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

Hall A Collaboration Meeting
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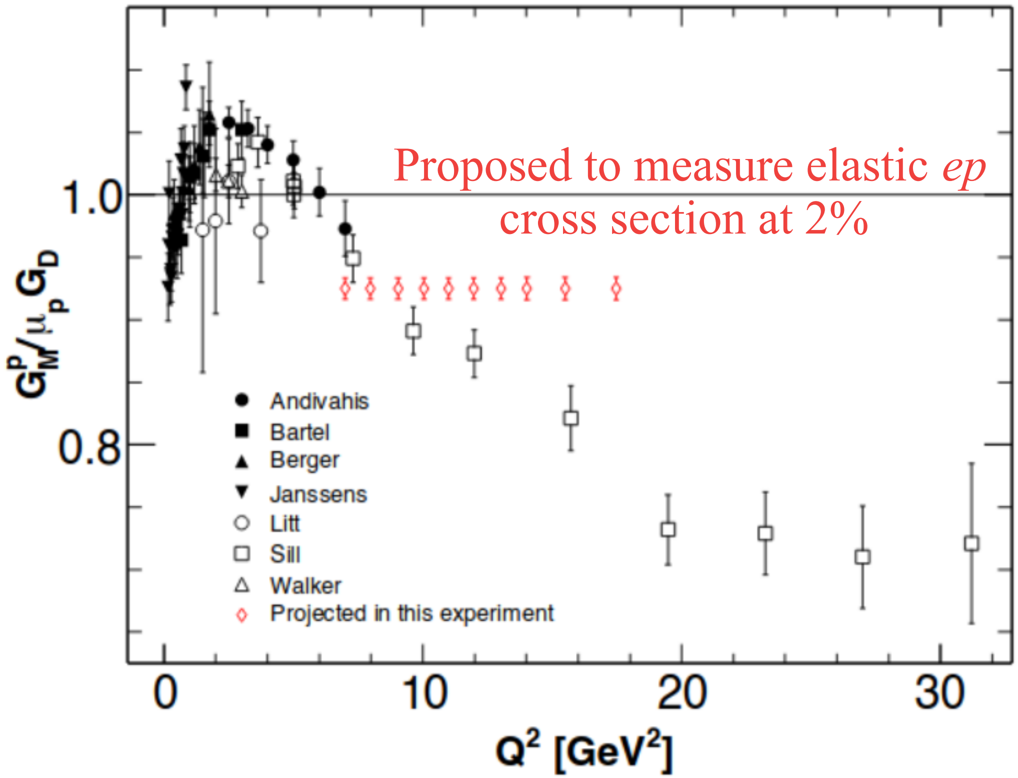
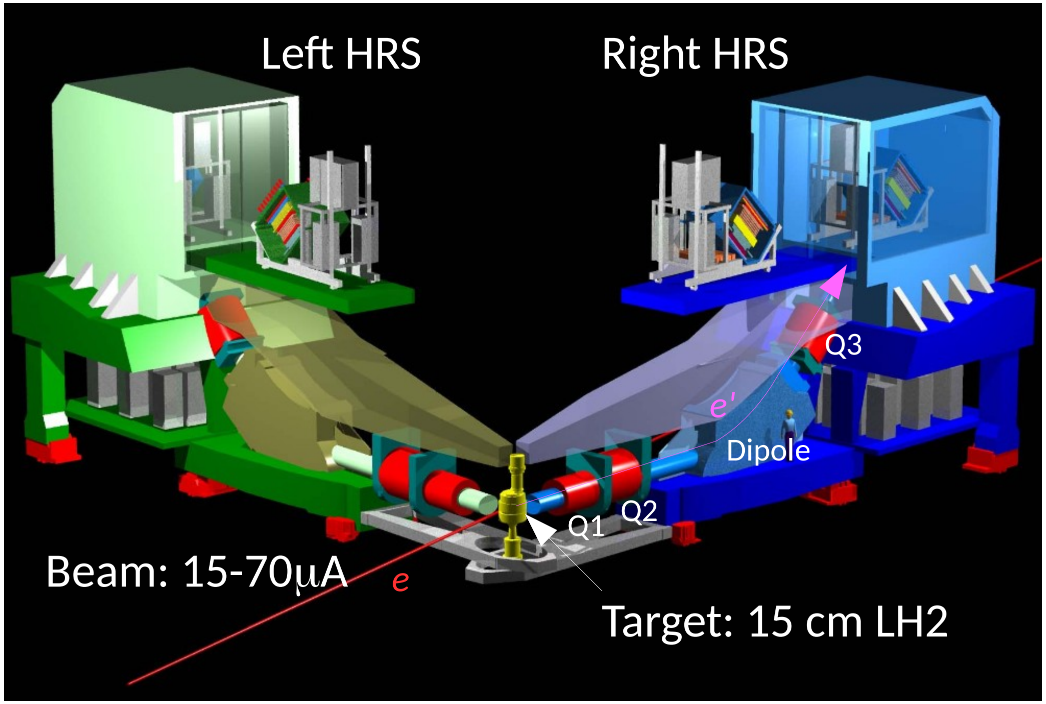
Overview of GMp Experiment

- Performed measurements of elastic *ep* cross section over a Q^2 range up to 16 $(GeV/c)^2$, where the only existing measurements were from SLAC
  - Improve cross section precision at large Q^2 by a factor of 3 or better
  - Provide normalization for other JLab 12 GeV experiments at similar kinematics
- Provide insight into scaling behavior of form factors at large Q^2
- Constrain the 2-γ contribution at high Q^2 when combined with form factor ratios from polarization measurements

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



Experiment Setup



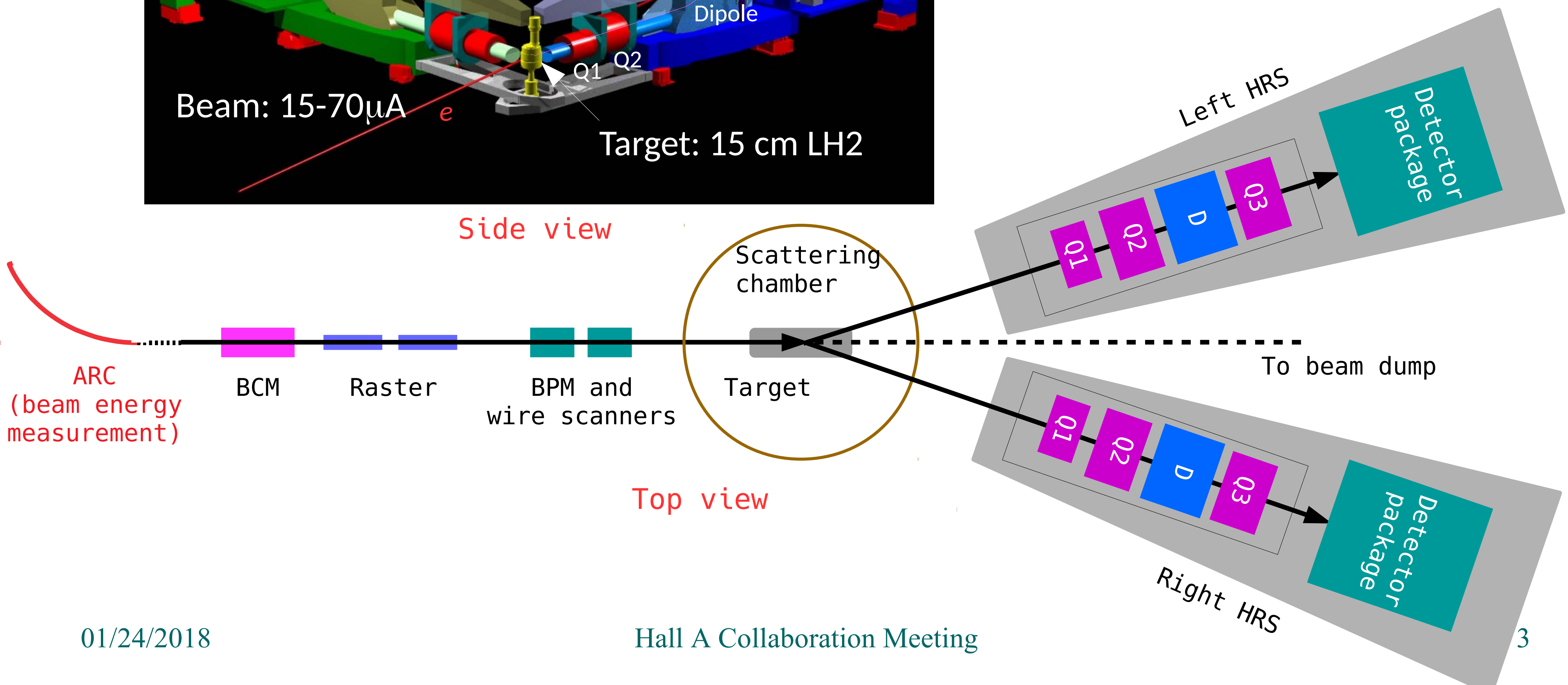
Side view

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

HRS parameters:

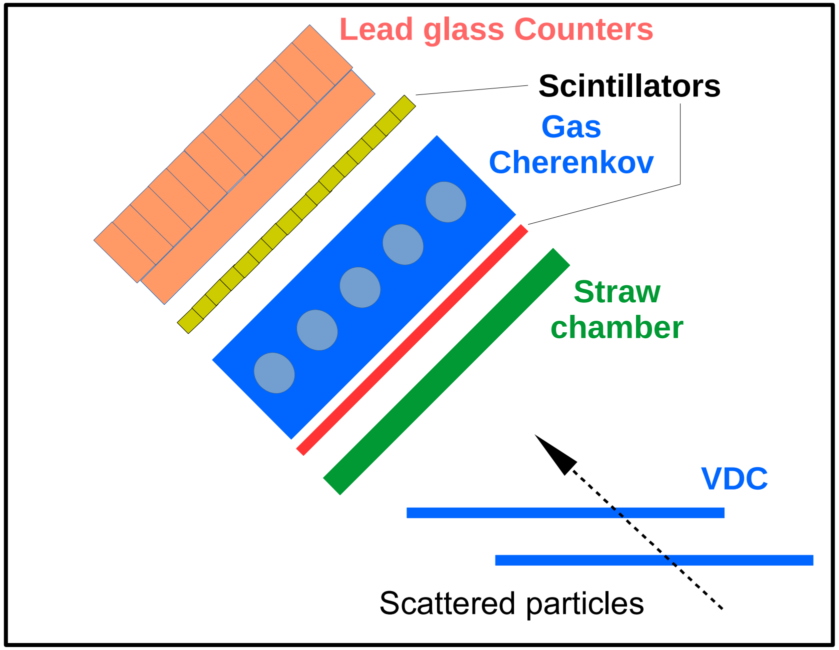
Acceptance: -4.5%<Δp/p<4.5%, 6 msr

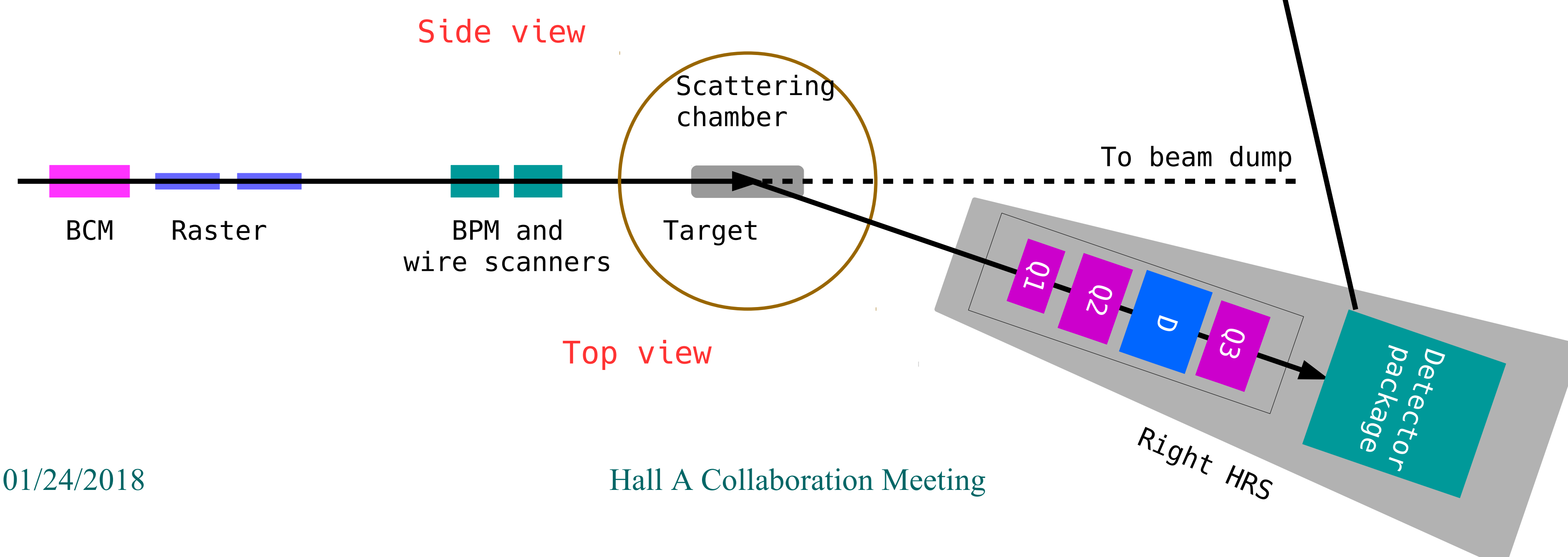
Resolution: $\delta p/p \leq 2\times10^{-4}$
$\delta\phi$=0.5 mrad (Horizontal)
$\delta\theta$=1.0 mrad (Vertical)



Top view

Experiment Setup





Recap of GMp Setup (I)

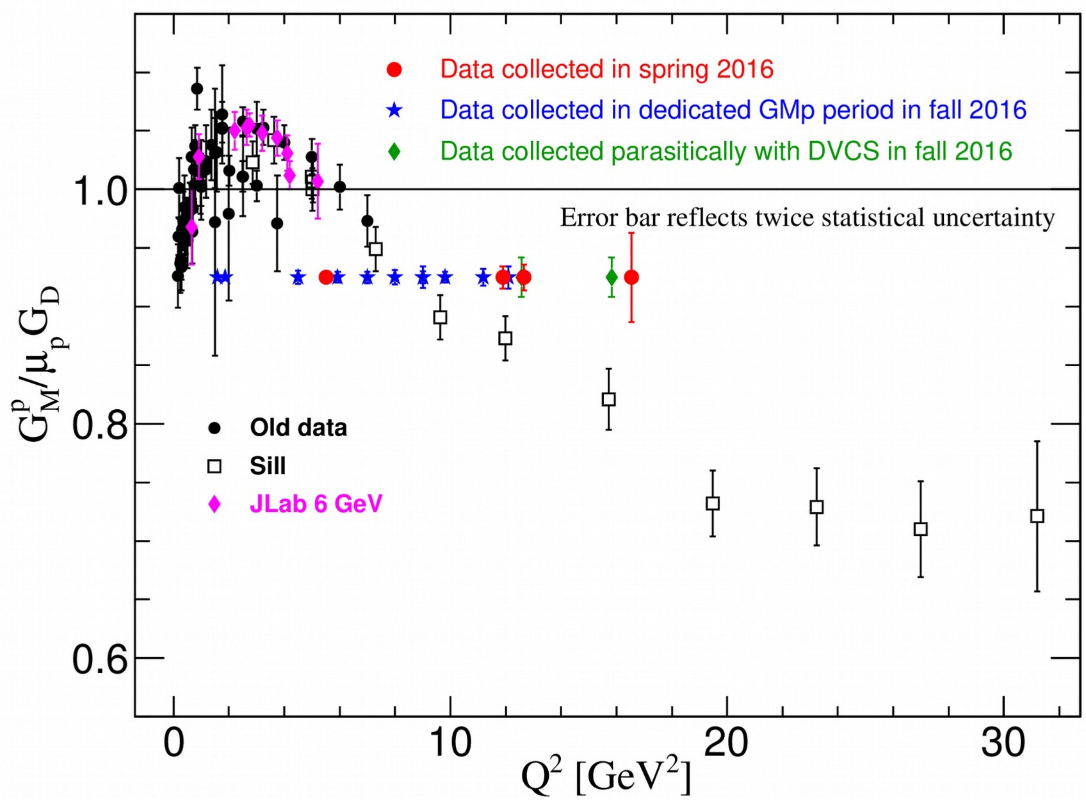
- The GMp experiment collected *ep* elastic data over three run periods, and the actual effective beam time is about 40% of what was approved by PAC

