OLD DOMINION UNIVERSITY

Exclusive Reactions in NPS

Exclusive Channels, Experimental Set up, Challenges, and Success

Christine Ploen

Support from DOE DE-FG02-96ER40960

January 13, 2025

NPS Overview from September 2023 - May 2024 (RG1a)

NPS

- Precision coincidence cross section measurements of neutral particles (γ and π^0)
- Uses existing SHMS carriage to allow remote rotation
- Angle reach between 5.5 and 21 degrees
  - Production range 9.0 to 20.6 degrees

HMS

- Detects scattered e^-
- Rotation to 11.7 degrees
- Excellent momentum resolution (0.1%)
- Momentum from 0.5 -7.5 GeV/c

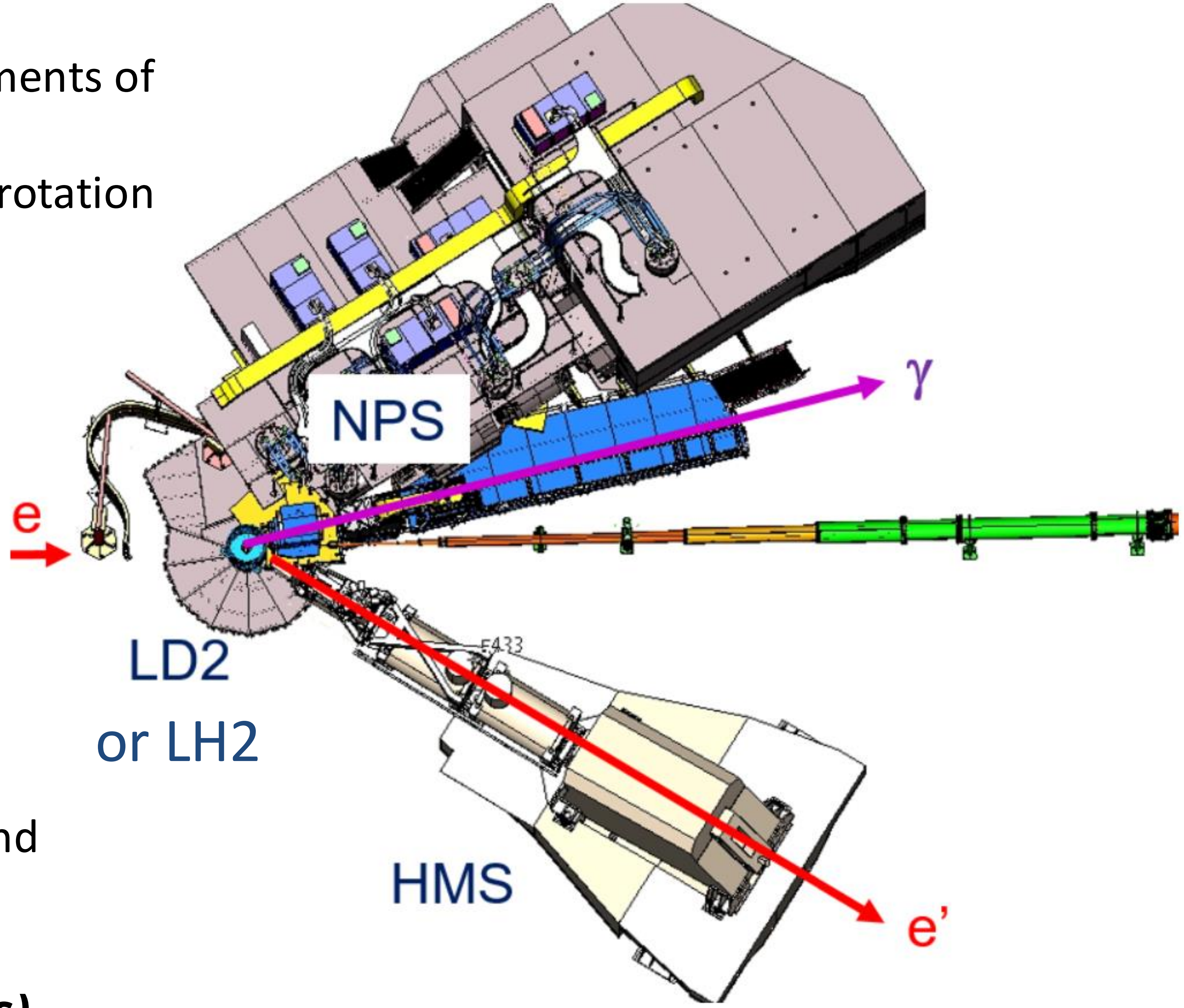
Beamline/Instrumentation

- Modified beam pipe
- 0.3Tm Sweep Magnet 1.5m from target (NPS)
  - Vertical bend, reducing charged background

Targets

- 10 cm Cryogenic LH2 or LD2

DAQ, CH, Computing ➔ $\mathcal{L}$ ~ 7.5 • 10^{37} /(cm^2s)



NPS Science Program: Exclusive Channels

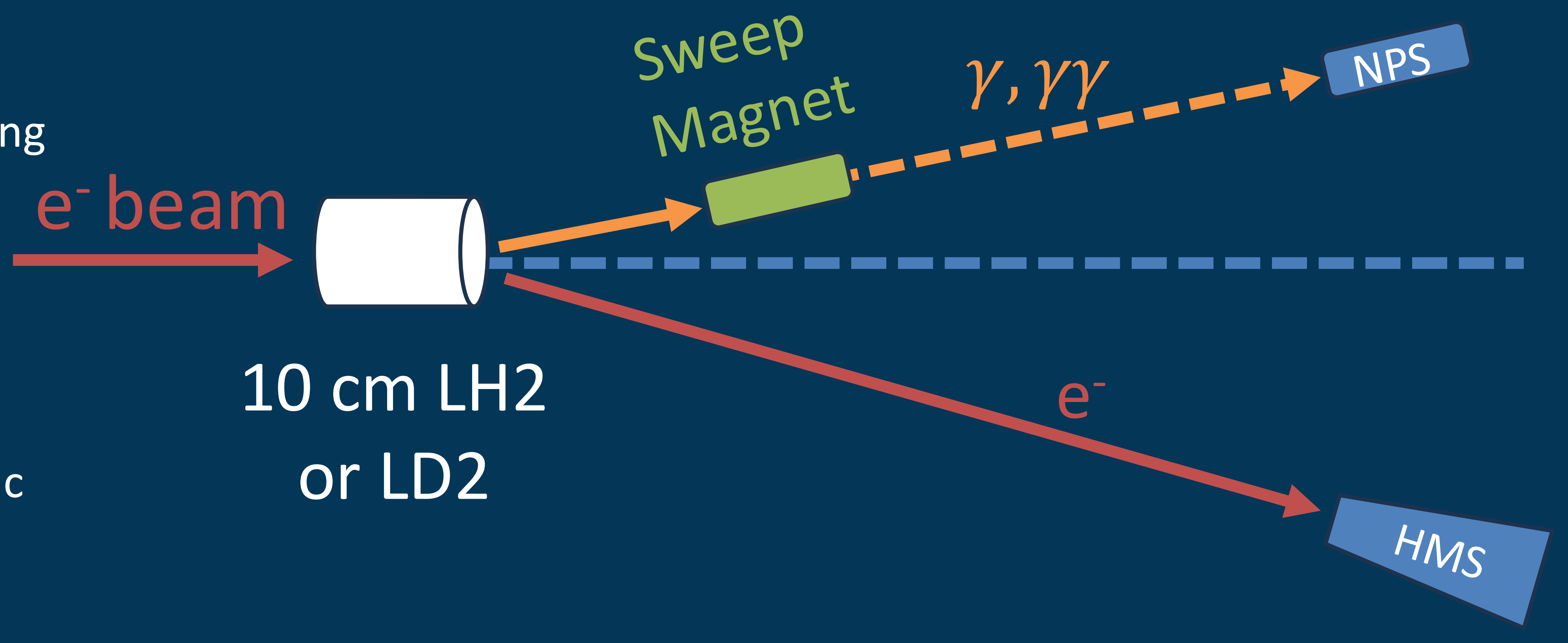
- **E12-13-010**: Exclusive DVCS and π^0 Cross-Section Measurements
- **E12-13-007:** Semi-Inclusive π^0 Production
- **E12-22-006:** DVCS off the neutron with the NPS

NPS achieves *precision coincidence cross section measurements* of neutral particles ($\boldsymbol{\gamma}$ and π^0) by taking advantage of the well-understood HMS and SHMS, offering:

- fixed pivot
- precision kinematics
- excellent detector shielding

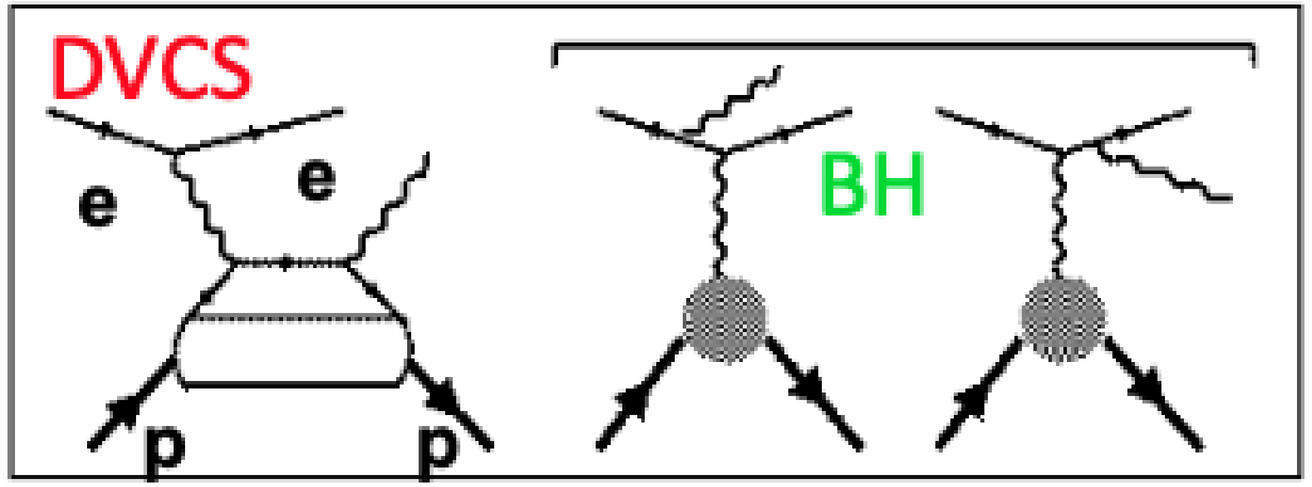
These features offer excellent control over systematic uncertainties

→ crucial for L/T separation



E12-13-010 DVCS/π^0 cross sections

Simplest process: e + p → e' + p + γ (DVCS)



