Status of GMp Experiment

Nuclear physics group meeting
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Preview

- Highlights:
  - → Better than 2% statistics
  - → High Q^2(up to 16 GeV/c^2)
  - → Relatively low ϵ: the contributions from G_E^p is smaller than those for the large ϵ SLAC data
  - → Multiple kinematic settings over the range of Q^2
- Calibration of detectors is complete
- First iteration of optics calibration is nearly complete
- Preliminary results for first pass is done
- We project data analysis to be completed at the end of this year

Outline

- Physics and experimental goals of GMp
- Hall A beamline, spectrometer and detectors
- Statistics collected
- Status of analysis
- Elastic Cross section extraction procedure
- Spectrometer optics study
- Preliminary results (Data/MC method)

Proton magnetic form factor

- Form factors encode electric and magnetic structure of the target

  → At low Q^2, form factors characterize the spatial distribution of electric charge and magnetization current in the nucleon

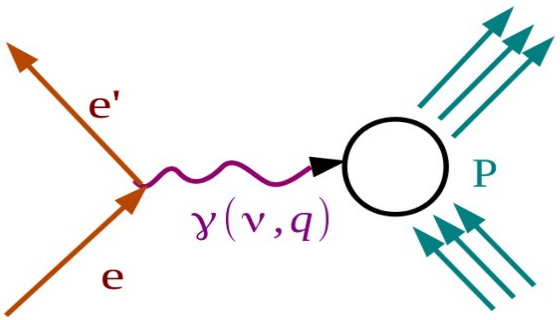
$$|\text{Form Factor}|^2 = \frac{\sigma(\text{Structured object})}{\sigma(\text{Point like object})}$$

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

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

- 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:

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



Where,

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

Goals of GMp experiment as approved

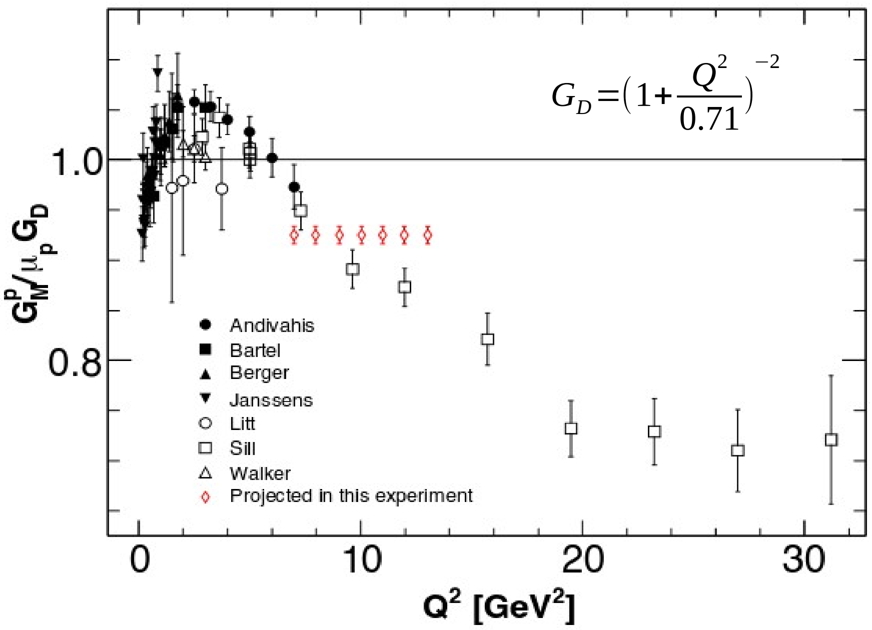
- Precision measurement of the elastic *ep* cross-section in the Q^2 range of 7-14 GeV^2 and extraction of proton magnetic form factors

