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

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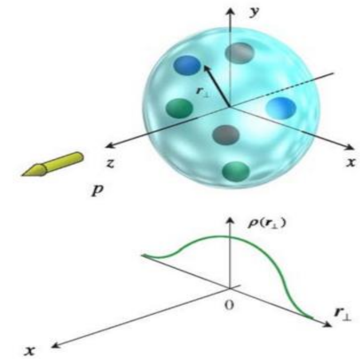
Outline

- Motivation and introduction
- Experimental setup
- Energy calibration of Neutral Particle Spectrometer (NPS)
  - Calibration with cosmic data
  - Elastic calibration
  - π^0 calibration
- Summary

Investigate the proton structure

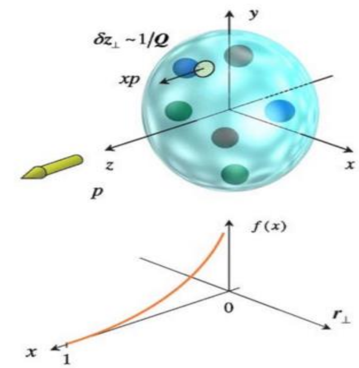
Nucleon Form Factors (FFs)

- ✓ Access via elastic scattering: e + p → e' + p'
- ✓ Spatial distribution of electric charge



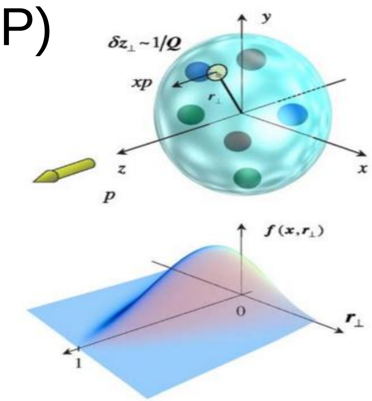
Parton Distribution Functions (PDFs)

- ✓ Access via deep inelastic scattering: e + p → e' + X
- ✓ Momentum distribution of partons



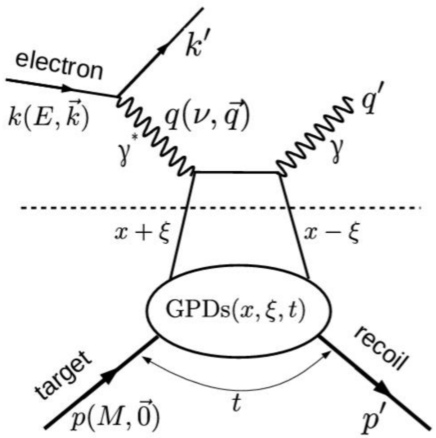
Generalized Parton Distributions (GPDs)

- ✓ Access via exclusive processes:
  - Deeply Virtual Compton Scattering (DVCS)
  - Deeply Virtual Meson Production (DVMP)
  - Double DVCS (DDVCS)
  - etc.
- ✓ Spatial and momentum distribution

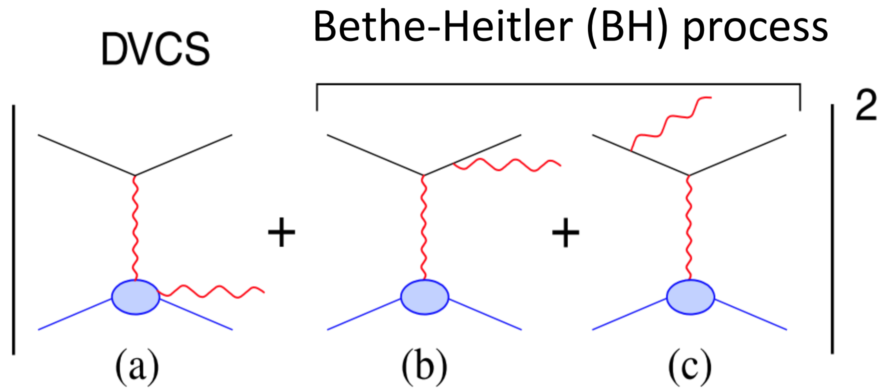


Deeply Virtual Compton Scattering (DVCS)

