DVCS experiment with the Neutral Particle Spectrometer in Hall C at Jefferson Lab

Hao Huang

Carlos Munoz Camacho

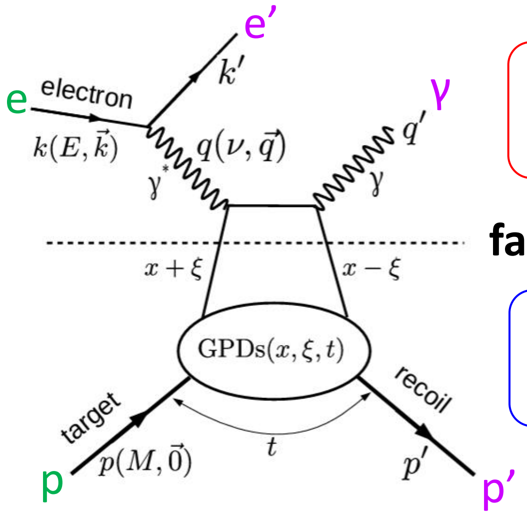
2025.06.13

Deeply Virtual Compton Scattering (DVCS)

- DVCS ($ep \longrightarrow e'p'\gamma$) is the simplest probe to investigate GPDs

See Alan's slides for more details

- Experimentally, GPDs are accessed by DVCS via Compton form factors (CFFs)
- DVCS and Bethe-Heitler process cannot be separated experimentally



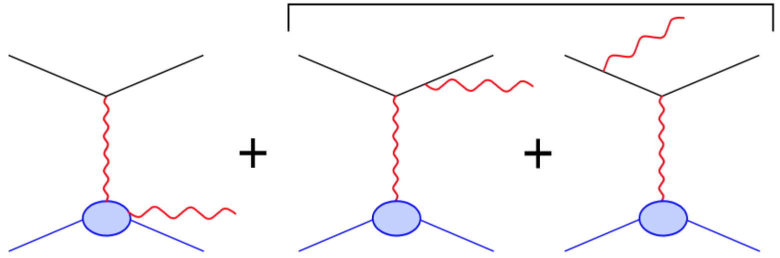
Hard process
- perturbatively calculable

factorization

Soft process
- parametrized by GPDs

DVCS   Bethe-Heitler (BH) process

$ep \longrightarrow e'p'\gamma$ =



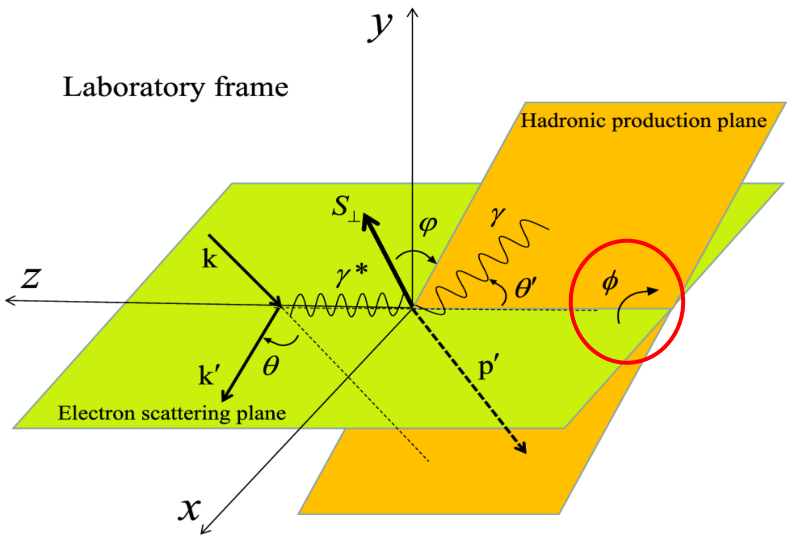
- $\sigma(ep \to e'p'\gamma) \propto \underbrace{|T_{BH}|^2}_{\text{pure QED process}} + \underbrace{|T_{DVCS}|^2}_{\text{bi-linear combination of CFFs}} + \underbrace{I(BH \cdot DVCS)}_{\text{linear combination of CFFs and FFs}}$

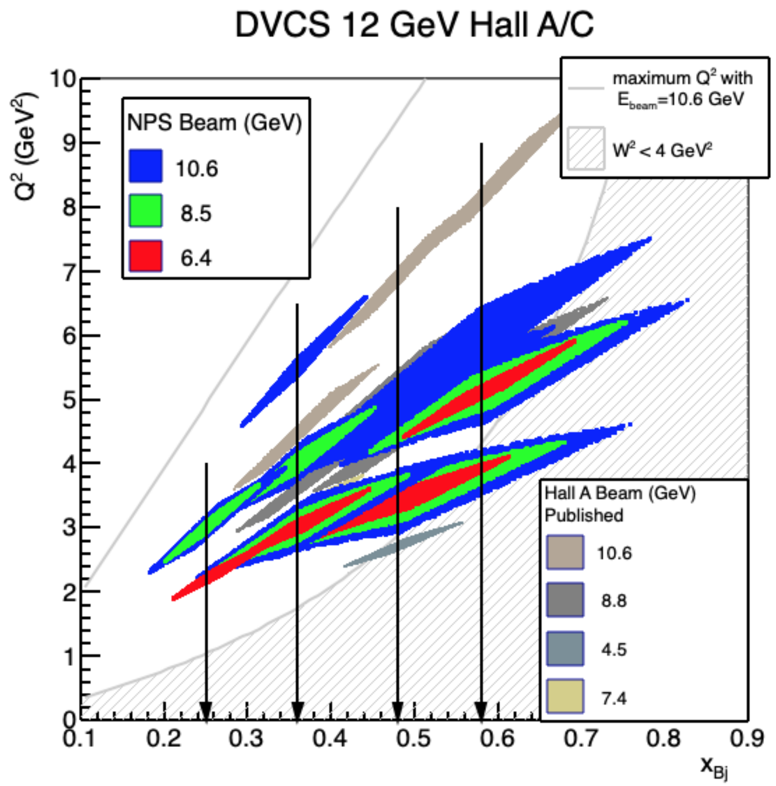
T_{BH}: Amplitude of Bethe-Heitler process
T_{DVCS}: DVCS amplitude
I: interference term

Disentangle DVCS and interference term by kinematical dependence

- $$\frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{2} \propto \Im[I(BH \cdot DVCS)]$$
- $$\frac{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}}{2} \propto \underbrace{|T_{BH}|^2}_{\text{known to 1\%}} + \underbrace{|T_{DVCS}|^2}_{\propto E_{beam}^2,\ \phi \text{ dependence}} + \underbrace{\Re[I(BH \cdot DVCS)]}_{\propto E_{beam}^3,\ \phi \text{ dependence}}$$

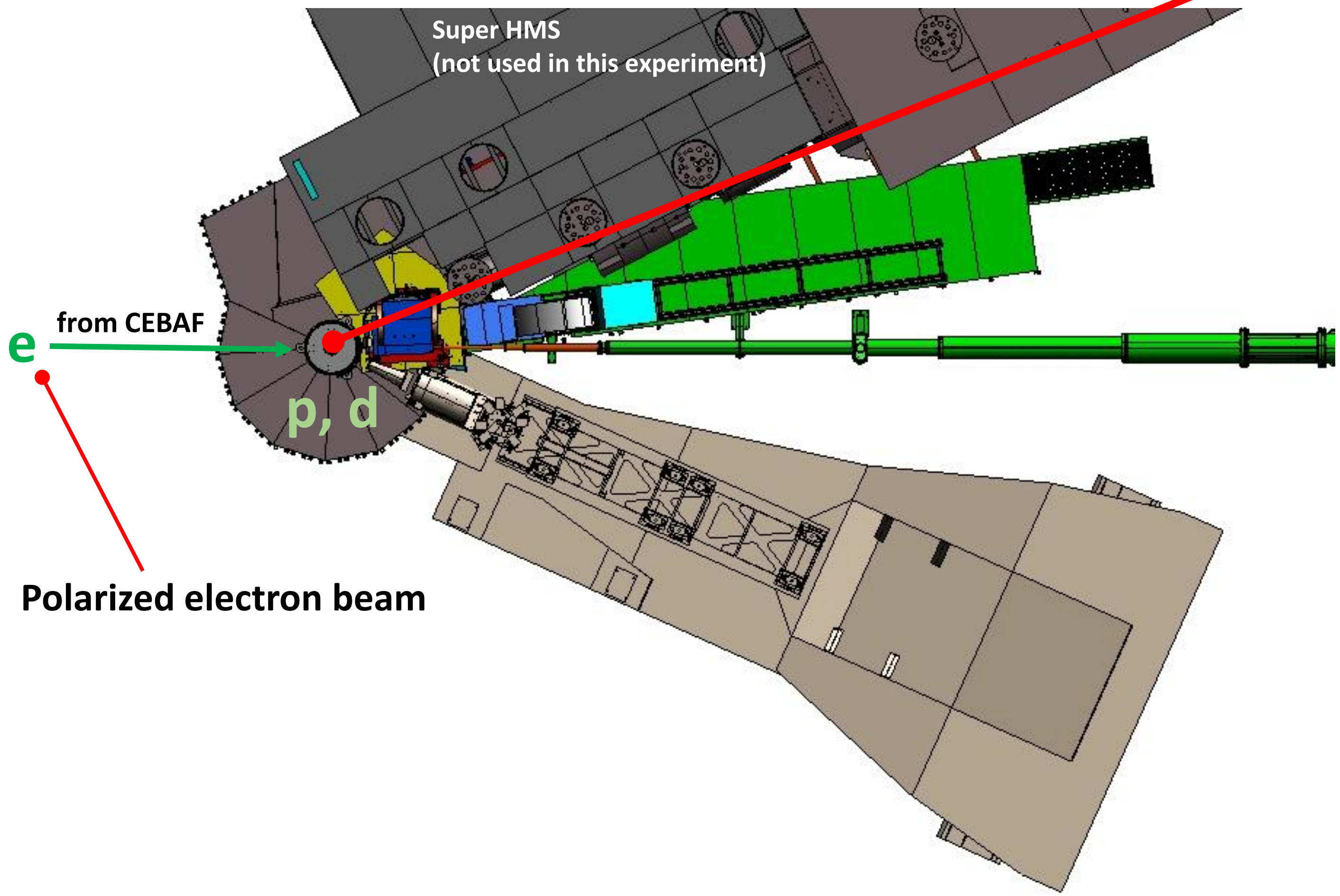
Beam helicity dependence





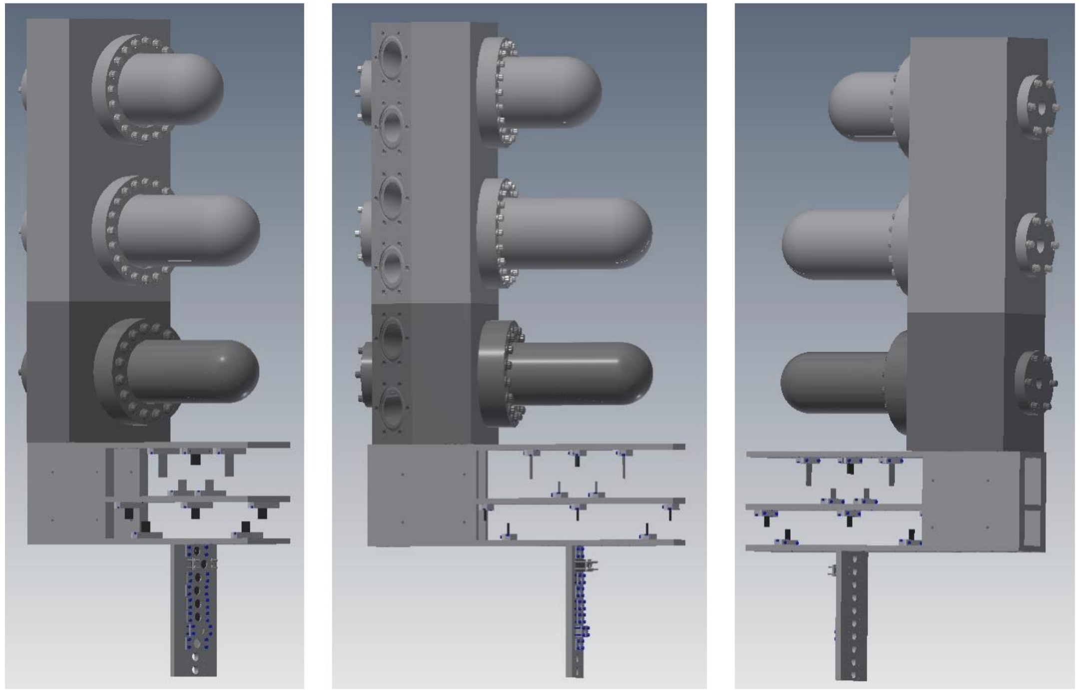
DVCS experimental setup in Hall C

Run period: Sep. 2023 – May 2024



Target chamber

- Unpolarized targets in 10 cm AL cell
- Liquid H_2 (LH2): proton DVCS
- Liquid D_2 (LD2): neutron DVCS

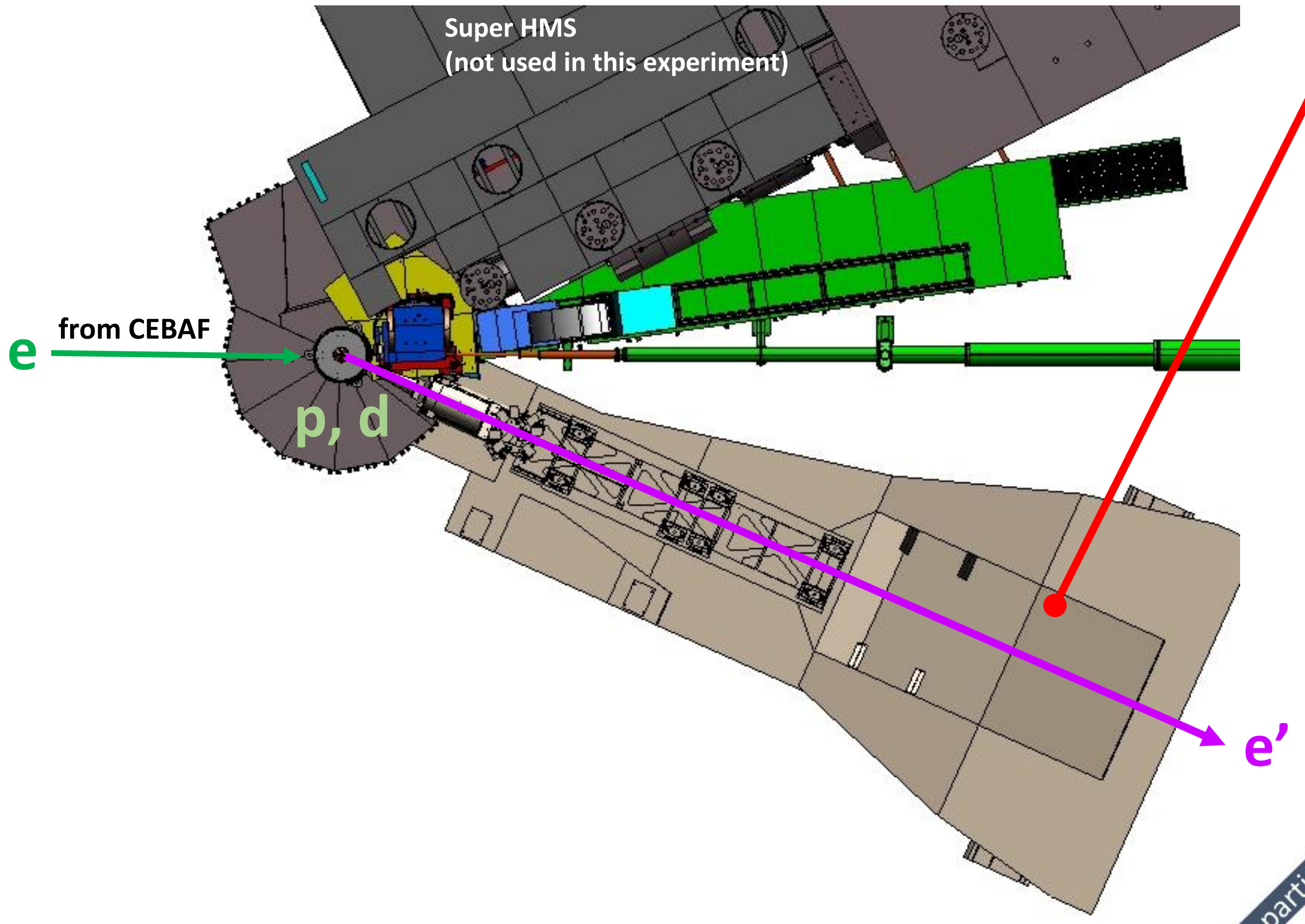


⬆ CAD views of the cryogenic and solid target ladders

Jefferson Lab Hall C Standard Equipment Manual

DVCS experimental setup in Hall C

Run period: Sep. 2023 – May 2024



High Momentum Spectrometer (HMS)

