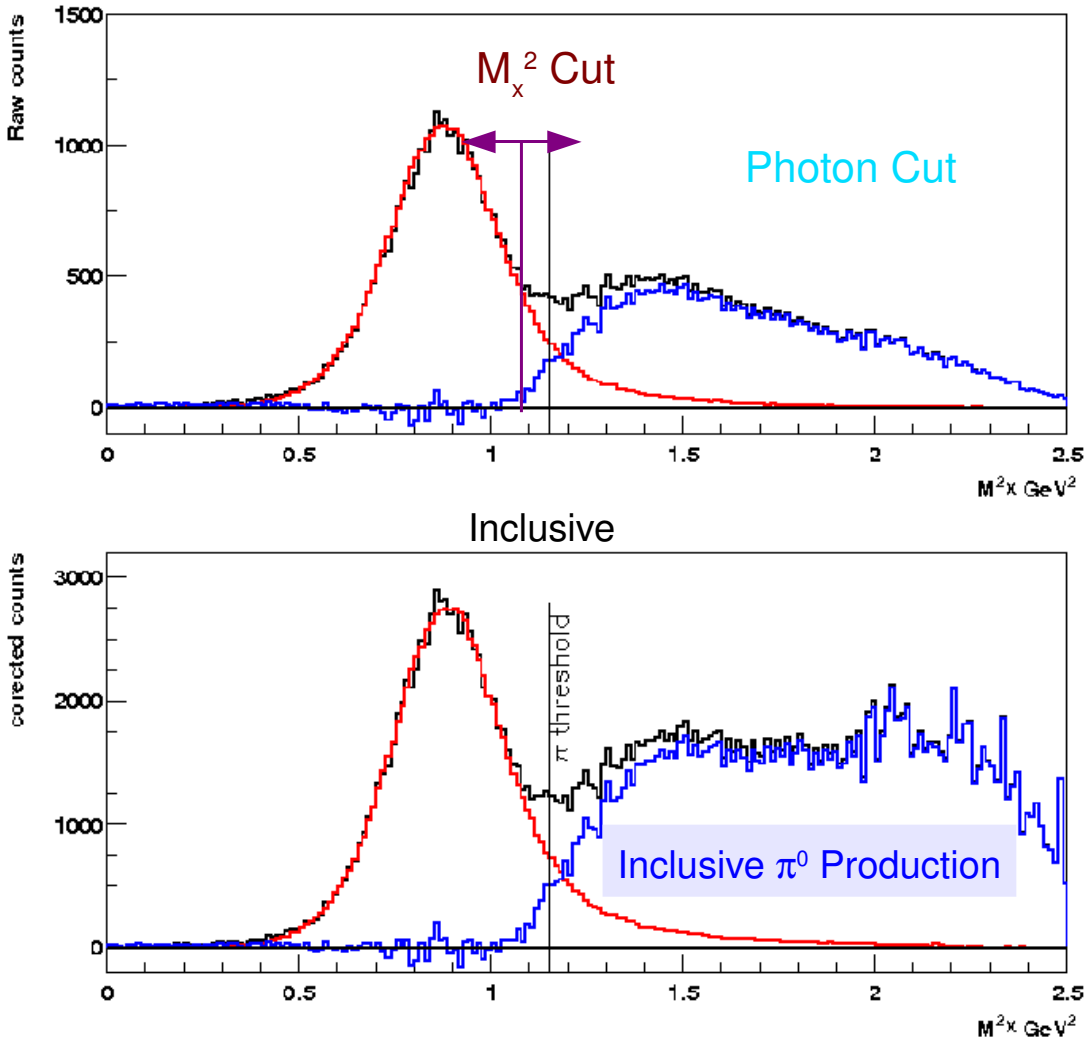
# Azimuthal dependence of the cross section

$$\frac{d\sigma}{dt} = 2\pi\left(\frac{d^2\sigma}{dtd\phi_\pi}\right) =$$

$$\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin\phi$$

- $\phi-$dependence allow separation of 4 different cross section
- Rosenbluth technique needed for L/T separation

