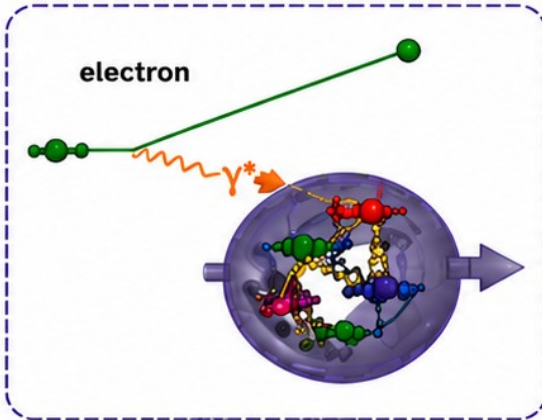




Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C



Wassim Hamdi

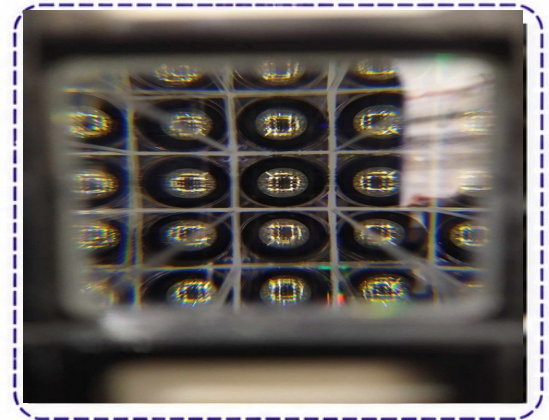
ECA, JLab Hall A/C post-doc



For the **NPS** collaboration



20th of July 2026



Towards improved hadron femtography with hard exclusive reactions

Outline

01



Physics motivation

02



NPS experimental setup

03



Data acquisition

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Detector performance

05



Preliminary physics plots



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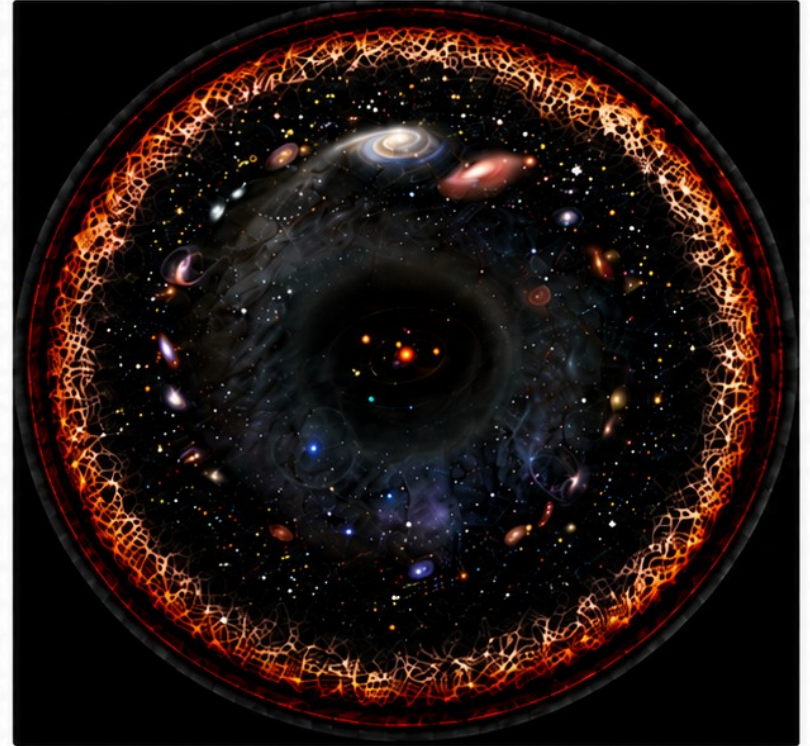


Detector performance

05



Preliminary physics plots

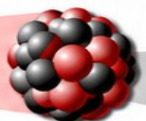




The Spin Crisis



atom
~ 10^{-8} cm



nucleus
~ 10^{-12} cm

proton
(neutron)



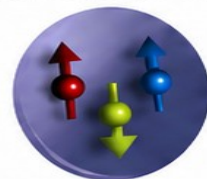
~ 10^{-13} cm

quark
< 10^{-16} cm



$$\frac{1}{2} =$$

The spin of all
Quarks and Gluons



???

Spin decomposition of the nucleon

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

**Quark spin
($\Delta\Sigma$)**

Contribution from the
intrinsic spins of
quarks (u, d, s, ...)

**Gluon spin
(ΔG)**

Contribution from the
intrinsic spins of
gluons

**Quark orbital
angular momentum
(L_Q)**

Orbital motion of
quarks

**Gluon orbital
angular momentum
(L_G)**

Orbital motion of
gluons

The puzzle:

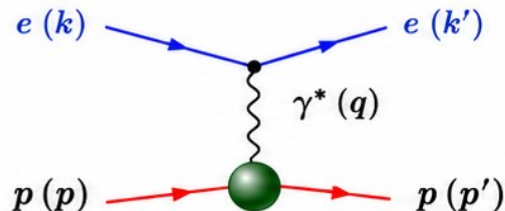
Experiments in the 1980s–90s
found that quark spins contribute
only ~30% to the proton spin.

Where is the rest?



3D Structure with GPDs

1. Elastic Scattering (Form Factors)



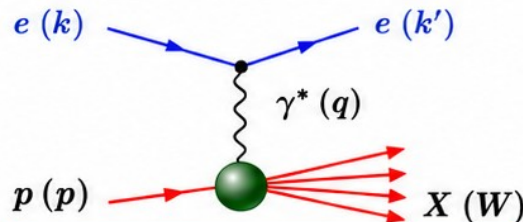
Measures:

$G_E(Q^2) \rightarrow$ charge
 $G_M(Q^2) \rightarrow$ magnetization

Limits:

$\xi = 0, \quad t = 0$

2. Deep Inelastic Scattering (DIS)



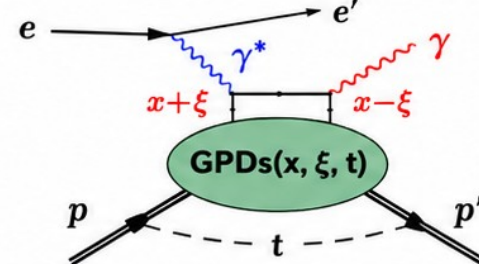
Measures:

$F_1(x_B, Q^2), \quad F_2(x_B, Q^2)$
 (pdfs in Bjorken limit)

Limits:

$Q^2 \rightarrow \infty, \quad \nu \rightarrow \infty \quad (x_B \text{ fixed})$

3. Generalized Parton Distributions (GPDs)



Depends on:

$x, \xi, t, Q^2 \rightarrow H, \tilde{E}, \tilde{H}, E, \dots$

$\xi \rightarrow 0, \quad t \rightarrow 0$
 (Elastic limit)

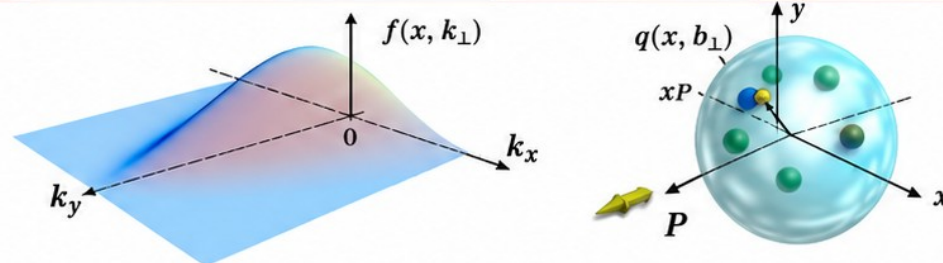
GPDs unify both worlds

$H(x, \xi, t, Q^2), \quad E(x, \xi, t, Q^2), \dots$

$Q^2 \rightarrow \infty, \quad \nu \rightarrow \infty$
 (DIS limit)

4.3D Structure with GPDs

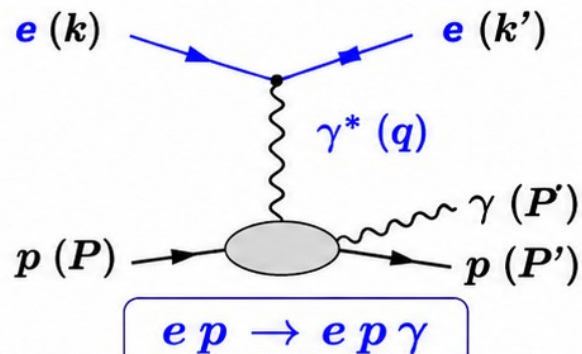
→ GPDs provide simultaneous access to the **transverse position of quarks** and their **longitudinal momentum**, which allows us to determine the **orbital angular momentum** of quarks.





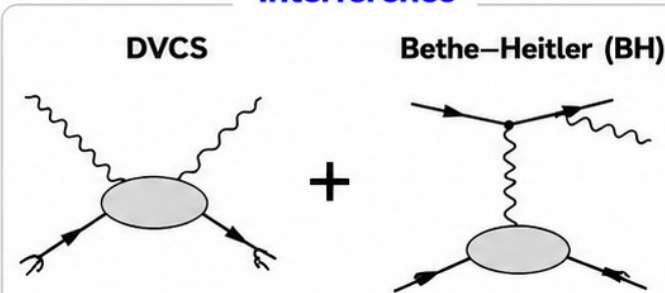
From DVCS to GPDs: The Golden Channel

1. DVCS: The Golden Channel



2. From Measured Observables to CFFs

Interference



Cross section

$$|T|^2 = (T_{DVCS} + T_{BH})^2 \\ = |T_{BH}|^2 + |T_{DVCS}|^2 + I$$

I : DVCS-BH interference

3. Extracting GPDs from DVCS Cross Sections

Proton DVCS (on proton)

$$ep \rightarrow ep\gamma$$

Measure experimentally
the cross section

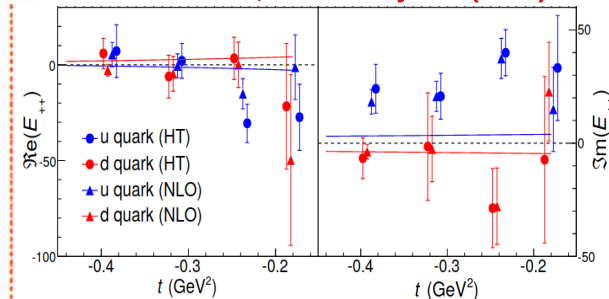
Neutron DVCS (on deuteron)

$$eD \rightarrow eD\gamma \quad (\text{D: deuteron})$$

Measure experimentally
the cross section

Extract GPDs
 $H, E, \tilde{H}, \tilde{E}(x, \xi, t)$
for each quark flavor

M. Benali et al., Nature Physics (2020).



The DVCS measurements on proton and deuteron provide access to the GPDs $H, E, \tilde{H}, \tilde{E}(x, \xi, t)$ for each quark flavor.

This is the golden channel to unveil the 3D structure of the nucleon!



Why Neutron DVCS?