- Tracking of scattered electrons
- Trigger on events
- Particle identification

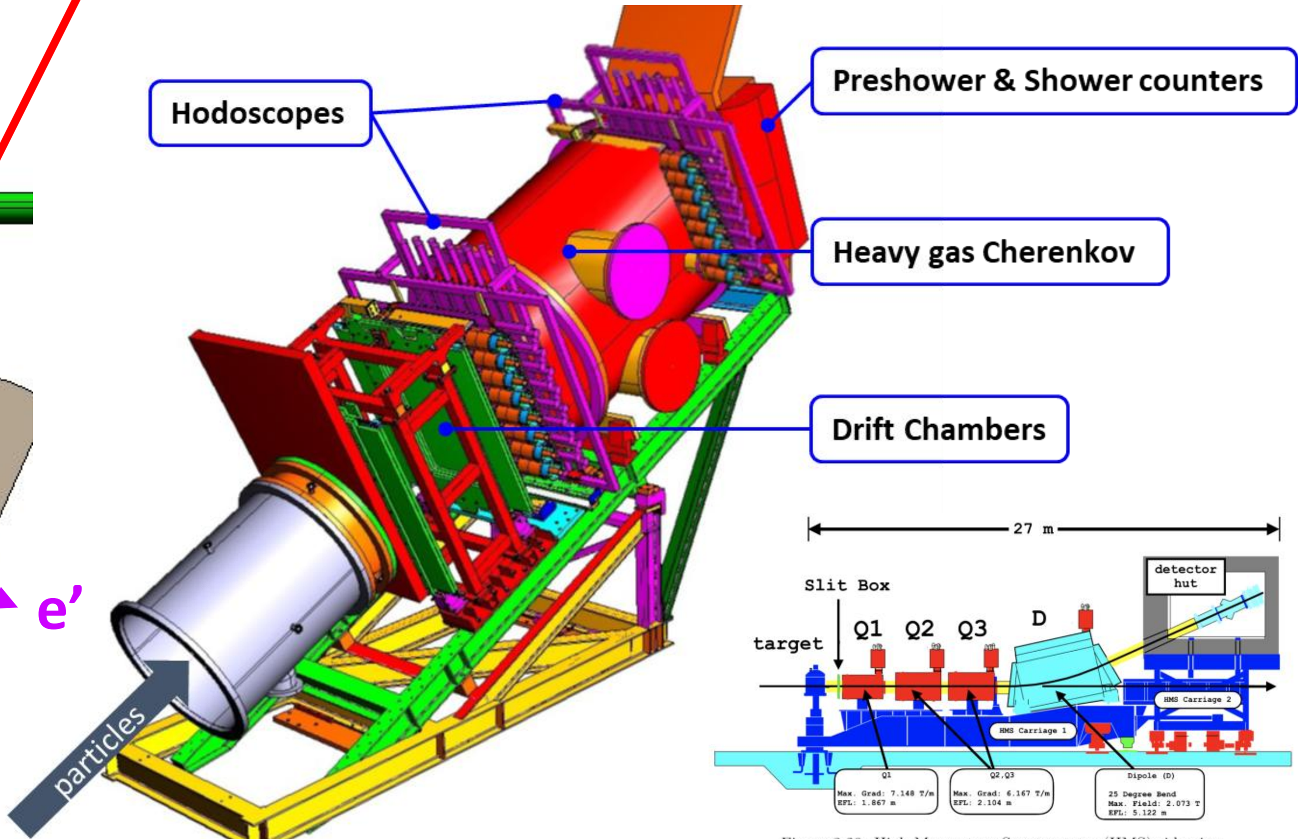
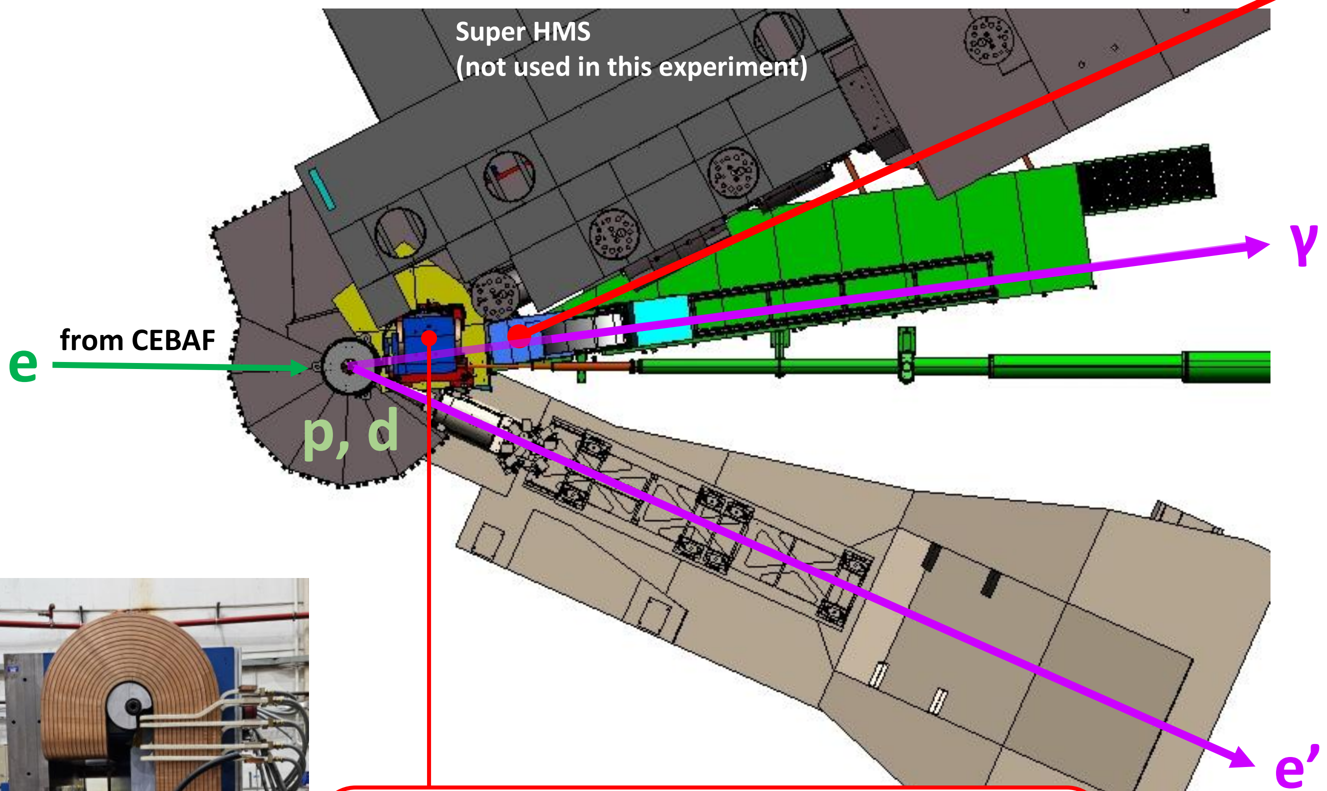
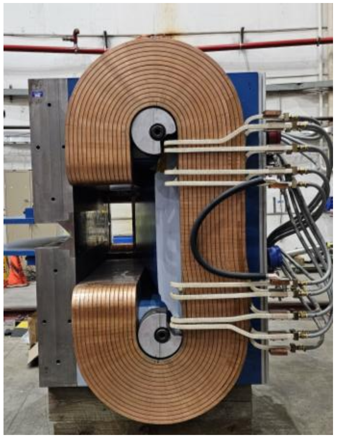


Figure 3.20: High Momentum Spectrometer (HMS) side view.

DVCS experimental setup in Hall C

Run period: Sep. 2023 – May 2024

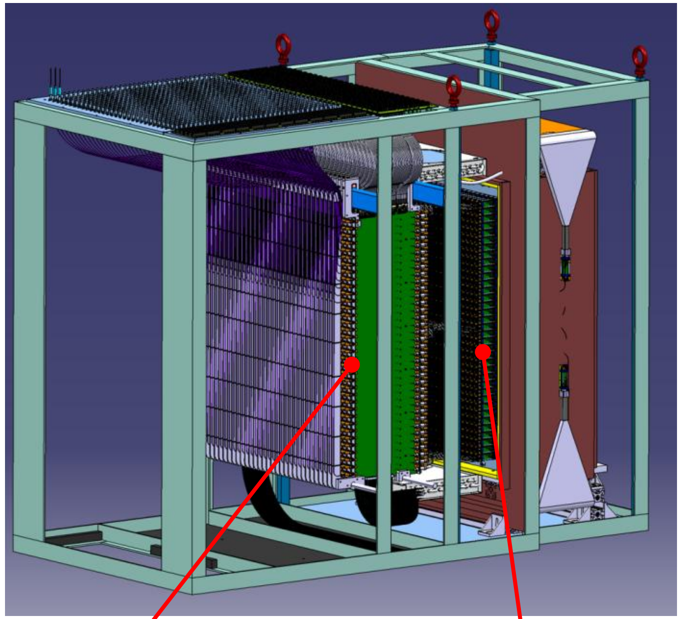




Sweep magnet
- Between target chamber and NPS
- 0.3 T·m of magnetic field
- Reduce the low energy background electrons

Neutral Particle Spectrometer (NPS)

- Detect emitted photon with high resolution
- Array of 1080 $PbWO_4$ crystals
- Newly installed on a platform attached to Super HMS



Distribution boards for signal and high voltages

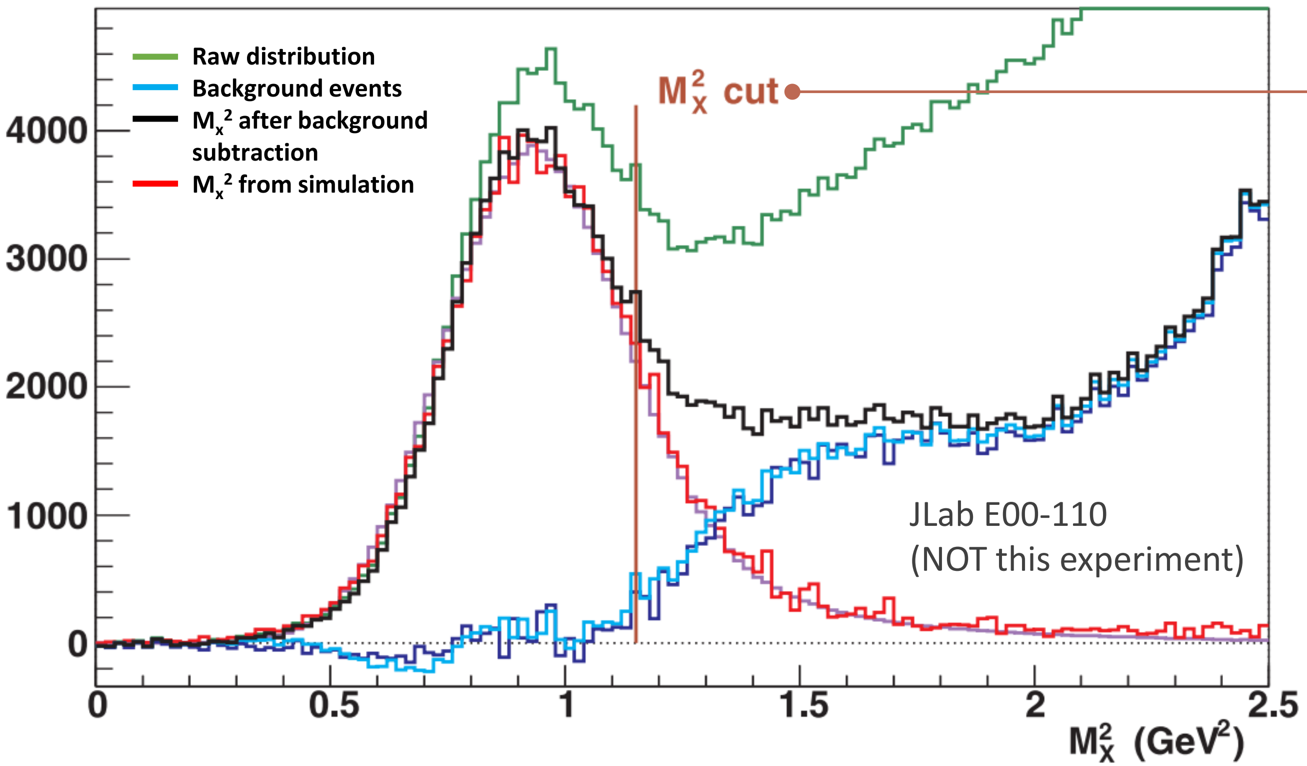
Photomultipliers (**PMTs**) and **HV divider base**

⬆ Front view of **30×36 NPS crystal array**

No proton detection? Look at the missing mass!

- Missing mass square of recoil proton: $M_x^2 = (k_e + P_p - k'_e - q_\gamma)^2$ for DVCS event extraction
- Energy resolution of photons is a key role for better resolution and background separation
- NPS data to be analyzed and calibrated as refined as possible

DVCS signal extraction with Missing-mass method

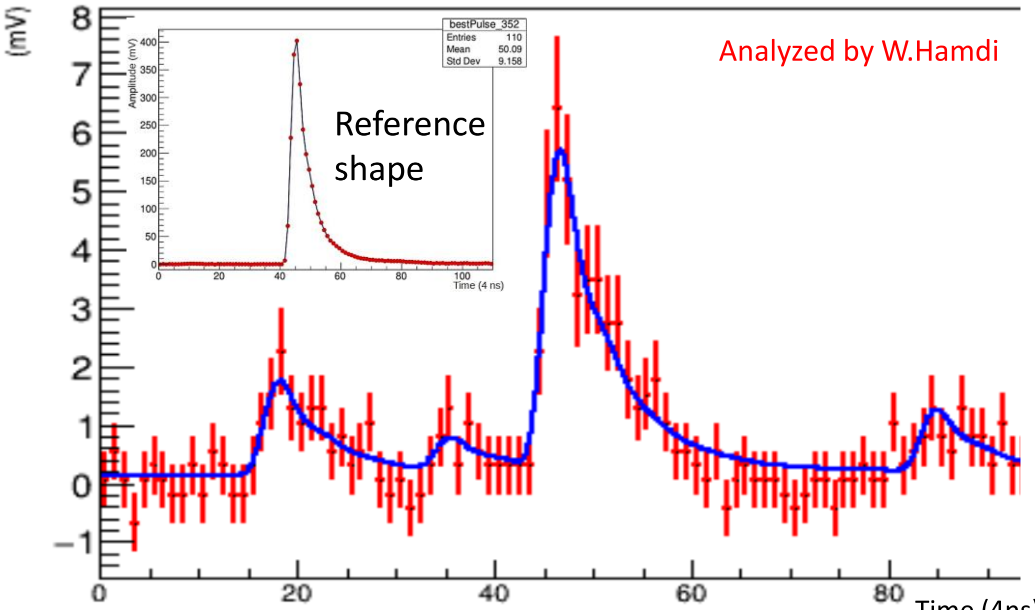


- To remove SIDIS background
- Lowest M_x^2: ep → e'p'γπ^0 ~ 1.15 GeV^2

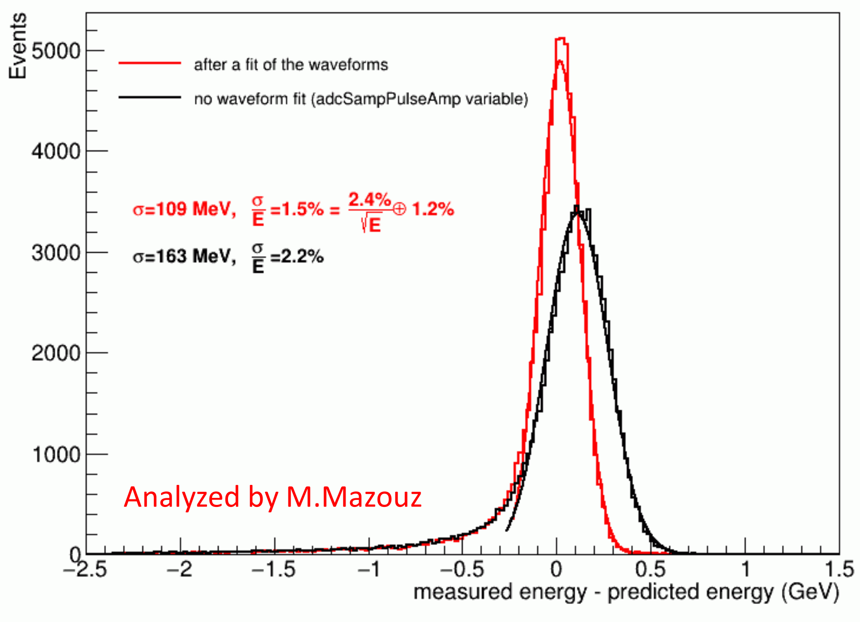
Waveform fit analysis

- More accurate amplitudes and timing of signal pulses are required
- Waveforms were readout for this purpose (each channel and each event!)
- Reference shapes from elastic data are used to fit and extract new amplitudes and times
- Measured energy resolution is improved (expectation from simulation: $\sim 2\%/\sqrt{E} \oplus 1\%$ ~1.2%)