- The GMp team adjusted the kinematics on the fly based on the limited beam time and other limitations (e.g., spectrometer angle) to optimize the physics impact

  - ➔ Collected data at 20 Q^2 points ranging from 1 – 16 $(GeV/c)^2$

  - ➔ Low Q^2 *ep* elastic data were taken to fully study the systematics of the setup

  - ➔ Several high Q^2 data were taken parallel to DVCS run



Recap of GMp Setup (II)

- Effectively 4 different spectrometers were used (2 different Q1 for both L and R HRS)
  - New Q1 was tuned to match the B*dl of superconducting Q1 used in 6 GeV era
  - Saturation of Q1 magnetic field at high set current was discovered after the experiment completed → Require modification in the simulation package
- Performed beam energy measurement
- The angle measurement device was implemented but not used due to limited beam time

Measurement of Elastic Cross Section

- Cross section:

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

- Reduced cross section:

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

- 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

Status of Analysis

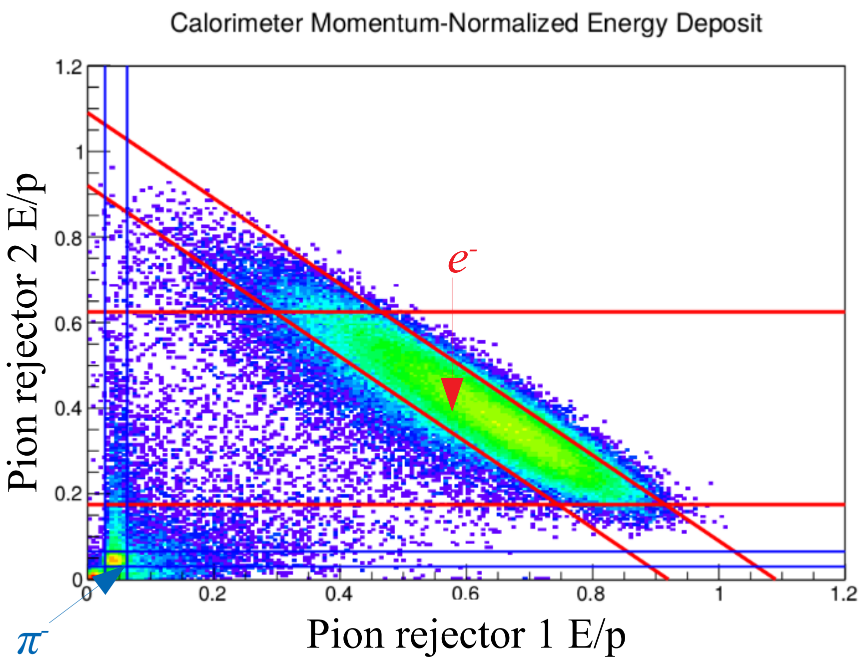
System calibration:

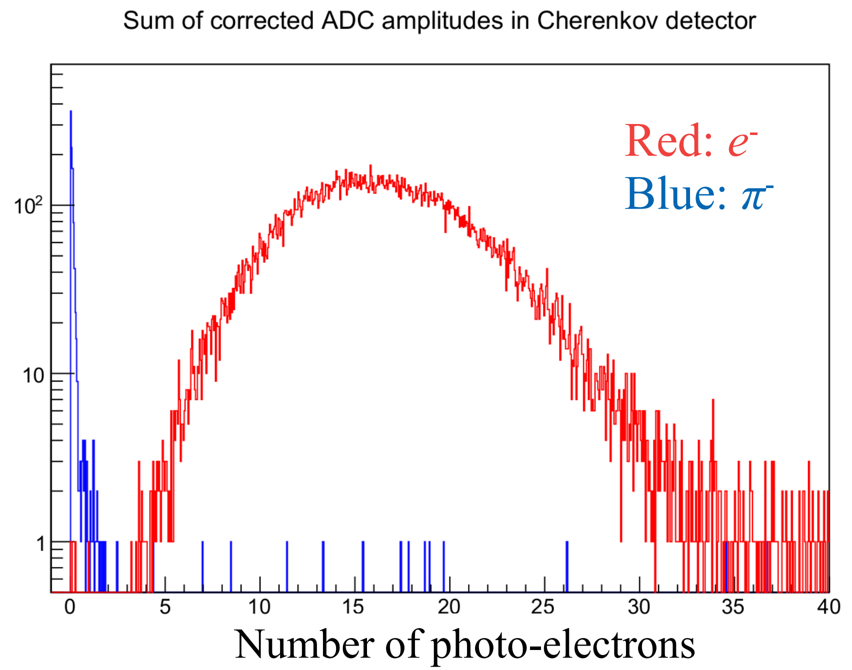
- Beamline component calibrations ✔
- PID detector (Gas Cherenkov, calorimeter) calibrations ✔
- Tracking detector (VDC, straw chamber) calibrations ✔
- Timing detector (S0, S2m) calibrations ✔
- Optics calibrations (first pass ✔)

Data analysis:

- Tracking efficiencies, trigger efficiencies ✔
- DAQ livetime ✔
- PID efficiencies ✔
- Target boiling study ✔
- Study of HRS acceptance (ongoing)
  - → Detailed aperture checks in the simulation model (ongoing)
- Extraction of cross section with acceptance correction method in near future

Efficiency of Gas Cherenkov





- Selected clean electron and pion samples using the calorimeter
- Evaluated the fraction of events survived the Cherenkov cut

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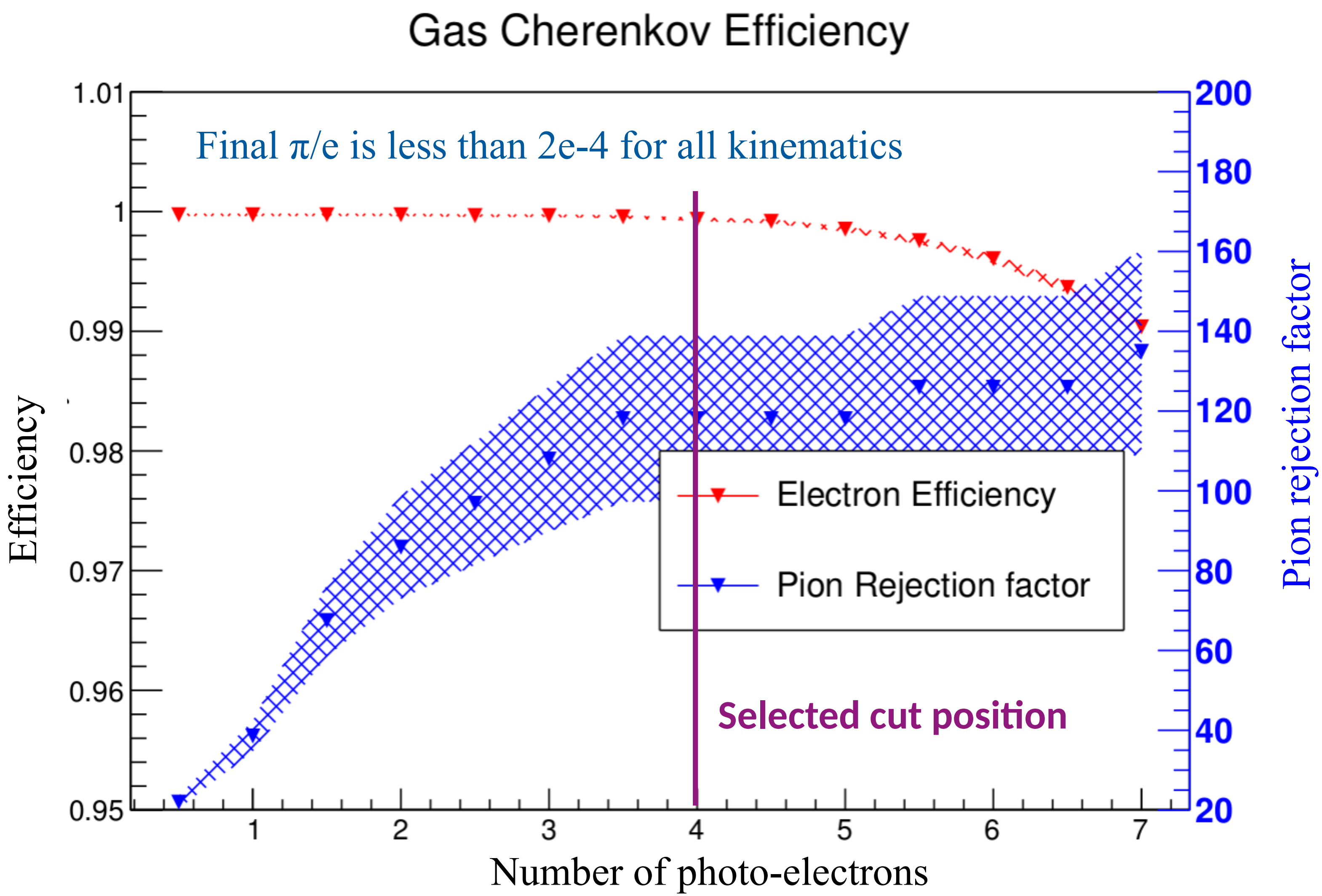
Bashar Aljawrneh (NC A&T)

