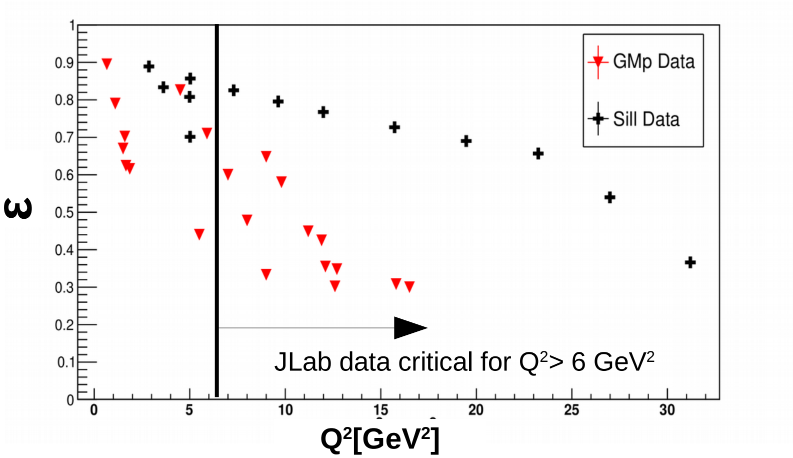
Precision measurement of the electron-proton elastic scattering cross section at High Q^2
(The GMp experiment, E12-07-108)

Hall A collaboration meeting
30-31 Janauary 2019

Thir Gautam,
Hampton University,

in the behalf of GMp collaboration

Preview



- Highlights:
  - → Improved precision over existing data by a factor of 3 for $Q^2 > 6$ GeV^2
  - → Relatively low ε :
    - more sensitive to G_M^p than previous measurement
    - ε lever arm allow the possible sensitivity to 2y studies
- We further reduced our systematic uncertainties since last collaboration meeting (<2% Fall 2016 LHRS data set)
- First publication being prepared

Outline

- Overview of GMp experiment
- Status and overview of analysis
- Systematic uncertainties
- Cross section and GMp results

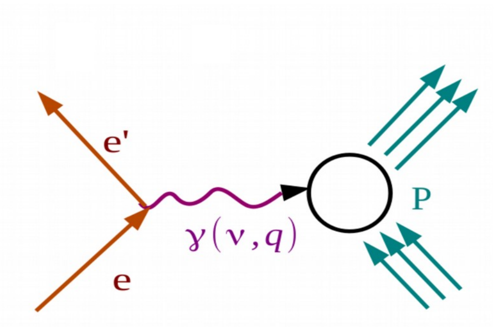
Proton magnetic form factor

- Form factors encode electric and magnetic structures 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 the 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:



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

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

Where,

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

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

Methods of measurements

- **Rosenbluth separation method:**

Within one-photon-exchange framework

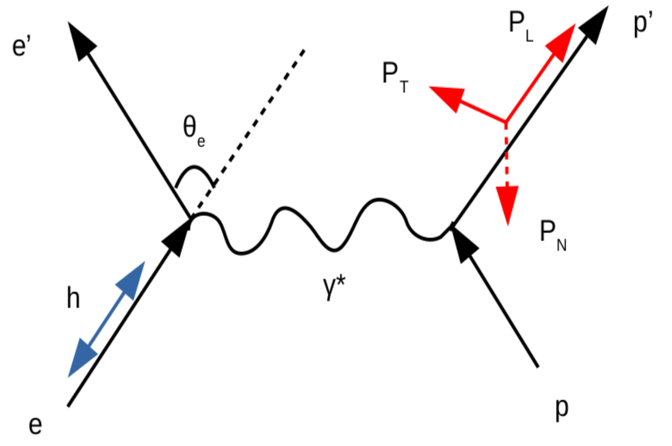
$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \varepsilon\left(G_E^p\right)^2 + \tau\left(G_M^p\right)^2,$$

The slope of $\sigma_R(\varepsilon)$ is directly related to G_E^p and the intercept to G_M^p

- **Recoil polarization technique (measurement of the ratio between electric and magnetic FF)**

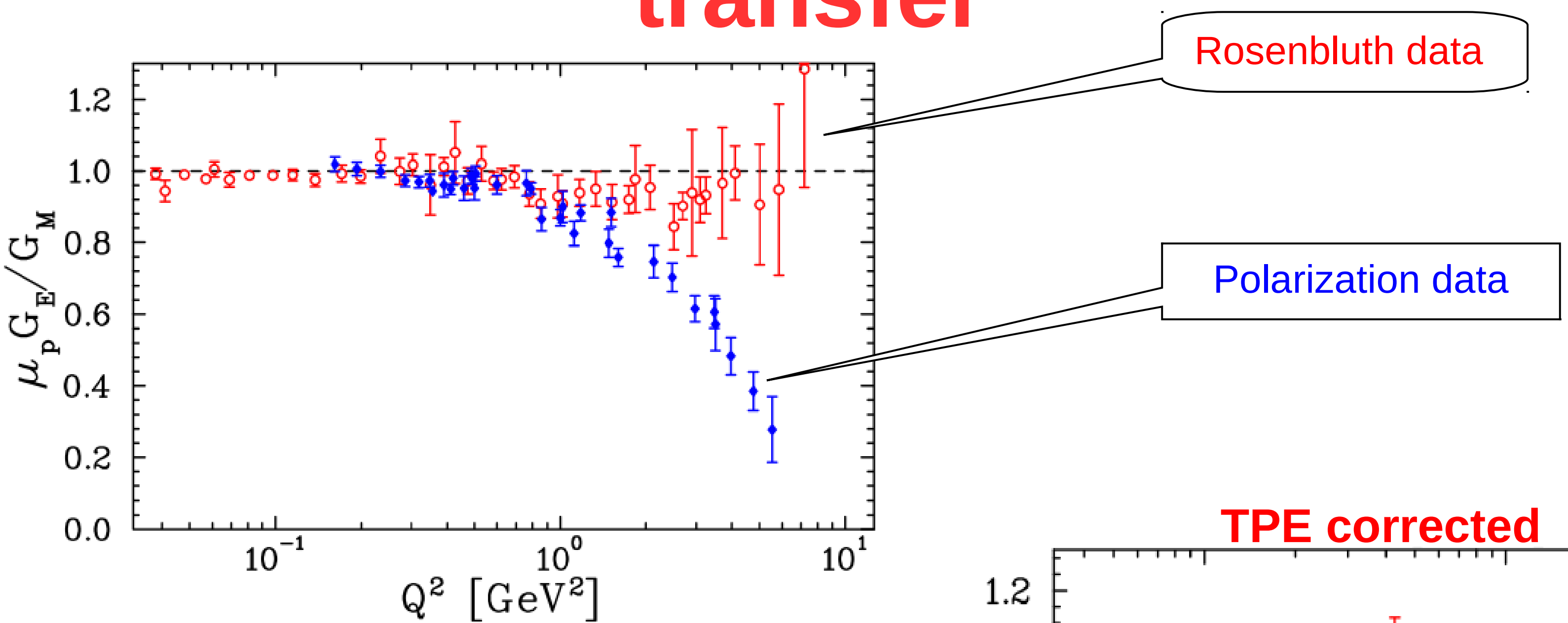
Polarized electron transfers longitudinal polarization to G_E^p, but transverse polarization to G_M^p

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

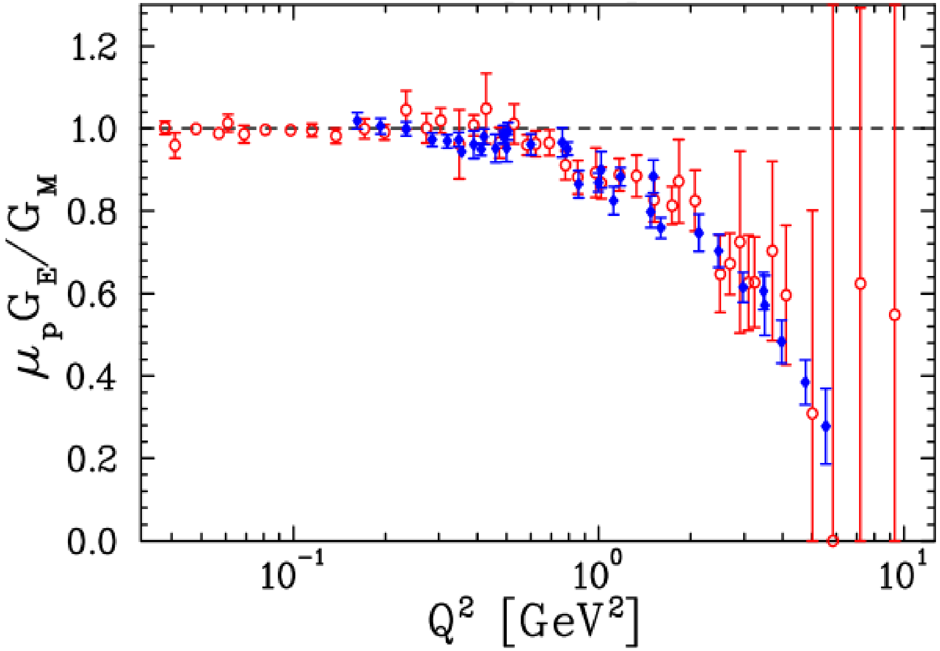


Polarization transfer cannot determine the values of G_E and G_M but can determine the from factor ratio.