Waveform fit using the reference shape



NPS energy resolution at 7.3 GeV

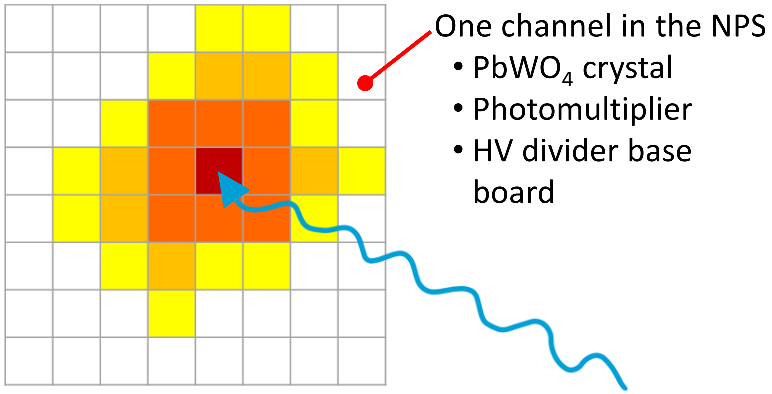


Energy calibration with $\pi^0 \to \gamma\gamma$ in the NPS

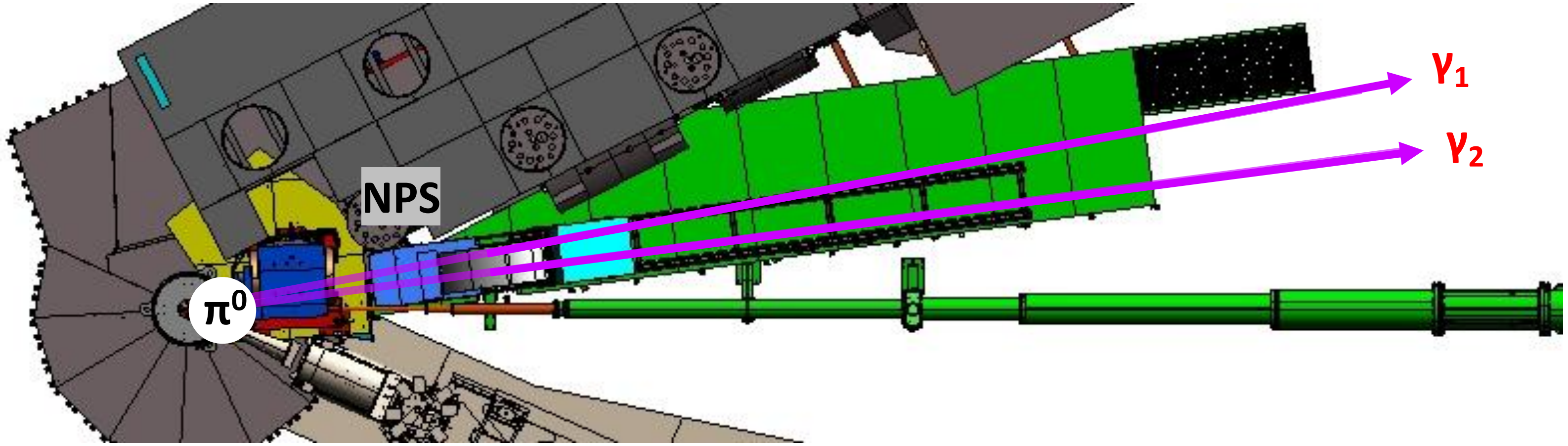
- Measured energy of a particle in the NPS: $E_{cluster}^{NPS} = \sum_j C_j A_j$
  - j: channels in the cluster
  - A: amplitude measured in the channel [mV]
  - C: calibration coefficient, convert amplitude to energy [GeV/mV]
- Calibration by optimizing the width of π^0 peak

$$F = \underbrace{\boxed{\sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)^2}}_{\text{resolution term}} + \underbrace{\boxed{2\lambda \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)}}_{\text{constraint } \langle m_i^2 \rangle = m_0^2}$$

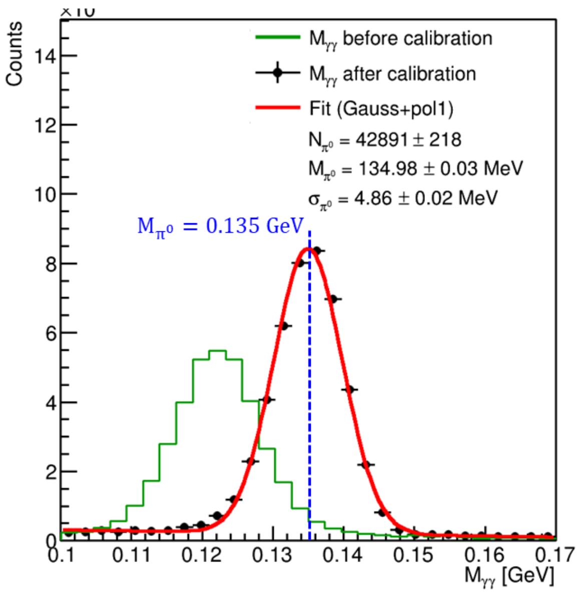
$m_0 = M_\pi = 0.1349766$ GeV
m_i: reconstructed $M_{\gamma\gamma}$
λ: Lagrange multiplier
(Nuclear Instruments and Methods in Physics Research A 566 (2006) 366–374)



Cluster forms in the NPS when a particle is detected



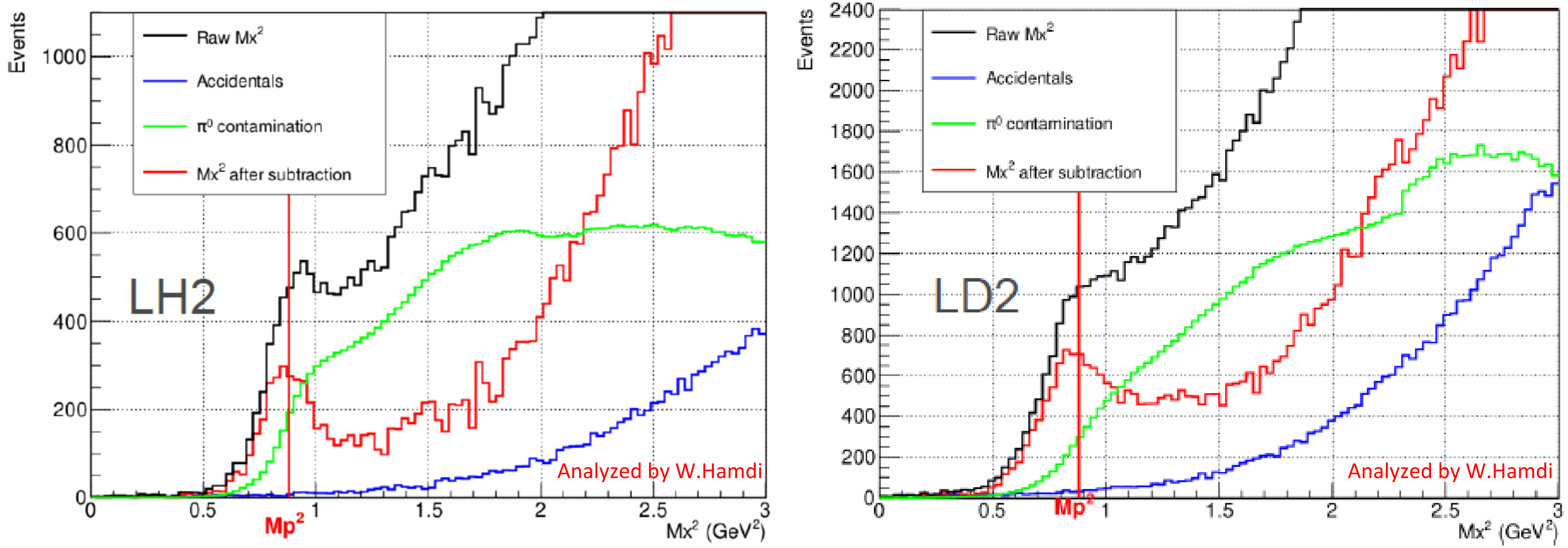
γγ invariant mass after π0 calibration



Preliminary results of extracted DVCS events

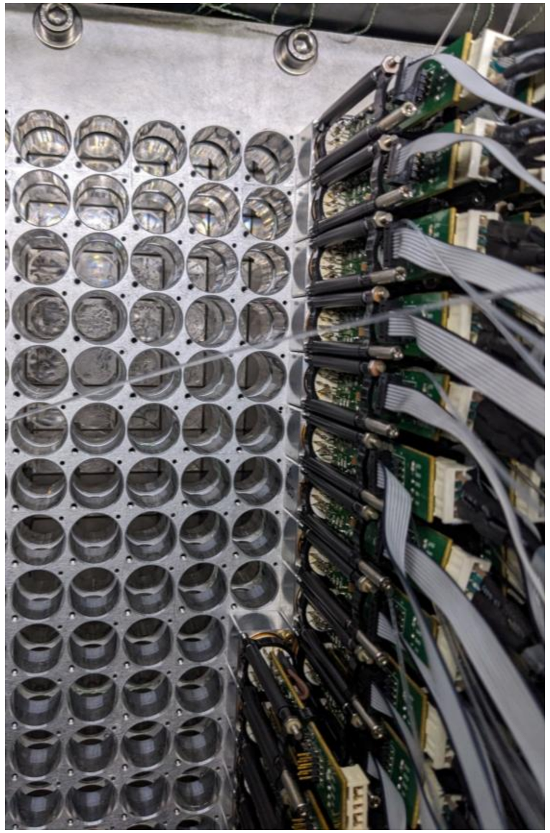
- Clear peak of missing mass square after:
  - Waveform fit analysis and energy calibration for NPS
  - Subtraction of accidental events (e’ and γ from different events)
  - Subtracted $\pi^0 \rightarrow \gamma+\gamma$ contamination

Missing mass square from data with different target

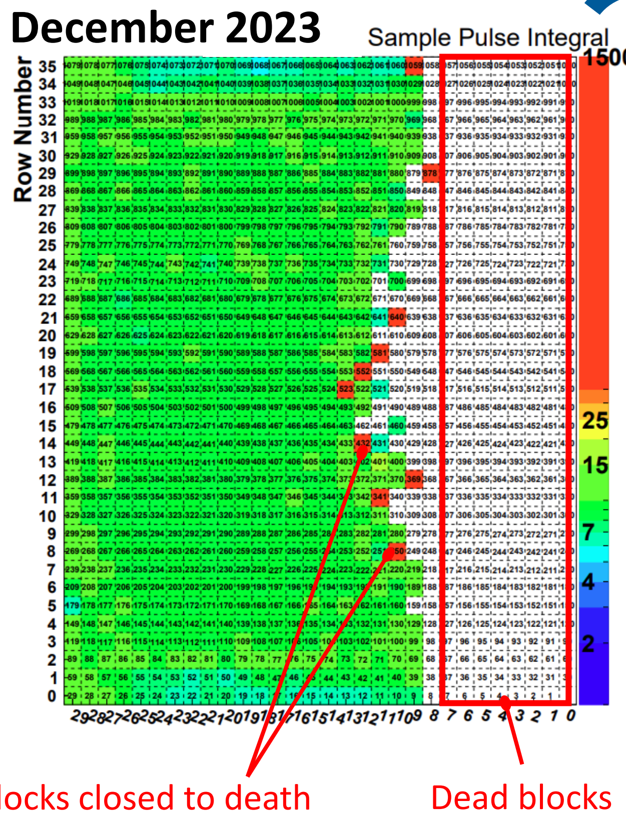


Biggest challenge during the experiment

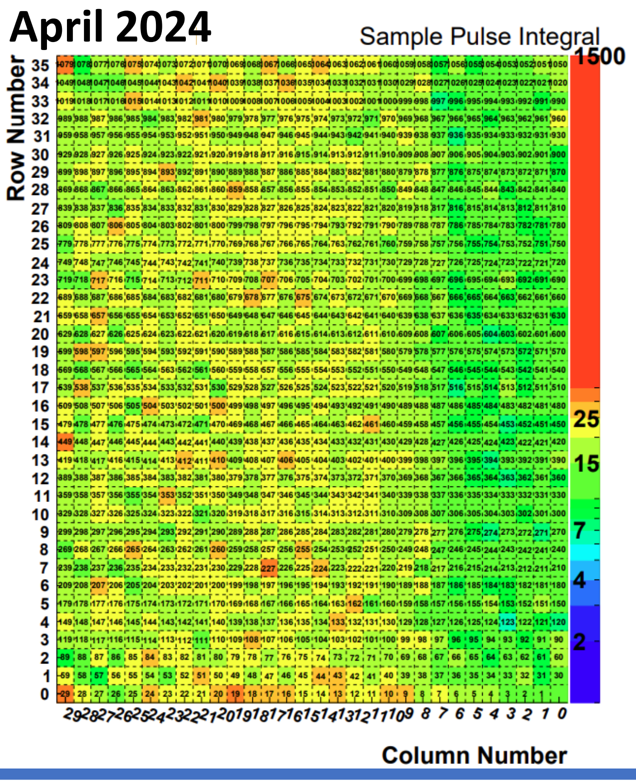
- Radiation damage to the LV regulators on the PMT base pre-amps
- LV regulators were bypassed and re-installed



Divider base boards were removed for bypassing



No major problems with the bases till the end of experiment



Lots of work, lots of fun!

Installing bypassed modules ➡

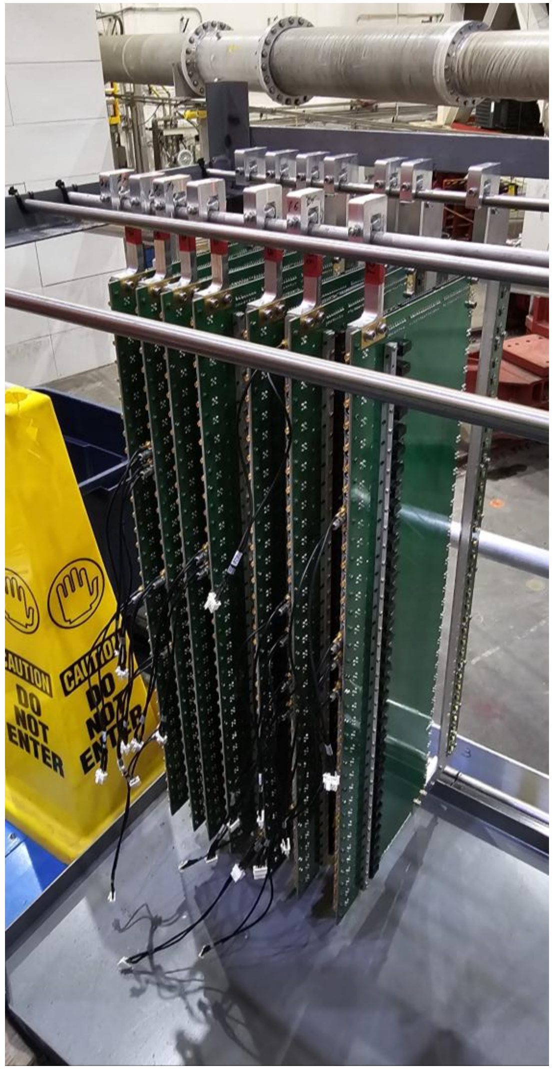
⬆ Assembling bypassed PMT modules

Modules ready to go ➡

Acknowledgements

⬆ The tech team helped us a lot during the experiment

Amazing rack for hanging ➡ the distribution boards
It's an upside down TABLE!!!