➢ The simplest probe to access the GPDs

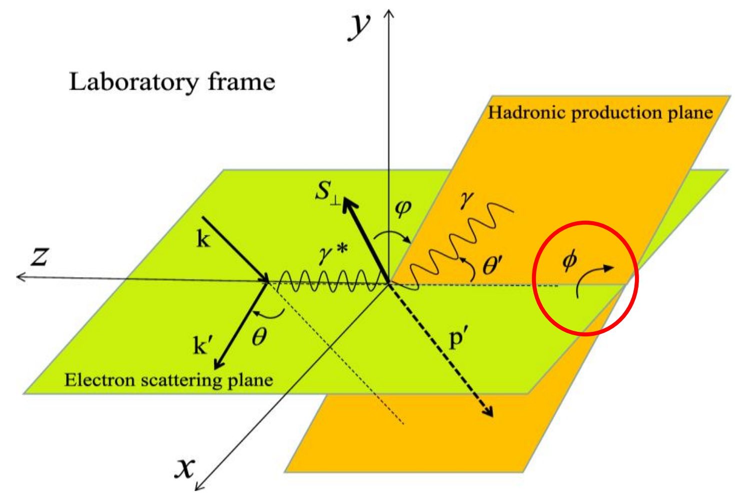


ep ⟶ epγ =



➢ $\sigma(ep \rightarrow ep\gamma) = |DVCS|^2 + |BH|^2 + interference$

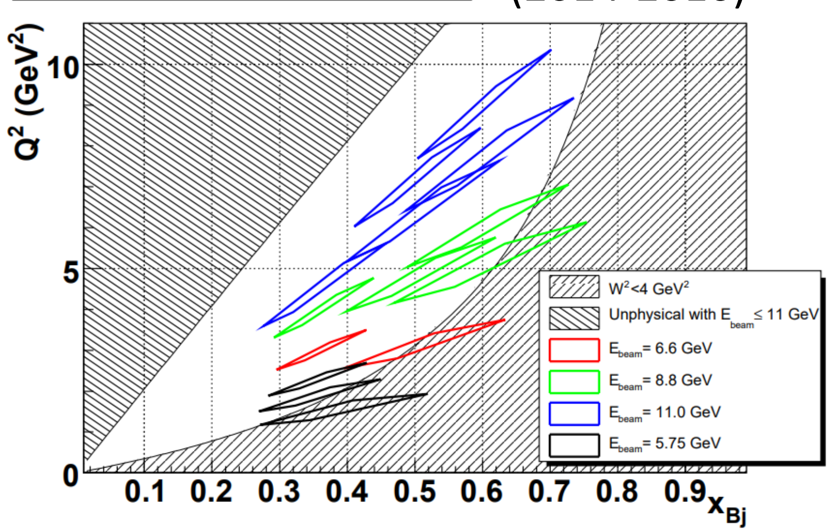
- $|BH|^2$: calculable precisely with QED
- Interference terms: separated by beam energy dependence and ϕ

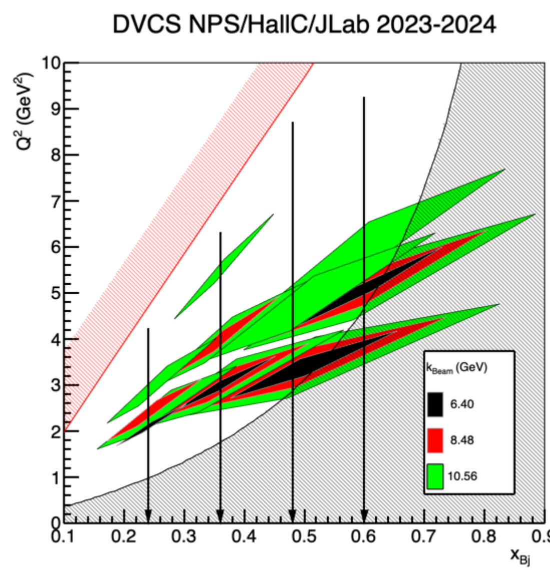


DVCS experiment in Hall C

- The upgraded 12 GeV electron beam provides an opportunity for a new kinematic region
- The Hall C High Momentum Spectrometer (HMS) provides sufficient momentum reach to separate the interference and $|\mathrm{DVCS}|^2$ terms using different beam energies
- Measurement with low x_B provides the cross-check with results from other experiments (CLAS, COMPASS, …)

DVCS measurements in Hall A/JLab (2014-2016)





