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

- Introduction
- Experimental setup in Hall C
- Data analysis & calibration for the NPS
- Summary & outlook

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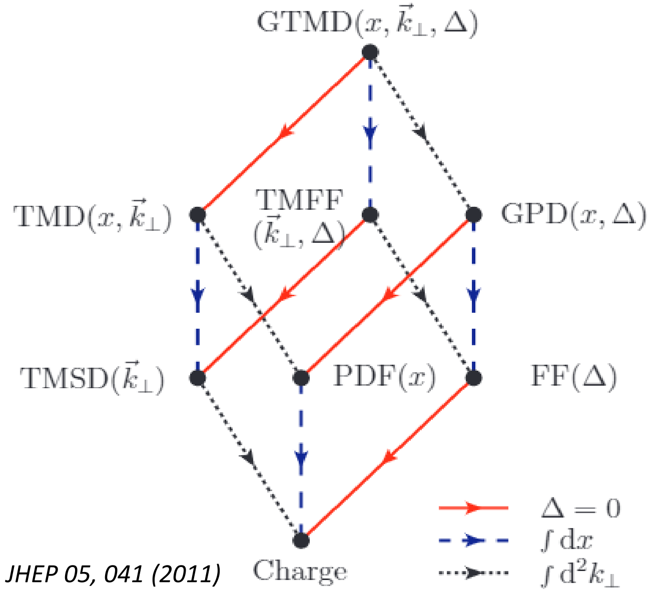
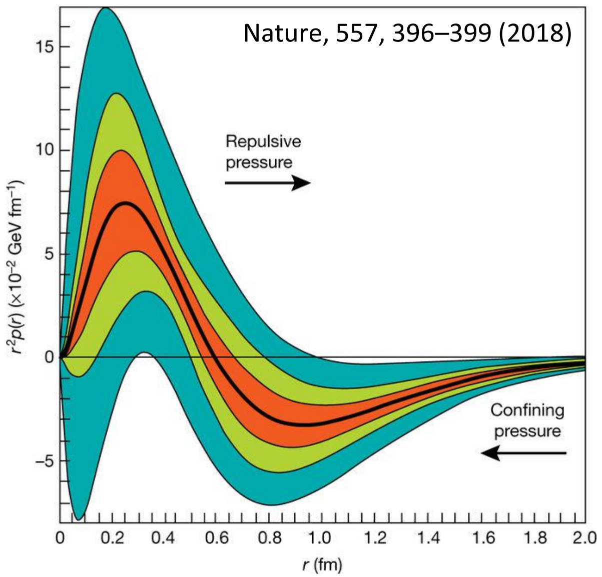
Generalized Parton Distributions (GPDs)

- FFs and PDFs lack spatial–momentum correlation information
- GPDs, introduced in 1990s, offer insights into the 3D structure of the nucleon



JHEP 05, 041 (2011)

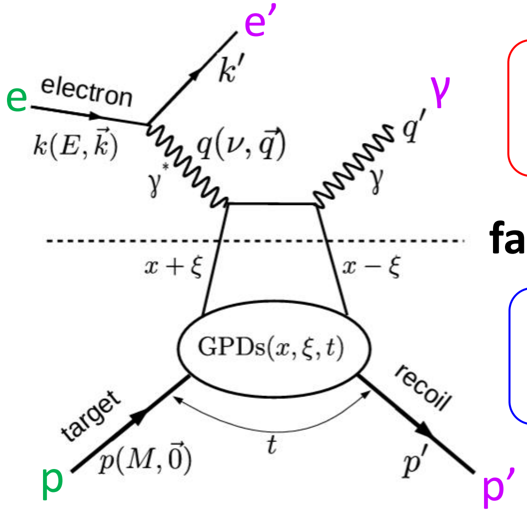


- ✓ Correlation between spatial and momentum distributions
- ✓ Access to radial pressure distribution
- ✓ Quark and gluon total angular momentum contribute to nucleon spin (Ji's sum rule)

- GPDs are accessible via exclusive processes
  - Deeply Virtual Compton Scattering (DVCS)
  - Double DVCS (DDVCS)
  - Deeply Virtual Meson Production (DVMP)

Deeply Virtual Compton Scattering (DVCS)

- DVCS (ep ⟶ e’p’γ) is the simplest probe to investigate GPDs
- Experimentally, GPDs are accessed by DVCS via Compton form factors (CFFs)
- DVCS and Bethe-Heitler process cannot be separated experimentally

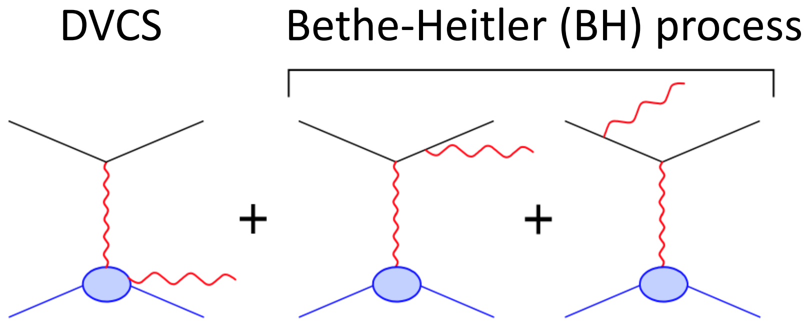


Hard process
- perturbatively calculable

factorization

Soft process
- parametrized by GPDs

ep ⟶ e’p’γ =



- $\sigma(ep \rightarrow e'p'\gamma) \propto |T_{BH}|^2 + |T_{DVCS}|^2 + I(BH \cdot DVCS)$

$|T_{BH}|^2$: pure QED process; $|T_{DVCS}|^2$: bi-linear combination of CFFs; $I(BH \cdot DVCS)$: 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

- At leading twist:

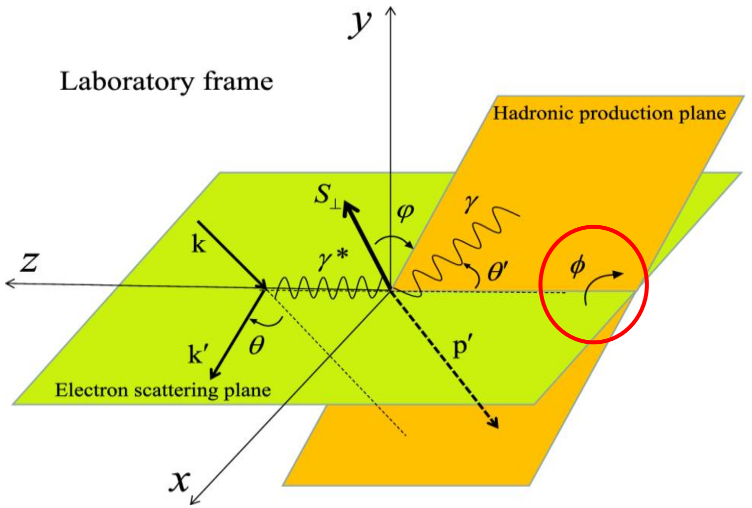
  - $\frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{2} \propto \Im[I(BH \cdot DVCS)]$
  - $\frac{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}}{2} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + \Re[I(BH \cdot DVCS)]$

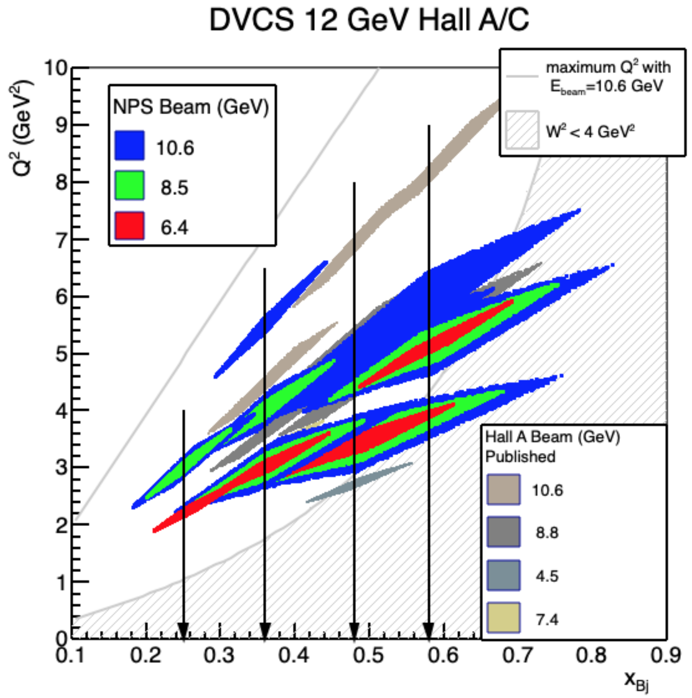
Beam helicity dependence

$|T_{BH}|^2$: known to 1%

$|T_{DVCS}|^2$: $\propto E^2_{beam}$, ϕ dependence

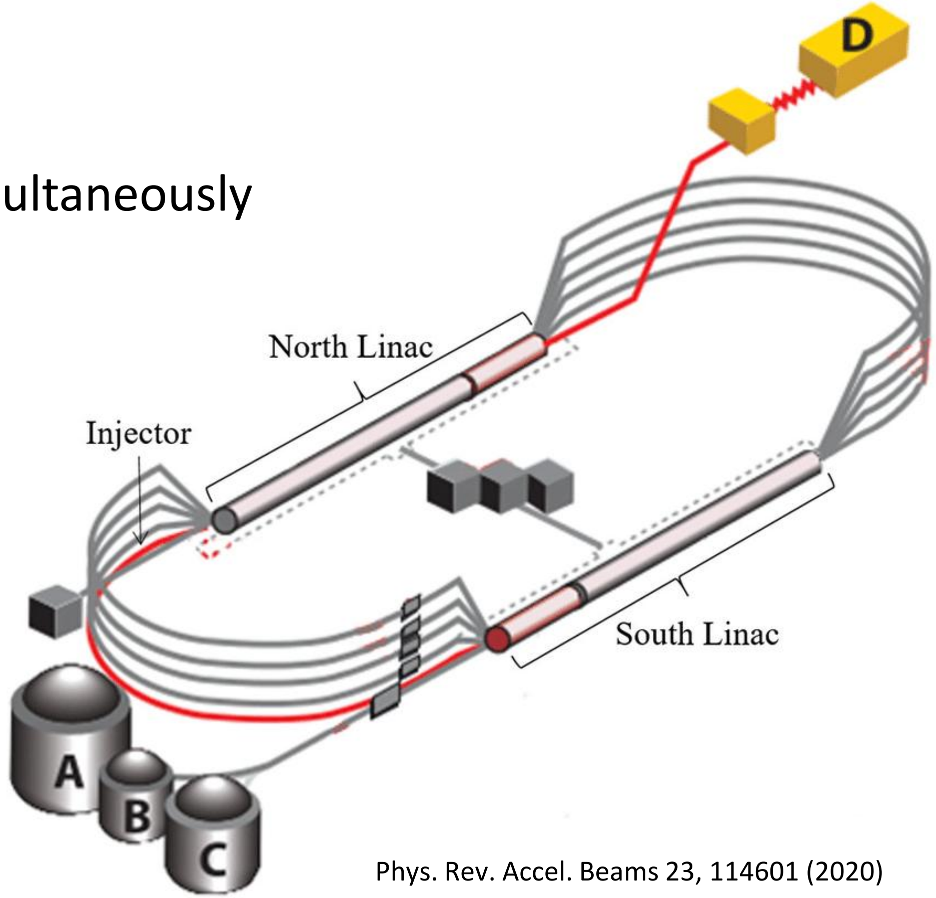
$\Re[I(BH \cdot DVCS)]$: $\propto E^3_{beam}$, ϕ dependence





Jefferson Lab

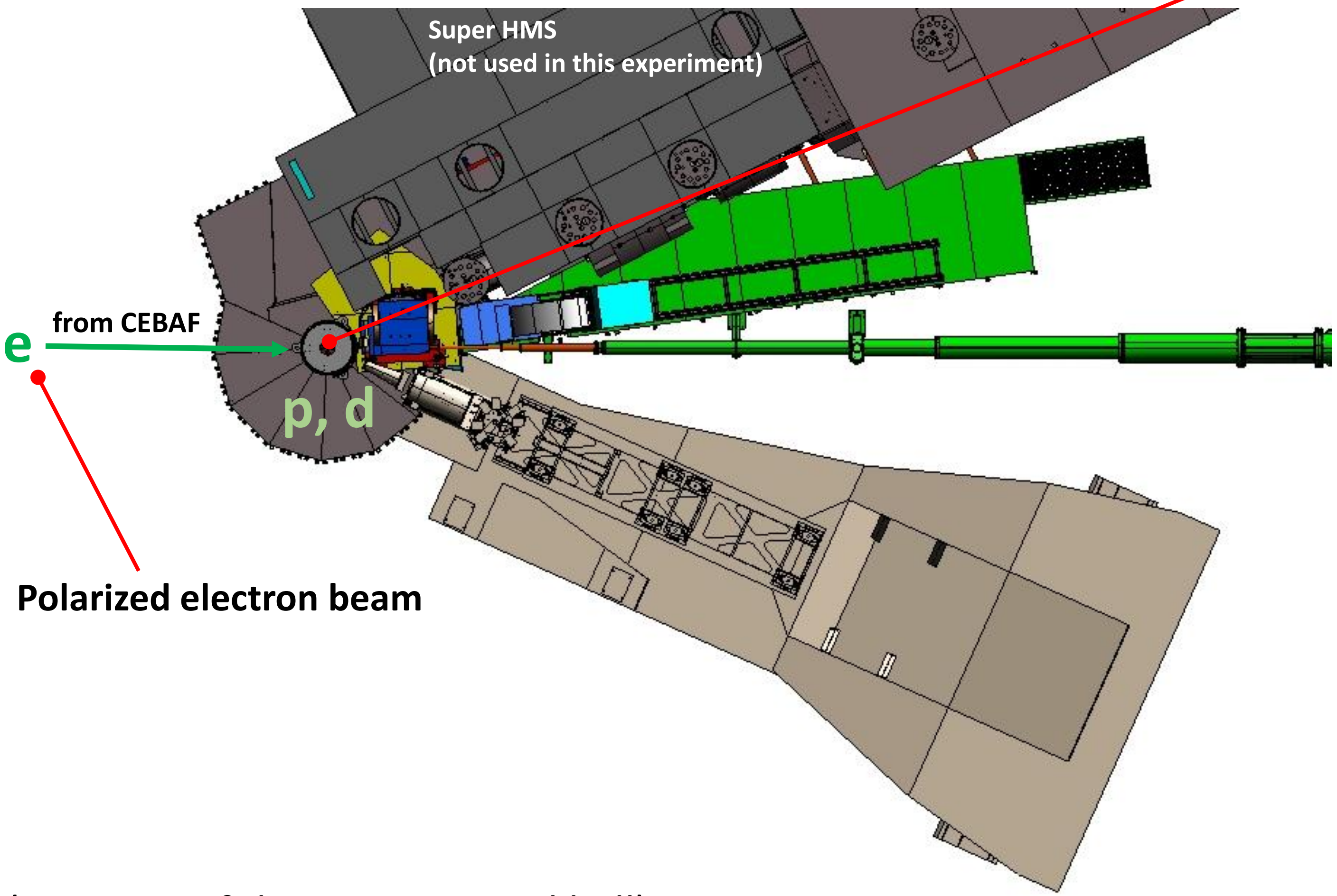
- Newport News, Virginia, USA
- Continuous Electron Beam Accelerator Facility (CEBAF)
  - Polarized electrons, up to 12 GeV
  - Delivers continuous beam to different Halls (A, B, C ,and D) simultaneously
  - Rich opportunities for nuclear physics