Many thanks to the Hall C Tech team, staff, and collaborators

Analysis status

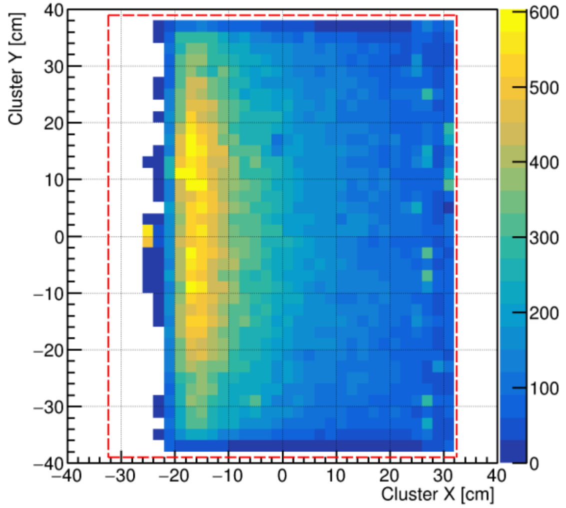
Data production

- ➢ Beam and HMS calibration were done at the end of 2024
- ➢ Waveform analysis is ongoing
- ➢ Energy calibration for the NPS is upcoming

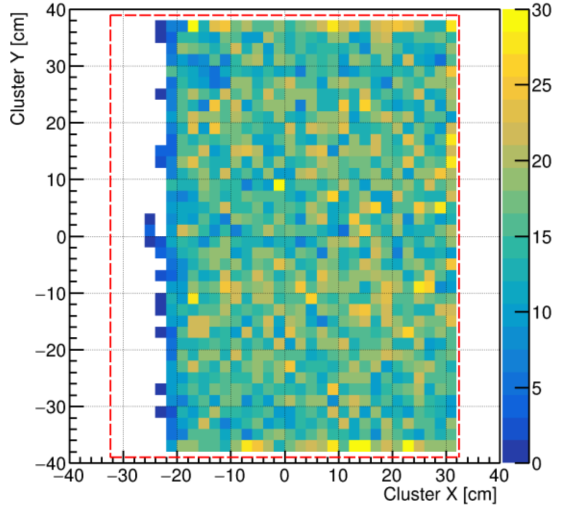
Simulation (for acceptance and bin migration correction)

- ➢ Package of "Event generator + Geant4 (NPS) + Single-arm MC (HMS)" is ready

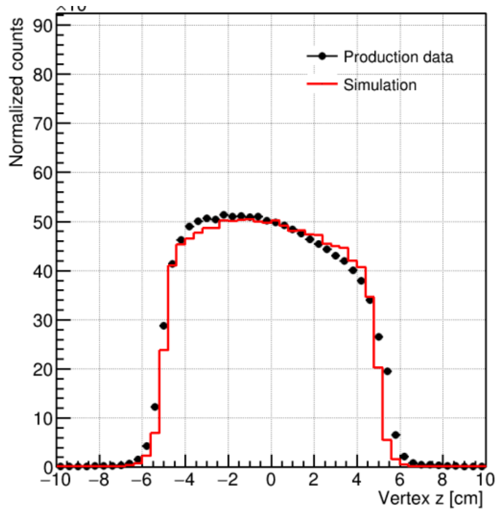
NPS cluster (real data)



NPS cluster (simulation)



Vertex z reconstructed using HMS variable



Summary

- DVCS reaction provides the cleanest way for accessing GPDs
- The DVCS experiment in Hall C during 2023 and 2024 provides sufficient kinematical difference to separate the DVCS and interference terms
- High energy resolution for DVCS photon reconstruction
  - Achieved by the newly installed NPS calorimeter
  - Refined offline analysis and energy calibration also play a crucial role
- Analysis is on-going and physics results will come up soon

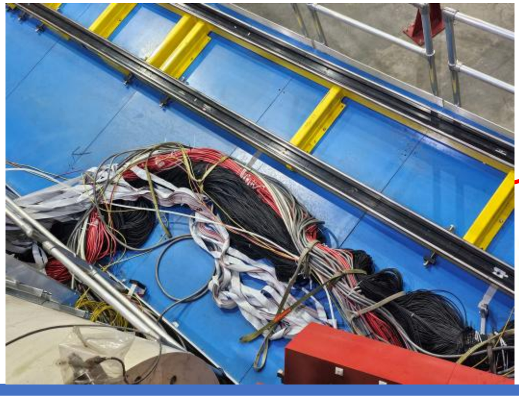
More information and details

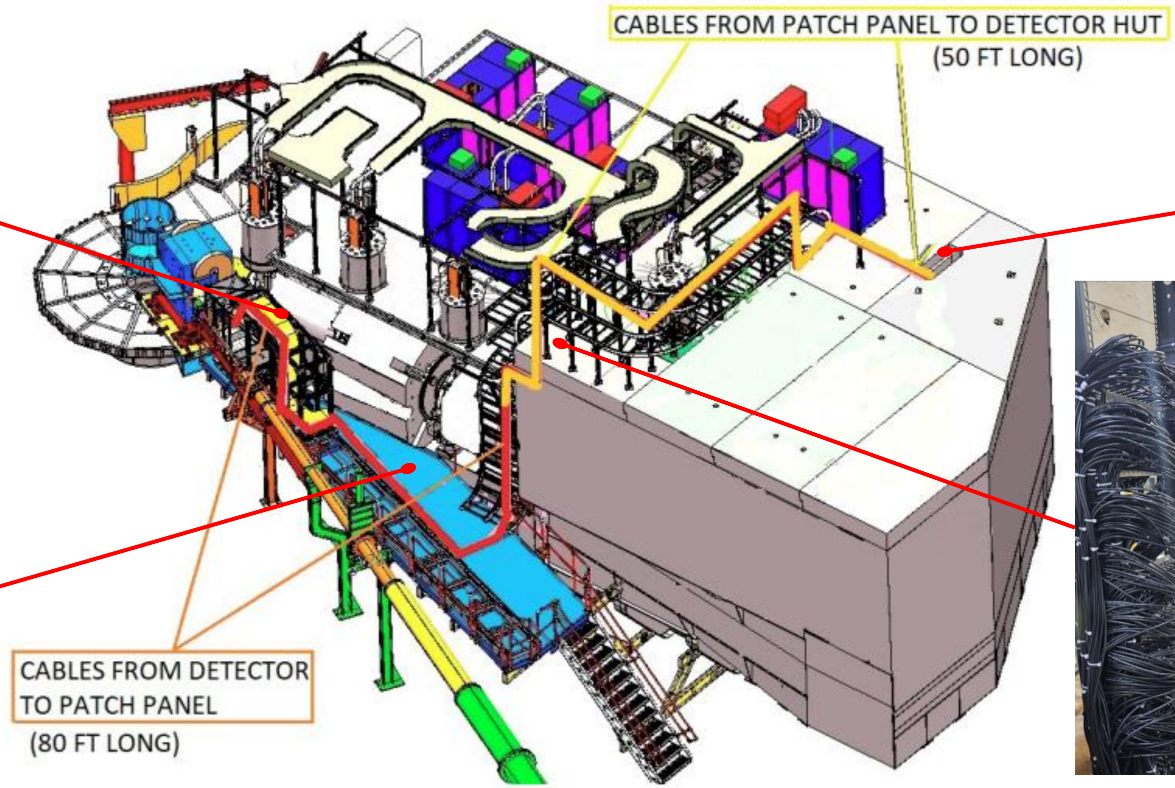
- Backup slides of this presentation
- Proceeding of JRJC2024 conference, p71-75: https://hal.science/hal-05110108
- 2024 NPS collaboration meeting: https://indico.jlab.org/event/866/
- 2025 NPS collaboration meeting: https://indico.jlab.org/event/946/

Backups

Installation of the NPS

- Installation and cabling
  - Began in mid-May 2023 and finished in 2 months
  - Signal, High voltage and low voltage cables, cooling system
- Test and troubleshooting using cosmic data till the beginning of the experiment



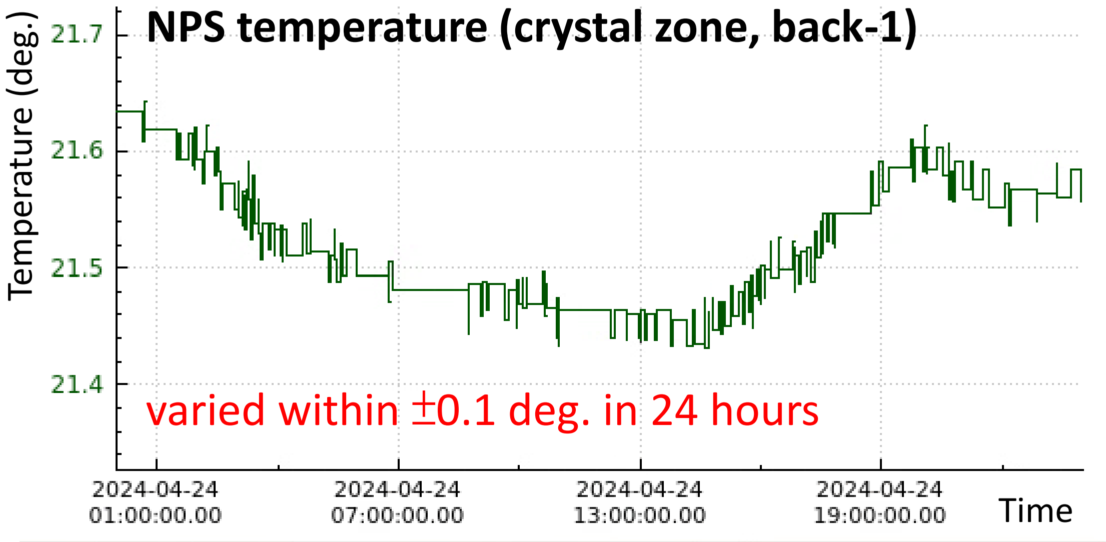


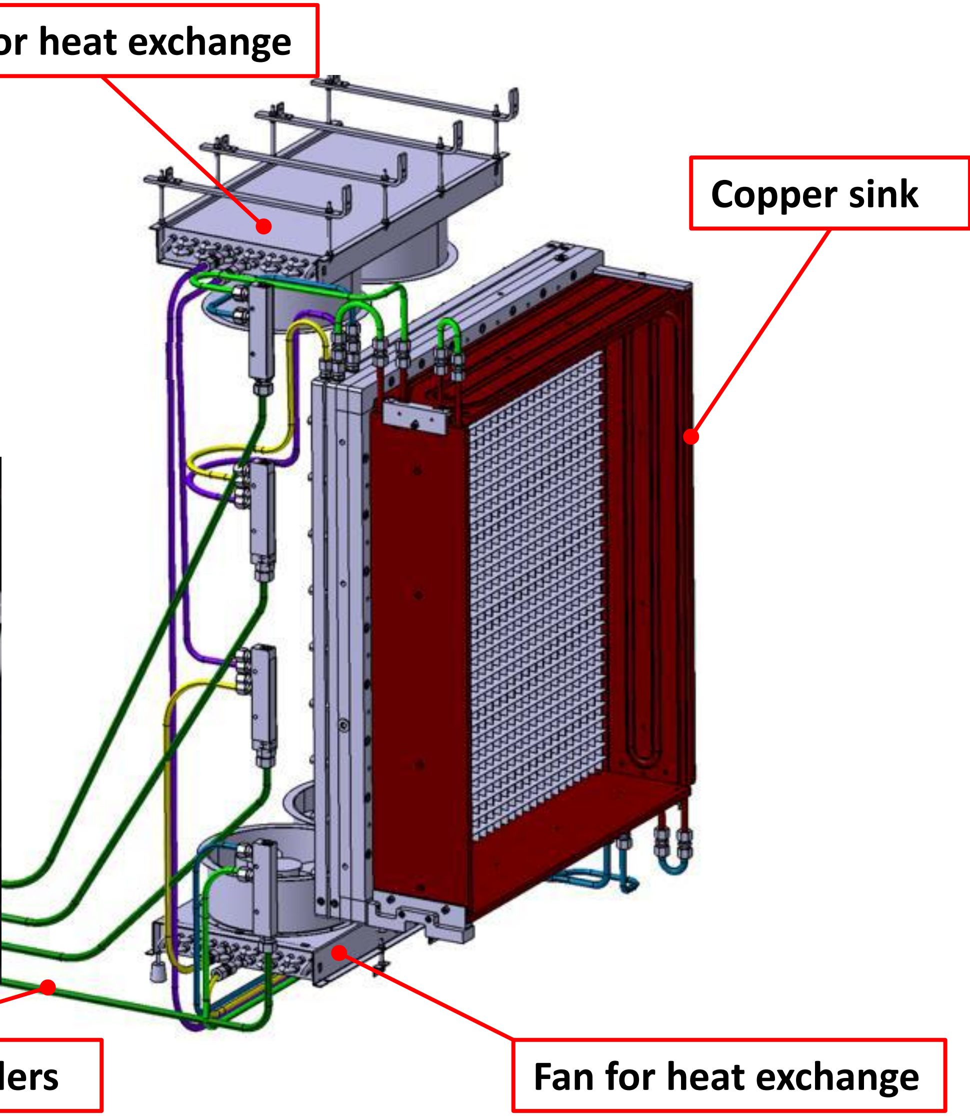
↑ In the detector hut

← The patch panel

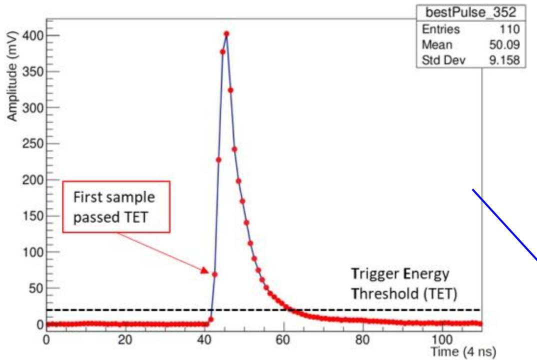
Temperature control system

- Heat generate by PMTs and electronics
- Light yield in $PbWO_4$ crystals are sensitive to their temperature (-2% / $^{\circ}$C at 20°C)
- Keep the temperature as stable as possible
- 56 sensors on the back and front of crystals for temperature monitoring