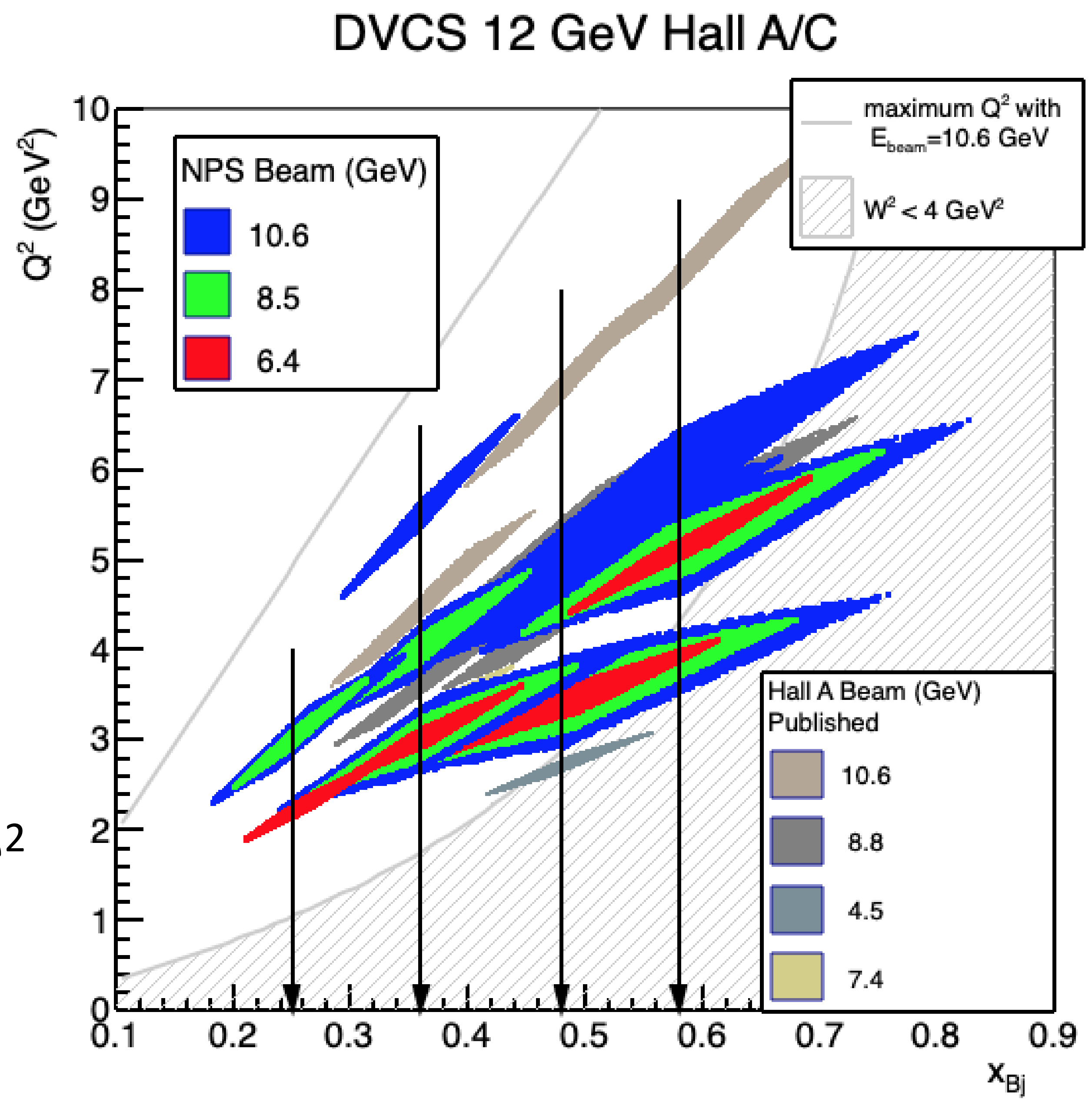
E12-13-101 DVCS: complements and expands measurements in Hall A:

- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:
  $\sigma = |BH|^2 + \mathcal{Re}[DVCS^\dagger BH] + |DVCS|^2$
  $\sim E^2_{beam}$ $\sim E^3_{beam}$
- L/T separation of π^0 production
  - Crucial for probing transversely GPDs

To extract the real part of the CFFs from DVCS, cross section measurements at **multiple beam energies** are needed (**DVCS² – $\mathcal{Re}$[DVCS†BH] separation**)

$\mathcal{Im}$ **[DVCS†BH]** is extracted from the ***sin(∅)*** **dependence** of the **helicity-dependent cross section**

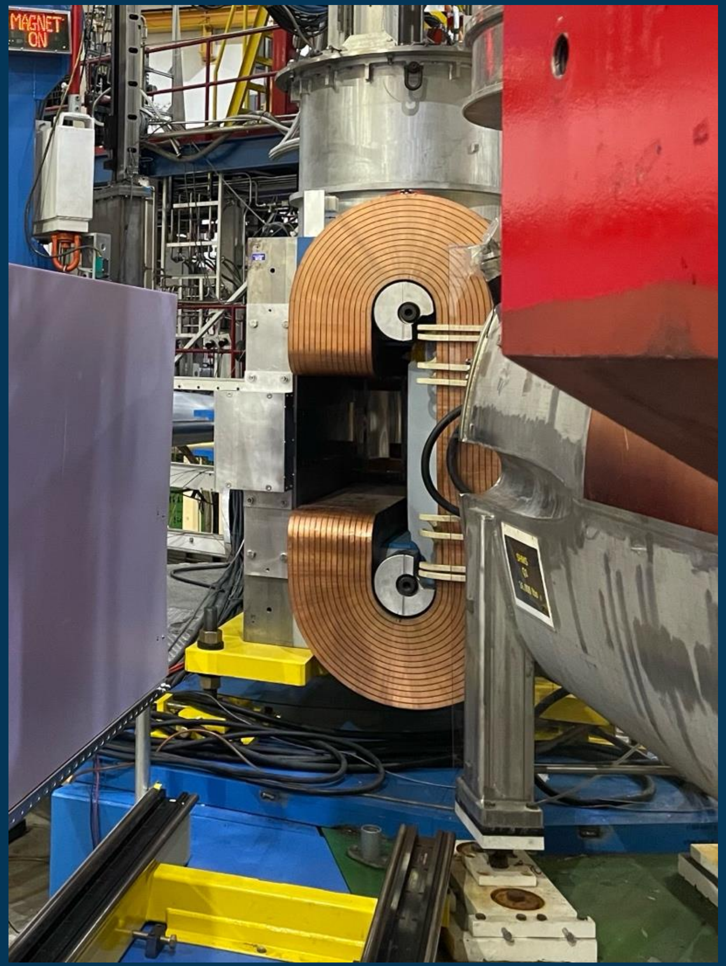
$\mathcal{Re}, \mathcal{Im} \propto$ e$^-$ charge^3
Cross section terms ∝ charge^2



NPS Installation

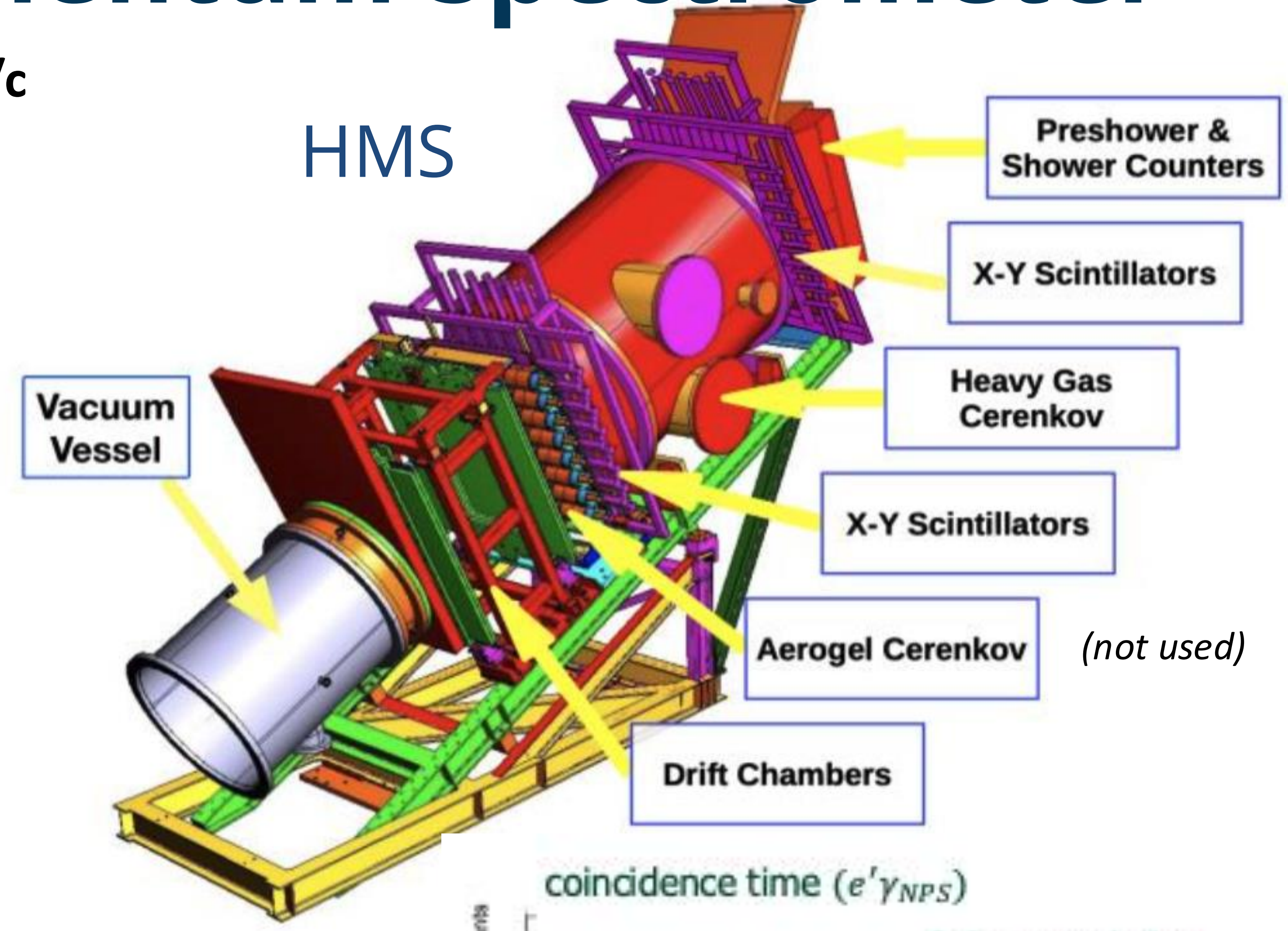
- Neutral particle detector made up of 1080 lead tungstate crystals ($PbWO_4$) in a 30x36 array.
- Temperature-controlled frame with gain monitoring and curing.
- Nearly streaming readout with deadtime-less digitizing electronics: JLab-developed Flash ADCs sample the entire pulse form for each crystal.