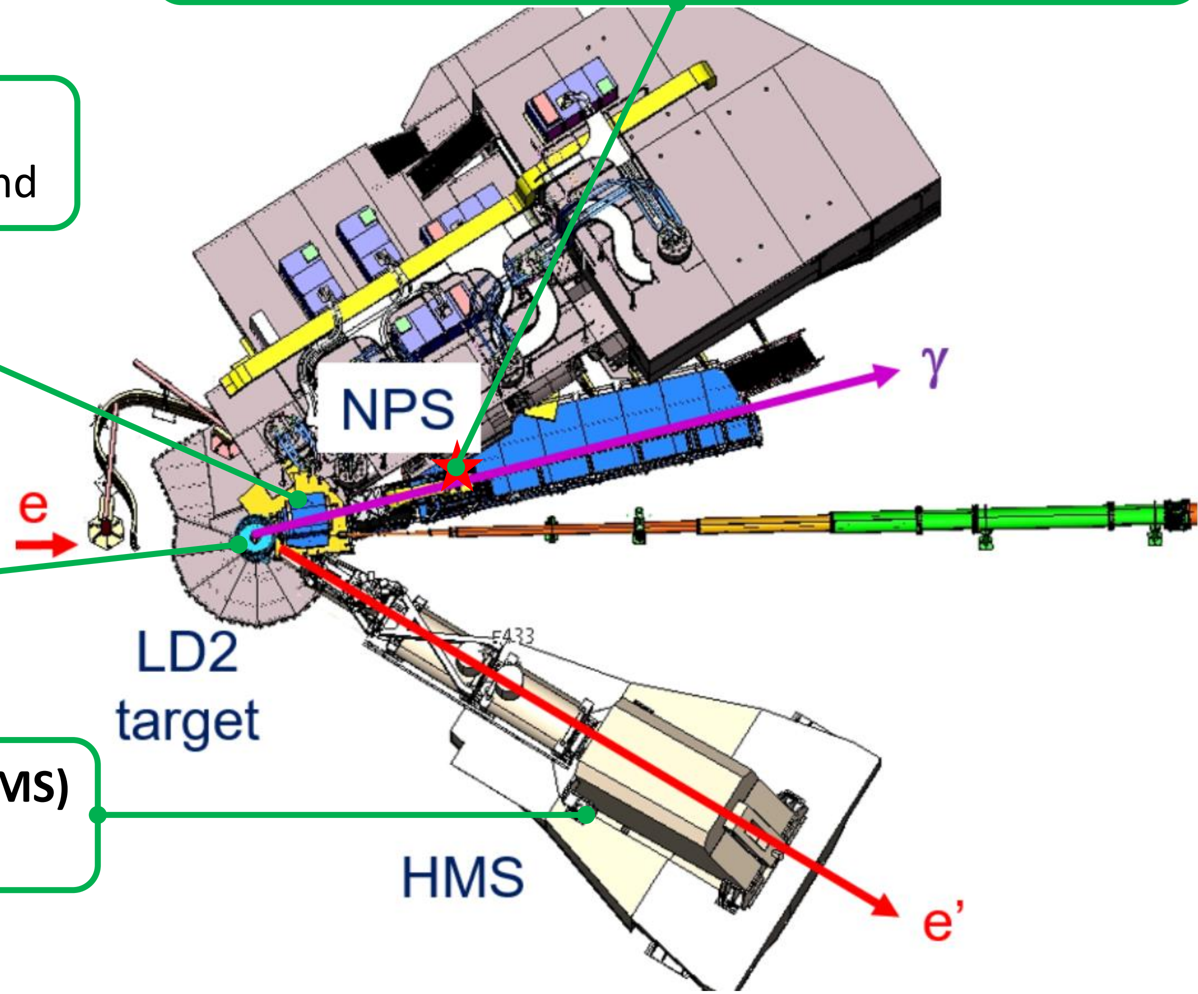
Experimental setup

Neutral Particle Spectrometer (NPS) calorimeter
- Detect photon with an array of 1080 crystals

Sweep magnet
- Reduce the low energy background

Target chamber
- For liquid H_2 or D_2

High Momentum Spectrometer (HMS)
- Detection of scattered electron



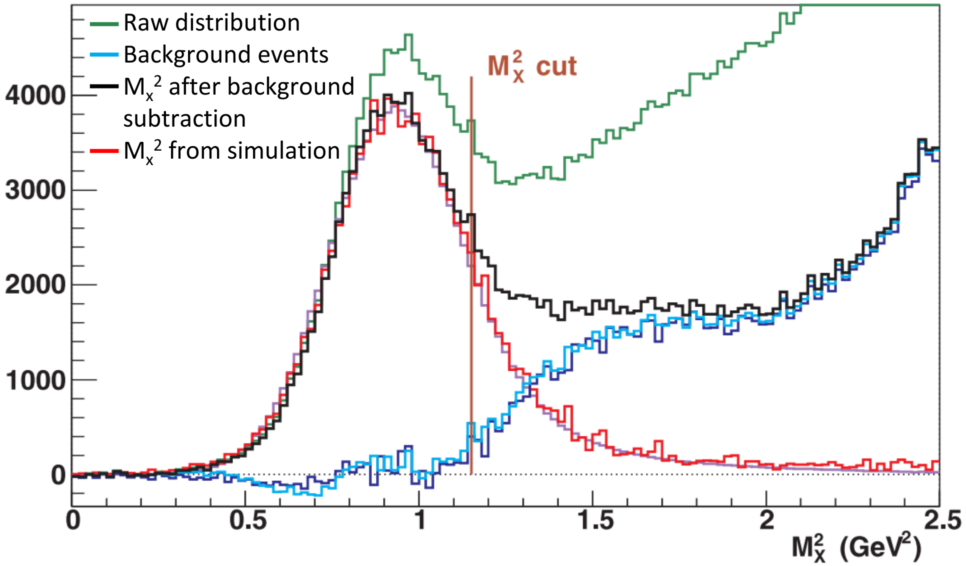
Extraction of DVCS events

- The DVCS events are extracted using missing mass technique

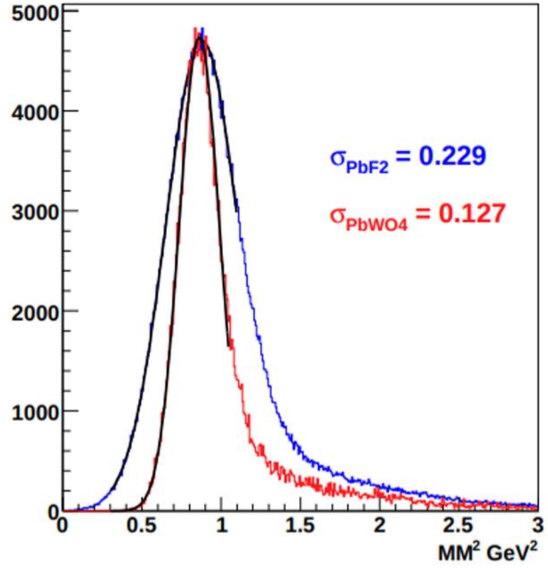
$$M_x^2 = (k + P_p - k' - q_\gamma)^2$$

- Energy resolution in the NPS plays a crucial role for better missing-mass resolution
- Energy calibration should be performed as well as possible