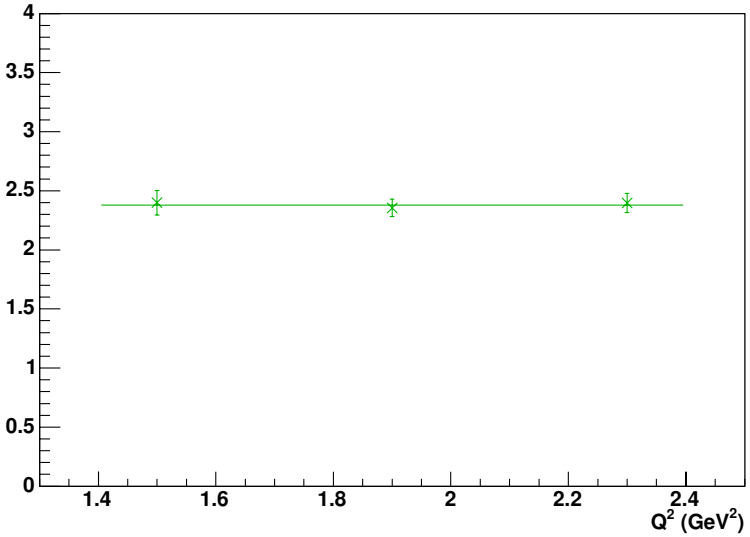
# Missing mass squared: $ep \rightarrow e\gamma X$

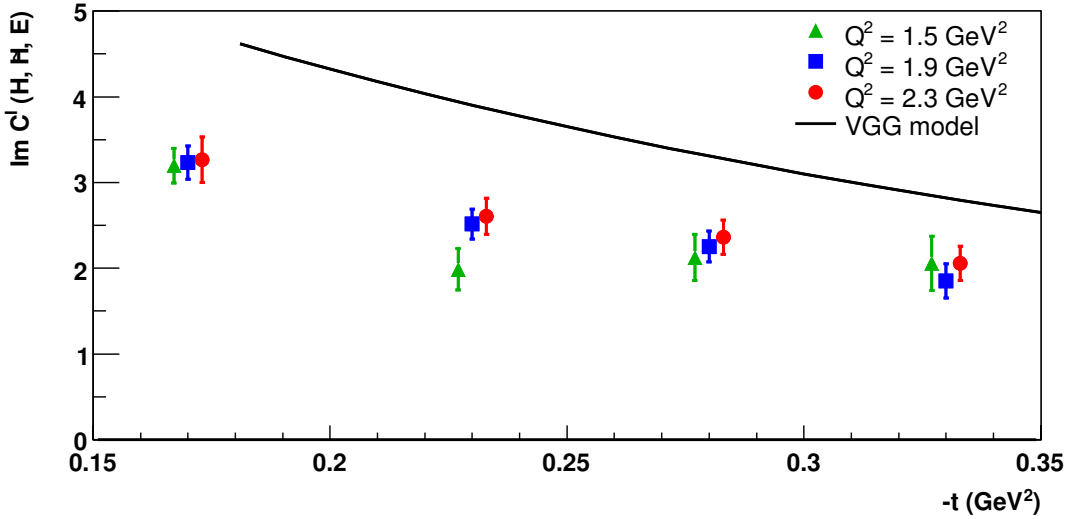


# Further DVCS experiments

## What we learned in E00-110:

- DVCS helicity-dependent cross section as a function of $Q^2$:
  - Strong indications factorization
  - First linear combination of GPDs along the kinematic line $x = \pm\xi$

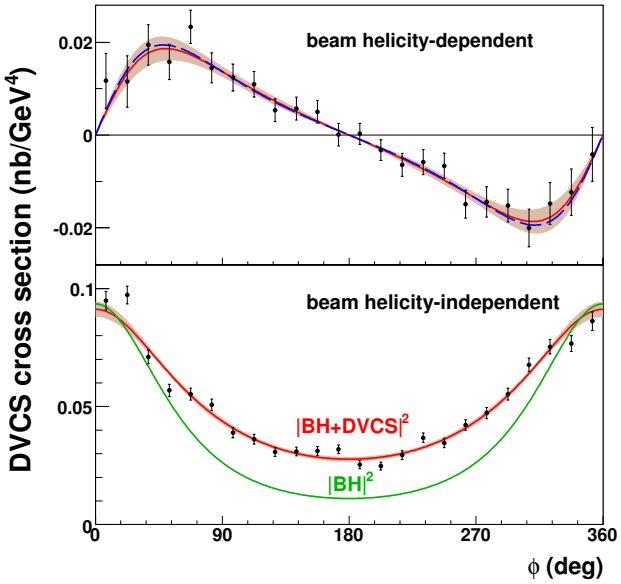


# Further DVCS experiments

## What we learned in E00-110:

- DVCS helicity-independent cross section at one $Q^2$ point *only*:
  - BH only a small part of the total cross section
    $\Rightarrow$ both BH-DVCS interference and DVCS$^2$ are significant
    $\Rightarrow$ Need to separate these two contributions to extract a clean measurement of GPDs integrals