Efficiency of Gas Cherenkov



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Bashar Aljawrneh (NC A&T)

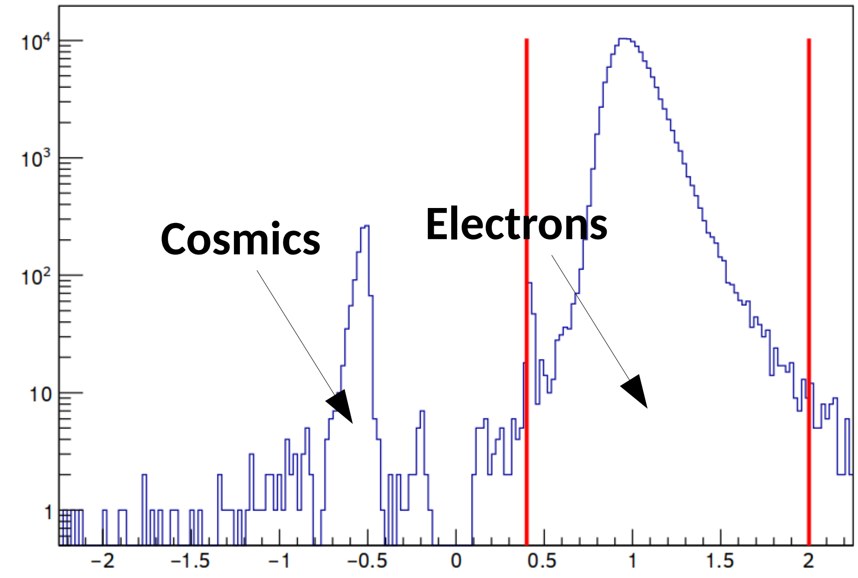
Event Selection

- The Hall A analysis software used for Gmp analysis has known issues in reconstructing events with more than one clusters in any VDC planes

- We selected events with one cluster in each VDC plane for robust reconstruction of trajectories at focal plane

- The VDC reconstruction efficiency is used to compensate for the loss of *ep* elastic events due to the single-cluster cut

- One of the difficulties is the elimination of cosmic background in the selected sample since
  - cosmic events are prone to produce multi-clusters in the VDC
  - cosmic rate can be ten times larger than elastic scattering at some large Q^2 settings



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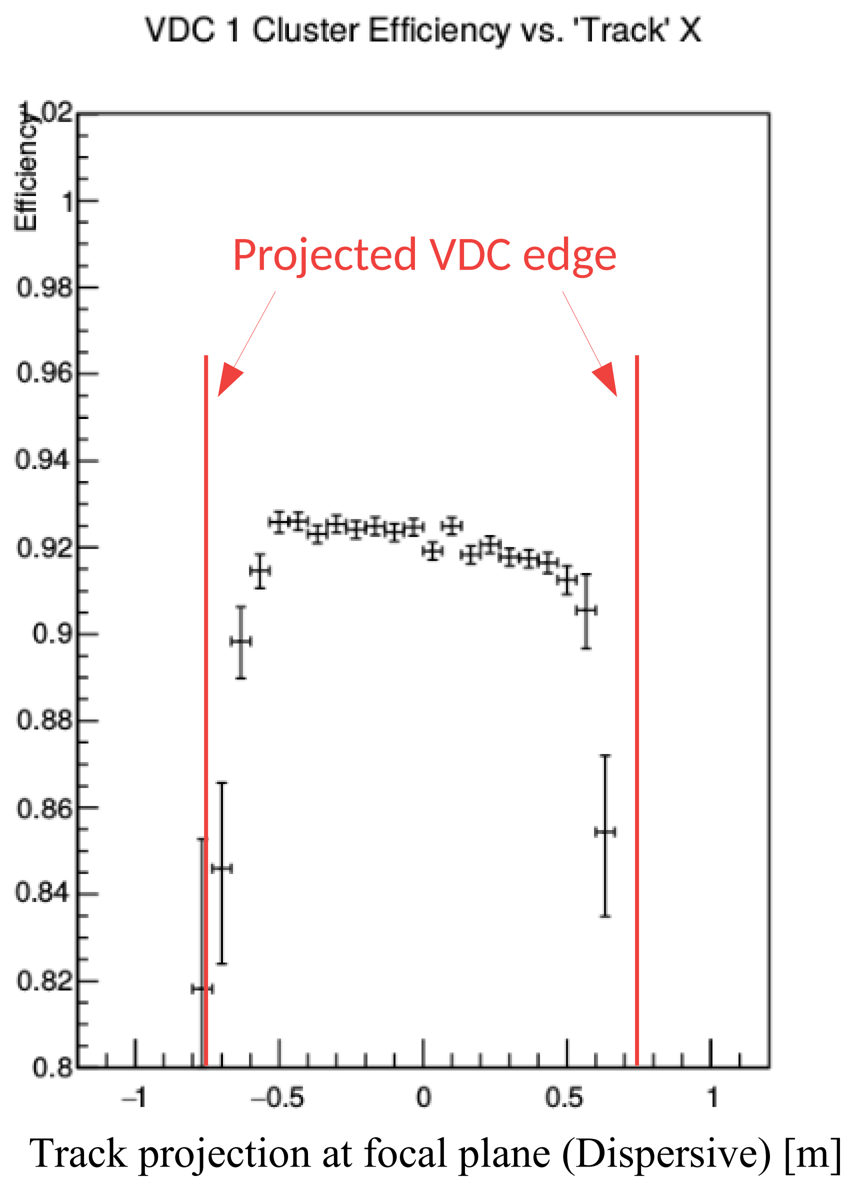
VDC Reconstruction Efficiency

- We also examined the reconstruction efficiency as a function of the intercept position
- A “coarse” track was formed using hit information at the S2m scintillator plane and straw chamber. This method enables us to estimate the track intercept at the focal plane without using VDC hits
- About 1% variation in the reconstruction efficiency was observed and needs to be taken into account in the analysis



