Waveform analysis of NPS data and preliminary physics plots

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Outlines

- Waveform analysis
- Time resolution
- Energy Resolution
- Pi0 energy calibration
- $eN \rightarrow e\gamma N$ and $eN \rightarrow e\pi^0 N$ analysis
Waveform Analysis

**First step:** Select from the elastic data a reference waveform for each NPS channel using certain criteria

- **Pulses should be:**
  - In Coincidence (+/- 5 samples)
  - Highest amplitude
  - Lowest noise in the Background
  - No multiples or pile-up

- **Add a constant vertical shift** to have an average baseline equal to 0 mV

- **Normalization of the ref. wf. to 1 mV amplitude**

Remove any fluctuation by setting all the ref. wf. samples to 0 mV in the bkg region.
Waveform Analysis

Second step: Produce a Fit function for each block

- Interpolate the 110 samples of the ref. wf. with Spline to create a function $f(t)$

- The fit function:

$$F(t) = B + \sum_{i=1}^{N_{\text{pulses}}} A_i f(t - t_i)$$

  - Baseline
  - Amplitude
  - Time of pulse #i (4*ns) relatively to the ref wf time

![Waveform Analysis Diagram](image_url)
Waveform Analysis

Third step: Detect the number of pulses in the waveform, estimate the amplitude and time

- The identification of a pulse is based on 4 consecutive samples with increasing values followed by 2 consecutive samples with decreasing values.

- The time and the rough estimate of the amplitude of the pulses found are used to help the fit.
Fitted Waveforms

Block 857

LH2

Very convenient fit for the coincidence pulse

Block 286

Multiple pulse fit

Block 589

LD2

Block 549
TIME RESOLUTION STUDY

Elastics data

Production data

-22.5 ns

Time of the coincidence pulse is taken with respect to the arrival time of the elastic reference waveform

LD2 + LH2 RUNS COMBINED (2 middle columns blocks)

σ = 0.58 ns resolution

Block 619

Pulses above 5 MeV

σ = 0.4 ns resolution

Block 701

0.60 ns resolution

Block 701

Pulse (>20mV) time (ns) (all found pulses included)
Clustering Scheme

Steps:
- For each block: $|\text{time}[i]| < 5 \times \text{rmstime}[i]$
- Search for the seed block
- Apply the 5x5 clustering
- Calculate the cluster energy and the impact position:

$$E_i = C_i A_i \left/ \bar{x} = \frac{\sum_i w_i \bar{x}_i}{\sum_i w_i} \right/ w_i = \max \left\{ 0, \left[ W_0 + \ln \left( \frac{E_i}{E} \right) \right] \right\}$$

$$W_0 = \ln \left( \frac{100 E(\text{GeV})}{2.02 e^{-\frac{d}{r_M}} + \left[ 4.98 e^{-\frac{d}{r_M}} + 0.30 \right] E(\text{GeV})} \right)$$

- Calculate 4-vector using the shower depth (a) correction (G4 simulation)

$$a(cm) = \frac{0.00507955}{0.999238 - e^{(-0.0010705 \times E(\text{GeV}))}} + 9.31622$$

• **33% improvement** in energy resolution at **7.3 GeV** from elastic $H(e,e'p)$ calibration runs after applying the waveform analysis

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**Energy Resolution**

- NPS energy resolution at 7.3 GeV, elastic runs 1974 to 1982

- After a fit of the waveforms
- No waveform fit (adc:SampPulseAmp variable)

- $\alpha = 109 \text{ MeV}$, $\frac{E}{E} = 1.5 \% = 2.4\% \oplus 1.2\%$
- $\alpha = 163 \text{ MeV}$, $\frac{E}{E} = 2.2\%$

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**Invariant Mass (GeV)**

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- **0.128 GeV**
- **0.135 GeV**

Not sufficient → **Calibration using $\pi^0$ is needed**
**π0 energy calibration**

**Method:**

- With exclusive π0 events, the expected energy of the π0 can be calculated using its scattering angle. A minimization between the measured energy and the expected π0 energy allows to calibrate the NPS channels.