Missing-mass method for event selection



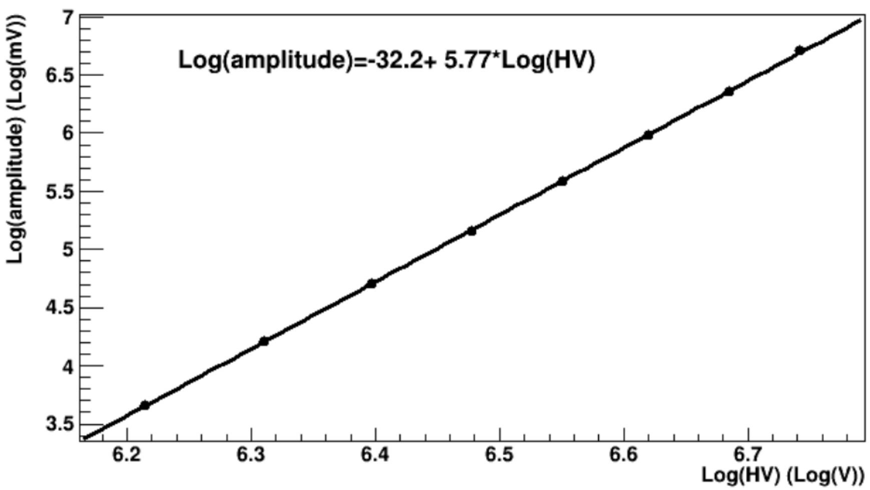
Simulated MM^2 resolution



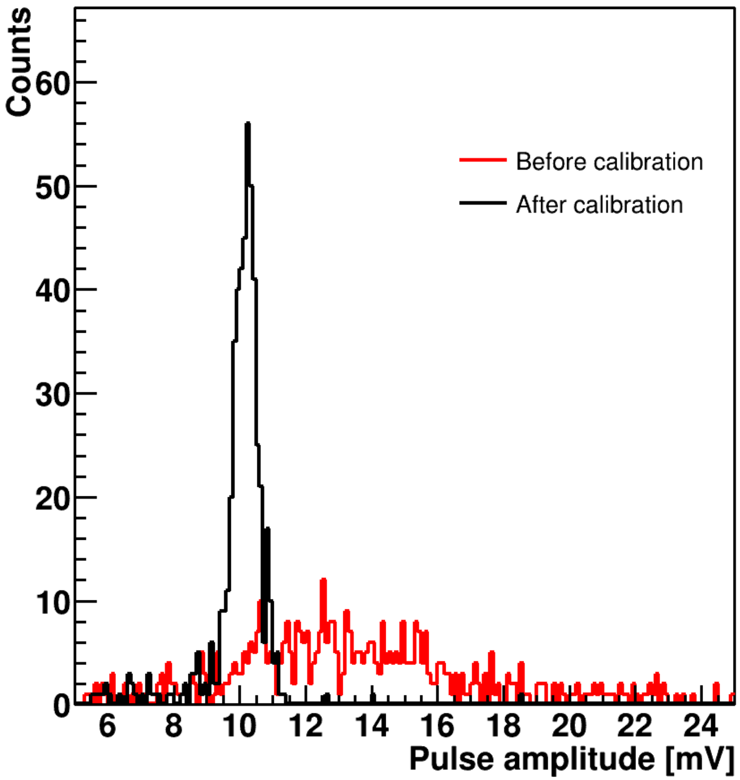
Proposal PR12-13-010

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

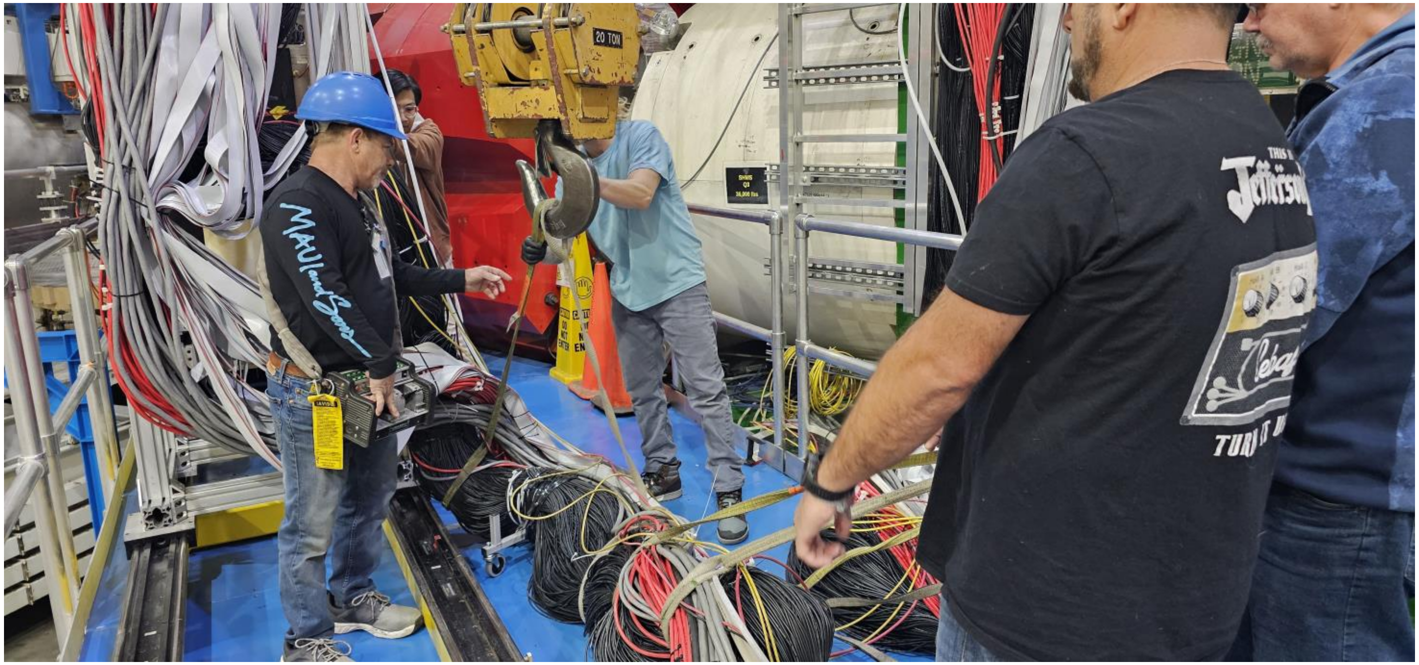


Amplitudes before & after calibration



Elastic calibration

- Preparation of taking data of elastic events (e + p ⟶ e’ + p’)
  - Move the NPS to 9.5-meter position (coordinate with the Techs)
  - Change the polarity to detect scattered electron (e’) in the NPS and recoil proton (p’) in the HMS
  - Three different angles of the NPS are required to illuminate the whole calorimeter and have enough statistics at the edge