Phys. Rev. Accel. Beams 23, 114601 (2020)

DVCS experimental setup in Hall C

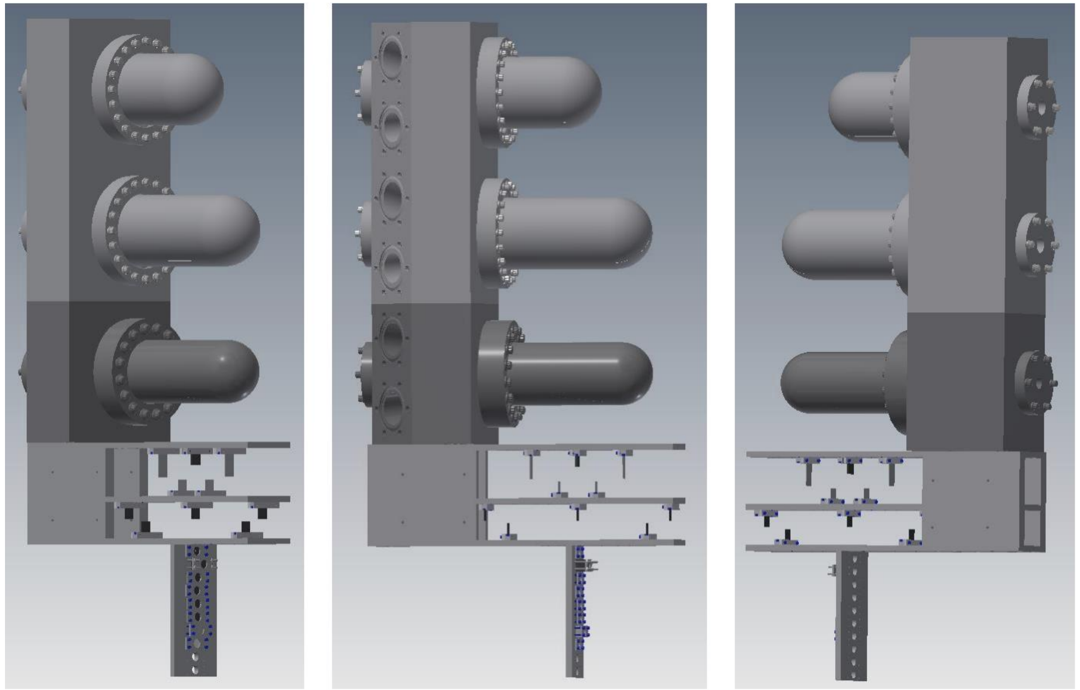
Run period: Sep. 2023 – May 2024



(Top view of the experimental hall)

Target chamber

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

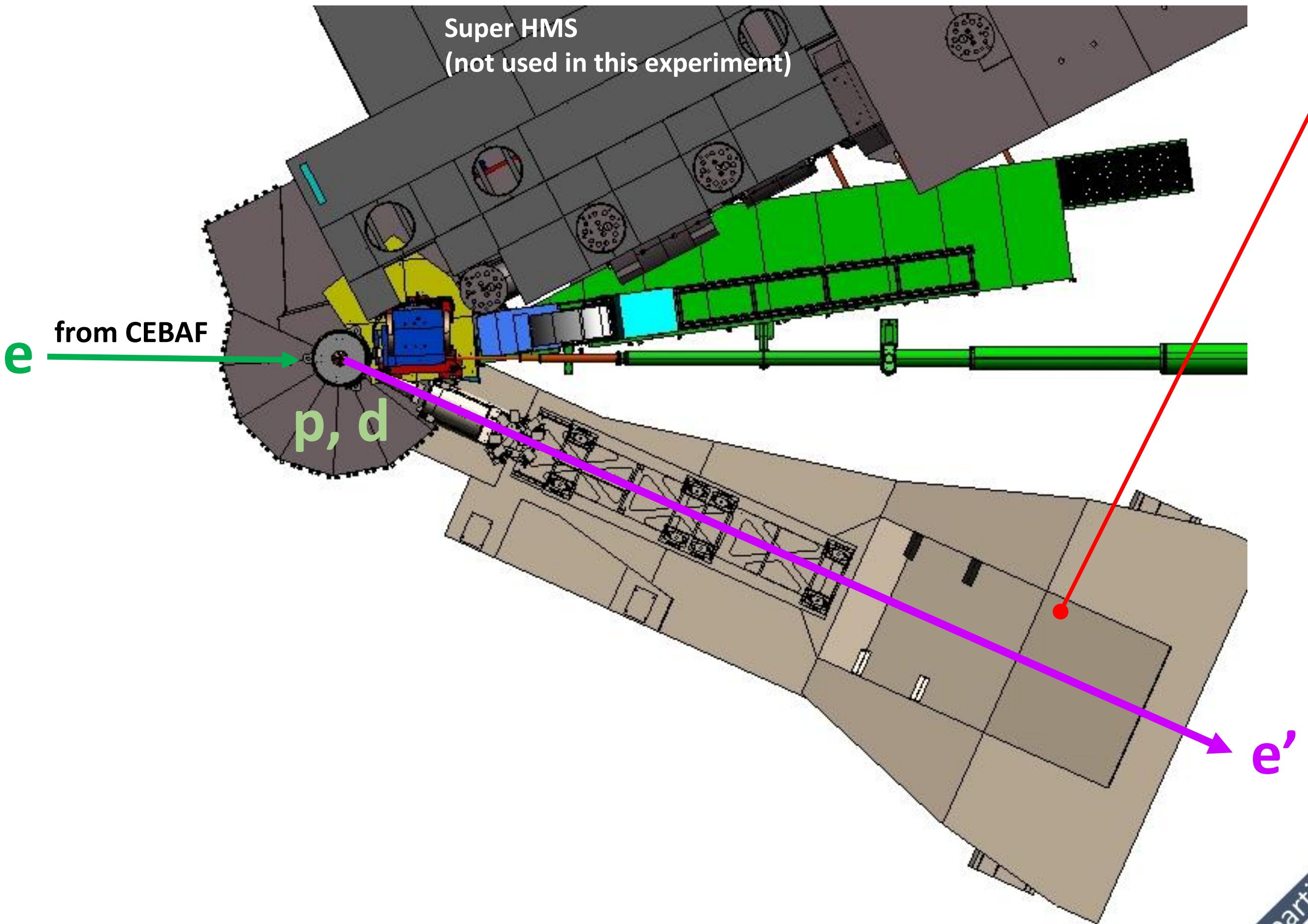


⬆ CAD views of the cryogenic and solid target ladders

Jefferson Lab Hall C Standard Equipment Manual

DVCS experimental setup in Hall C

Run period: Sep. 2023 – May 2024



(Top view of the experimental hall)

High Momentum Spectrometer (HMS)

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

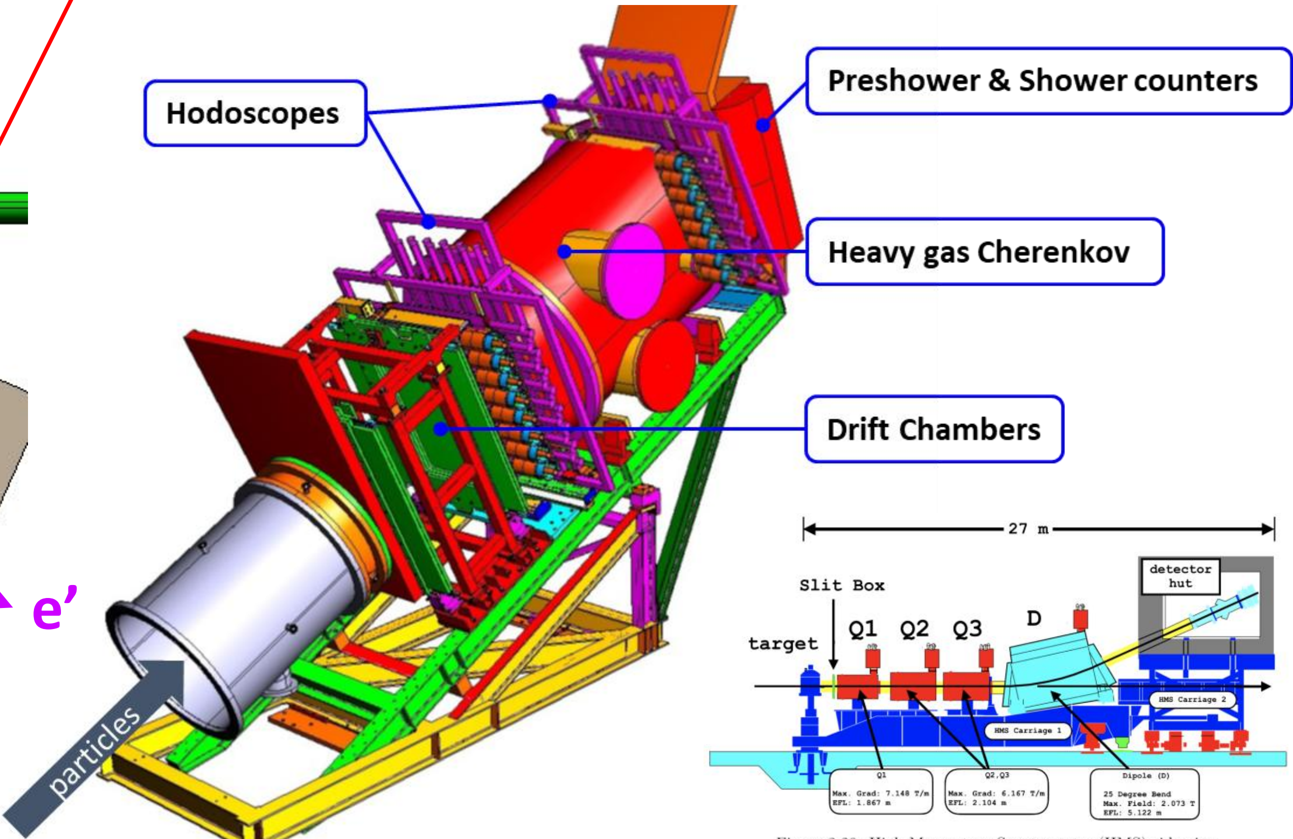


Figure 3.20: High Momentum Spectrometer (HMS) side view.

DVCS experimental setup in Hall C

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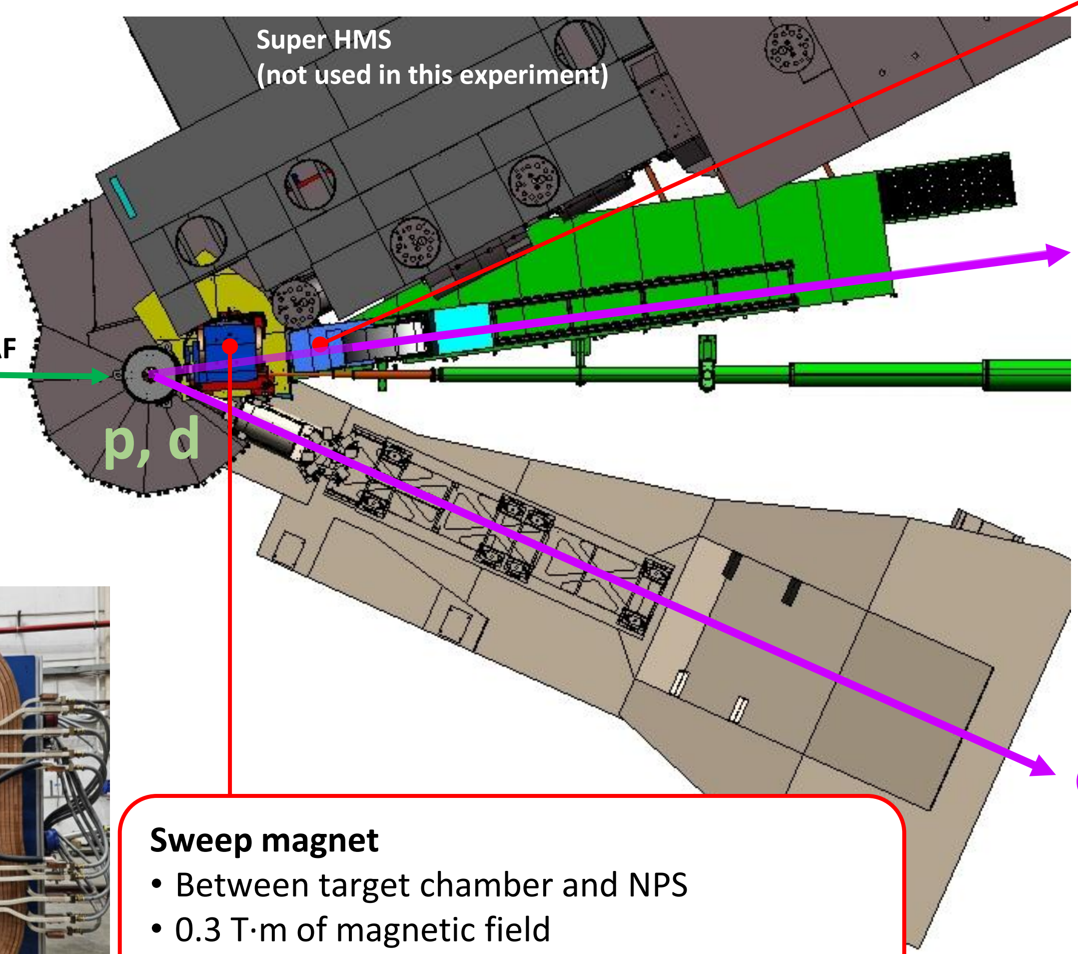
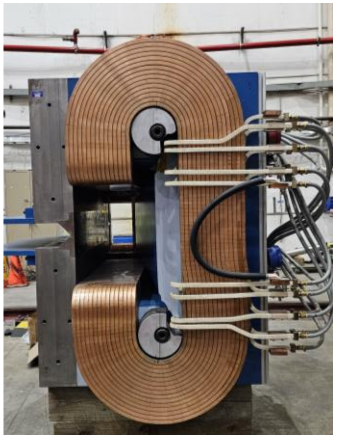
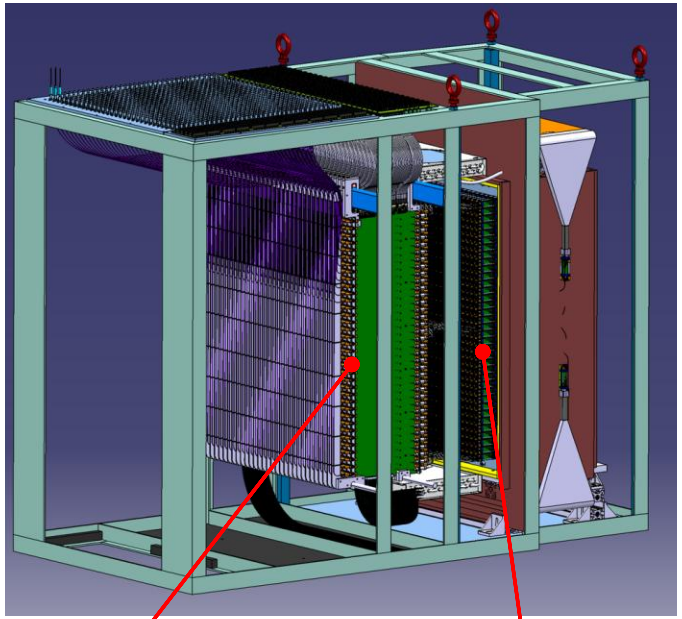