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

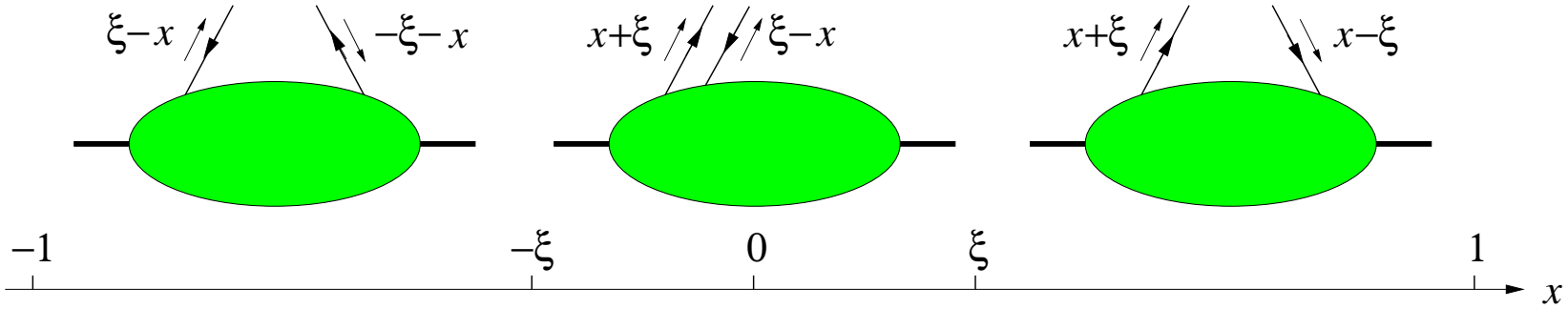
- $Q^2-$dependence of the helicity-independent cross section:
  stringent test of factorization

# GPDs in the $x$ domain

Emission and reabsorption of antiquarks

Creation of a quark-antiquark pair

Emission and reabsorption of a quark

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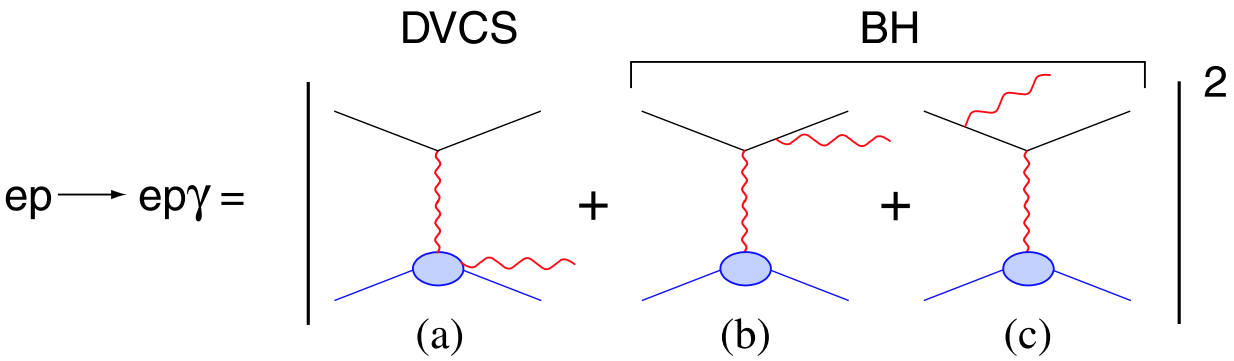
**The helicity-independent cross section samples a wide variety of parton configurations**

