Current Results from the Hall A GMp Experiment

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on behalf of the GMp collaboration

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Outline

- Physics and experimental goals of GMp
- Experiment overview
- Cross section extraction procedure
- Analysis status
- Current Cross section results

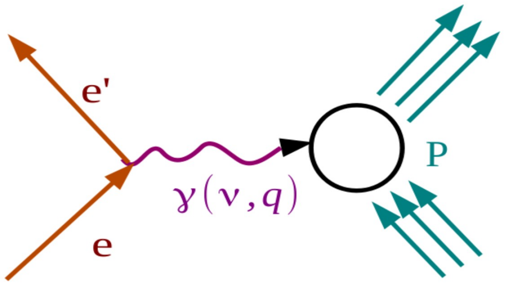
Proton magnetic form factor

- Form factors encode electric and magnetic structure of the nucleon

  → Form factors characterize the spatial distribution of the electric charge and the magnetization current in the nucleon

$$|\text{Form Factor}|^2 = \frac{\sigma(\text{Structured object})}{\sigma(\text{Point like object})}$$

- In one photon exchange approximation the cross section in *ep* scattering when written in terms of G_M^p and G_E^p takes the following form:



$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \frac{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}{\epsilon (1+\tau)}, \quad \sigma_{Mott} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E}$$

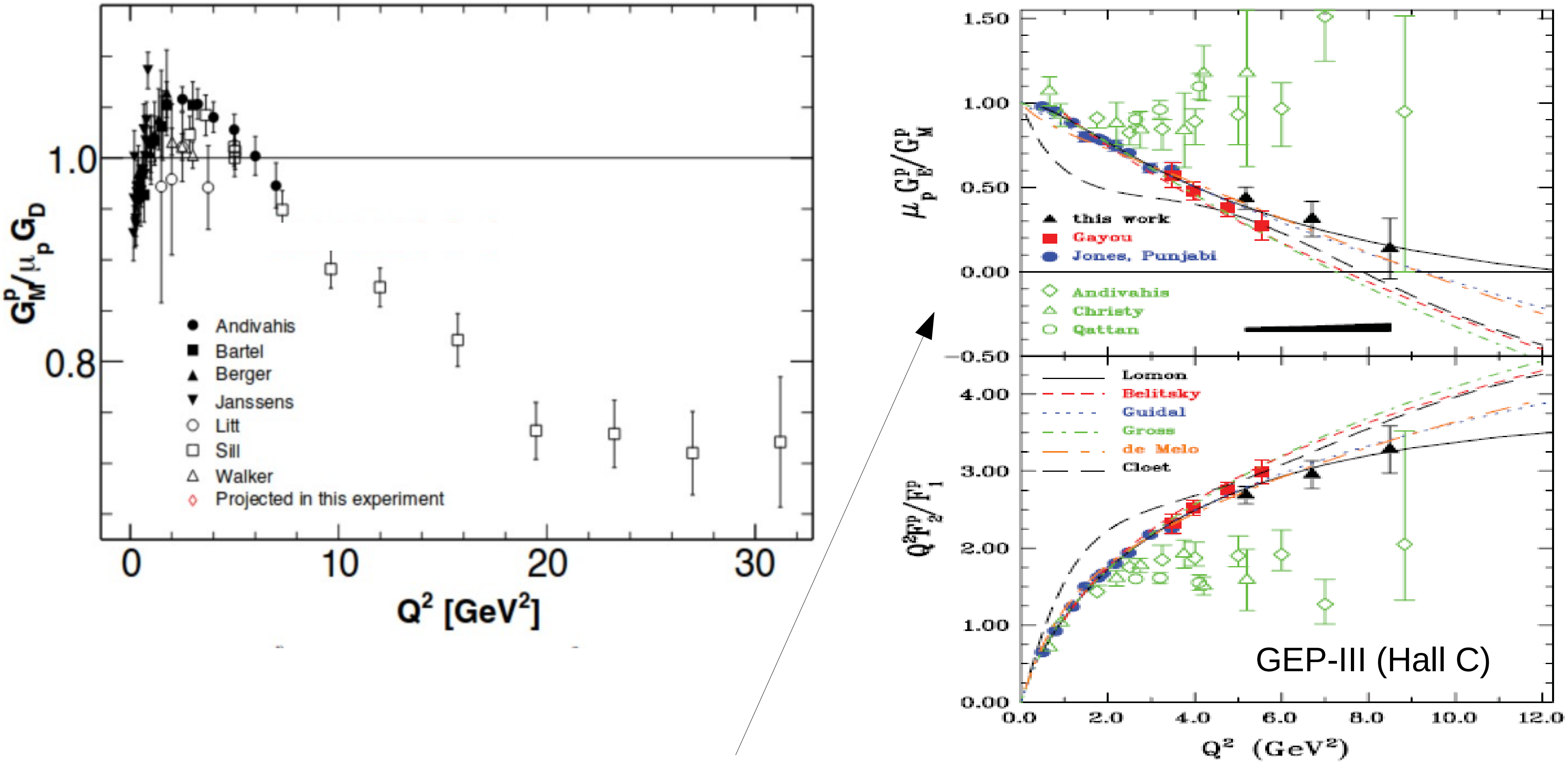
$$\mathcal{J}_{\text{proton}} = e\bar{N}(p')\left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(Q^2)\right] N(p)$$

$$G_E = F_1 - \tau F_2 \qquad G_M = F_1 + F_2$$

Where,

$$\tau = \frac{Q^2}{4M^2}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$

Experimental Status of Poton Form Factors



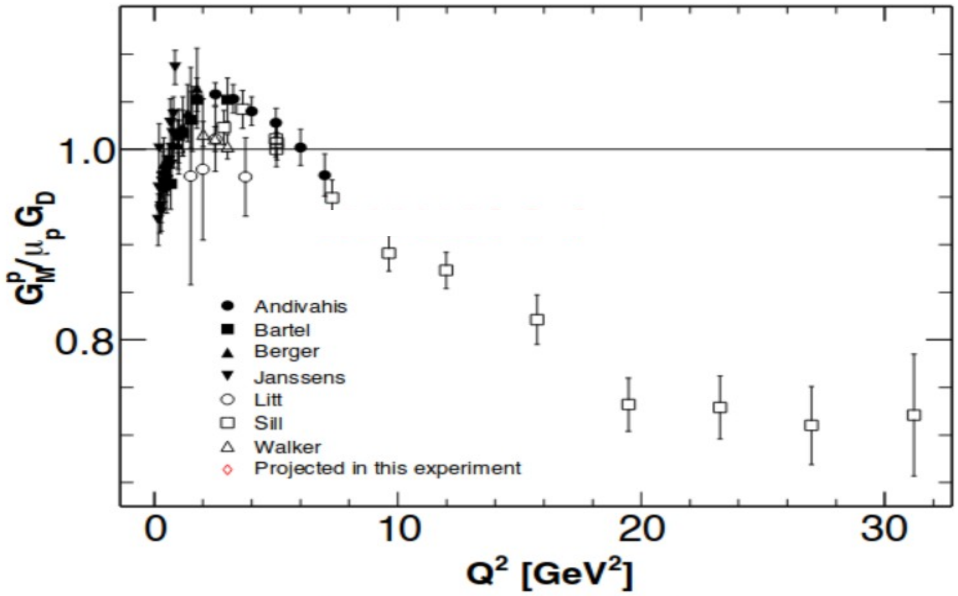
→ Discrepancy in G_E/G_M polarization transfer results and Rosenbluth (ε) separations

No clear smoking gun from any single experiment

→ Global fit of cross sections and polarization transfer G_E / G_M

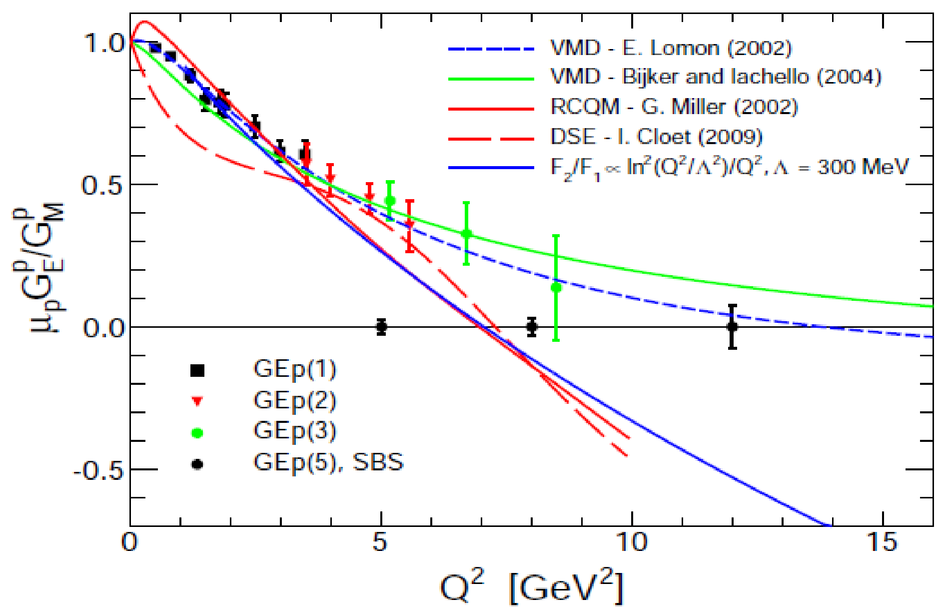
=> Sensitivity to 2-photon exchange terms.

Precision GMp critical for 12 GeV Form Factors Program



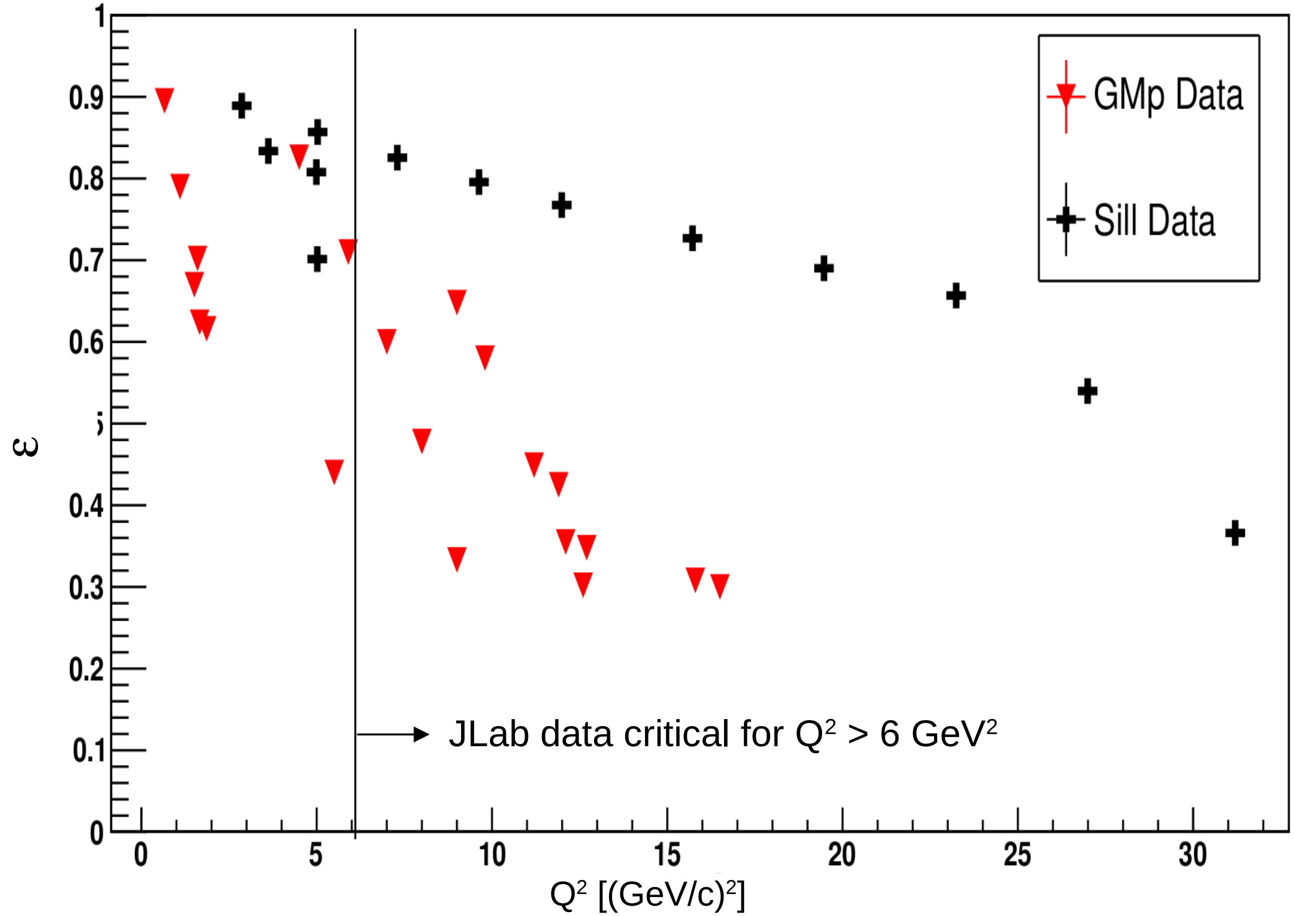
→ Precision G_M required to study approach of QCD scaling in Dirac F_1

$$F_1 = (G_E + Q^2/4M_N^2 \times G_M)/(1 + Q^2/4M_N^2)$$



→ Precision G_M upto Q^2 ~12 GeV^2 complementary to 12 GeV polarization Transfer measurements of G_E/G_M

GMp12 and World Data



→ GMp12 data at much smaller ε than existing data

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

- Less sensitivity to G_E in extracting G_M
- Lever arm in ε provides sensitivity to:
  - 2γ from global fit utilizing G_E / G_M from polarization transfer

Experiment Overview

- Precision measurement of the elastic *ep* cross-section over the wide range of the Q^2 and extraction of proton magnetic form factor

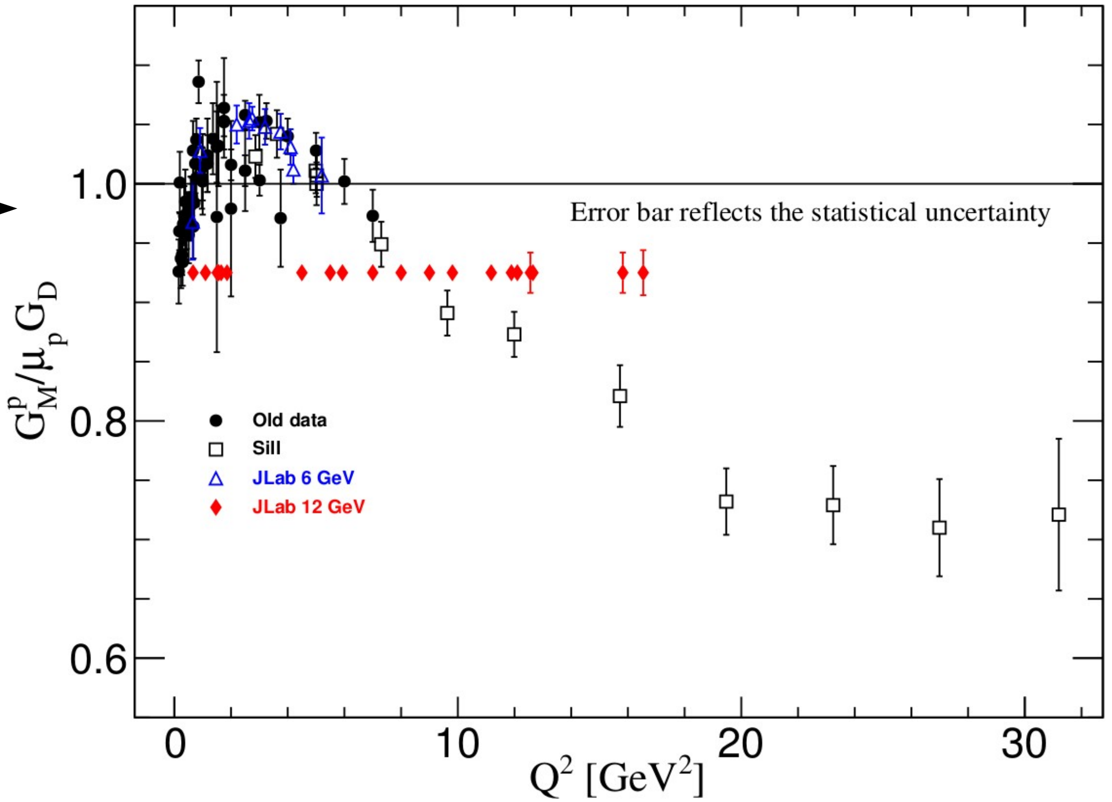
➢ To improve the precision of cross section at high Q^2 by a factor of 3

➢ To provide insight into scaling behavior of the form factors at high Q^2

<u>GMp Uncertainties:</u>

<u>Statistical:</u> Significant improvement over existing data for $Q^2 > 6$

<u>Systematic Goals:</u>
Point to point: 0.8-1.1%
Normalization: 1.3%



Need a good control on:

- Beam charge
- Beam position
- Scattering angle
- target density, ...

Data collected during GMp

Spring 2015:

E_{beam} (GeV)	HRS	P_0 (GeV/c)	Θ_{HRS} (deg)	Q^2 $(GeV/c)^2$	Events(k)
2.06	R	1.15	48.7	1.65	157
2.06	L	1.22	45.0	1.51	386
2.06	L	1.44	35.0	1.1	396
2.06	L	1.67	25.0 *	0.66	405

Spring 2016:

* Surveyed angles

E_{beam} (GeV)	HRS	P_0 (GeV/c)	Θ_{HRS} (deg)	Q^2 $(GeV/c)^2$	Events(k)
4.48	R	1.55	52.9	5.5	108
8.84	R	2.10	48.8*	12.7	8
8.84	L	2.50	43.0*	11.9	11
11.02	R	2.20	48.8*	16.5	0.7

Fall 2016: *Most complete systematic studies during this period

E_{beam} (GeV)	HRS	P_0 (GeV/c)	Θ_{HRS} (deg)	Q^2 $(GeV/c)^2$	Events(k)
2.22	R	1.23	48.8*	1.86	356
2.22	L	1.37	42.0*	1.57	2025
8.52	L	2.53	42.0*	11.2	18.9
8.52	L	3.26	34.4	9.8	57.6
8.52	L	3.69	30.9*	9.0	11.6
6.42	L	3.22	30.9*	5.9	48.6
6.42	L	2.16	44.5*	8.0	27.2
6.42	L	3.96	24.3	4.5	30.5
6.42	L	2.67	37.0	7.0	41.4
6.42	R	1.59	55.9*	9.0	11.6
8.52	R	2.06	48.6*	12.1	11
8.52	R	1.80	53.5*	12.6	3.4
10.62	R	2.17	48.8*	15.8	3.6

Recap of GMp Setup

- 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
  - ➔ 2 spectrometers + quad replacements for each => 4 different tunes
  - ➔ Q1 ***Bdl*** tuned to best match tune with old superconducting quads at 1 GeV
- 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 21 Q^2 points ranging from 1 – 16.5 $(GeV/c)^2$
  - ➔ Low Q^2 *ep* elastic data were taken to fully study the systematics of the setup
  - ➔ Several high Q^2 data were taken in parallel with DVCS run with reduce beam currents

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

Extraction of Elastic *ep* Cross Section

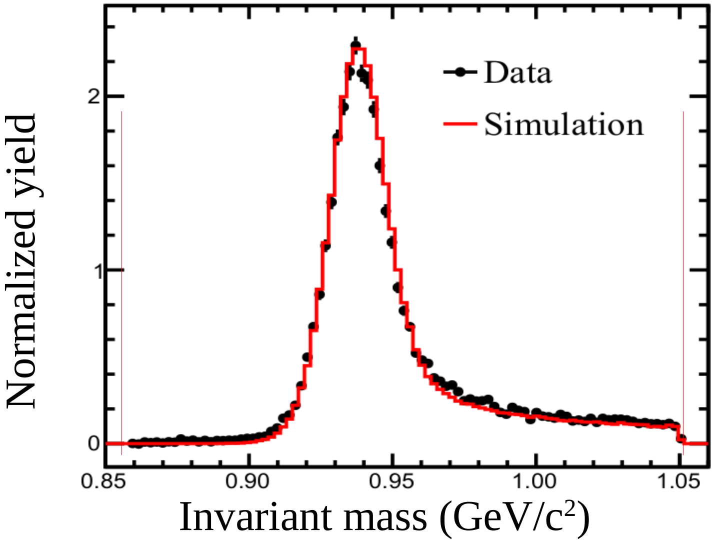
$$\frac{d\sigma}{d\Omega}^{data}(\theta) = \int dE' \frac{N^{data}(E',\theta) - N_{BG}(E',\theta)}{\mathcal{L}^{data}.\epsilon.LT} \cdot \frac{RC^{data}}{A^{data}(E',\theta)} \qquad (1)$$

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

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

Assuming acceptance and ratiative contributions are correctly modeled:

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



→ **Will cross check with acceptance Correction (1) method in future**

Monte Carlo Model

- Monte Carlo Model is the **SIMC** code developed for Hall C with HRS spectrometer model incorporated
- Optics (COSY) and "aperture checking" Monte Carlos of spectrometers
- Includes cross section model based on fits existing data (Arrington, Tjon, Melnitcouk)
- Includes radiative effects, multiple scattering, ionization energy loss
- Significant efforts by GMp to:

  → include **All** relevant apertures (over 20 checks in total including detector edges) (Barak Schmookler).

  → perform detailed checks of focal plane shapes determined by aperture edges (Thir Gautam)

  → check radiative corrections against separate code (Longwu Ou, Thir Gautam, Bashar Alijawrneh)

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 (finalizing)
- Systematics on beam energy determination (ongoing)

Data analysis:

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

Kinematic determination

- Arc measurements of beam energy performed at every energy

  → current estimated uncertainties of **$5x10^{-4}$ (1-4 pass)**
  $1x10^{-3}$ (5pass)

- Spectrometer pointing surveys performed at most angles

- 12C point target runs taking at all angles

  => Utilized point target runs and surveys to determine:

  → angles at all kinematic

  → z-target position

  → in plane beam position relative to pivot

- Study of LHRS reconstructed elastic peak position, $W\text{-}M_p$, consistent with estimated beam uncertainties and pt-pt **$\Delta\theta < 0.25$ mrad**

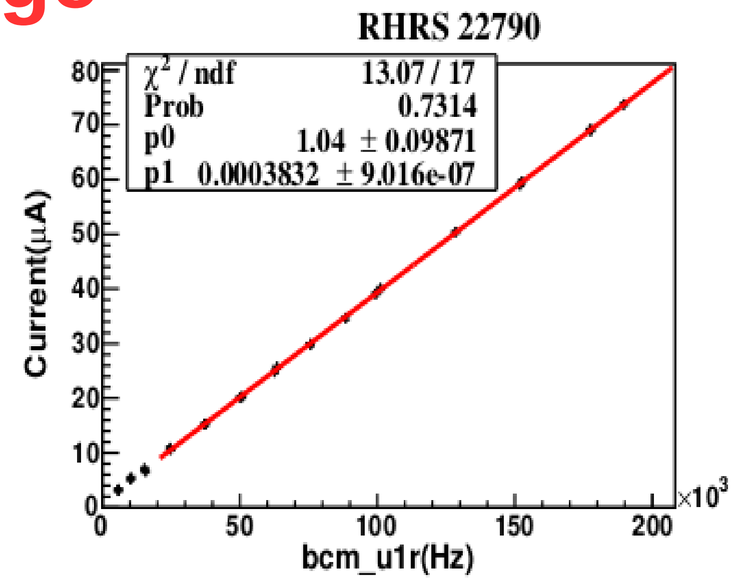
Beam charge

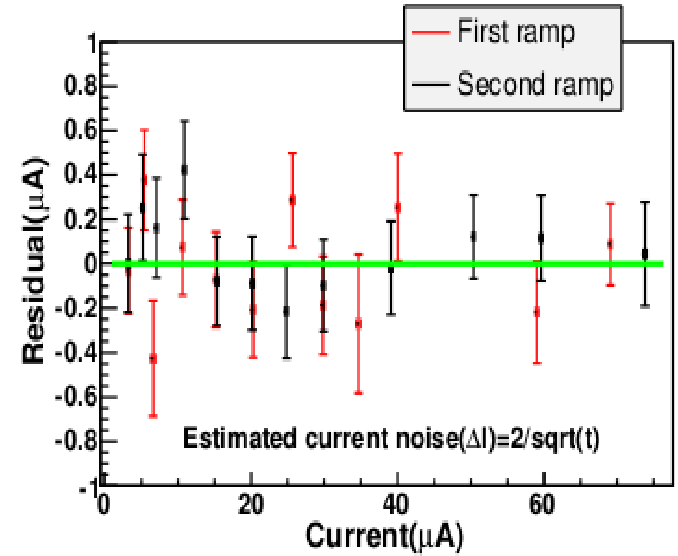
Thir Gautam (HU)

- Multiple BCMs calibrated against Unser
- Unser calibrated against precision current source passed though inserted wire
- Small (< 0.1 μA) offset determined from ^{12}C boiling

Uncertainty:

Pt-pt: 0.06 μA
Correlated: 0.06 μA





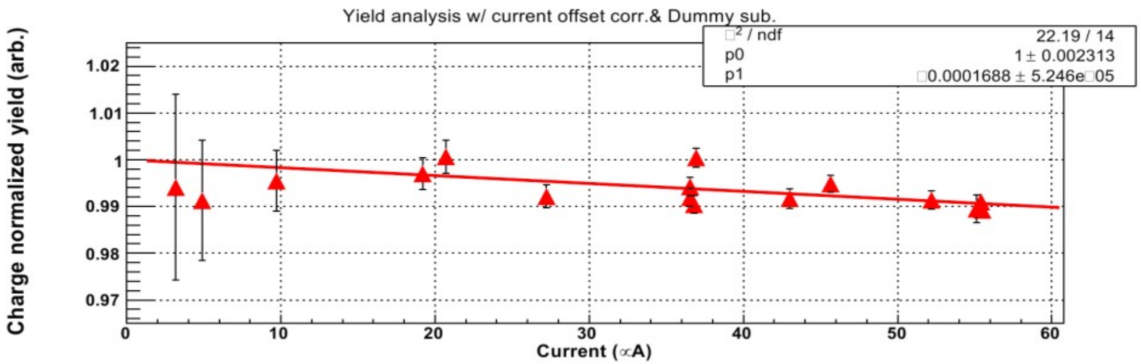
Target boiling

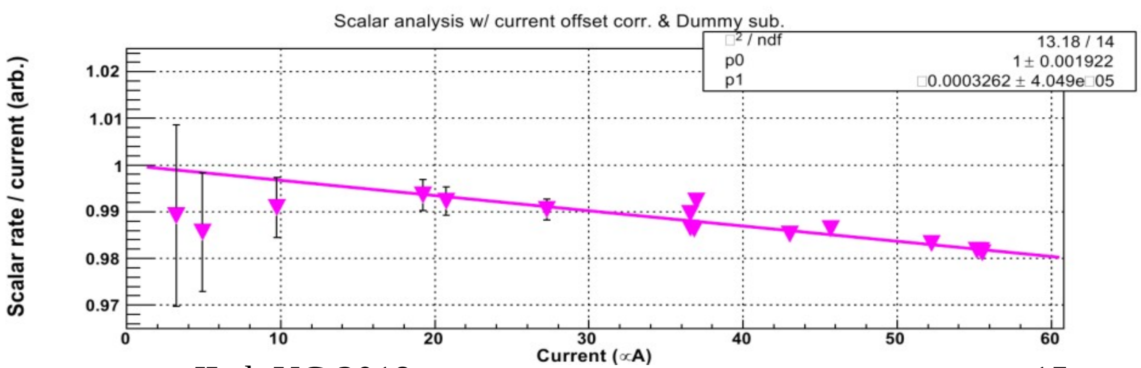
Barak Schmookler (MIT)

Bashar Aljawrneh (NC A&T)

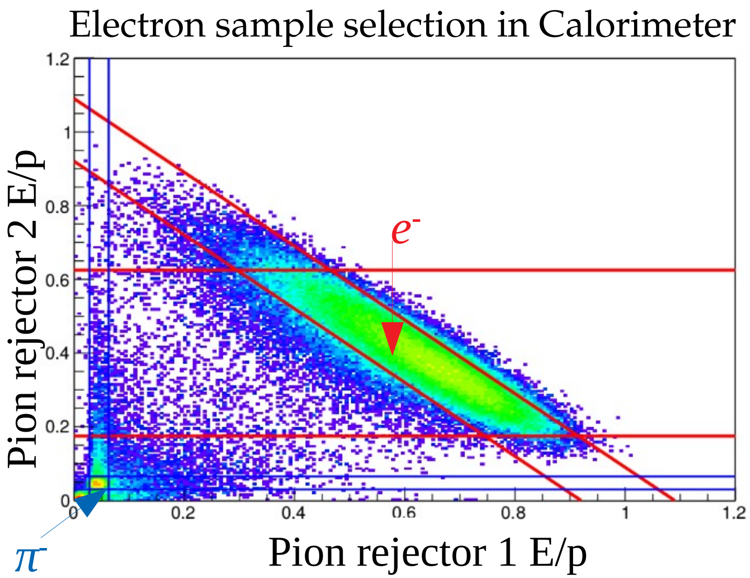
Fall 2016 Yield analysis: 1.7% / 100 μA
Uncertainty: 0.6 / 100 μA

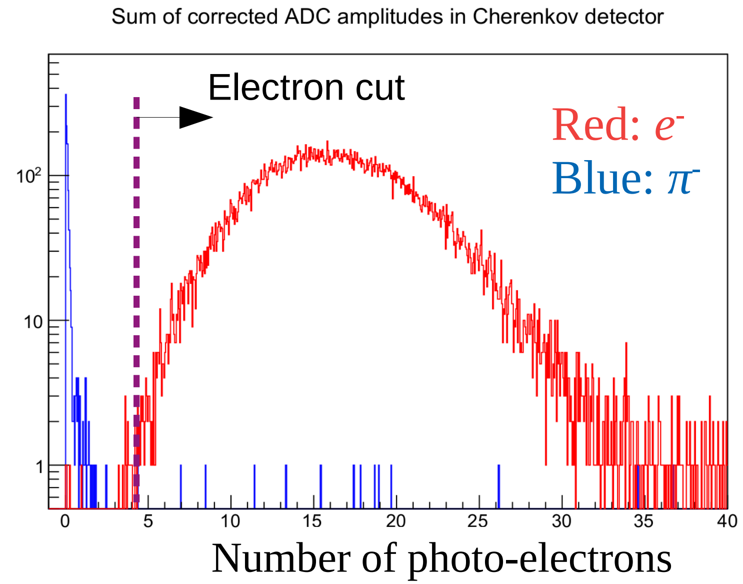
6 μA: < 0.03%
40 μA: < 0.24%

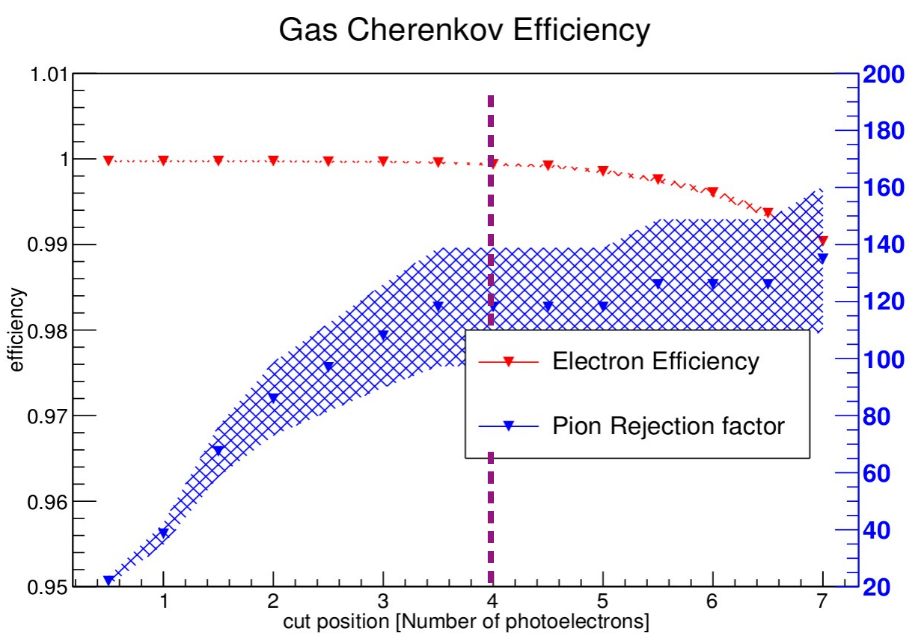




PID efficiencies: Cerenkov





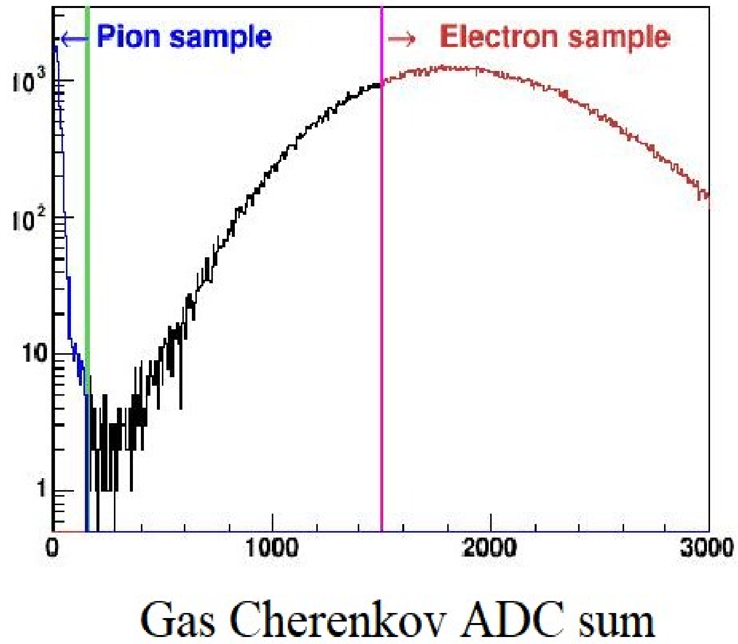


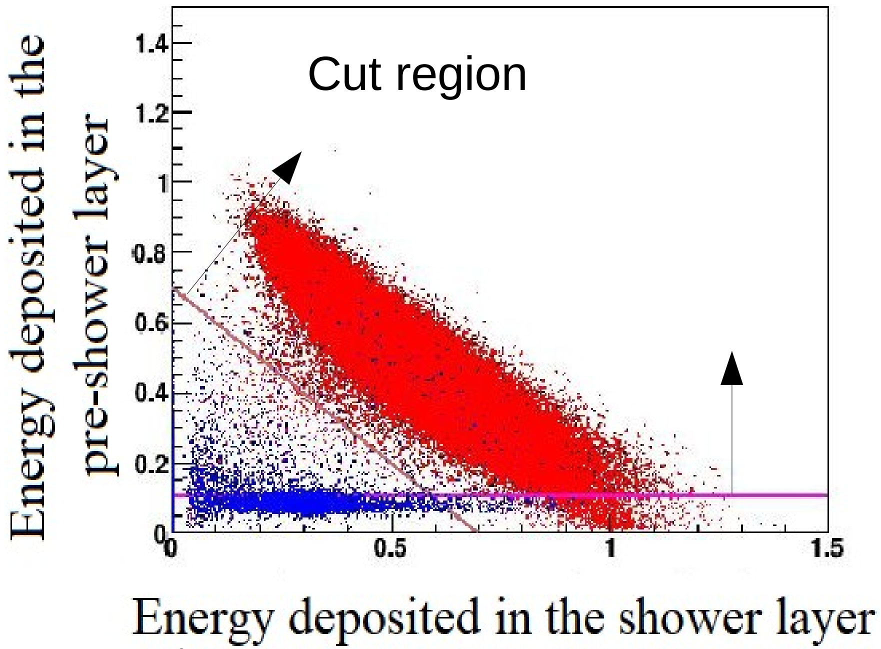
Barak Schmookler (MIT)

Bashar Aljawrneh (NC A&T)

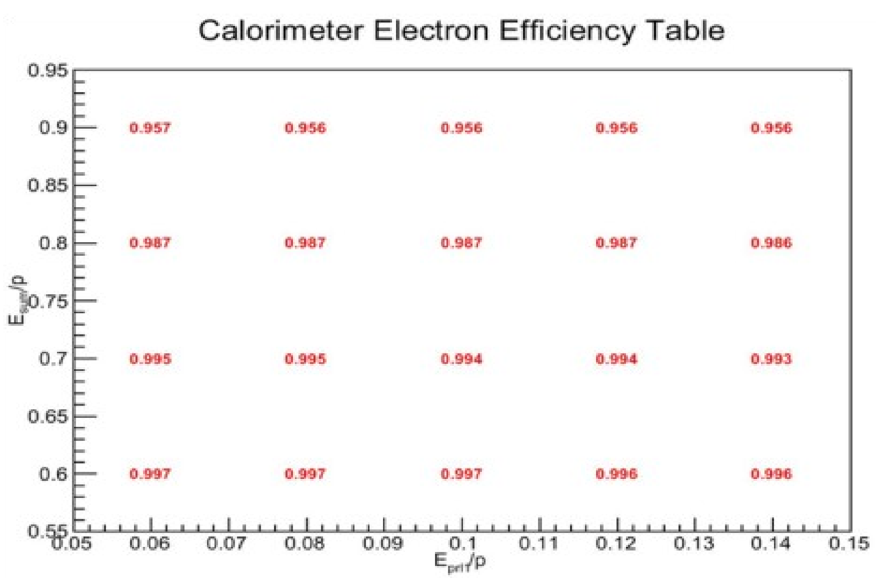
- ε_{cer} > 99.8%
- Uncertainty < 0.1%

PID efficiencies: Calorimeter





Energy distribution in the Gas Cherenkov (Left), and Calorimeter (Right).



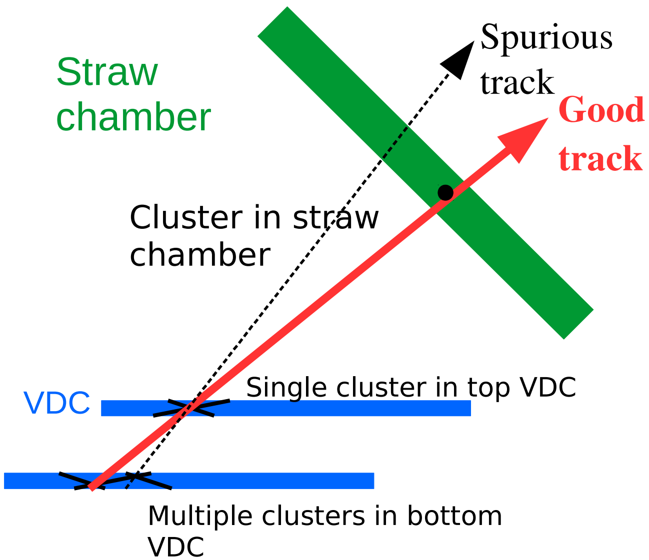
Barak Schmookler (MIT)

Bashar Aljawrneh (NC A&T)

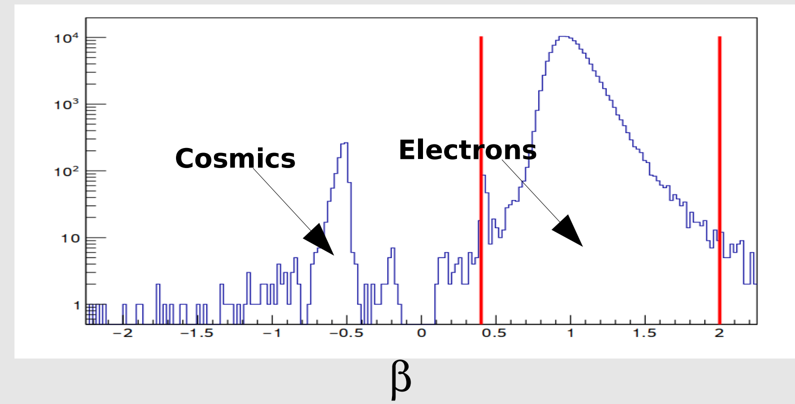
- ε_{cer} > 99.9%
- Uncertainty < 0.1%

VDC Track Reconstruction Efficiency (I)

- Standard Tracking for HRS VDCs utilizes single cluster only in each chamber
- GMp utilized additional Straw Chamber to perform precise checks on efficiency determination



- Selection of good electron trigger sample requires cuts on β to remove cosmics (critical!)



- Elastic events were reconstructed with:

1. single cluster in both VDCs
2. single cluster in 1 VDC + SC

Longwu Ou (MIT)

Kinematic	K3-4	K3-6	K3-7	K3-8	K4-9	K4-10	K4-11
Corrected Yield ratio	1.0016	0.9994	0.9993	0.9985	1.0007	1.0021	0.9997

Corrected yields agree to better than 0.2%

VDC Track Reconstruction Efficiency (II)

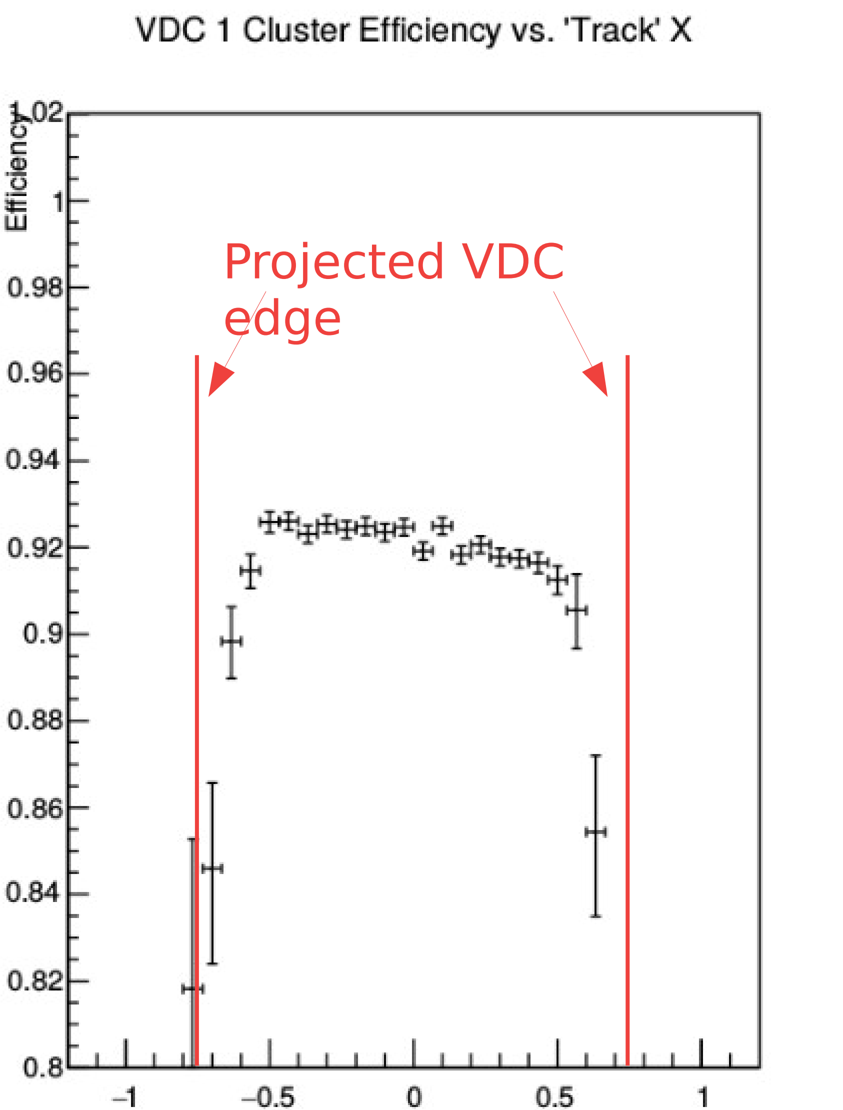
- Examined the reconstruction efficiency vs. focal plane dispersive position

- 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 will be included in final results (<< 1% impact on current results)

Barak Schmookler (MIT)

Bashar Aljawrneh (NC A&T)



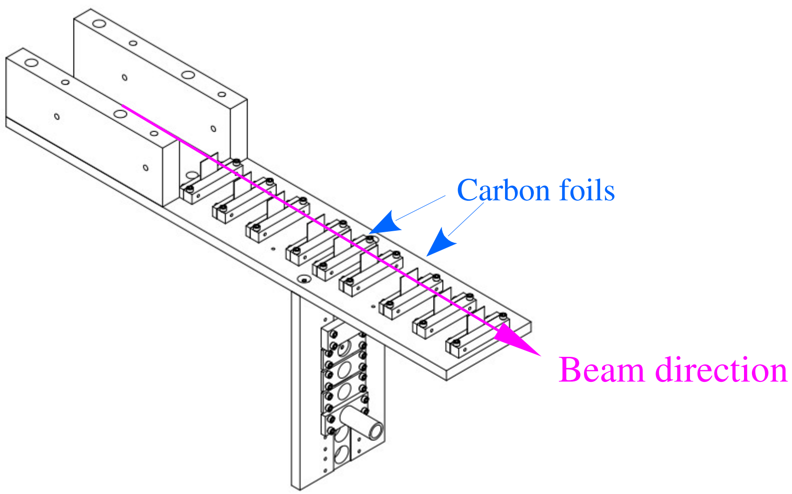
Track projection at focal plane (Dispersive) [m]

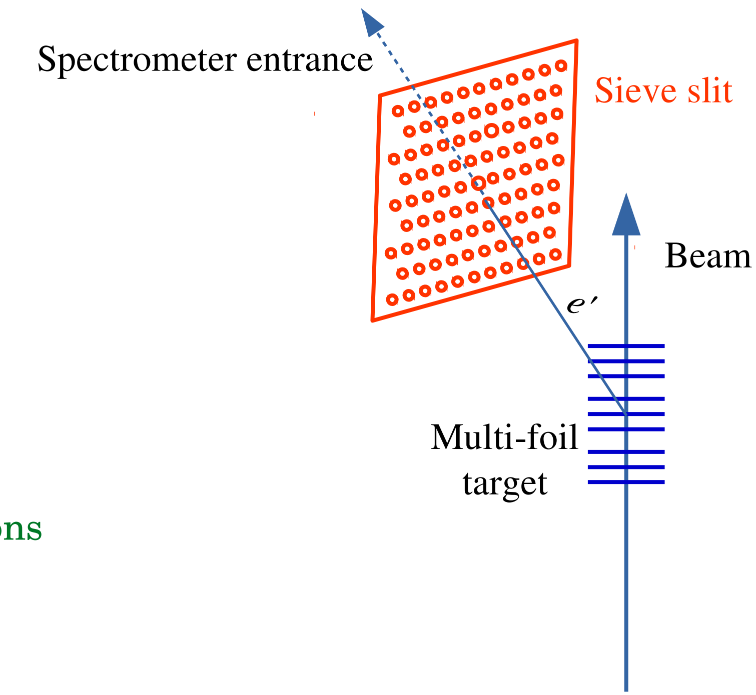
Significant Effort to Improve Optics Calibration

Longwu Ou (MIT)

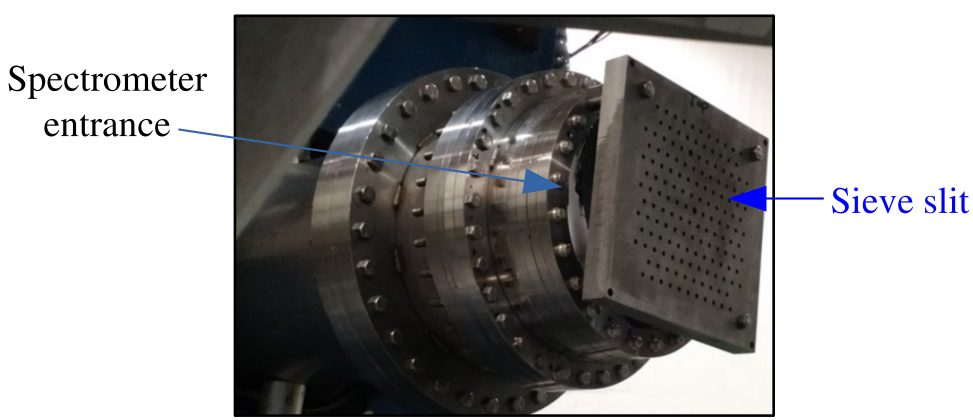
- **Angle and vertex calibration:** used deep inelastic electrons from multi-foil carbon target

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

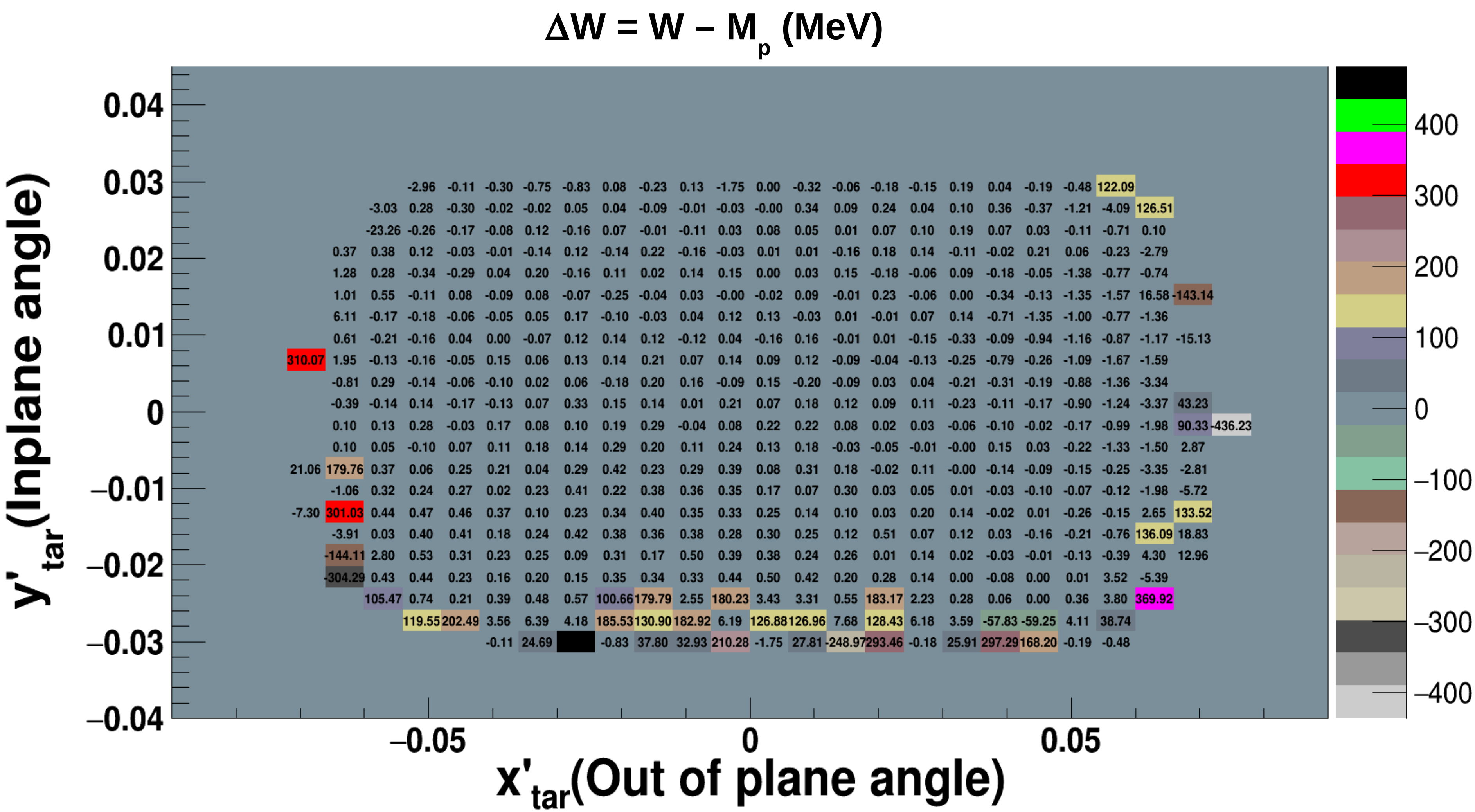


- Algorithm: Minimization of χ^2 by varying the optics coefficients

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

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

Check Elastic peak reconstruction across angular acceptance

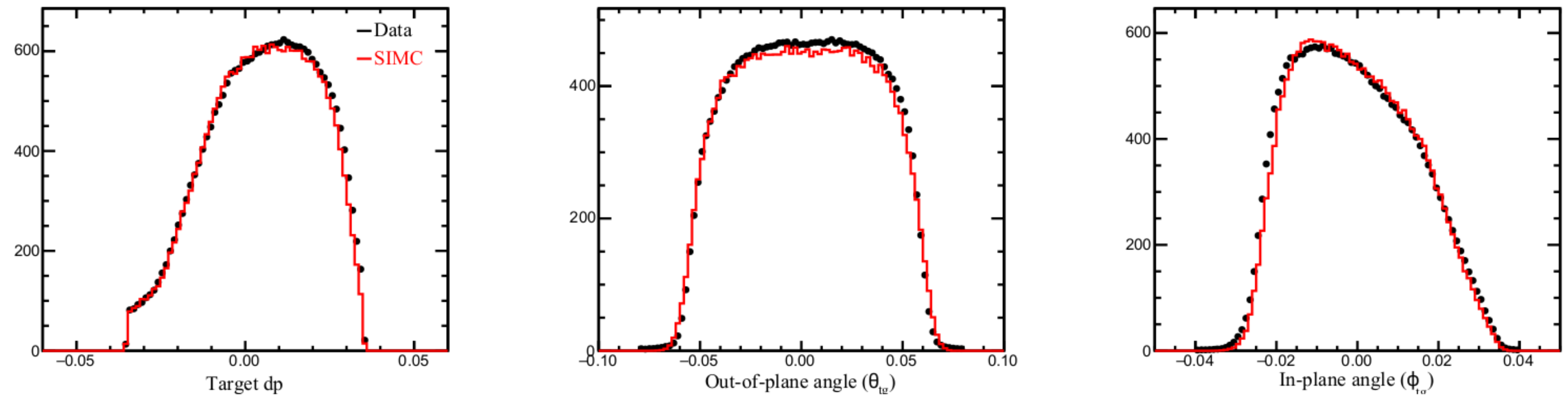


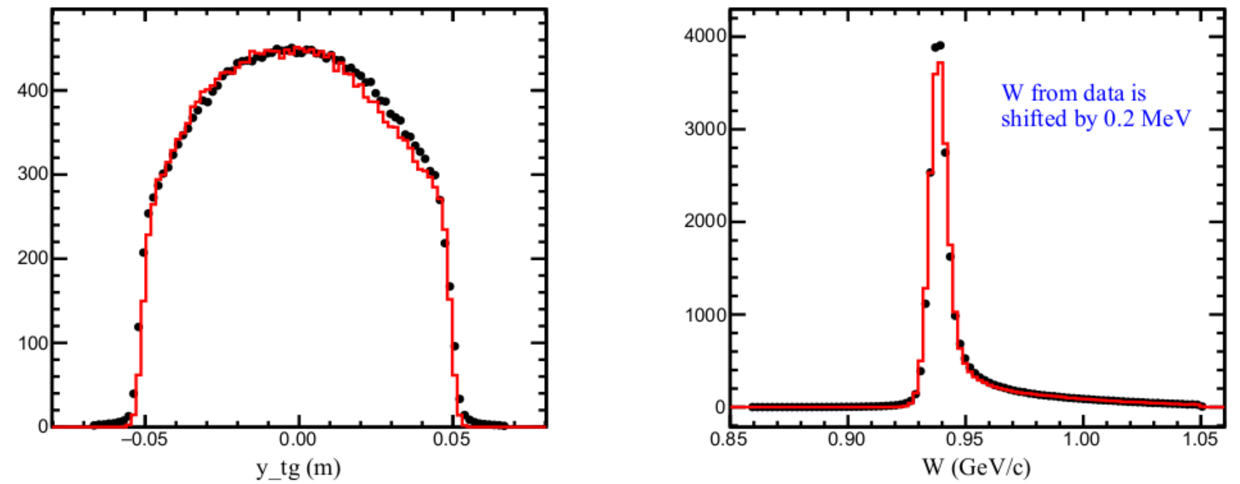
→ W reconstructs to better than 0.4 MeV across most of angular acceptance

=> $\delta p/p$ deviation < **2x10^{-4}**, $\delta\theta$ deviation< **0.2 mrad**

Example Data to Monte Carlo Comparison: LHRS

K1-1





Data to MC ratio: 1.0204

P_0: 1.3660 GeV/c

Beam energy = 2.222 GeV

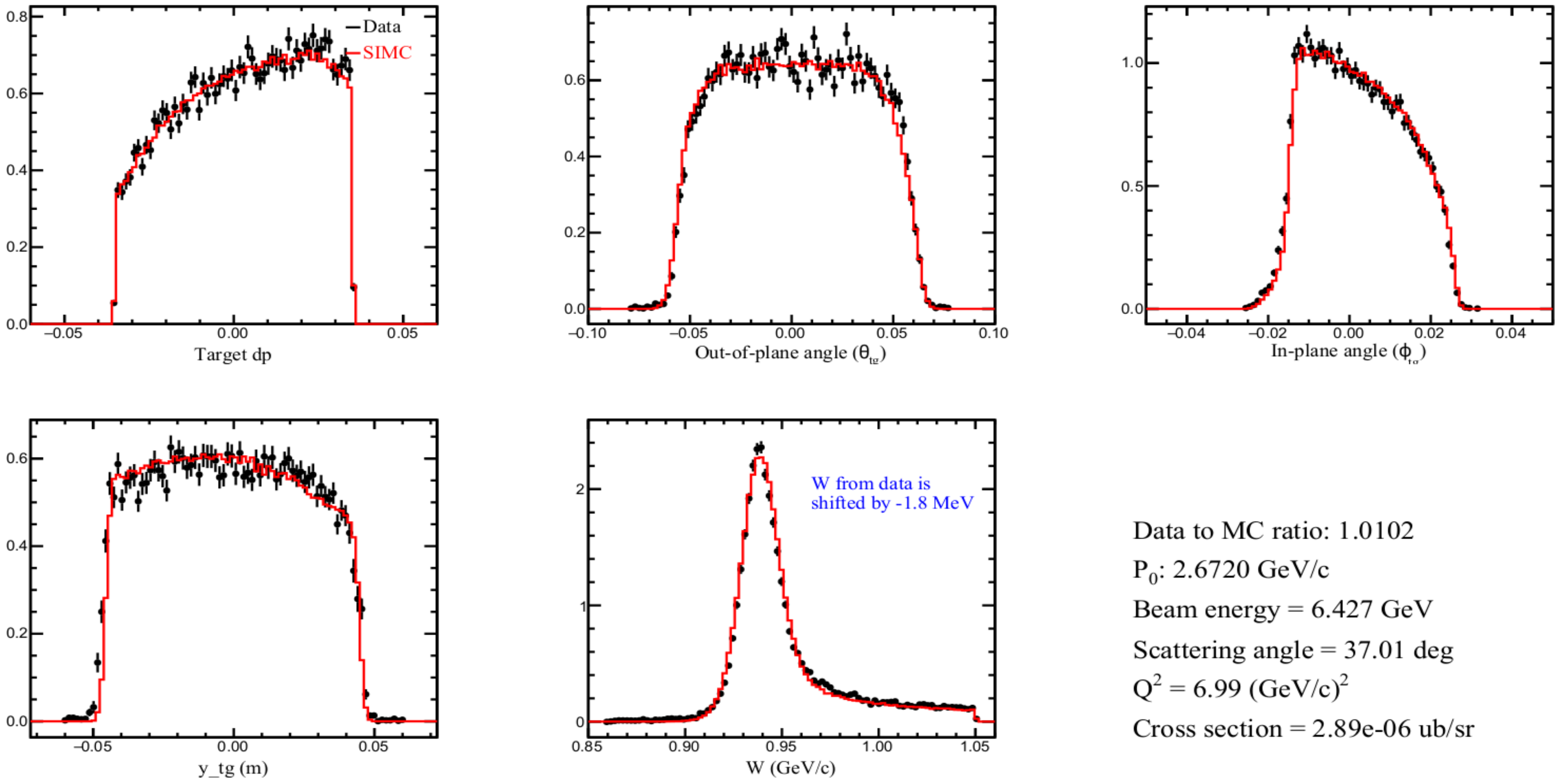
Scattering angle = 42.00 deg

Q^2 = 1.58 $(GeV/c)^2$

Cross section = 1.45e-03 ub/sr

Example Data to Monte Carlo Comparison: LHRS

K3-7

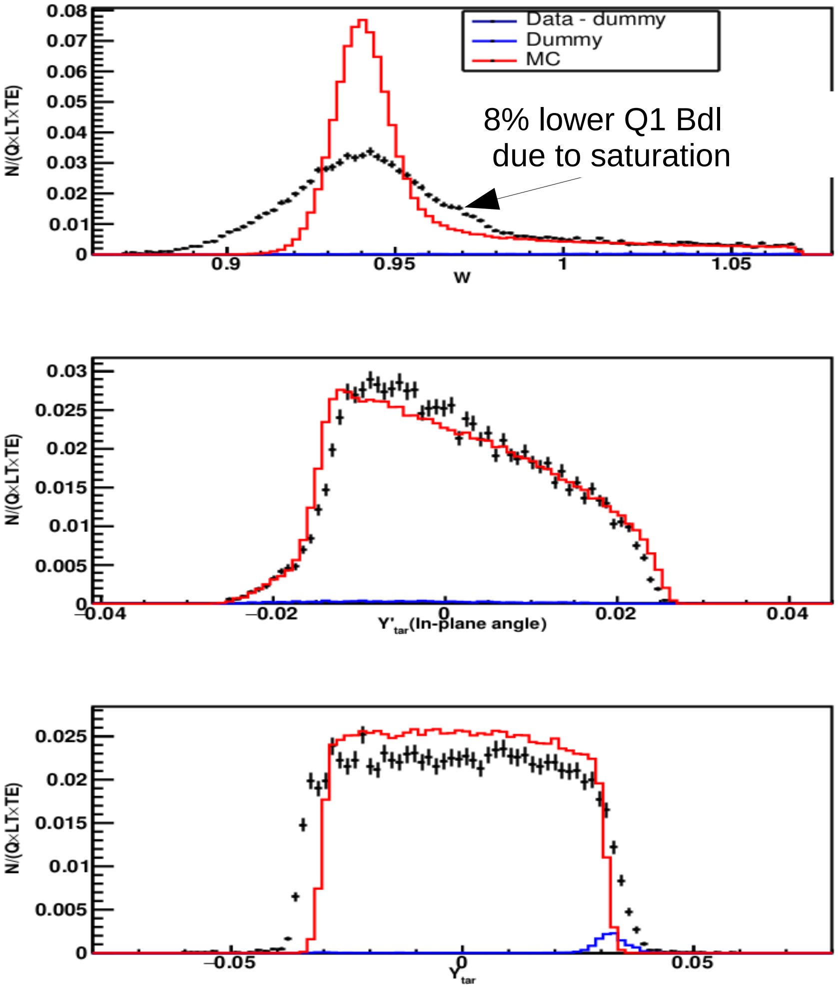


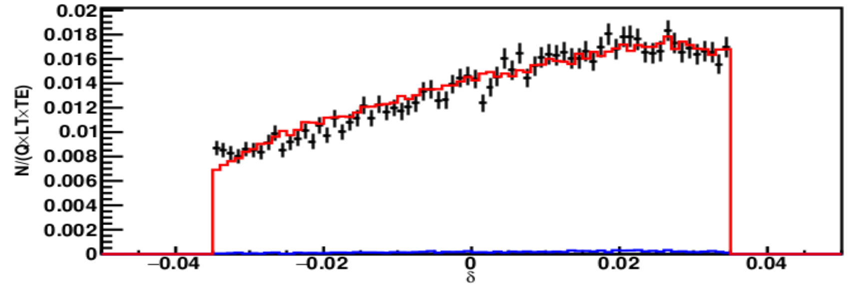
Data to MC ratio: 1.0102
P_0: 2.6720 GeV/c
Beam energy = 6.427 GeV
Scattering angle = 37.01 deg
Q^2 = 6.99 $(GeV/c)^2$
Cross section = 2.89e-06 ub/sr

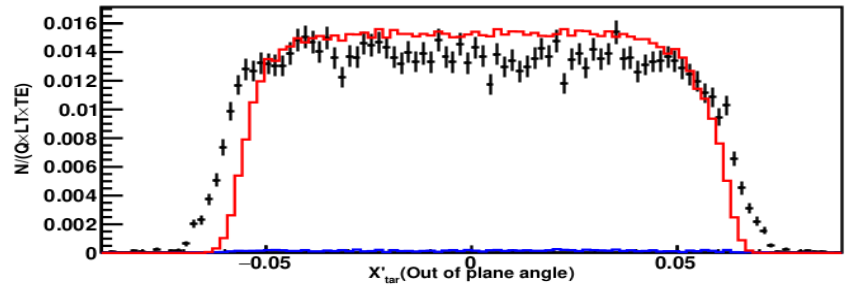
- Excellent comparison after subtraction of target cell endcaps via dummy (~3%)
- Small offsets in W consistent with estimated kinematic uncertainties

Largest problem encountered due to uncorrected saturation in setting replacement Q1 magnet for E' > 3 GeV

Problem: Altered Bdl magnet ratios changes tune of spectrometer with no corresponding optics data taken.







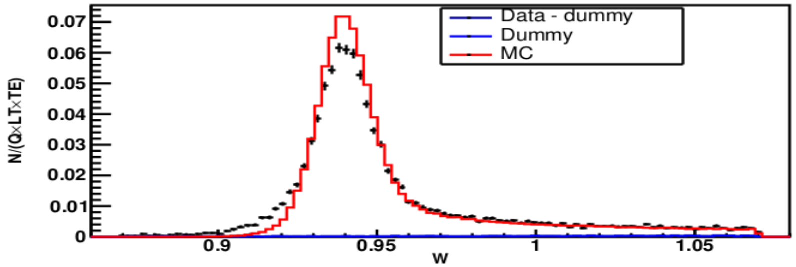
Kinematics: K34
E = 6.427 GeV, θ = 24.2 °, p_0 = 3.962GeV , Q2 = 4.543 GeV^2
Y^{data}/Y^{MC} = 0.990213 ± 0.006800
Cross section = 7.633132e-05 ± 5.241957e-07 μbarn/sr

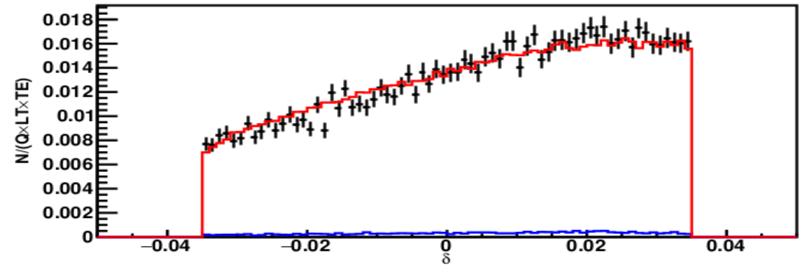
Cuts:
PID, One cluster cut
-0.035<δ<0.035
-0.04<y'_{tar}(rad)<0.040, 0.87<W(GeV)<1.07
-0.080<x'_{tar}(rad)<0.080, |y_{tar}(cm)|<6

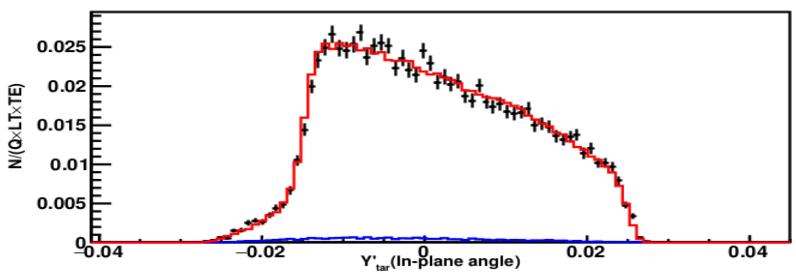
Largest problem encountered due to uncorrected saturation in setting replacement Q1 magnet for E' > 3 GeV

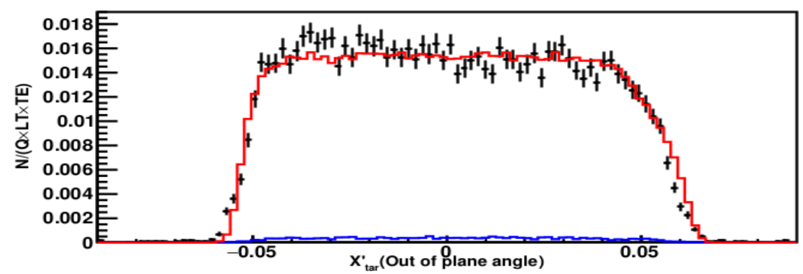
Solution: Developed procedure to determime satureed optics utilizing optics data at nominal tune and the COSY magnetic model

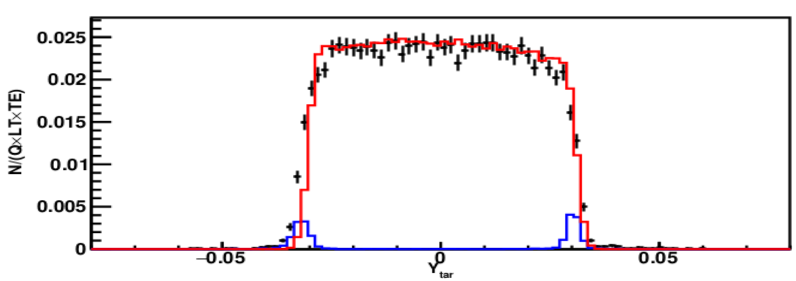
Thir Gautam (HU)











Kinematics: K34

E = 6.427 GeV, θ = 24.2 °, p_0 = 3.962GeV , Q2 = 4.543 GeV^2

Y^{data}/Y^{MC} = 1.002462 ± 0.007027

Cross section = 7.727558e-05 ± 5.416744e-07 μbarn/sr

Cuts:

PID, One cluster cut

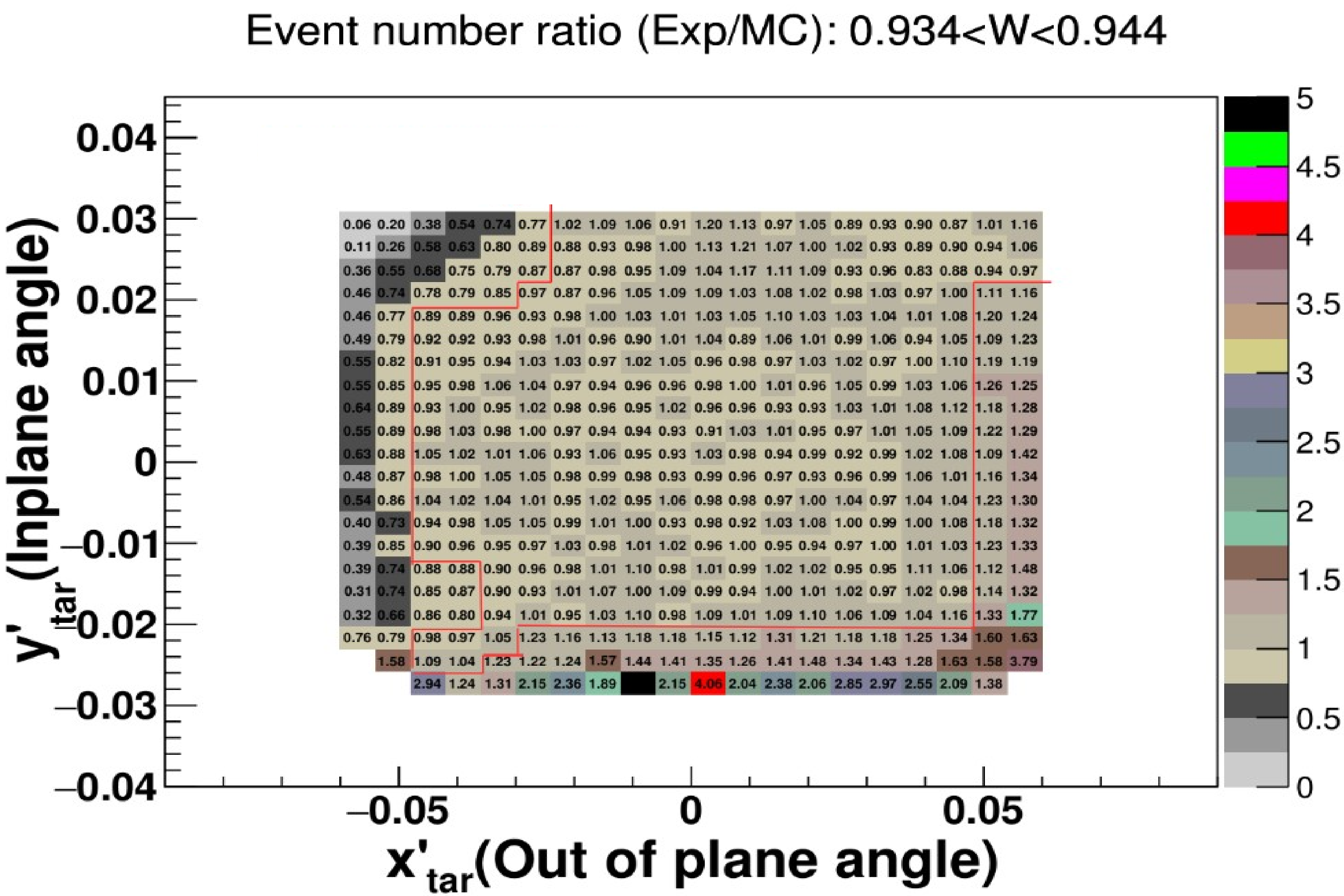
-0.035<δ<0.035

-0.04<y'_{tar}(rad)<0.040, 0.87<W(GeV)<1.07

-0.080<x'_{tar}(rad)<0.080, |y_{tar}(cm)|<6

Study of Spectrometer Acceptance

- Low-Q^2 *ep* elastic utilized to check acceptance model across angular phase space (~2% statistics per bin).



Thir Gautam
Hampton U.

Uncertainties in Acceptance Modeling

Unceraintу due to dominant aperture positions

Aperture shift(in cm)	Solid angle (Ω)	δΩ(%)
No shift (k3-7)	5.989	0.00
15(xs - 0.1)	5.993	0.07
15(xs + 0.1)	5.99	0.02
15(ys - 0.1)	6.001	0.19
15(ys + 0.1)	5.995	0.10
17(xs - 0.1)	5.994	0.09
17(xs + 0.1)	5.997	0.13
17(ys - 0.1)	6.021	0.53
17(ys + 0.1)	6.002	0.32

→ Average +/-
→ estimated error 0.5 mm

Total for 0.5mm:
0.25%

Unceraintу due to individual Bdls for forward tune (pt. target)

→ estimated Bdl errors 0.2%

Quad	Solid angle(Ω)	Ω/Ω_0	$d\Omega/\Omega_0$(%) (ΔBdl of 1%)	$d\Omega/\Omega_0$(%) (ΔBdl of 0.25%)
Default (k3-7)	5.989	1.000	0.00	0.00
Q1 field *1.01	5.987	0.999	0.02	0.005
Q1 field *0.99	6.049	1.010	1.00	0.25
Q2 field *1.01	6.123	1.022	2.24	0.5
Q2 field *0.99	5.929	0.990	1.00	0.25
Q3 field *1.01	5.981	0.998	0.13	0.03
Q3 field *0.99	6.043	1.009	0.90	0.22

Total for 0.25%:
0.40%

→ **Total quadrature sum: 0.5%**
→ **Studies of uncertainties in extended target at most backward angles to be finalized.**

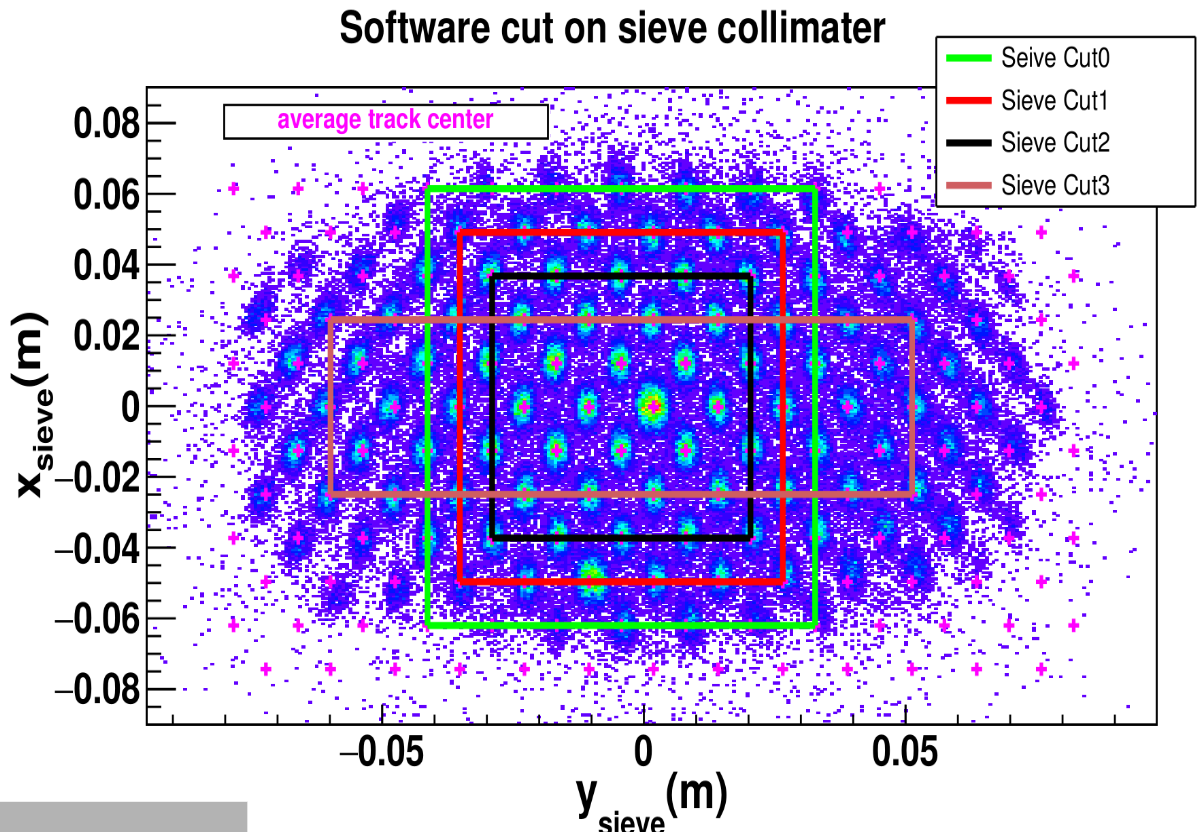
Current Estimated Uncertainties: 0.7% pt-pt and 0.8% normalization

Acceptance Studies: separating optics from Acceptance

Procedure:

→ Utilize software cuts at sieve slit position to determine variation in Acceptance / Extracted dσ

→ Place software cuts through center of sieve slit hole positions, where optics is best constrained.



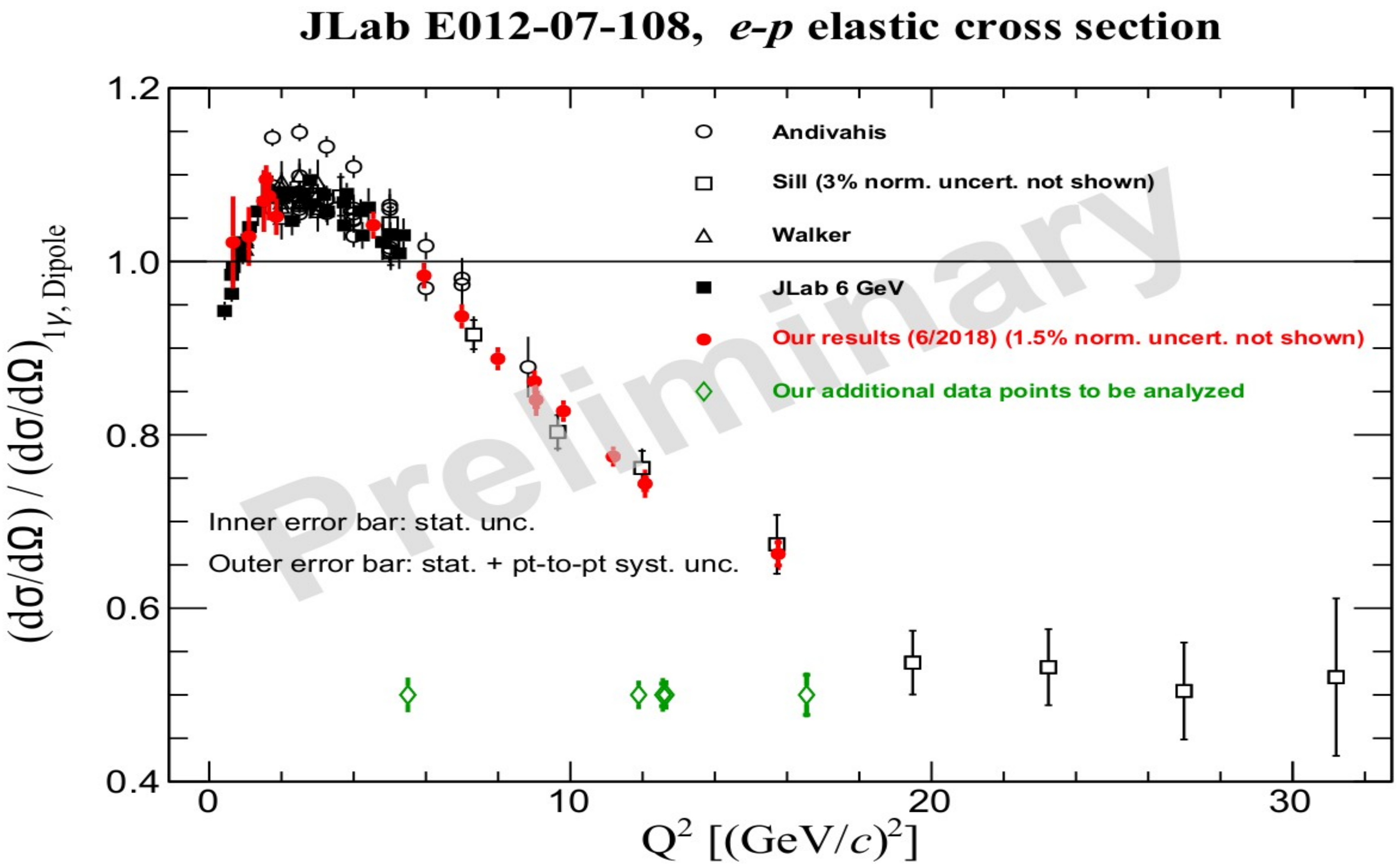
cut	$d\sigma_{cut} / d\sigma_{nocut}$
0	1.00
1	1.005
2	1.006
3	1.007

Variation < 0.5% for cuts least sensitive to optics

Status of Error Budget (LHRS Fall 2016)

Source	Point-point $\Delta\sigma$(%)	Norm $\Delta\sigma$(%)
Acceptance	0.7	0.8
Optics	0.3	0.3
Lunimosity:		
charge	0.15% – 1% (40 μA) (6 μA)	0.1
Areal density	< 0.2	0.25
Boiling	<0.1% - 0.24% (6 μA) (40 μA)	0.25 (@40 uA)
Kinematics		
ΔE (5×10^{-4} – 1×10^{-4})	0.5	0.5
$\Delta\theta$ (0.2 mrad)	0.5	0.5
PID	0.1	0.1
Trigger	0.2	0.1
Livetime	< 0.1	< 0.1
Track Reco	0.2	0.2
Radiative correction	0.8	1.0
Backgrounds	0.1	< 0.1
Total:	1.25 – 1.6 %	1.5%

GMp results (June 2018)



- Significant improvement in precision for $Q^2 > 6$.
- Systematic uncertainties on Fall 2016 data ~1.6-2.0% (pt-pt), 1.5% (norm)

→ Expected to complete all kinematics and reduce uncertainties to final values by the end of summer 2018

Summary

- 12 GeV era GMp experiment successfully completed with 21 cross section measurements covering Q^2 from 1 to 16.5 GeV^2 significantly reducing experimental uncertainties for $Q^2 > 6$ GeV^2
- Data analysis is appoaching completion including all systematic studies.
- Current systematic uncertainties for Fall 2016 data of:

  1.25 - 1.6% pt-pt

  1.5% normalization

- Final cross section results with further reduced systematics and first publication in 3-4 months.

GMp Analysis Team

- Spokesperson:
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  - Shalev Gilad
  - Vincent Sulkosky
  - Bogdan Wojtsekhowski
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Thanks!

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