Calculation of calibration coefficients

- Precise prediction of scattered electron from the measured proton in the HMS

- 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

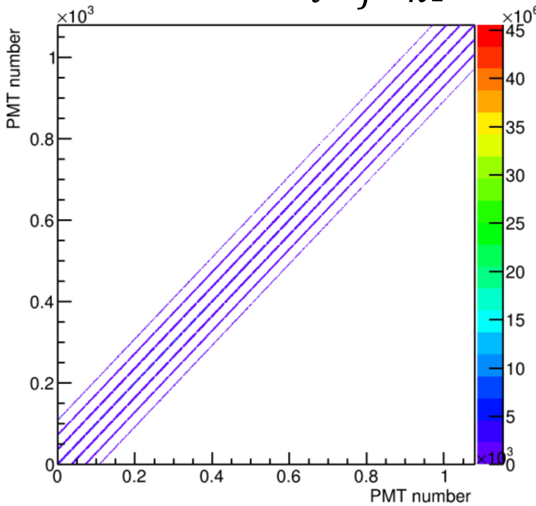
    we can build $\chi^2 = \Sigma_i (E_i - \Sigma_j C_j A_j^i)^2$
  - The calibration coefficient C_j can be calculated by minimizing the χ^2:

    $$\frac{\partial \chi^2}{\partial C_k} = -2C_k \Sigma_i (E_i - \Sigma_j C_j A_j^i) A_k^i = 0$$

    which can be witten as:

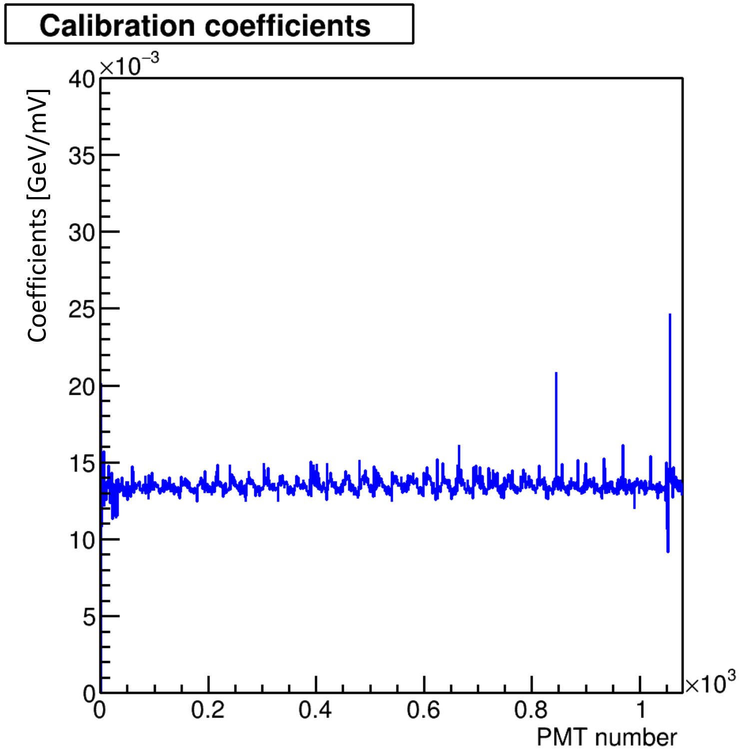
    $$\Sigma_i E_i A_k^i = \Sigma_j [\Sigma_i A_j^i A_k^i] C_j$$
  - Then, C_j can be calculated by inverse the matrix $[\Sigma_i A_j^i A_k^i]$ and multiply $\Sigma_i E_i A_k^i$