# E07-007 (Hall A)

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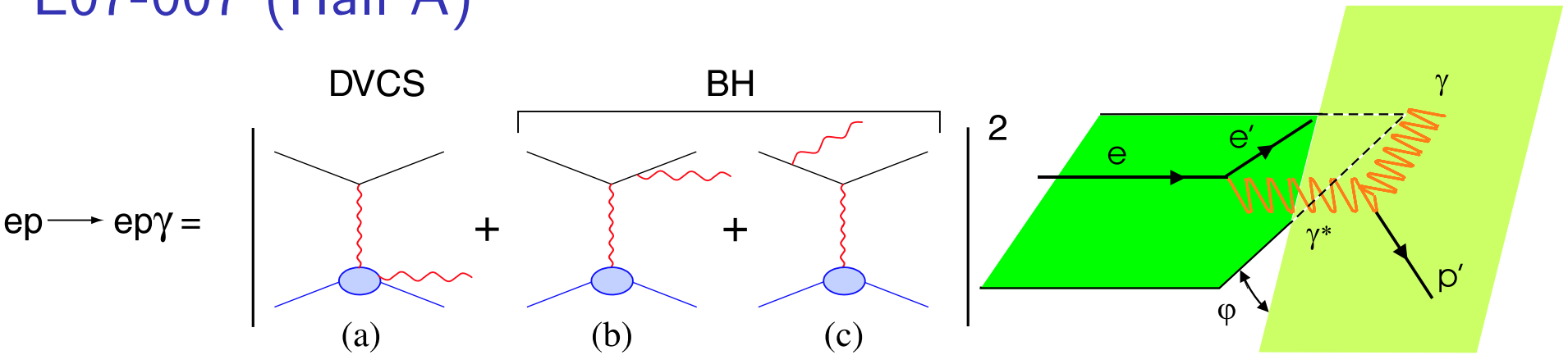
DVCS cross section has a very rich azimuthal structure:

- Azimuthal analysis allows the separation of the different contributions to $\mathcal{I}$ if DVCS$^2$ is negligeble.
- If DVCS$^2$ is important, $\mathcal{I}$ and DVCS$^2$ terms **MIX** in an azimuthal analysis.
- The **different energy dependence** of $\mathcal{I}$ and DVCS$^2$ allow a full separation.

# E07-007 (Hall A)




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

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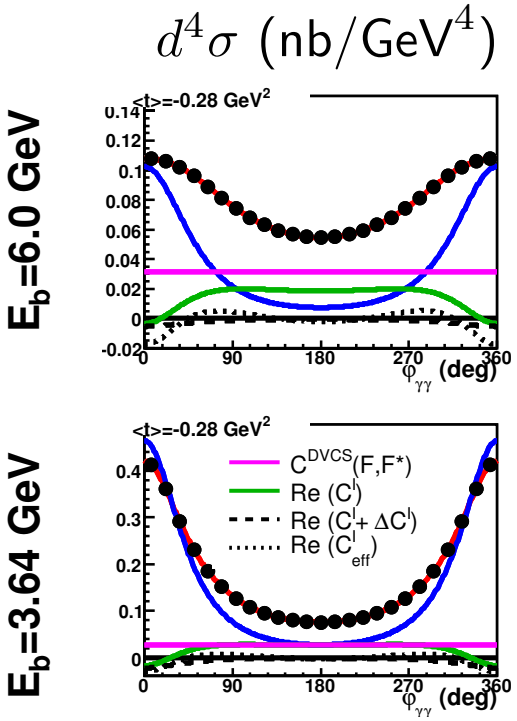
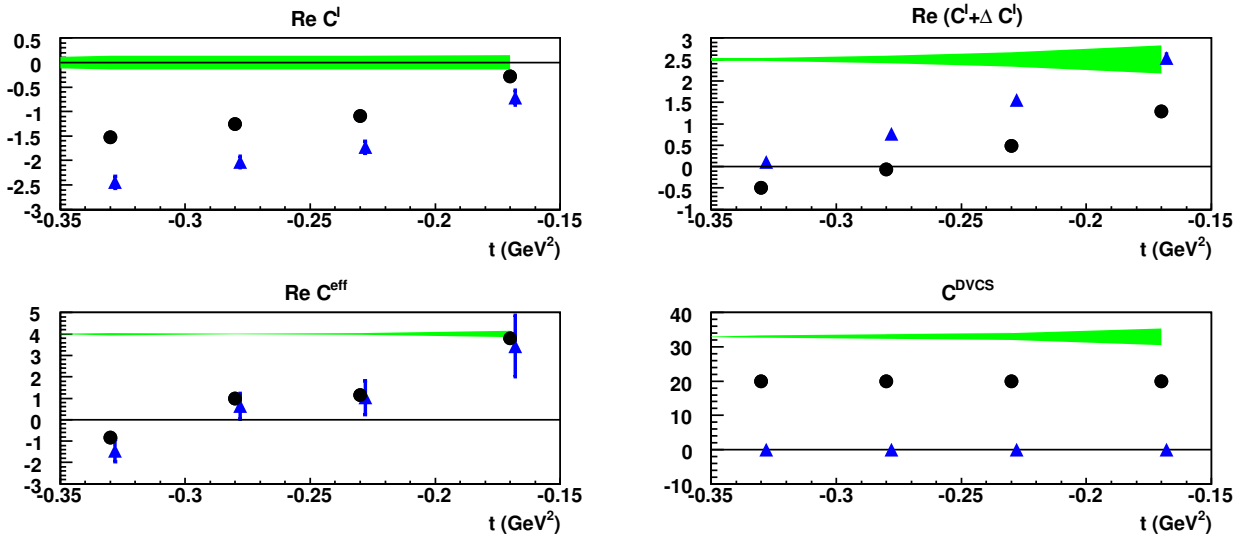
- The **different energy dependence** of $\mathcal{I}$ and DVCS$^2$ allow a full separation.