Rosenbluth compared to polarization transfer

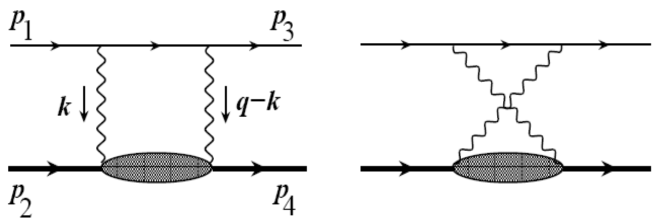


TPE corrected



How to explain it?

Two photon exchange may explain the difference



→ TPE effect can be large on RS method at large Q^2
→ TPE effect can be smaller on PT method

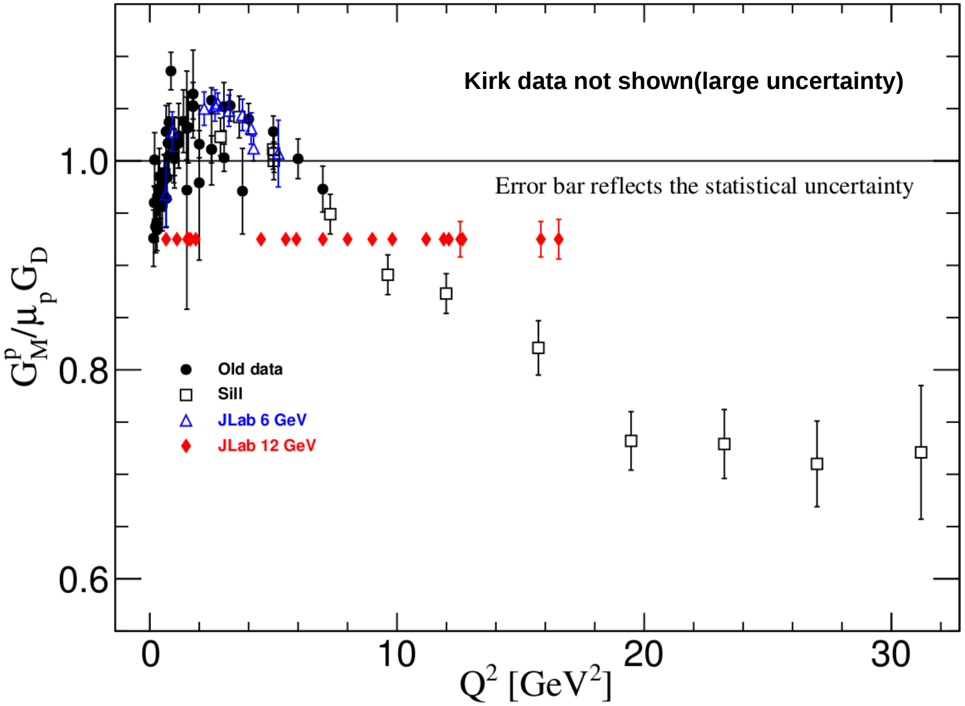
Overview of GMp experiment

- Precision measurement of the elastic *ep* cross-section over a wide range of 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

Statistical: Better than 2%

Systematic:
Point to point: 0.8-1.1%
Normalization: 1.0-1.3%
Total Error Budget: 1.2-2.6%



Need a good control on:

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

Experimental setup

→ RHRS Q1 was replace by new quad

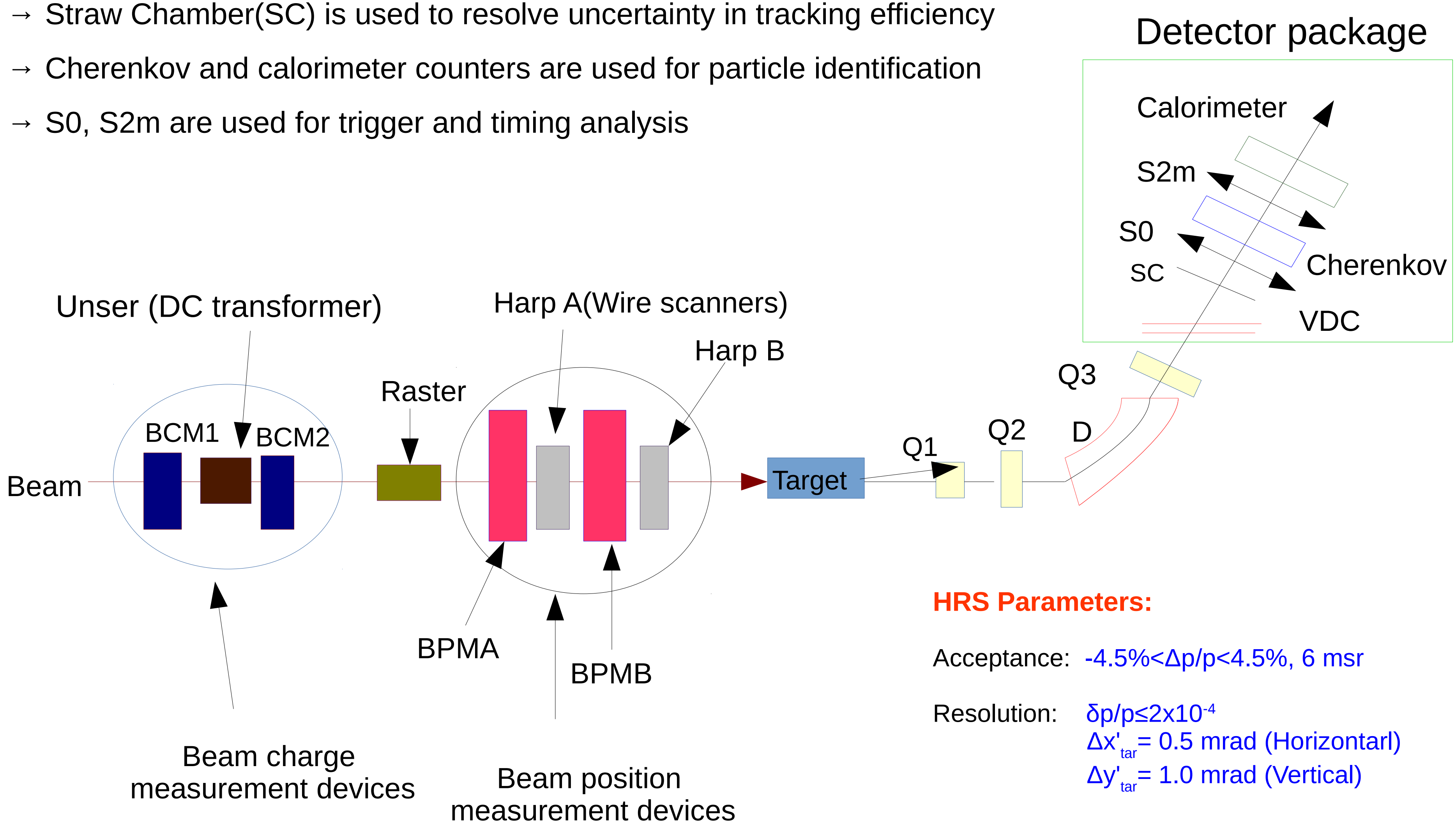
→ LHRS Q1 was replaced by SOS quad

→ VDC with new A/D cards is used for tracking information

→ Straw Chamber(SC) is used to resolve uncertainty in tracking efficiency

→ Cherenkov and calorimeter counters are used for particle identification

→ S0, S2m are used for trigger and timing analysis



HRS Parameters:

Acceptance: -4.5%<Δp/p<4.5%, 6 msr

Resolution: $\delta p/p \leq 2\times10^{-4}$
$\Delta x'_{tar}$= 0.5 mrad (Horizontarl)
$\Delta y'_{tar}$= 1.0 mrad (Vertical)

GMp analysis status

System Calibration:

→ Beamline component Calibration (done)
→ PID detector calibration (done)
→ Tracking detector(VDC, Straw chamber) calibration (done)
→ Timing (s0, s2m) calibration (done)
→ Optics calibration (done for LHRS Fall 16 kinematics)

Data Analysis:

→ Tracking, trigger, PID efficiencies, DAQ live-time (done)
→ Target boiling analysis (done)
→ HRS acceptance studies and detailed aperture checks in the simulation model(done)
→ Extraction of cross section with both data to MC ratio and acceptance correction method (done)

Elastic cross section extraction

$$\frac{d\sigma}{d\Omega}=\frac{N_{evt}}{\Omega Q t_{tar}}$$

Relative impact on cross section:

$$\frac{\partial\sigma}{\sigma}=\sqrt{\left(\frac{\partial E}{E}\right)^2+\left(\frac{\partial\theta}{\theta}\right)^2+\left(\frac{\partial N}{N}\right)^2+\left(\frac{\partial L}{L}\right)^2+\left(\frac{\partial eff}{eff}\right)^2+\left(\frac{\partial t_d}{t_d}\right)^2+\left(\frac{\partial\Omega}{\Omega}\right)^2}$$

- Beam energy, scattering angle (very important)
- Statistical uncertainty: 1/√N
- Luminosity: temp/pressure, boiling, z-reconstruction
- Impact of PID cuts, reconstruction efficiency, dead time(t_d)
- Acceptance: software collimator method
- Optics: lack of data (Spring 16) + Q1 saturation (Fall 16)

Beam charge calibration and boiling study

Charge calibration:

- Multiple instruments of charge measurement: Unser and two BCMs
- Calibration coefficients from multiple measurement have negligible drift within uncertainties

Uncertainty:

Pt-pt: 0.06 μA
Correlated: 0.06 μA

Boiling study:

- Target used: 15 cm LH2 target in Loop2 and single foil carbon target
- Carbon target is used to separate possible rate systematic from boiling

→ Raster size: 2×2 mm^2

→ Range of beam current: 3 - 67 μA

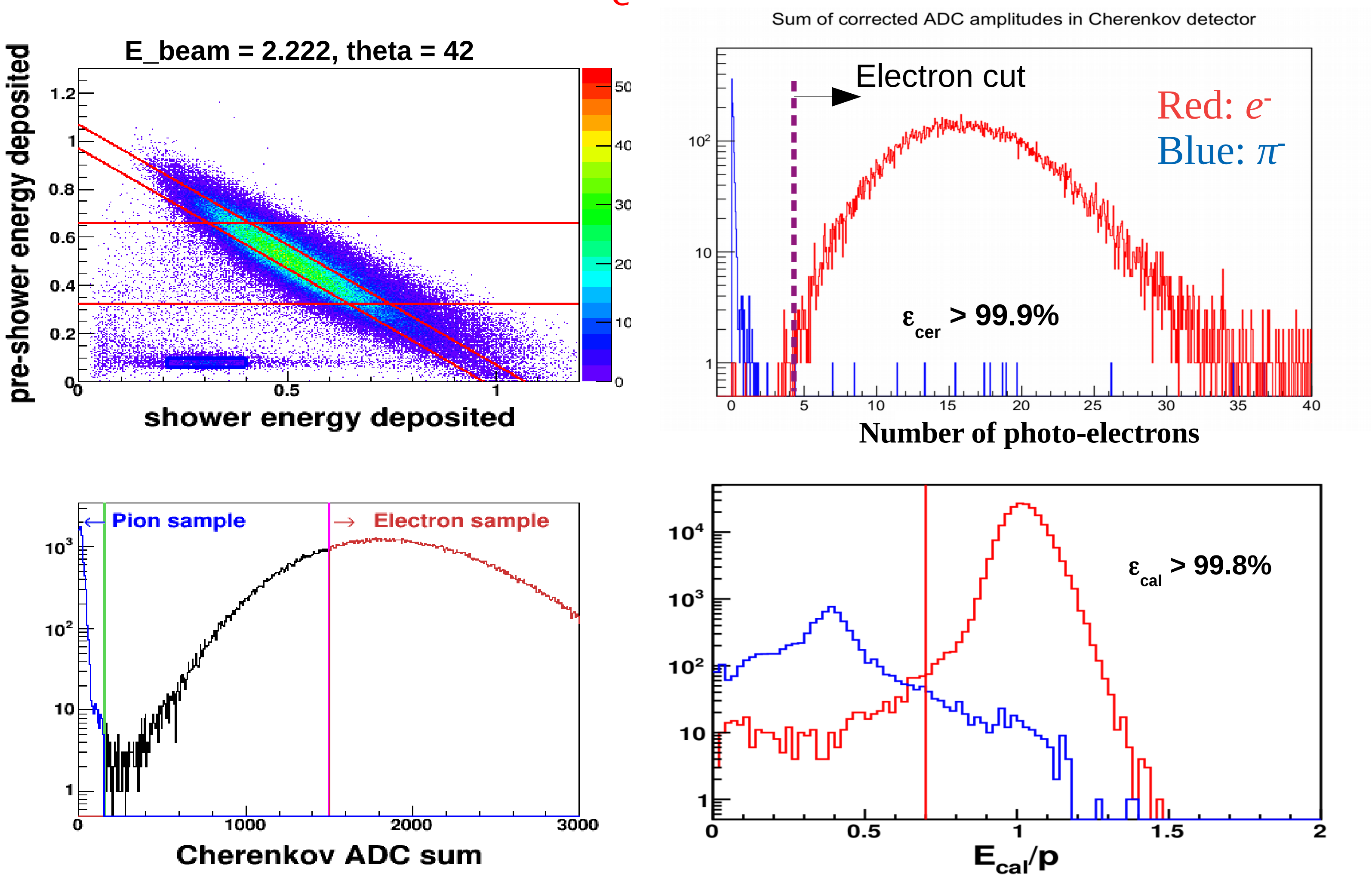
Uncertainty:

$$\frac{\delta L}{L} : 0.0015 - 0.33\,\% \qquad \frac{\delta L}{L} = 0.5\,\% \times \frac{J(\mu A)}{100(\mu A)}$$

Detector efficiencies

→ We did particle identification studies using Cherenkov and calorimeter

→ Got PID efficiencies for all kinematics and the cuts were set to select good electrons $\frac{\delta\epsilon}{\epsilon} < 0.1\%$

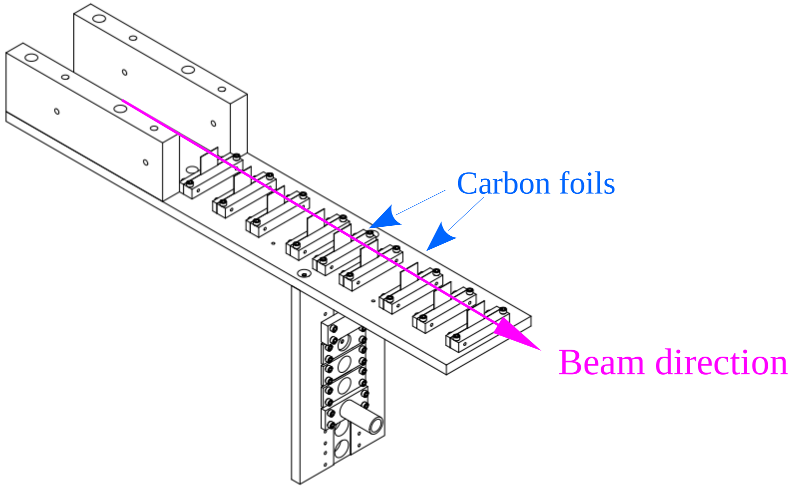


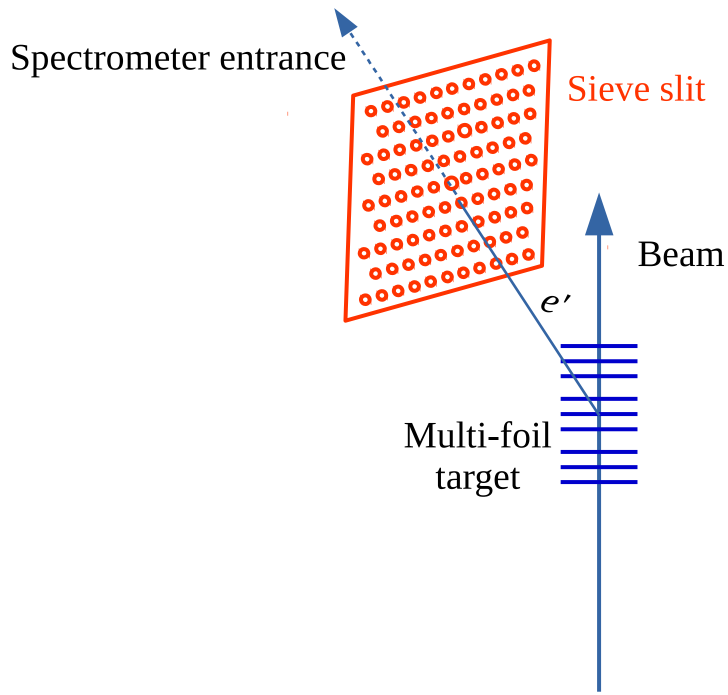
Barak Schmookler (MIT)
Bashar Aljawrneh (NC A&T)

Optics Calibration (LHRS)

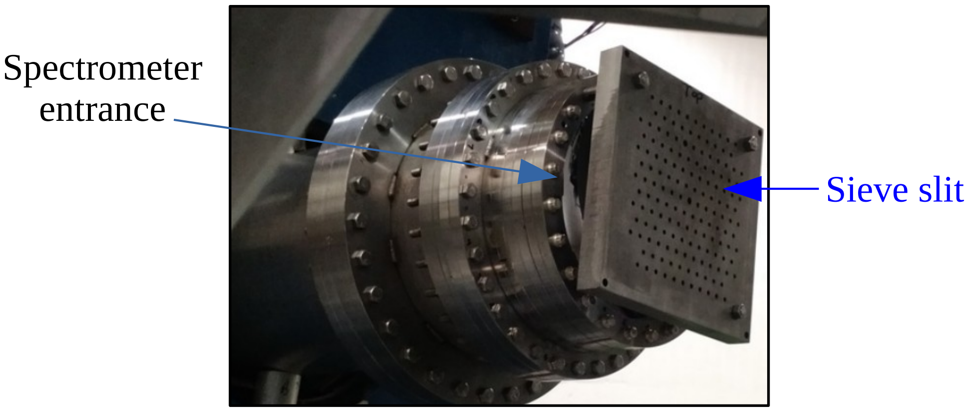
- **Angle and vertex calibration:** used deep inelastic electrons from multi-foil carbon target