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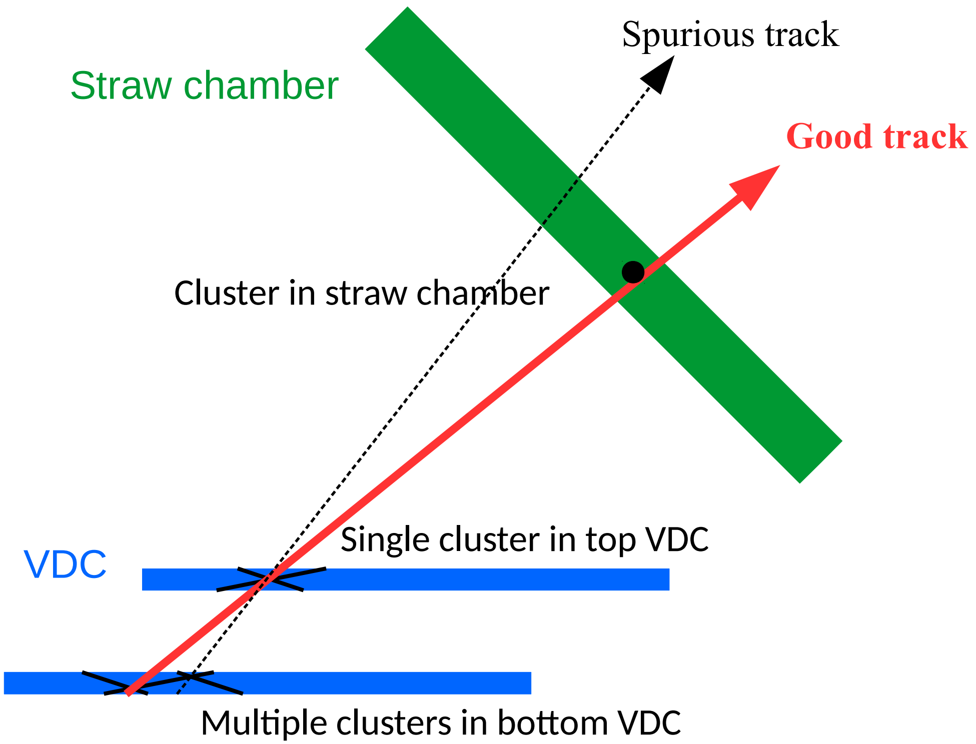
Straw Chamber

- Straw chamber was used during GMp run to measure the systematic uncertainty of the VDC reconstruction efficiency
  - Traditional method only estimates the fraction of one-track events, where the knowledge of VDC absolute reconstruction efficiency was never known to the accuracy that GMp dictates
  - Using straw chamber to reconstruct events where multiple clusters are present in the VDC, the uncertainty in the track reconstruction efficiency was reduced to less than 0.5%



Usage of Straw Chamber in HRS Tracking

- We first counted number of elastic events that have one cluster in each VDC plane, and then corrected it by the fraction of one-cluster-type events in the electron sample. The correction is typically 8-10% for GMp kinematics.
- With the help of SC, we were able to reconstruct events where multiple clusters are only present in one of two VDC chambers
- For these events, we formed the track using hits in SC and one of two VDC chambers. This technique allowed us to reconstruct about 95% of all electron events

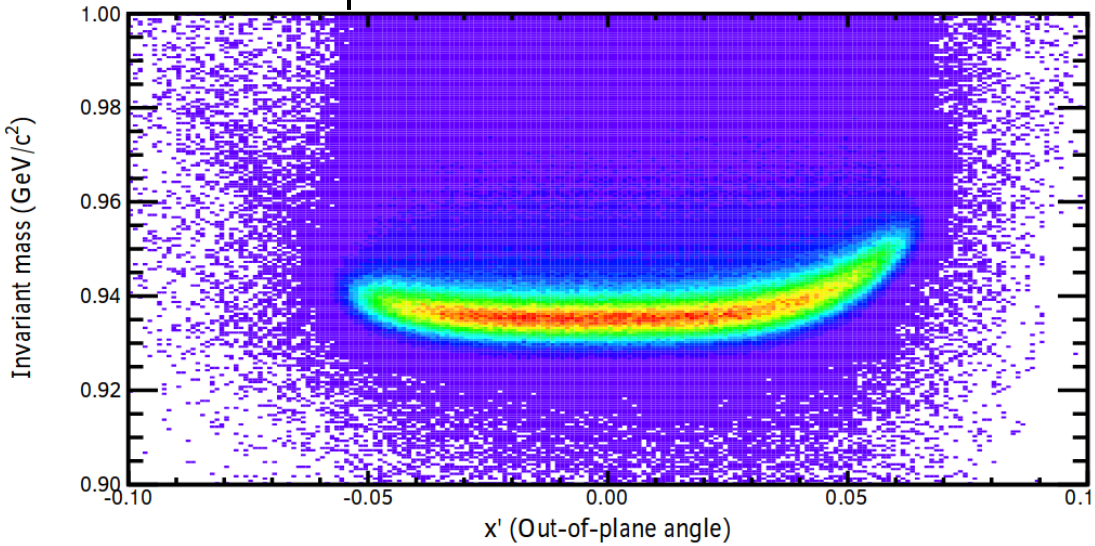
Kinematics	K3-4	K3-6	K3-7	K3-8	K4-9	K4-10	K4-11
VDC track eff	0.880 +/- 0.001	0.893 +/- 0.001	0.904 +/- 0.001	0.912.9 +/- 0.001	0.884 +/- 0.001	0.891 +/- 0.001	0.902 +/- 0.001
#Elastic (corrected for track eff)	29750	45975	39012	25237	36896	40086	17299
VDC track eff with SC	0.945 +/- 0.001	0.952 +/- 0.001	0.958 +/- 0.001	0.966 +/- 0.001	0.944 +/- 0.001	0.947 +/- 0.001	0.956 +/- 0.001
#Elastic with SC (corrected for track eff)	29702	46003	39041	25274	36871	40002	17304

The corrected elastic yields agree to better than 0.2%

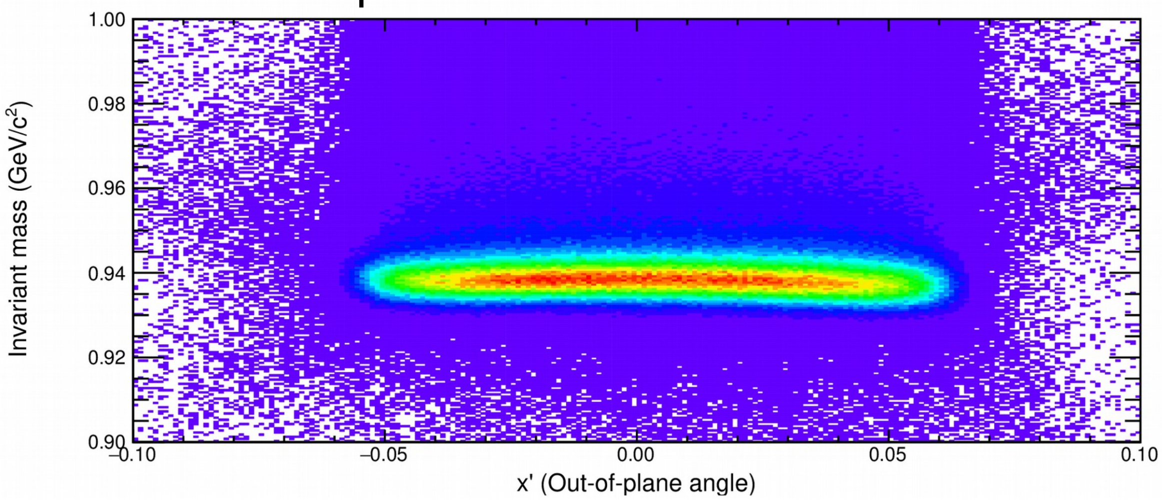
Improvement of Optics Matrices

- First pass of optics calibration was done in Nov. 2016
- A recent check of the calibration results revealed an issue of reconstructed delta at large out-of-plane angle
- A re-calibration of the optics matrices were conducted with careful selection of elastic events to cover all phase space
- The orders of the optics matrices were also reduced from 5 to 3-4 to mitigate potential over-fitting