# E07-007: Rosenbluth-like DVCS$^2$–$\mathcal{I}$ separation

- Scaling test on the real part of the DVCS amplitude
- Clean separation of BH-DVCS intereference term from pure DVCS$^2$
- Rosenbluth separation of $\sigma_L/\sigma_T$ for $ep \to ep\pi^0$



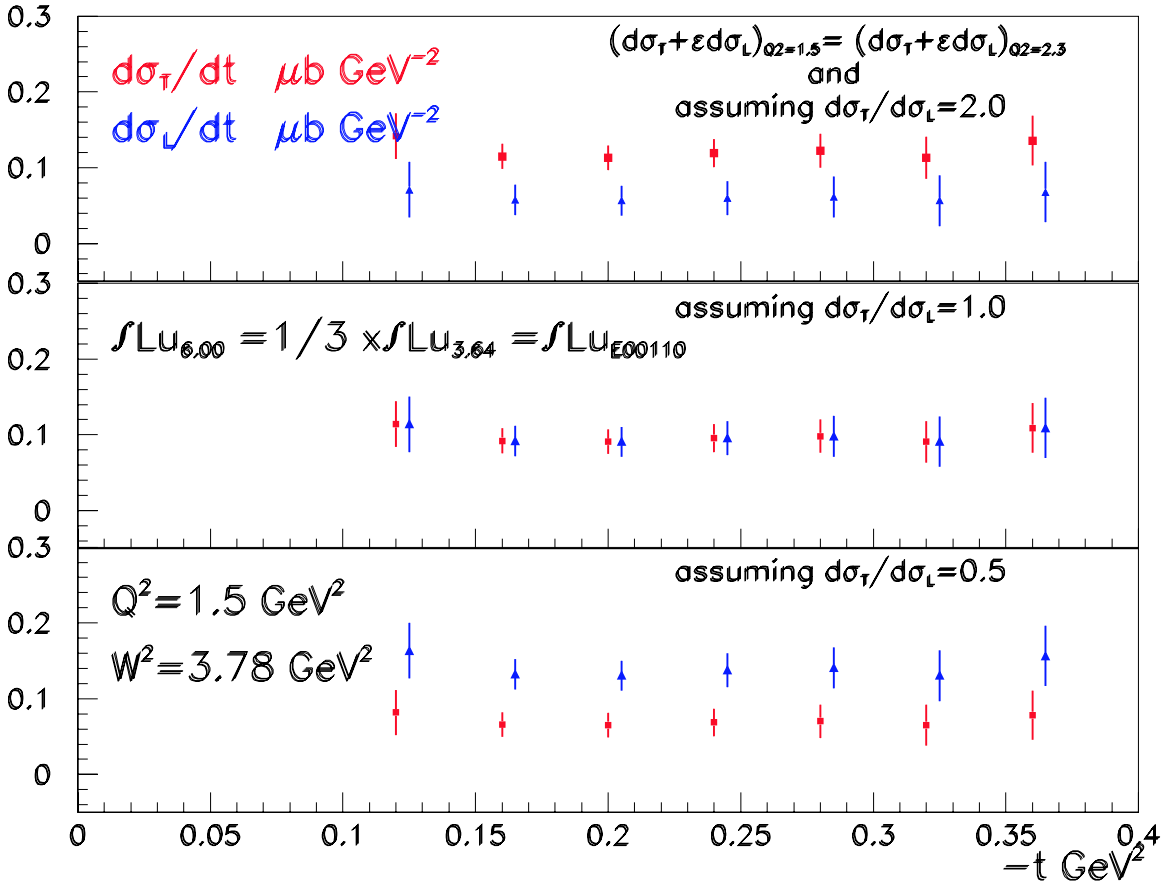

● E07-007 ▬ Systematic uncertainty

▲ E00-110: assuming DVCS$^2$=0

**Approved by JLab PAC-31 (2007) with A-rating**

# E07-007: $\sigma_L$ Rosenbluth separation ($Q^2 = 1.5$ GeV$^2$)

**$\sigma_L$ with statistical accuracy $\ll \sigma_T + \epsilon\sigma_L$**

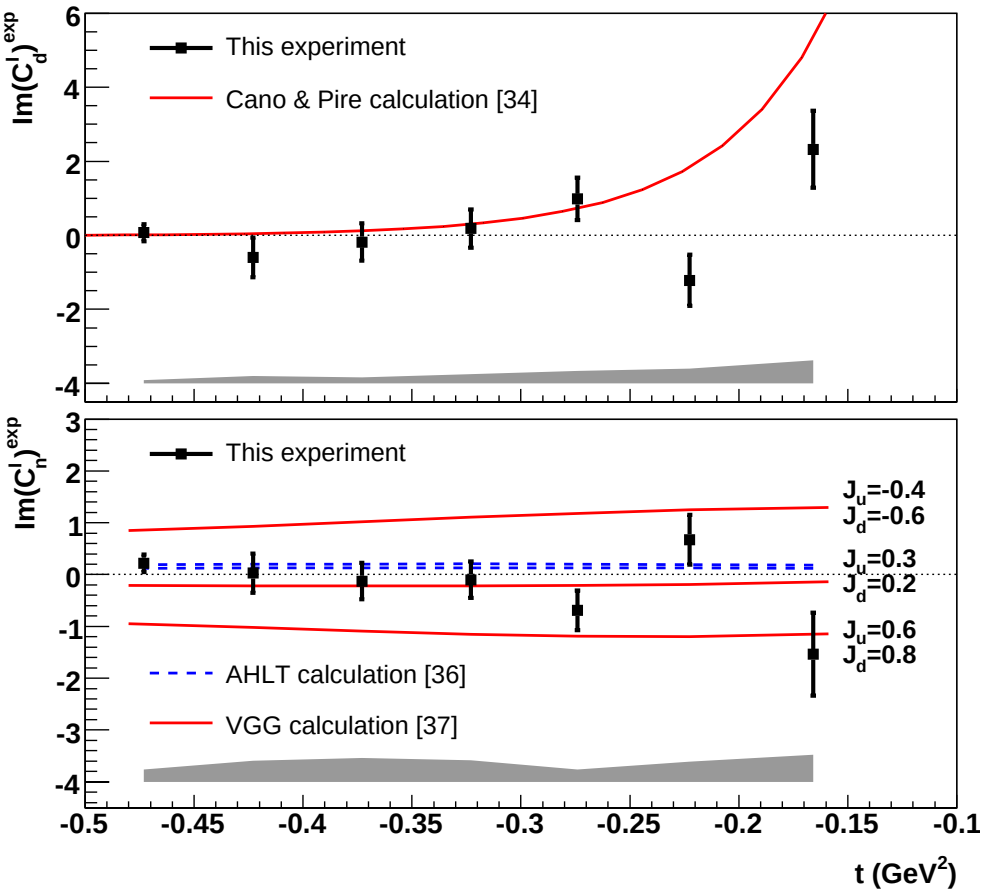



$$\frac{\sigma_T}{\sigma_L} = 2.0$$

$$\frac{\sigma_T}{\sigma_L} = 1.0$$