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

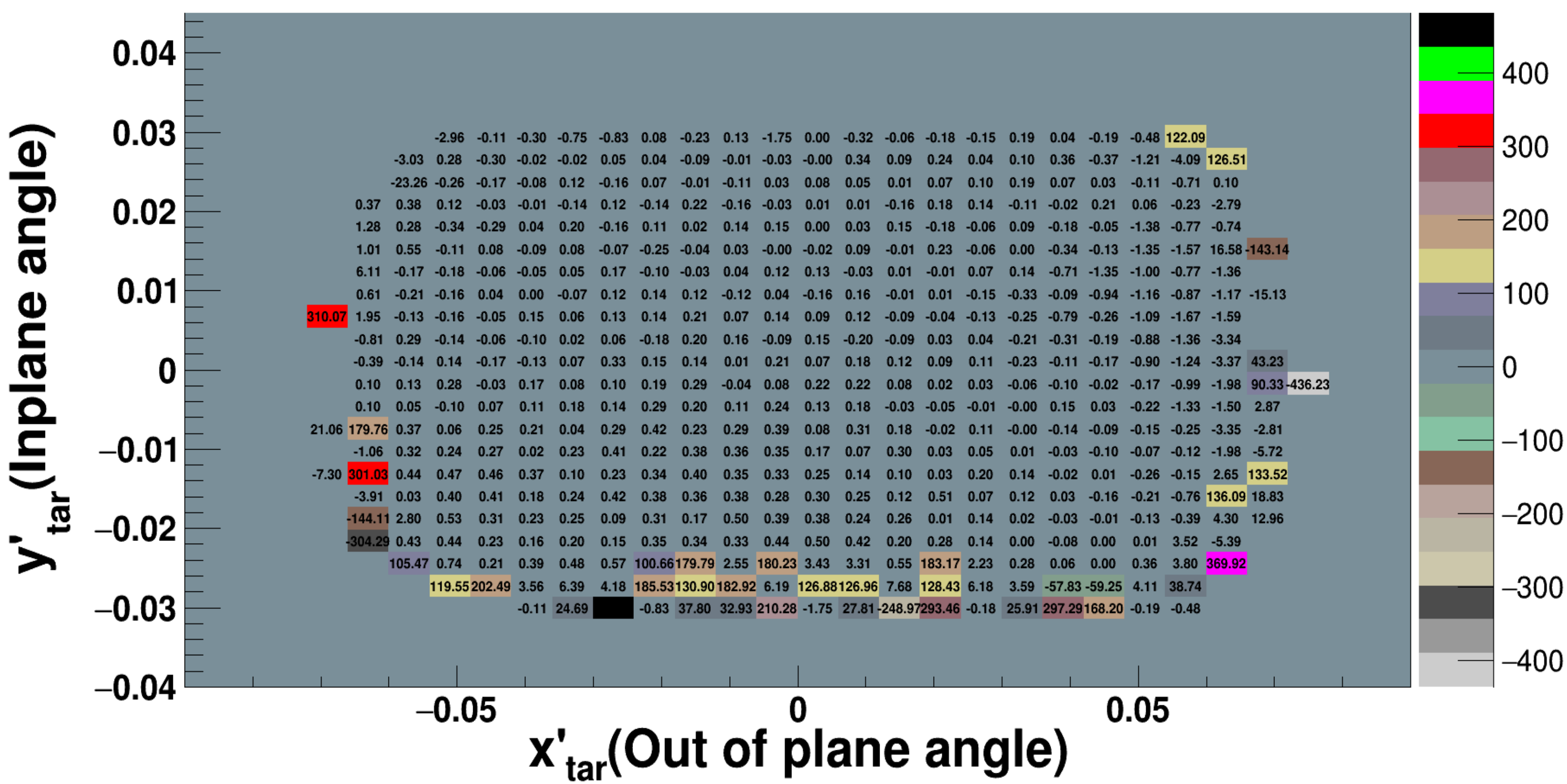
$$\chi^2(y_{tg}) = \sum_{\text{events}} (Y_{ijkl} x^i_{fp} \theta^j_{fp} y^k_{fp} \phi^l_{fp} - y^{\text{survey}}_{tg})^2$$

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

Check of optics across angular acceptance utilizing elastic peak (LHRS Fall 16)

→ This plot shows invariant mass peak is stable and optics is good

Data: (W_{peak} - 938[MeV])



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

=> δp/p deviation < **2×10^{-4}**, δθ deviation< **0.2 mrad**

Elastic cross section (Monte carlo ratio method)

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

→ Monte Carlo is a COSY transport model use to transport events through the magnetic fields

→ Scattering events are generated at the target and weighted by the physics cross section model (Included radiative effects, energy loss and multiple scattering)

→ Compare MC yield to data yield for same normalized luminosity

$$\frac{d\sigma}{d\Omega}^{mod}(\theta) \;=\; \int dE' \frac{N^{MC}(E',\theta)}{\mathcal{L}^{MC}} . \frac{RC^{MC}}{A^{MC}(E',\theta)} \longrightarrow \quad (2)$$

$$\frac{d\sigma}{d\Omega}^{data}(\theta) / \frac{d\sigma}{d\Omega}^{mod}(\theta) \;=\; \frac{\int^{E_{max}} (N^{data}(E',\theta) - N_{BG}(E',\theta))dE'}{\int^{E_{max}} N^{MC} dE'} . \frac{A^{MC}(E',\theta)}{A^{data}(E',\theta)} . \frac{RC^{data}}{RC^{MC}} \longrightarrow \quad (3)$$

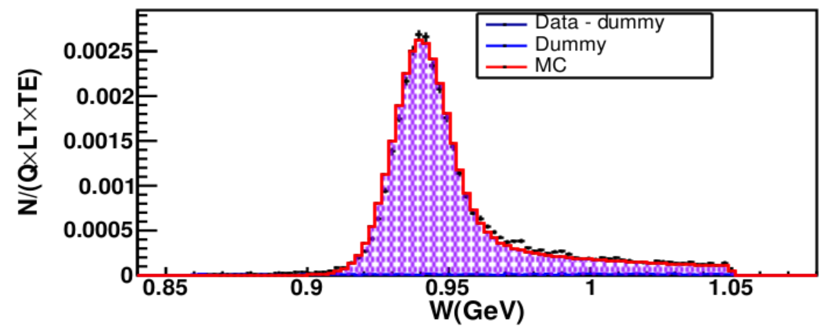
Assuming acceptance and radiative contributions are correctly modeled:

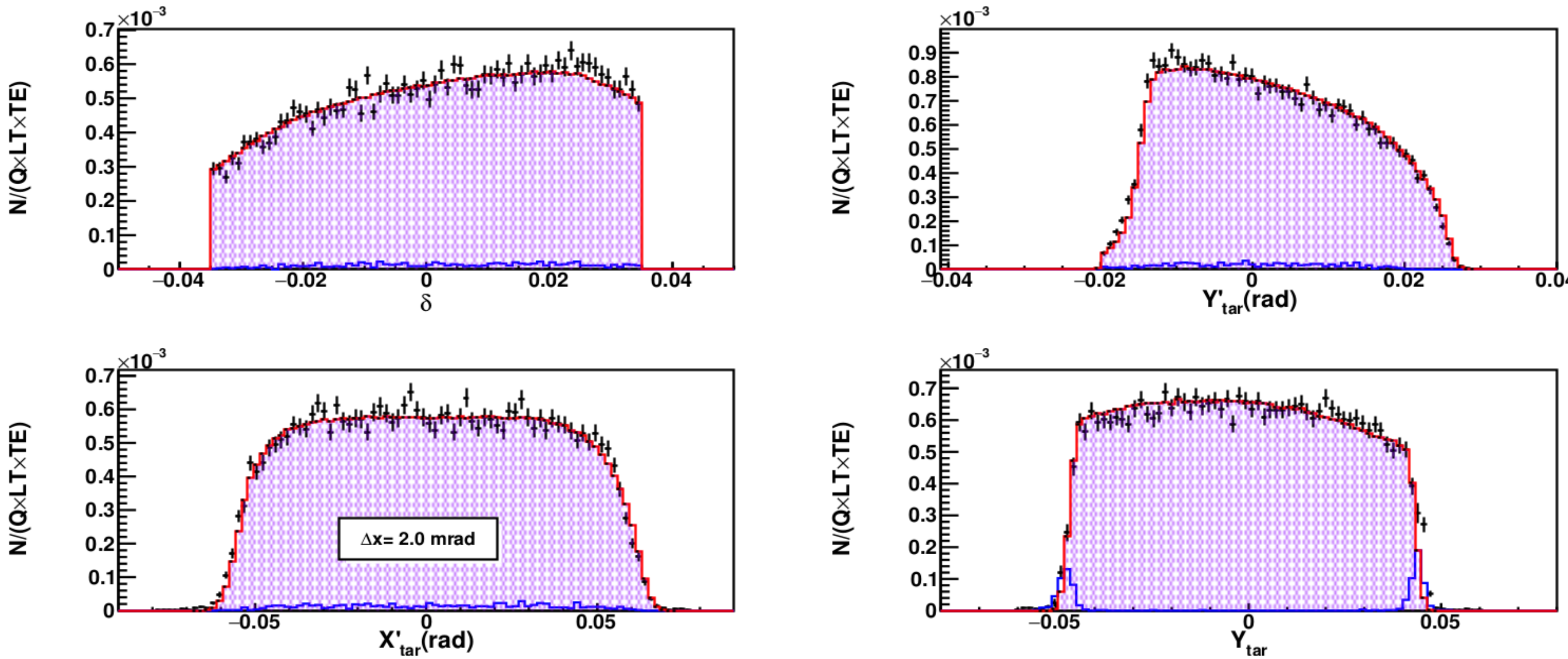
$$\boxed{\frac{d\sigma}{d\Omega}^{data}(\theta) \;=\; \frac{d\sigma}{d\Omega}^{mod}(\theta) . \frac{Y^{data}}{Y^{MC}}} \longrightarrow \quad (4)$$