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

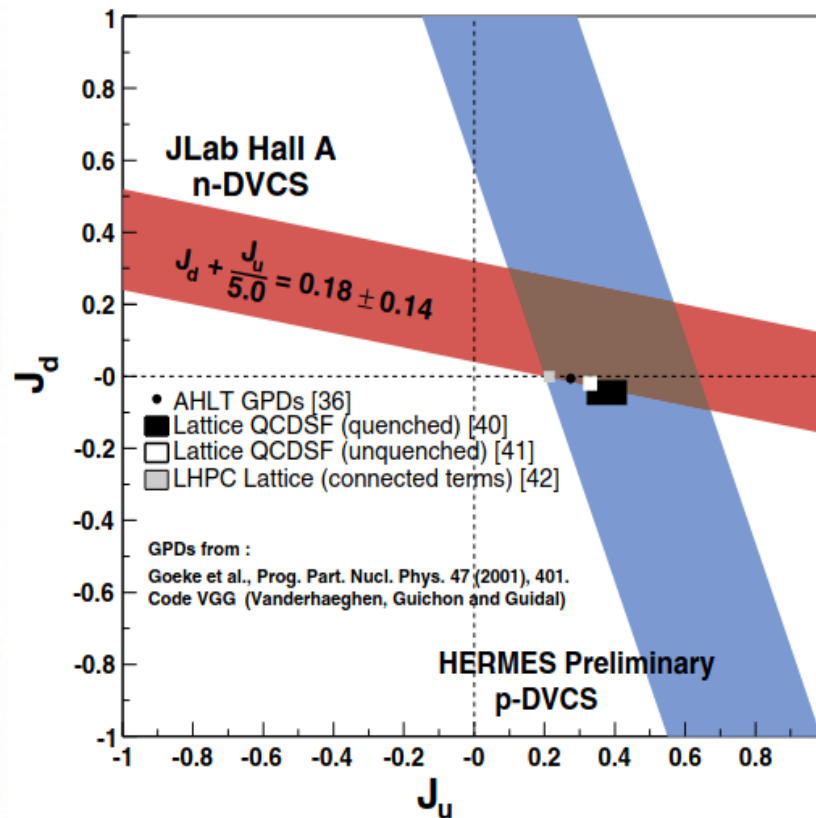
$$H^p = \frac{4}{9}H^u + \frac{1}{9}H^d$$

$$H^n = \frac{1}{9}H^u + \frac{4}{9}H^d$$

- 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**:

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

X. Ji, X. Xiong, and F. Yuan, Phys. Rev. Lett. 109, 152005 (2012).



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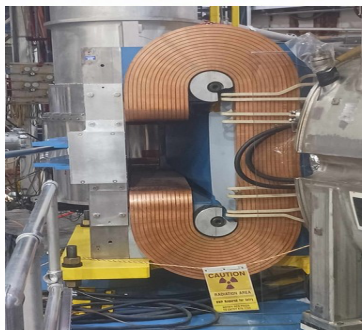
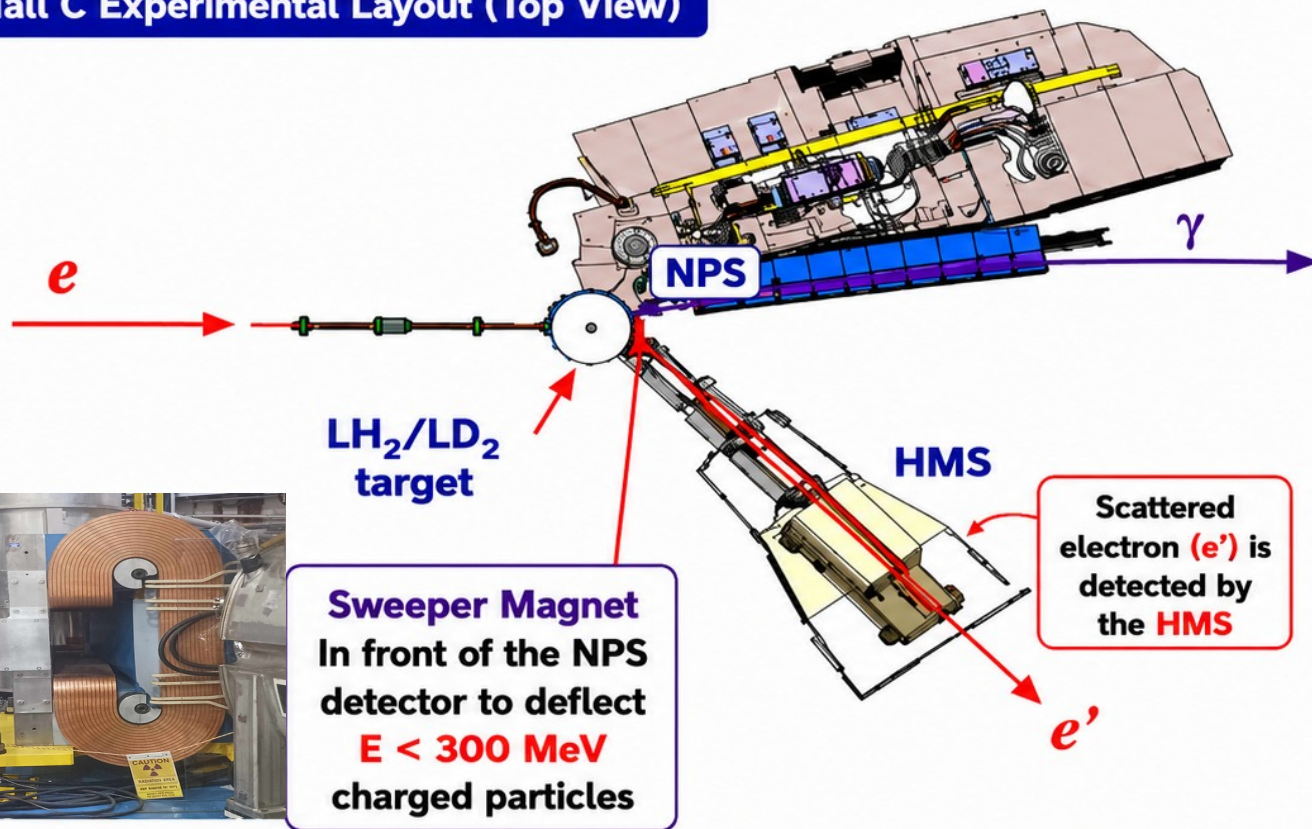
Preliminary physics plots





Experimental setup: DVCS experiment

Hall C Experimental Layout (Top View)



Sweeper Magnet
In front of the NPS
detector to deflect
 $E < 300 \text{ MeV}$
charged particles



Photon (γ) is
detected by
the **NPS**

Scattered
electron (e') is
detected by
the **HMS**

- **1080** Lead Tungstate crystals
- **1080** Hamamatsu PMTs



NPS detector



- 1080 PbWO_4 crystal blocks provide high energy resolution, fast response time, and radiation hardness.



- Temperature controlled frame ensures stable detector performance and precise energy measurements.



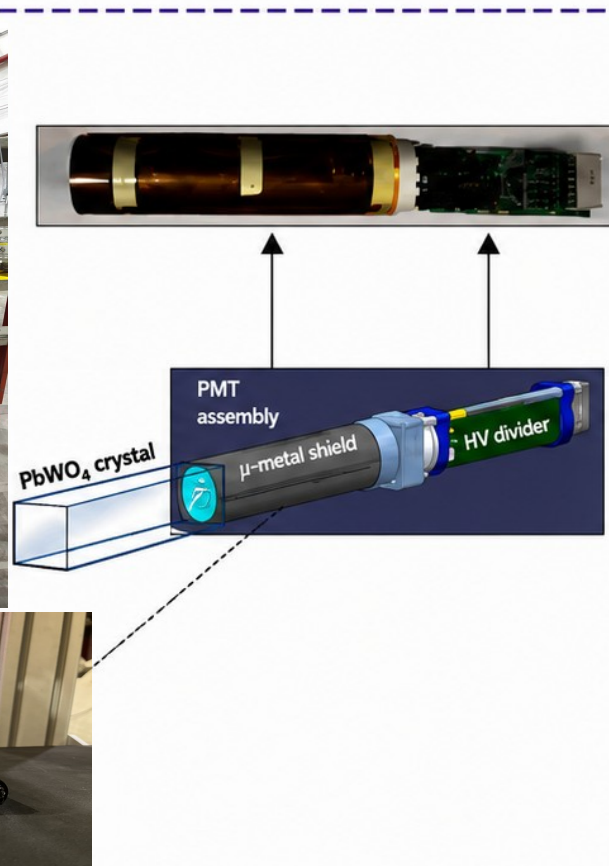
- Hamamatsu 4125 PMTs on the back of each crystal for efficient light collection and signal readout.



- HV divider and signal amplifier designed for high background environment.



- LED system for curing and calibration with HV, LV, and LED signals distributed to all crystals via the distribution board.





DVCS Kinematics

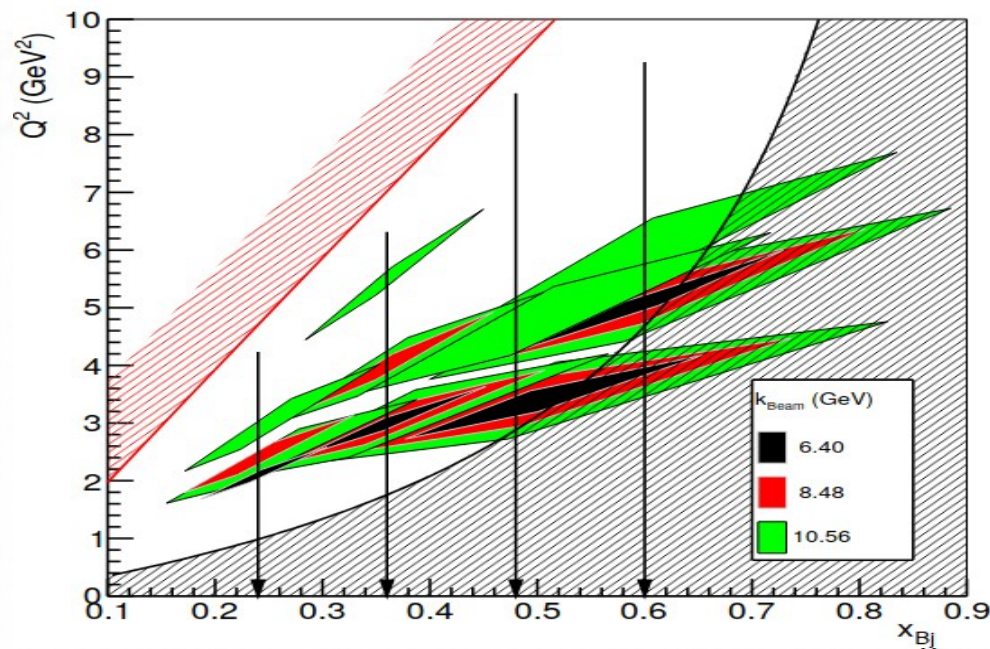
- The neutron is obtained by subtracting the hydrogen data from the deuterium data. Within the impulse approximation:

$$\mathcal{D}(e, e'\gamma)np - \mathcal{H}(e, e'\gamma)p = n(e, e'\gamma)n + d(e, e'\gamma)d$$

- **High x_B** → **high $|t|$** → 2 consequences:
- 1 Better kinematic separation between $n(e, e'\gamma)n$ and $d(e, e'\gamma)d$ channels.
 - 2 The $d(e, e'\gamma)d$ contribution becomes negligible at very high $|t|$.
- 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).

