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

Carlos Muñoz Camacho

Laboratoire de Physique Corpusculaire, Clermont Ferrand, IN2P3/CNRS

6th Int. Conference on Perspectives in Hadronic Physics
Outline

1. Pseudoscalar 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:

\[ d^5 \sigma - \bar{d}^5 \bar{\sigma} = \Im m \left( T_{BH} \cdot T_{DVCS} \right) \]
\[ d^5 \sigma + \bar{d}^5 \bar{\sigma} = |BH|^2 + \Re e \left( T_{BH} \cdot T_{DVCS} \right) + |DVCS|^2 \]

\[ T_{DVCS} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} + \cdots = \]
\[ \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(x = \xi, \xi, t) + \cdots \]

Access in helicity-independent cross section

Access in helicity-dependent cross-section
\( \pi^0 \) electroproduction \((ep \rightarrow ep\pi^0)\)

At leading twist:

\[
\frac{d\sigma_L}{dt} = \frac{1}{2\Gamma} \sum_{h_N, h'_N} |M^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \quad \sigma_T \propto \frac{1}{Q^8}
\]

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

Different quark weights: flavor separation of GPDs

\[
|\pi^0\rangle = \frac{1}{\sqrt{2}} \{|u\bar{u}\} - |d\bar{d}\}\rangle \quad \tilde{H}_{\pi^0} = \frac{1}{\sqrt{2}} \left\{ \frac{2}{3} \tilde{H}^u + \frac{1}{3} \tilde{H}^d \right\}
\]

\[
|p\rangle = |uud\rangle \quad H_{DVCS} = \frac{4}{9} H^u + \frac{1}{9} H^d
\]
Beam spin asymmetries

**CLAS (Hall B) results**

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

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

### Graphs

- Graph 1: $Q^2$ vs $x_B$
- Graph 2: $A(\phi)$ vs $x_B$
- Graph 3: $\alpha$ vs $Q^2$

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

π^0 electroproduction

Cross-section measurements

Outlook

Upcoming 6 GeV experiments

Hall A experimental setup

High Resolution Spectrometer

100-channel scintillator array

132-block PbF_2 electromagnetic calorimeter

Carlos Muñoz Camacho

DVCS/DVMP at JLab (2)
Cross-section measurements

\( \pi^0 \) 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

Carlos Muñoz Camacho
DVCS/DVMP at JLab (2)

LPC-Clermont/IN2P3-CNRS
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: $ep \rightarrow e\gamma X$
Introduction

Electroproduction

Upcoming 6 GeV experiments

Outlook

E07-007: DVCS-BH – DVCS$^2$ separation

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
    ⇒ both BH-DVCS interference and $DVCS^2$ are significant
    ⇒ Need to separate these two contributions to extract a clean measurement of GPDs integrals

$$
\sigma(ep \to ep\gamma) = |BH|^2 + T(BH \cdot DVCS) + |DVCS|^2
$$

- $Q^2$–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

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

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

**Access in helicity-independent cross section**

**Access in helicity-dependent cross-section**

---

The helicity-independent cross section samples a wide variety of parton configurations
E07-007 (Hall A)

\[ \sigma(ep \rightarrow ep\gamma) = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2 \]

Known to $\sim 1\%$  
Linear combination of GPDs  
Bilinear combination of GPDs

DVCS cross section has a very rich azimuthal structure:

- Azimuthal analysis allows the separation of the different contributions to $I$ if DVCS$^2$ is negligible.
- If DVCS$^2$ is important, $I$ and DVCS$^2$ terms MIX in an azimuthal analysis.
- The different energy dependence of $I$ and DVCS$^2$ allow a full separation.
E07-007 (Hall A)

\[ \sigma(ep \rightarrow ep\gamma) = |\text{BH}|^2 + \mathcal{I}(\text{BH} \cdot \text{DVCS}) + |\text{DVCS}|^2 \]

- Known to \( \sim 1\% \)
- Linear combination of GPDs
- Bilinear combination of GPDs

**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 negligible.
- 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: Rosenbluth-like DVCS$^2–\mathcal{I}$ separation

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

$\int d^4\sigma \left( \frac{\text{nb}}{\text{GeV}^4} \right)$

- 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 ($Q^2 = 1.5 \text{ GeV}^2$)

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

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

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

$\frac{\sigma_T}{\sigma_L} = 0.5$
E08-025: DVCS/$\pi^0$ on the neutron/deuteron

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

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

**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
1. Expanded $PbF_2$ calorimeter: $11 \times 12 + 76$ 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 $4 \times \text{E00-110 rate}$

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-negligible 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 ($n/d$)