Optics matrices from Fall 2016



New optics matrices with reduced order



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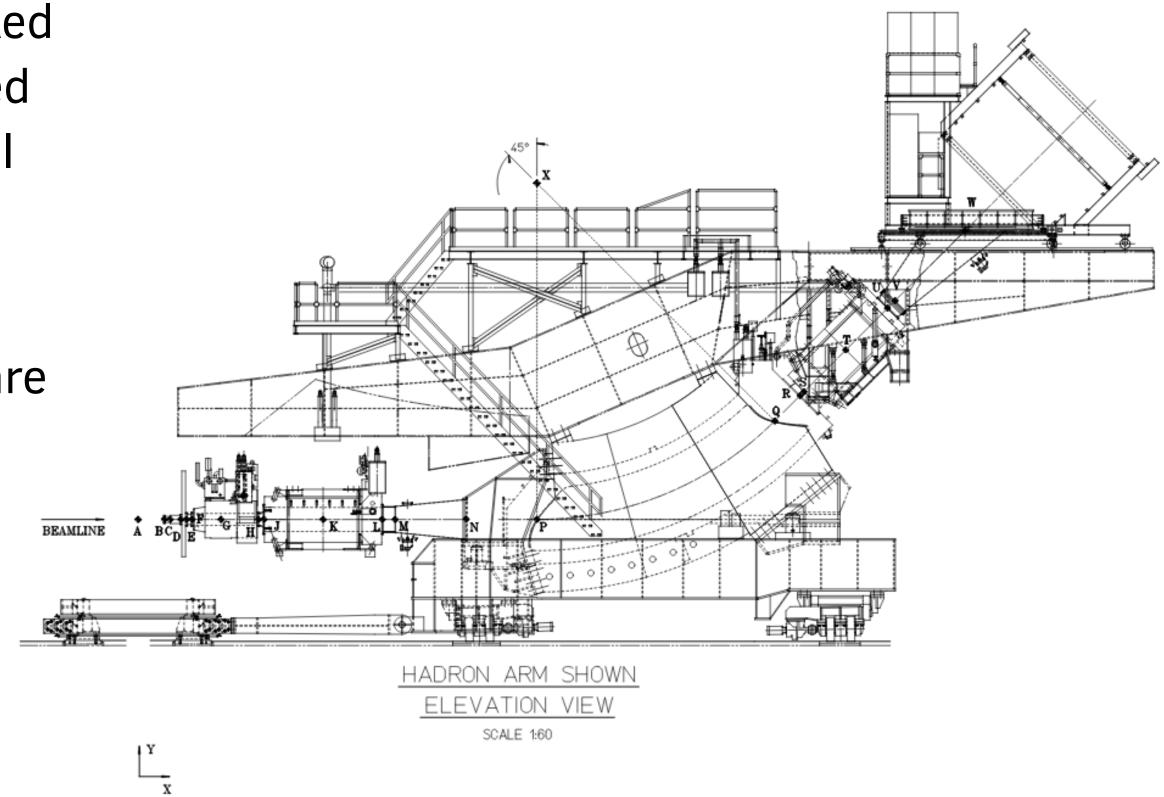
Simulation Package

- The SIMC simulation package has a model of HRS in the 6GeV era
- We adapted the simulation to account for the aperture changes due to replacement of Q1 with the SOS quad
- The transport of charged particles in the spectrometer is dictated by a series of matrices generated by the COSY Infinity program
- The scattering events were generated uniformly at the target and weighted by an empirical cross section model before comparing to observed data
- All physics processes, including energy loss, radiation of photons, are incorporated in the simulation package



Extraction of Elastic *ep* Cross Section

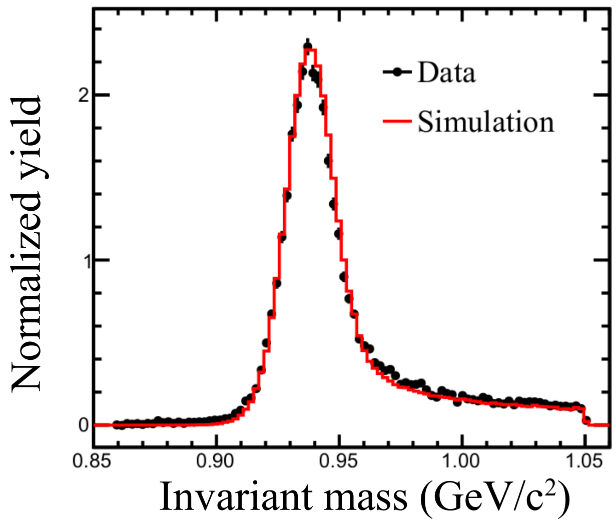
$$\frac{d\sigma}{d\Omega}^{data}(\theta) = \int dE' \frac{N^{data}(E',\theta) - N_{BG}(E',\theta)}{\mathcal{L}^{data}.\epsilon.LT} \cdot \frac{RC^{data}}{A^{data}(E',\theta)} \qquad (1)$$

$$\frac{d\sigma}{d\Omega}^{mod}(\theta) = \int dE' \frac{N^{MC}(E',\theta)}{\mathcal{L}^{MC}} \cdot \frac{RC^{MC}}{A^{MC}(E',\theta)}$$

$$\frac{d\sigma}{d\Omega}^{data}(\theta) / \frac{d\sigma}{d\Omega}^{mod}(\theta) = \frac{\int^{E_{max}} (N^{data}(E',\theta) - N_{BG}(E',\theta))dE'}{\int^{E_{max}} N^{MC} dE'} \cdot \frac{A^{MC}(E',\theta)}{A^{data}(E',\theta)} \cdot \frac{RC^{data}}{RC^{MC}}$$

Assuming acceptance and ratiative contributions are correctly modeled:

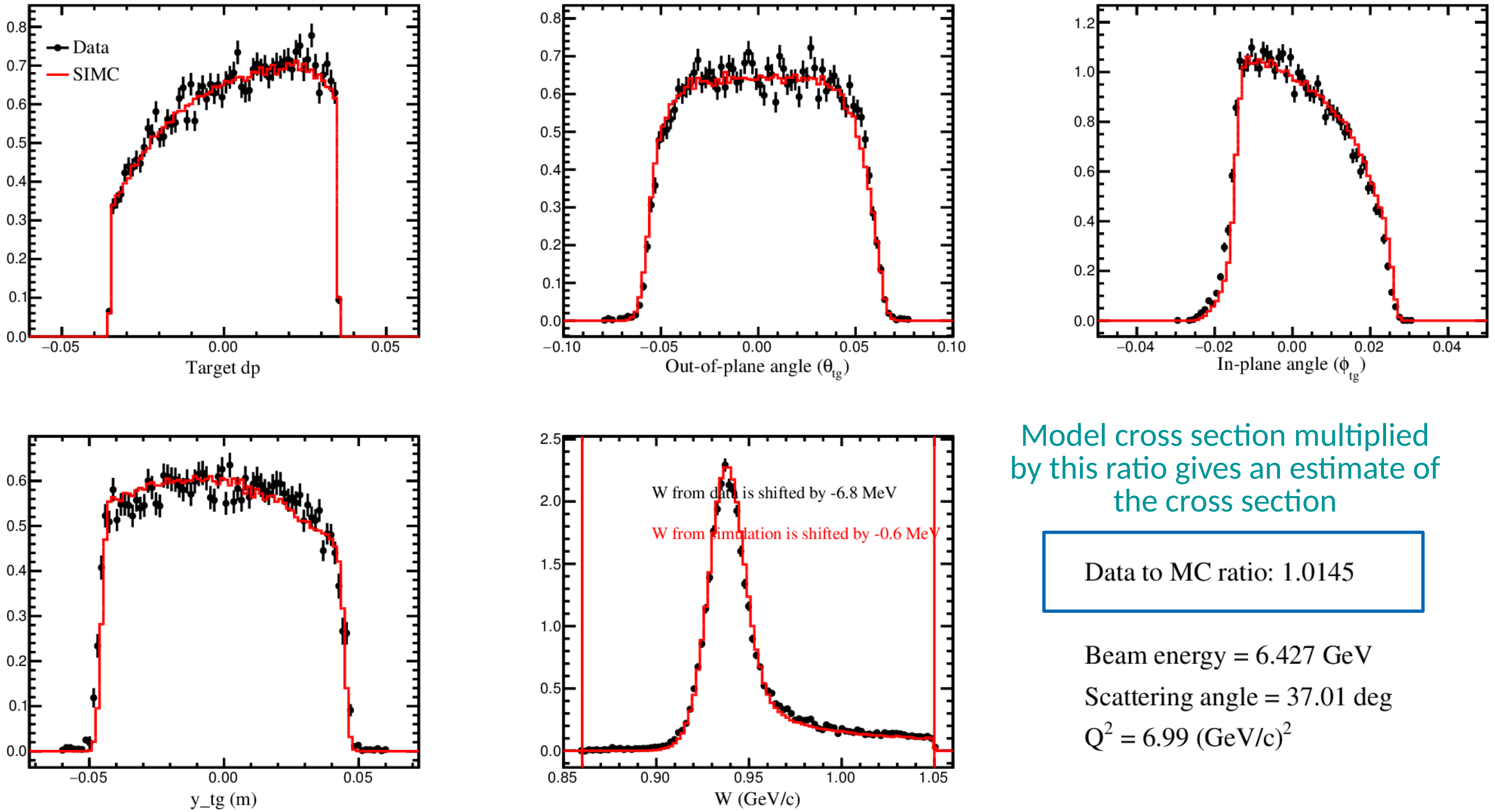
$$\frac{d\sigma}{d\Omega}^{data}(\theta) = \frac{d\sigma}{d\Omega}^{mod}(\theta) . \frac{Y^{data}}{Y^{MC}}$$