→ Total: **32 kinematics** collected in 2023–2024

DVCS NPS/HallC/JLab 2023-2024



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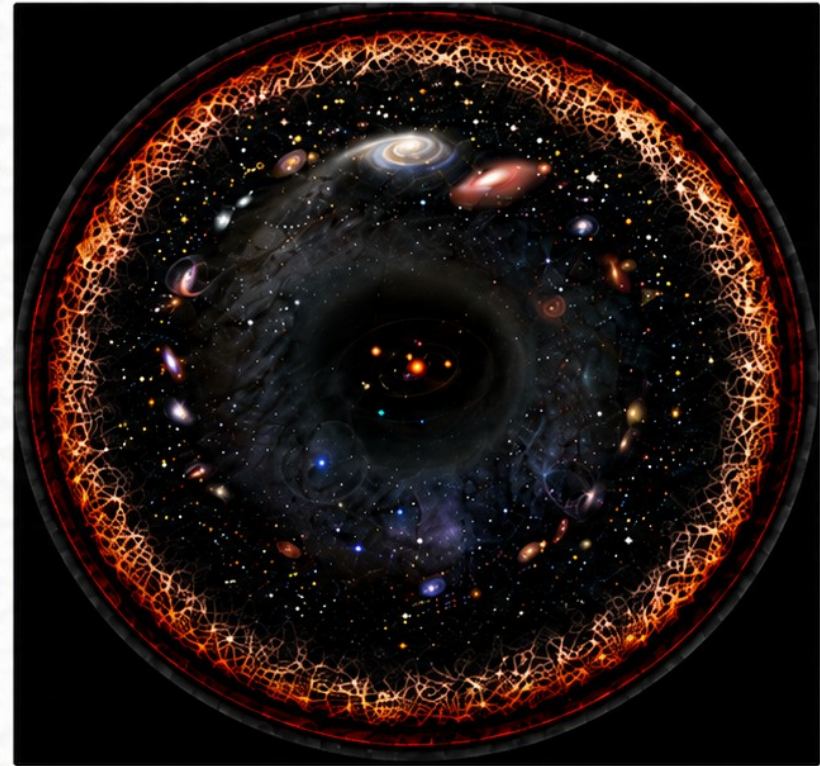


Detector performance

05



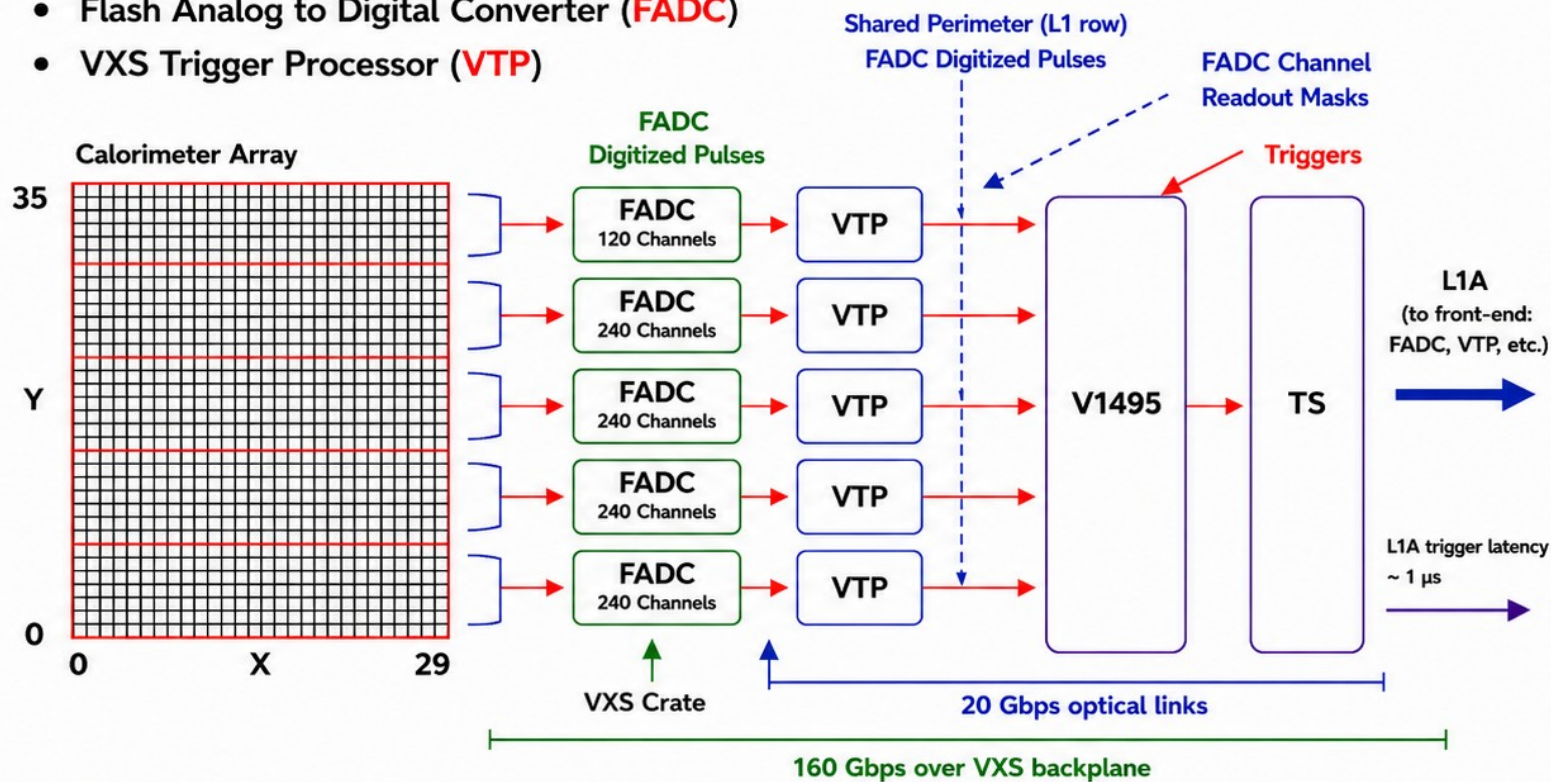
Preliminary physics plots





NPS Data Acquisition and electronics

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



Compatible mezzanine connector

Enables use of commercially available **ECL/TTL/NIM/ADC/DAC** modules



High Throughput

- 20 Gbps optical links
- 160 Gbps VXS backplane



Low Latency

- L1A latency ~ 1 μs



Data Flow



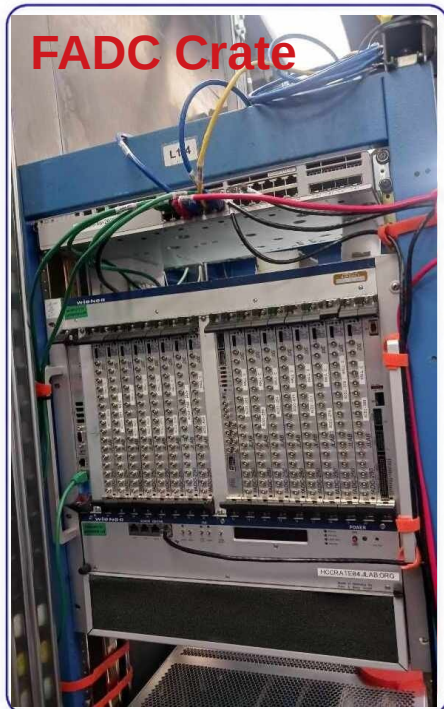
Control / Configuration



Trigger / Timing



Data Stream



Data is stored in an **8 μ s buffer** memory and always streamed (8GB/s) every **~ 1 ns** to the VTP

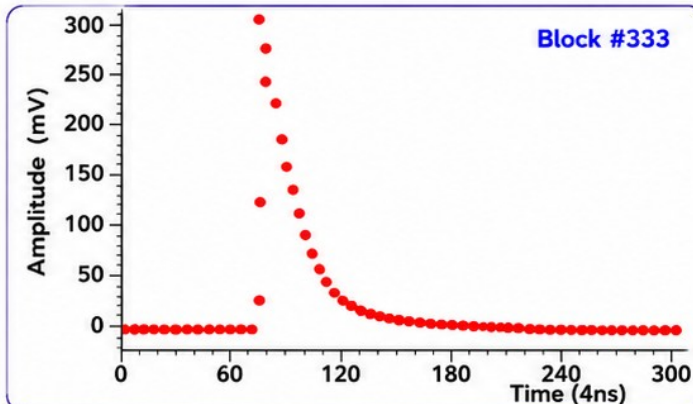


Each event (block) is analyzed



FADC computes:

- Integral
- DC subtraction
- Gain
- Energy (13 bit)



If sample > PEDESTAL + Threshold



HIT is detected in the FADC



Processed data is forwarded to the VTP (8 GB/s)



Data Flow (8 GB/s)



On-board Processing (FADC)



Buffer Memory (8 μ s)



VTP (Trigger Processor)

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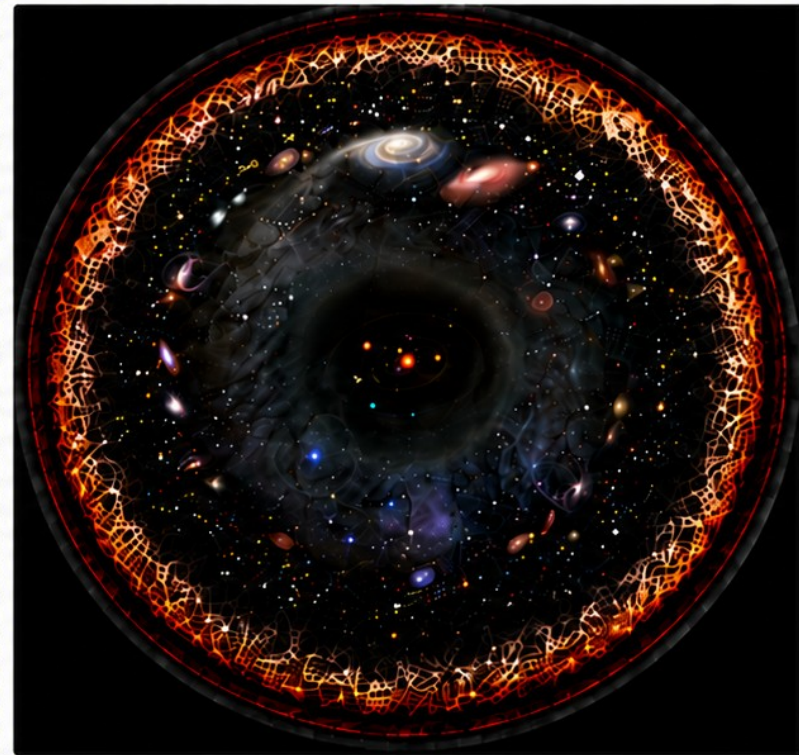