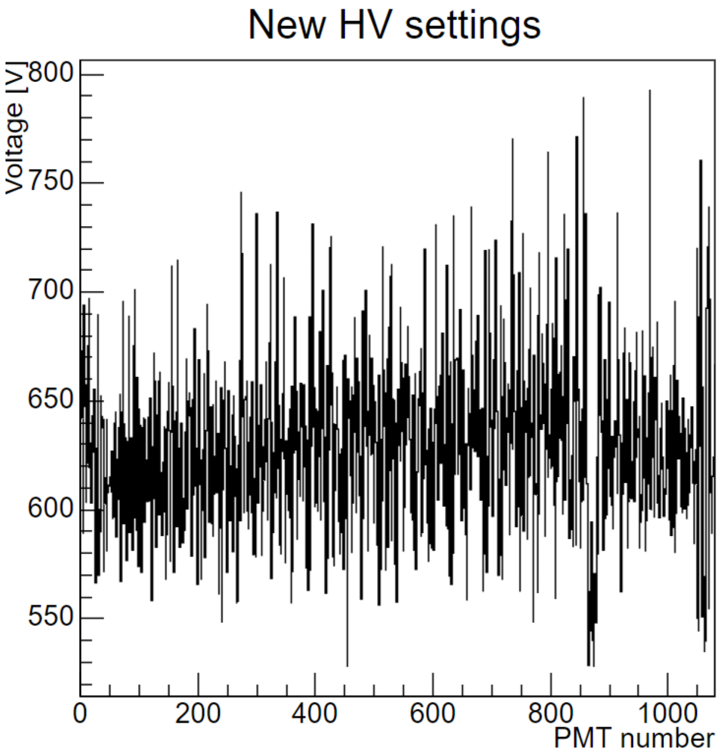
Matrix $[\sum_i A_j^i A_k^i]$



Elastic calibration

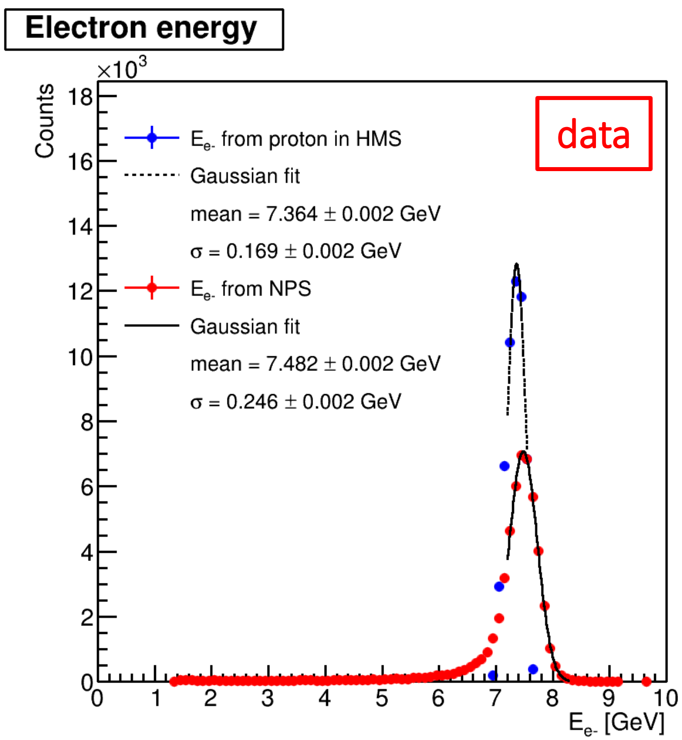
- Adjust the high voltage (HV) of PMTs to have 600 mV of amplitude for the photon from DVCS process
- Based on the gain curve and their calibration coefficients

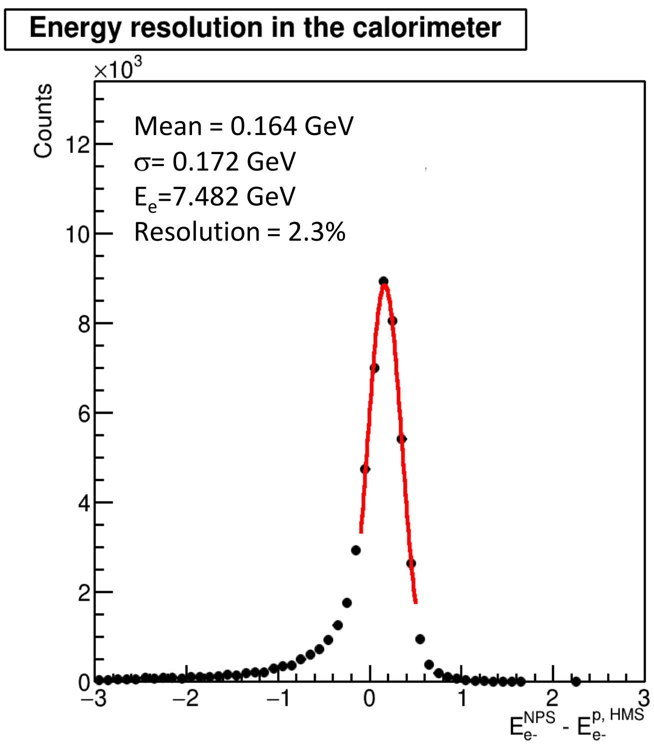




Results of elastic calibration

- Good agreement of the electron energy between the prediction from HMS and the measurement in NPS after calibration
- The measured energy resolution is still larger than the expectation ($\sim 2\%/\sqrt{E} \oplus 1\% \sim 1.2\%$) from simulation (work ongoing)

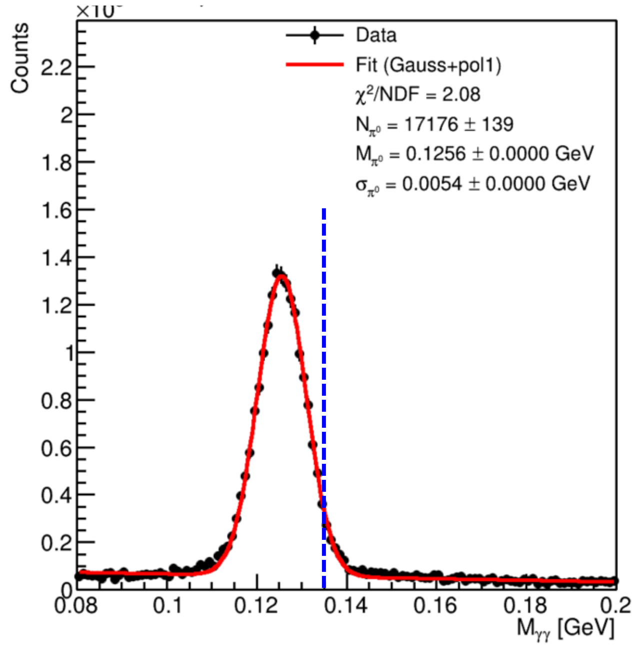




Energy calibration with π^0

- The energy in the NPS are shifted when taking production data
- Possible causes: fringe field effects from the magnet on PMTs, non-linear effects on the energy response of the calorimeter
- Calibration with $\pi^0 \rightarrow \gamma\gamma$ is another approach to extract the correct calibration coefficients in each crystal

π^0 invariant mass before π^0 calibration



Method of π^0 calibration

- The minimization method is based on the paper "*A bootstrap method for gain calibration and resolution determination of a lead-glass calorimeter*" *(Nuclear Instruments and Methods in Physics Research A 566 (2006) 366–374)*
- This 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 $\langle m_i^2 \rangle = m_0^2$