➢ To improve the precision of prior measurement at high Q^2

➢ 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%



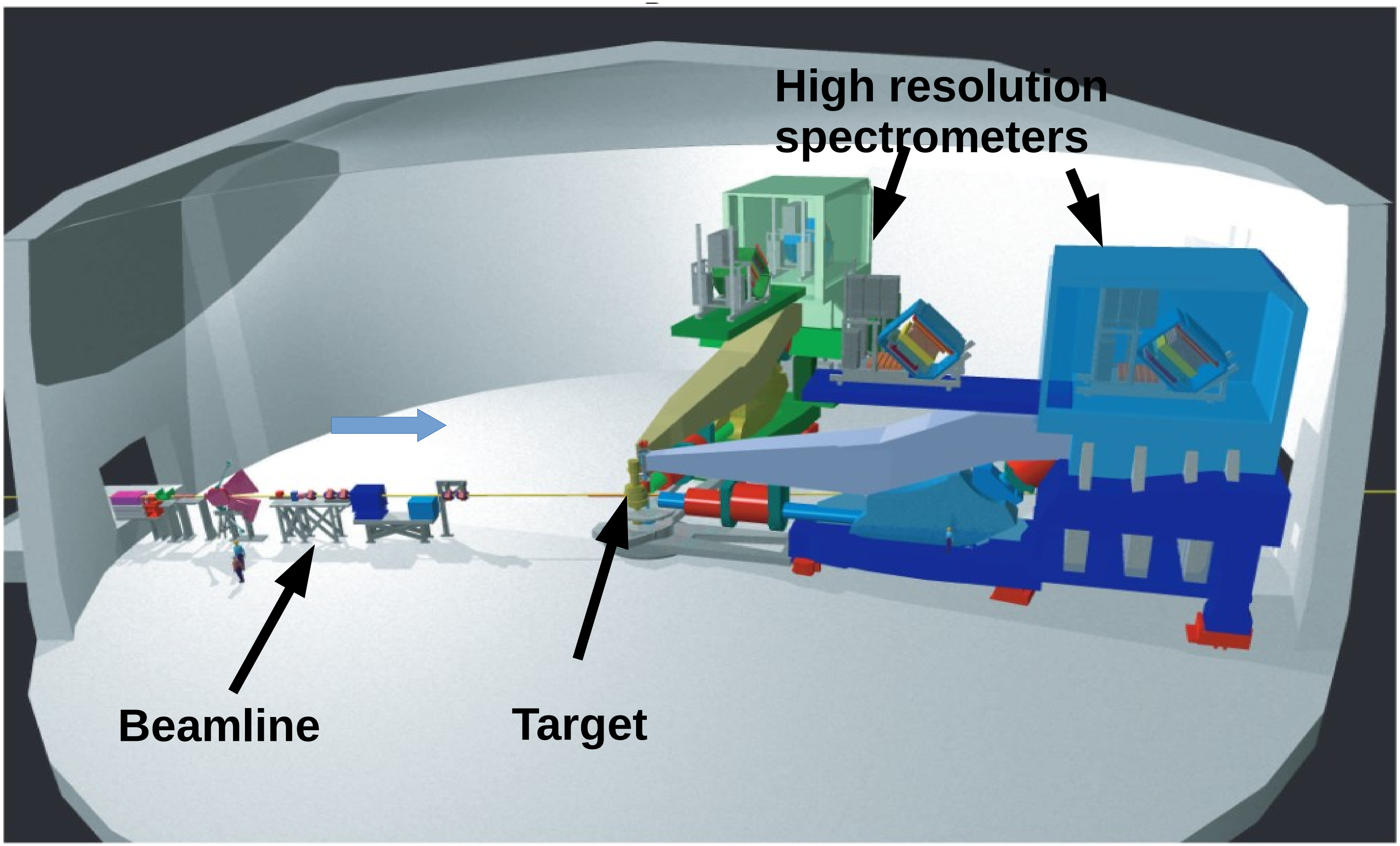
Need a good control on:

•Beam charge

•Beam position

•Scattering angle, target density, ...