Detector performance

05



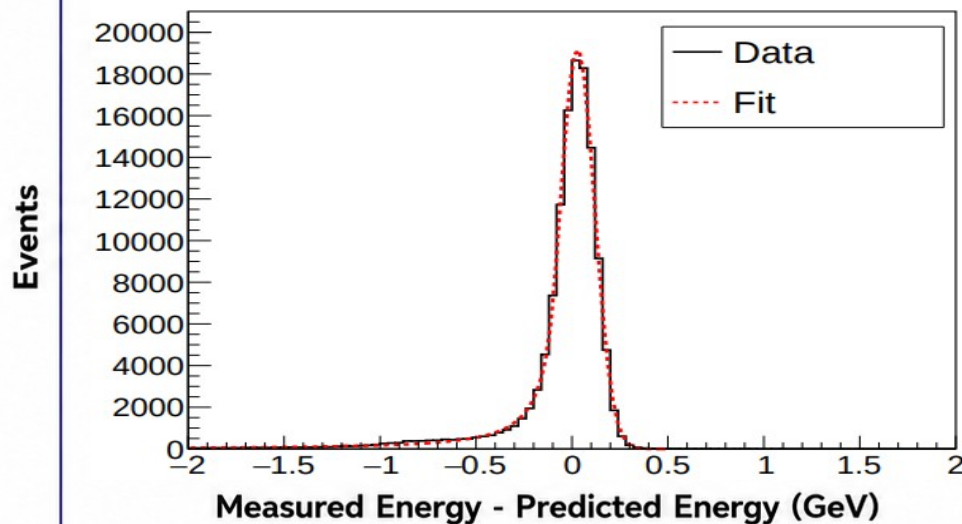
Preliminary physics plots



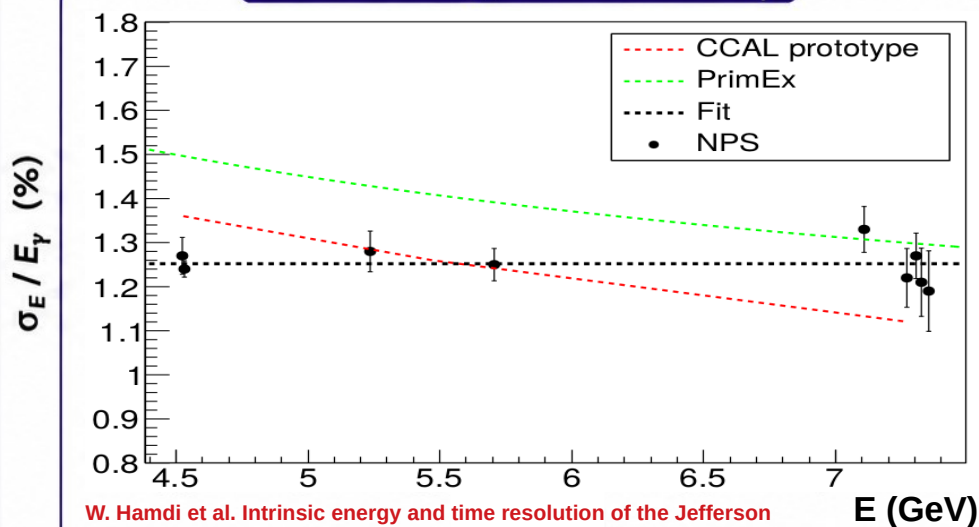


Energy Resolution

Energy Spectrum in the NPS



Relative Energy Resolution vs. E_γ



W. Hamdi et al. Intrinsic energy and time resolution of the Jefferson Lab Hall C Neutral Particle Spectrometer. Nucl. Instrum. Meth. A, 2026



- The **predicted energy** in the HMS is known to a high precision



- A **Crystal ball fit** function was used to get the relative energy resolution



- A relative energy resolution between **1.2%** and **1.3%** was obtained in the **4.5–7.3 GeV** energy range



Time Resolution



- These are the **intrinsic time resolution** results

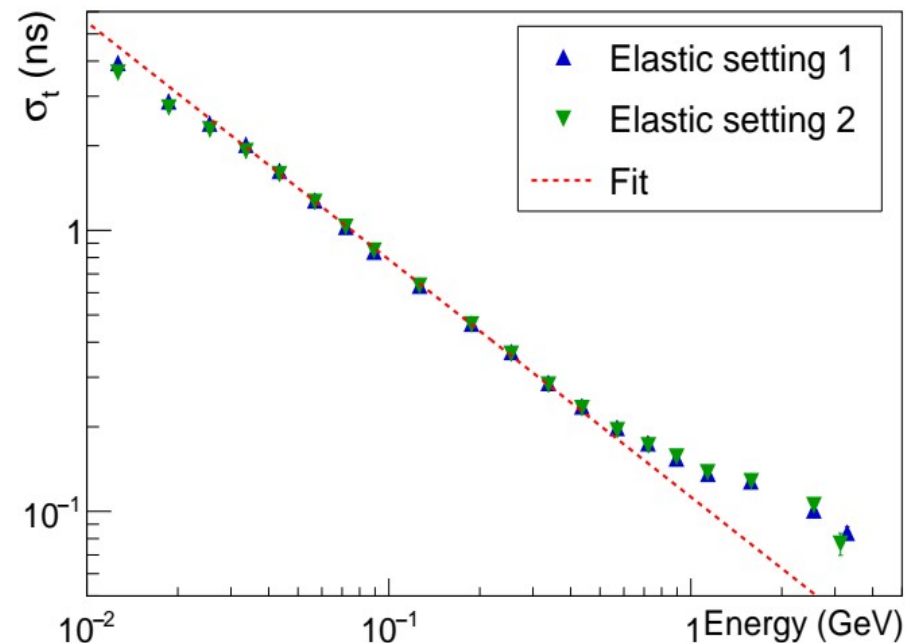


- The resolution obeys the following **power law**:

$$\sigma_t(E) = (0.112 \text{ ns}) \left[\frac{E}{(1 \text{ GeV})} \right]^{-0.845}$$



- An **intrinsic** timing resolution better than **200 ps** for energies above **500 MeV**



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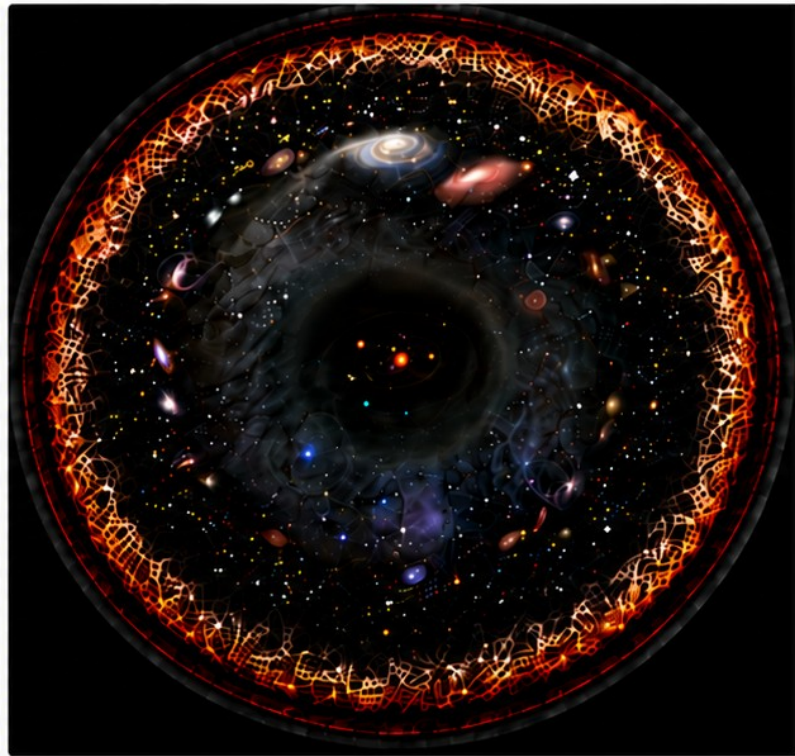


Detector performance

05



Preliminary physics plots

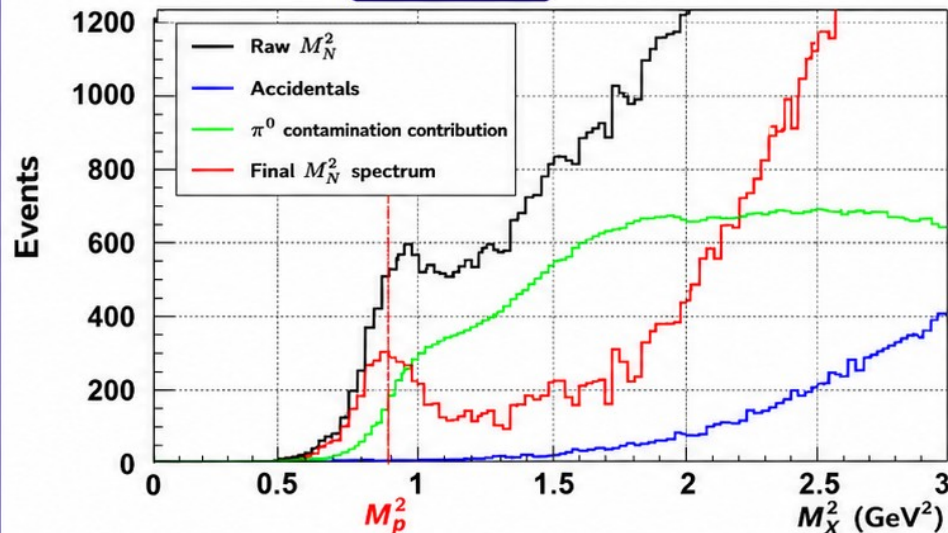




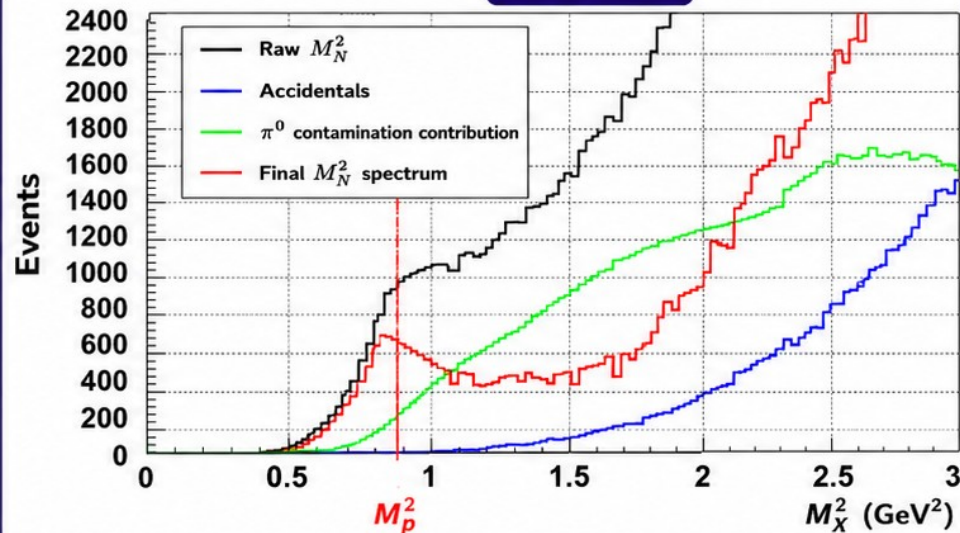
Preliminary DVCS physics plots

$$M_N^2 = (k + p - k' - q_\gamma)^2 \quad (N = \text{nucleon})$$

LH2



LD2

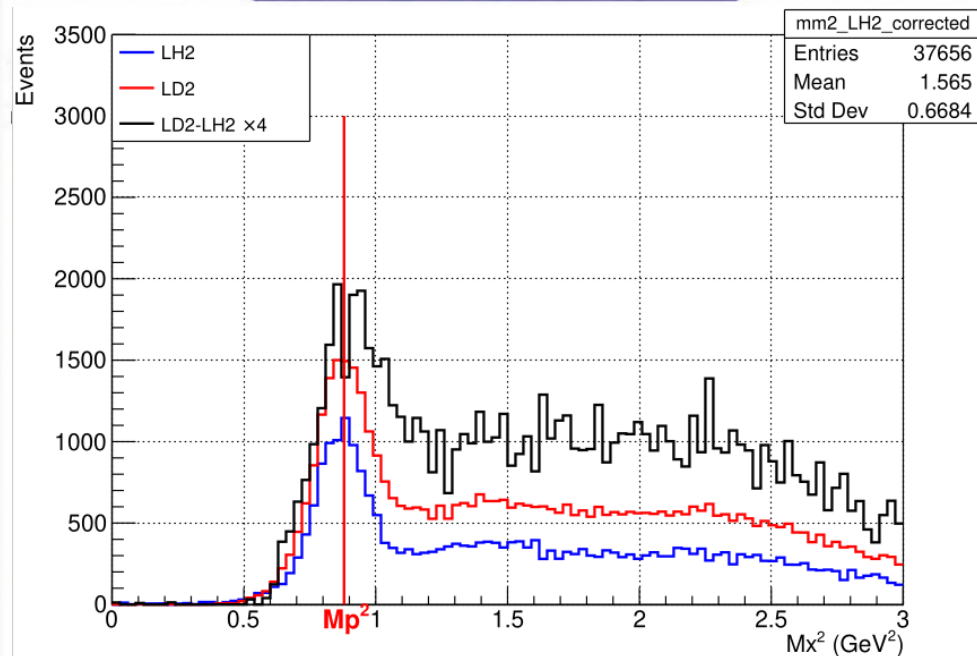


- **Black curve:** raw missing mass spectrum.
- **Blue curve:** accidental background contribution.
- **Red curve:** final missing mass spectrum.
- **Green curve:** π^0 contamination contribution.
- M_N^2 after subtraction (**Red**) clearly shows the exclusive DVCS peak near $M_N^2 = M_p^2$.

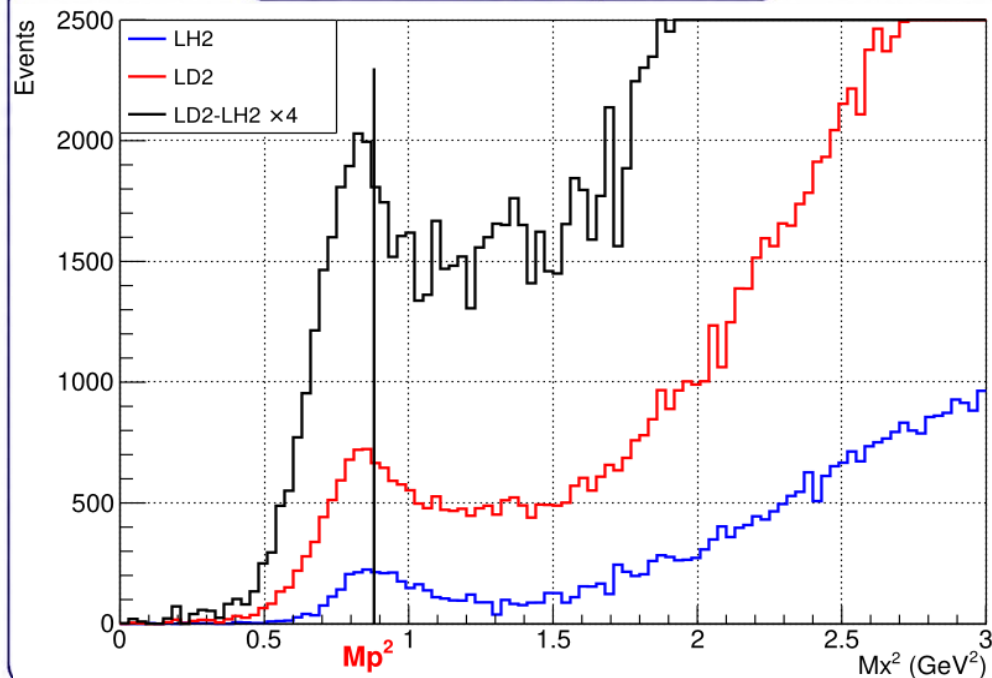


• Preliminary physics plots •

$en \rightarrow en \pi^0$



$en \rightarrow en \gamma$



The physics $en \rightarrow en \gamma$ and $en \rightarrow en \pi^0$ peaks are clear and well defined, which is promising for the precise extraction of $en \rightarrow en \gamma$ cross sections.

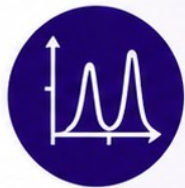
Summary



- The NPS is a key detector for NPS physics: it provides **excellent energy resolution**, **fine spatial segmentation**, and **sub-nanosecond timing capability**, enabling precise reconstruction and clean identification of final-state particles.



- We achieved an **energy resolution** between **1.2%** and **1.3%** in the **4.5–7.3 GeV** range, and an intrinsic **time resolution** better than **200 ps** for energies above **500 MeV**.



- Preliminary **deeply virtual Compton scattering** ($en \rightarrow en\gamma$) and **neutral pion electroproduction** ($en \rightarrow en\pi^0$) plots show clear and well-defined peaks, demonstrating the high quality of the NPS performance.



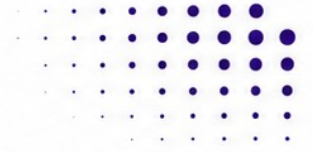
- Cross section analysis of $en \rightarrow en\gamma$ (DVCS) and $en \rightarrow enX$ will be performed for **32** different kinematics.



**A special thanks to my great team of graduate students
and to everyone who brought this experiment to life!**



THANK YOU FOR YOUR ATTENTION!



Backup Slides



Waveform Analysis



Goal: Determine the **pulse arrival time** and **amplitude** efficiently



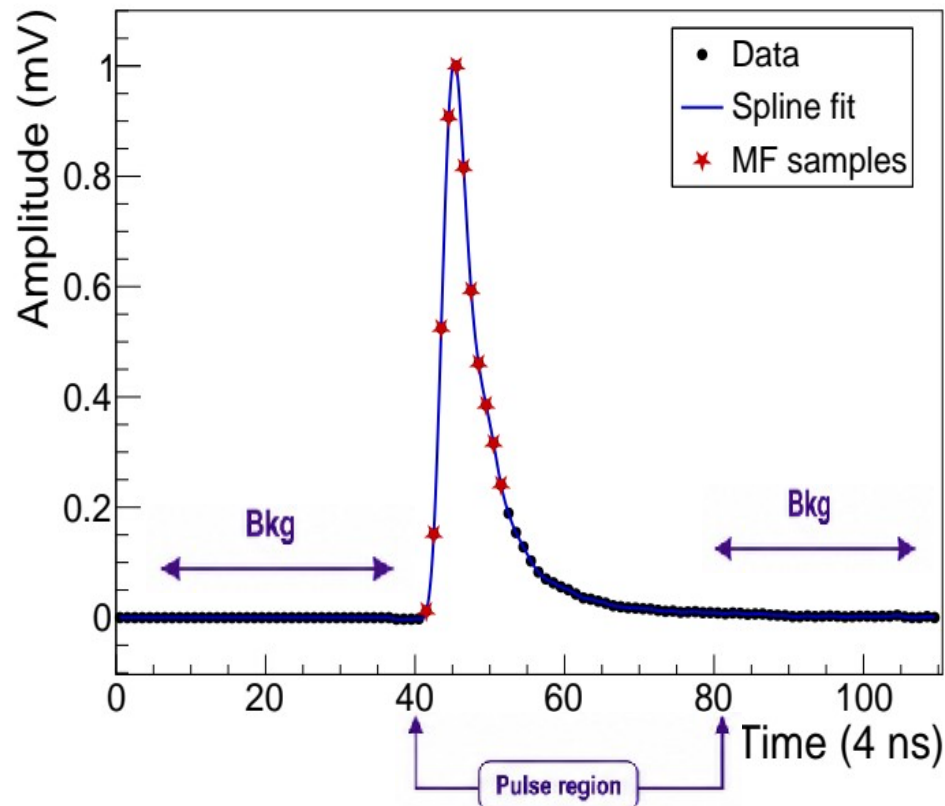
- NPS detector at **9.5 m** from the target to **Minimize** the background



- A **reference shape** is determined for each block:
 - + Highest amplitude
 - + In coincidence (± 5 samples)
 - + No double pulses in the background



- Spline interpolation** modeling the reference shape pulse with a continuous fit function





Fit of the waveforms



- **Matched filter** scheme to determine the **number of pulses** and the approximate **time** and **amplitude**

 $f(x)$

- The fit function:

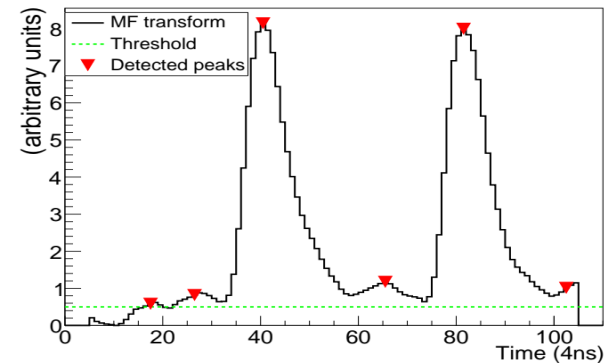
$$F(t) = B + \sum_{i=1}^{N_{pulses}} A_i f(t - t_i)$$

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

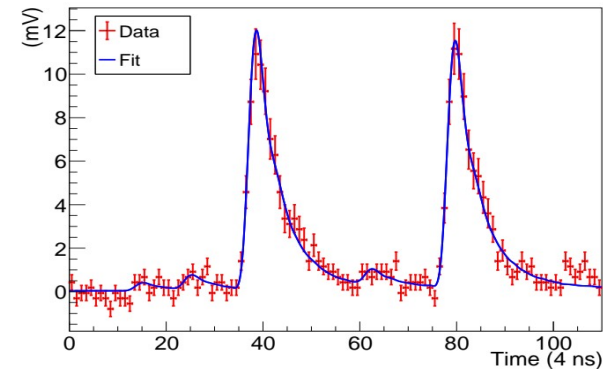


- Fit of the production data waveforms and retrieval of the **time** and **amplitude**

Matched Filter Output



Fit to Production Data





Clustering Scheme



Clustering Scheme



Steps:

- 01 Keep only the blocks that have a pulse in the coincidence region.
- 02 Search for the **seed** block.
- 03 Apply the **5×5** clustering.
- 04 Calculate the cluster **energy** and the **impact position**.



$$E = \sum_i E_i = \sum_i C_i A_i$$

C_i : calibration coefficient for channel i

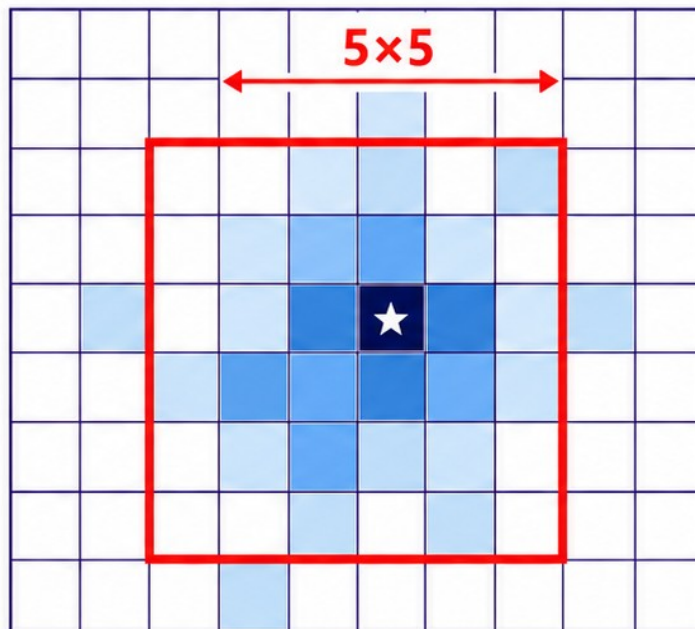
A_i : signal amplitude in channel i

- 05 Calculate the **particle 4-vector**.
- 06 **0.5 GeV** as a cluster threshold.