- We usually do 3 to 4 iterations before converging to the most suitable calibration coefficients.

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**Exclusive events selection**

**2D cut**
**e p → e π0 p results**

- **Kinematics:** \texttt{KinC_x60_3}
- Only the basic HMS cuts: 
  \[ |dp| < 8\% \text{ and } |ph| < 0.04 \text{ and } |th| < 0.08 \text{ and } |react.z| < 4 \]

**LH2**

- $\sigma_{hcana} = 5.4 \text{ MeV}$
- $\sigma_{WF} = 3.9 \text{ MeV}$
- \(~28\%\) improvement!

**LD2**

- $\sigma_{hcana} = 6.4 \text{ MeV}$
- $\sigma_{WF} = 4.1 \text{ MeV}$
- \(36\%\) improvement!

- Used the following relationship for the corrected missing mass: $mm2 + a \times minv - b$
A noticeable improvement
DVCS Analysis
(Pi0 Contamination)

Method:

- **3 Main criteria** for the $\pi^0$ events selected from data:
  - No edge block clusters
  - Energy of the photons is **above the trigger threshold**
  - A correct invariant mass

- Simulate the decays of each detected $\pi^0$ by randomizing the photon angles 5000 times in the c.m. frame:
  - $\cos \theta$ [-1, 1]
  - Azimuthal angle \([0, 2\pi]\)

- Divide the decays by number of photons generated:
  - $N_0$ = events with no $\gamma$ detected
  - $N_1$ = events with 1 $\gamma$ detected
  - $N_2$ = events with 2 $\gamma$ detected

- Each event with $N_1$ is subtracted from the DVCS events and before hand multiplied by 2 factors:
  - $a_1 = 1/5000$ and $a_2 = 5000/N_2$

$$W = a_1 \times a_2 = 1/N_2$$
DVCS Analysis
(π0 Contamination)

Threshold Scan

- Steps of 0.1 GeV for the π0 threshold from 0.6 GeV (black plot) to 1.3 GeV (Grey plot)

- Chose the 1 GeV Threshold for both since it’s stable+higher in [0.5, 1.5] GeV²

- LH2 trigger threshold: 0.75 GeV
DVCS Analysis

Multi-cluster correction

- Calculated the yield of exclusive $\pi^0$ events between 0.5 GeV$^2$ and 1.1 GeV$^2$ for the case of 2 cluster events → 9422
- For 3 clusters event → 598 (6.43%)
- For 4 clusters event → 28 (0.29%)
- All the histogram of different contributions are added to the 2 cluster $Mx^2$ raw spectrum

DVCS Analysis
(DVCS Yield Study)

- Calculated the yield of DVCS events between 0.5 GeV² and 1.1 GeV² for the case of 1 cluster events → 6256
- For 2 clusters events → 315 (5.03%)
- For 3 clusters events → 17 (0.27%)
- All the histogram of different contributions are added to the 1 cluster Mx² raw spectrum

One Case:

- Each cluster in a multi-cluster event is systematically considered as a potential DVCS event if it does not originate from a π0 decay (the invariant mass of that photon when combined with another photon is different from the mass of π0)
DVCS Analysis
(DVCS Accidentals)

- Window: +/- 10 ns from the coincidence pulse time

- For each block:
  \[|time[i]-10|<5*rmstime[i] \]
  \[|time[i]+10|<5*rmstime[i]\]

- The accidentals are obtained with the same method used for the coincidence events:
  - If cluster number 0 in 2-cluster events contributes to the coincidence \( Mx2 \) spectrum then its contribution is also determined and added to the total accidental \( Mx2 \) spectrum
Preliminary Results

Better resolution and exclusivity than previous DVCS experiments
DVCS Analysis
(\(\pi^0\) Accidentals)

- N0: 2 photons are in coincidence with each other and with the scattered electron
- N1 + N2: 2 photons are in coincidence with each other but not in coincidence with the scattered electron
- N3_T + N3_B + N4_L + N4_R: both photons are not in coincidence with each other and only one of them is in coincidence with the scattered electron
- N5 + N6: both photons are neither in coincidence with each other nor with the scattered electron

All Accidentals = 0.5 * (N1+N2+N3_B+N4_L+N3_T+N4_R) - (N5+N6)
DVCS Analysis
(π0 Resolution Check)

- Small differences between the 2 resolutions of the π0 invariant mass

- Will be multiplying the cluster energy of LD2 in order to bring it up to the same resolution by the following ratio: mean_LH2/mean_LD2
Fermi Smearing

LH2 not smeared \[ \rightarrow \quad M_x^2 = (P'_p)^2 = (q + P - q')^2 \]

How to smear it?

- For the DVCS off the deuteron reaction:

\[ \gamma^* + ^1D \rightarrow \gamma + n' + p' \]

\[ P_d = (M_d, 0) \]

\[ q + P_d = q' + P_n + P'_p \]

Deuteron mass

Nucleon mass

With

\[ = \left( \sqrt{M^2 + P^2_f, P_f} \right) + \left( \sqrt{M^2 + P^2_f, -P_f} \right) + \left( M_d - 2 \sqrt{M^2_d + P^2_f, 0} \right) \]

- We can rewrite the previous equation as follows:

\[ q + P_n + P_p + P_{add} = q' + P'_n + P'_p \]

With

\[ P_{add} = \left( M_d - 2 \sqrt{M^2_d + P^2_f, 0} \right) \]

- The missing mass of the deuteron can be then written as follows:

\[ M_x^2 = (P'_p + P - P_p - P_{add})^2 \]

With

\[ P = (M, 0) \]

- Then we smear the LH2 data as follows:

\[ M_x^2 = \left( q + P - q' + P - P_p - P_{add} \right)^2 \]

Fermi momentum distribution

Smearing term

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**e N \rightarrow e \pi^0 N** analysis

Corrected missing mass without any target correction

Corrected missing mass with (0.72) correction

Multiplied the neutron peak by 4

Neutron peak is below the proton peak

Multiplied the neutron peak by 4

Neutron peak is Disappeared!
eN → eγN analysis

DVCS missing mass squared without any correction

Multiplied the neutron peak by 4

Neutron peak is above the proton peak
Summary

- Waveform analysis is a crucial tool to extract the highest resolution possible obtained by the NPS calorimeter

- Better **exclusivity** and **resolution** than the previous DVCS experiments is already conducted

- More sophisticated analysis is ongoing...
Back up Slides
DVCS with (0.72) correction
Fermi smearing effect

\[ ep \rightarrow e\pi^0 X \]
Comparison between old DVCS fermi smearing and the new method used

Corrected missing mass squared (GeV²)

- Entries: 37132
- Mean: 1.565
- Std Dev: 0.6681

Raw missing mass squared (GeV²)

- Entries: 37114
- Mean: 1.563
- Std Dev: 0.6728

**b = 2.83**
Shower depth correction

- For each energy value, we determine “a” in such a way that the difference between the position \( x_c \) (centroid position of the cluster) and \( x'c \) obtained by a Geante 4 simulation is centered around 0 and has the lowest RMS.
Exclusive Pi0 Missing Mass Squared

LH2

LD2

Log scale

Events

Mx^2 (GeV^2)

Entries 38116
Mean 1.582
Std Dev 0.6682

Entries 85873
Mean 1.627
Std Dev 0.6644

Entries 38116
Mean 1.582
Std Dev 0.6682

Entries 85873
Mean 1.627
Std Dev 0.6644

Log scale
**Exclusive Pi0 Invariant Mass**

- **Red** ==> N1
- **Green** ==> N2
- **Black** ==> N3_B (bottom) + N4_L (left)
- **Pink** ==> N3_T (Top) + N4_R (right)
- **Sky Blue** ==> N5 + N6
LD2 $\pi^0$ ACCIDENTALS
DVCS missing mass squared with the factor 0.72 applied
π0 energy calibration

Electron beam $k(k_0, \bar{k})$ → Target $p(M_N, \vec{0})$ → Recoil nucleon (not detected)

Scattered electron $k'(k'_0, \bar{k}')$

Photon or π0 $q'(q'_0, \vec{q}')$

Electromagnetic calorimeter
π0 energy calibration

Method:

\[ E'_i(j) = C'_i A_i(j) \quad \rightarrow \quad E_i(j) = \varepsilon_i C'_i A_i(j) = \varepsilon_i E'_i(j) \]

Deposited energy \quad Corrected Energy \quad Correction factor

With

\[ C_i = \varepsilon_i C'_i \] \quad Corrected calibration coefficient

1) Identification of \( eN \rightarrow eN\pi^0 \) reaction:

\[ |M_{\text{inv}} - M_{\text{peak}}| < 3 \sigma_{M_{\text{inv}}} \quad + \quad M_x^2 < M_{\text{peak}}^2 + \sigma^2_{M_x^2} \]

With

\[ M_{\text{inv}} = \sqrt{(q'_1 + q'_2)^2} \]

Missing mass squared resolution

2) Calculate the expected Pi0 energy:

\[ M_N^2 = (k + p - k' - q'_1 - q'_2)^2 = (k + p - k')^2 + M_{\pi^0}^2 - 2(k_0 - k'_0 + M_N)E_{\pi^0}^{\text{cal}} + 2\|\vec{q}\|\sqrt{(E_{\pi^0}^{\text{cal}})^2 - M_{\pi^0}^2} \cos \theta \]

Solution: \[ E_{\pi^0}^{\text{cal}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \]

With

\[ a = 4(k_0 - k'_0 + M_N)^2 - 4\|\vec{q}\|^2 \cos^2 \theta, \]
\[ b = 4(k_0 - k'_0 + M_N) \left[ M_N^2 - (k - k' + p)^2 - M_{\pi^0}^2 \right], \]
\[ c = 4M_{\pi^0}^2 \|\vec{q}\|^2 \cos^2 \theta + \left[ M_N^2 - (k - k' + p)^2 - M_{\pi^0}^2 \right]^2. \]

3) Minimization:

- The following minimization between the calculated energy and the reconstructed one:

\[ \chi^2 = \sum_{j=1}^{N_{\pi^0}} \left( E_{\pi^0}^{\text{cal}}(j) - E_{\pi^0}^{\text{rec}}(j) \right)^2 \]

With \( N_{\pi^0} \rightarrow \) Number of Pi0 events

\[ E_{\pi^0}^{\text{rec}}(j) = \sum_{i=1}^{N_{\pi^0}} \epsilon_i E_i'(j) d_i(j) \rightarrow \text{Reconstructed energy} \]

- We get the following linear set of equations:

\[
\sum_{i=1}^{N_{\pi^0}} \left[ \sum_{j=1}^{N_{\pi^0}} E_i'(j) d_i(j) E_k'(j) d_k(j) \right] \epsilon_i = \sum_{j=1}^{N_{\pi^0}} E_{\pi^0}^{\text{cal}}(j) E_k'(j) d_k(j)
\]

- The correction factors are obtained by inverting the following matrix:

\[
\alpha_{ik} = \sum_{j=1}^{N_{\pi^0}} E_i'(j) d_i(j) E_k'(j) d_k(j)
\]
Detector Performance

**Energy Resolution**

- 1.3% energy resolution at 7.3 GeV from elastic \( H(e,e'_\text{Calo}^{PHMS}) \) calibration run, applying waveform analysis and a non-linearity correction

**Time Resolution**

- A very good timing resolution (0.58 ns) is recorded

The 2ns structure of the beam is clearly visible.
TIME RESOLUTION STUDY
(LD2+LH2 RUNS COMBINED)

$h_{\text{time tot}}$

$\chi^2 / \text{ndf} = 2.372e+05 / 116$

mean $= -0.008649 \pm 0.000286$

sigma $= 0.6012 \pm 0.0002$

$p2 = 7.908e+05 \pm 3.737e+00$

$p3 = 8.398e+04 \pm 4.125e+01$

0.6 ns resolution
From DVCS to GPDs

- **Factorization in Bjorken limit**

  - Hard scattering process (**Perturbative calculation**)
  - PQCD factorization theorem
  - Soft process (**non Perturbative calculation**)

**Handbag Diagram**

\[ |\mathcal{T}|^2 = (\mathcal{T}_{DVCS} + \mathcal{T}_{BH})^2 = |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{I} \]

\[ \Im(m(\mathcal{T}_{DVCS}) \propto -i\pi \left( \text{GPD}(\xi, t) \pm \text{GPD}(-\xi, t) \right) \]

\[ \Re(\mathcal{T}_{DVCS}) \propto P \int_{-1}^{1} dx \left( \frac{1}{x - \xi} \pm \frac{1}{x + \xi} \right) \text{GPD}(x, \xi, t) \]
Spin Crisis

Orbital momentum of the quarks and gluons

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_Q + L_G
\]

Quarks contribution (u,d,s)

Gluons contribution

Spin of all Quarks

???
3D STRUCTURE OF THE NUCLEON

Elastic Scattering (ep)

Form Factors

Partons Distribution Functions

Deeply Virtual Compton Scattering (DVCS)

Deep Inelastic scattering (DIS)

Exclusive Pi0 Meson Electroproduction (DVMP)

GPDs
Wigner Distributions and GPDs

**General formalism for a quantum system**

\[ W(r, p) = \int_{-\infty}^{+\infty} dz e^{ipz} \psi^*(r - z/2) \psi(r + z/2) \]

**For the case of relativistic quarks and gluons**

\[ W^q_\Gamma(r, k) = \frac{1}{2M} \int \frac{d^4q}{(2\pi)^4} < p' | W^q_\Gamma(r, k) | p > \]

\[ W^q_\Gamma(r, k) = \int d^4z e^{ikz} \bar{\psi}^q(r - z/2) \Gamma \psi^q(r + z/2) \]

**In the infinite momentum reference frame**

\[ F^q_\Gamma(P, x, \Delta) = \frac{P^+}{4\pi} \int dz^- e^{ixP^+z^-} < p' | \bar{\psi}(r - z/2) \Gamma \psi(r + z/2) | p > |_{z^+ = z^\perp = 0} \]

**Particle with \( S = 1/2 \)**

\[ F^q_{\gamma^+}(x, \xi, t) = H^q(x, \xi, t) U(p') \gamma^+ U(p) + E^q(x, \xi, t) U(p') \sigma^{+\nu} \frac{\Delta^\nu}{2M} U(p) \]

\[ F^q_{\gamma^+, \gamma^5}(x, \xi, t) = \tilde{H}^q(x, \xi, t) U(p') \gamma^+ \gamma^5 U(p) + \tilde{E}^q(x, \xi, t) U(p') \gamma^5 \gamma^+ \frac{\Delta^+}{2M} U(p) \]
DVCS on the neutron

- Using the Approximate isospin symmetry of QCD we obtain the simplest way to perform a flavor decomposition of the $u$ and $d$ quark GPDs:

\[
H^p = \frac{4}{9}H^u + \frac{1}{9}H^d \\
H^n = \frac{1}{9}H^u + \frac{4}{9}H^d
\]

- The unpolarized “n-DVCS” cross sections at low $t$ have a direct relevance in the determination of the quark angular momentum via Ji’s sum rule:

\[
J^q = \frac{1}{2} \int_{-1}^{1} x dx [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)] \quad \forall \xi
\]

Mazouz et al. Physical review letters, 99(2007), 242501
n-DVCS and d-DVCS separation
(Hall A results and upcoming steps)

- Exclusive events are obtained with the missing mass technique after the subtraction of accidentals and the neutral pion contamination:

\[ D(e, e' \gamma)X = d(e, e' \gamma)d + n(e, e' \gamma)n + p(e, e' \gamma)p \]

Coherent elastic channel

2 terms separated by missing mass

\[ \Delta M_X^2 = t(1 - M_n/M_d) \approx t/2 \]

incoherent quasi-elastick channels

Subtracted from the LH2 data interleaved

- Separation between incoherent \( n(e,e'\gamma)n \) and coherent \( d(e,e'\gamma)d \) can be achieved with a fit of the exclusive region of the missing mass spectrum

Benali et al. Nat Phys 16 (2020) 191
But using a polarized electron beam: Asymmetry appears in $\Phi$

The cross-section difference accesses the imaginary part of DVCS and therefore GPDs at $x=\xi$

The total cross-section accesses the real part of DVCS and therefore an integral of GPDs over $x$

Kroll, Guichon, Diehl, Pire ...
Experimental Setup

- The photon will be collected by the NPS lead tungsten calorimeter.

- The scattered electron will be detected in the HMS.

- The recoil particle off the LH2/LD2 target will be identified by missing mass.
n-DVCS Kinematics

Data Taken in 2023

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- **High $x_B$ --> high $|t|$ --> better separation**

- Different beam energies that will further give a better extraction of the different CFFs from the DVCS cross sections

- **To reduce systematic uncertainties, LH2 and LD2 run periods are interleaved frequently (every few hours)**

- Sharp drop of the deuteron form factors as $|t|$ increases
HMS Single Arm Pre-Trigger

Credits to C.Yero
NPS/HMS Coincidence

Credits to B. Michaels, J. Poudel, B. Raydo, C. Ghosh, Y. Zhang
How do we store the waveforms?

Data always streamed every 4 ns to the VTP

PEDESTAL + FADC Threshold

If sample > PEDESTAL + Threshold ==> HIT detected in the FADC

FADC computes the integral + PED substraction + Gain applied ==> Energy in MeV (13 bit) streamed to the VTP
Data Acquisition and electronics

- Flash Analog to Digital Converter (FADC)
- VXS Trigger Processor (VTP)

- Compatible mezzanine connector exists that allow use of commercially available ECL/TTL/NIM/ADC/DAC modules

Credits to Ben Raydo
FADC Data Stream

Reports to VTP:
- 13bit energy (in MeV)
- 4ns timing
- Channel number
- 32ns double pulse resolution
Cluster Trigger

- Single photon cluster trigger (S.P.T):

1) The first Basic Steps by the VTP

2) The Cluster Energy Is Above The S.P.T (1400 MeV)

    >>> We have a DVCS cluster in hand

3) **Readout threshold energy** (500 MeV) is applied:

   - We use the 7x7 Clustering around the seed block

   - The VTP sends the readout channels masks in the 7x7 to the FADC in order to read out the raw wavefoms of these channels
VTP and Clusters reconstruction

• VTP BASIC STEPS:

1) If the seed Energy is above the threshold value (70 MeV) ✓

2) If the seed energy is a local maximum with respect to the 8 neighbors within the value of the time window (+/- 20 ns from the seed) ✓

3) The Cluster Energy is calculated by summing up all the energies from the 9 blocks ✓

4) Information stored:
   - The x pos (column number), y pos (row number)
   - Time of the seed block
   - Total energy of the 3 by 3 cluster

=> Coda file words => ROOTfile variables => Waveforms
VTP Performance

- 7x7 readout patterns for separate and overlapping cluster events
- A significant reduce in terms of the data stored
Preliminary Results

Exclusive neutral pion contamination

Symmetric decay

Asymmetric decay

• Better resolution than the previous DVCS experiments

Sigma = 4.1 MeV

LD2
Thanks for everyone who contributed to the experiment

Thank you for your attention!