Sweep magnet
- Between target chamber and NPS
- 0.3 T·m of magnetic field
- Reduce the low energy background electrons

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

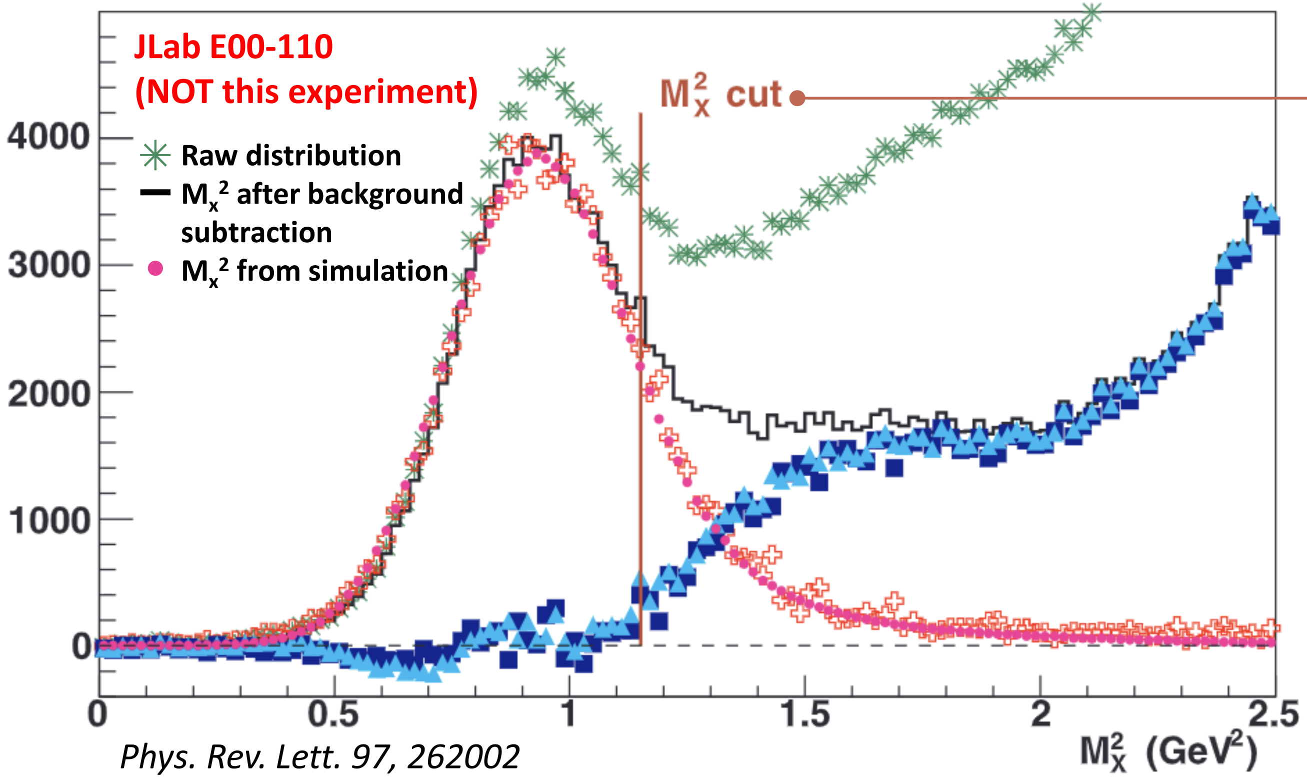
Photomultipliers (**PMTs**) and **HV divider base**

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

Method of DVCS signal extraction

- Missing mass square $M_x^2 = (k_e + P_p - k'_e - q_\gamma)^2$ of recoil proton (undetected)
- E_γ resolution in NPS is a key role for better signal–background separation
- NPS data to be analyzed and calibrated as refined as possible

DVCS signal extraction with Missing-mass method

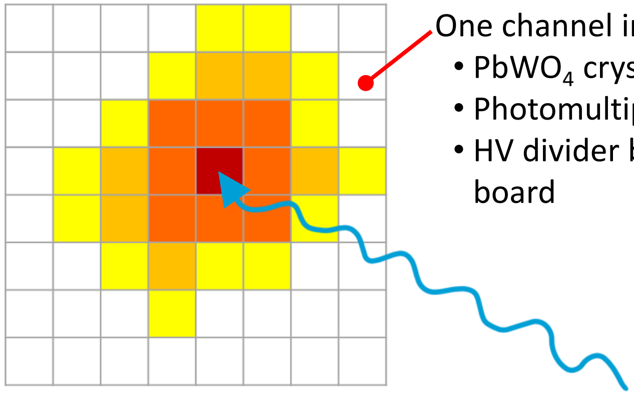


Phys. Rev. Lett. 97, 262002

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

Improving E_γ resolution: energy calibration

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



Cluster forms in the NPS when a particle is detected

- Calibration by optimizing the width of $\pi^0 \to \gamma\gamma$ peak

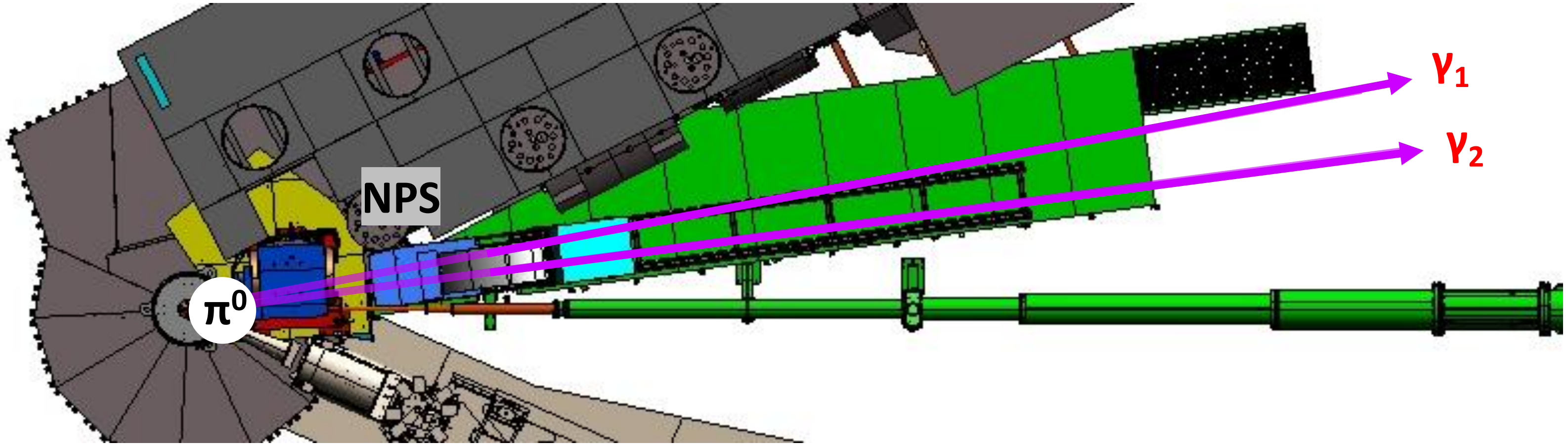
$$F = \underbrace{\sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)^2}_{\text{resolution term}} + \underbrace{2\lambda \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)}_{\text{constraint } \langle m_i^2 \rangle = m_0^2}$$

resolution term

constraint $\langle m_i^2 \rangle = m_0^2$

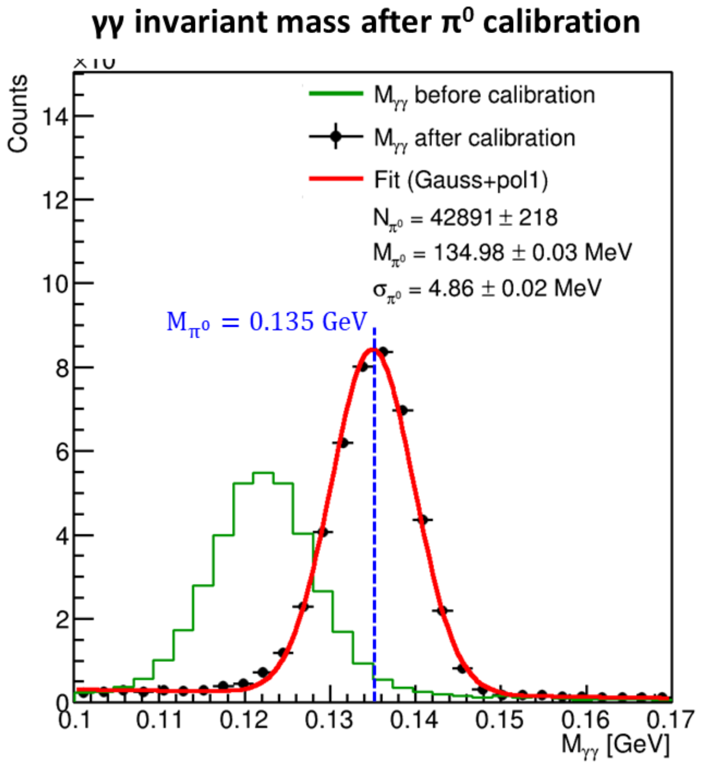
$m_0 = M_\pi = 0.1349766$ GeV
m_i: reconstructed $M_{\gamma\gamma}$
λ: Lagrange multiplier

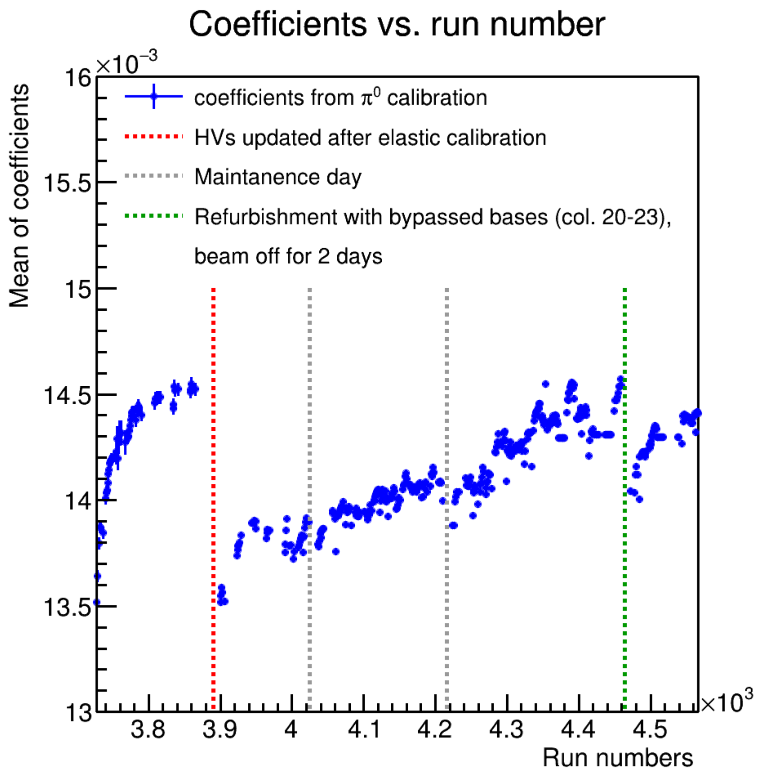
(Nuclear Instruments and Methods in Physics Research A 566 (2006) 366–374)



Online calibration results

- Reduced the width of π^0 invariant mass → better energy resolution
- Coefficients as a function of time
  - Increased due to the radiation damages
  - Decrease after updating high voltages or long time of beam OFF