Mazouz, M., L. Ghedira, and E. Voutier. "Determination of shower central position in laterally segmented lead-fluoride electromagnetic calorimeters." *Journal of Instrumentation* 11.07 (2016).

5×5 Clustering Window



Crystal



Energy
deposition



Higher
energy



Seed block
(highest energy)



Threshold
≈ 1 mV



Time Resolution

Method:



- The **main goal** is to determine the **intrinsic time resolution** of a single **calorimeter** block using the **NPS** elastic calibration data



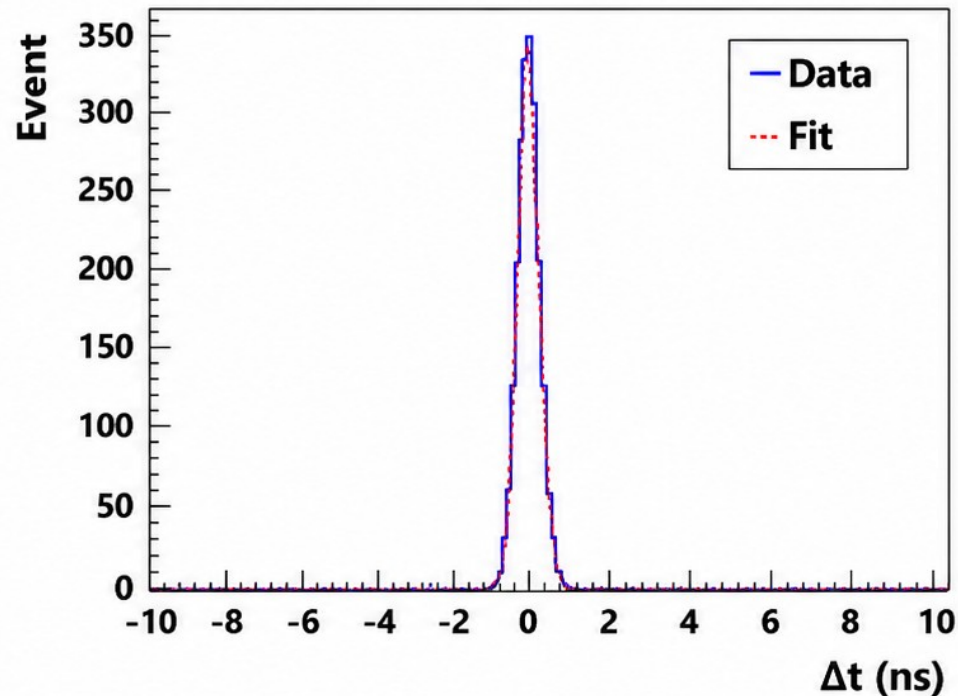
- Chose multiple **energy-deposition** intervals in the **NPS** crystals with similar **statistics**.



- Computed the **time difference** between **pulses** in every pair of blocks belonging to the **same cluster** and the **same energy interval**



- Applied a **Gaussian fit** to the histograms to get the values of **sigma**





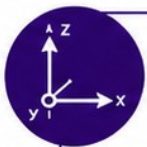
Elastic scattering



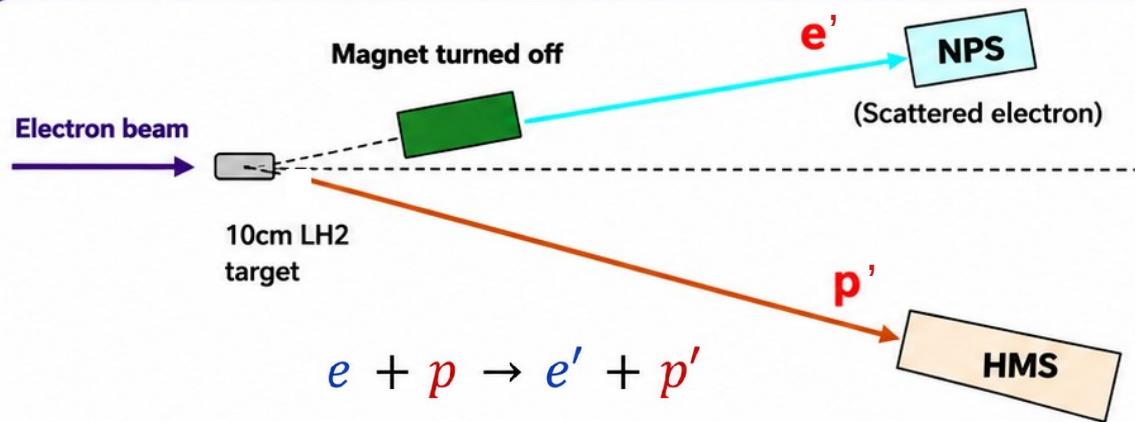
- NPS elastic calibration runs are conducted to **calibrate** the **energy deposited** in crystals



- The **scattered electron** and the **proton** will be respectively detected by the **NPS** and the **HMS**



- Specific **kinematics** were taken during the elastic calibration runs



Number of settings	Beam energy (GeV)	HMS Momentum (GeV/c)	HMS angle (degree)	Scattered electron energy (GeV)	NPS angle (degree)
2	6.40	2.62	35.96	4.52 – 4.53	18.31 – 21.16
2	8.48	3.58 – 4.07	27.61 – 30.76	5.24 – 5.70	19.84 – 22.96
5	10.54	4.05 – 4.31	29.67 – 29.86	7.27 – 7.35	12.11 – 18.16



• NPS Energy Calibration •



- Using the **conservation** of energy for a j event:

$$E_j = E_b + m - E_p^p$$

Predicted energy of
the **scattered electron**

Beam energy

Proton mass

Energy of the **proton** in
the **HMS**



- The **measured** electron energy in the **NPS**:

$$E_j^{rec} = \sum_i C_i A_j^i$$

Calibration coefficient
of a block i

Amplitude of the pulse of a
block i for an event j in the **NPS**



- We define the following **minimization** procedure:

$$\chi^2 = \sum_{j=1}^N \left(E_j - \sum_i C_i A_j^i \right)^2 \quad \rightarrow \quad \frac{\partial \chi^2}{\partial C_k} = -2 \sum_{j=1}^N \left(E_j - \sum_i C_i A_j^i \right) A_j^k = 0$$

$$\rightarrow \sum_i \left[\sum_j A_j^i A_j^k \right] C_i = \sum_j E_j A_j^k \quad \rightarrow \quad MC = \vec{E} \quad \rightarrow \quad \vec{C} = M^{-1} \vec{E}$$



- By **inverting** the M matrix we get the calibration coefficients C_i of each block



Steps to select DVCS events



1 π^0 Calibration

Calibrate the π^0 peak by minimizing the difference between calculated and reconstructed energies and extract the **correction factors**.



2 Event selection

Apply strict **geometrical** and **kinematic cuts** on both HMS (electron) and NPS (photon) to retain **clean, exclusive events** from the target.



3 Accidentals subtraction

Estimate and subtract **random coincidences** by analyzing time sidebands around the prompt peak to isolate the **true (physical) yield**.



4 π^0 Contamination subtraction

Determine and subtract remaining **neutral pion background** using **asymmetries** between target cells and **missing mass analysis** in the NPS.

• Pi0 Contamination subtraction •



Background Source

- Dominant background to DVCS: exclusive production of neutral pions ($\pi^0 \rightarrow \gamma\gamma$).



Origin of Contamination

- In **asymmetric π^0 decays**, one photon is detected in the NPS calorimeter.
- Such events can **mimic DVCS** reactions and contaminate the missing-mass distributions.



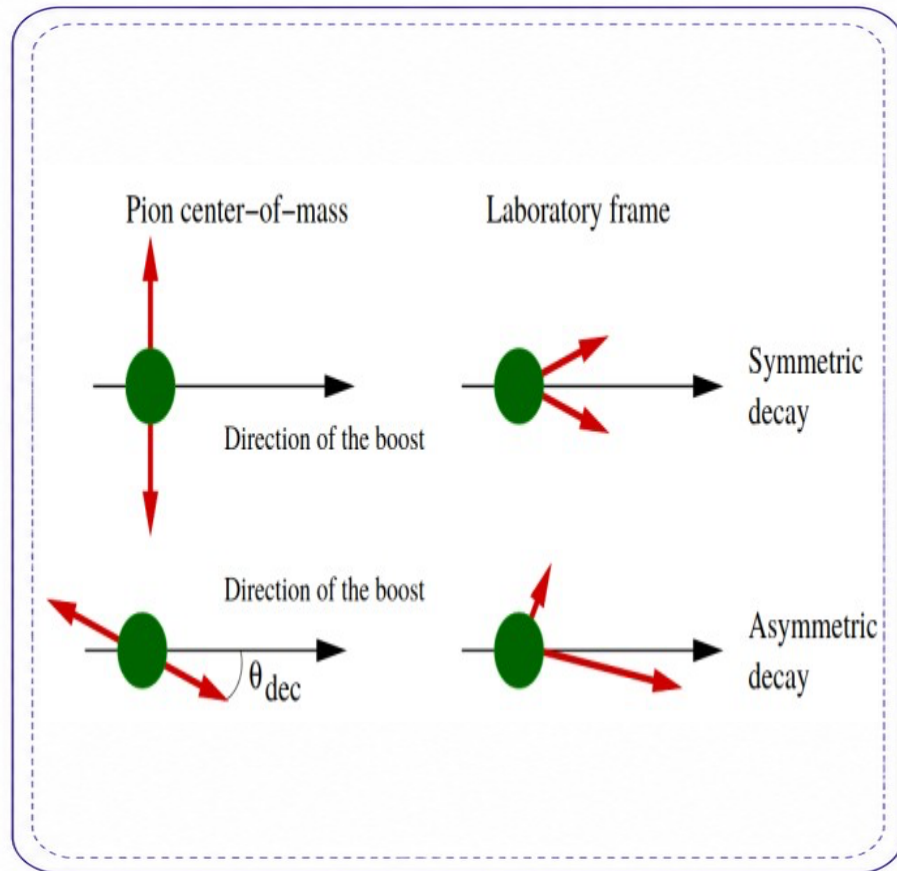
Subtraction Method

- Select a **high- p_T π^0** sample from the data.
- Require both **photons** to be at the **calorimeter edges**.
- Apply: (i) photon energies above **trigger threshold**.
- (ii) reconstructed two-photon invariant mass within a tight window around M_{π^0} .
- Simulate the decay in the pion rest frame 10,000 times with:
 - $\cos\theta \in [-1, 1]$
 - $\phi \in [0, 2\pi]$
- **Boost** photons to the lab frame using measured π^0 momentum.