- → **Method for 1st pass cross sections**
- → **Will cross check with acceptance correction**

Extraction of Elastic *ep* Cross Section

K3-7: E_0=6.427 GeV, E'=2.701 GeV, θ=37.0°



Model cross section multiplied by this ratio gives an estimate of the cross section

Data to MC ratio: 1.0145

Beam energy = 6.427 GeV

Scattering angle = 37.01 deg

Q^2 = 6.99 $(GeV/c)^2$

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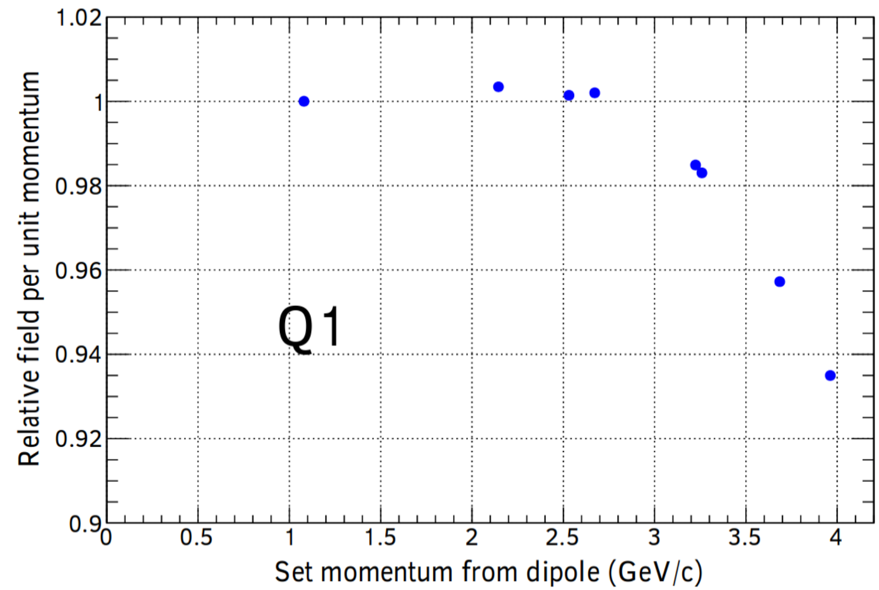
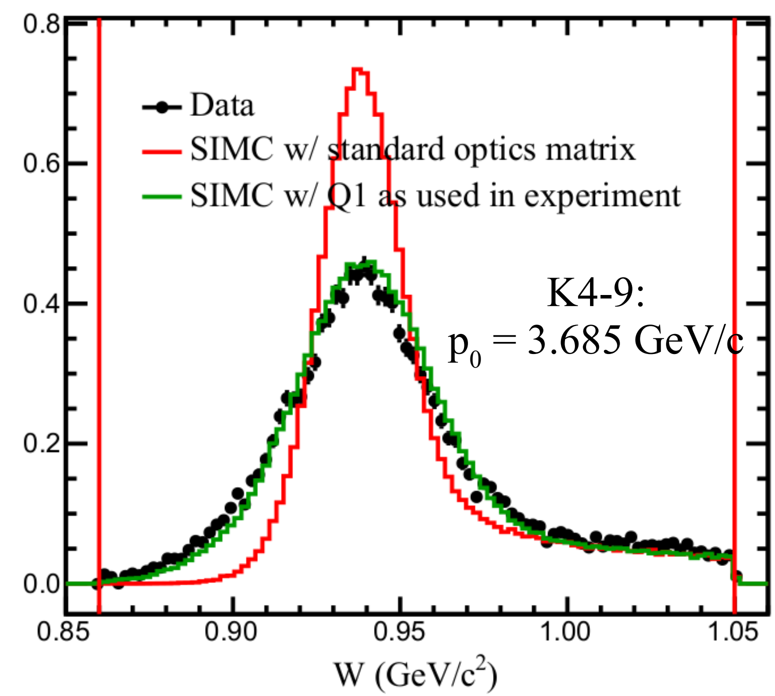
Extraction of Elastic *ep* Cross Section

- Comparison between data and simulation shows reasonable agreement for $p_0 < 3$ GeV/c

- The measured magnetic field in SOS quad exhibits saturation when $p_0 > 3$ GeV/c, which was then confirmed by the deteriorated resolution in invariant mass

- We generated forward matrix for saturated magnets and improved the agreement between data and simulation for these settings





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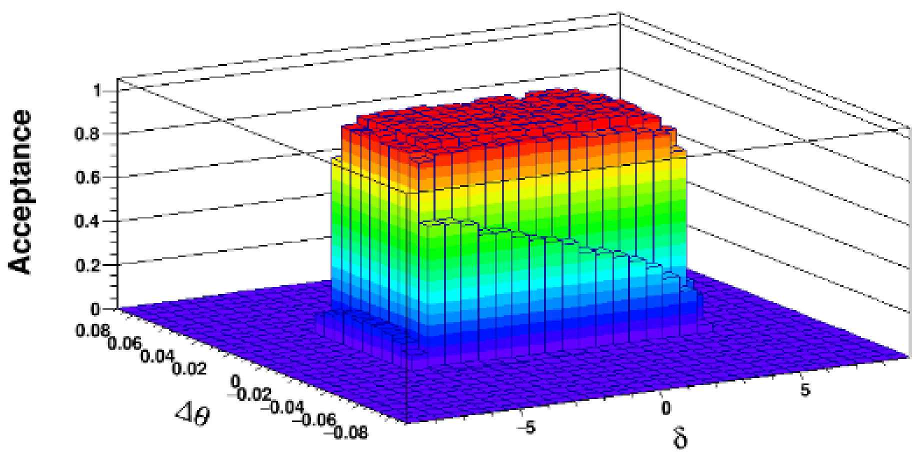
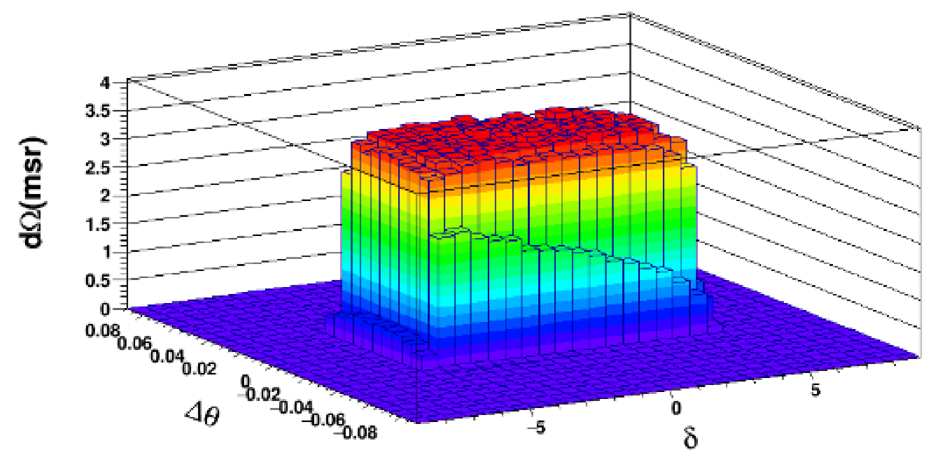
Study of Spectrometer Acceptance

- The elastic cross section can also be extracted by the acceptance correction method
- This requires a careful study of HRS acceptance and effective solid angle as a function of δ and scattering angle
- A uniform generator in phase space was applied to the SIMC HRS model to study the HRS acceptance