Example of cross section extraction for 3 pass $Q^2 = 7GeV^2$ kinematics

Kinematics: K3-7
E = 6.427 GeV, θ = 37.0 °, p_0 = 2.672GeV , Q2 = 6.993 GeV^2
Y^{data}/Y^{MC} = 1.007396 $\pm$ 0.006004
Cross section = 2.881614e-06 $\pm$ 1.717473e-08 μbarn/sr

Cuts:
PID, One cluster cut
-0.035<δ<0.035
-0.02<y'_{tar}(rad)<0.030, 0.86<W(GeV)<1.05
-0.080<x'_{tar}(rad)<0.080, $|y_{tar}$(cm)$|$<6





Thir Gautam (HU)
Longwu Ou (MIT)

Check of acceptance using low Q^2 kinematics (Validation kinematics)

→ Cross-section for $Q^2 = 1.5\ GeV^2$ is well known to better than 2%

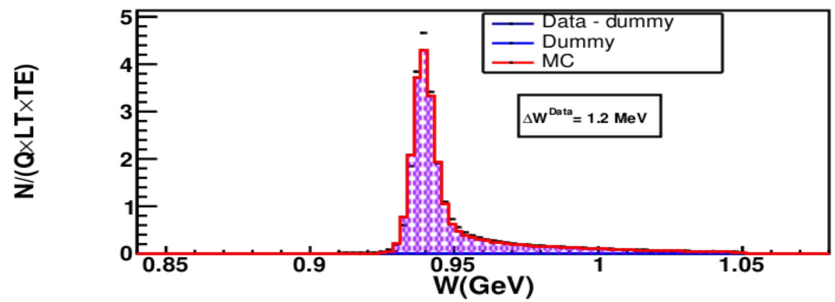
→ Checked the spectrometer model across the acceptance by shifting various apertures and increasing field of magnets

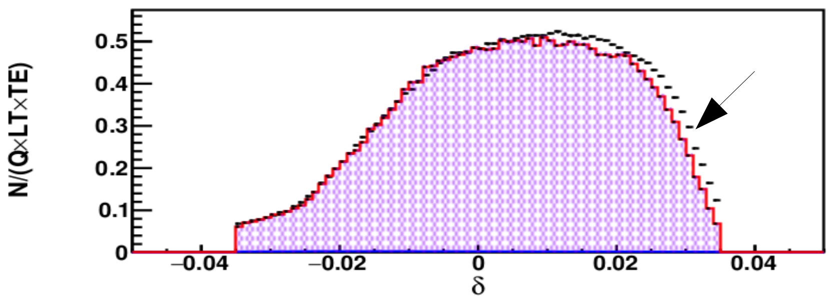
Check of acceptance using low Q^2 kinematics before tuning spectrometer model (Validation kinematics)

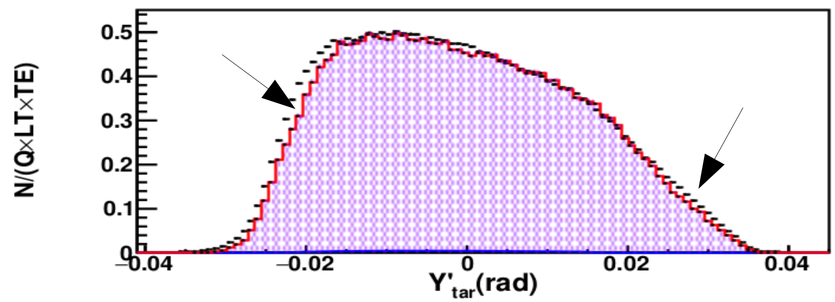
Outstanding issue: discrepancy in target variables

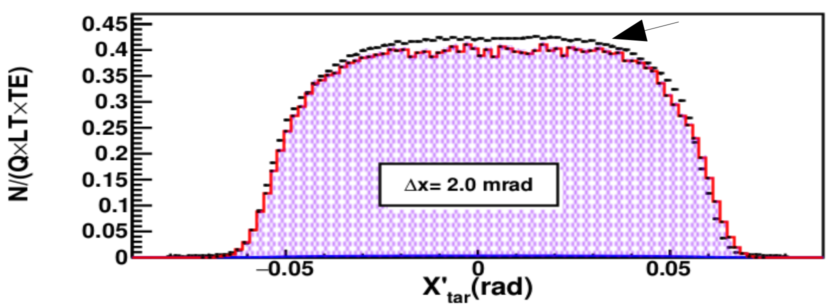
Kinematics: K1-1
E = 2.222 GeV, θ = 42.0 °, p_0 = 1.366GeV , Q2 = 1.577 GeV^2
Y^{data}/Y^{MC} = 1.043762 $\pm$ 0.002081
Cross section = 1.481589e-03 $\pm$ 2.953388e-06 μbarn/sr

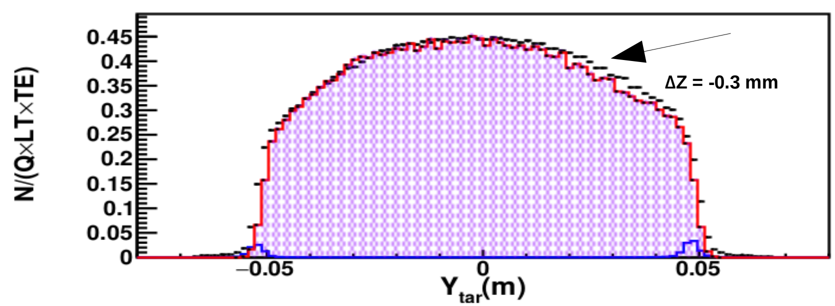
Cuts:
PID, One cluster cut
$-0.035<\delta<0.035$
$-0.04<y'_{tar}$(rad)<0.040, $0.86<W$(GeV)<1.05
$-0.080<x'_{tar}$(rad)<0.080, $|y_{tar}$(cm)$|<7$







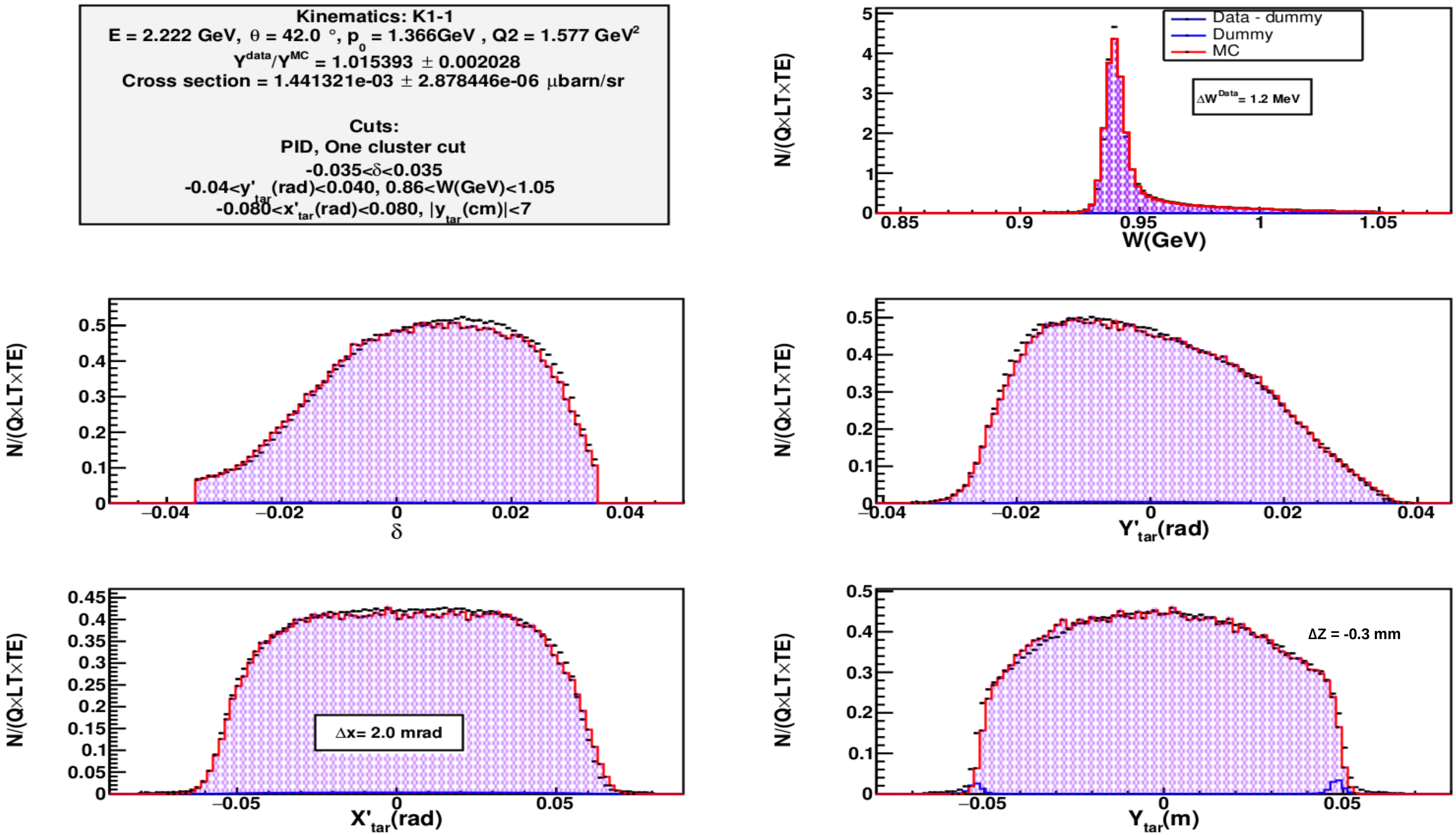




~4.4% discrepancy in cross section

Check of acceptance using low Q^2 kinematics (Validation kinematics)

→ Resolved by increasing field of Quad Q2 by 0.9% in the model



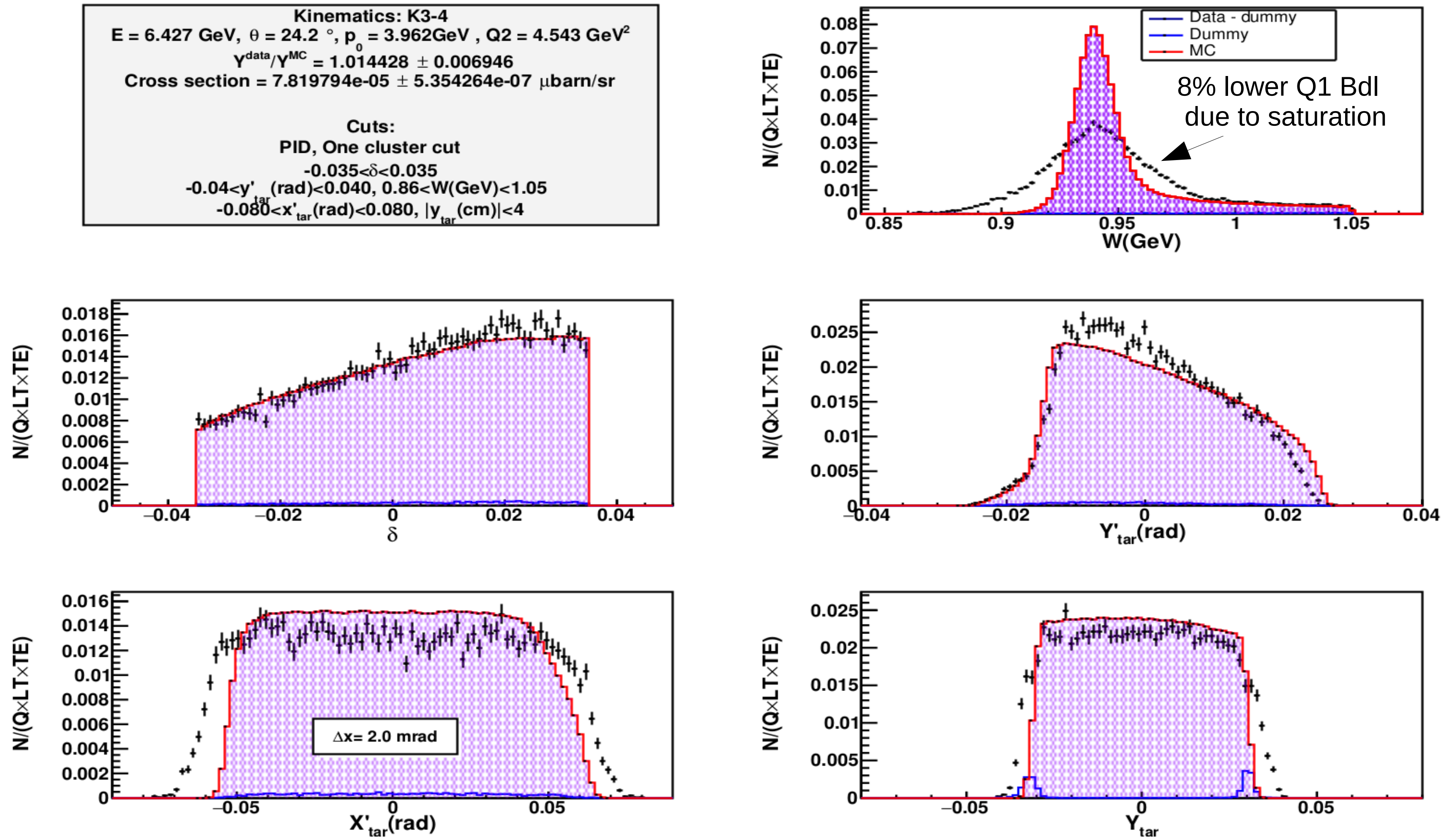
What we learn from the study of validation kinematics?

→ We learn that we need to make some adjustment in Q2 field to match the acceptance of MC to data for validation kinematics

→ Extracted cross section closer to the well known cross section

→ We have found very little impact on high Q^2 data

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

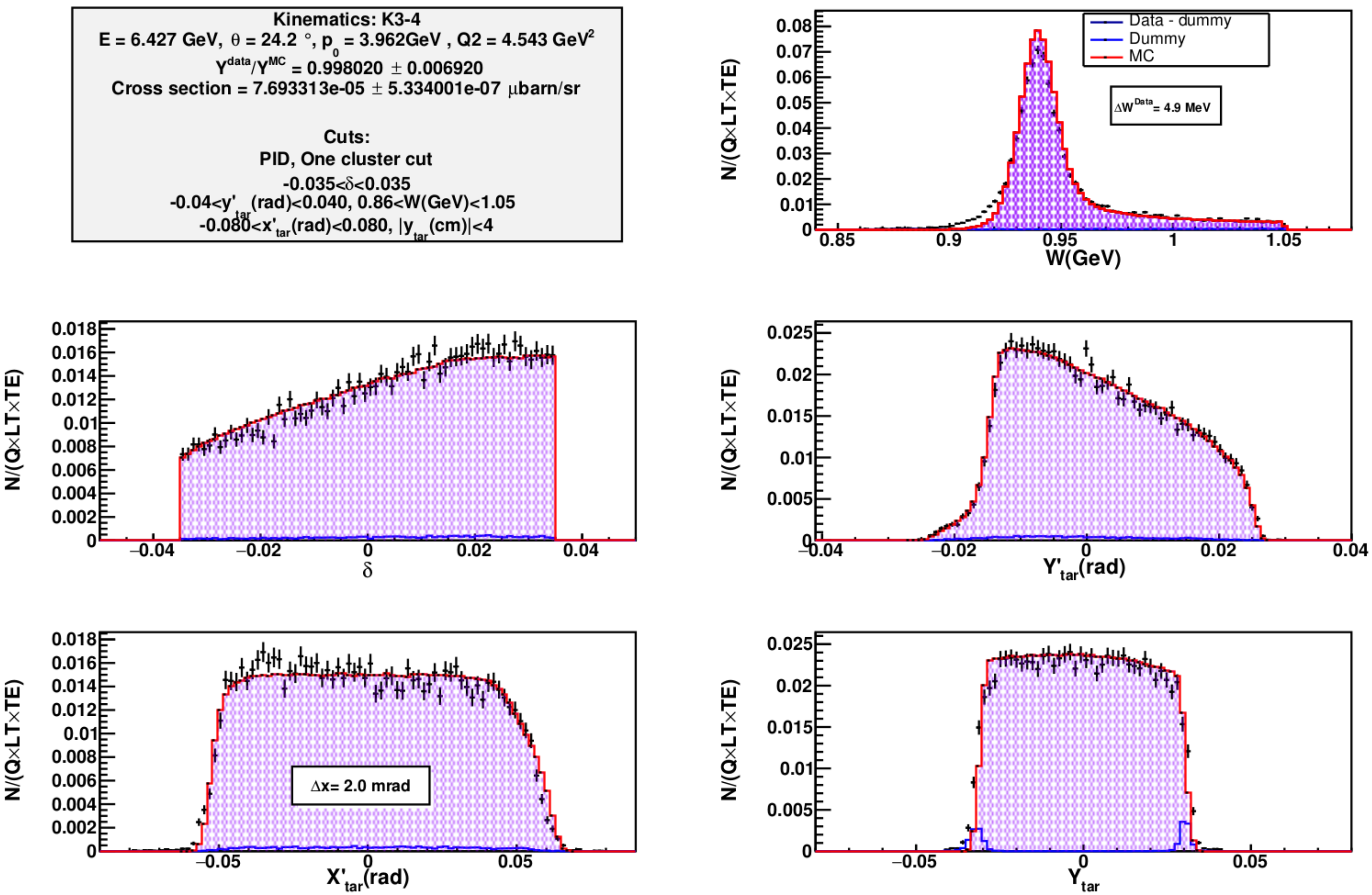


→ This discrepancy is due to the Q1 saturation problem

How to solve? ➡ Need correct optics but we don't have sieve slit data

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

→ We tuned Q1 field integral to minimize W peak width to get new optics



Cross section calculation by acceptance correction method

The cross section in each theta bin is given by

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{RC\left(W_{max}^2\right)}{L}\int^{W_{max}^2} dE'\,\frac{N\left(E',\theta\right) - BG\left(E',\theta\right)}{Eff\,.\,\Delta\Omega\left(E',\theta\right)}$$

RC → Radiative correction
W_{max} → Invariant mass at cut-off in E’
Eff → Tracking efficiency
BG → Background processes
L → Integrated luminosity

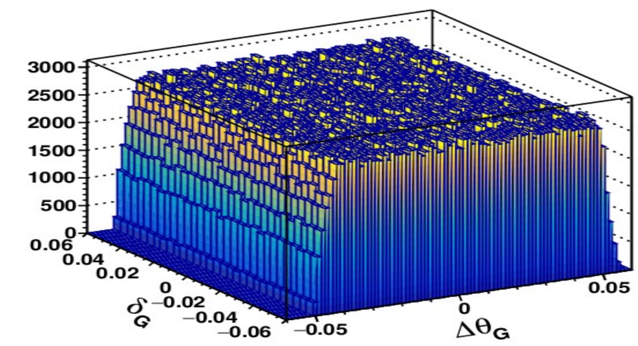
→ Radiative correction include re-scaling of α due to the hard vertex correction and Bremstrahlung

Determination of effective solid angle

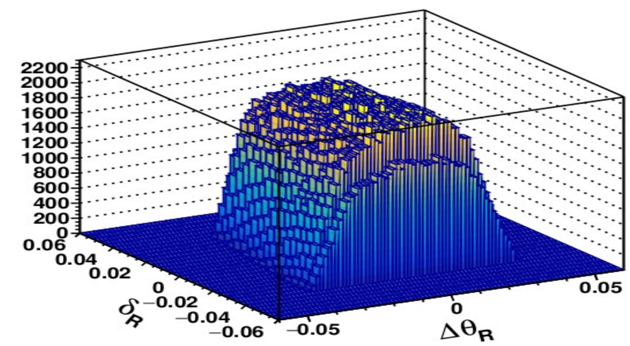
→ Used uniform generator to generate events uniformly at the target

→ Calculated effective solid angle in 2-D δ and θ bins

Generated 2-D histogram

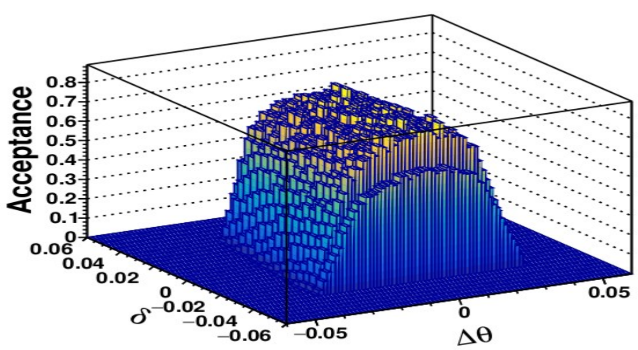


Reconstructed 2-D histogram

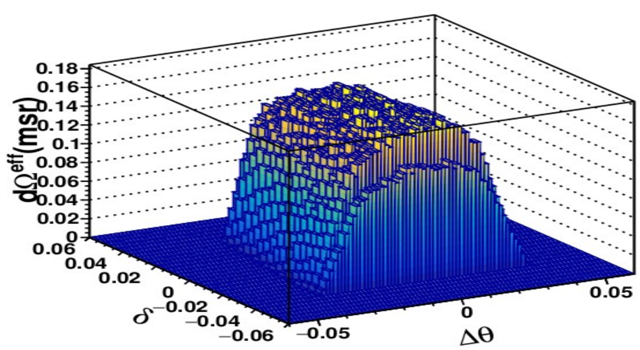


Generation ranges:
x'_{tar} → ±80 mrad
y'_{tar} → ±50 mrad
δ → ±6%

Fractional acceptance



Effective solid angle



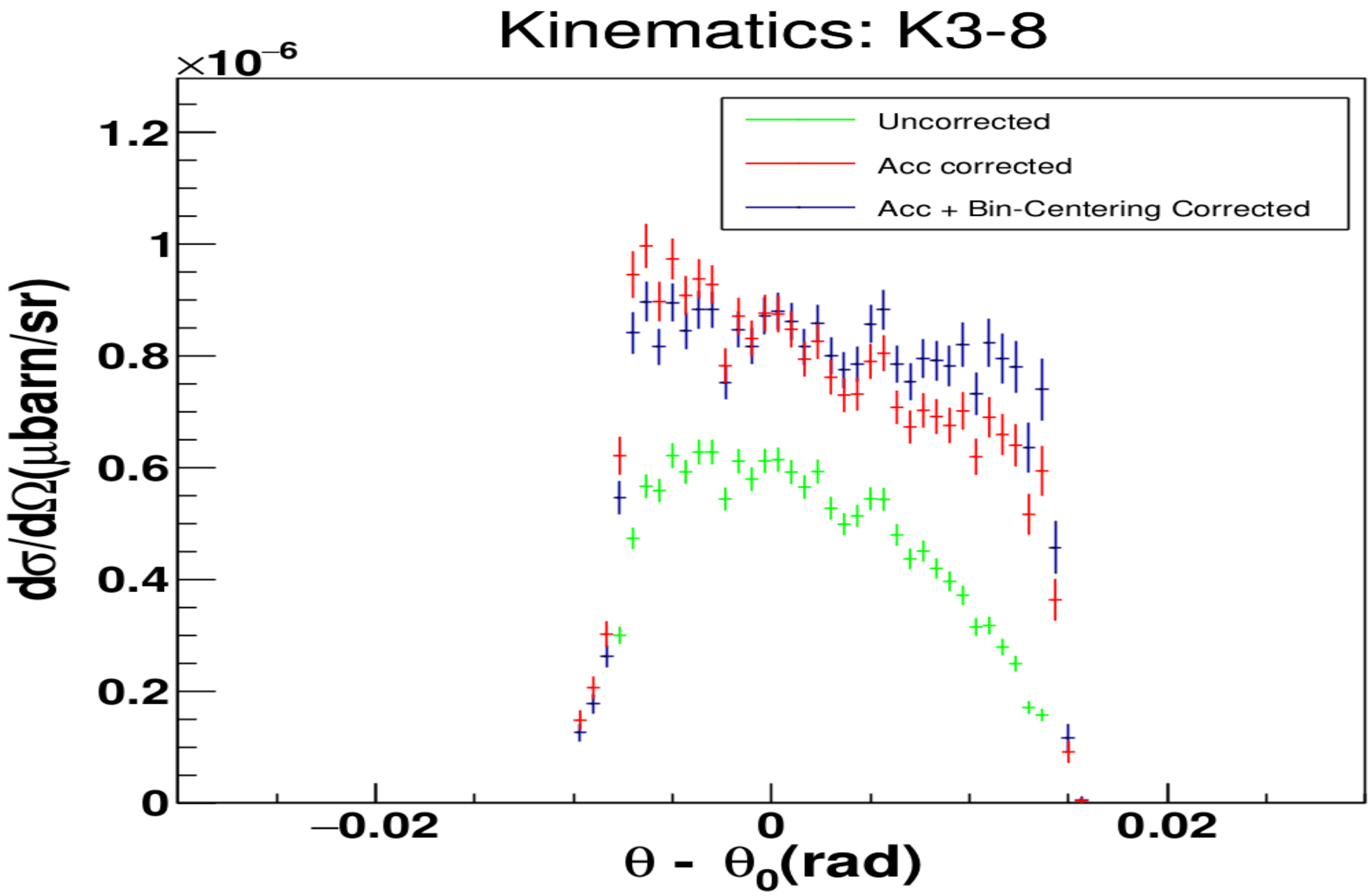
$$A(\delta,\theta) = \frac{N_{Acc}(\delta,\theta)}{N_{Gen}(\delta,\theta)}$$

Where,

$$\Delta\Omega_{eff}(\delta,\theta) = A(\delta,\theta)\times\Delta\Omega_{gen}(\delta,\theta)$$

$$\Delta\Omega_{gen}(\delta,\theta) = \frac{N_{gen}(\theta)\times\Delta X'_{tar}\times\Delta Y'_{tar}}{N_{gen}^{total}}$$

Cross section calculation by acceptance correction method



Bin centering correction →

$$\left[\frac{d\sigma}{d\Omega}\right]_{BC,i} = \frac{d\sigma(\theta_i)}{d\Omega} \cdot \frac{\sigma^{Mod}(\theta)}{\sigma^{Mod}(\theta_i)}$$

Tabular comparison of extracted cross section from two method

Kinematics	Sp. central angle(θ_0)	Sp. central Momentum(P_0) (GeV)	Cross section (Data to SIMC ratio method) (μbarn/sr)	Cross section (Acc. Correction method) (μbarn/sr)	% difference (Ratio - Acc)/Ratio*100
K1-1	42.0	1.366	1.440E-03	1.430E-03	0.6
K3-4	24.2	3.962	7.693E-05	7.618E-05	0.9
k3-6	30.9	3.224	1.101E-06	1.082E-06	1.7
K3-7	37.0	2.672	2.882E-06	2.866E-06	0.5
K3-8	44.5	2.145	8.143E-07	8.130E-07	0.2
K4-9	30.9	3.685	1.277E-06	1.275E-06	0.2
K4-10	34.4	3.259	5.835E-07	5.830E-07	0.1
K4-11	42.0	2.531	1.532E-07	1.570E-07	-2.4

→ For six out of eight points we got an average cross section better than ½ of percent

→ We are investigating why those two points have more than 1% difference in average

Status of Error Budget (LHRS 2016)

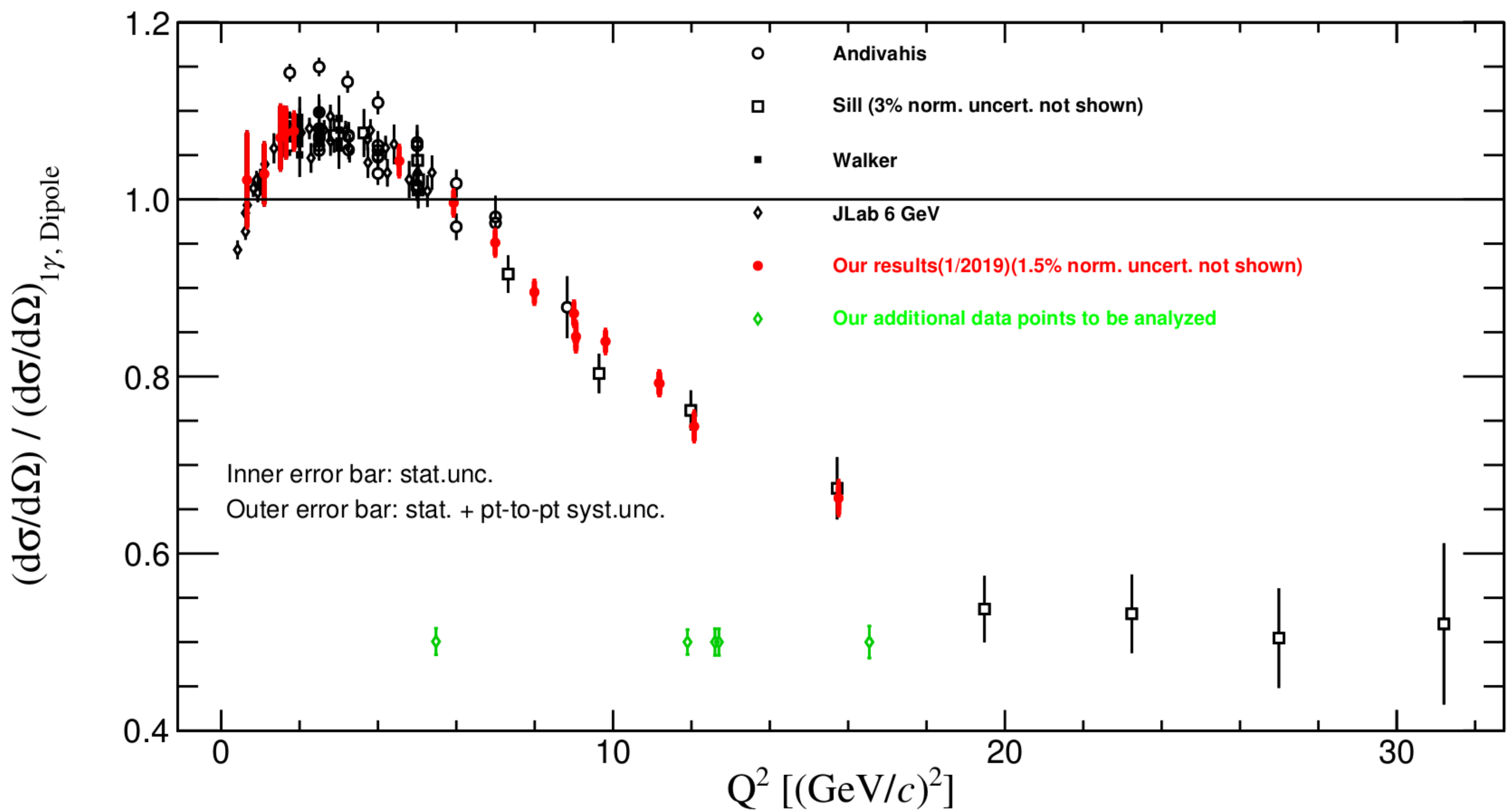
Summary of major point-to-point and normalization uncertainties in the cross section for Fall 2016 run

Source	**Δσ/σ (%) (pt-pt)**	**Δσ/σ (%) (Norm.)**
Beam charge	0.6(at 10uA) – 0.15(at 40uA)	0.1 (0.03 corr)
Scattering angle	0.5	0.5
Beam energy	0.5	0.5
Boiling	<0.1(at 10 uA) – 0.24(at 40 uA)	0.25 (at 40 uA)
Optics	0.3	0.3
Track Reco	0.2	0.2
PID	0.1	0.1
Trigger	0.2	0.1
Spectrometer acceptance	0.7	0.8
Radiative correction	0.8	1.0
Background subtraction	0.1	< 0.1
Total	1.25 -1.6%	1.5%

***correlated from high to low current due to absolute current offset**

GMp - E012-07-108 results

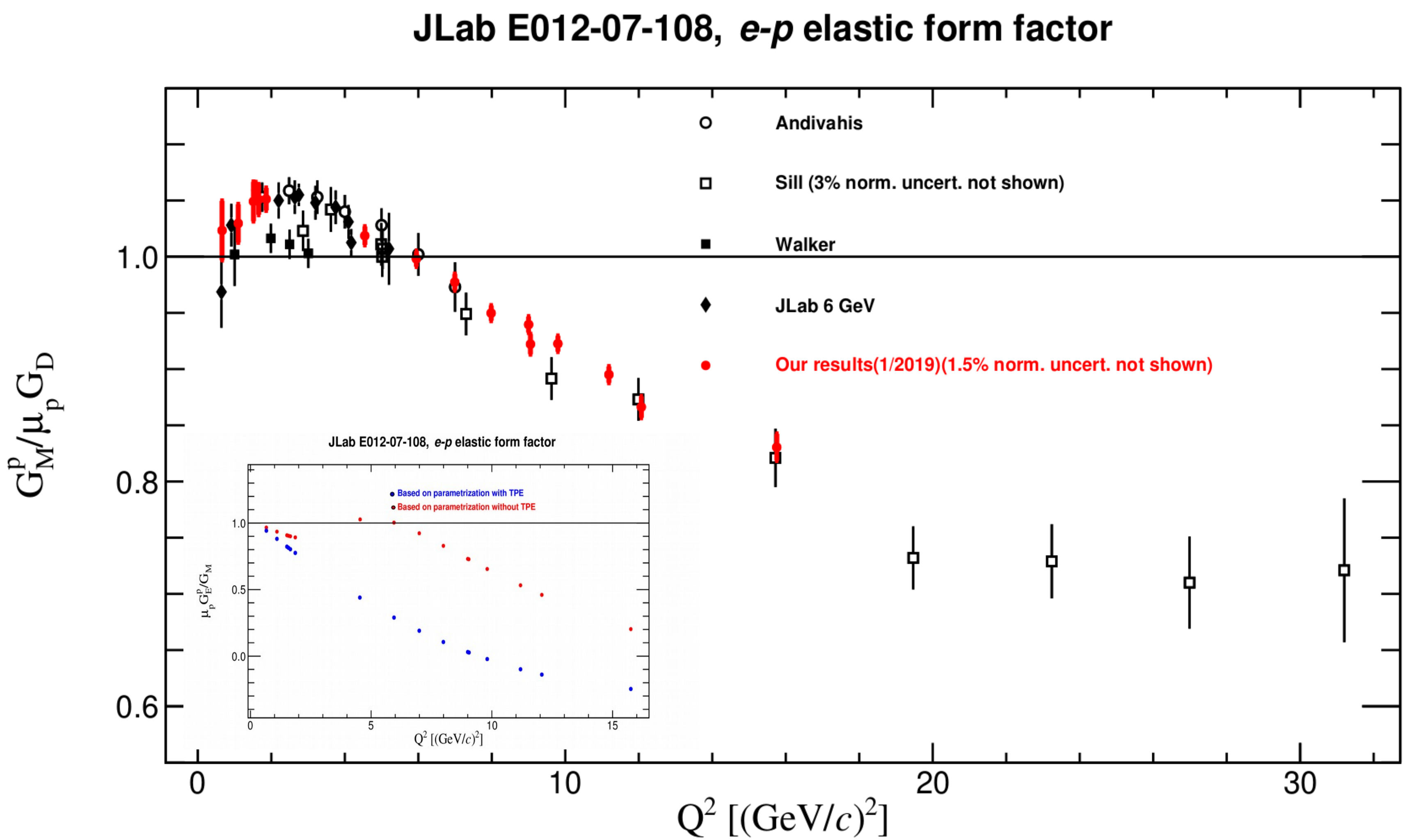
- Cross-section results presented below with ~1.25-1.6 %(pt-pt), 1.5%(norm)



1γ refers to single photon approximation and Dipole corresponds to both form factor

GMp - E012-07-108 results

- Magnetic form factor results presented below with ~1.25-1.6 %(pt-pt), 1.5%(norm)



→ $G_E/\mu G_M$ ratio is used based on fit to the cross section data
(Ref: J. Arrington et.al. arXiv:0707.1861v2 [nucl-ex] 2 Aug 2007)
→ G_M from older experiments are taken from the publication

Summary

- 12 GeV era GMp experiment data taking is completed successfully.
- Data analysis is approaching proposed uncertainty goals.
- Current systematic uncertainties for January 2019 data of:

  1.25 - 1.6% pt-pt

  1.5% normalization

- Final cross section results with further reduced systematic and first publication in 2 months.

GMp collaboration

- Hall A collaboration, physics staff, technical staff, accelerator team and shift takers
- Spokesperson: J. Arrington, E. Christy, S. Gilad, B. Moffit(“retired”), V. Sulkosky, B. Wojtsekhowski (contact)
- Postdoc: K. Allada (MIT)
- Graduate students: Y. Wang (W&M), B. Schmookler (MIT), L. Ou (MIT), T. Gautam (Hampton U.), B. Aljawrneh (NCA&T Uni.)

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Thank you very much!