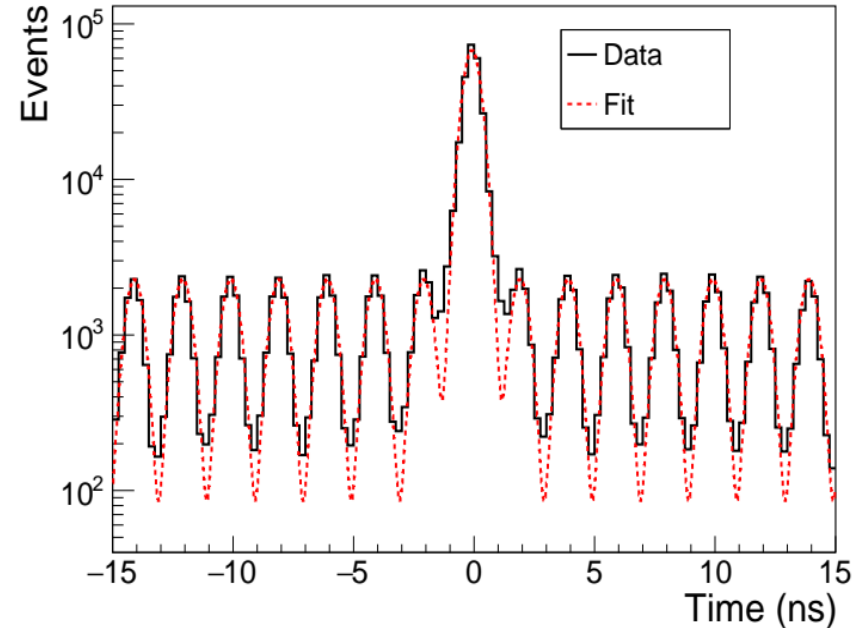
Result

- Generates a large ensemble of possible π^0 decays accounting for **acceptance, detector thresholds, and energy smearing**.
- This background contribution is **subtracted** from the measured yield to **isolate the true DVCS signal**.



Accidentals subtraction

- ➔ Accidental coincidences arise from **uncorrelated particles** randomly arriving within the coincidence window.
- ➔ Estimated by **shifting the analysis time window** to regions on both sides of the prompt peak (outside the physical coincidence region).
- ➔ The resulting distribution represents the **accidental background**.
- ➔ Accidental background is **subtracted** from the measured coincidence yield **to obtain the true (physical) yield**.
- ➔ This procedure removes random backgrounds and **isolates genuine physics interactions**.



• π^0 Calibration •



Method:

$$E(j) = C_i A_i(j)$$

Deposited energy



$$E(j) = \epsilon C_i A_i(j) = \epsilon E_j(j)$$

Corrected Energy



$$C_i = \epsilon_i C_i$$

Correction factor



Corrected calibration coefficient

1 Identification of $eN \rightarrow eN\pi^0$ reaction:

$$|M_{inv} - M_{peak}| < 3 \sigma_{M_{inv}} + M_x^2 < M_{peak}^2 + \sigma_{M_x^2}^2$$



2 main cuts applied

With

$$M_{miss} = \sqrt{(q_l + q_i)^2}$$



Missing mass squared resolution

2 Calculate the expected π^0 energy:

$$M_\pi^2 = (k + p - k' - q_l - q_i)^2 = (k + p - k')^2 + M_c^2 - 2(k_0 - k'_0 + M_N)E_\pi^{c.m.} + 2|\vec{q}_l| \sqrt{(E_\pi^{c.m.})^2 - M_c^2} \cos \theta$$

Solution:

$$E_\pi^{c.m.} = \frac{b \pm \sqrt{b^2 - 4ac}}{2a}$$

With

$$\begin{aligned} b &= 4(k_0 - k'_0 + M_N) [M_\pi^2 - (k - k' + p)^2 - M_c^2], \\ c &= 4|\vec{q}_l|^2 [(k_0 - k'_0 + M_N)^2 - (k - k' + p)^2 - M_c^2], \\ a &= 4(k_0 - k'_0 + M_N)^2 - 4|\vec{q}_l|^2 \cos^2 \theta. \end{aligned}$$

• π^0 Calibration •

3

Minimization:

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

$$\chi^2 = \sum_{j=1}^{N_{\pi^0}} (E_j^{cal}(j) - E_j^{rec}(j))^2$$

With $N_{\pi^0} \longrightarrow$ **Number of Pi0 events**

$$E_j^{rec}(j) = \sum_i C_i E_i(j) A_i(j) \longrightarrow \text{Reconstructed energy}$$

- We get the following linear set of equations:

$$\sum_i \left[\sum_{j=1}^{N_{\pi^0}} E_j(j) A_i(j) E_k(j) A_k(j) \right] C_k = \sum_{j=1}^{N_{\pi^0}} E_j^{rec}(j) E_i(j) A_i(j)$$

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

$$z_k = \sum_i M_{ik}^{-1} \sum_{j=1}^{N_{\pi^0}} E_j(j) A_i(j) E_j^{rec}(j) A_i(j)$$

Event selection



HMS Selection (Electron)

- ➔ Detect scattered electrons over a limited solid angle with well-defined optical characteristics.
- ➔ Apply fiducial cuts on reconstructed variables within its acceptance.

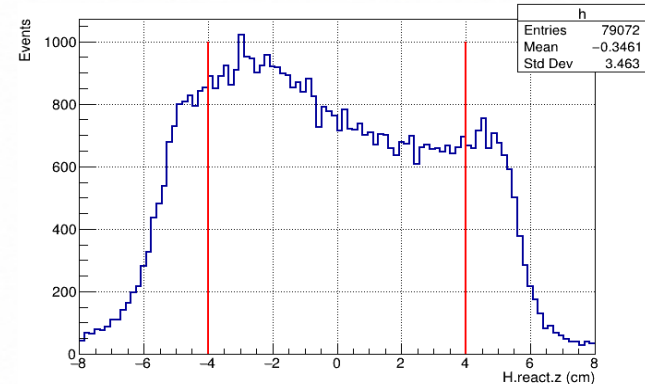
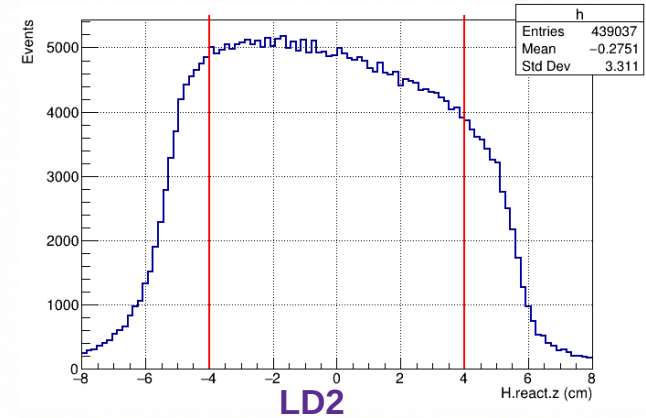
HMS Cuts (Applied to Reconstructed Quantities)

- $|\phi| < 0.08$ rad, $|\phi| < 0.04$ rad, $|\delta p/p_0| < 8\%$,
- $|z| < 4$ cm



NPS Side – Additional Selection

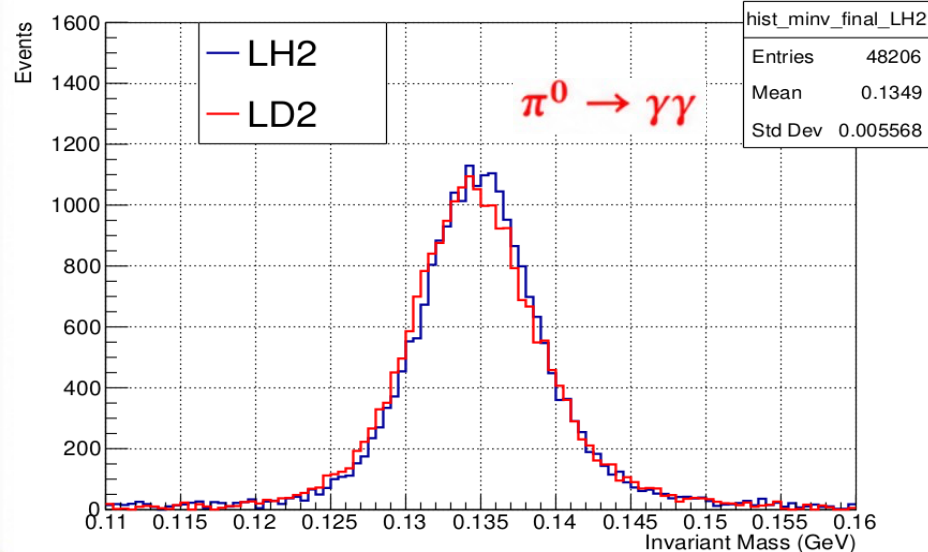
- ➔ Select events originating within the physical target volume.
- ➔ Ensure interactions occur inside the cryogenic target.
- ➔ Impose additional selection criteria on NPS observables.
- ➔ Remove background and out-of-window events.
- ➔ Retain only clean, well-reconstructed exclusive events.





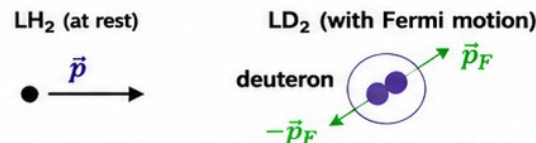
Resolution check and Luminosity calculation

Invariant Mass Comparison: LH₂ vs. LD₂



- Comparison of the $\gamma\gamma$ invariant mass distributions for LH₂ and LD₂ runs.
- Both distributions show a peak centered around the π^0 mass and have similar width.

- Fermi smearing was applied to the LH₂ data to account for nucleon Fermi motion present in LD₂.



Fermi smearing:

$$\vec{p}' = \vec{p} + \vec{p}_F$$

- Integrated luminosity over the beam time:

$$\mathcal{L}_{int} = \frac{Q \times N_A \rho \ell}{A_{tar}}$$

where ρ is the target density, A_{tar} the atomic mass (g/mol),
 $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$ Avogadro's number, and
 $e = 1.30 \times 10^{23} \text{ C}$ the electron charge.

- Integrated luminosities (in nb^{-1}) for LH₂ and LD₂ runs:

Target	Run 1	Run 2	Run 3	Run 4	Run 5	Total
LH ₂	0.13707	0.07273	1.48073	3.05612	1.54972	6.29637
LD ₂	0.11311	0.06318	1.44761	2.33842	1.20453	5.16685

- The integrated luminosities for hydrogen and deuterium are of the **same order of magnitude**.

$$\frac{\mathcal{L}_{int}^{\text{LH}_2}}{\mathcal{L}_{int}^{\text{LD}_2}} = 1.20.$$

I : beam current (A)
 ℓ : target length (cm)
 Q : total beam charge (C)
 ρ : target density (g/cm³)
 A_{tar} : atomic mass (g/mol)

Fermi smearing

LH₂ **not smeared** →

$$M_X^2 = (P_f^*)^2 = (q + P - q')^2$$

How to smear it?