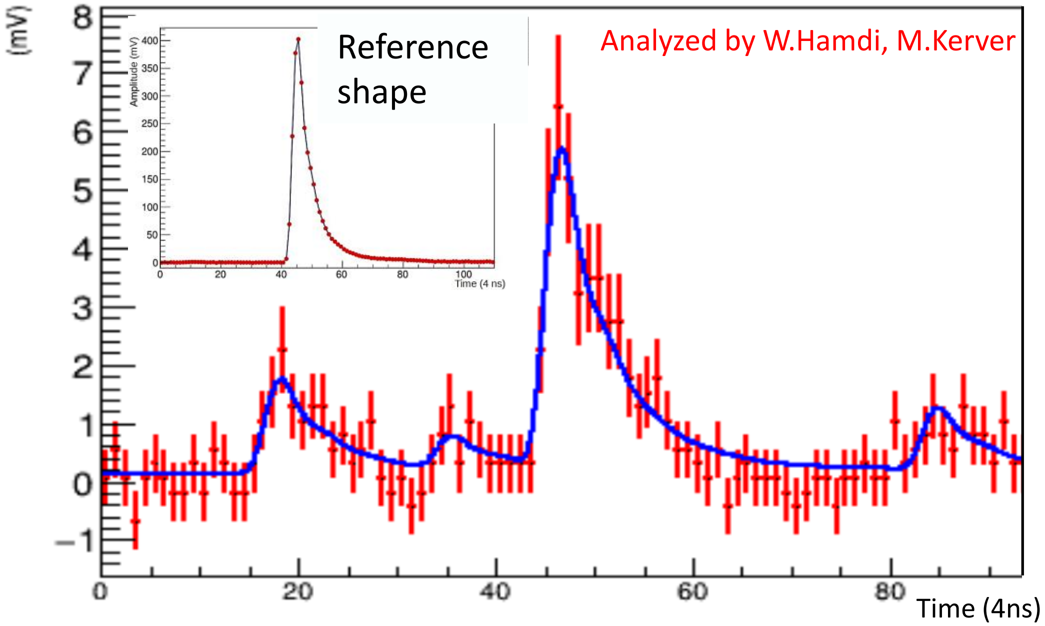




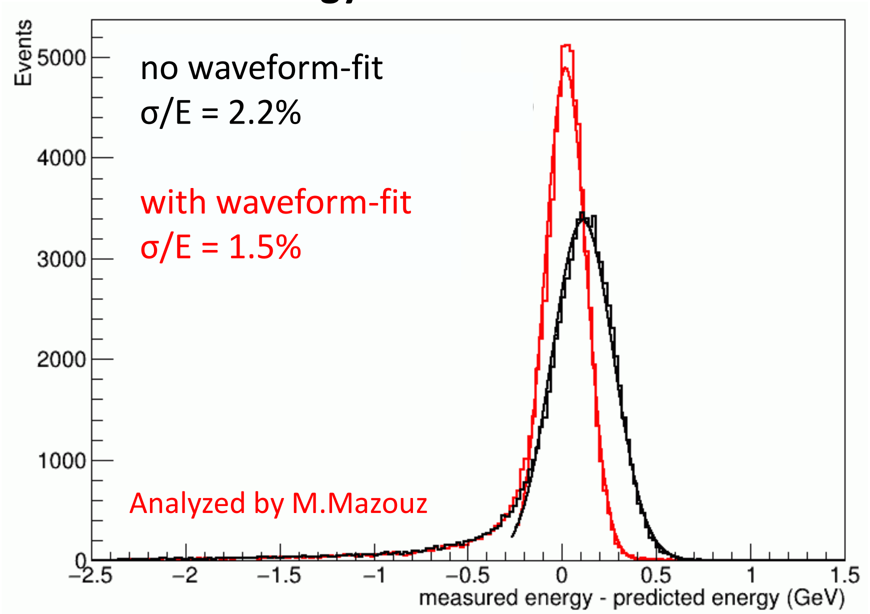
Improving E_γ resolution: waveform fit analysis

- Waveforms were readout for this purpose (each channel and each event!)
- Fitted using the reference shapes from elastic data
- More accurate amplitudes & timing of pulses are extracted
- Closed to expectation from simulation: $\sim 2\%/\sqrt{E} \oplus 1\% \sim 1.2\%$

Waveform fit using the reference shape



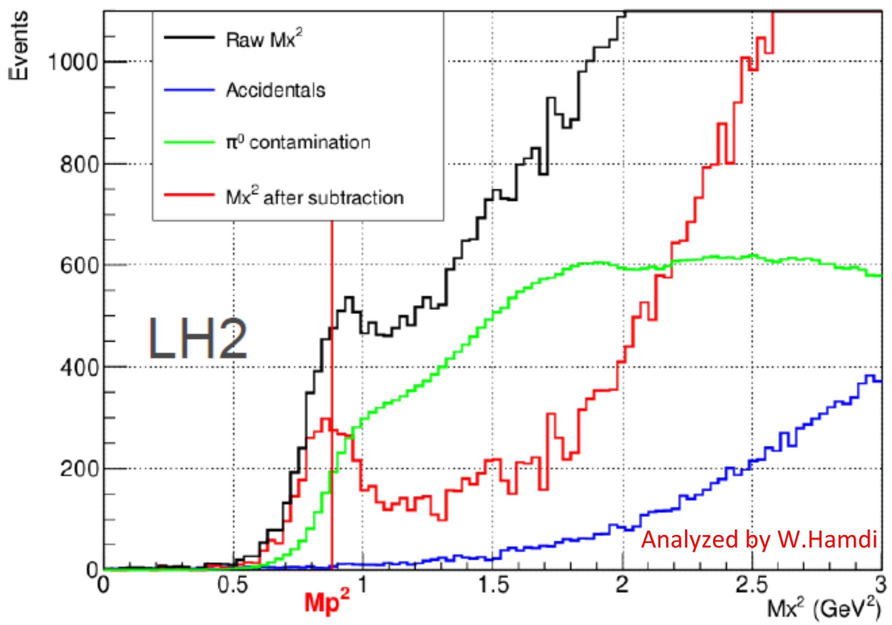
NPS energy resolution at 7.3 GeV

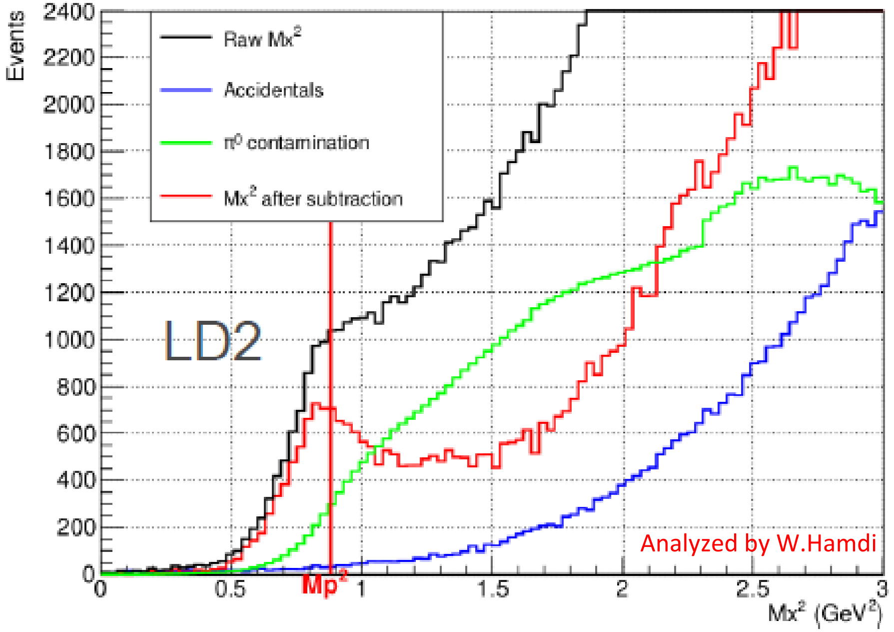


Online results of extracted DVCS events

- 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





- KinC_x60_3
- LH2: 5.19%
  LD2: 6.14%
  (of the data in this kinematics)

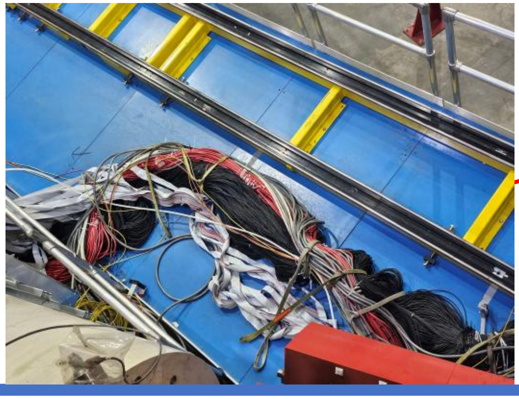
Summary and outlook

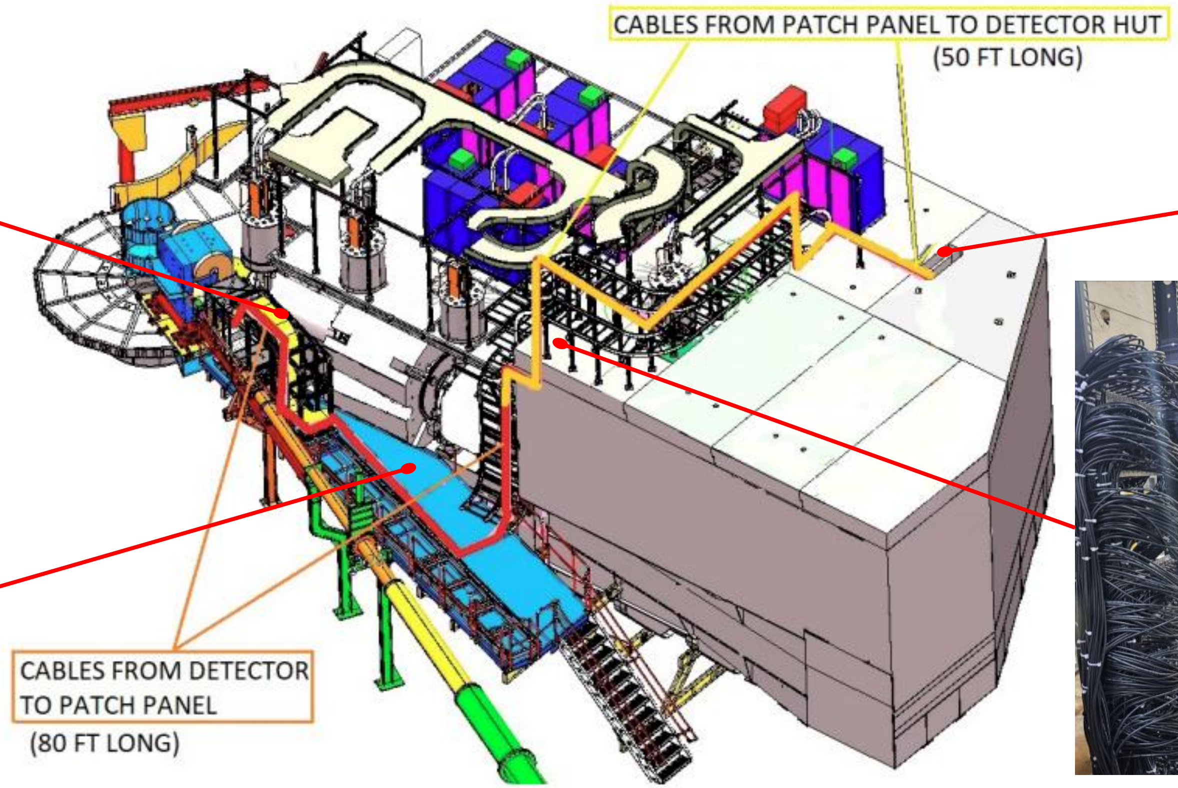
- The DVCS experiment in Hall C at JLab
  - The cleanest way for accessing GPDs
  - Sufficient kinematical coverage for DVCS-interference separation
- High energy resolution for DVCS photon reconstruction
  - New NPS calorimeter
  - Refined offline analysis & calibration
- Outlook
  - Beam and HMS calibration: finished
  - Waveform analysis + energy calibration: ongoing
  - Physics results: coming soon