$$\frac{\sigma_T}{\sigma_L} = 0.5$$

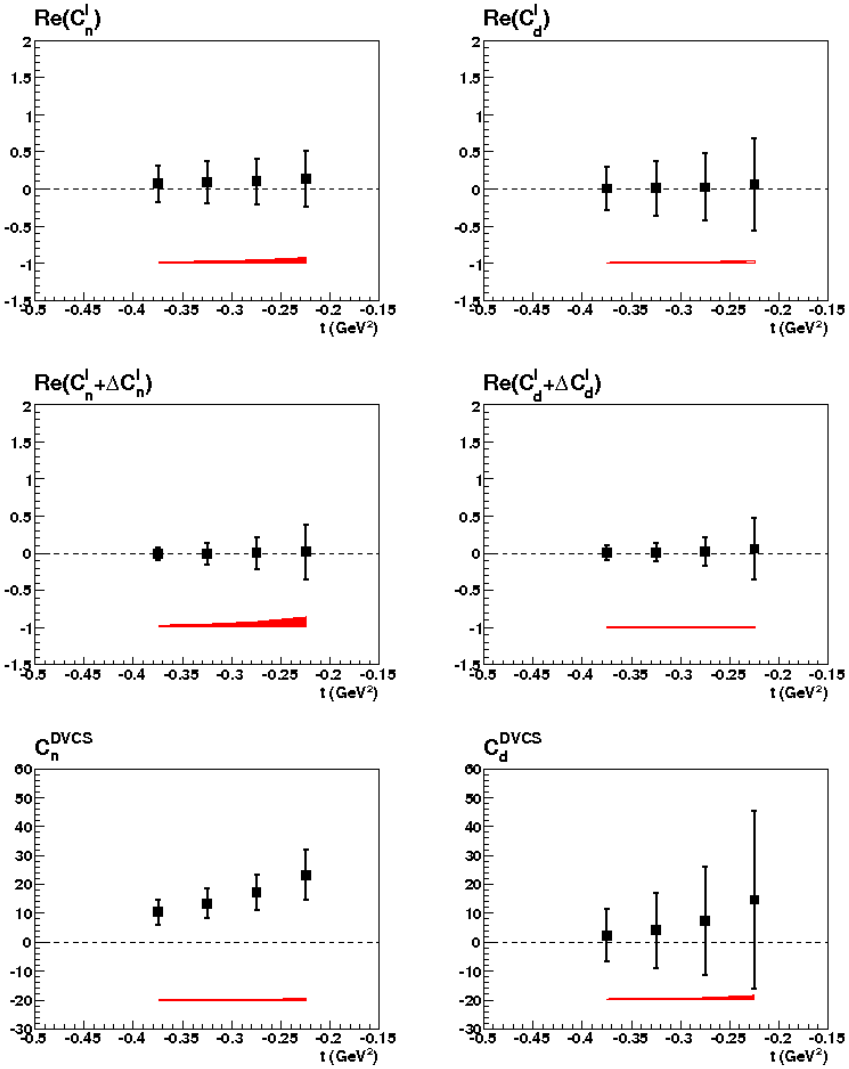
# Previous results (E03-106): constraints on the $\Im$m part




- Different flavor sensitivity (proton & neutron)
- Uncertainties will be reduced by upcoming measurements

M. Mazouz *et al.*, Phys. Rev. Lett. **99**, 242501 (2007)

# DVCS/$\pi^0$ Rosenbluth separation on the neutron/deuteron




**E08-025 experiment:**

- Unpolarized cross section
- Rosenbluth separation

*Recently approved to run simultaneously with E07-007*

# Upgrades (from E00-110/E03r-106)

1. Expanded $PbF_2$ calorimeter: $11\times12+\underline{76}$ blocks.
   - Higher acceptance for $\pi^0$ 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 $ep\rightarrow ep\pi^0$ 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 $\pi^0\rightarrow\gamma\gamma$ from target)

# Summary

- $\pi^0$ electroproduction:
  - L/T separation needed (upcoming experiment at 6 GeV)
  - Some hints of non-negligeable T components at moderate $Q^2$
- DVCS:
  - Some indications of scaling at moderate $Q^2$:
    - Upcoming experiment will provide stronger tests
  - Both interference BH-DVCS and DVCS$^2$ are important:
    - Absolute cross section measurements needed
    - New experiment will separate all contributions
- Parallel DVCS/$\pi^0$ program with a deuterium target $(n/d)$