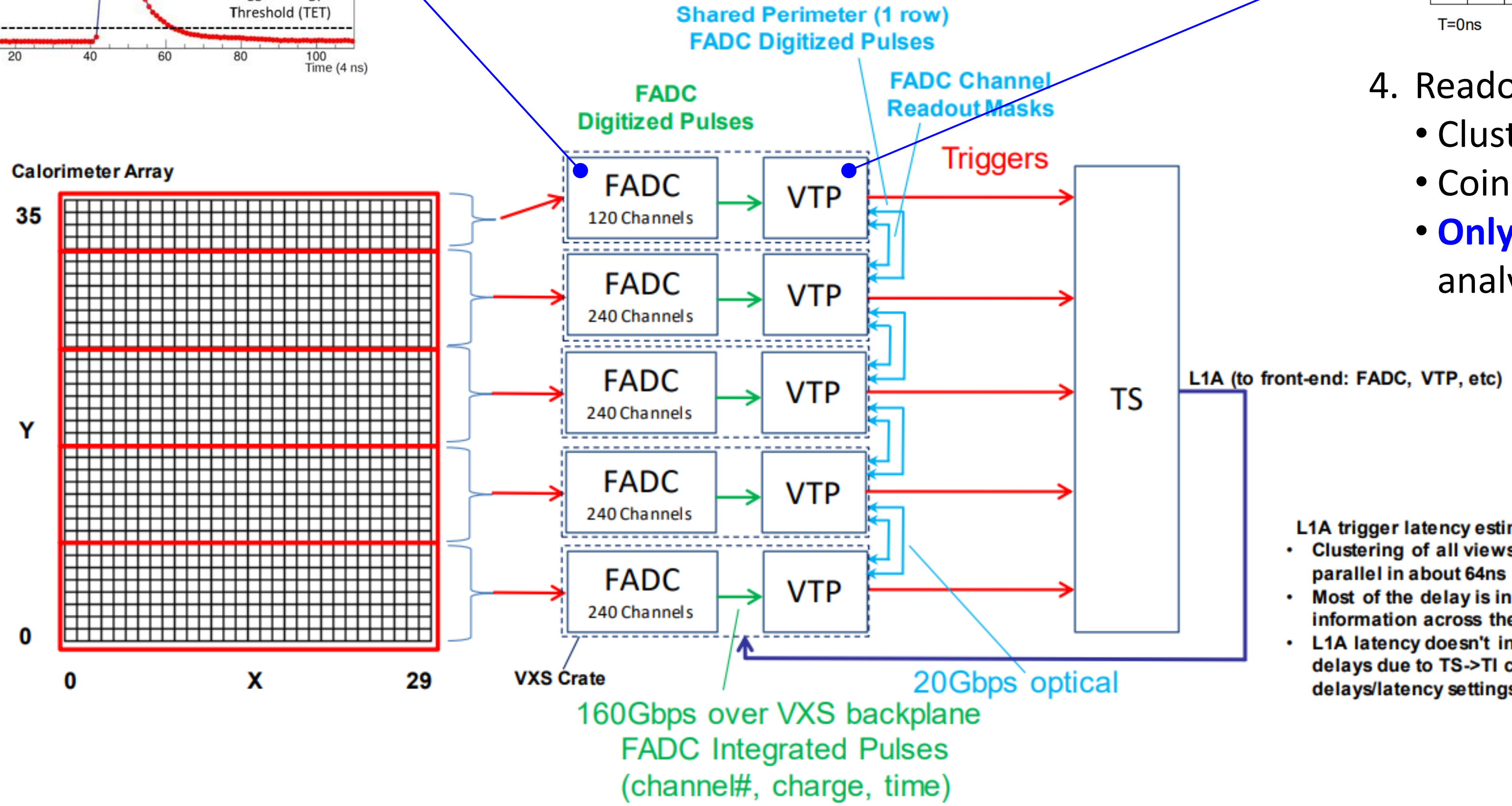




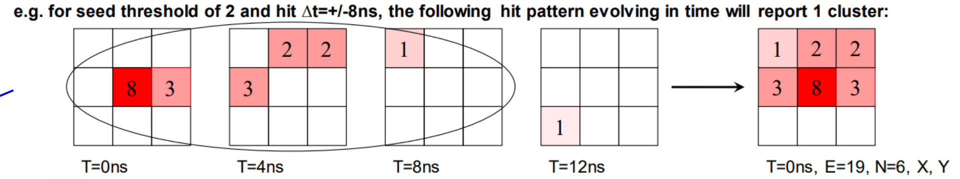
NPS Streaming Data Acquisition



1. Waveform samples are digitalized by JLab developed flash Analog-to-digital converter (FADC)
2. Hits information are sent to VXS trigger processor (VTP) for triggers

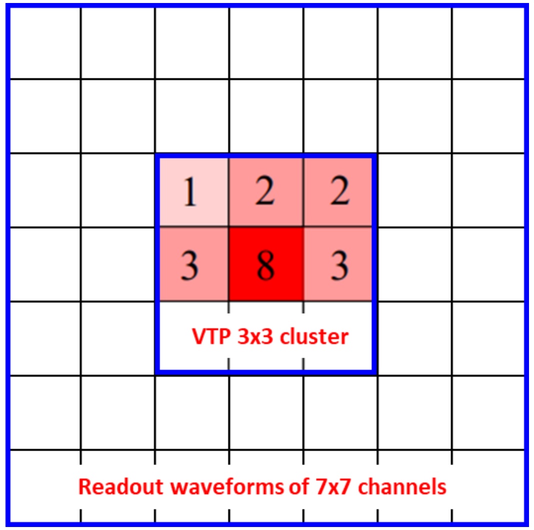


3. VTP performs 3x3 clustering and trigger
   - Based on seed energy threshold and timing of hits



4. Readout waveforms, amplitudes, timing, …
   - Cluster energy above single photon trigger threshold
   - Coincidence with HMS signal
   - **Only readout waveforms of 7×7 channels** for further analysis to reduce the event size on the disk

L1A trigger latency estimated around 1μs
- Clustering of all views happens in parallel in about 64ns
- Most of the delay is in transporting information across the serial links
- L1A latency doesn't include additional delays due to TS->TI cable delays/latency settings



Reconstruction of events

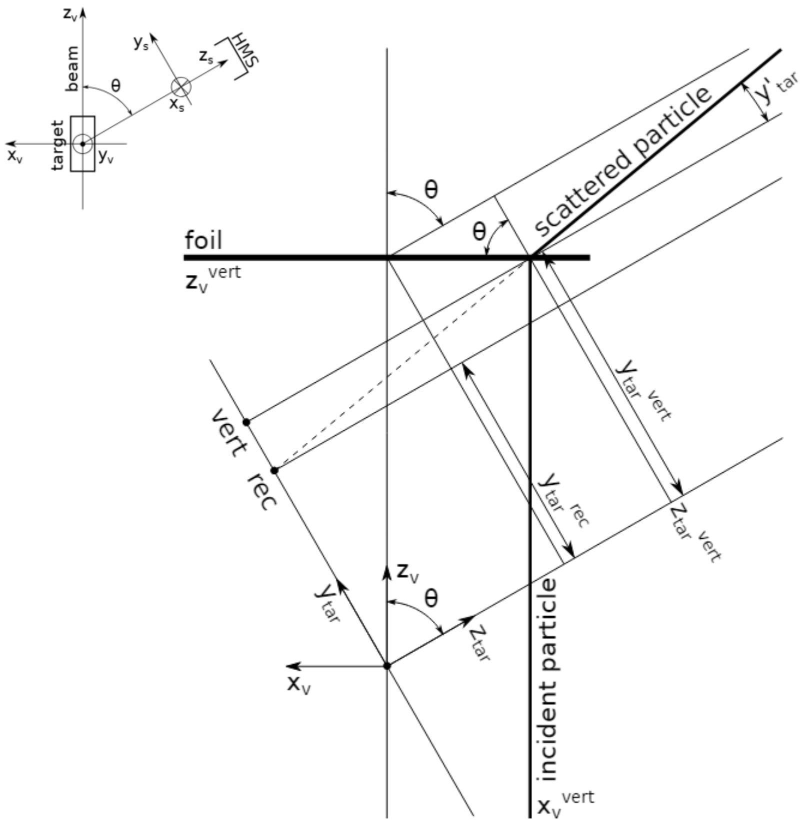


Figure 2: Detailed drawing of event coordinates. The subscript "v" denotes the vertex coordinate system while "tar" stands for target. The "vert" point marks the vertex projection of the interaction vertex onto the target coordinate system. On the other hand, the "rec" point is the reconstructed point as given by Equation 1. The vertex projection must be calculated from the reconstructed point.

$$x'_{\rm tar} = \sum_{i,j,k,l,m} X'_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1a}$$

$$y^{\rm rec}_{\rm tar} = \sum_{i,j,k,l,m} Y_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1b}$$

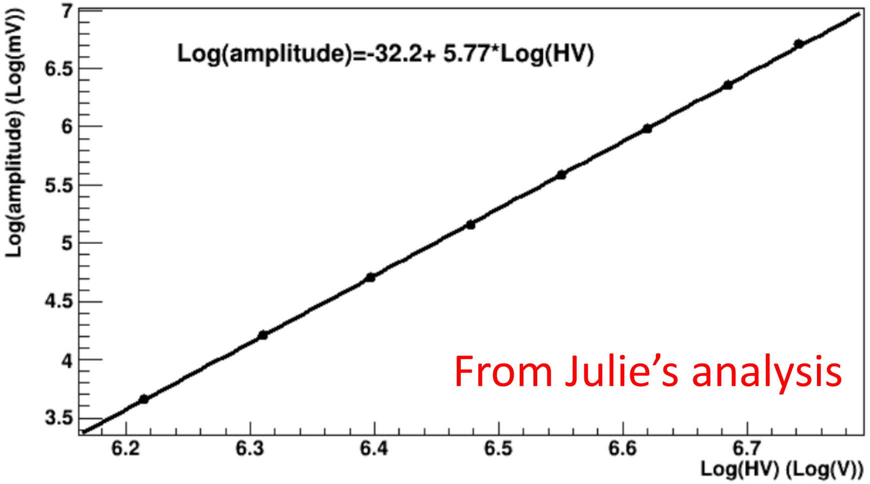
$$y'_{\rm tar} = \sum_{i,j,k,l,m} Y'_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1c}$$

$$\delta_{\rm tar} = \sum_{i,j,k,l,m} D_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1d}$$

$$z^{\rm vert}_{\rm v} = \frac{y^{\rm rec}_{\rm tar} + x^{\rm beam}(\cos(\theta) + y'_{\rm tar}\sin(\theta))}{\sin(\theta) - y'_{\rm tar}\cos(\theta)}$$

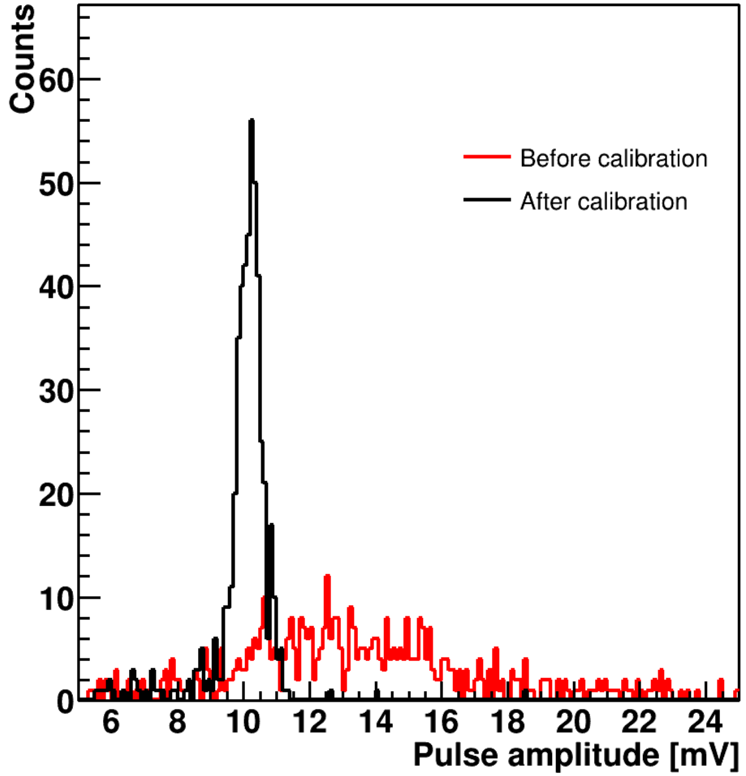
NPS calibration with cosmic rays

- Check the performance after installation, troubleshooting, etc.
- Pre-calibration before calibrating with elastic data
  - Gain matching for similar amplitudes in each block
  - $Amp. = \alpha \times HV^{\beta}$
  - $new\ HV = old\ HV \times (\frac{new\ Amp.}{old\ Amp.})^{\frac{1}{\beta}}$
  - $\beta = 5.77$
  - New amplitudes are set to 10 mV



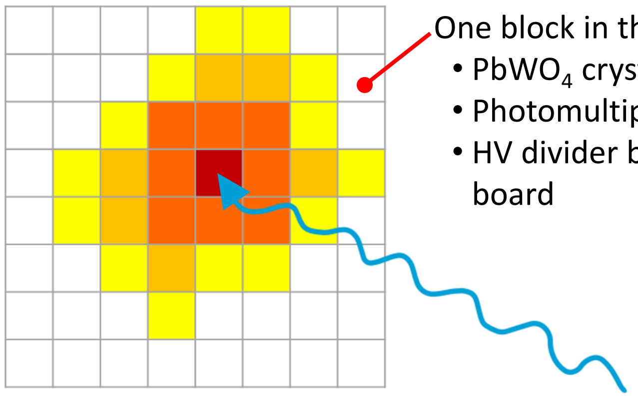
From Julie's analysis

Amplitudes before & after calibration



Energy calibration for NPS using elastic events

- Measured energy of a particle in the NPS: $E_{cluster}^{NPS} = \sum_j C_j A_j$
  - j: blocks in the cluster
  - A: amplitude measured in the block [mV]
  - C: calibration coefficient, convert amplitude to energy [GeV/mV]

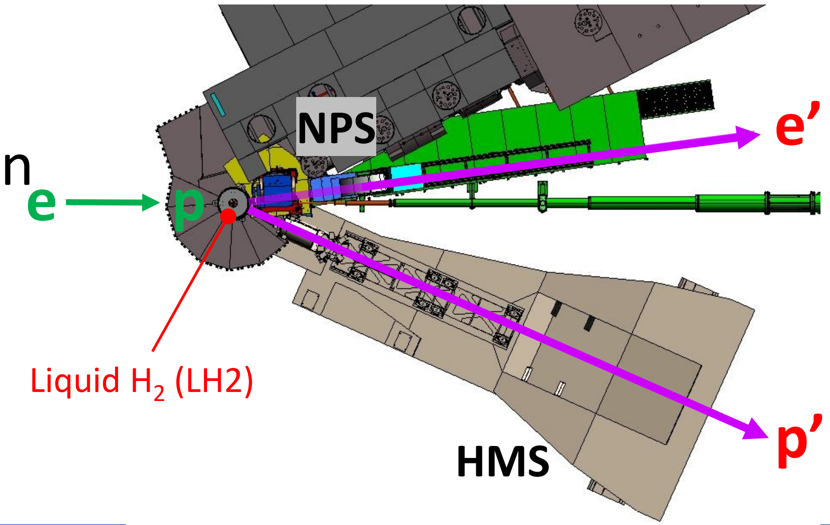


Cluster forms in the NPS when a particle is detected

- The amplitude is controlled by the HVs: $A_j = \alpha \times HV_j^{\beta}$

α, β: constant from gain curve of PMTs

- For better trigger of the DVCS photons, a uniform gain in each PMT block is required
  - Appropriate high voltage (HV) setting is required!
  - C_j is the key variable for calculate the new HVs
- Elastic collisions (e + p ⟶ e' + p') were used for this calibration
  - Scattered electron (e'): detected in the NPS
  - Recoiled proton (p'): measured in the HMS
    (for precise prediction of scattered electron energy)



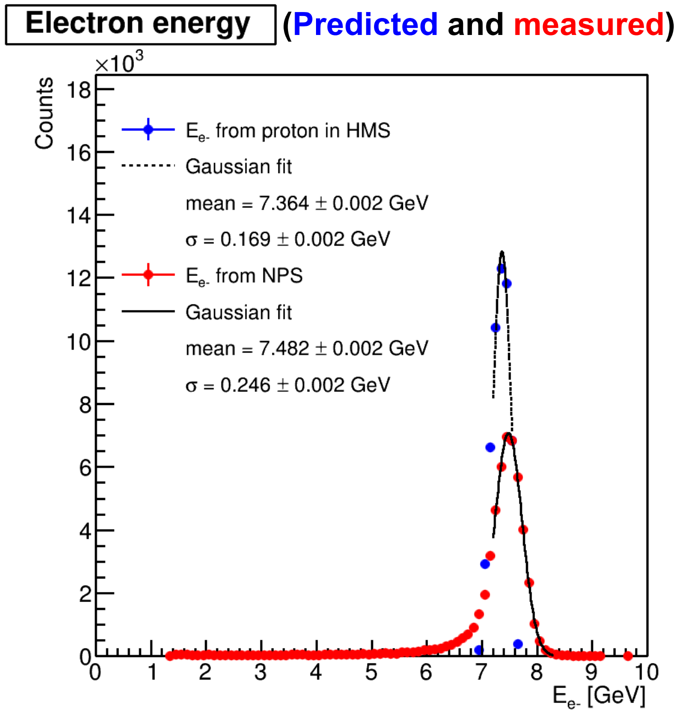
Calibration coefficients and new HV setting

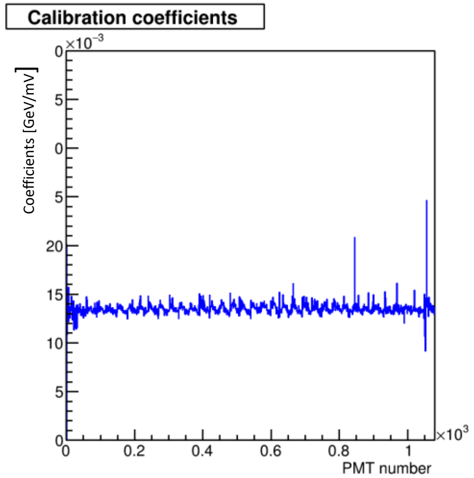
- Linear equations of 1080 crystals are used for the minimization:
  - According to energy conservation, the energy E_i of scattered electron in event i is:

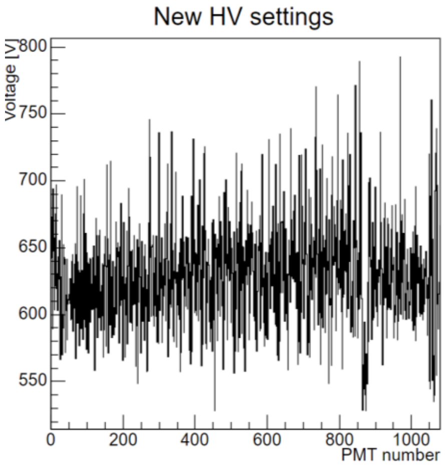
    $$E_i = E_b + M_p - E_i^p$$

    where E_b is the beam energy, M_p is the mass of target proton, E_i^p is the energy of proton detected in the HMS
  - By comparing E_i with $\Sigma_j C_j A_j^i$
    - C_j is the calibration coefficient of block j in the caloremeter
    - A_j^i is the amplitude (deposited energy) if block j in event i

    we can build $\chi^2 = \Sigma_i (E_i - \Sigma_j C_j A_j^i)^2$
  - The calibration coefficient C_j can be calculated by minimizing the χ^2:



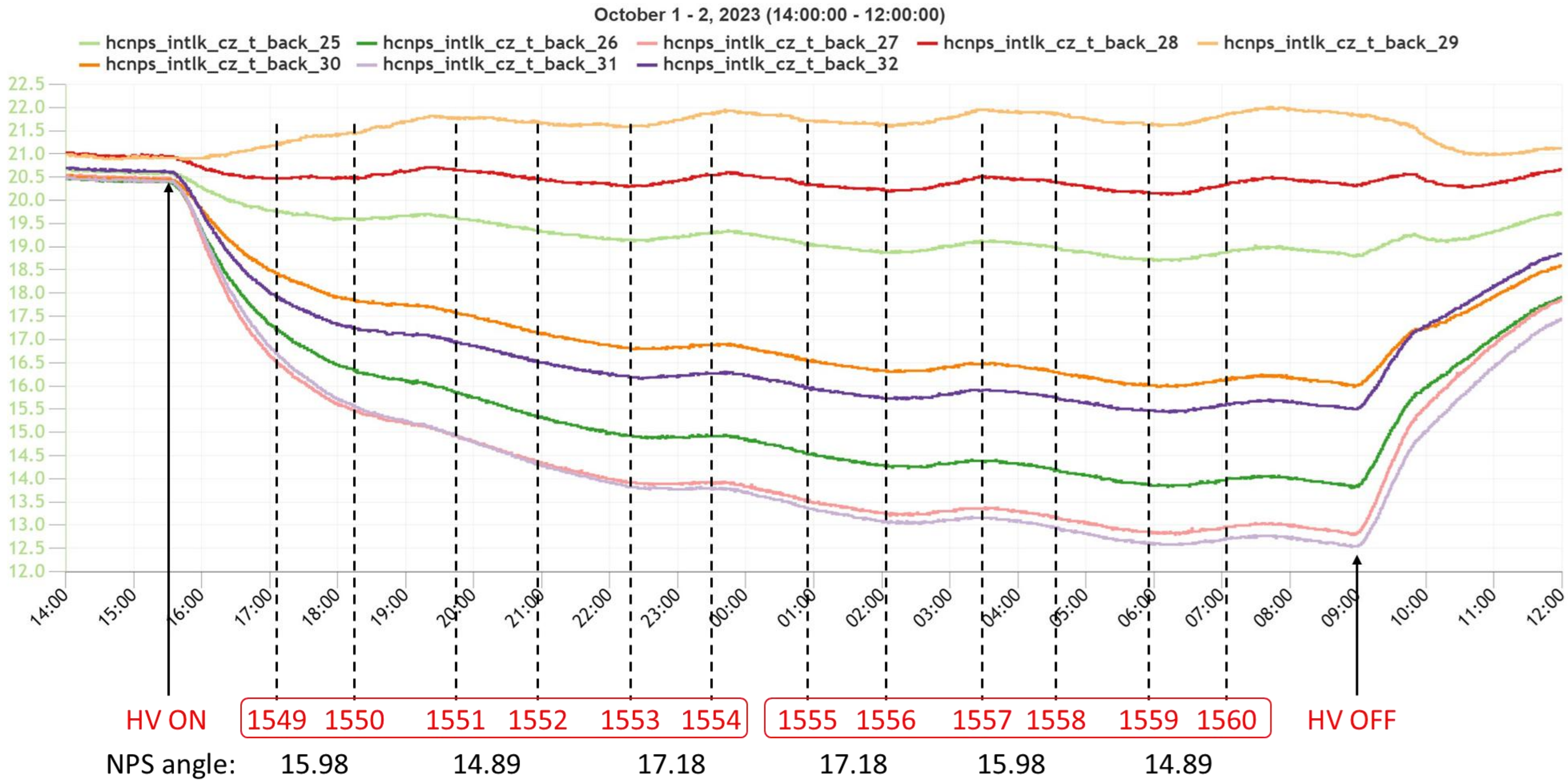




- High voltage (HV) of PMTs are adjusted to have 600 mV of amplitudes for DVCS photon (coefficients after calibration ~ 0.013)
- Based on the gain curve and their calibration coefficients

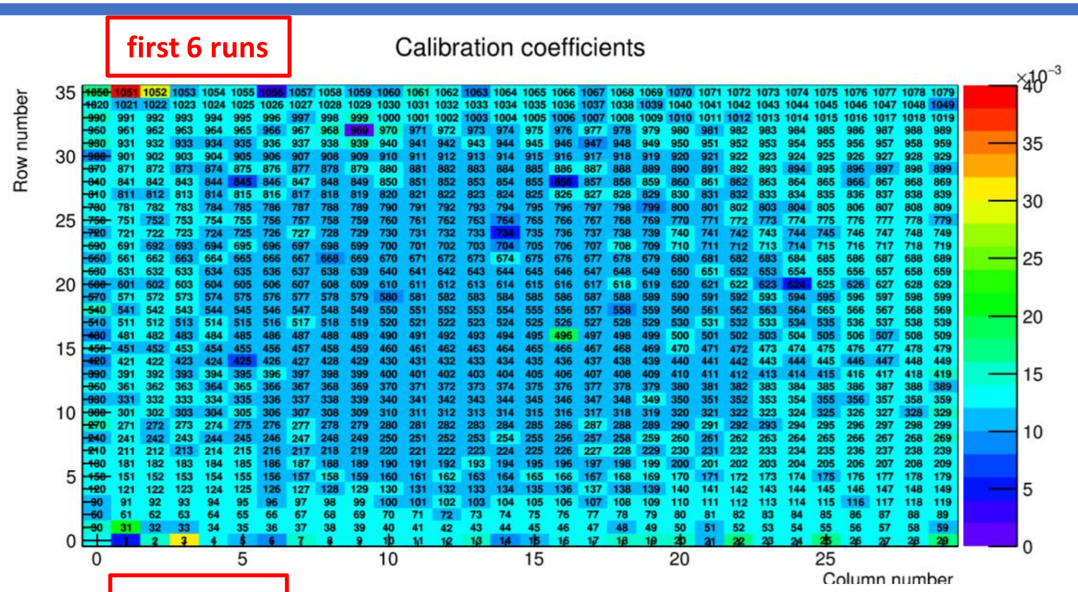
Effects of temperature on elastic calibration

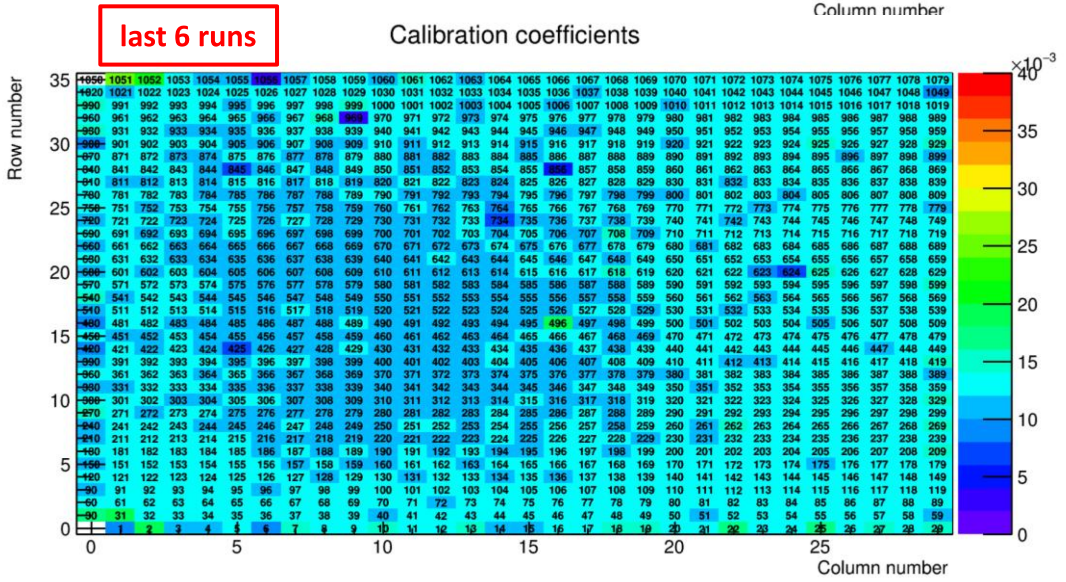
Thermal sensor at middle column (back 25-32)



- Data from EPICS
- Reversed values due to the reversed wire connection (Fixed by Josh closed to the end of the experiment)

Results of calibration associated with temperature





- ➢ Higher temperature in the calorimeter reduces the light yield of the crystals
- ➢ First 6 runs
  - Taken right after turning on the HVs
  - Non-uniform calibration coefficients due to the non-steady temperature in the calorimeter
- ➢ Last 6 runs
  - More uniform calibration coefficients after the temperature got more steady
- ➢ Conclusion
  - Data for calibration and production should be taken after the temperature is steady

π^0 calibration

- This minimization method is used to constrain the mean of π^0 invariant mass and reduce its width based on:

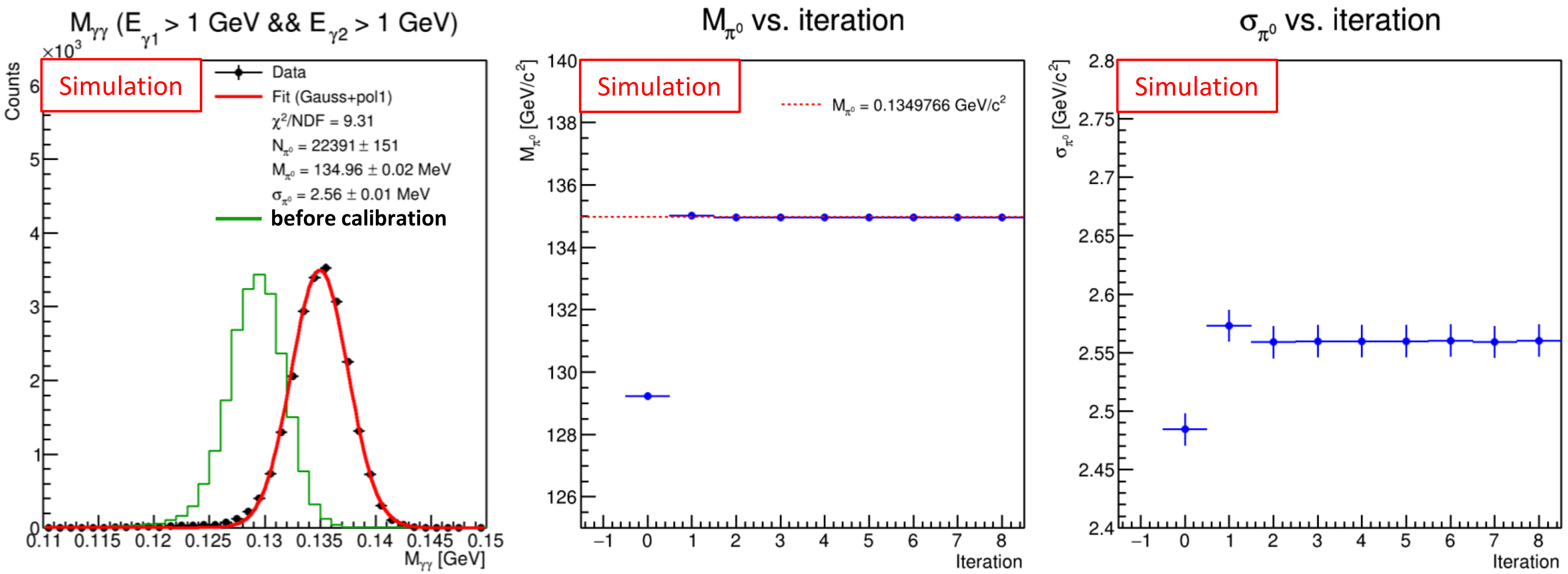
$$F = \boxed{\sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)^2} + \boxed{2\lambda \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)}$$

resolution term — embody the constraint $\langle m_i^2 \rangle = m_0^2$

$m_0 = M_\pi = 0.1349766$ GeV
m_i: reconstructed $M_{\gamma\gamma}$
λ: Lagrange multiplier

(Nuclear Instruments and Methods in Physics Research A 566 (2006) 366–374)

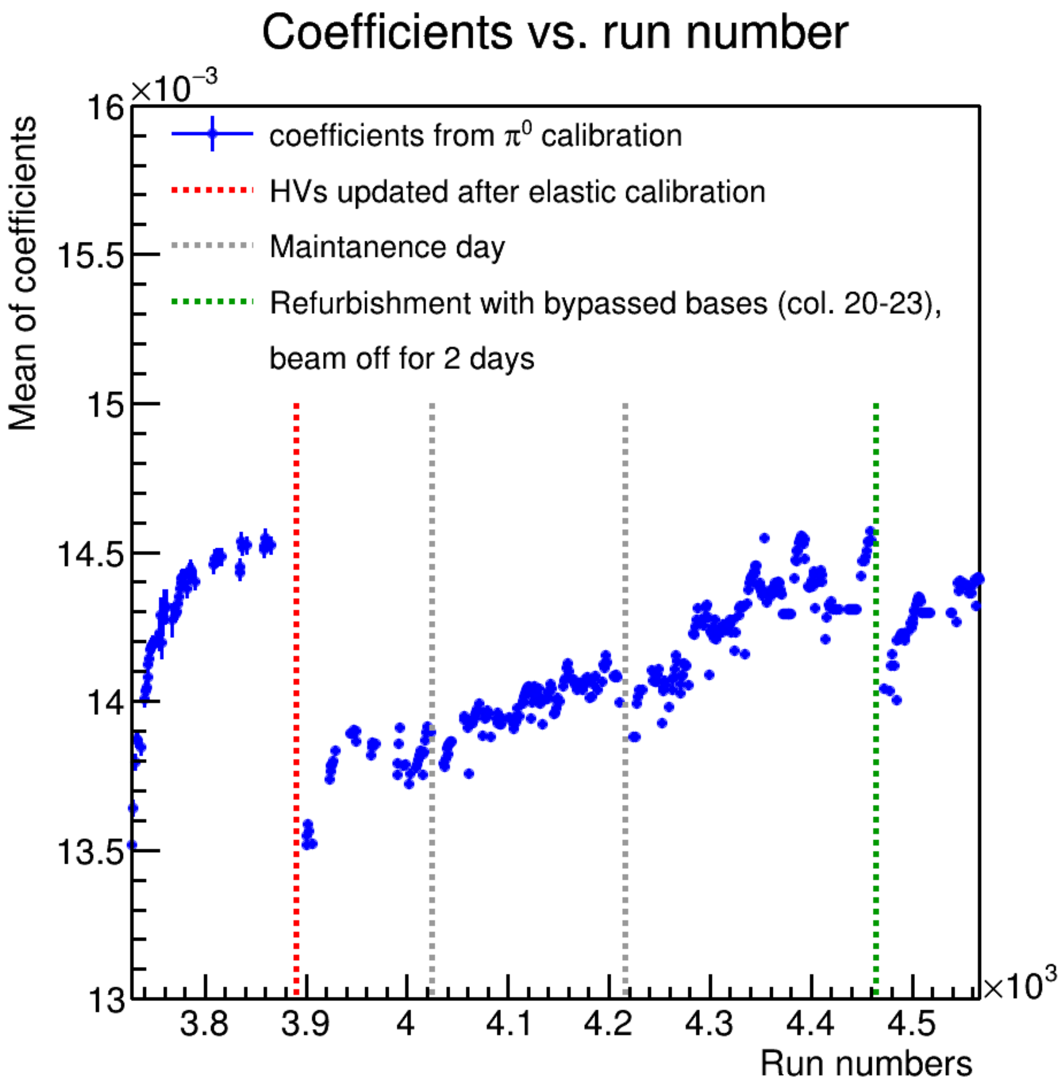
- Iterations are required till the mean and width of π^0 are converged



- Simulation of $\pi^0 \to \gamma\gamma$ using Geant4
- Very good performance of the calibration scripts
- Mean and width are converged in few iterations

Results of calibration as a function of run number

- Calibrated for the first month of data after we came back from the Xmas break
- Gain changed due to the radiation damages to the crystals
- An elastic calibration was done after taking 7 days of production data
- Decrease of coefficients after updating HVs and long time of beam OFF
- Using ~100k π^0 events for each calibration (few runs of data)

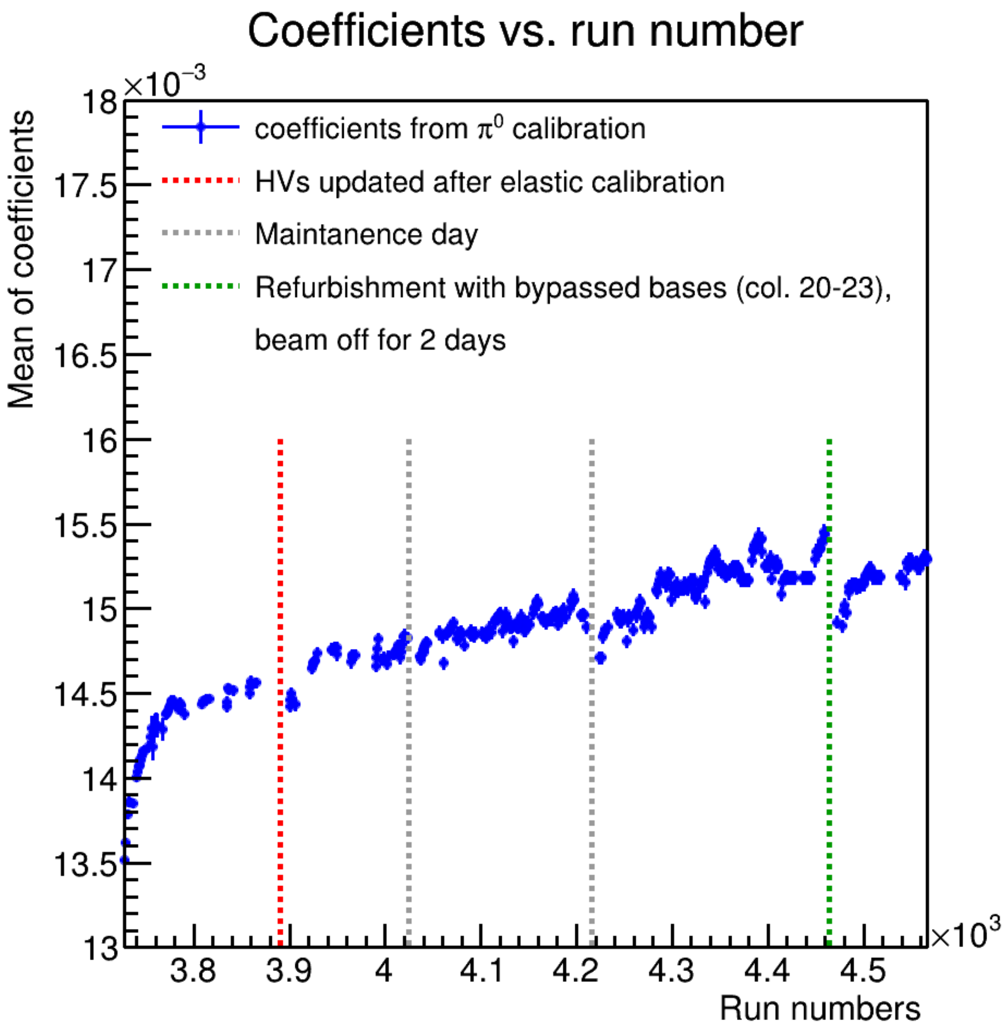


If we didn't update HVs

- Restore to the old coefficients with

$$C^{k}_{old} = C^{k}_{new} \times \left(\frac{\mathrm{HV}_{new}}{\mathrm{HV}_{\mathrm{old}}}\right)^{b},\ b = 5.9$$

- Radiation damages of the crystal were saturated and increased steady after some point
- Cure of the crystals might be meaningless if the damages come back too fast

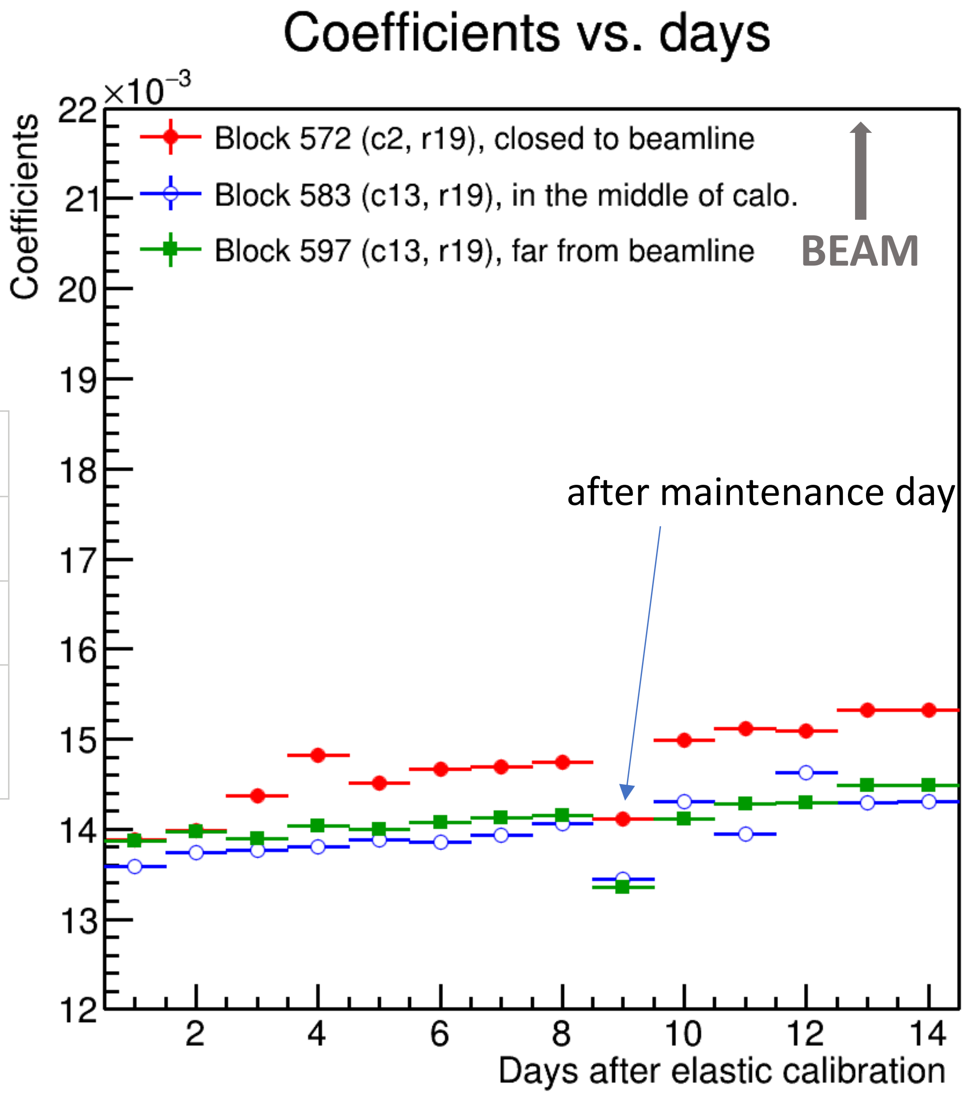


Comparison between different blocks

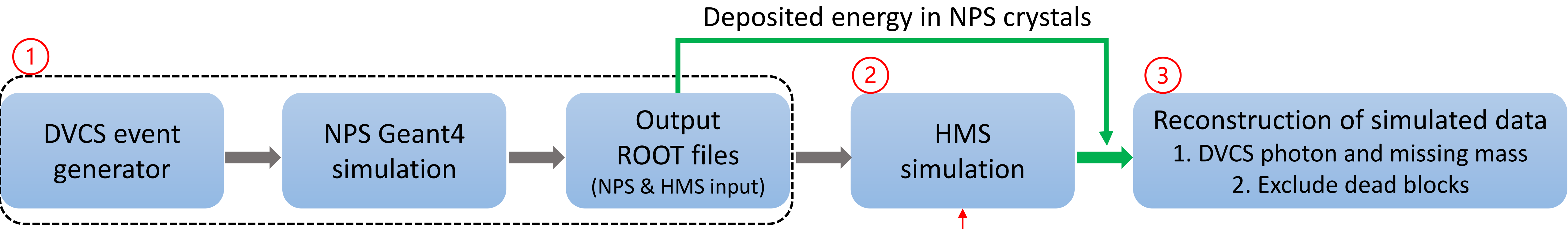
- Average of coefficients at the edge and in the middle of NPS
- Coefficients of blocks closed to the beamline were increased more than the others as we expected

Block number	572	583	597
Coefficients (right after elastic calibration) [MeV/mV]	13.8860	13.5846	13.8736
Coefficients (two weeks after elastic calibration) [MeV/mV]	15.3157	14.2997	14.4826
Increased coefficients [MeV/mV]	1.4297 (10.3%)	0.7157 (5.27%)	0.6090 (4.39%)

BEAM



Strategy of DVCS event simulation



Generate events and NPS simulation (original setup by Ho San KO)
- Done by the NPS Geant4 package
- Generated variables
  - Vertex position
  - Initial electrons (before vertex)
  - Scattered electrons
  - DVCS real photons
  - Q^2, x_B, t, ϕ
- Reconstructed variables
  - Initial electrons (beam electrons)
  - Deposited energy in NPS crystals (by Geant4)

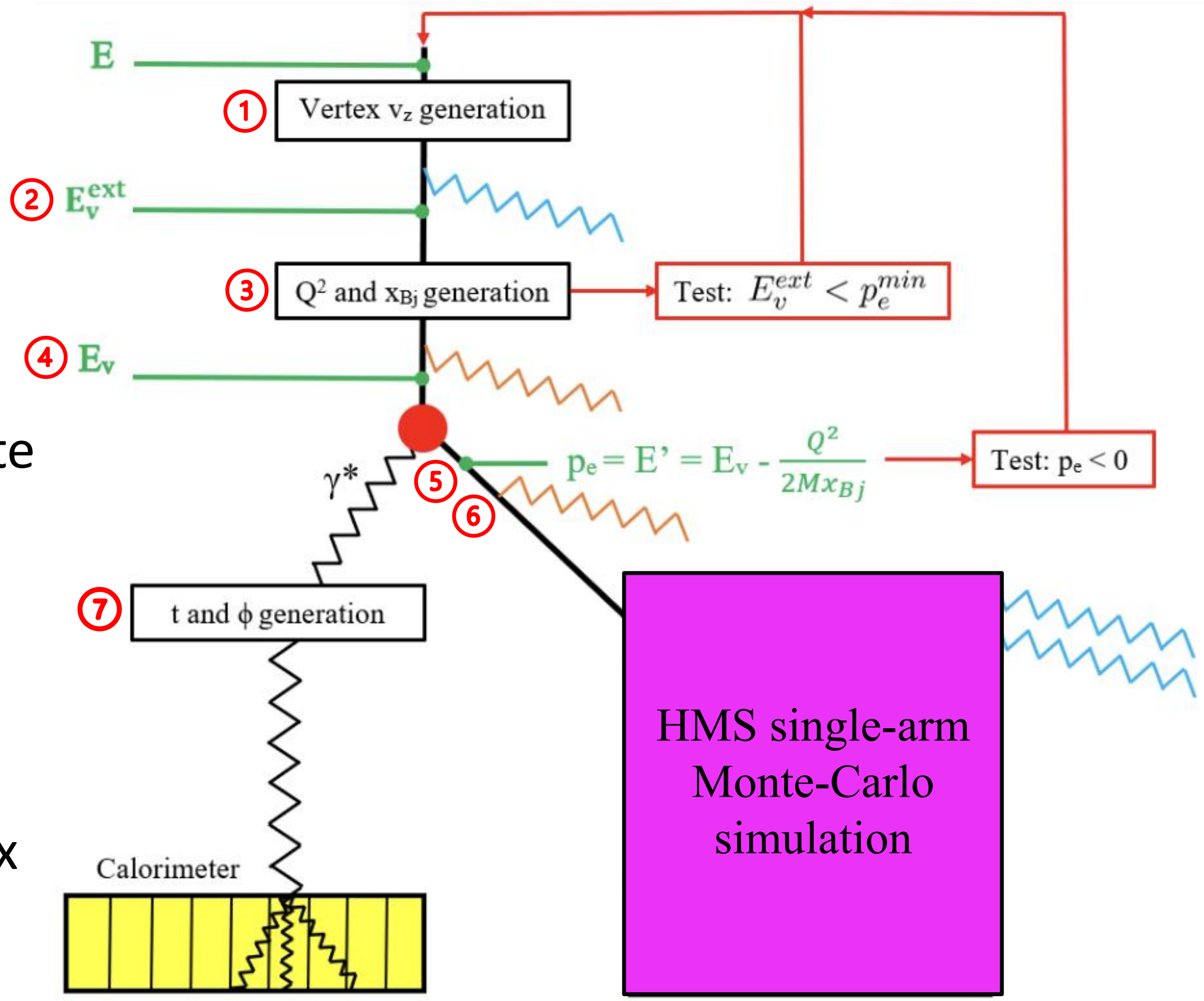
Input for HMS simulation

HMS simulation (credit: D. Gaskell, Y. Zhang)
- HMS single arm Monte-Carlo
- Input variables
  - Generated vertices & scattered electrons
  - HMS angle & central momenta
- Output variables
  - HMS focal plane variables for vertex reconstruction
  - Reconstructed scattered electrons

Reconstruction
- Output reconstructed variables
  - NPS Cluster information
  - DVCS real photons
  - Q^2, x_B, t, ϕ

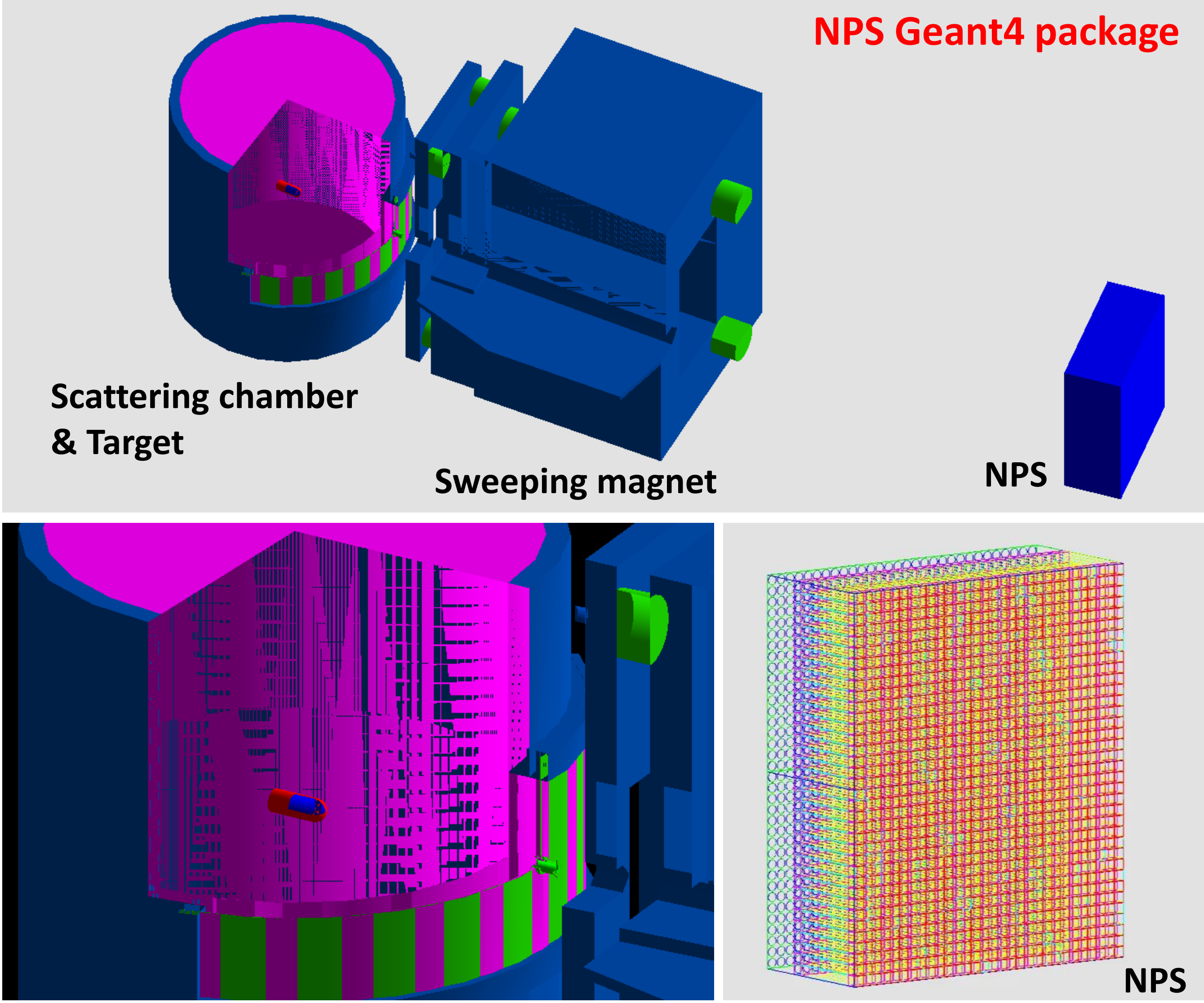
Event generator workflow

1. Generate the vertex position (uniformly along z with beam offset and raster)
2. Apply the external radiation correction before vertex ($E \longrightarrow E_v^{ext}$)
3. Generate Q^2 and x_B uniformly (within $[Q^2_{min}, Q^2_{max}]$ and $[x_B^{min}, x_B^{max}]$)
4. Apply the internal radiative corrections before verte ($E_v^{ext} \longrightarrow E_v$)
5. Calculate the corresponding p_e and $\cos\theta_e$ of scattered electrons using Q^2, x_B and E_v
   - $p_e = Ev - \frac{Q^2}{2MxB}, \cos\theta_e = 1 - \frac{Q^2}{2peEv}$
6. Apply the internal radiative corrections after vertex
7. Generated t and ϕ uniformly for the real photons
   - $\phi \in [\ 0, 2\pi\ ]$; $t \in [t_{min}(Q^2, x_B)\text{-}2, t_{min}(Q^2, x_B)\ ]$

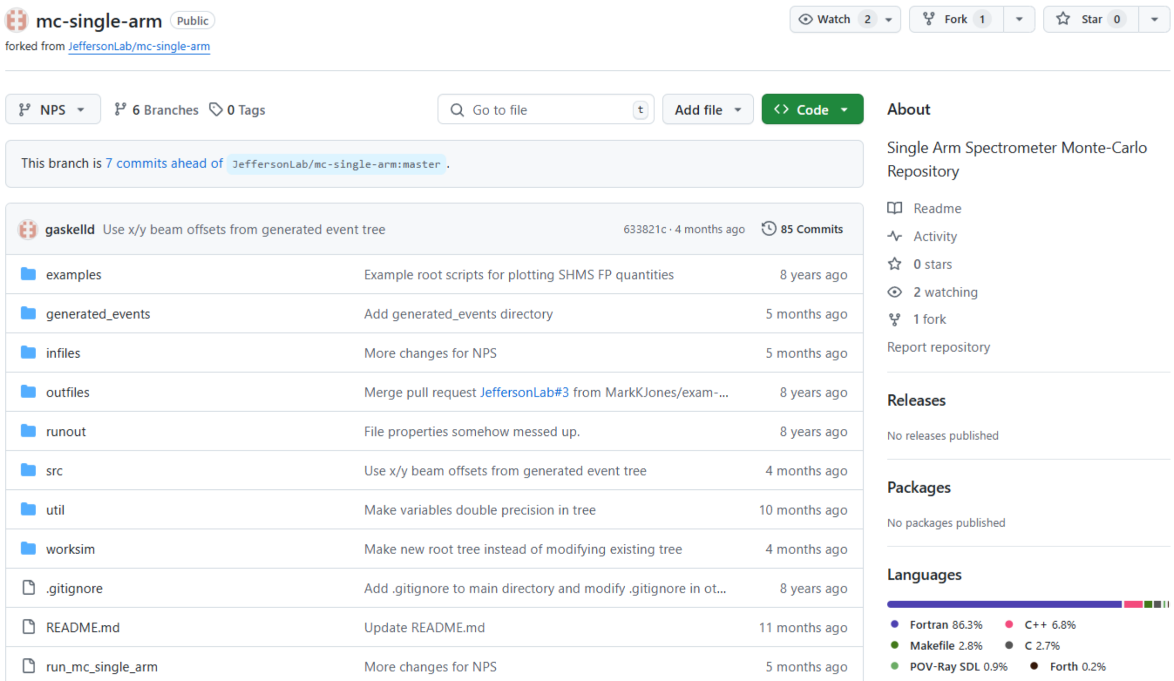


Simulation packages

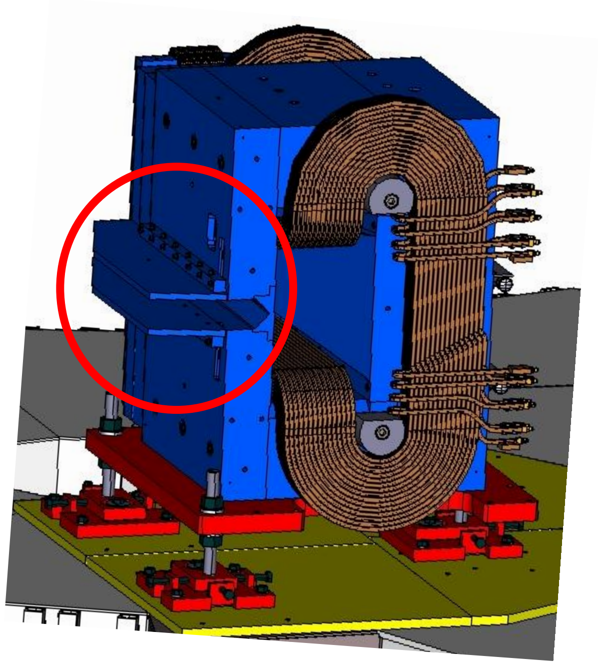
NPS Geant4 package

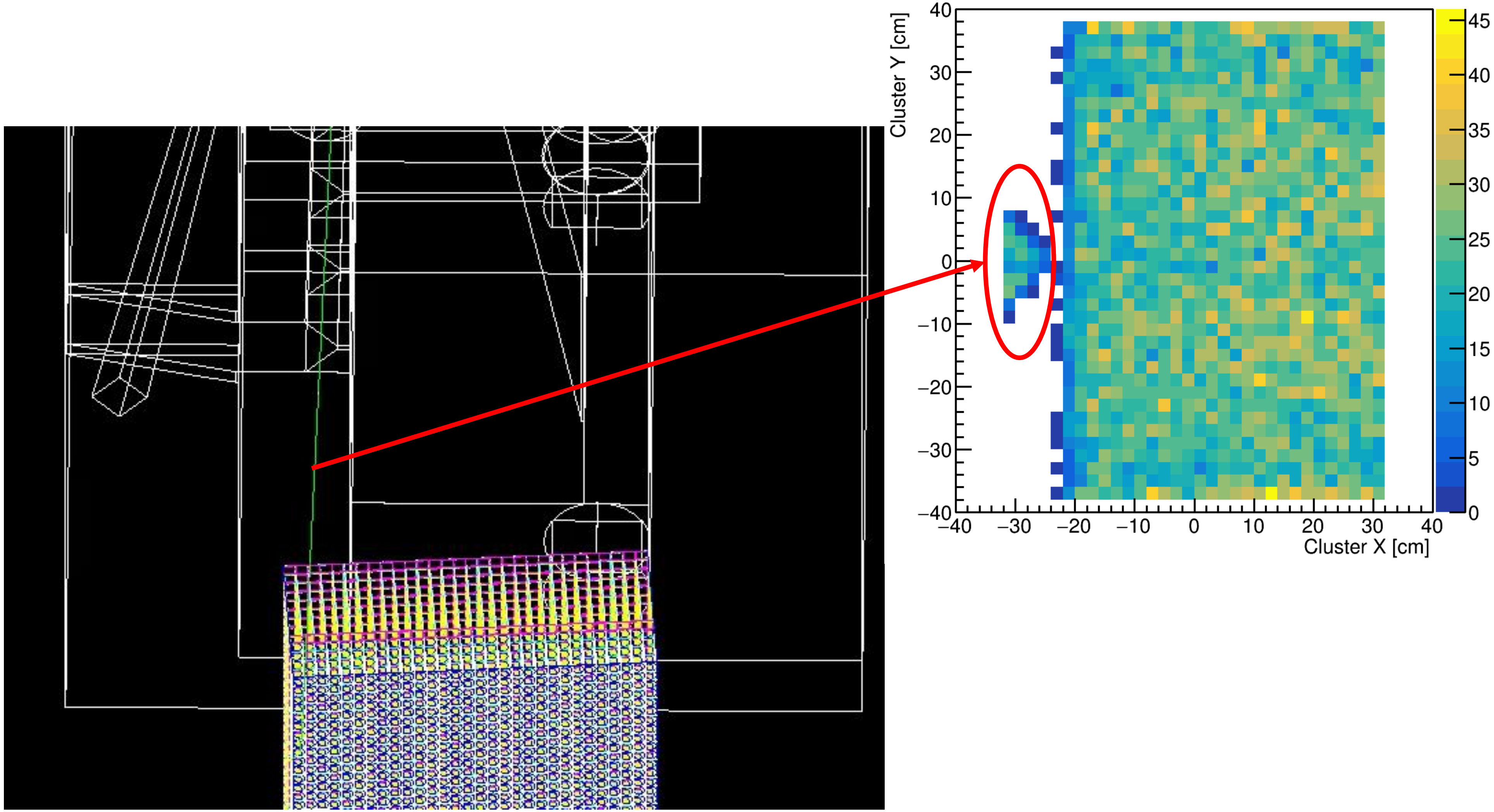


HMS single arm Monte-Carlo package



Additional clusters around x = -30 cm in simulation





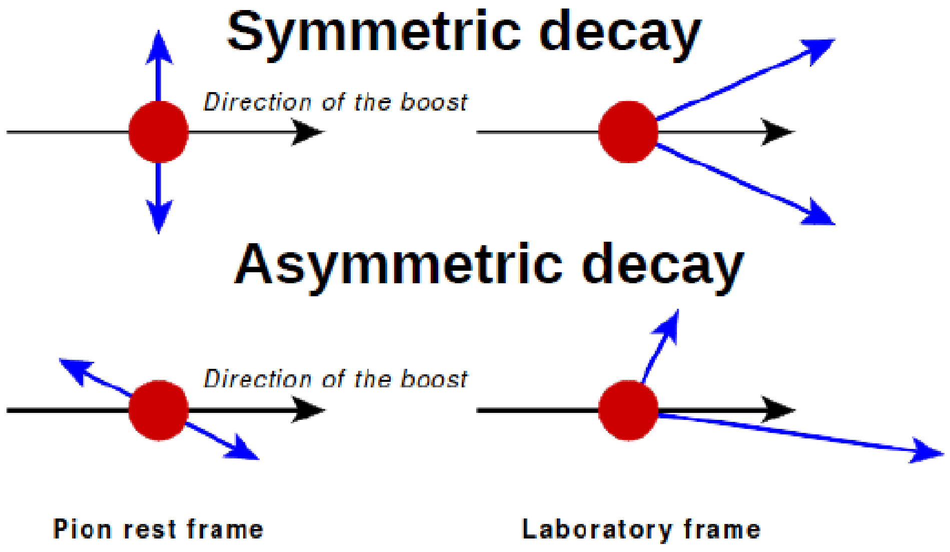
DVCS Analysis
(Pi0 Contamination)

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 θ [-1, 1] (θ= decay angle) Azimuthal angle [0, 2π]



- Divide the decays by number of photons generated:
  N0= events with no γ detected
  N1= events with 1 γ detected
  N2= events with 2 γ detected

- Each event with N1 is subtracted from the DVCS events and before hand multiplied by 2 factors:
  - a1 = 1/5000 and a2 =5000/N2 → W = a1*a2 = 1/N2

Credit to W.Hamdi,
2024 NPS collaboration meeting

Accidental event subtraction

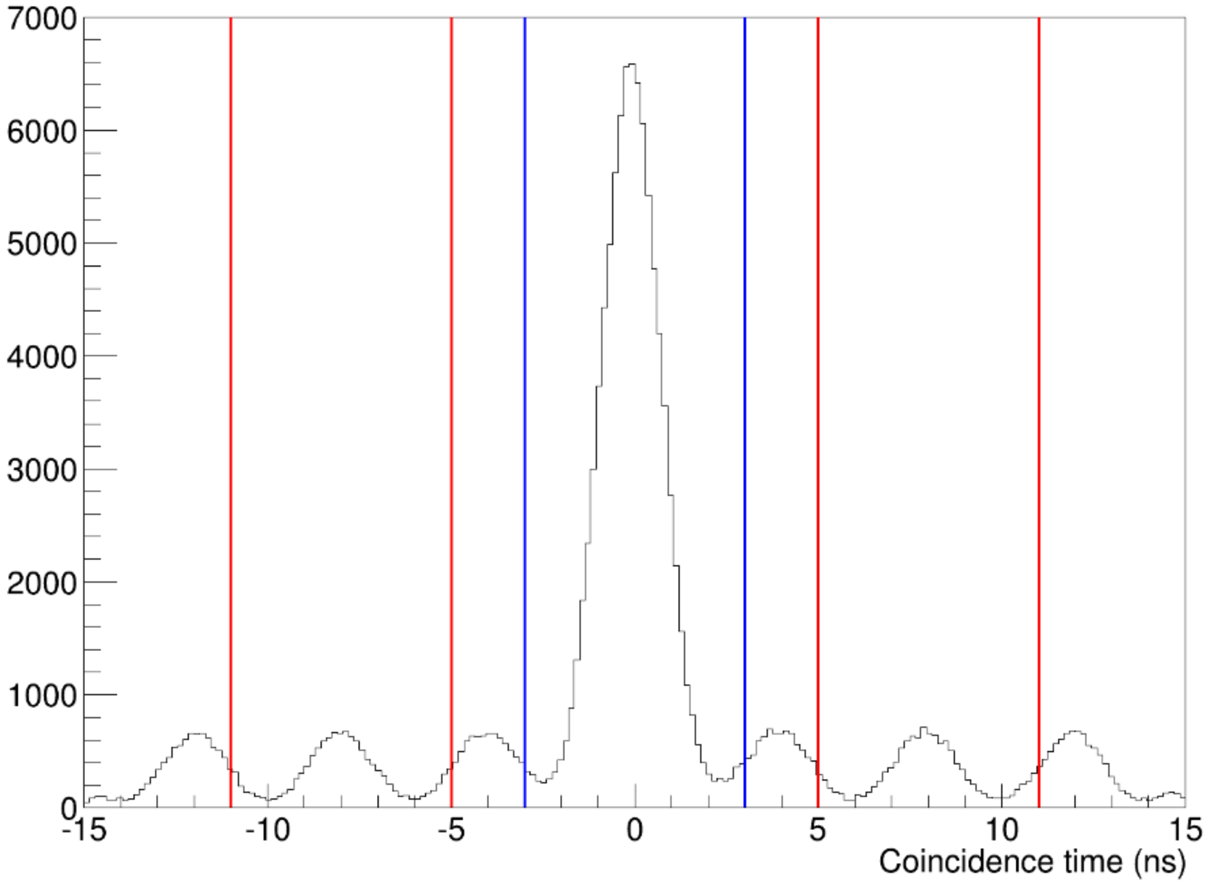


Figure 4.15: Coincidence time spectrum for kin48_4. The main coincidence time window $[-3\text{ ns}, 3\text{ ns}]$ is delimited by the blue lines. The accidental events subtraction windows $[-11\text{ ns}, -5\text{ ns}]$ and $[5\text{ ns}, 11\text{ ns}]$ are located between the red lines. They are shifted by 8 ns with respect to the main coincidence time window to account for the 4 ns time structure of the beam.

Frédéric Georges. Deeply virtual Compton scattering at Jefferson Lab. High Energy Physics - Experiment [hep-ex]. Université Paris-Saclay, 2018. English. ⟨NNT : 2018SACLS391⟩. ⟨tel-01925350⟩