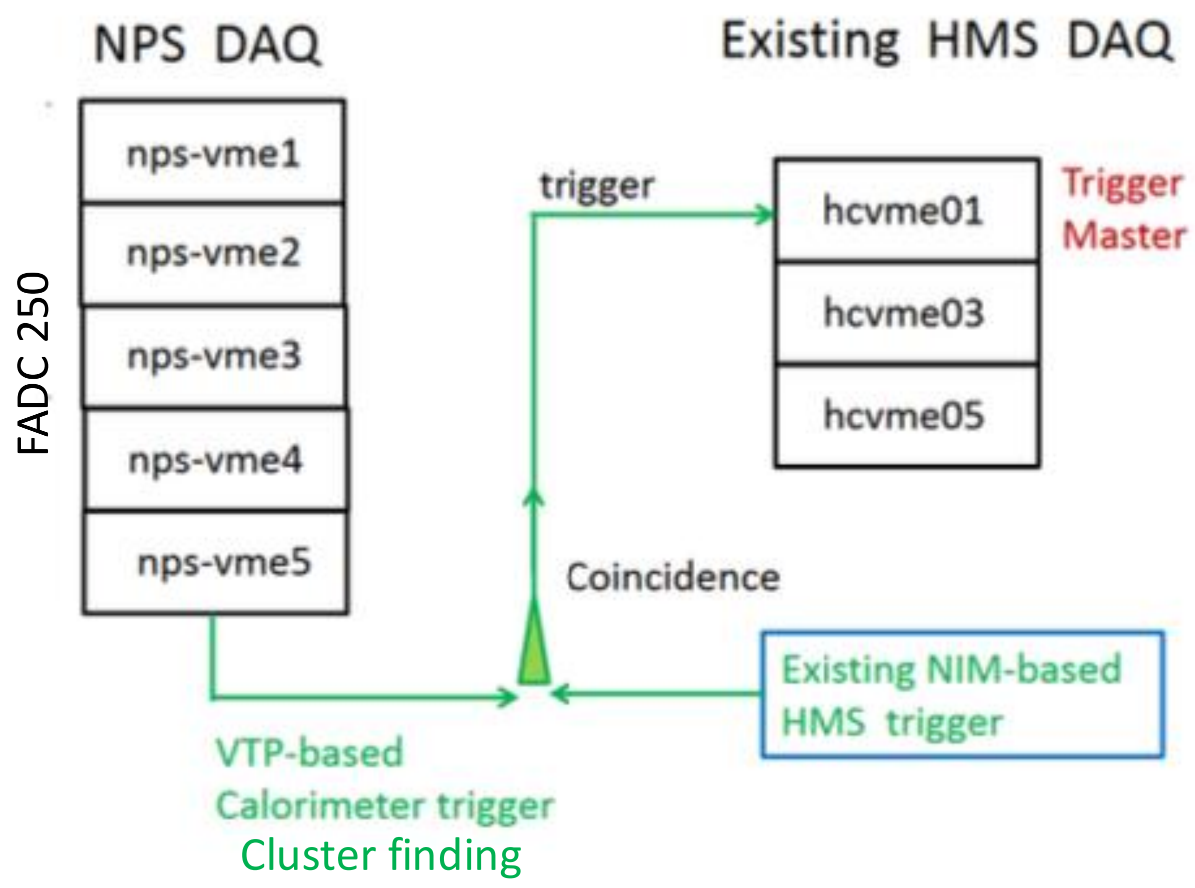
- Cantilevered platforms installed on SHMS carriage permits precise and remote rotation of the detector from 5.5 degrees to 21 degrees.
- 0.3Tm sweeping magnet allows small angle settings needed for high Q^2 measurements and much higher luminosity at larger angles.
- Rails on SHMS platform permit longitudinal calorimeter motion from 3.0 to 9.5 m from target.



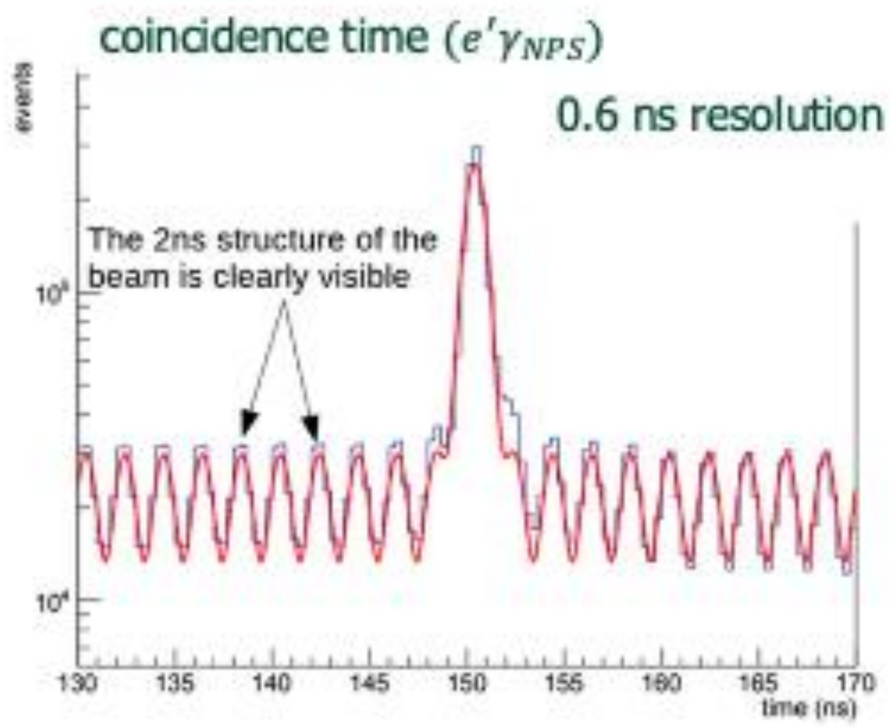
e^- Detection in the High Momentum Spectrometer

- **NPS program pushes HMS to highest momentum yet: -6.667 GeV/c**
  - Four new optics studies for precision reconstruction
- Small pt-to-pt uncertainties achievable for clean L/T separation
- Drift chambers for track reconstruction
- Fast trigger from scintillator planes
- Cerenkov detector and shower counter for e/π separation

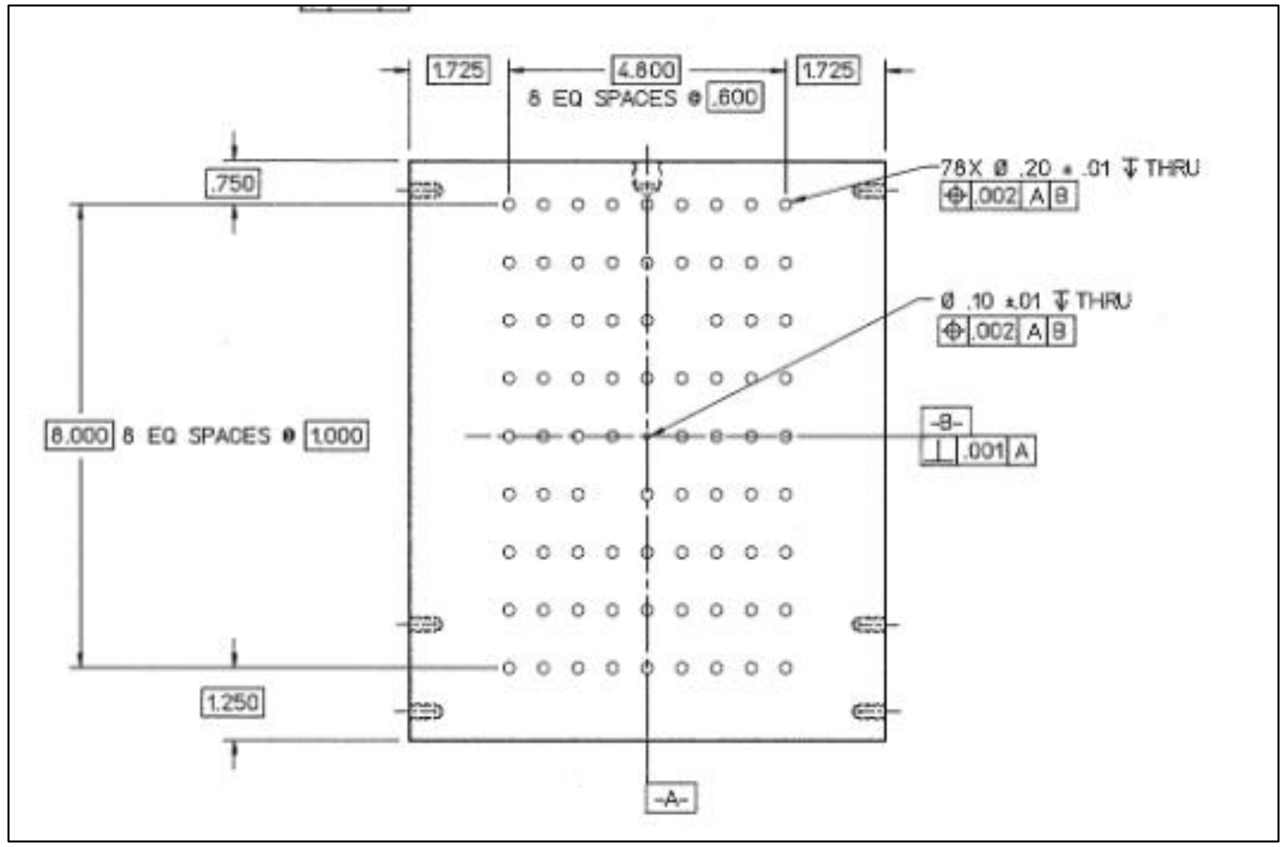




- Coincidence Trigger between NPS photon detection and HMS electrons



Optics Reconstruction in the HMS



HMS Sieve Slit Schematic: 9x9 array of pinholes

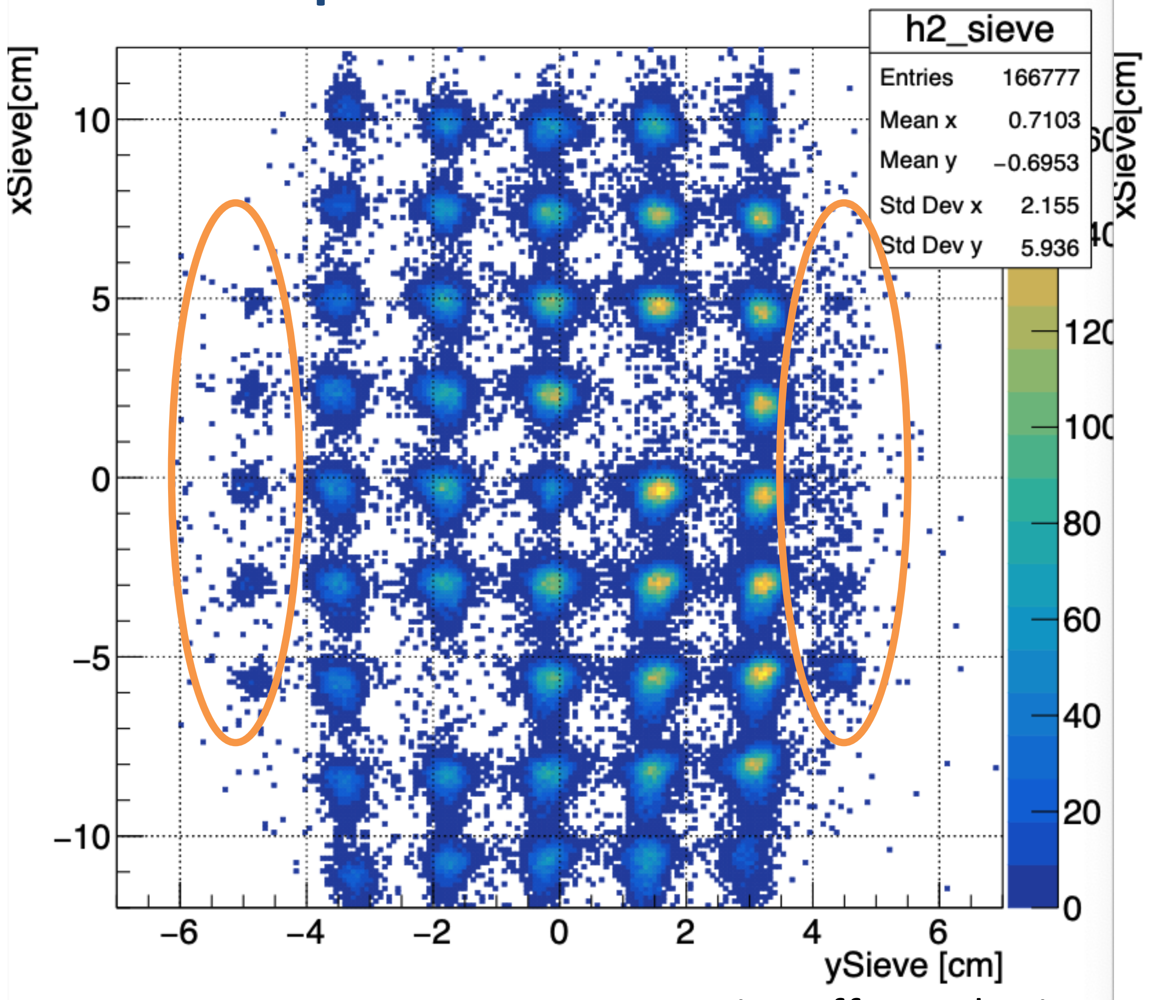
Goal: accurately reconstruct x'_{tar}, y_{tar}, y'_{tar} from the focal plane variables x_{fp}, x'_{fp}, y_{fp}, y'_{fp}, as well as x_{tar}

Data Taking Procedure: Beam on carbon foil target with sieve slit in place, HMS momentum set

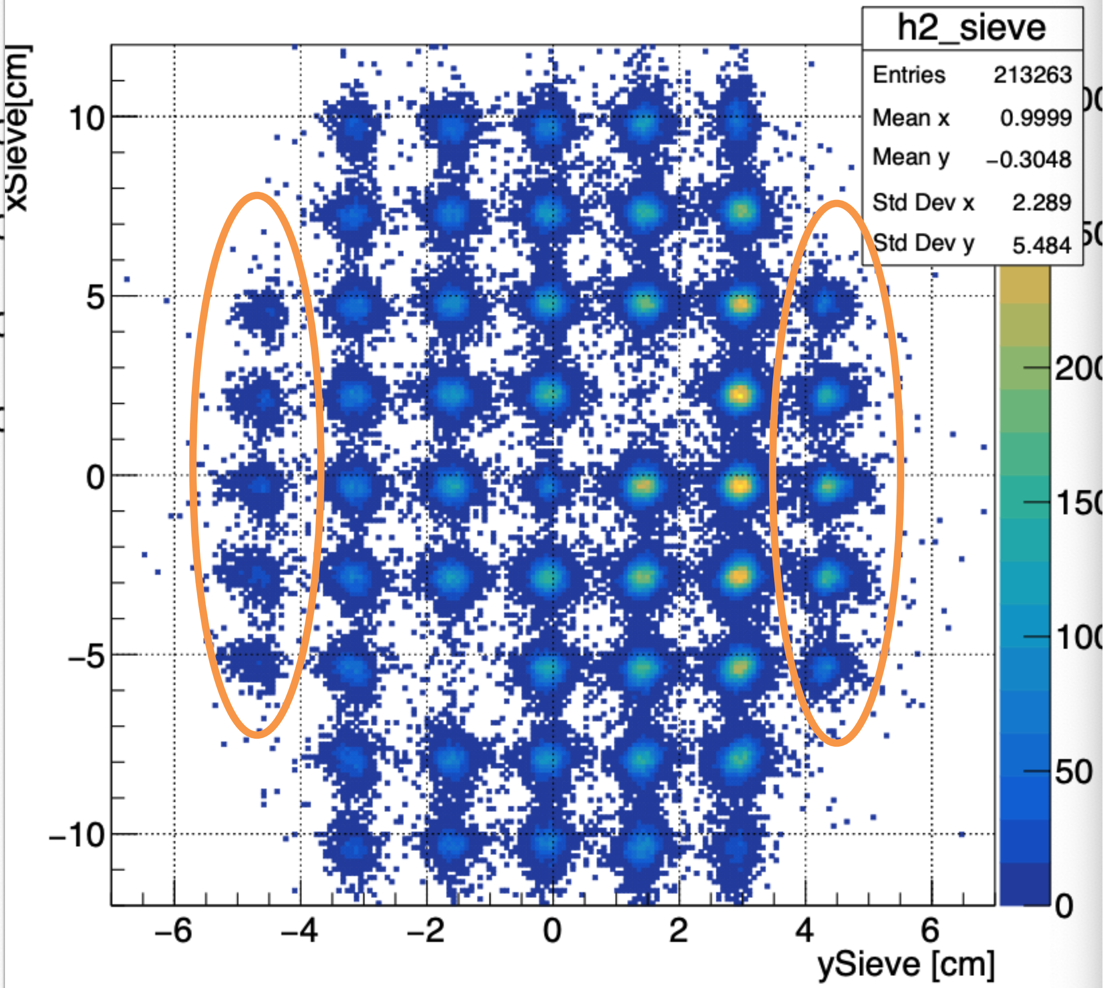
Sieve Slit data taken on **5 carbon foil positions**: +/-8 cm, +/- 3 cm, and 0 cm for excellent reconstruction throughout the extended target

Major improvements in reconstruction!

Reconstruction from 2018 optimization at low mom



***New Fit* from -6.667 GeV/c Sieve Slit Data**



Magnet saturation affects physics variable reconstruction at target!

New matrix elements for HMS P =
- **-5.639 GeV/c,**
- **-5.878 GeV/c,**
- **-6.117 GeV/c,**
- **-6.667 GeV/c – Highest P in HMS history**

Sweeper magnet also studied
→ So far, no evidence of fringe effects on HMS Optics

NPS Elastic Calibrations

Procedure:

- NPS is moved to 9.5 m with tech assistance
- HMS polarity switched to detect protons
- NPS detects scattered electrons (magnet off)
- 3 NPS angles to illuminate the whole calo

→ We can precisely predict energy of scattered e^- from the measured proton in the HMS

→ High Voltages of PMTs adjusted based on coefficients via chi^2 minimization

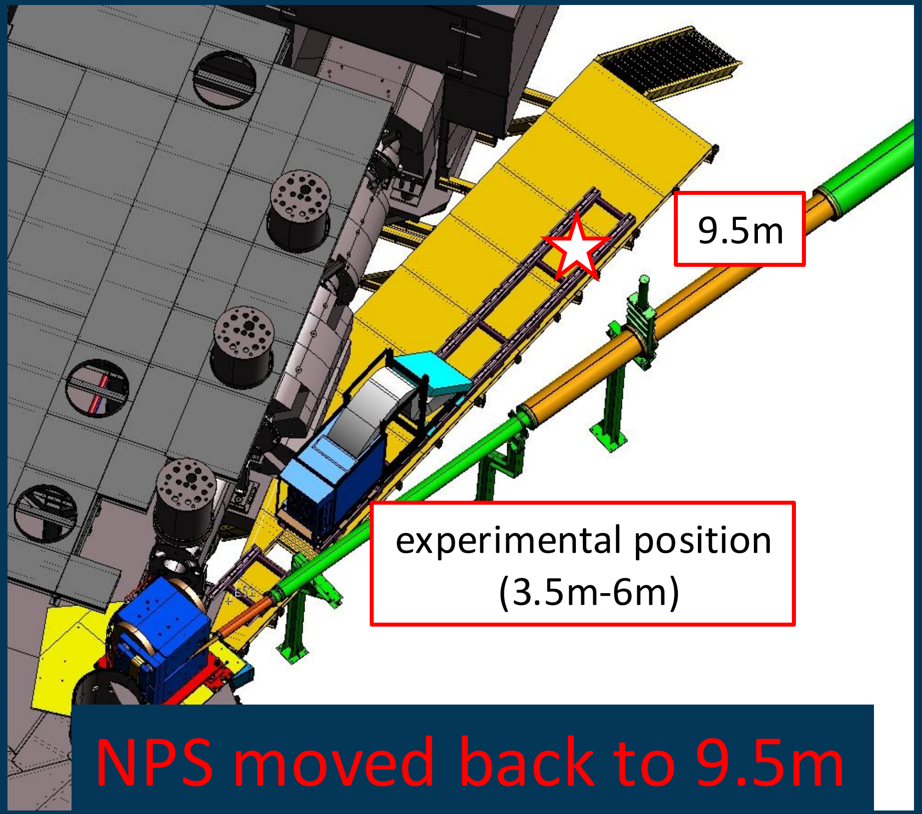
Reconstruct scattered electron via $e + p \rightarrow e_i' + p_i'$