- For the **DVCS off the deuteron** reaction:

$$\gamma^* + {}^2D \rightarrow \gamma + n' + p'$$

$$P_D = (M_D, \vec{0})$$

Deuteron mass

Nucleon mass

$$q + P_n = q' + P_n' + P_p' \quad \text{With} \quad \left(\sqrt{M^2 + P_n'^2}, P_n' \right) + \left(\sqrt{M^2 + P_p'^2}, -P_p' \right) + \left(M_d - 2\sqrt{M^2 + P_F^2}, \vec{0} \right)$$

- We can rewrite the previous equation as follows:

$$q + P_n + P_p + (P_{add}) = q' + P_n' + P_p'$$

$$\text{With} \quad P_{add} = \left(M_d - 2\sqrt{M^2 + P_F^2}, \vec{0} \right)$$

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

$$M_X^2 = (P_f^* + P - P_p - P_{add})^2$$

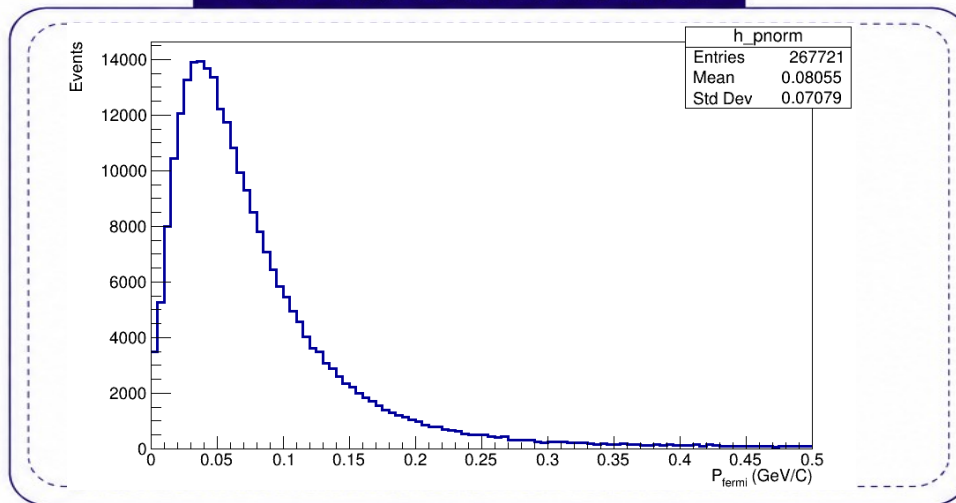
$$\text{With} \quad P = (M, \vec{0})$$

- Then we smear the **LH₂** data as follows:

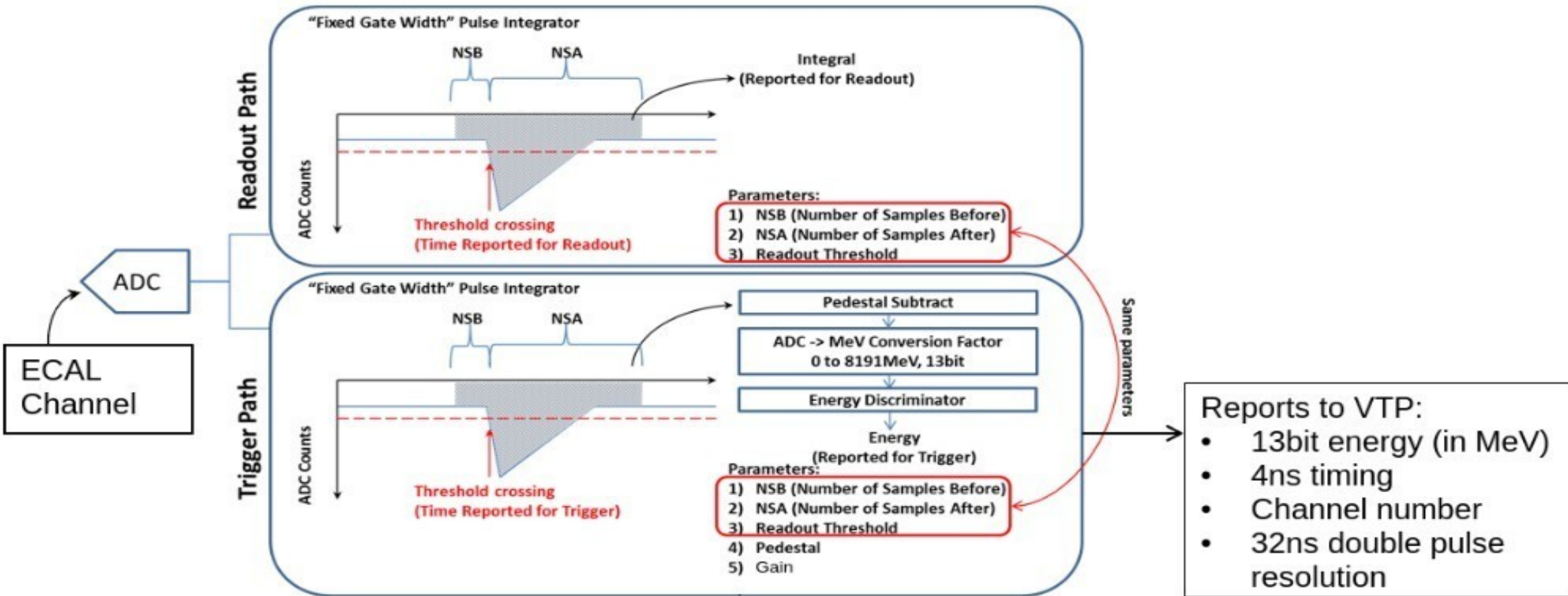
$$M_X^2 = \left(q + P - q' + \boxed{\vec{P} - P_p - P_{add}} \right)^2$$

Smearing term

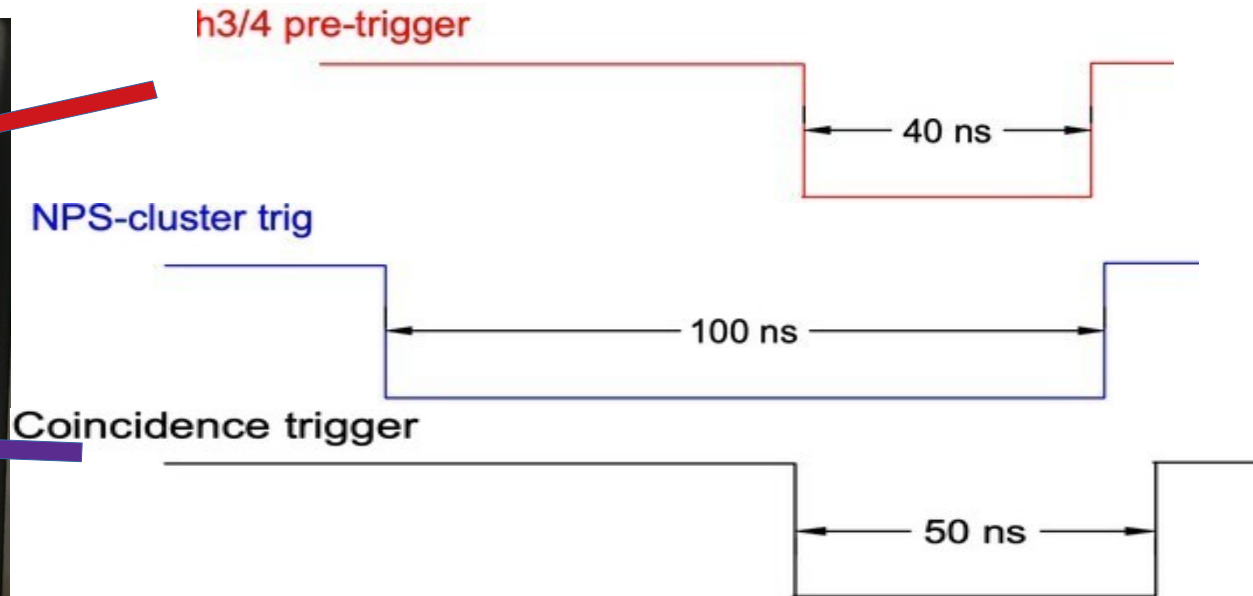
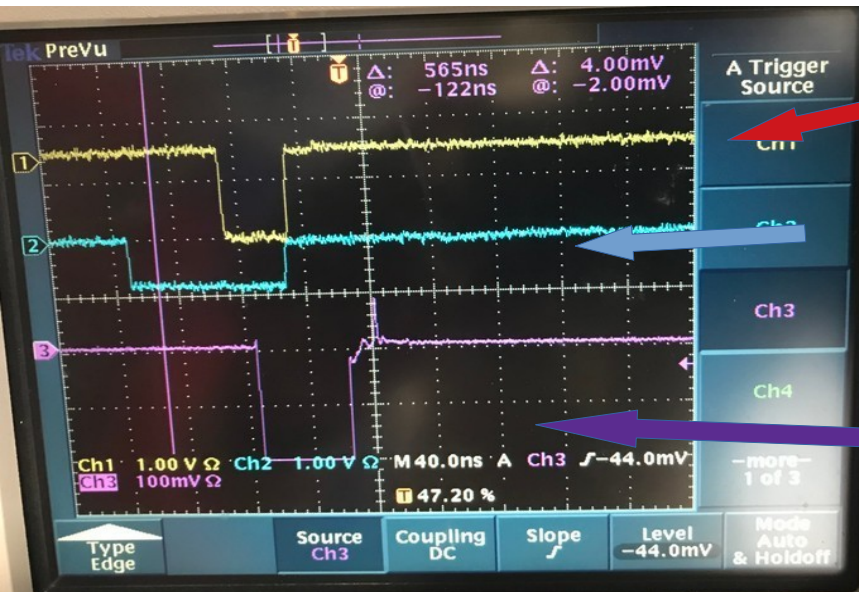
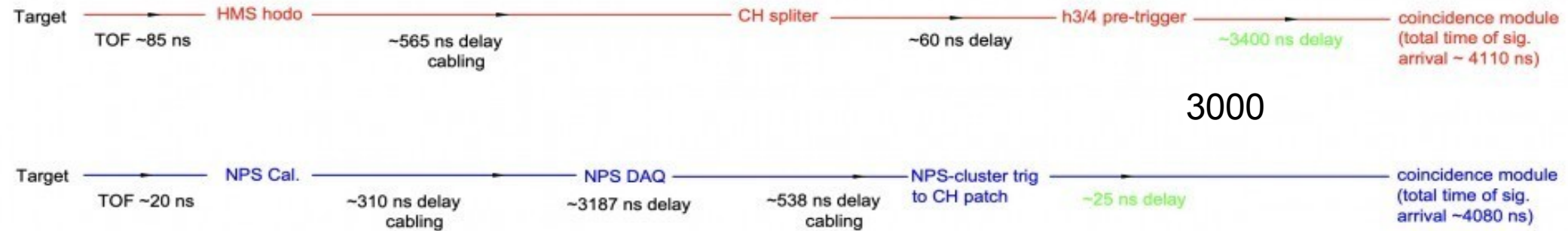
Fermi momentum distribution



FADC Data Stream



NPS/HMS Coincidence



Credits to B.Michaels, J.Poudel, B.Raydo, C. Ghosh, Y. Zhang