Hall A arms and beamline transport



Hall A beamline, spectrometer and detectors

→ RHRS SOS Quad is replaced by new quad

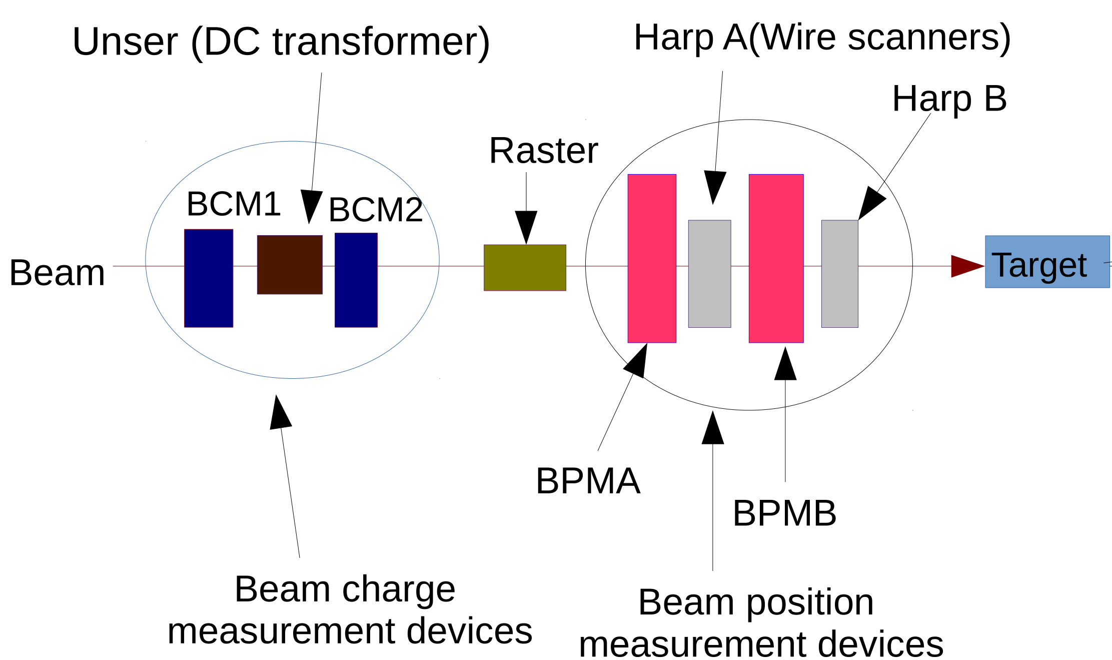
→ The SOS Quad is installed in LHRS

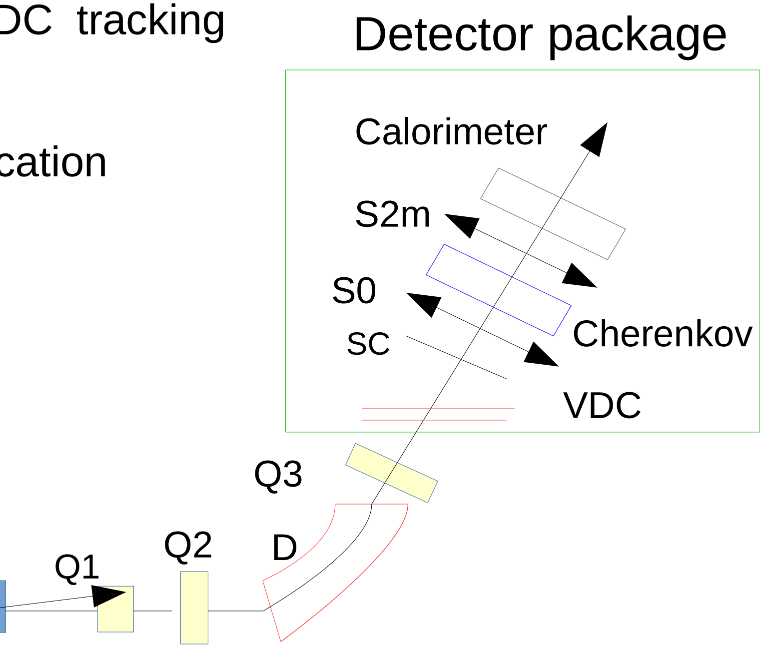
→ VDC is used for tracking information

→ Straw Chamber(SC) is used to reduce systematic on VDC tracking efficiency

→ Cherenkov and calorimeter are used for particle identification

→ S0, S2m are used for trigger and timing





HRS Parameters:

Acceptance: $-4.5\% < \Delta p/p < 4.5\%$, 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 Status of Analysis