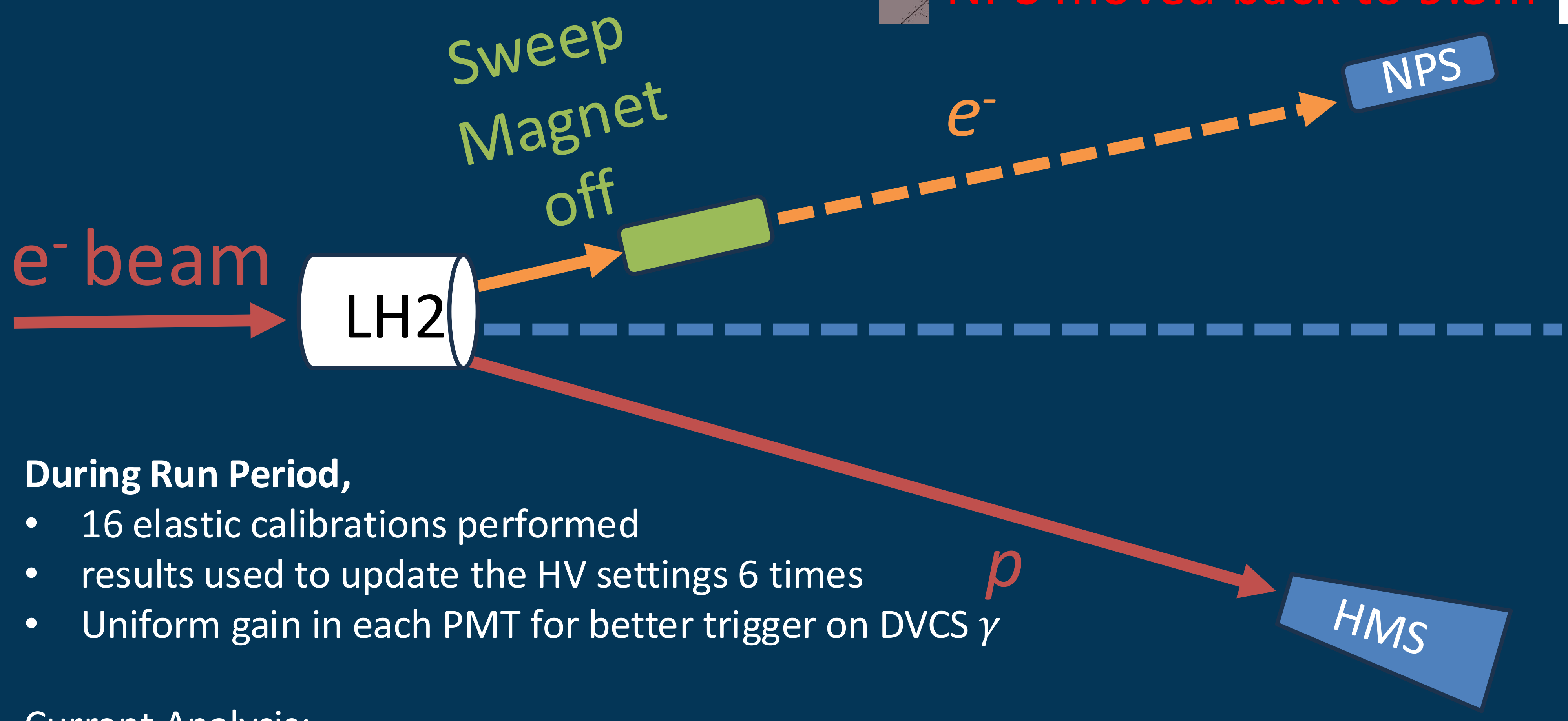
$E_i = E_b + M_p - E_i^p$

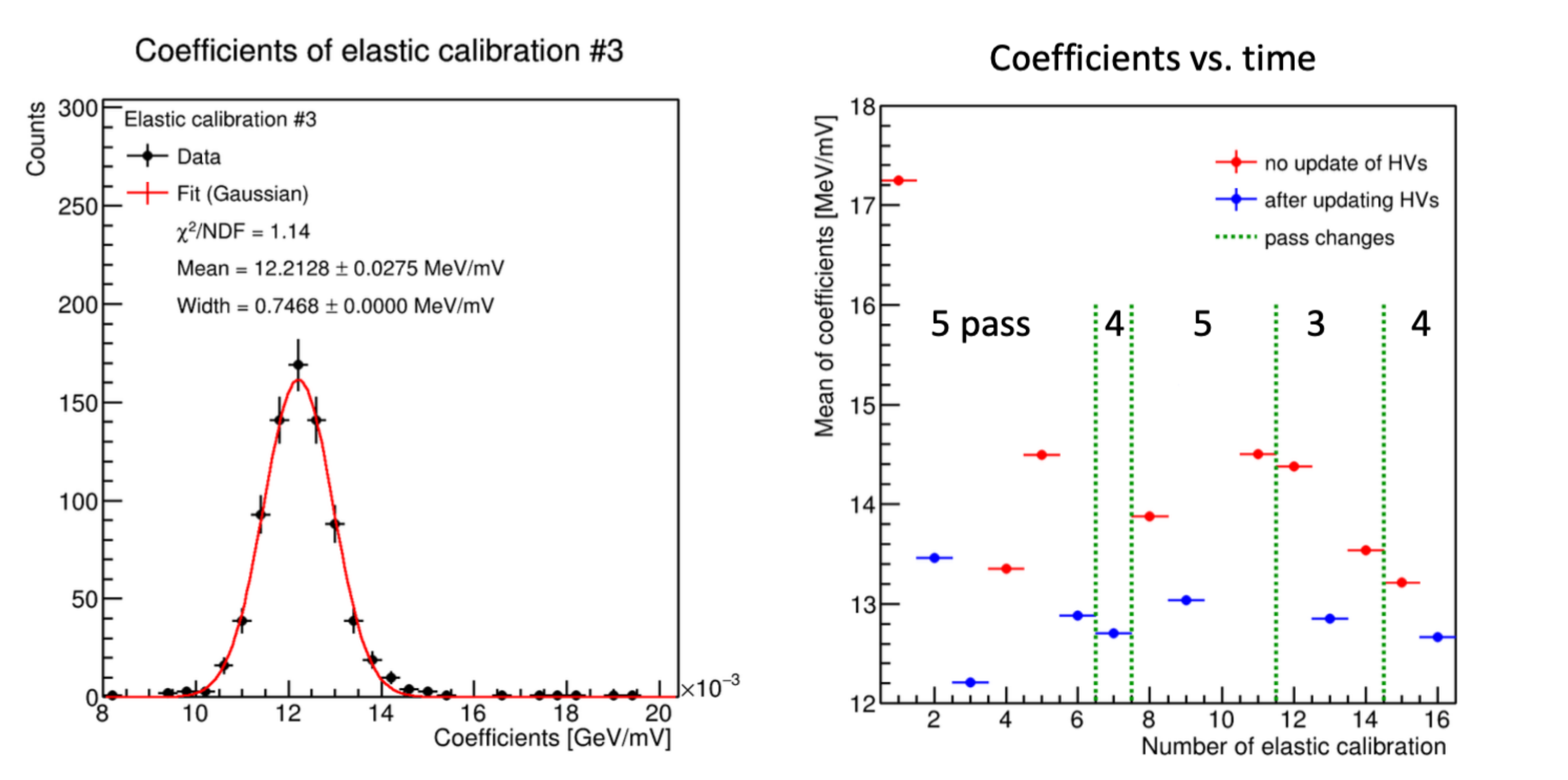
E_b = beam energy

M_p = mass of target proton

E_i^p = energy of recoil proton







During Run Period,

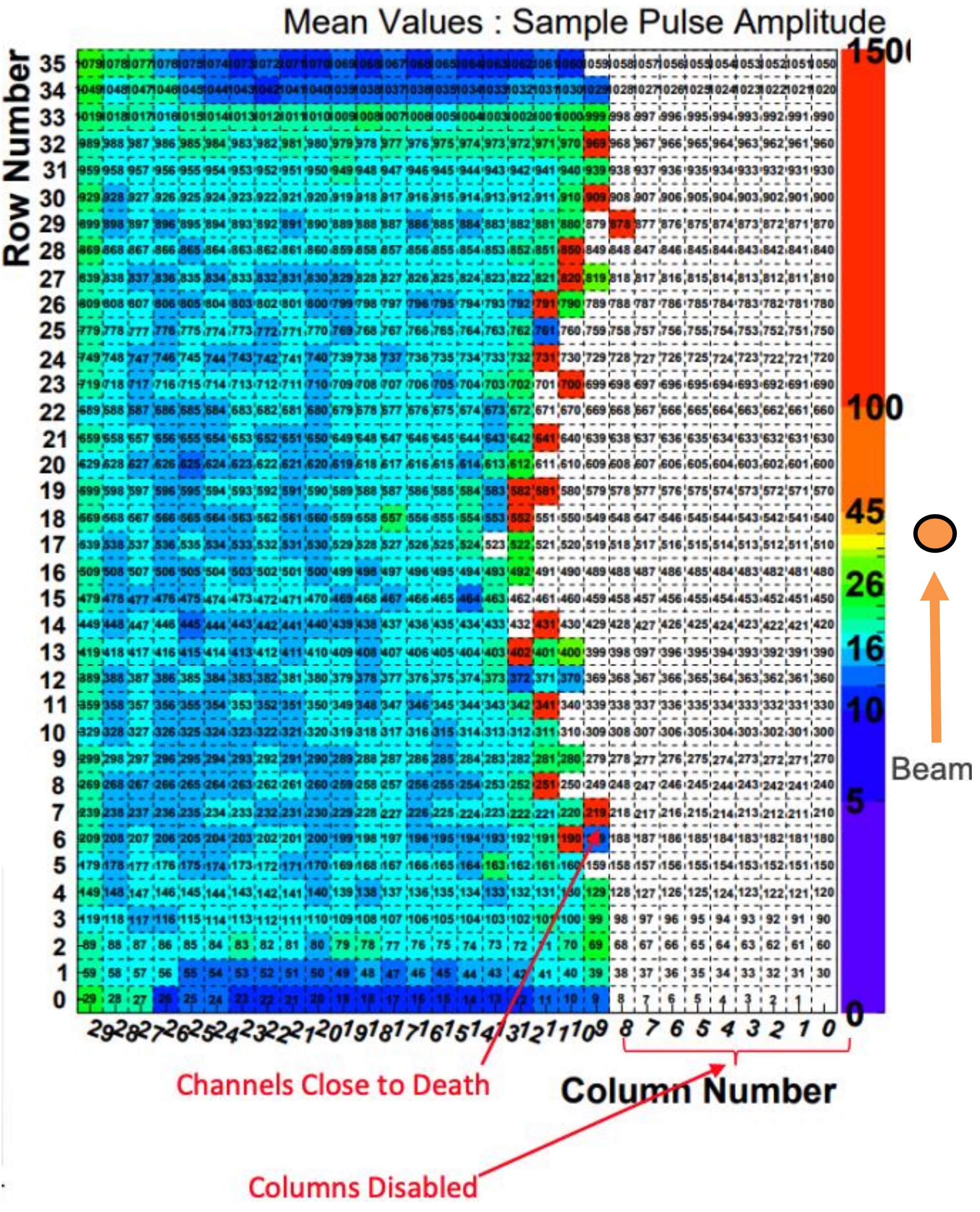
- 16 elastic calibrations performed
- results used to update the HV settings 6 times
- Uniform gain in each PMT for better trigger on DVCS γ

Current Analysis:

- Reference waveforms are selected from elastic data

Analysis by H. Huang

NPS Run Period Challenges



Problem:

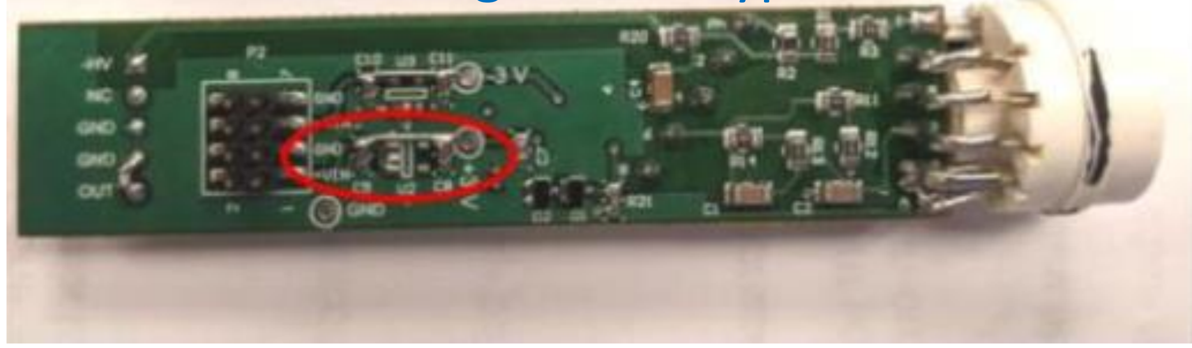
- Electronics issue discovered as we saw channels become unstable and fail.
- Channels died soonest closest to beam.
- Radiation damage in the LV regulators on the base pre-amps caused instability in the LV power supply for all channels in a column.

Solution:

- Disabled columns as they became unstable.
- Bypass the regulators in the preamps to refurbish the bases during the winter SAD.

Original base

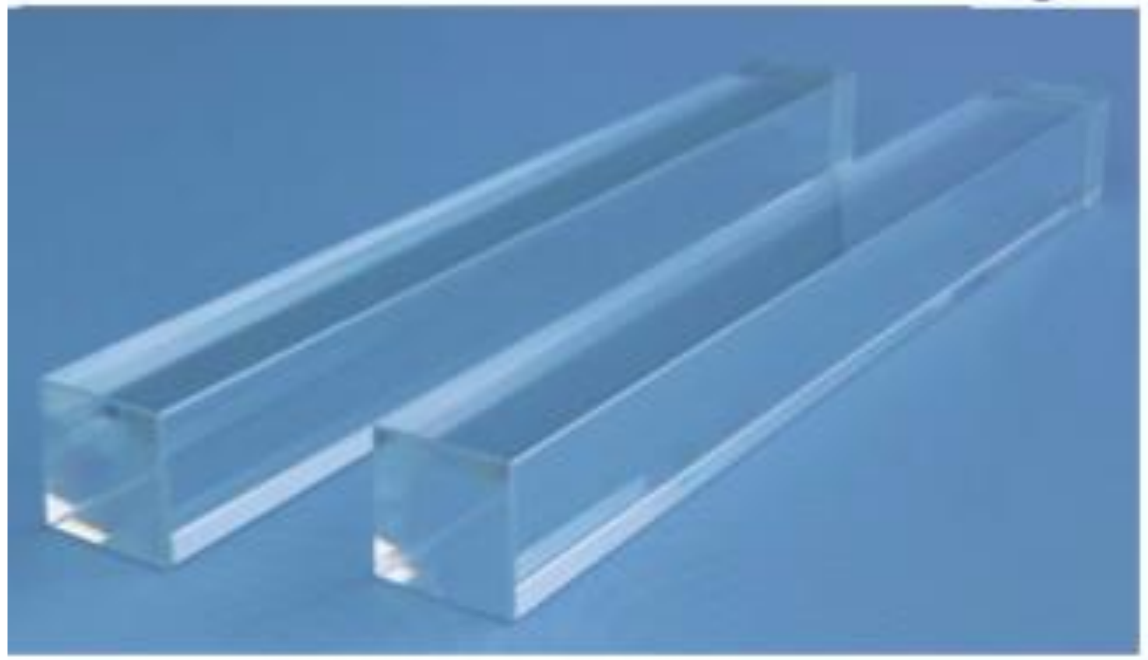
Refurbished base with regulators bypassed

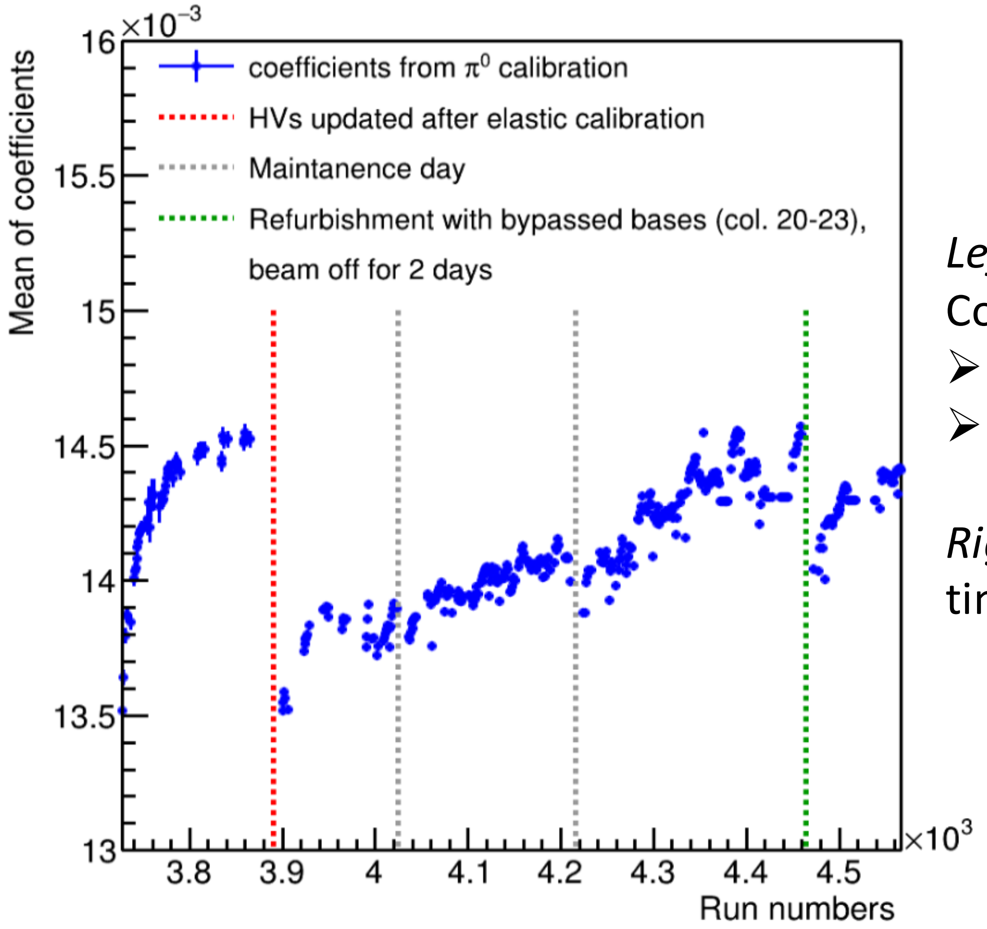


Checking the application of optical grease (top) and reconnecting the distribution boards (bottom) during 2023-2024 Winter SAD

NPS Run Period Challenges

- Essentially defect-free CRYTUR crystals provided consistent light yield and fast time response (5,15 ns)
- However, radiation exposure is known to cause crystal darkening and eventually reduces light transmission.
- Over time, we observed a shift in raw π^0 mass especially pronounced near calorimeter edges
- π^0 mass measurement calibrations were sufficient to adjust for gain shift, and *the crystals did not require bleaching*

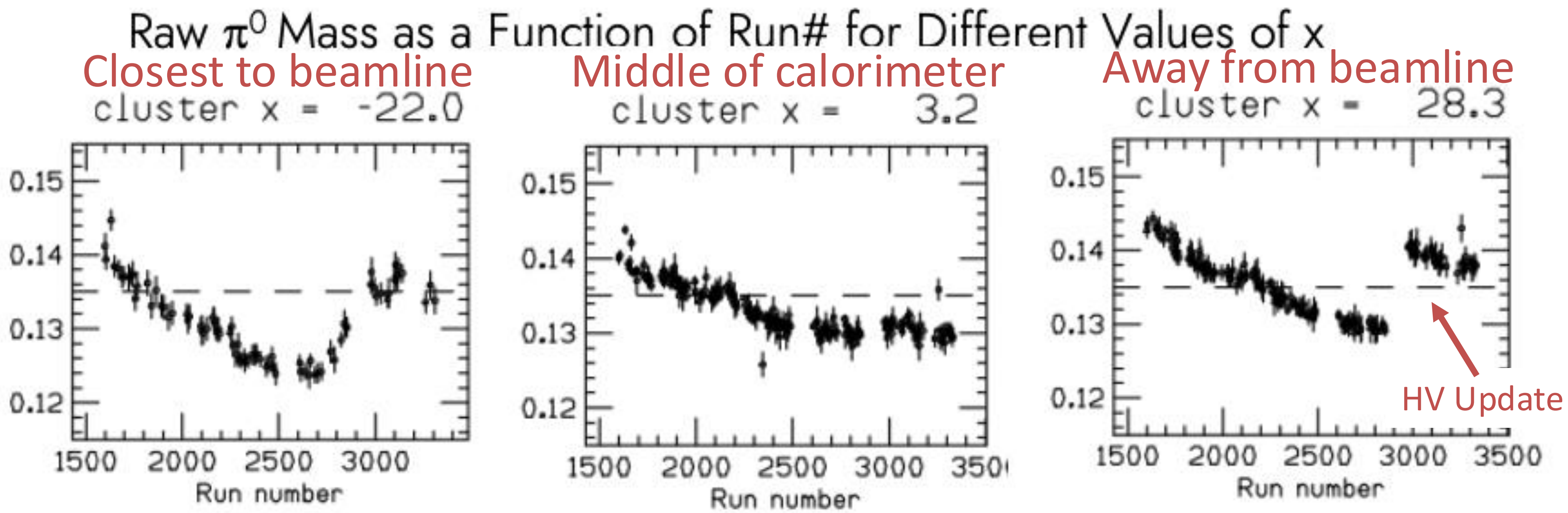




Study by H. Huang

Left: First month of data in 2024
Coefficients decrease
- ➢ Following beam off
- ➢ After HV update

Right: Raw π^0mass shifts over time, related to beam position



Runs shown span from September to December 2023, approximately

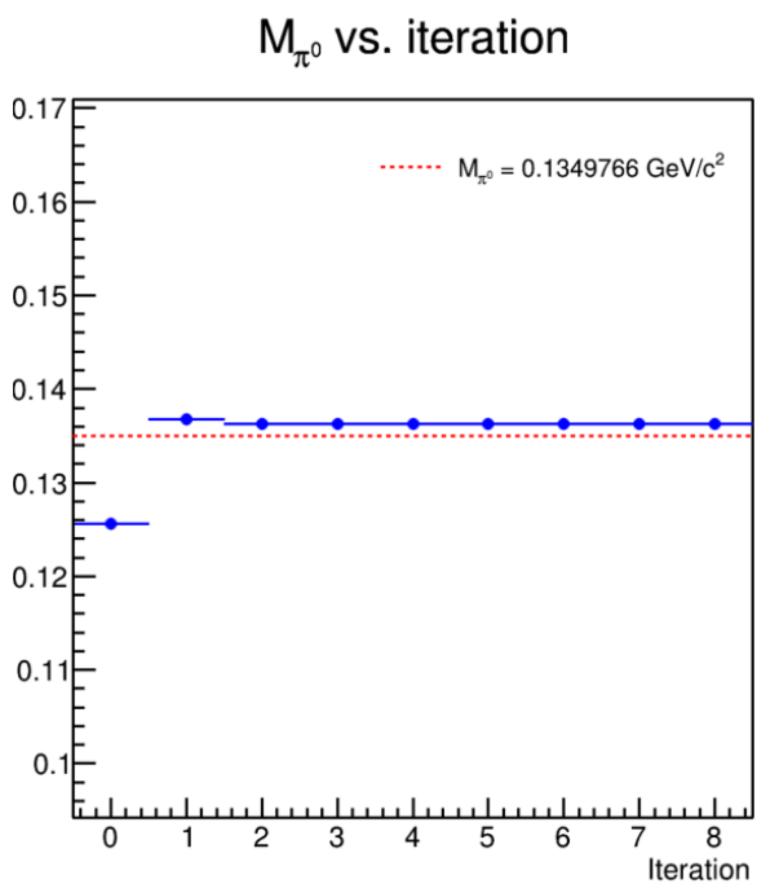
Study by P. Bosted

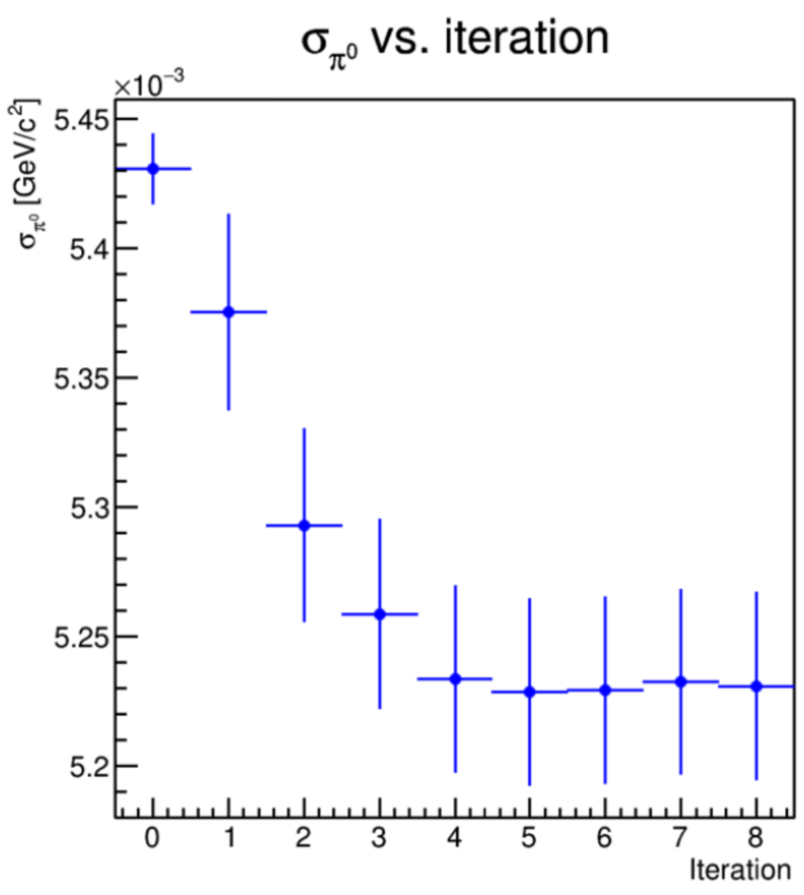
NPS Calibration via π^0 Mass Measurement

Reconstruct π^0 mass via $\pi^0 \rightarrow \gamma\gamma$
→ Adjust gain coefficients for each crystal after run period

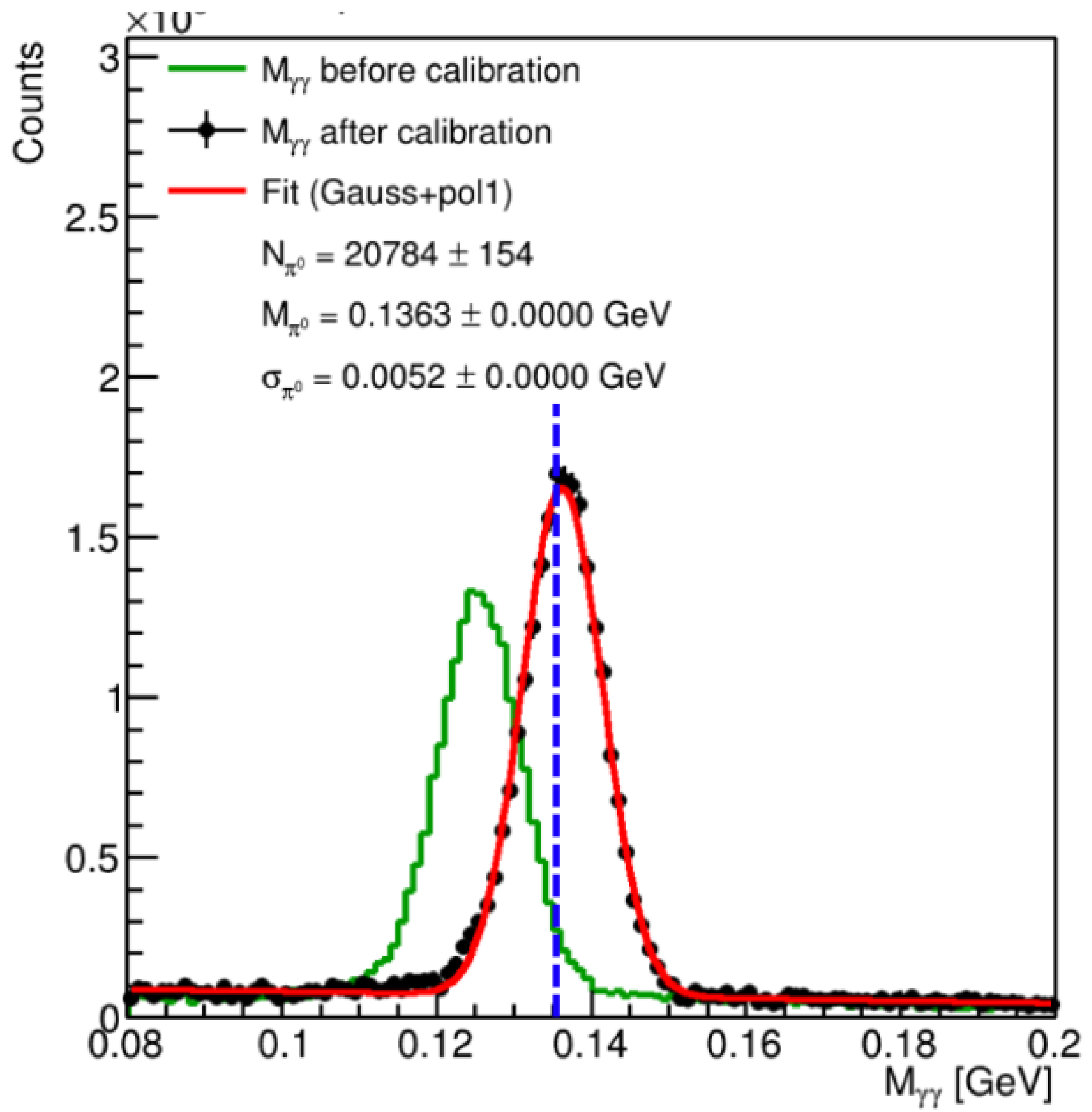
π^0 Mass Measurements require:

- e^- beam on cryo target in production configuration
- At least 20k π^0 events for calibration
  - Depending on kinematic setting, from 0.5 hours to 3 hours of beam time.
- Analysis requires ~3-5 iterations using minimization to achieve stability





π^0 invariant mass after π^0 calibration

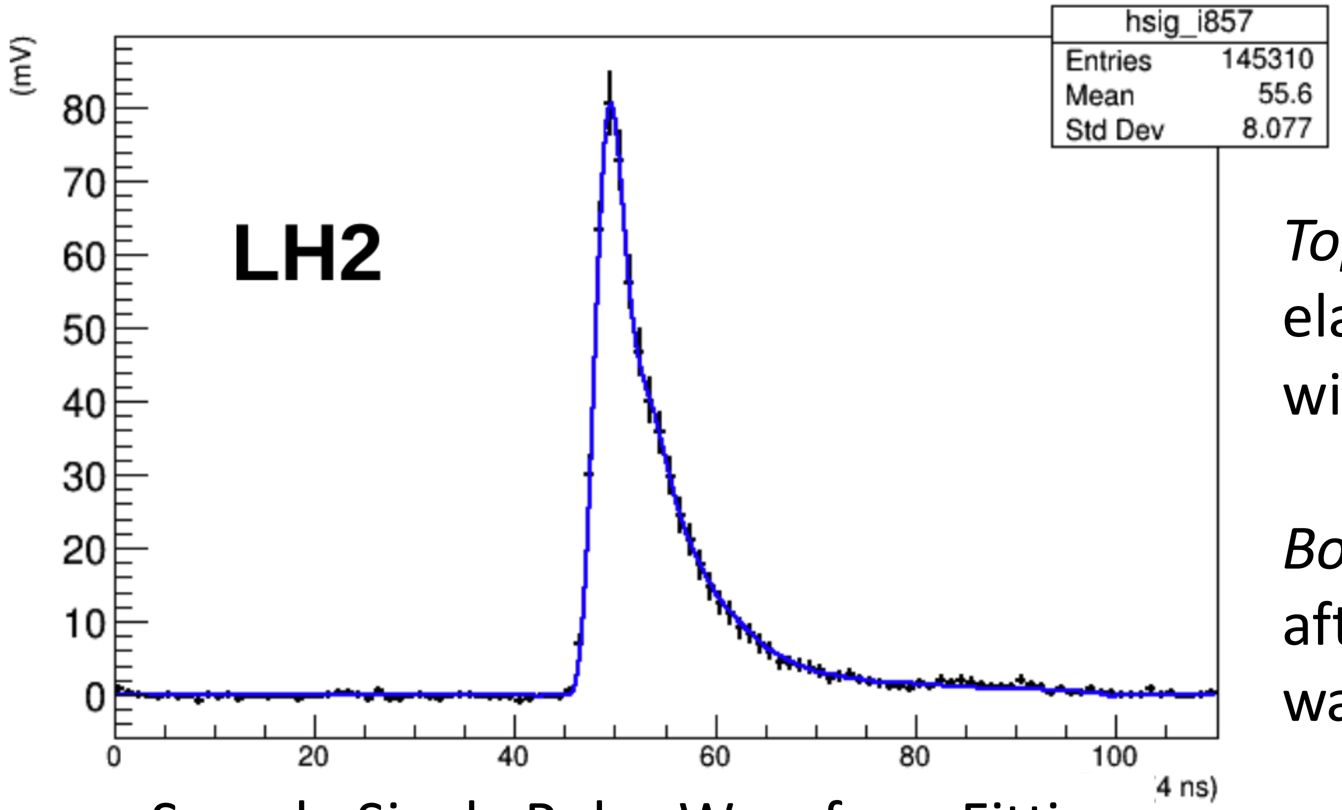


Analysis by H. Huang

NPS Preliminary Waveform Fittings

Waveform analysis is crucial for the best possible resolution

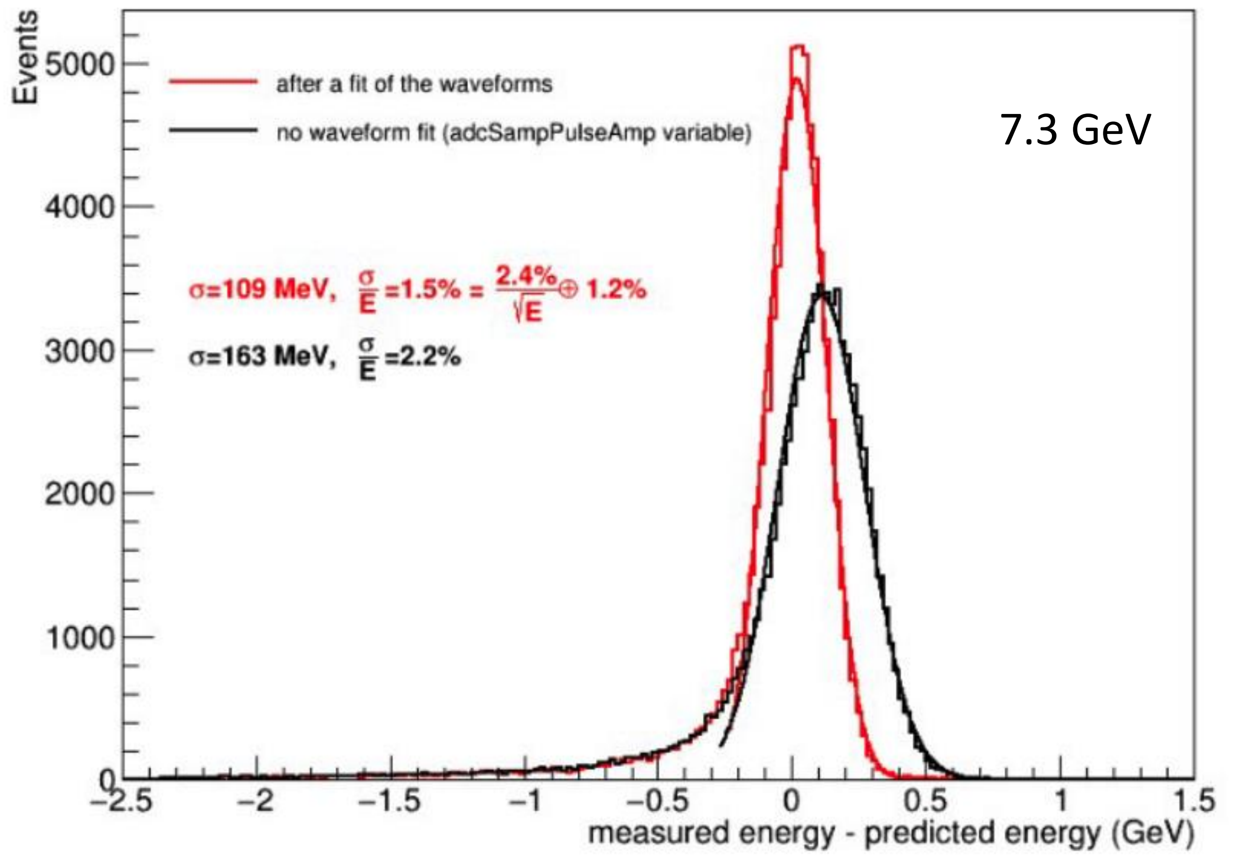
- Waveform fits extract pulse amplitude and time more accurately than using the online FADC peak analysis.
- A reference pulse shape is created from elastic data for each channel.
- A fit function is then created for each channel using spline interpolation between pulse samples and the reference shape.
- Waveform fitting of all data in progress for next 3-6 months.



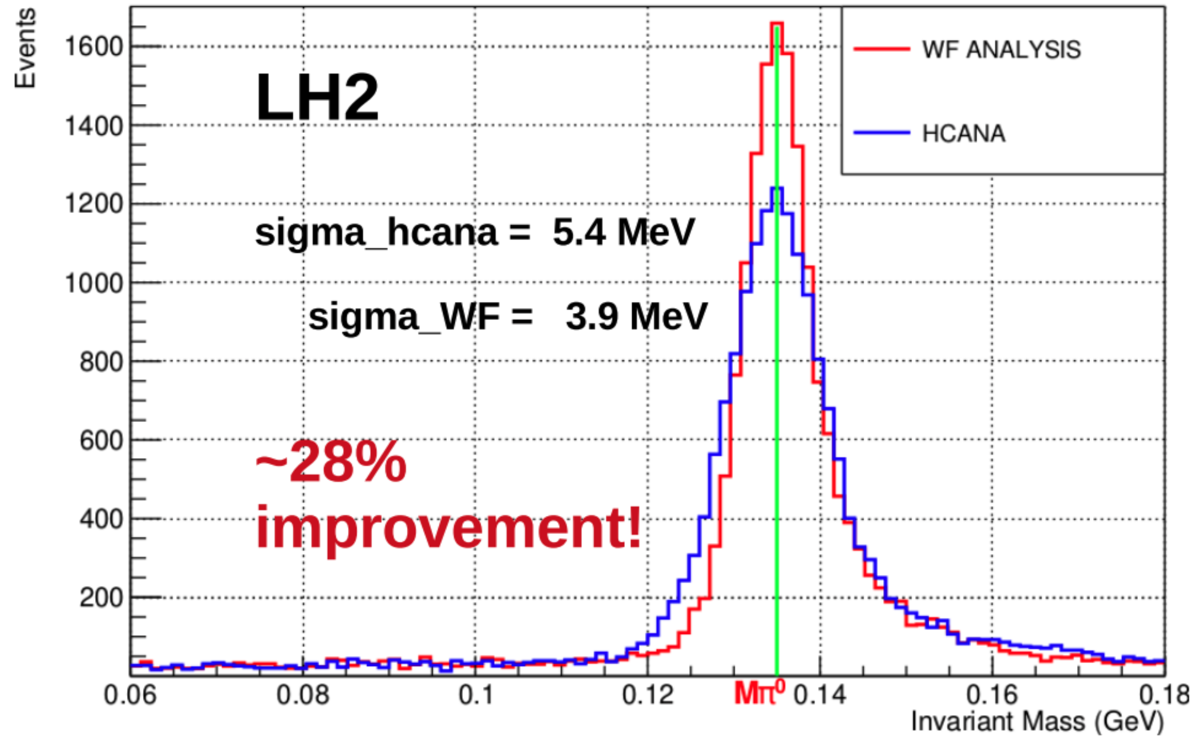
Sample Single Pulse Waveform Fitting

Top Right: Energy resolution from elastic calibration runs with and without waveform analysis (7.3 GeV).

Bottom Right: π^0 invariant mass peak after recalibration using fitted waveform information.

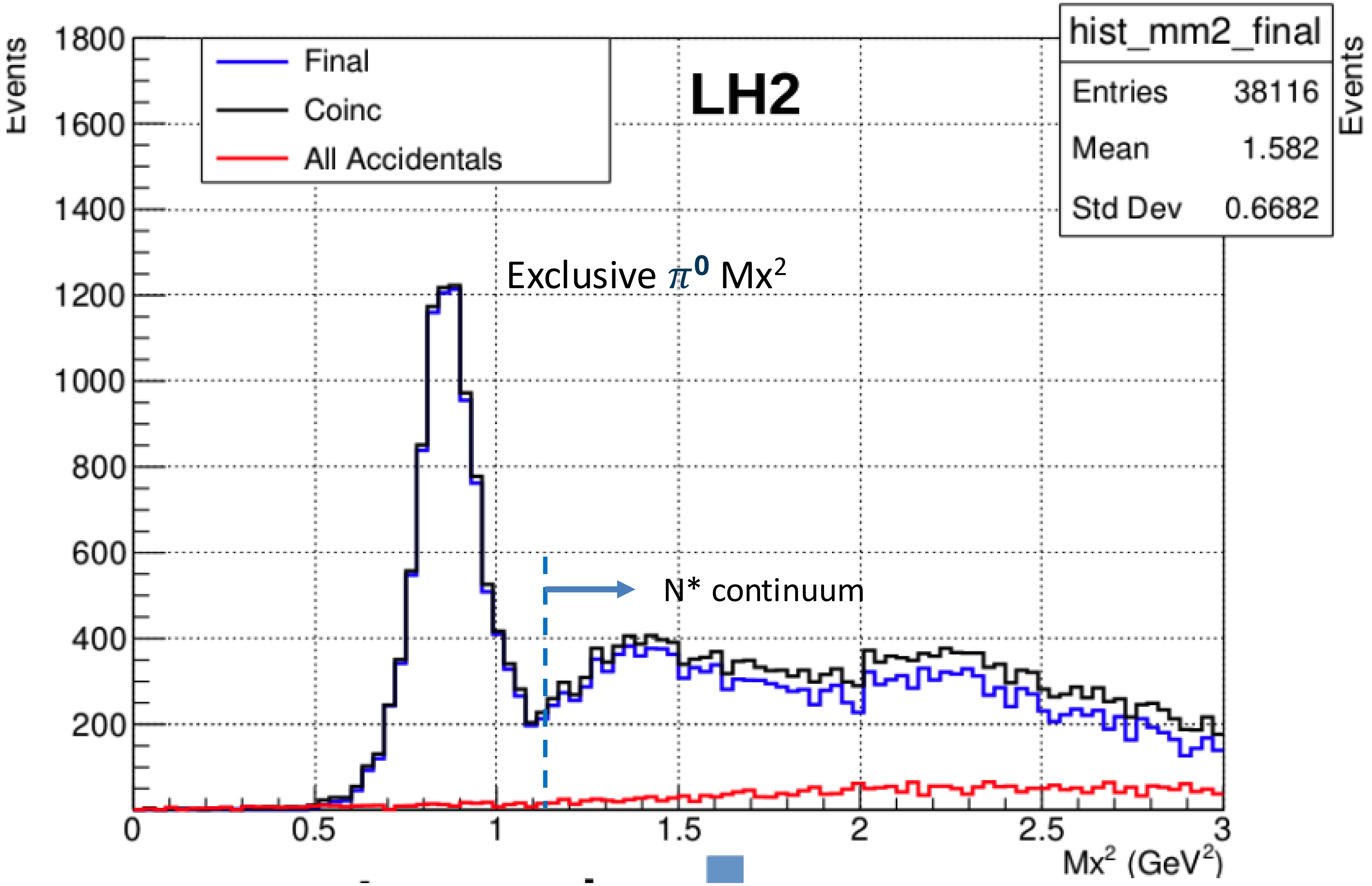


Invariant Mass (GeV)



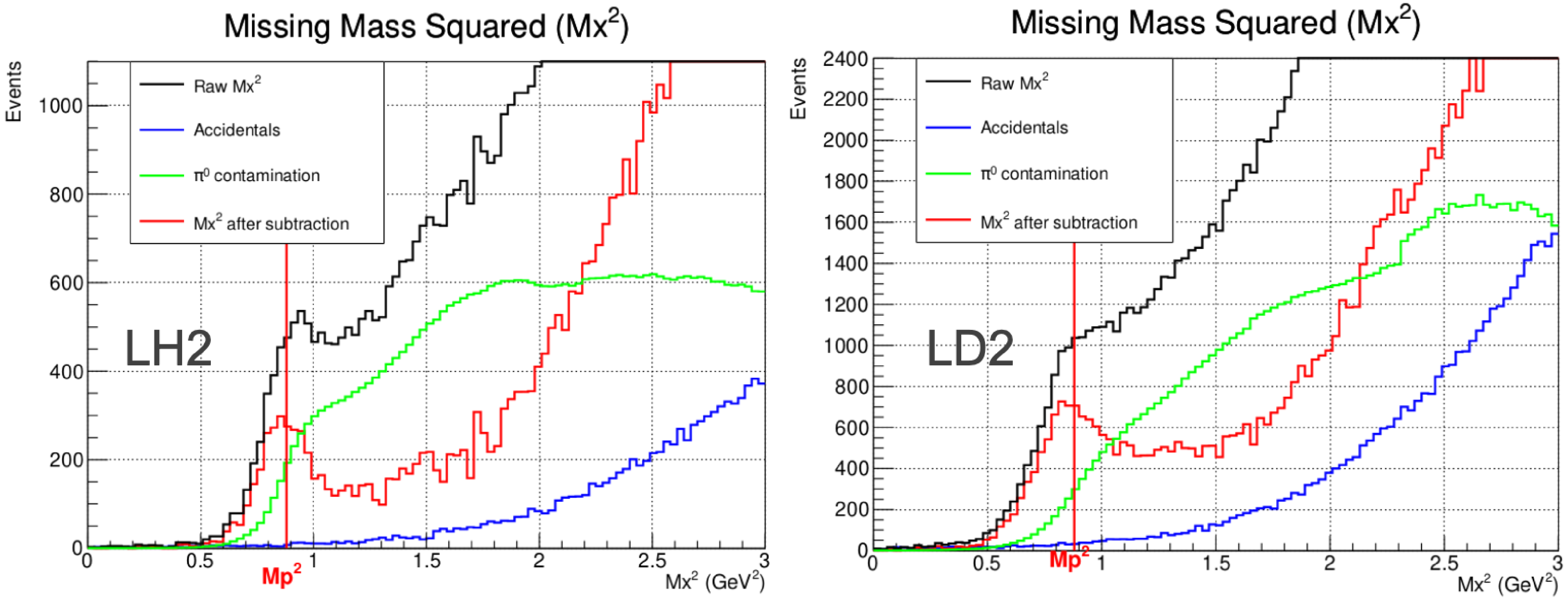
NPS Exclusivity Results – π^0

- π^0 Exclusivity: H$(e,e'\pi^0)p$ extracted using missing mass technique:
  - $M^2_x = (k + P_p - k' - q_{\gamma\gamma})^2$
- Analysis of t-dependence, $\varphi_{q\pi}$ - dependence, and beam helicity dependence of exclusive yield to follow



NPS Exclusivity Results – DVCS

- Exclusivity: H*(e,e'γ)p* from H*(e,e'γ)X*
- DVCS events extracted using missing mass technique
  - ➢ $M^2_x = (k + P_p - k' - q_\gamma)^2$
- DVCS peaks clear after subtraction of π^0 contamination and accidentals
  - ➢ π^0 subtraction: sample of H*(e,e'γ)X' γ* events estimated from measured H*(e,e'γ γ)X'*



Staff, Tech Team, NPS Collaboration – Thank you!