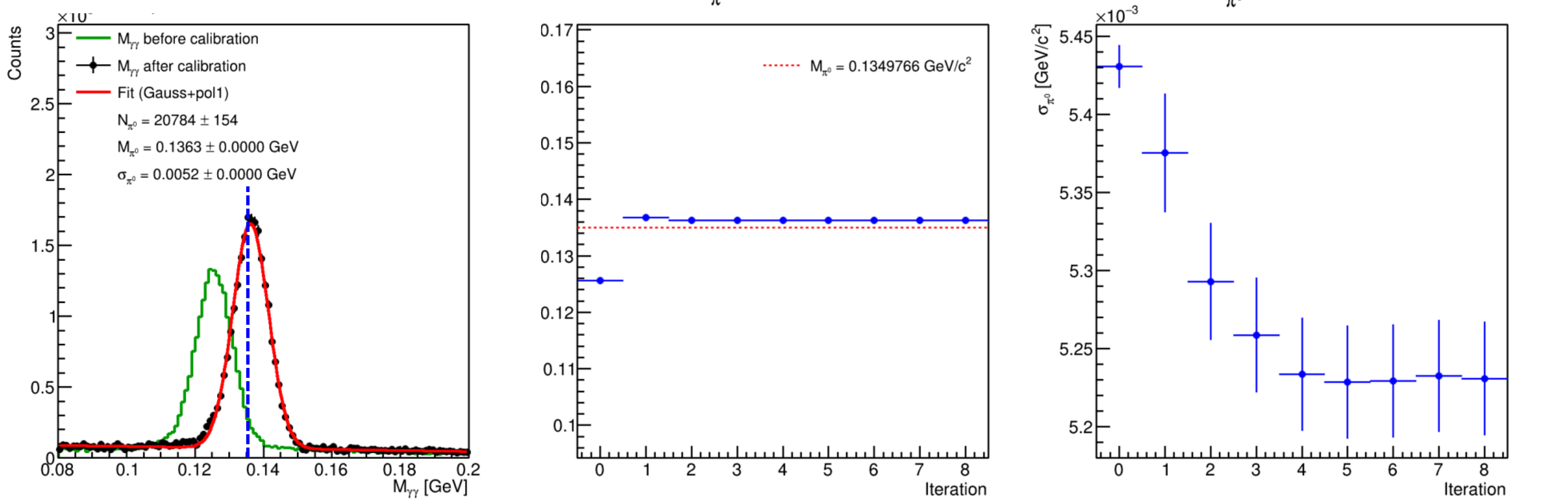
$m_0 = M_\pi = 0.1349766$ GeV
m_i: reconstructed $M_{\gamma\gamma}$
λ: Lagrange multiplier

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

Results of π^0 calibration

- Mean value of π^0 mass is stable after 3 iterations
- At least 5 iterations are required to make its width stable
- Both mean and width are improved after calibration

π^0 invariant mass after π^0 calibration



Summary

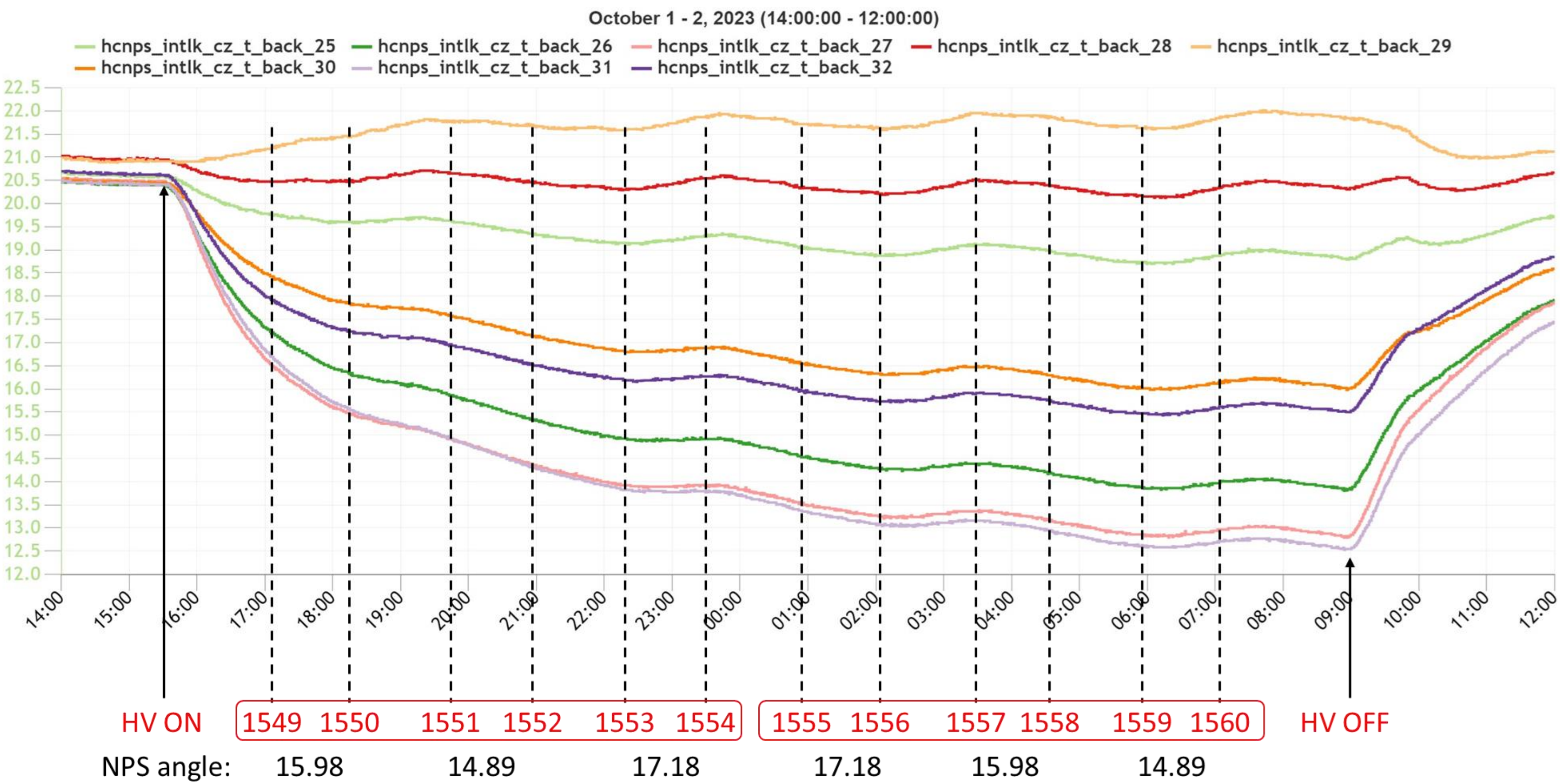
- The ongoing experiment with NPS in Hall C will provide high precision cross sections of DVCS at different values of x_B and Q^2 and for different beam energies.
- It will provide stringent constraints for GPDs in kinematic regions not accessible before the 12 GeV upgrade.
- The experiment success relies on the high energy resolution, and thus good calibration, of the NPS electromagnetic calorimeter
- Several methods are used and were described to best calibrate the response of the NPS crystals
- Improved energy resolution is expected by refined offline analysis currently underway

Thanks for all the people contributed to this experiment!!

Backups

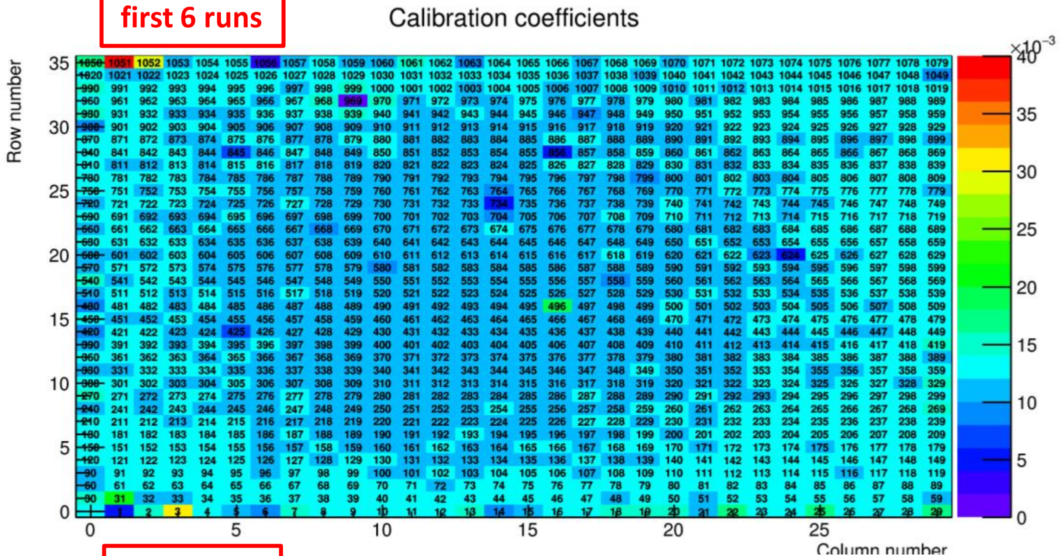
Effects of temperature on elastic calibration

Thermal sensor at middle column (back 25-32)

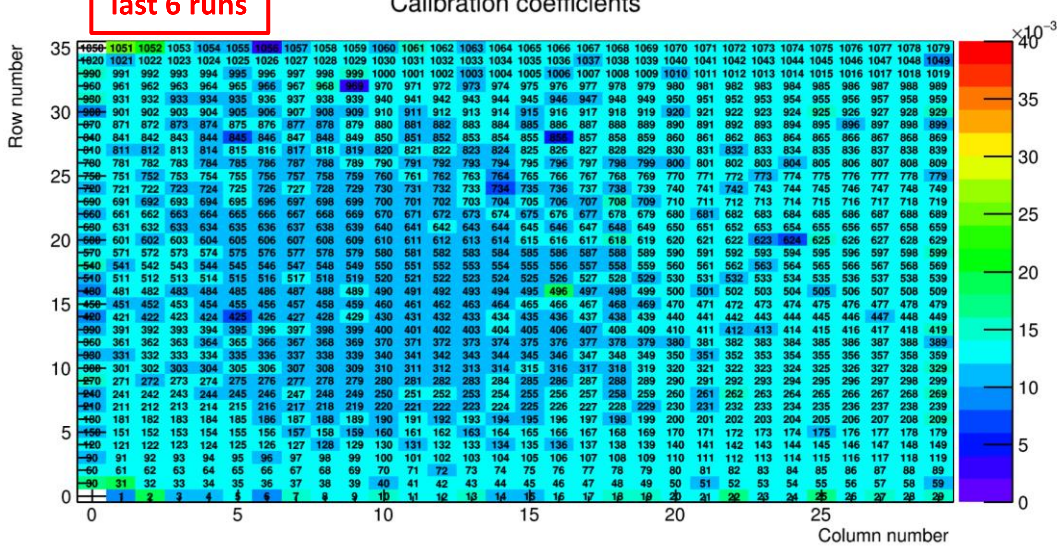


Results of calibration associated with temperature

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 was not steady in the calorimeter
- Last 6 runs
  - More uniform calibration coefficients after the temperature in the calorimeter got more steady
- Conclusion
  - The calorimeter should be calibrated after the temperature get more steady