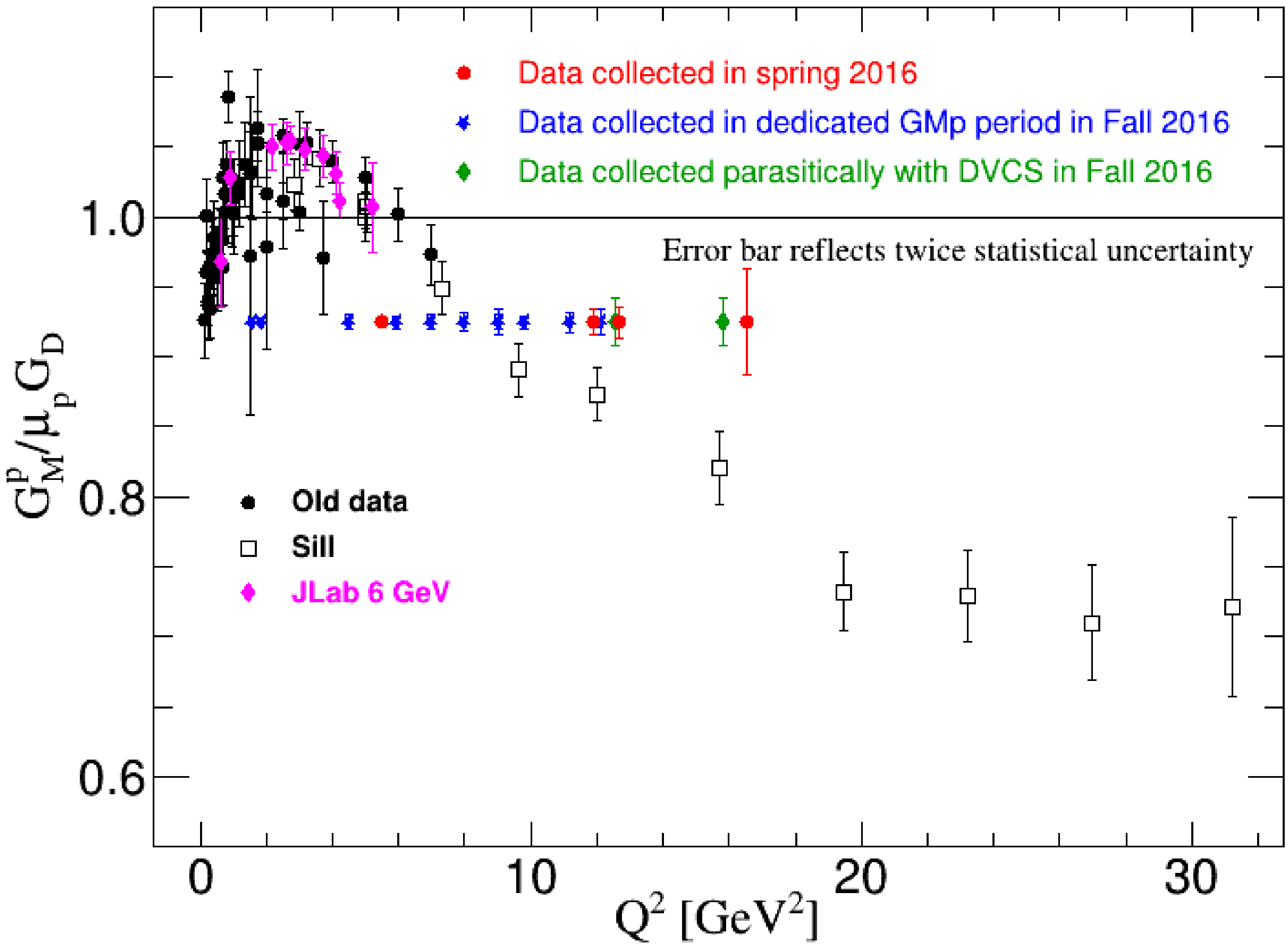
System Calibration:

→ Beamline component Calibration (done)
→ PID detector calibration (done)
→ Tracking detector(VDC, Straw chamber) calibration (done)
→ Timining (s0, s2m) calibration (done)
→ Optics calibration first iteration (nearly completed)

Data Analysis:

→ Target boiling analysis (done)
→ HRS acceptance studies (ongoing, 75% complete)
→ Tracking, trigger efficiencies, DAQ livetime (done)
→ First pass data analysis (nearly completed)
→ Second pass analysis with a goal of 2% measurement (ongoing)
→ Rediative correction analysis (nearly completed)

GMp collected statistics



Summary of GMp collected data (I)

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:

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

Summary of GMp collected data (II)

Fall 2016:

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

Elastic cross section extraction procedure

- Cross section

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

- Reduce Cross section:

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

- Parameters:

- N_{data} : Number of scattered electron detected
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- $\mathcal{L}$: Integrated luminosity
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- LT : Live time correction
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$$\mathcal{L} = \frac{n_e n_p}{a} = \frac{Q}{e}\rho L \frac{Z}{A} N_A$$

a : Target area
n_e : Number of electron beams
n_p : Number of targets
A : