The GMp Experiment:

Precision Measurement of the Proton Elastic Cross Section at High Q^2

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On behalf of the GMp Collaboration

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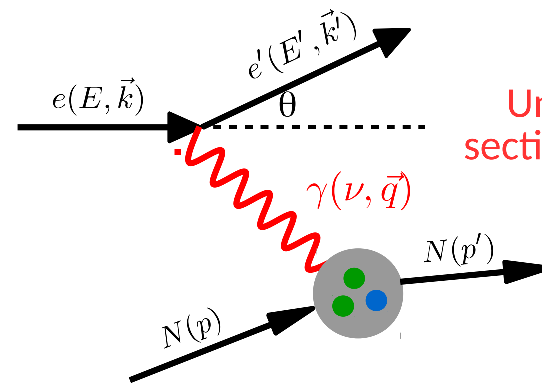
Motivation

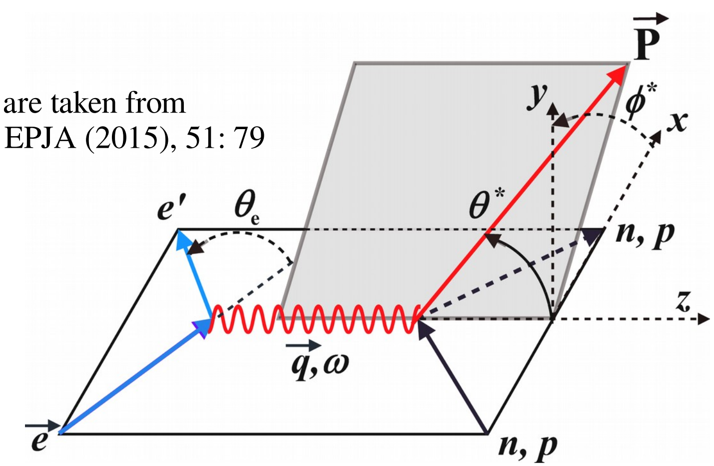
- Elastic electron-proton scattering is one of the most fundamental processes that allow for both high precision calculations and accurate measurements
  - Lowest order results are exactly calculable in both unpolarized and polarized experiments
  - Well-developed interpretation of experimental data in the *one-photon-exchange* mechanism



Unpolarized cross section measurements

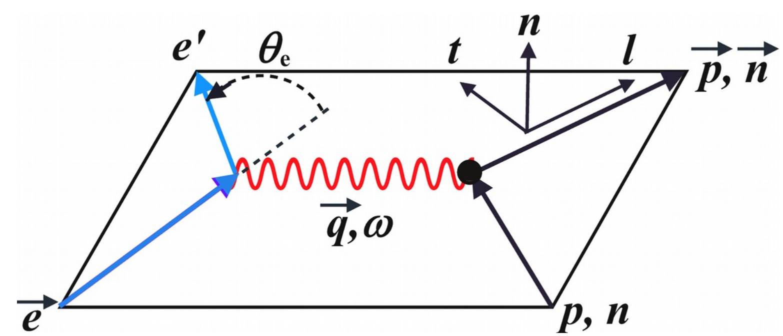
$$\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \frac{\epsilon(G_E)^2 + \tau(G_M)^2}{\epsilon(1+\tau)}$$

Pictures are taken from Punjabi, *et al.* EPJA (2015), 51: 79



Asymmetry measurement with polarized target

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}\frac{G_E}{G_M}}{(\frac{G_E}{G_M})^2 + \frac{\tau}{\epsilon}}$$



Polarization transfer experiment

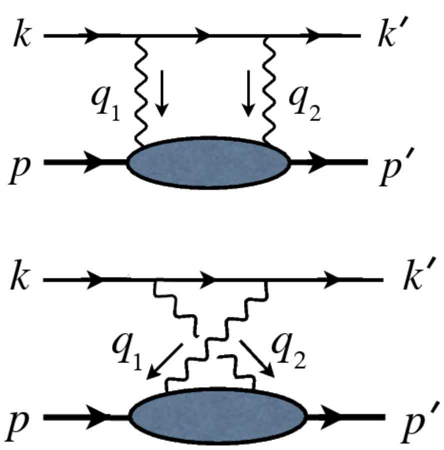
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_{beam}+E_e)}{2M}\tan\frac{\theta_e}{2}$$

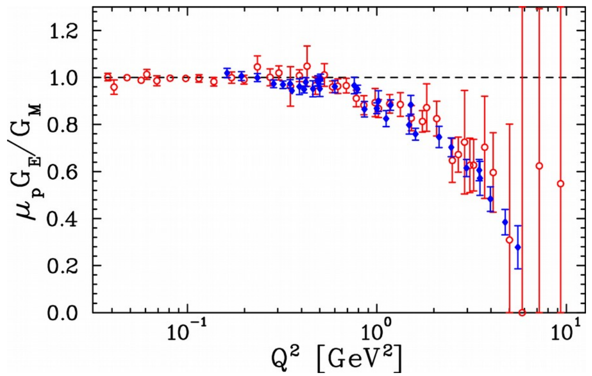
Motivation

But, our understanding of this "simple" process is still *NOT* complete …

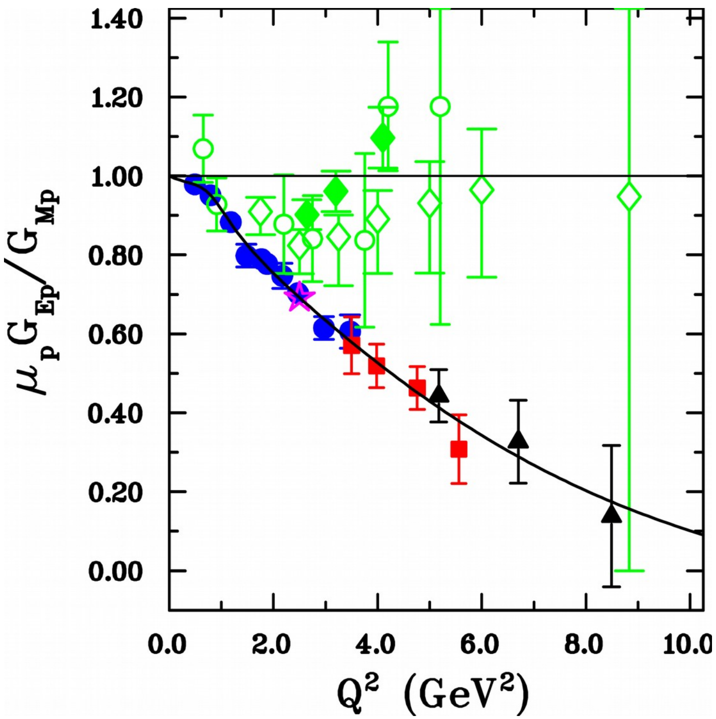
- Discrepancy of the form factor ratio results brings the validity of one-photon exchange approximation into question

Two-photon exchange





Arrington *et al.* PRC 76, 035205 (2007)



Green: Rosenbluth separation results

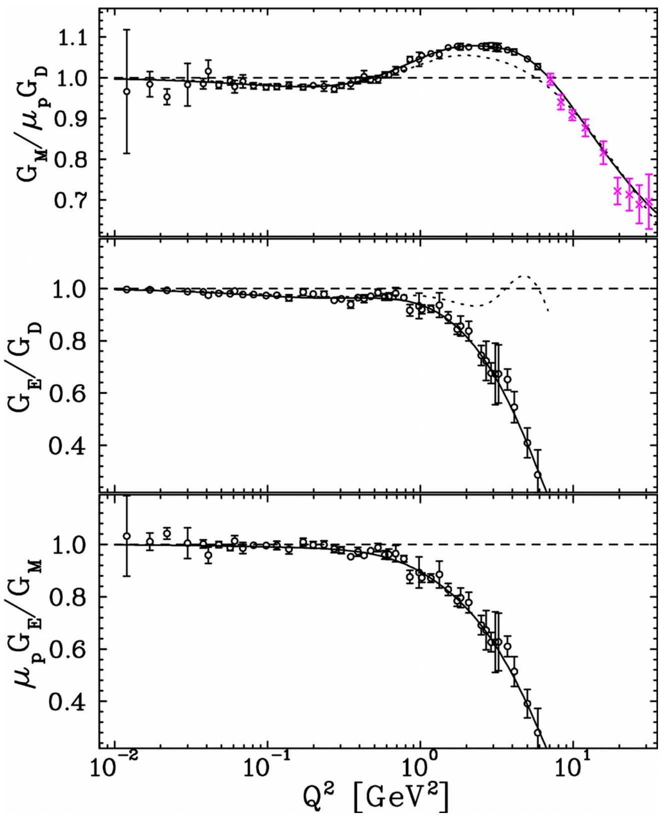
Other: Polarization transfer measurements

Punjabi, *et al.* EPJA (2015), 51: 79

- Current e^-p/e^+p scattering experiments have ***NOT*** found **decisive** evidence of hard two-photon process

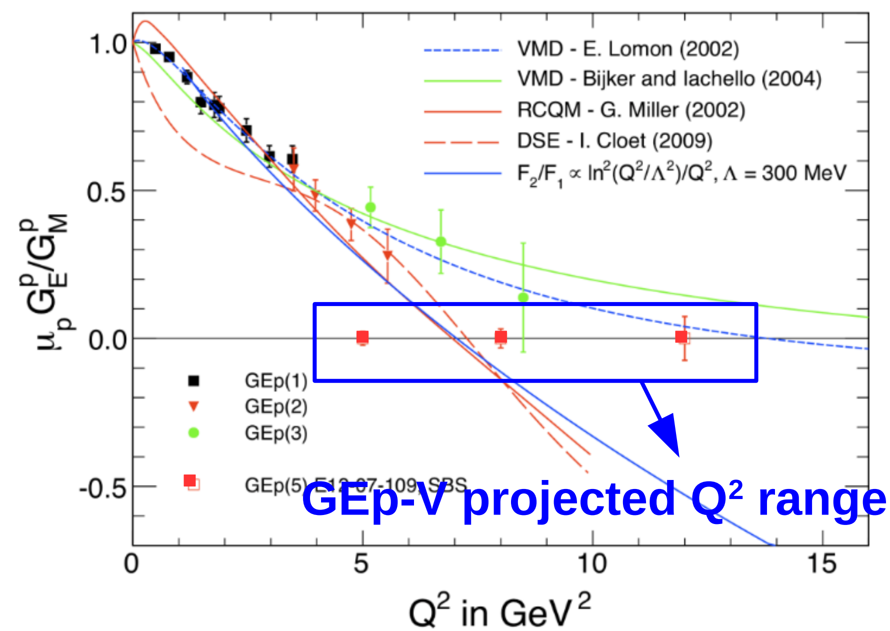
Motivation

- Accurate measurement of *ep* cross section in global analysis can be used to constrain the TPE contribution



Arrington *et al.* PRC 76, 035205 (2007)

- Precision cross section data at large Q^2 combined with future polarization measurements is necessary for determination of GEp, GMp and TPE effect



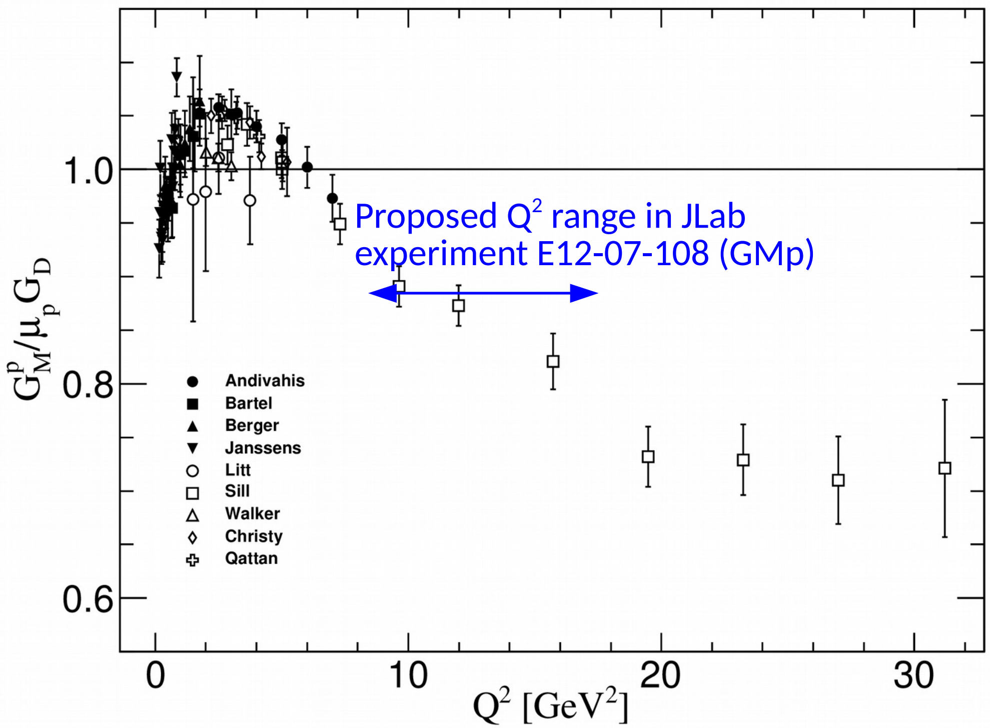
Motivation

- Despite the plenty of measurements at low Q^2, the ep elastic cross section data are very limited at $Q^2>8$ GeV^2
  - Highest Q^2 achieved so far is about 30 GeV^2
  - Cross section drops as $E^2/Q^4 \times G_M{}^2(Q^2) \sim E^2/Q^{12}$ → Hard to reach good statistical FOM due to low cross section
  - Precision measurements will take days or even weeks of beam time → Stability of spectrometer and detector performance becomes important

GMp: high precision measurement of elastic *ep* cross section

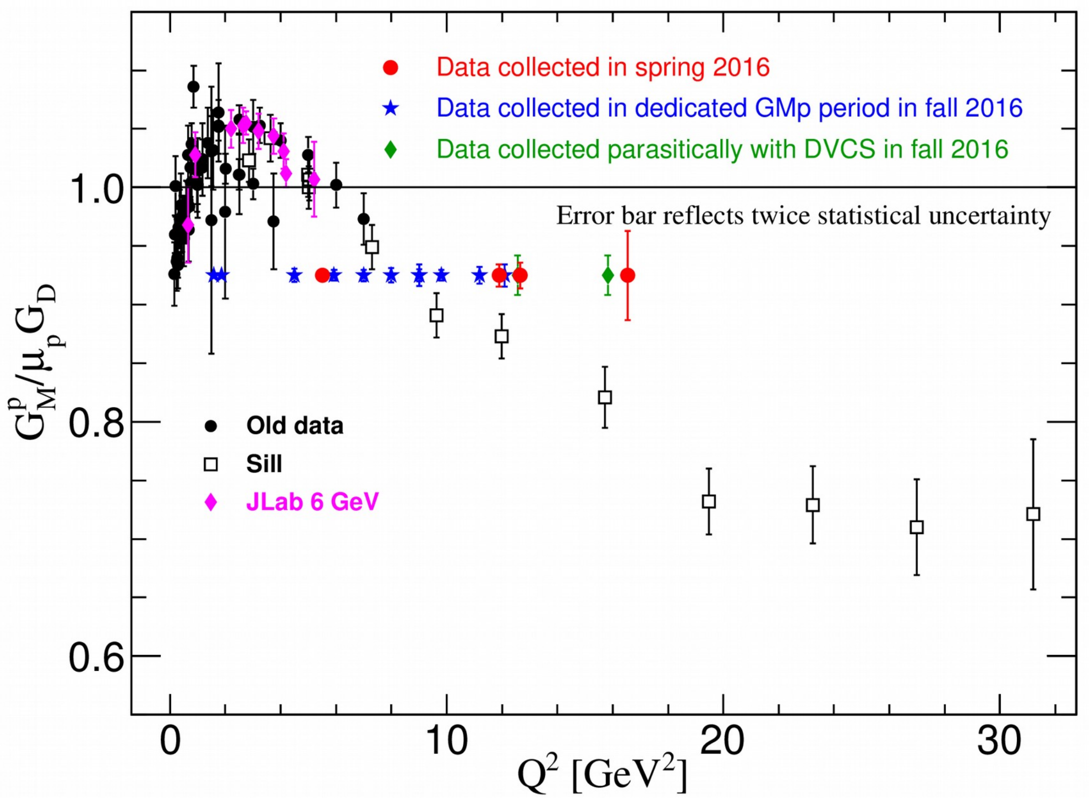
Q^2 range: 7-16 GeV^2

Total error budget: about 2%

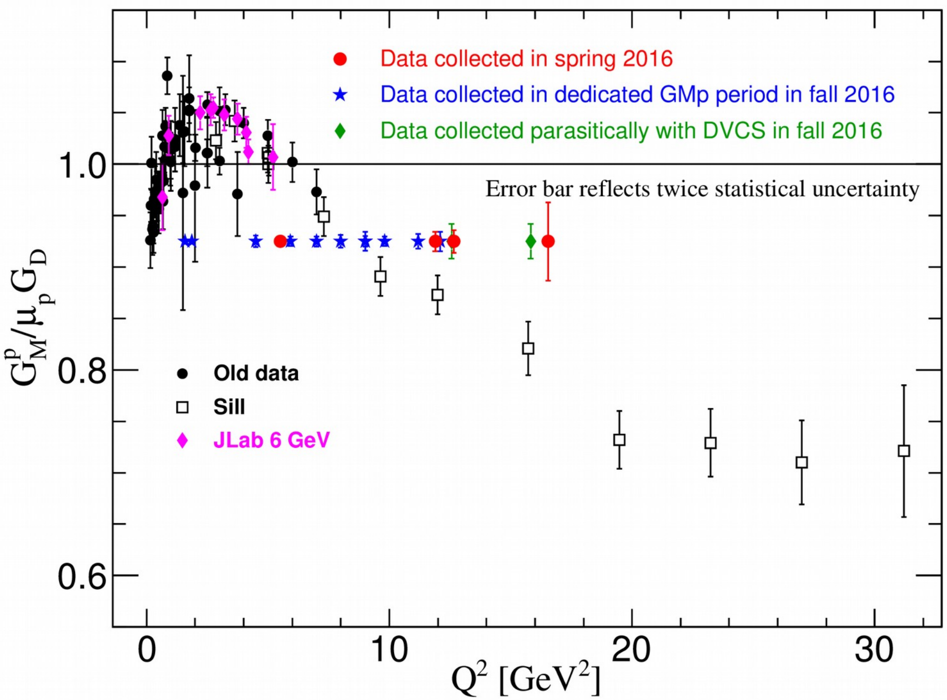


Overview of GMp Experiment

- Performed measurements of elastic *ep* cross section over a Q^2 range of 7-16 GeV^2
  - Precision on the cross section at large Q^2 is improved by a factor of 3 or better
  - Reduced contributions from the electric form factor compared to previous measurements
  - Useful input for many nuclear experiments at similar kinematics

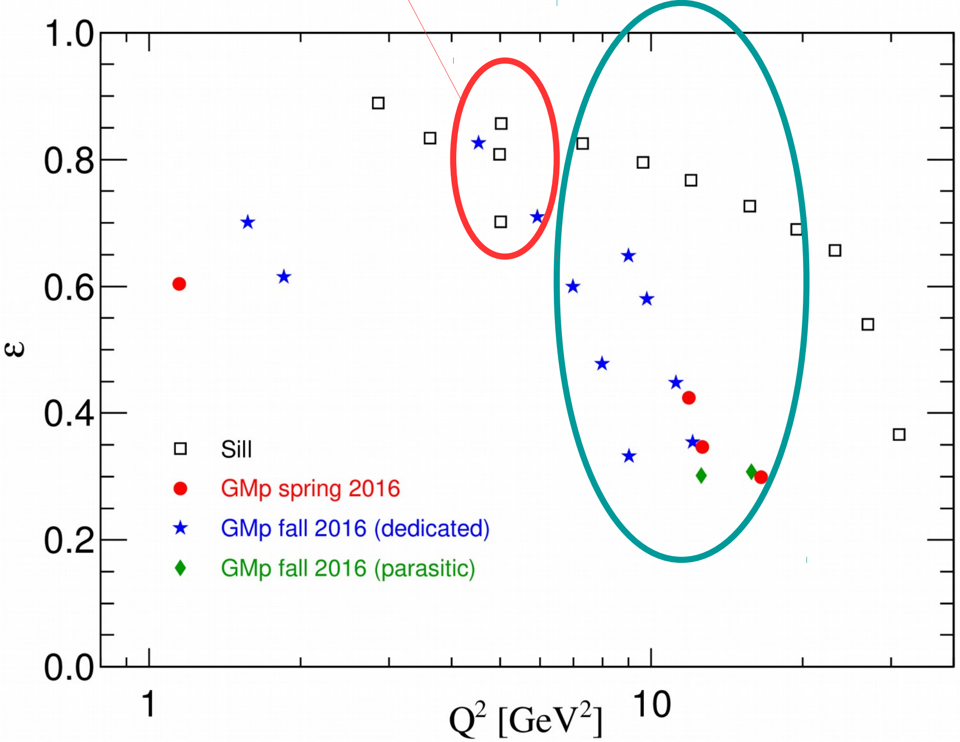


Kinematic Coverage



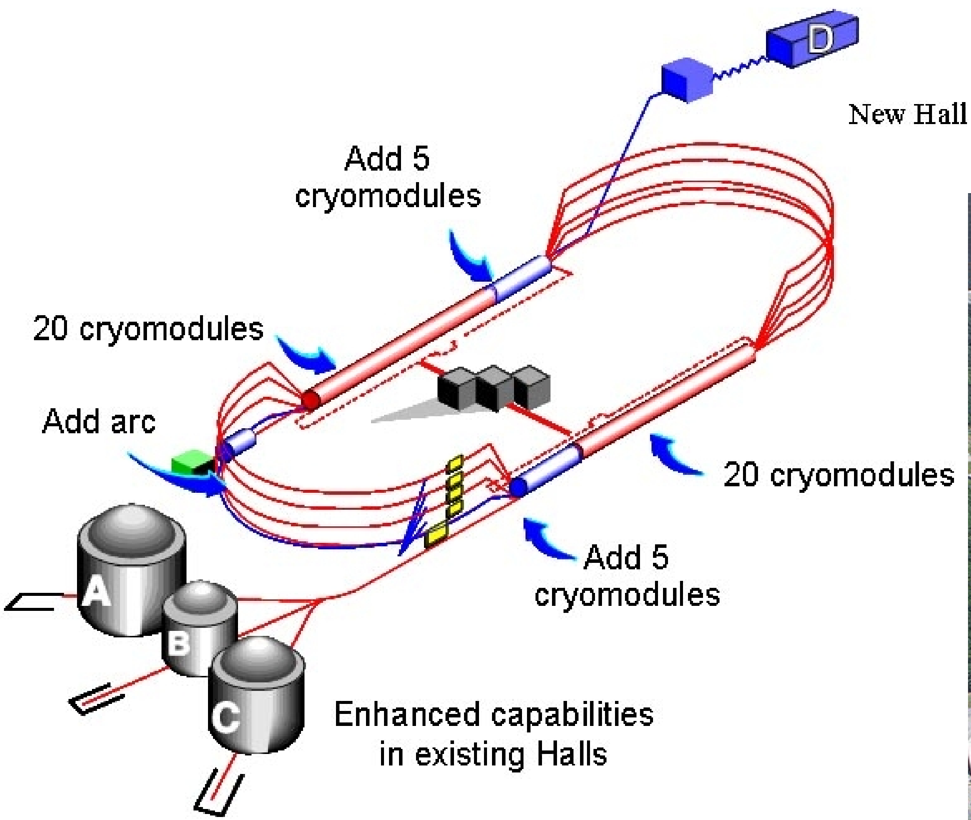
The ε dependence can be derived

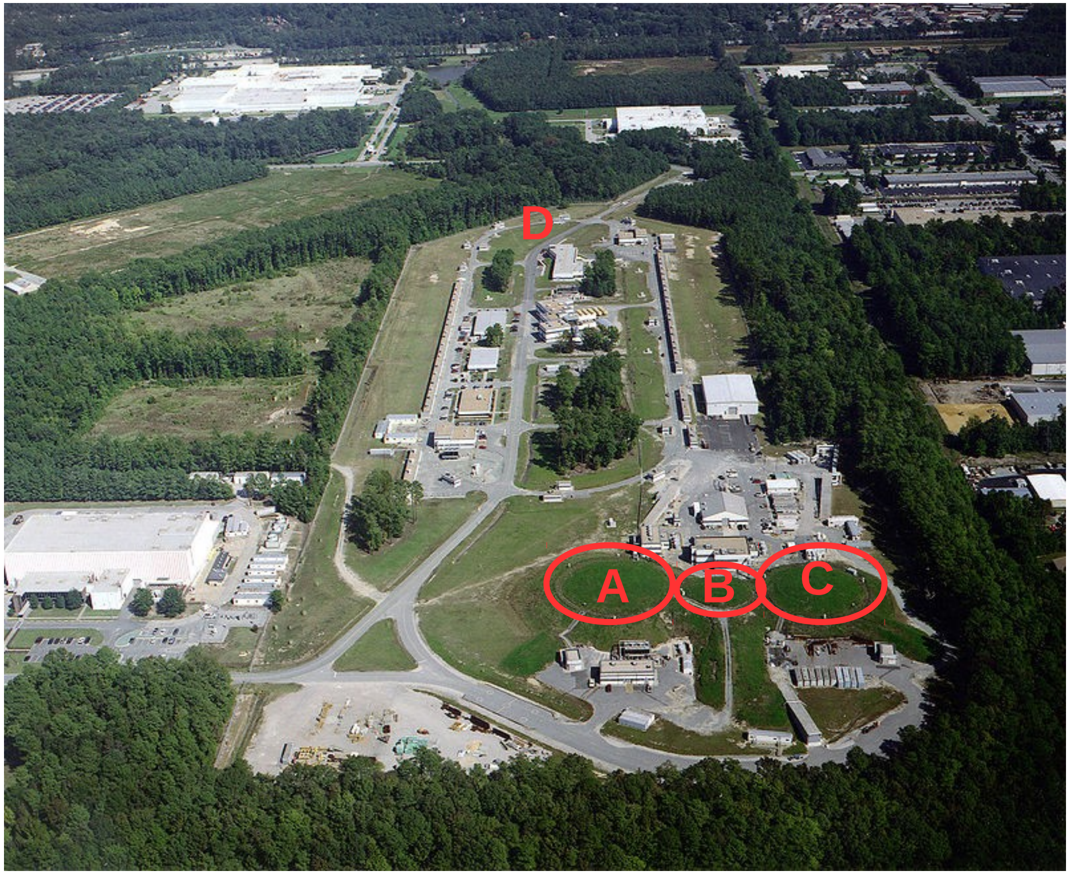
Similar kinematics to SLAC data. Constrain relative normalization



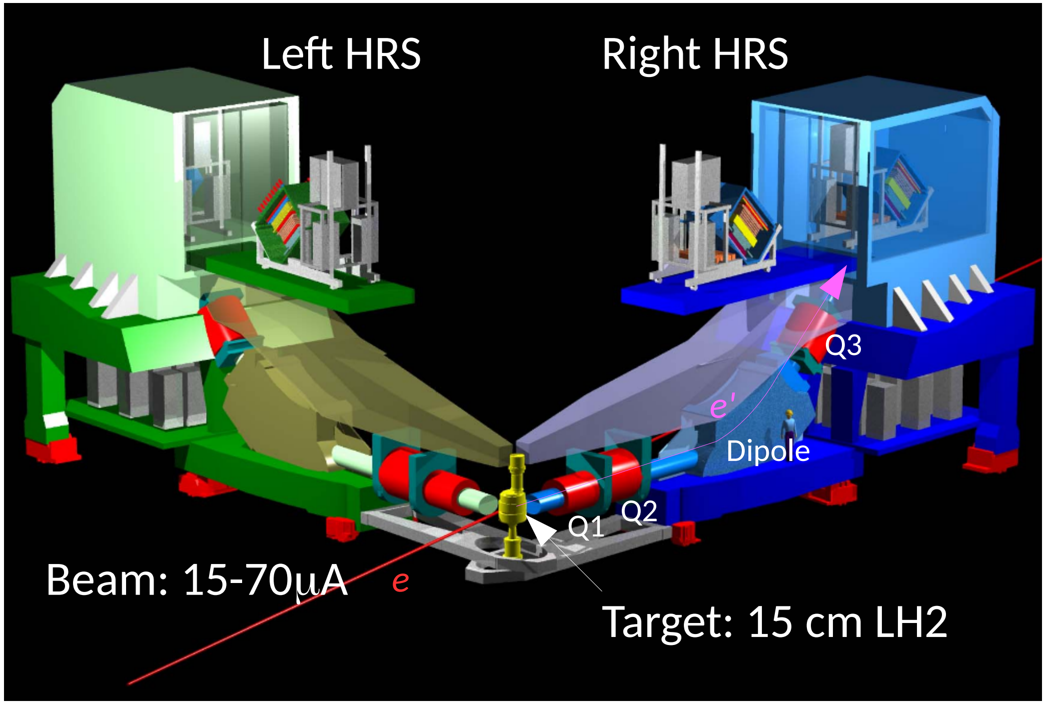
- Kinematic coverage is large enough to separate relative normalization from ε-dependence at large Q^2 in a combined analysis with SLAC data
- Constrain the TPE contribution at high Q^2 when combined with form factor ratios from polarization measurements

Continuous Electron Beam Accelerator Facility





Experiment Setup



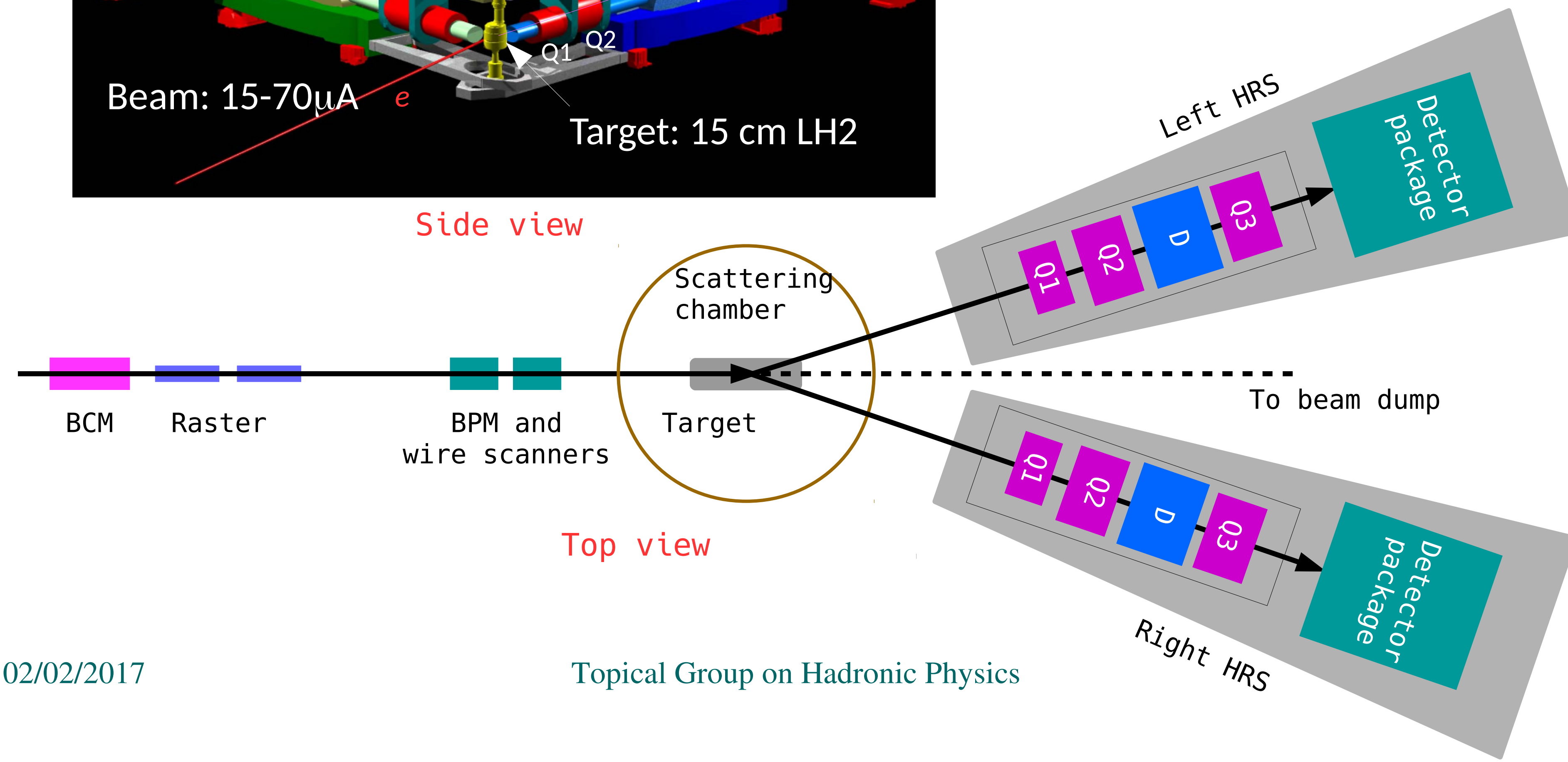
Side view

- *p(e,e')p* – Scattered electrons were detected in the high resolution spectrometer (HRS)

HRS parameters:

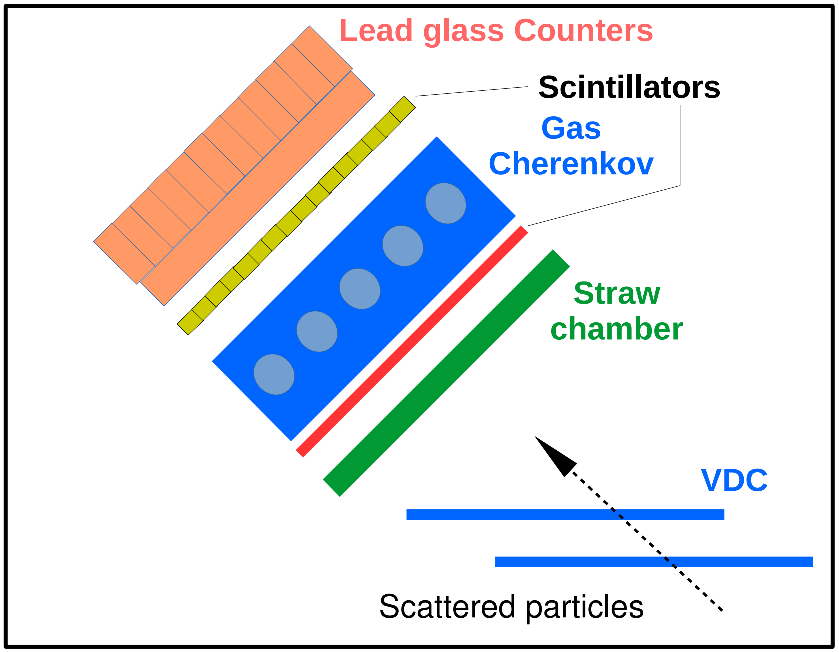
Acceptance: -4.5%<Δp/p<4.5%, 6 msr

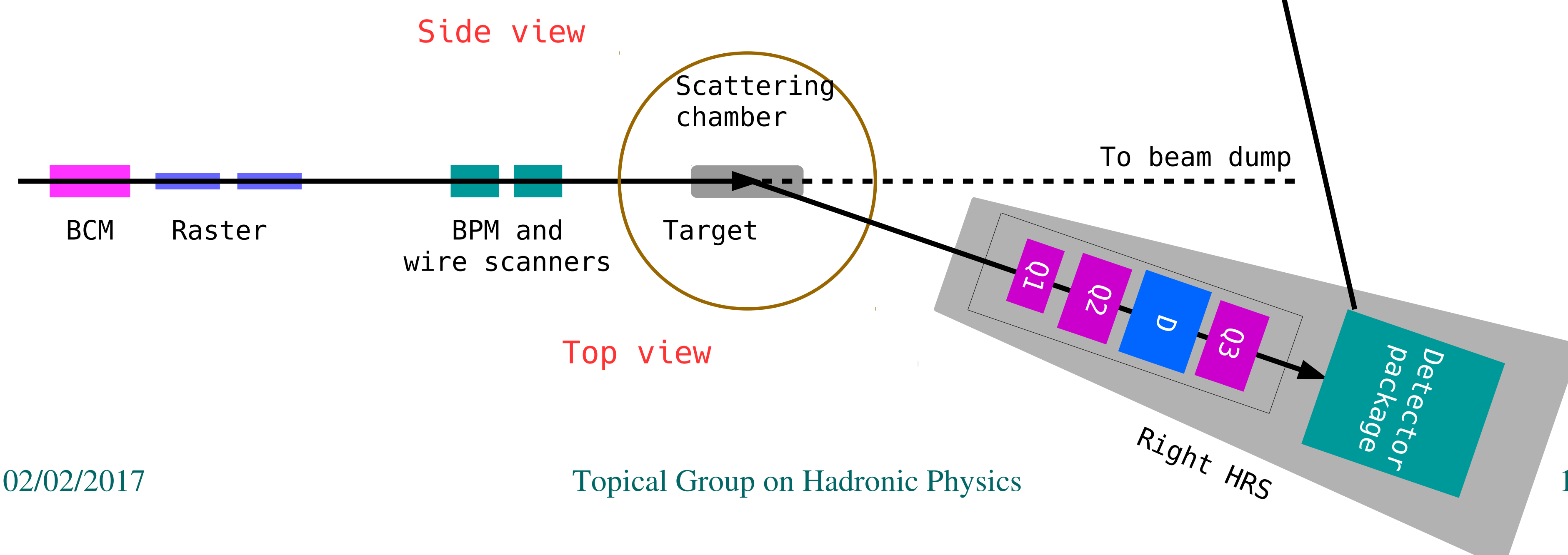
Resolution: $\delta p/p \leq 2\times10^{-4}$
$\delta\phi$=0.5 mrad (Horizontal)
$\delta\theta$=1.0 mrad (Vertical)



Top view

Experiment Setup





Procedure to Extract Elastic Cross Section

- Cross section:

$$\frac{d\sigma}{d\Omega}(\theta) = \int dE' \frac{N_{\text{det}}(E',\theta) - N_{\text{BG}}(E',\theta)}{\mathcal{L} \cdot \epsilon_{\text{eff}} \cdot \text{LT}} \cdot A(E',\theta) \cdot \text{RC}$$

- Reduced cross section:

$$\sigma_{\text{red}} = \frac{d\sigma}{d\Omega} \frac{\epsilon(1+\tau)}{\sigma_{\text{Mott}}} = \frac{4E^2 \sin^4\frac{\theta}{2}}{\alpha^2 \cos^2\frac{\theta}{2}} \frac{E}{E'} \epsilon(1+\tau) \frac{d\sigma}{d\Omega}$$

- Parameters:
  - N_{det}: number of scattered elastic electrons detected
  - N_{BG}: events from background processes
  - $\mathcal{L}$: Integrated luminosity
  - ϵ : Corrections for efficiencies
  - LT: live time correction
  - A(E',θ): spectrometer acceptance
  - RC: radiative correction factor
  - E: beam energy
  - θ: Scattering angle

A thorough understanding of all these parameters is crucial for a precision cross section measurement

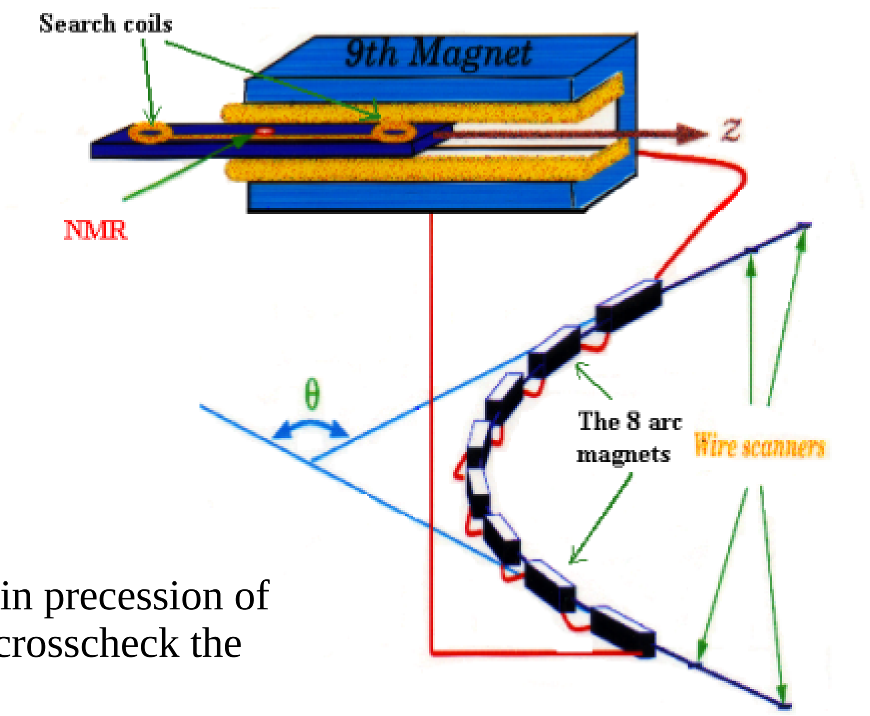
Beam Energy Measurement

- The energy of the beam was measured by the ARC method at each beam energy setting

$$p = k\frac{\int \vec{B}\cdot d\vec{l}}{\theta}$$

$$k = 0.299792 \text{ GeV rad T}^{-1}\text{ m}^{-1}/c$$

  - The bend angle is determined by using wire scanners
  - The magnetic field integral is based on the measurement on a reference magnet



- A second determination of beam energy by measuring the spin precession of polarized electrons in the accelerator was also performed to crosscheck the ARC results

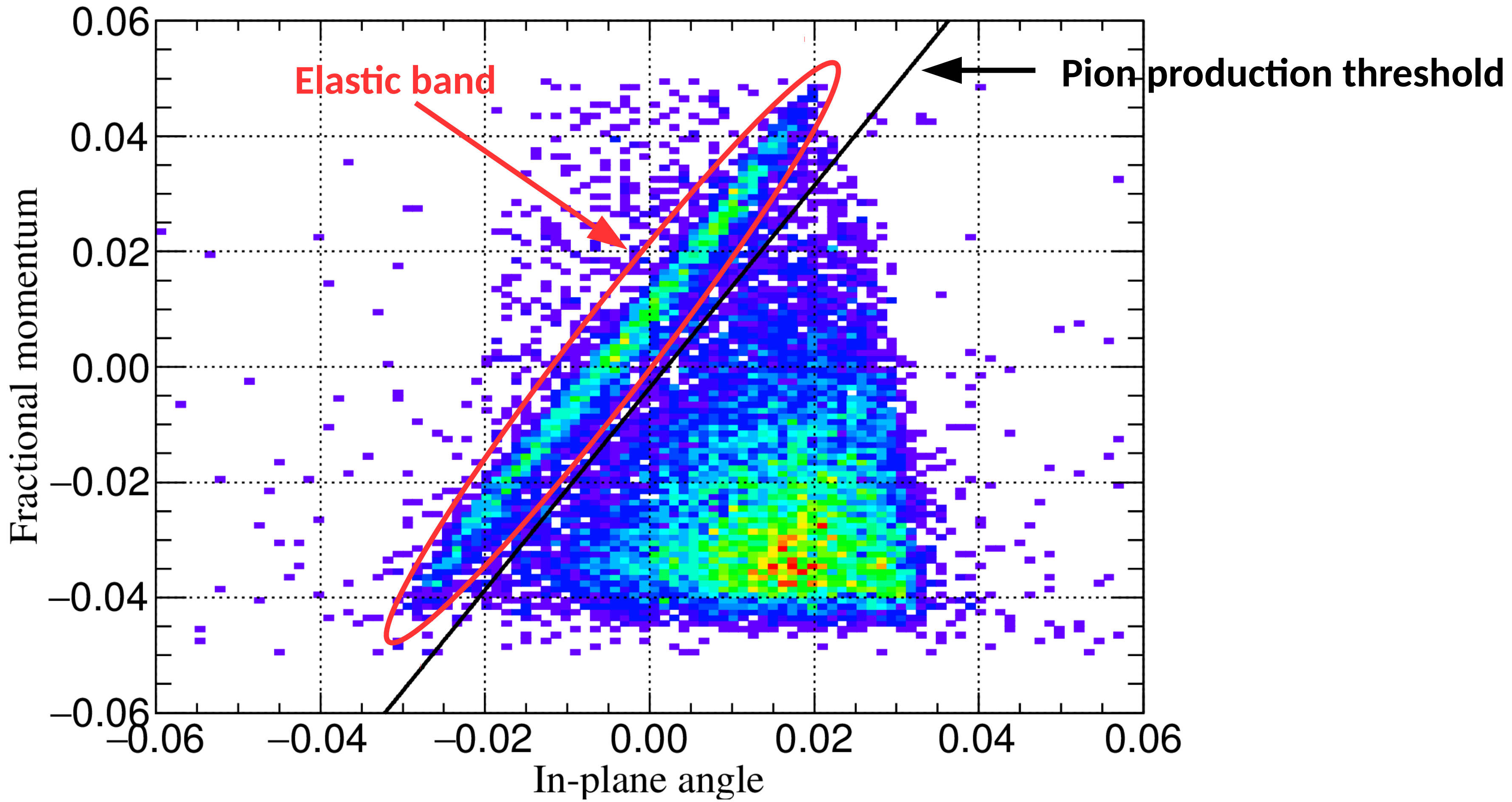
Uncertainty in beam energy is estimated to be about 0.05%

Scattering Angle

- The spectrometer angle at each kinematic setting was either surveyed or studied with a carbon-pointing run
  - The surveyed results are accurate to 0.1 mrad
  - The angle of incoming electron beam was measured by two beam position monitors on the beam line to about 80 μrad
  - The angle settings will also be checked by looking at reconstructed kinematics

Selection of Elastic Electrons

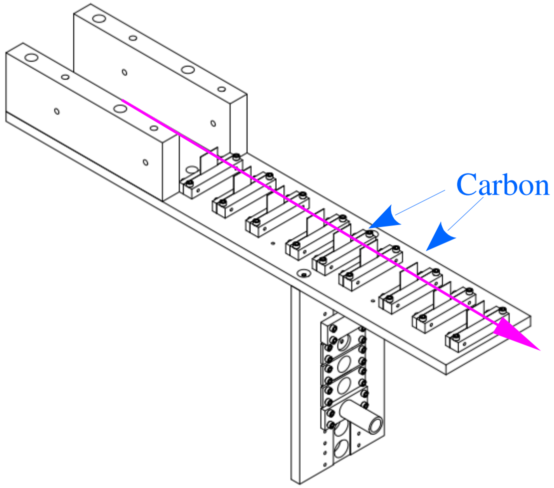
$Q^2 = 15.8\ \text{GeV}^2 \quad \epsilon = 0.3 \quad E_{\text{beam}} = 10.617\ \text{GeV} \quad \theta = 48.75\,\text{deg}$

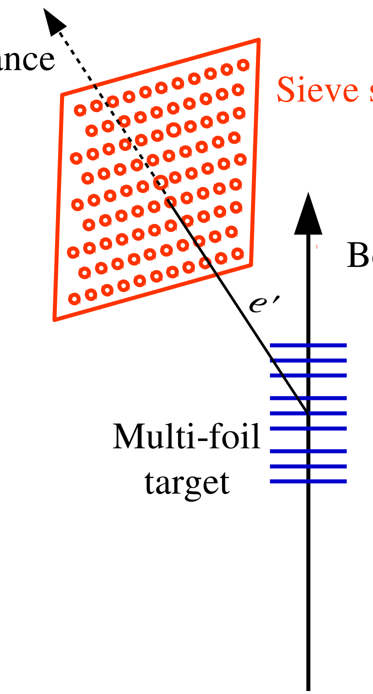


Optics Calibration for Extended Target

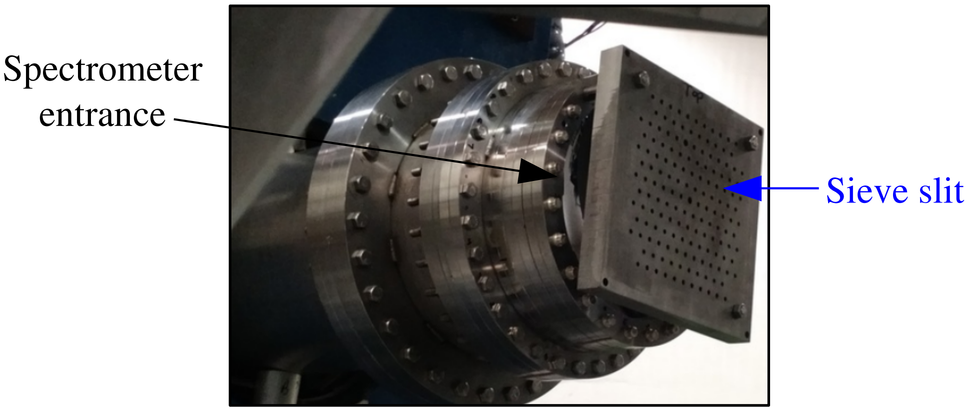
- **Angle and vertex calibration:** used deep inelastic electrons from multi-foil carbon target

A 9-foil carbon target covers a total length of 20 cm along the beam direction





A 1-inch-thick tungsten sieve slit with high density holes at the spectrometer entrance selects scattered electrons in specific directions

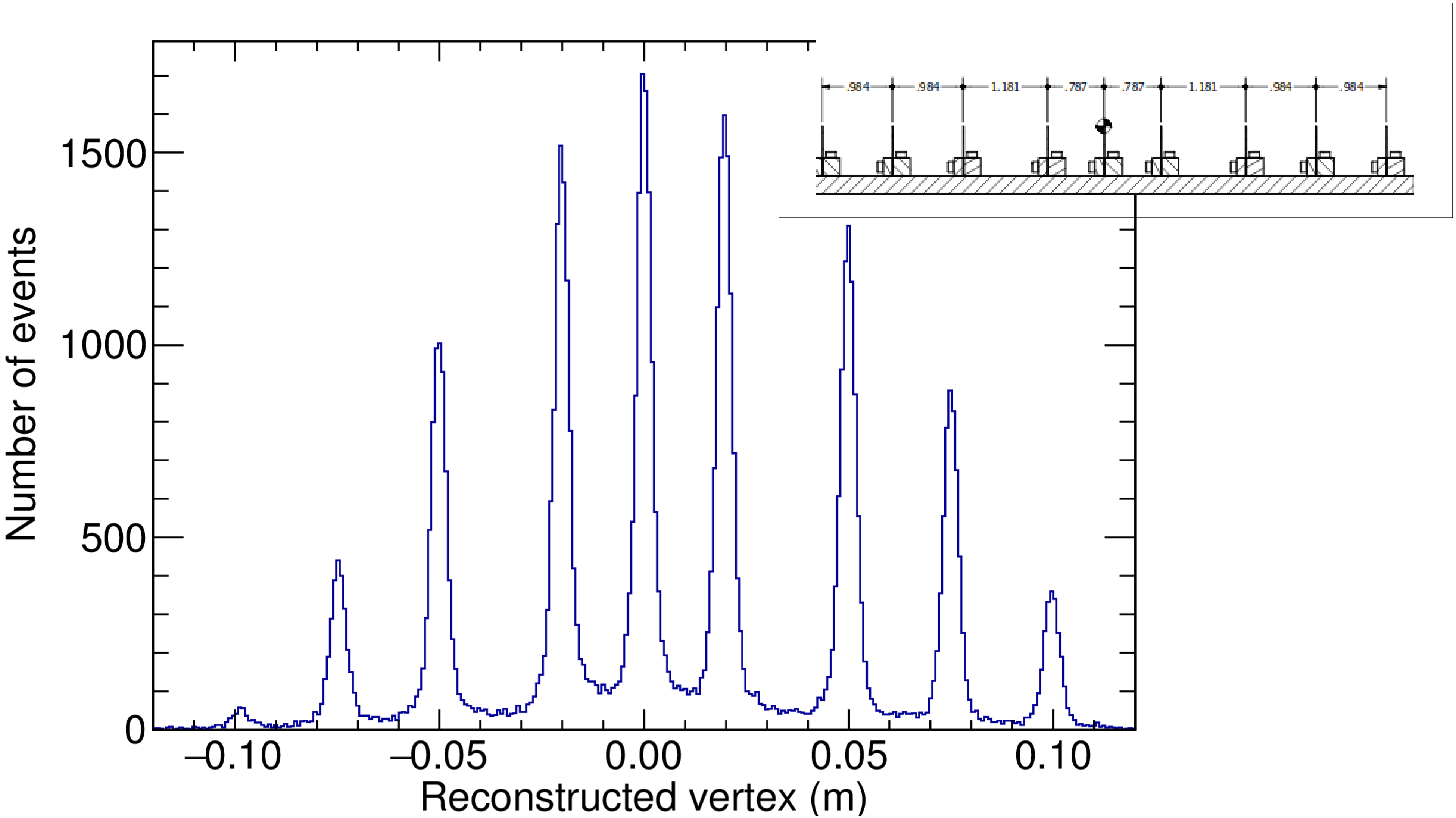


- Algorithm: Minimization of χ^2 by varying the optics coefficients

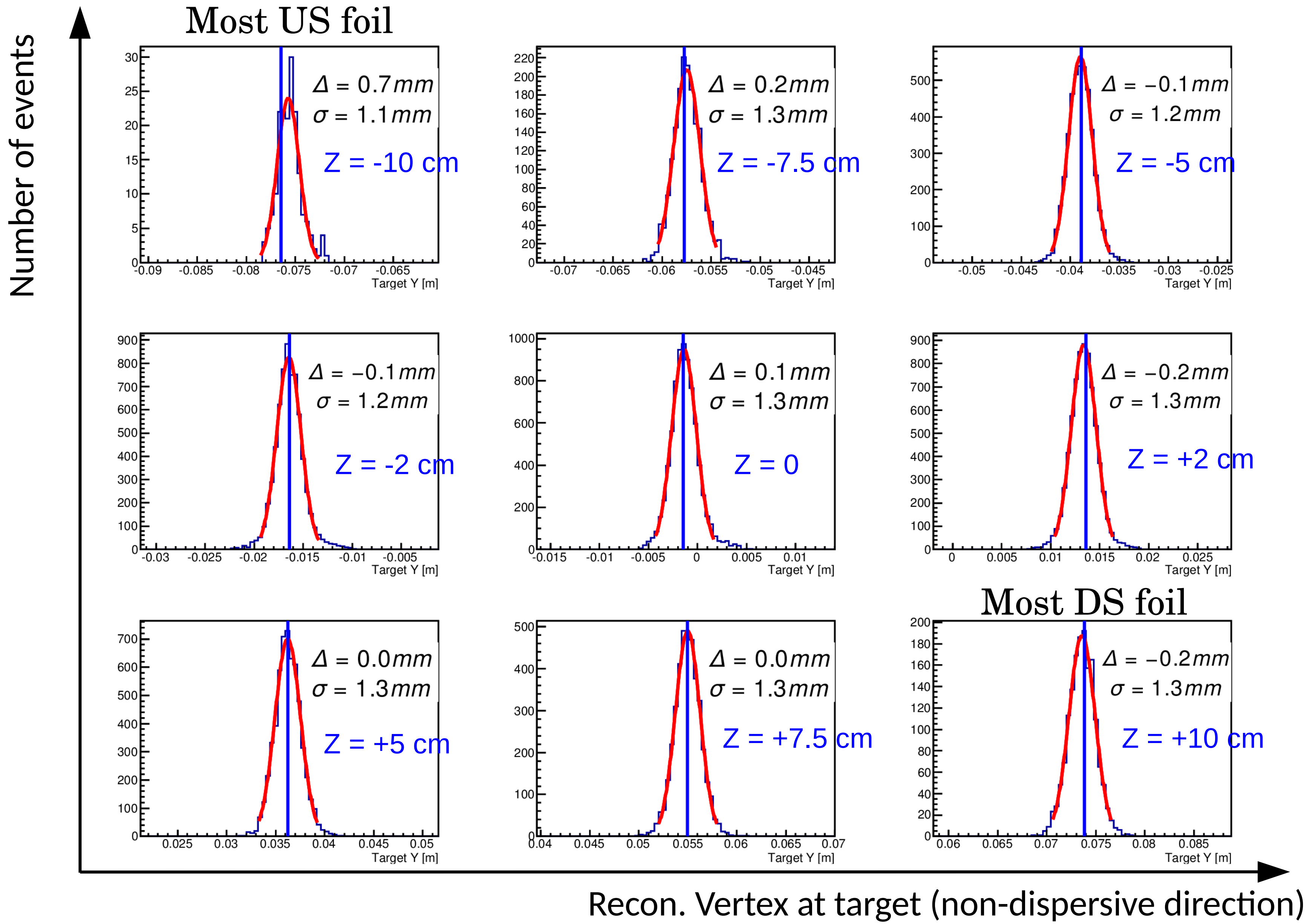
$$\chi^2(y_{tg}) = \sum_{\text{events}} (Y_{ijkl} x^i_{fp} \theta^j_{fp} y^k_{fp} \phi^l_{fp} - y^{\text{survey}}_{tg})^2$$

- **Momentum calibration:** used elastic electrons from liquid hydrogen target

Optics Calibration for Extended Target

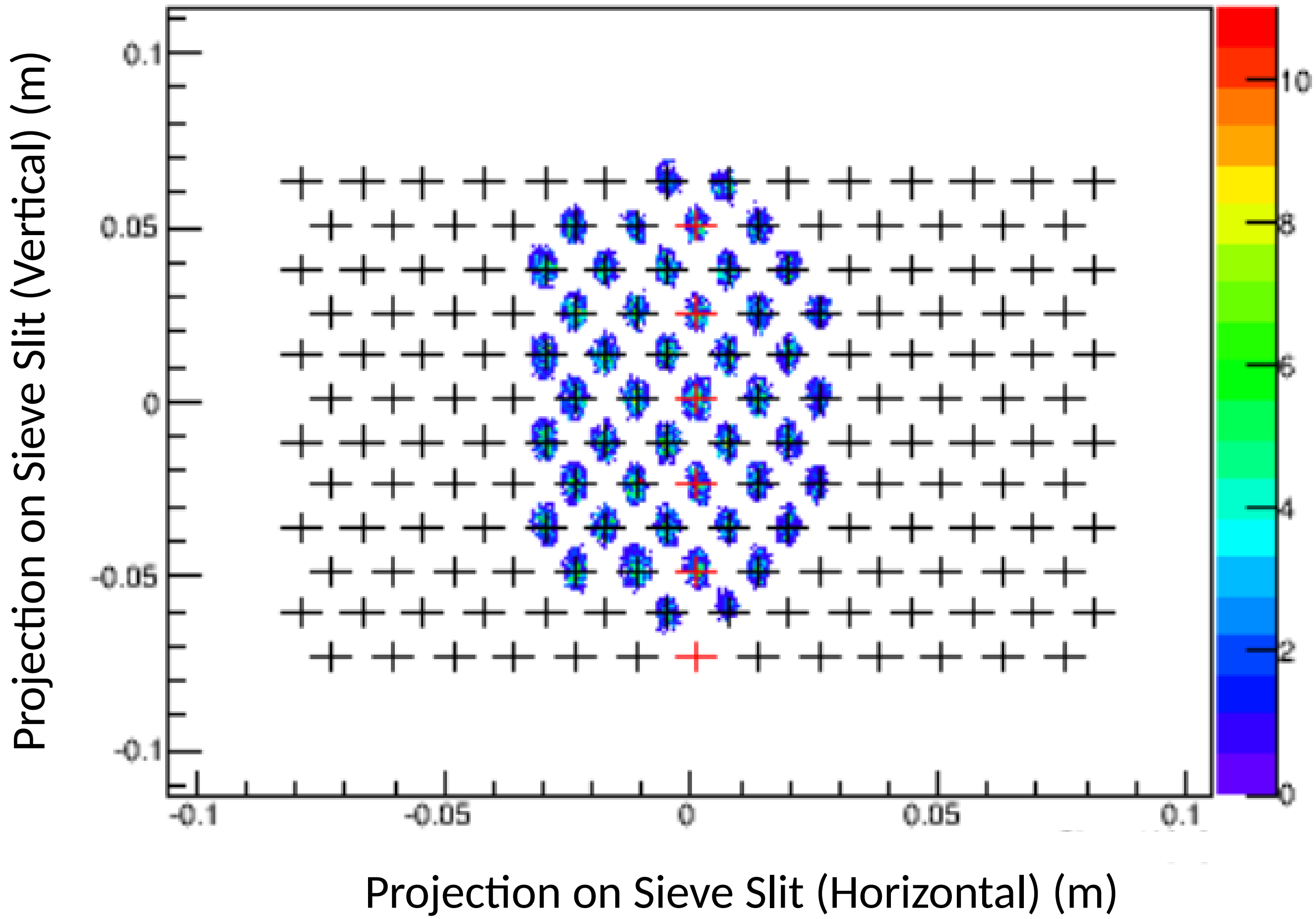


Optics Calibration for Extended Target



Optics Calibration for Extended Target

Sieve pattern of central carbon foil target



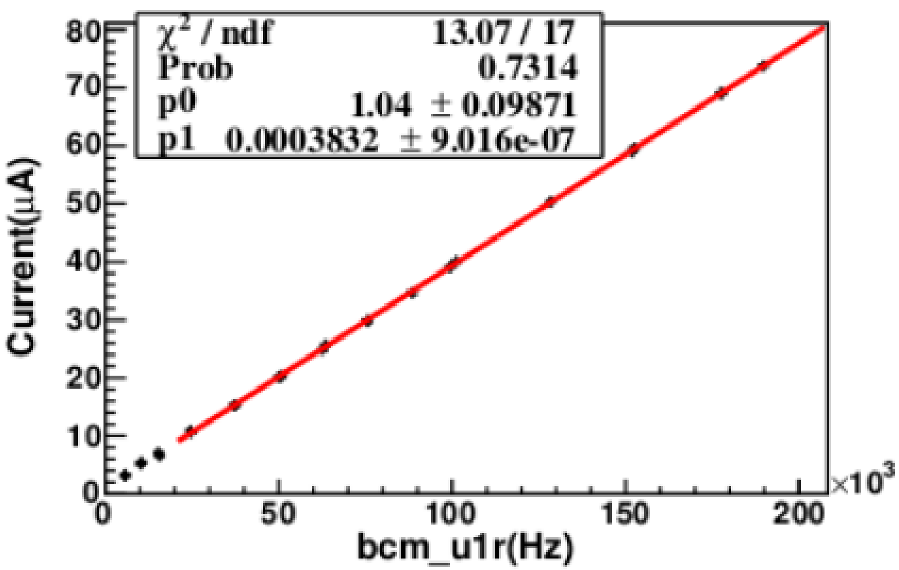
Acheived accuracy:

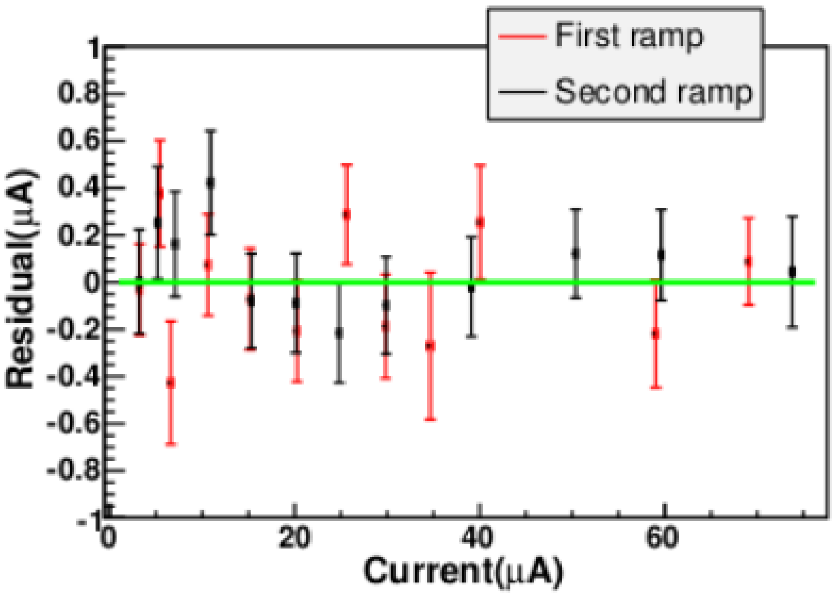
$\Delta\theta$ = 0.5 mrad (Vertical)

$\Delta\phi$ = 0.3 mrad (Horizontal)

Beam Charge Measurement

- Multiple devices in Hall A for high precision and non-destructive measurement of beam current: two BCM cavities and one Unser monitor
- The Unser monitor were calibrated by using a precise current source and provided an absolute reference during BCM calibrations
- Calibrated BCM measures the beam current with an uncertainty of less than 0.06 μA
- The stability of the gain and offset were studied by multiple calibration runs and the drifts were stable to within 0.1%





Target Boiling Studies

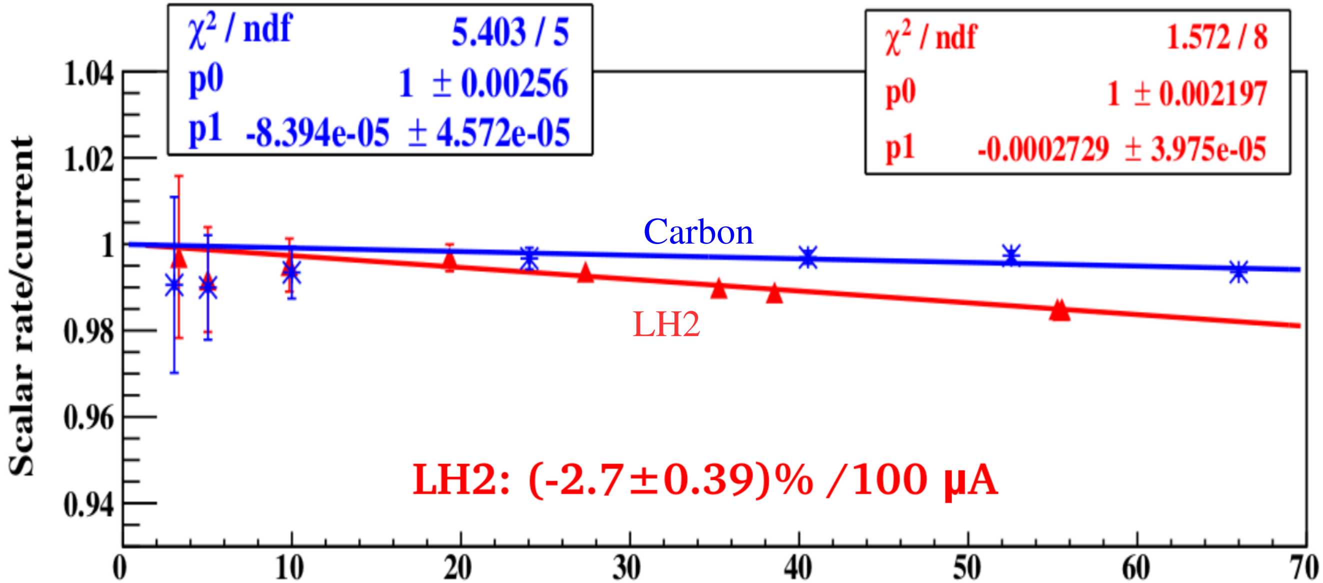
- Localized target density fluctuation can be caused by an intense incident beam in a cryogenic target
- The uncertainties in the boiling effect contribute directly to the systematic error of total cross section and needs to be known to a precision of about 0.2% for GMp experiment

Luminosity scan: take data at fixed kinematics with varying beam currents and compare the normalized scaler rates

Carbon data provide a calibration for the case with no density fluctuation

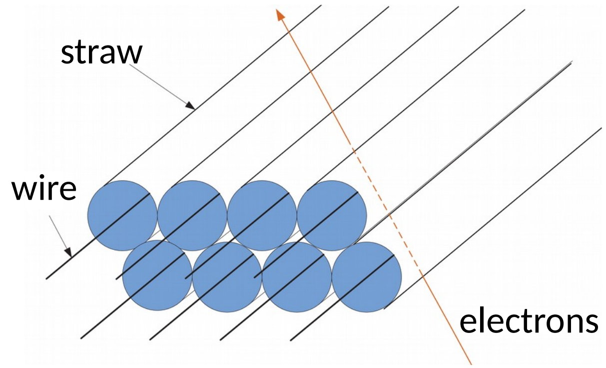
Correction factor for LH2 target: **(2.7±0.4)% @ 100 μA**

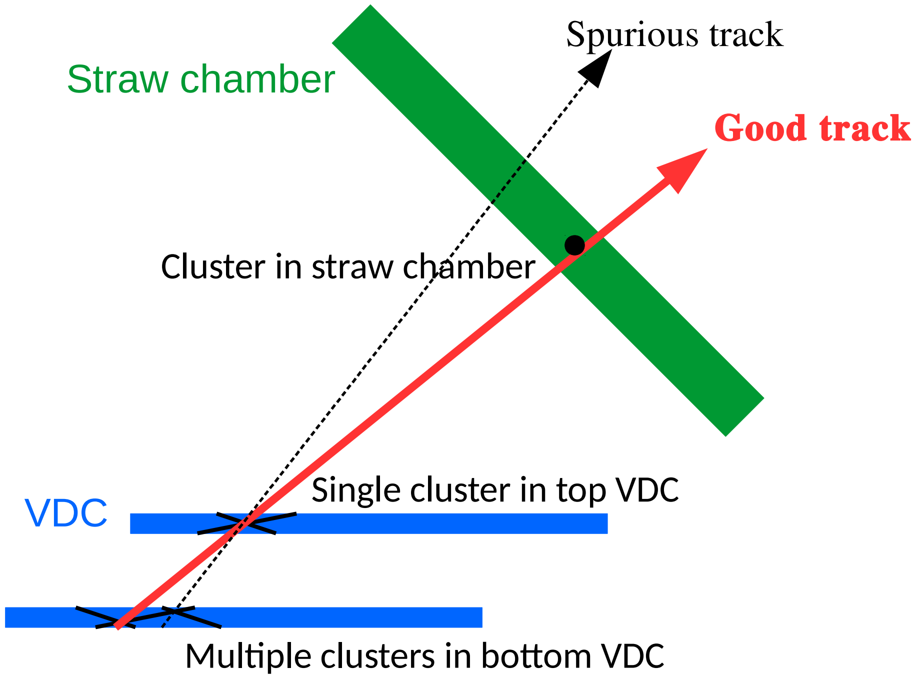
The **point-to-point uncertainty** in target density at 60 μA: **0.2%**



Track Reconstruction Efficiency

- The vertical drift chambers in HRS consist of two readout planes and are optimized for precision measurement of single tracks
- Ambiguities from multiple clusters increase the probability of misreconstructed events up to 5% and the uncertainty itself could be as large as 2%
- Straw chamber as a third readout plane were installed to reduce the uncertainty of track reconstruction efficiency to less than 0.5%





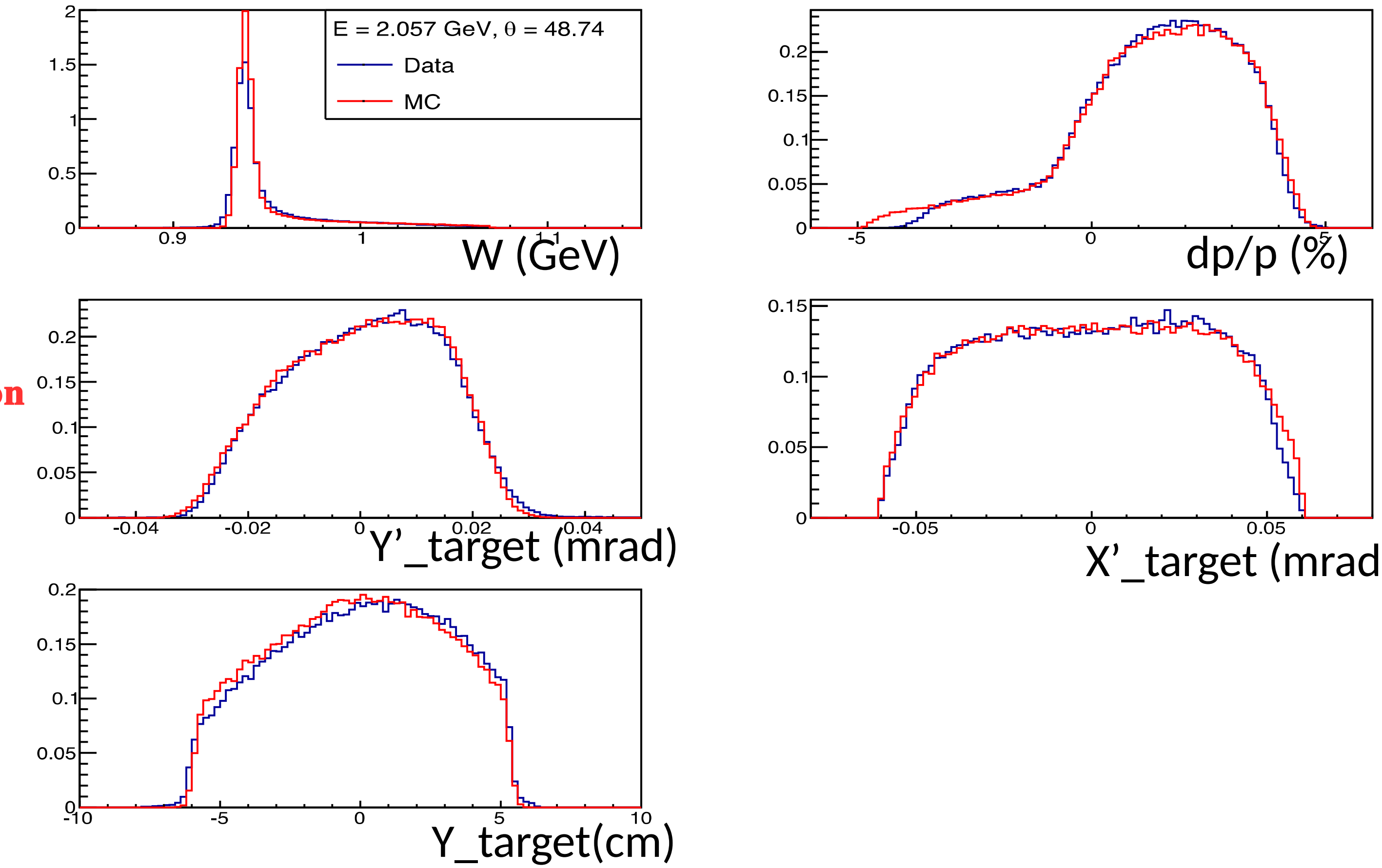
Simulation Studies of Acceptance

- Transport functions generated by the program COSY Infinity were used to model the particle trajectories in the HRS
- The hit positions at each aperture plane were checked and a flag was set if the particle was blocked
- The simulated events were generated uniformly in the phase space and then weighed by the physics cross section

Black: data

Red: simulation

Improvement of the spectrometer model is still in progress



Summary

- GMp experiment collected *ep* elastic data with high statistics at Q^2 up to 16 GeV^2 (highest Q^2 at Jlab so far)
- Detector calibrations are completed and significant progress has been made in the analysis of systematic
- A preliminary extraction of cross section at Q^2= 5.5 GeV^2 agrees with an empirical fit on world data to 3%
- Current and future work: study of spectrometer acceptance, detector efficiency, dead time analysis, radiative corrections, …
- Projected milestones:
    - Preliminary cross section results in four months
    - First publication to be submitted by the end of 2017

GMp Collaboration

- Spokesperson:
  - John Arrington
  - Eric Christy
  - Shalev Gilad
  - Vincent Sulkosky
  - Bogdan Wojtsekhowski
- Postdoc:
  - Kalyan Allada
- Hall A collaboration

- Graduate students:
  - Thir Gautam
  - Longwu Ou
  - Barak Schmookler
  - Yang Wang

- Acknowledgment:

Thanks to JLab accelerator team and many shift takers for their tremendous effort to make the GMp run successful

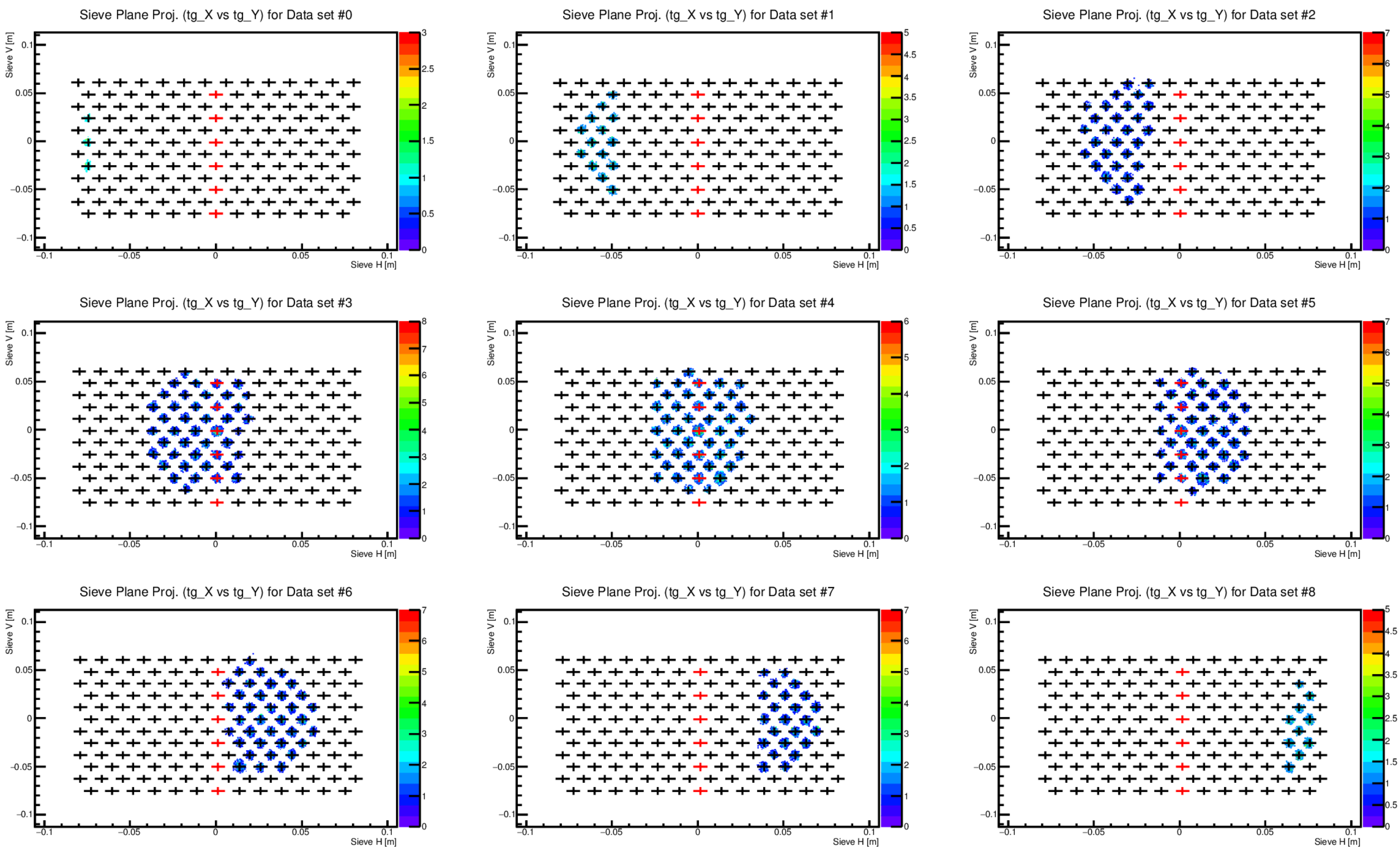
Thanks!

Backup Slides

Systematic Uncertainties

Source	$\Delta\sigma/\sigma$ (%)
Point to point uncertainties	
Incident Energy	<0.3
Scattering Angle	0.1–0.3
Incident Beam Angle	0.1–0.2
Radiative Corrections*	0.3
Beam Charge	0.3
Target Density Fluctuations	0.2
Spectrometer Acceptance	0.4–0.8
Endcap Subtraction	0.1
Detector efficiencies and dead time	0.3
Sum in quadrature	*0.8–1.1*
Normalization uncertainties	
Beam Charge	0.4
Target Thickness/Density	0.5
Radiative Corrections*	0.4
Spectrometer Acceptance	0.6–1.0
Endcap Subtraction	0.1
Detector efficiencies and dead time	0.4
Sum in quadrature	*1.0–1.3*
Statistics	*0.5–0.8*
Total (Scale+Rand.+Stat.)	**1.2–1.7**

Optics Calibration for Extended Target



PID and Detection Efficiency