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



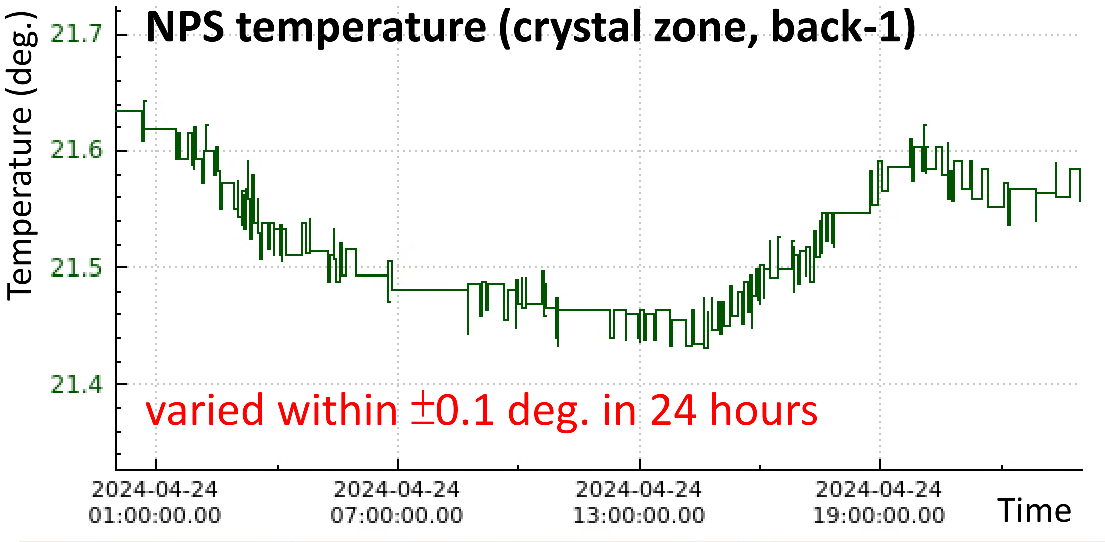


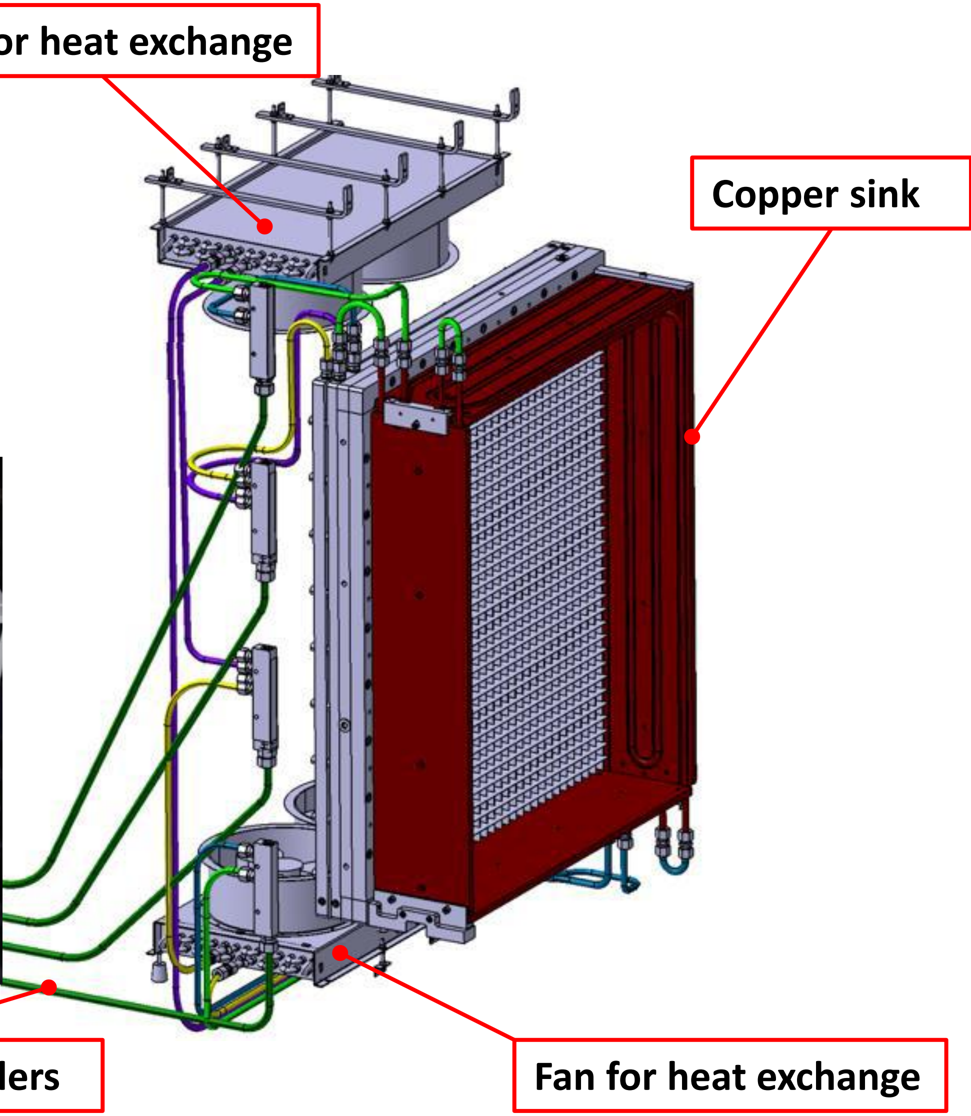
↑ In the detector hut

← The patch panel

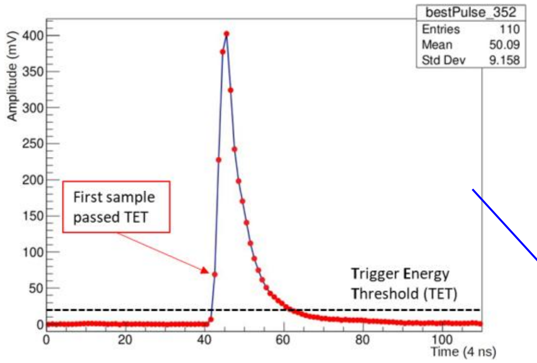
Temperature control system

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

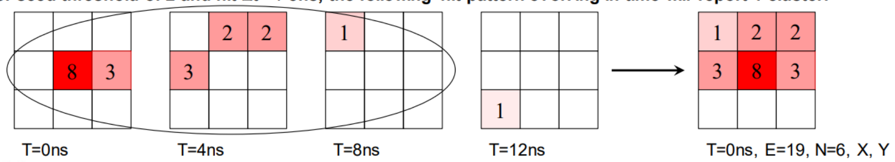




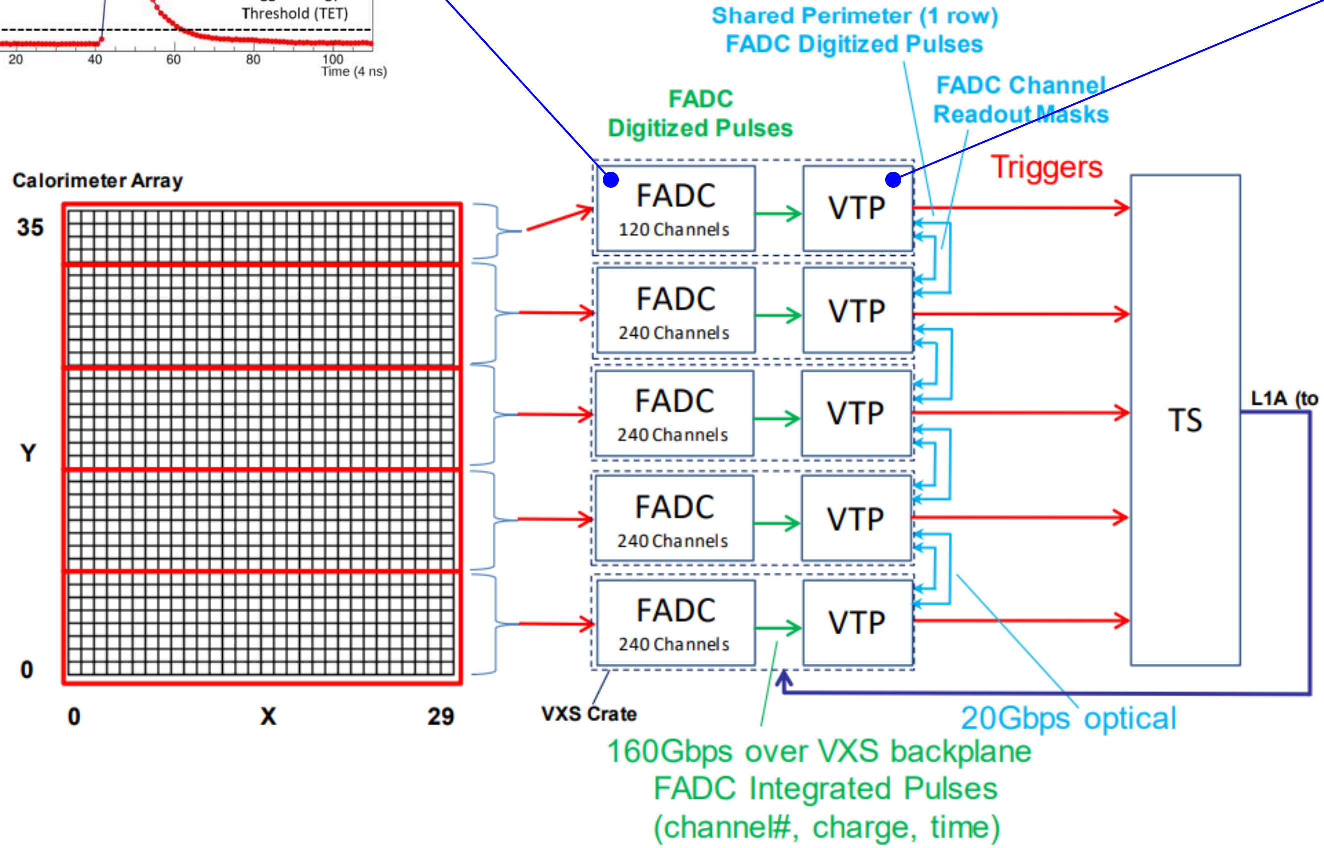
NPS Streaming Data Acquisition



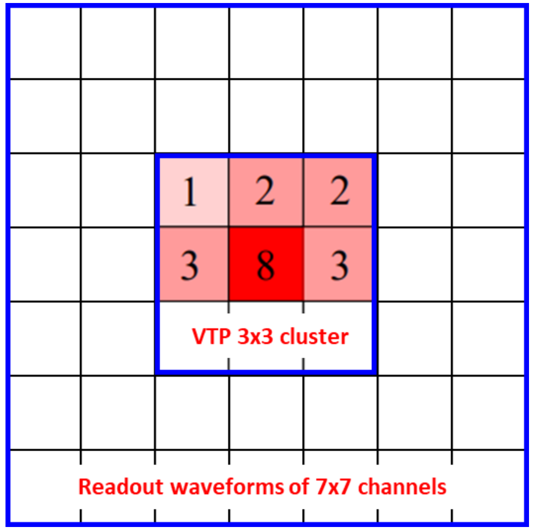
1. Waveform samples are digitalized by JLab developed flash Analog-to-digital converter (FADC)
2. Hits information are sent to VXS trigger processor (VTP) for triggers
3. VTP performs 3x3 clustering and trigger
   - Based on seed energy threshold and timing of hits



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

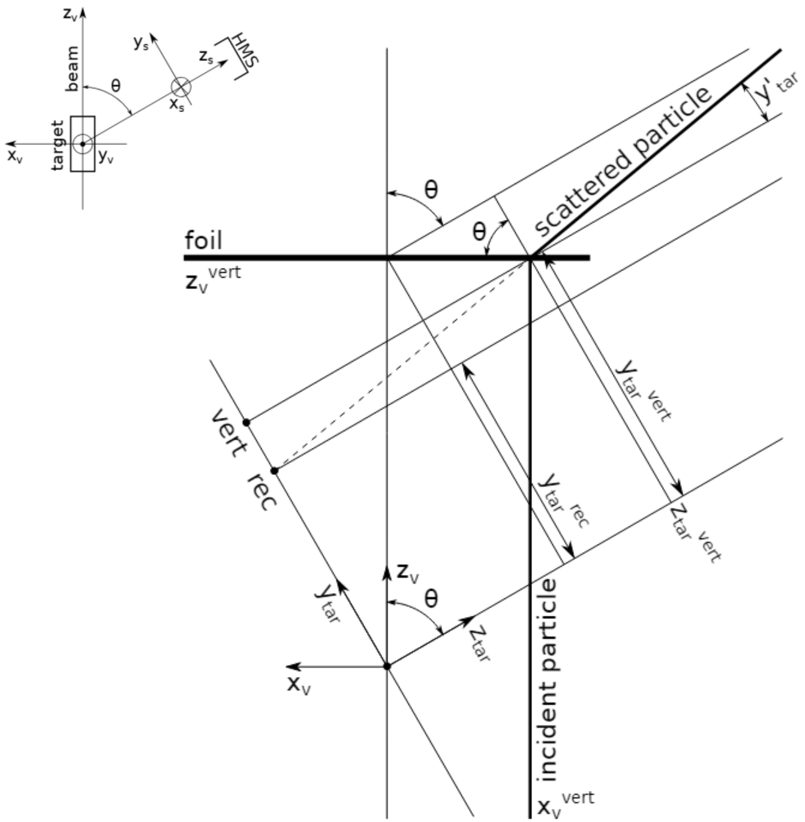


Figure 2: Detailed drawing of event coordinates. The subscript "v" denotes the vertex coordinate system while "tar" stands for target. The "vert" point marks the vertex projection of the interaction vertex onto the target coordinate system. On the other hand, the "rec" point is the reconstructed point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

$$x'_{\text{tar}} = \sum_{i,j,k,l,m} X'_{i,j,k,l,m} \cdot x^{i}_{\text{fp}}\, x'^{j}_{\text{fp}}\, y^{k}_{\text{fp}}\, y'^{l}_{\text{fp}}\, x^{m}_{\text{tar}} \tag{1a}$$

$$y^{\text{rec}}_{\text{tar}} = \sum_{i,j,k,l,m} Y_{i,j,k,l,m} \cdot x^{i}_{\text{fp}}\, x'^{j}_{\text{fp}}\, y^{k}_{\text{fp}}\, y'^{l}_{\text{fp}}\, x^{m}_{\text{tar}} \tag{1b}$$

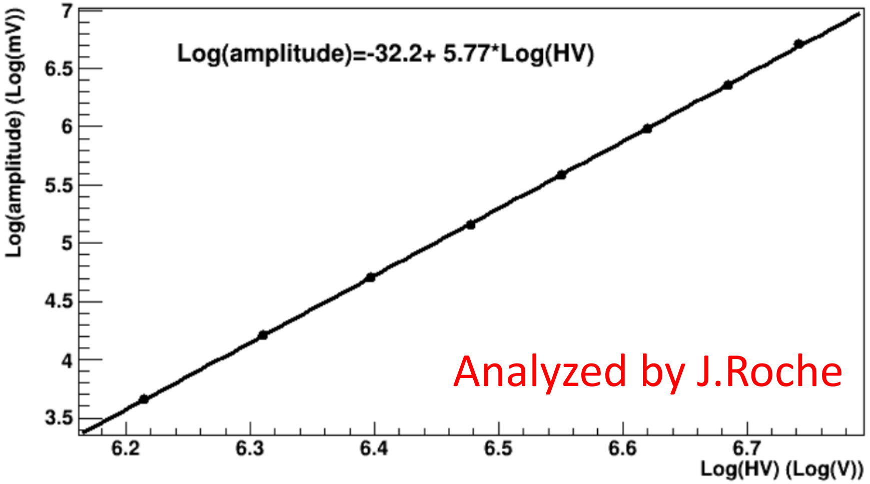
$$y'_{\text{tar}} = \sum_{i,j,k,l,m} Y'_{i,j,k,l,m} \cdot x^{i}_{\text{fp}}\, x'^{j}_{\text{fp}}\, y^{k}_{\text{fp}}\, y'^{l}_{\text{fp}}\, x^{m}_{\text{tar}} \tag{1c}$$

$$\delta_{\text{tar}} = \sum_{i,j,k,l,m} D_{i,j,k,l,m} \cdot x^{i}_{\text{fp}}\, x'^{j}_{\text{fp}}\, y^{k}_{\text{fp}}\, y'^{l}_{\text{fp}}\, x^{m}_{\text{tar}} \tag{1d}$$

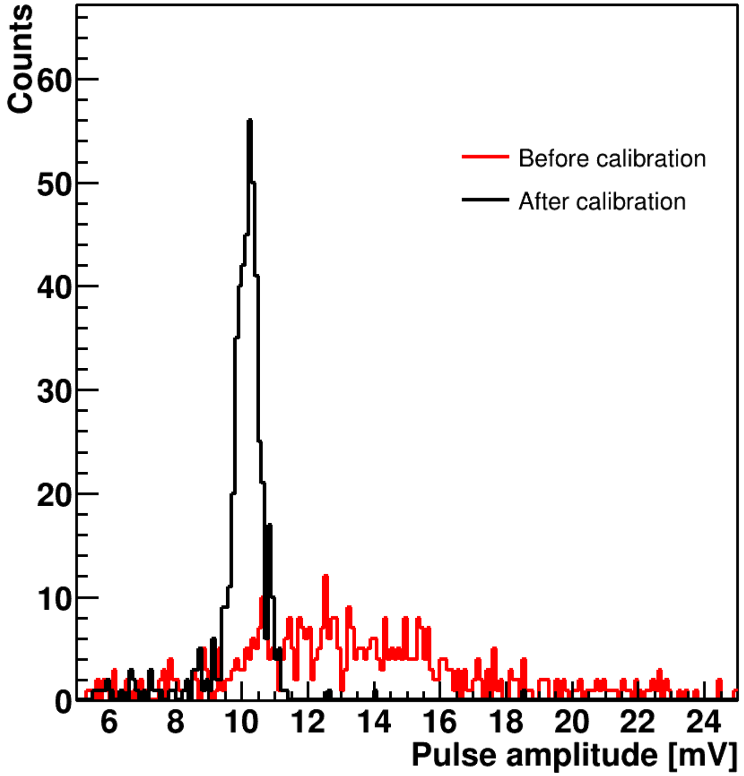
$$z^{\text{vert}}_{\text{v}} = \frac{y^{\text{rec}}_{\text{tar}} + x^{\text{beam}}\left(\cos(\theta) + y'_{\text{tar}} \sin(\theta)\right)}{\sin(\theta) - y'_{\text{tar}} \cos(\theta)}$$

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
  - $Amp. = \alpha \times HV^{\beta}$
  - $new\ HV = old\ HV \times \left(\frac{new\ Amp.}{old\ Amp.}\right)^{\frac{1}{\beta}}$
  - β = 5.77
  - New amplitudes are set to 10 mV



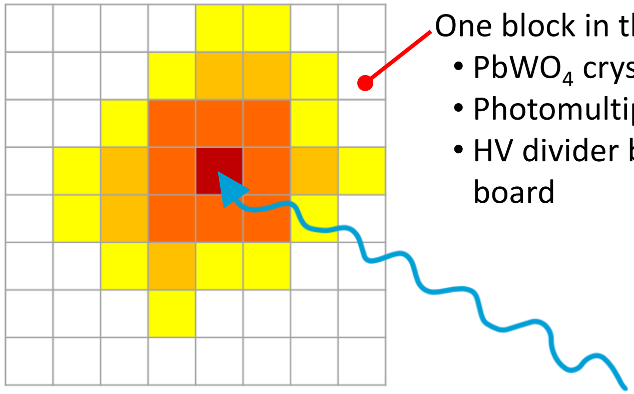
Amplitudes before & after calibration



Energy calibration for NPS using elastic events

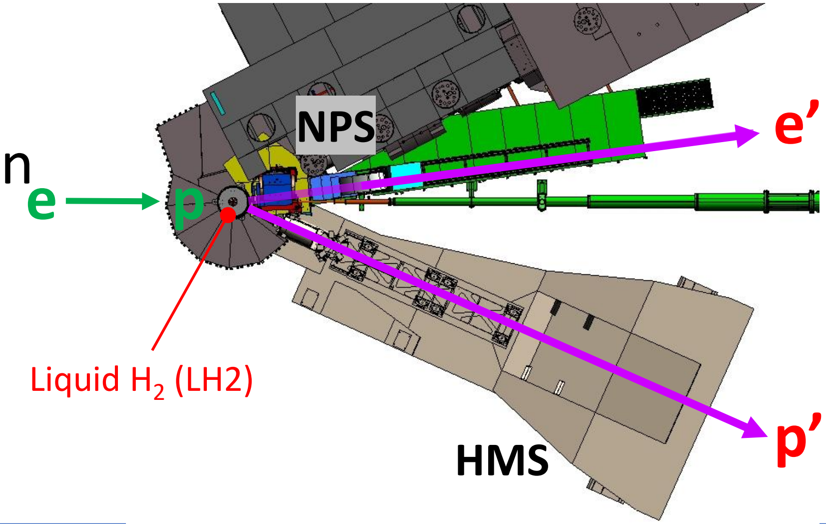
- Measured energy of a particle in the NPS: $E_{cluster}^{NPS} = \sum_j C_j A_j$
  - j: blocks in the cluster
  - A: amplitude measured in the block [mV]
  - C: calibration coefficient, convert amplitude to energy [GeV/mV]
- The amplitude is controlled by the HVs: $A_j = \alpha \times HV_j^{\beta}$

α, β: constant from gain curve of PMTs



Cluster forms in the NPS when a particle is detected

- 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)



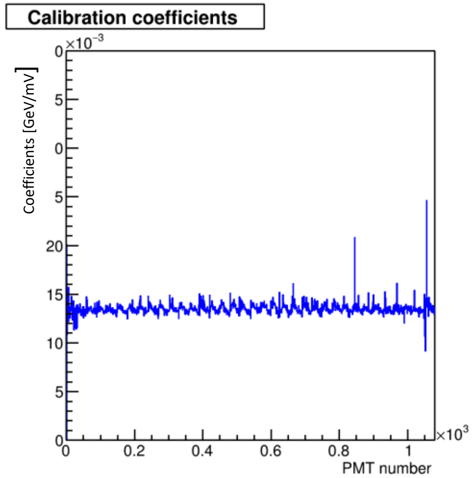
Calibration coefficients and new HV setting

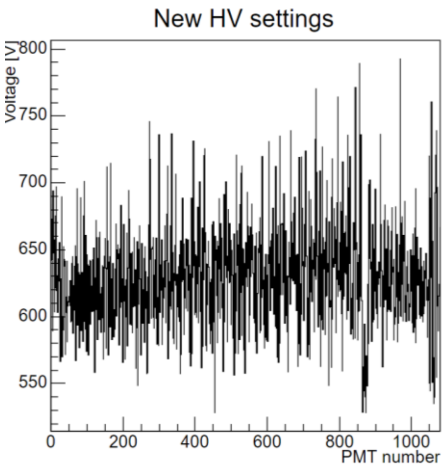
- Linear equations of 1080 crystals are used for the minimization:
  - According to energy conservation, the energy E_i of scattered electron in event i is:

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

    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

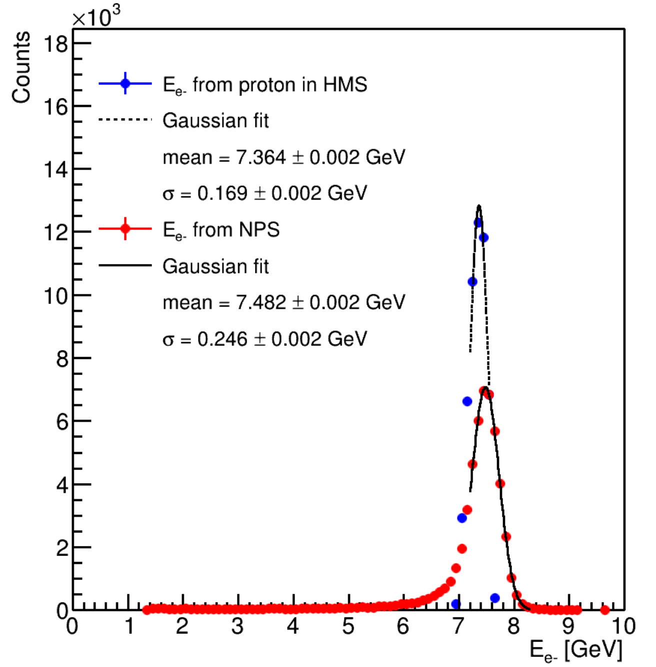
    we can build $\chi^2 = \Sigma_i (E_i - \Sigma_j C_j A_j^i)^2$
  - The calibration coefficient C_j can be calculated by minimizing the χ^2:





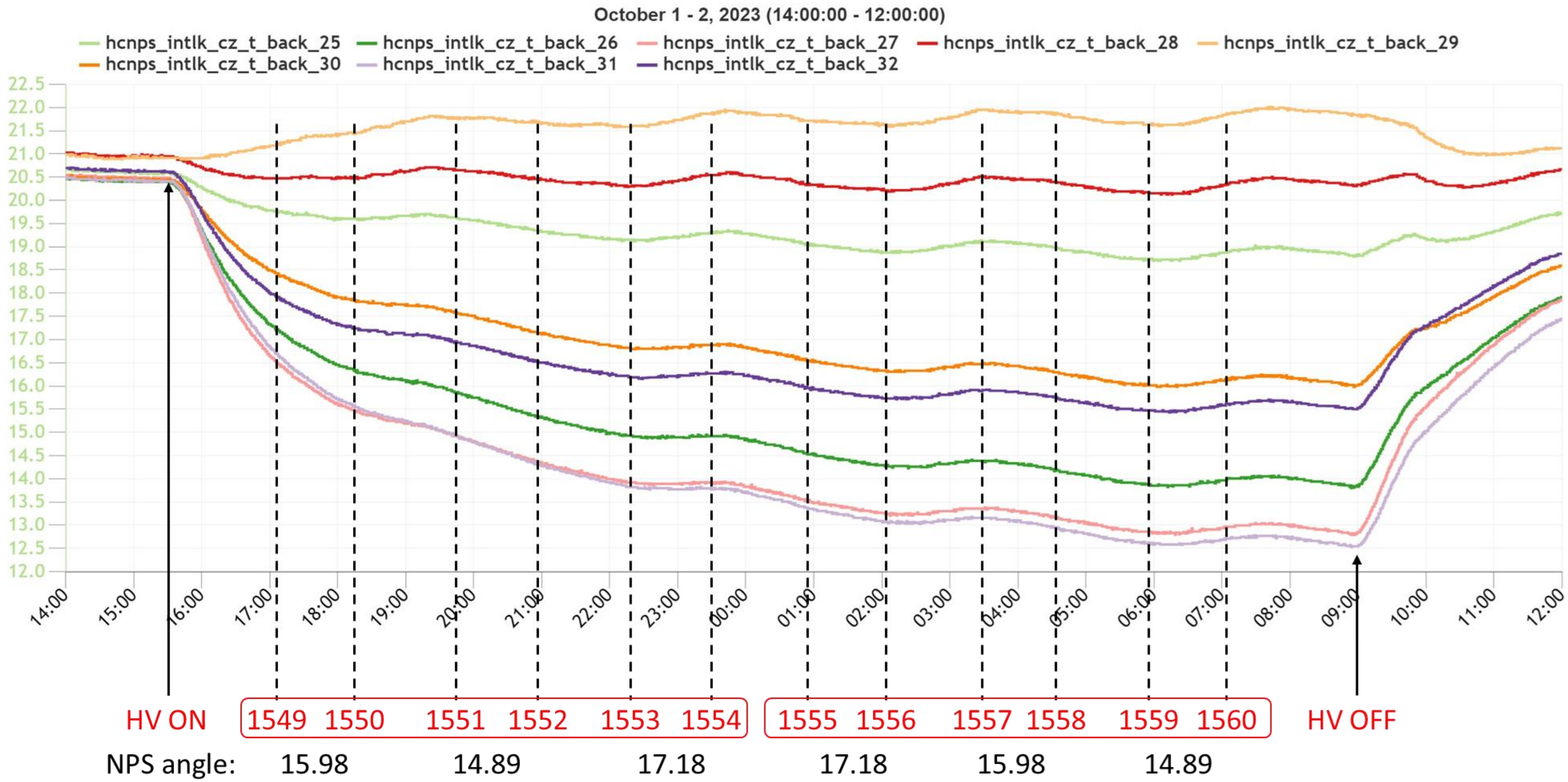
- High voltage (HV) of PMTs are adjusted to have 600 mV of amplitudes for DVCS photon (coefficients after calibration ~ 0.013)
- Based on the gain curve and their calibration coefficients

Electron energy (Predicted and measured)



Effects of temperature on elastic calibration

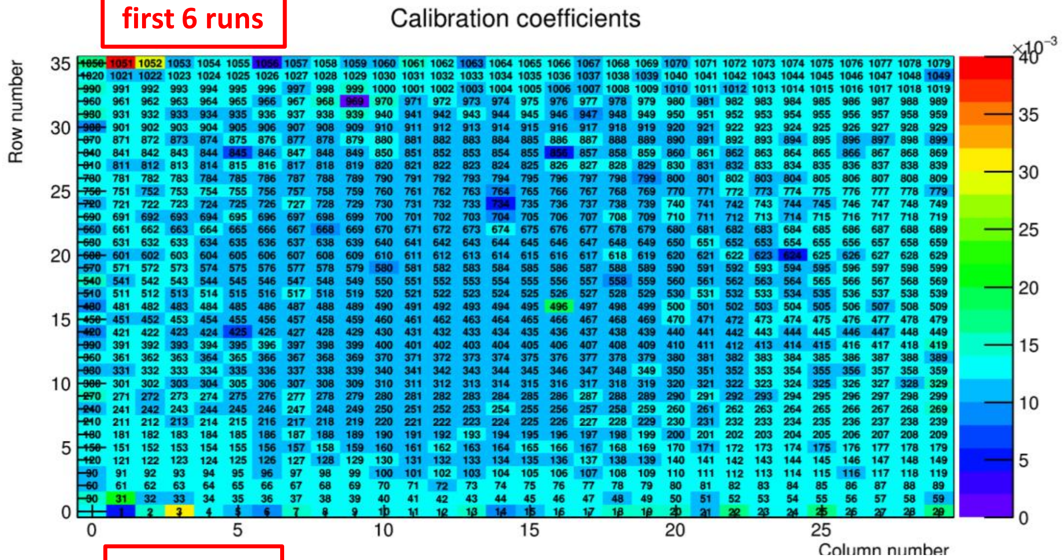
Thermal sensor at middle column (back 25-32)



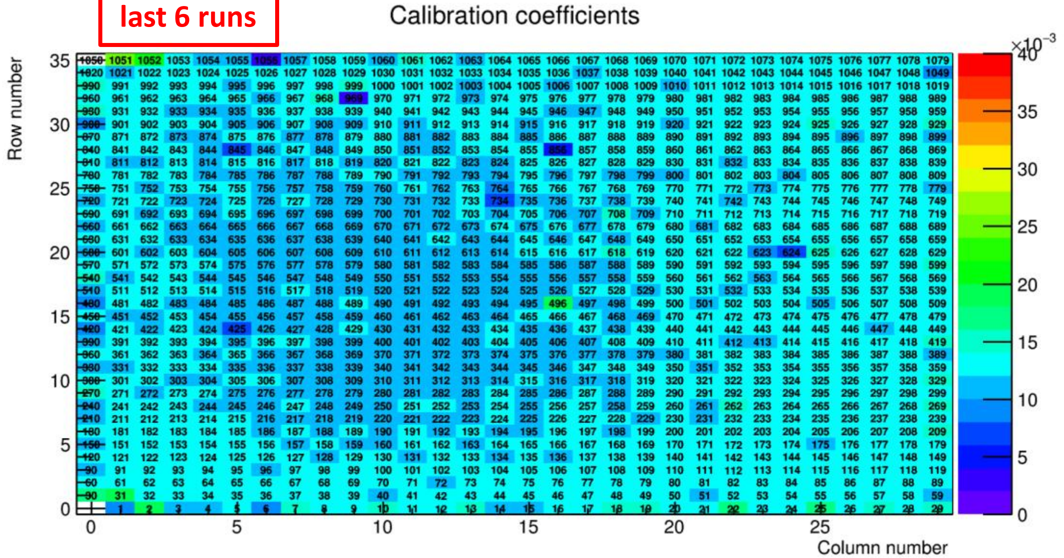
- Data from EPICS
- Reversed values due to the reversed wire connection (Fixed by Josh closed to the end of the experiment)

Results of calibration associated with temperature

first 6 runs



last 6 runs



- 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:

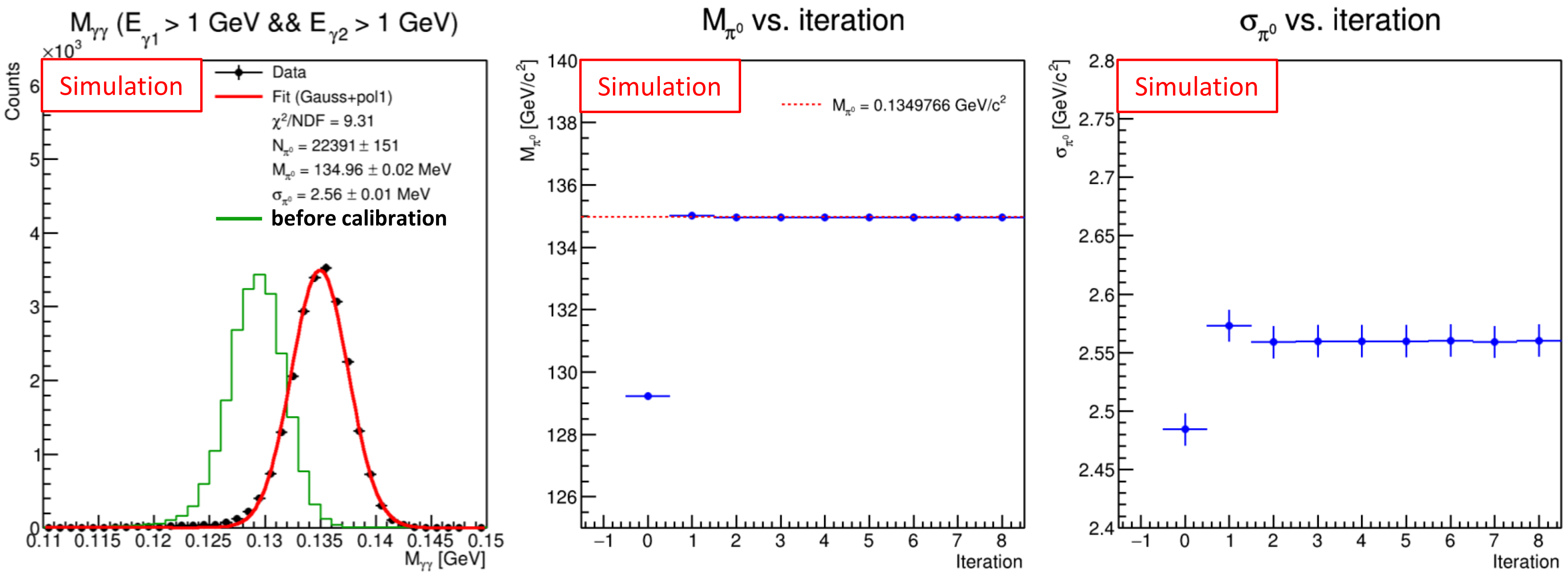
$$F = \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)^2 + 2\lambda \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)$$

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



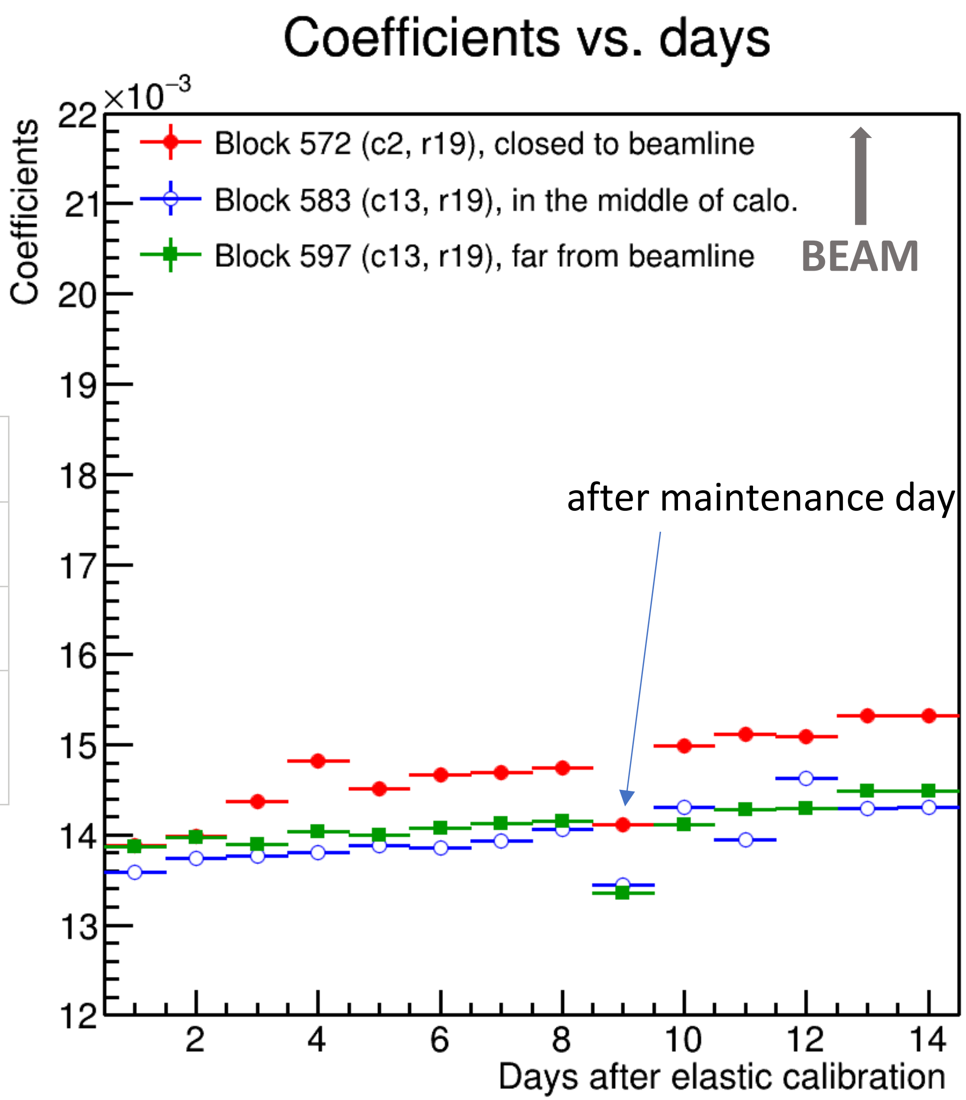
- Simulation of $\pi^0 \rightarrow \gamma\gamma$ using Geant4
- Very good performance of the calibration scripts
- Mean and width are converged in few iterations

Comparison between different blocks

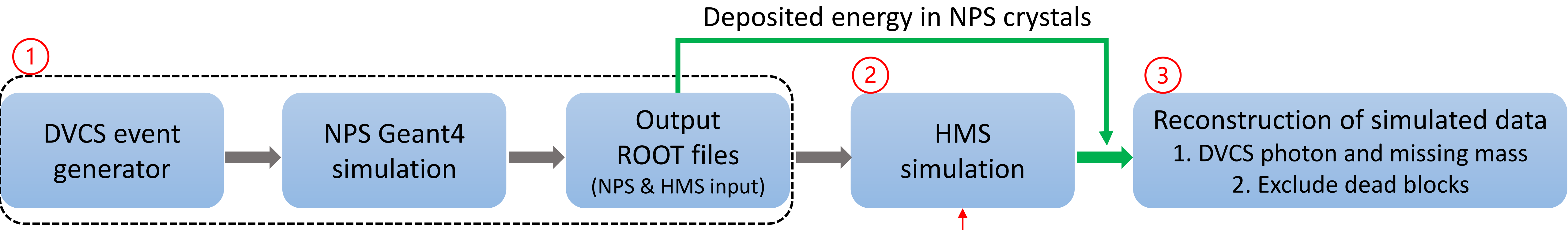
- Average of coefficients at the edge and in the middle of NPS
- Coefficients of blocks closed to the beamline were increased more than the others as we expected

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)

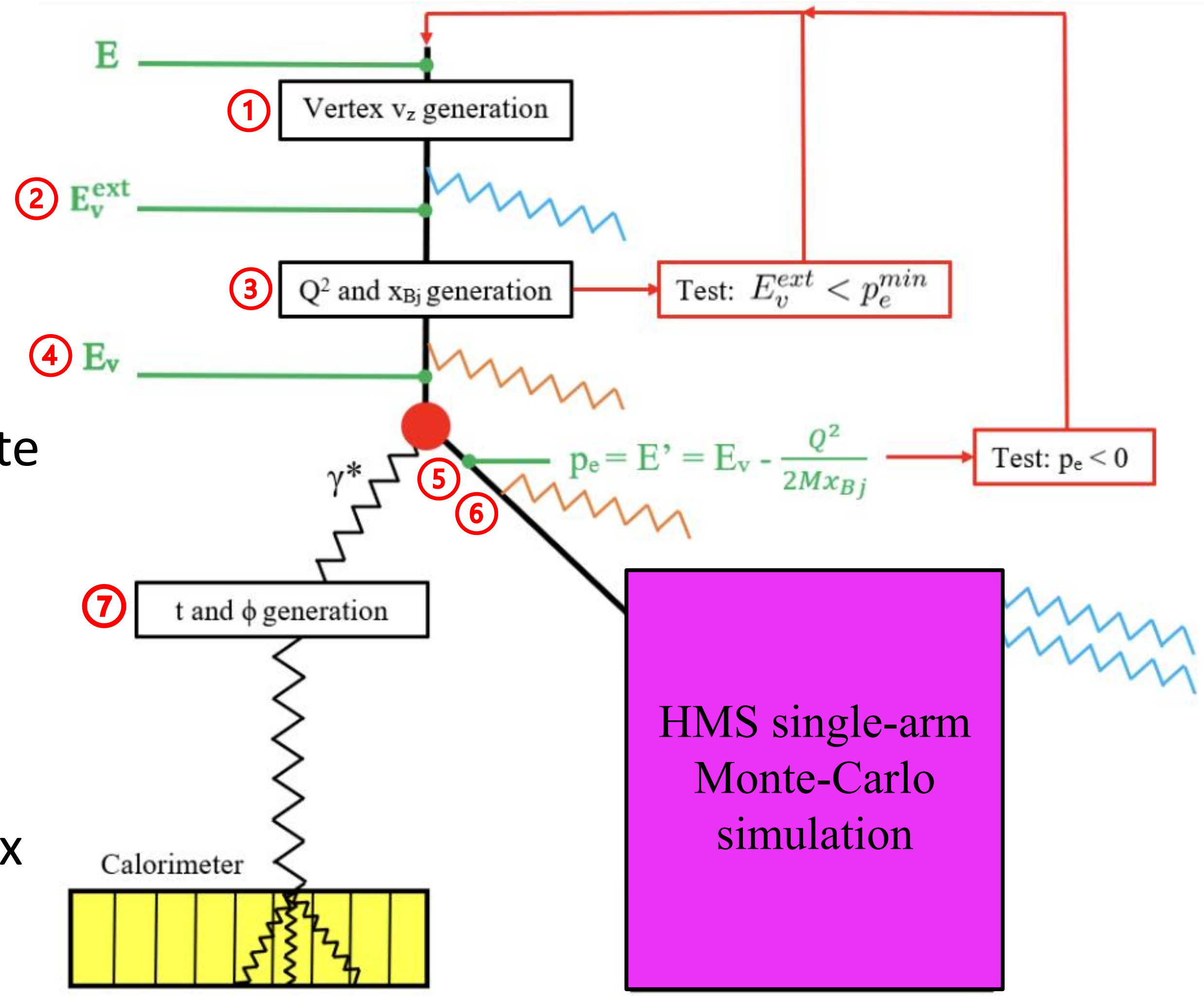
- HMS single arm Monte-Carlo
- Input variables
  - Generated vertices & scattered electrons
  - HMS angle & central momenta
- Output variables
  - HMS focal plane variables for vertex reconstruction
  - Reconstructed scattered electrons

Reconstruction

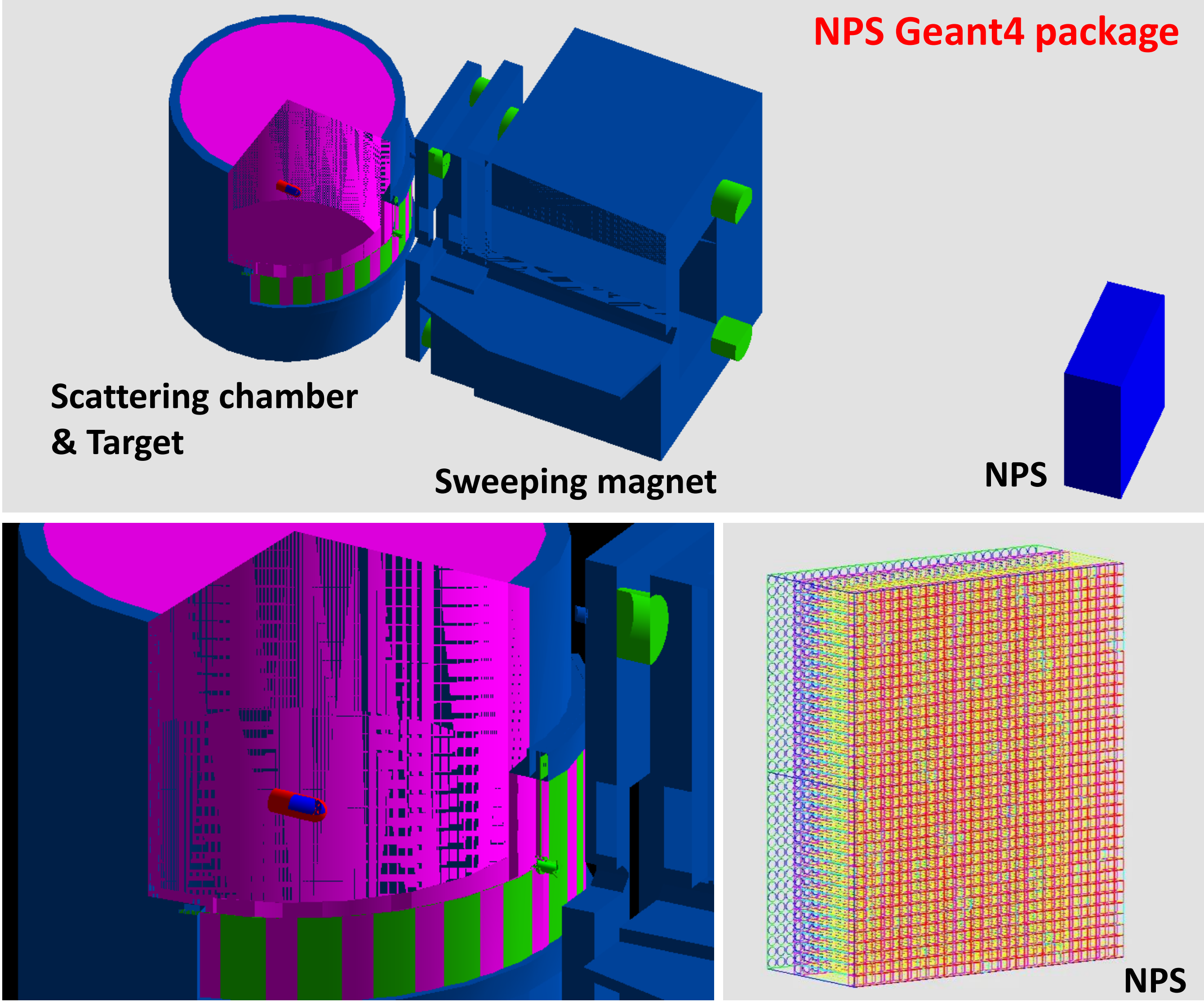
- Output reconstructed variables
  - NPS Cluster information
  - DVCS real photons
  - Q^2, x_B, t, ϕ