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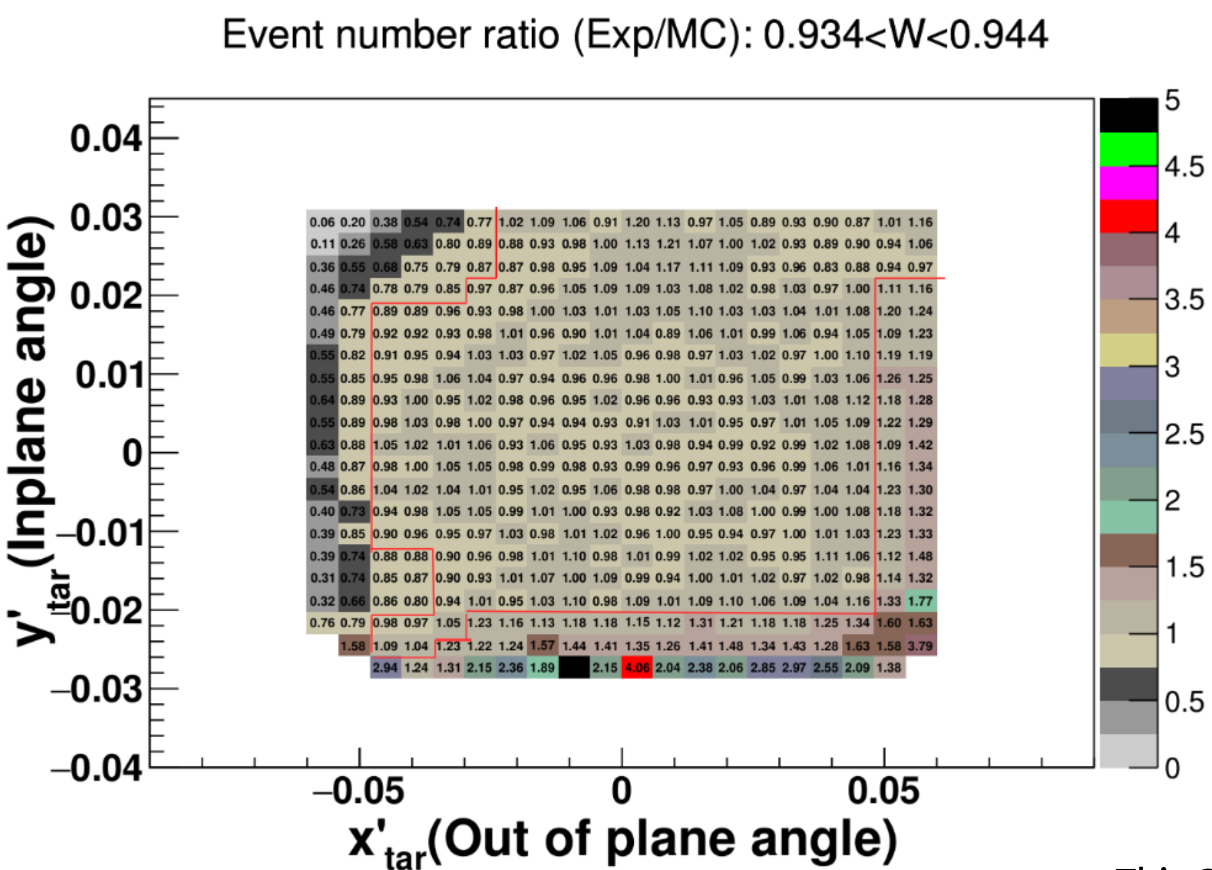
Study of Spectrometer Acceptance

- We used low-Q^2 *ep* elastic run to check against simulation and find the part of phase space where the acceptance is not well matched
- The generated acceptance table will be used for the acceptance correction method



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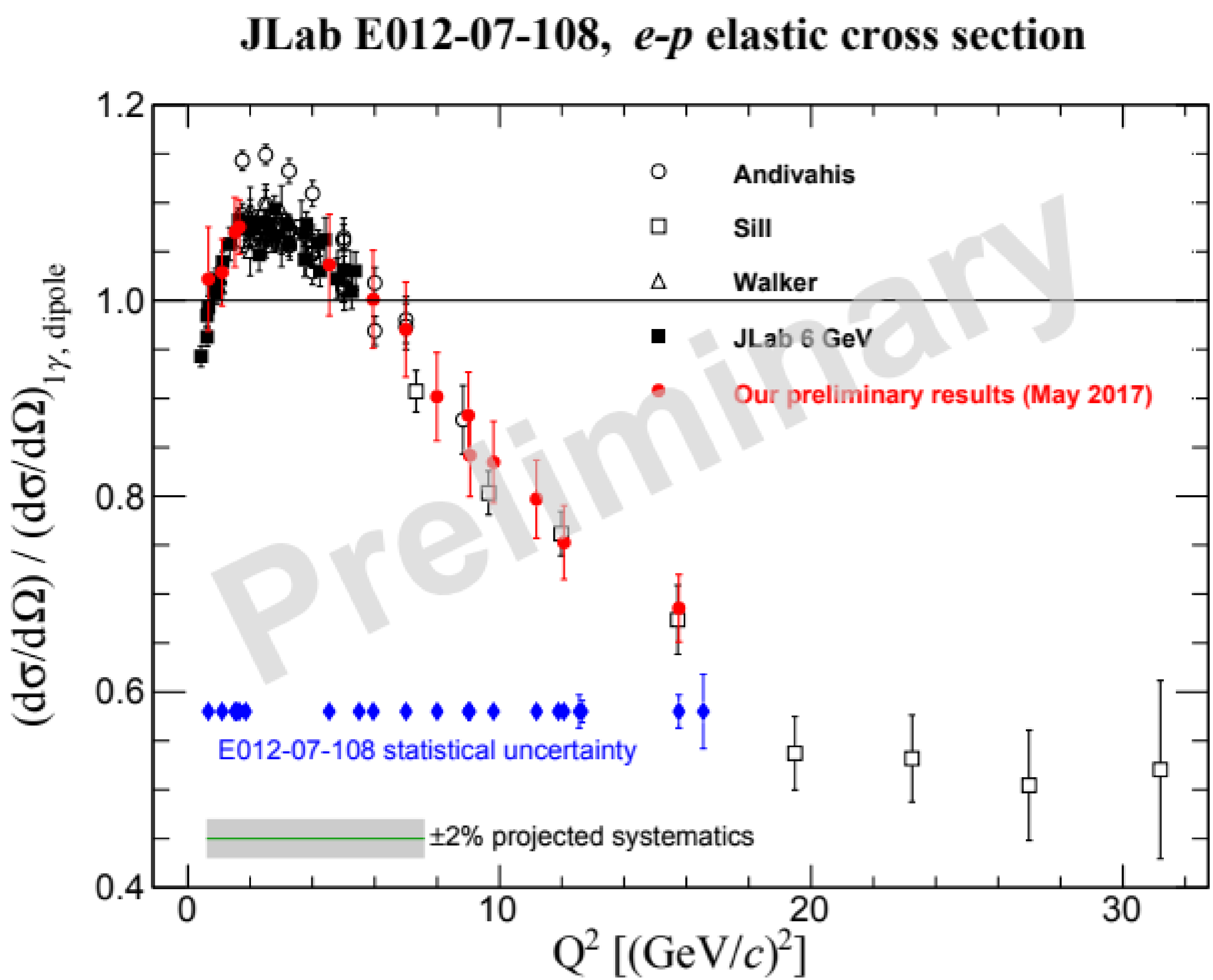
Preliminary Results (Data/MC Method)



Error Budget

Summary of statistical and major point-to-point uncertainties in the cross section for Fall 2016 run

Source	$\Delta\sigma/\sigma$ (%)
Beam current	0.3
Scattering angle	0.7–1.1
Beam energy	0.6
Track reconstruction efficiency	0.2
Spectrometer acceptance	Below 2%, ongoing
Radiative correction	Below 1%, ongoing
Background subtraction	Below 1%, ongoing
Statistics	0.5–1.2
Total	~3%

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 systematics
- Preliminary cross section results with a precision of 5% were extracted
- A detailed study of the spectrometer acceptance is underway
- Final (~2%) cross section results expected in Summer 2018

GMp Analysis Team

- Spokesperson:
  - John Arrington
  - Eric Christy
  - Shalev Gilad
  - Vincent Sulkosky
  - Bogdan Wojtsekhowski
- Graduate students:
  - Bashar Aljawrneh
  - Thir Gautam
  - Longwu Ou
  - Barak Schmookler
  - Yang Wang (defended Ph.D. in June 2017)
- Postdoc:
  - Kalyan Allada

Thanks to JLab accelerator team, Hall A target group, and all shift takers for their tremendous effort to make the GMp run successful

Thanks!