Event generator workflow

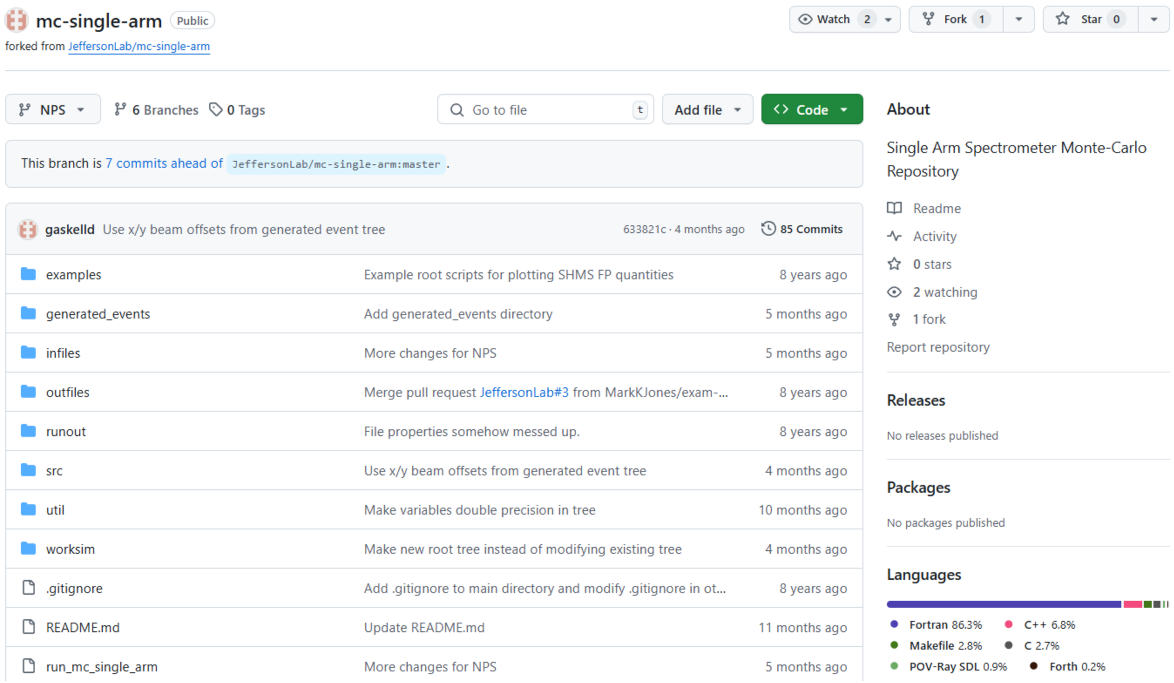
1. Generate the vertex position
   (uniformly along z with beam offset and raster)
2. Apply the external radiation correction
   before vertex ($E \longrightarrow E_v^{ext}$)
3. Generate Q^2 and x_B uniformly
   (within $[Q^2_{min}, Q^2_{max}]$ and $[x_B^{min}, x_B^{max}]$)
4. Apply the internal radiative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



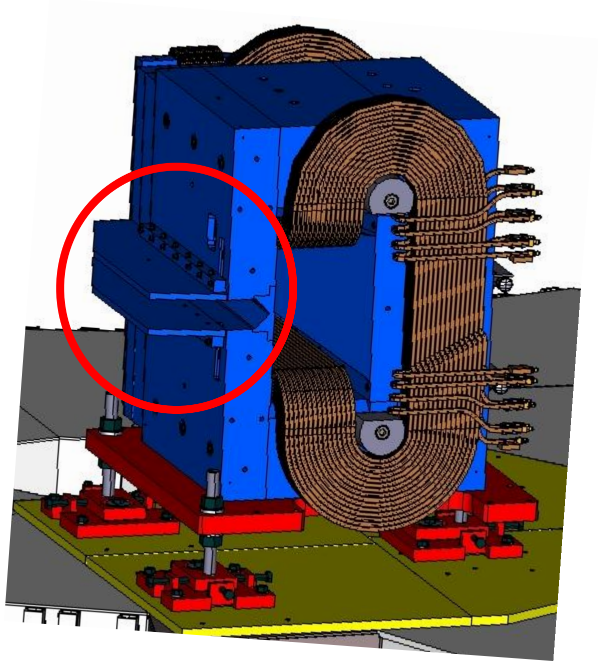
Simulation packages

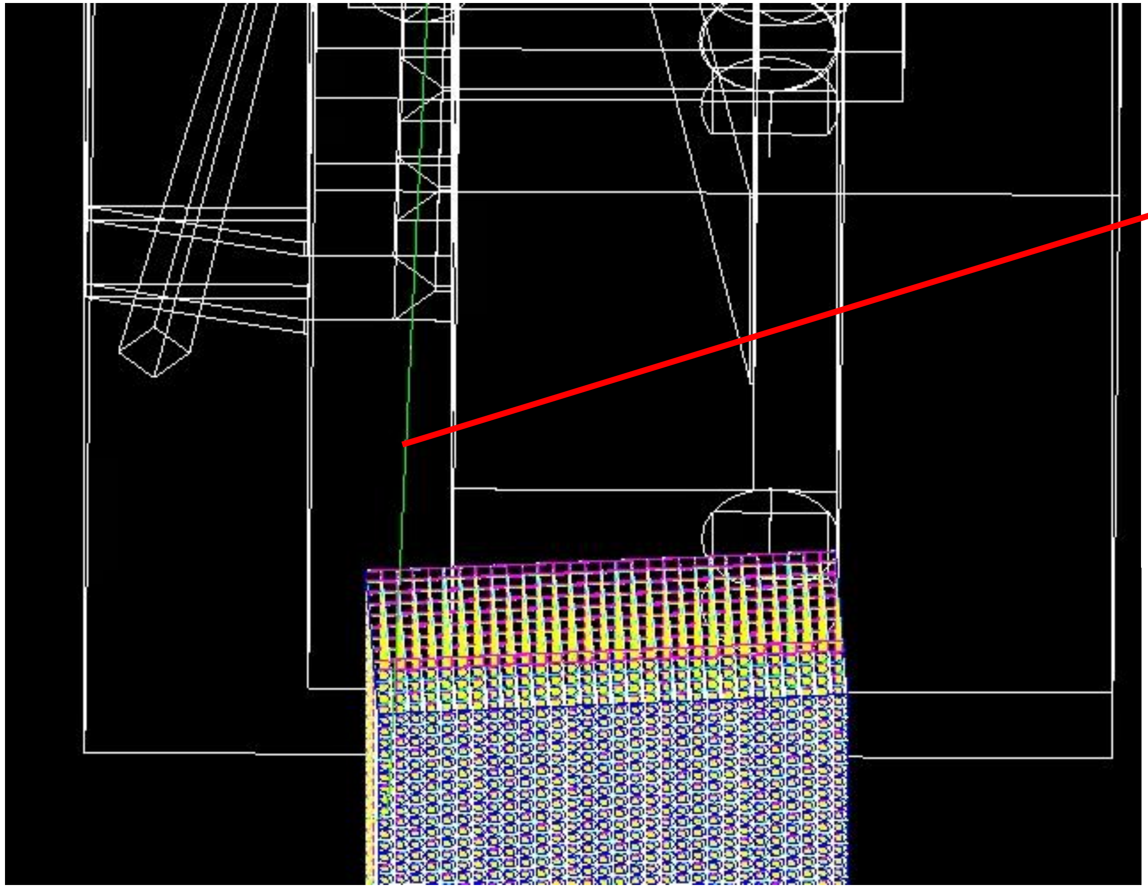


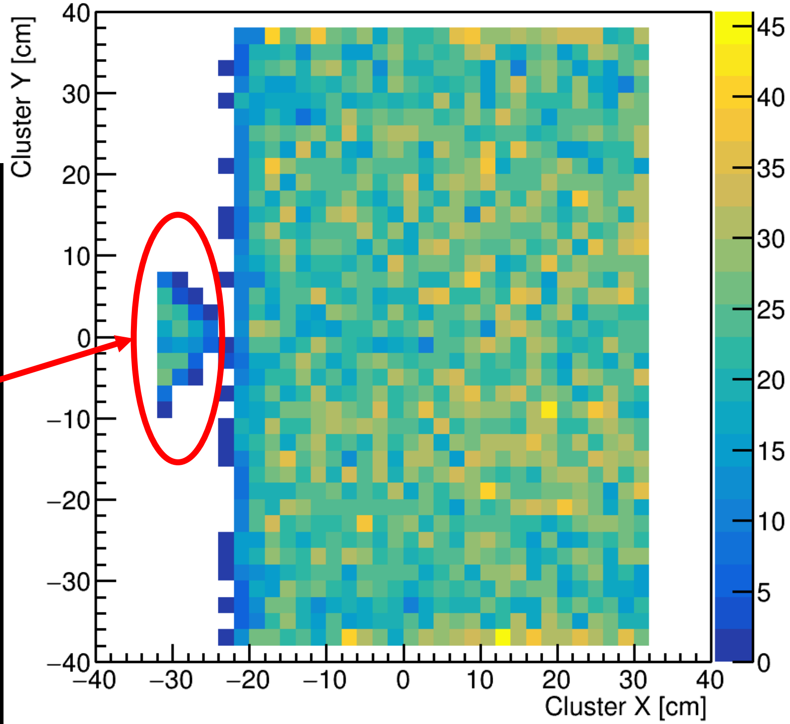
HMS single arm Monte-Carlo package



Additional clusters around x = -30 cm in simulation



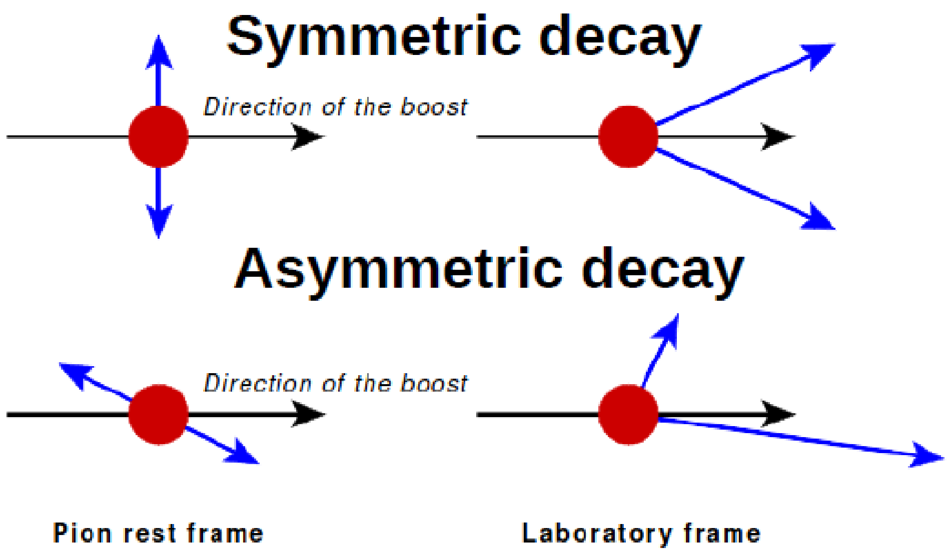




DVCS Analysis
(Pi0 Contamination)

Method:

- 3 Main criteria for the π0 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 π0 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

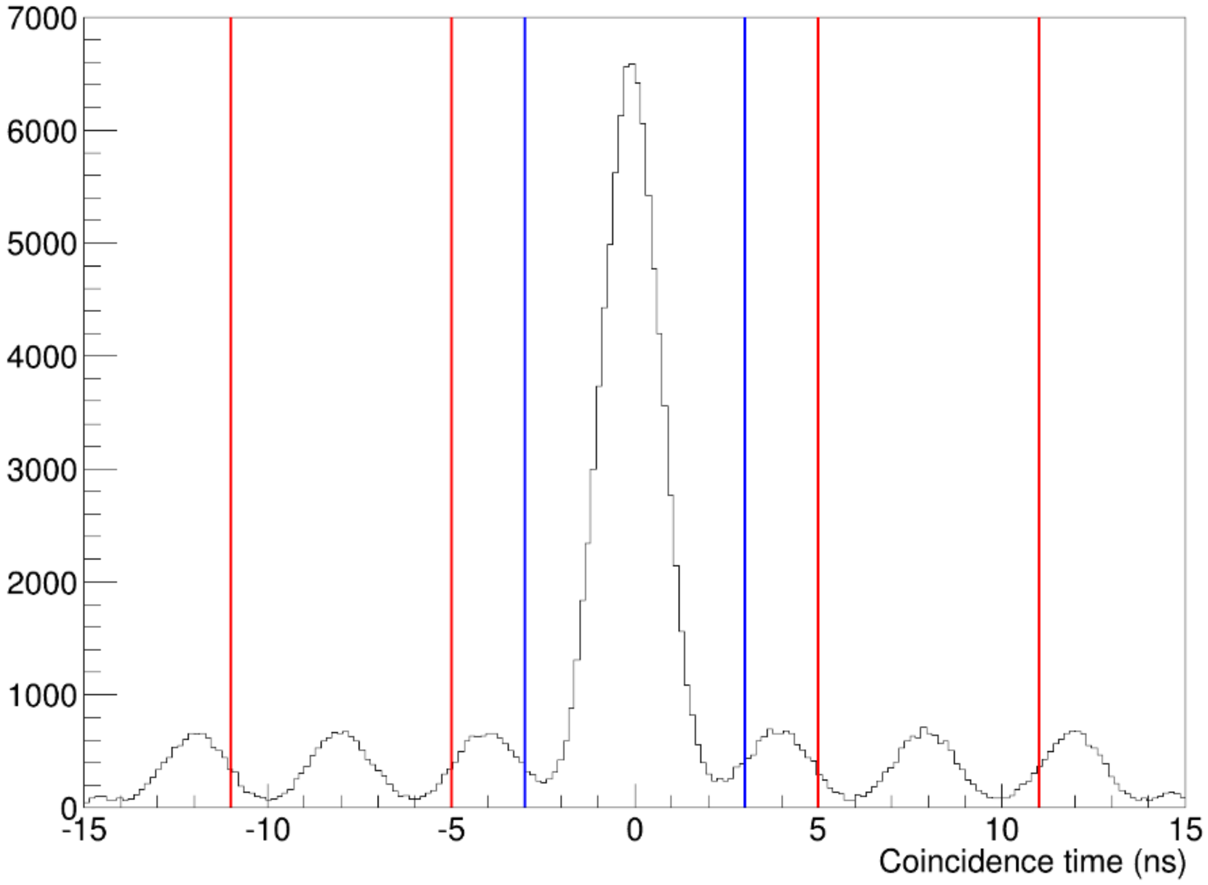


Figure 4.15: Coincidence time spectrum for kin48_4. The main coincidence time window [−3 ns, 3 ns] is delimited by the blue lines. The accidental events subtraction windows [−11 ns, −5 ns] and [5 ns, 11 ns] are located between the red lines. They are shifted by 8 ns with respect to the main coincidence 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⟩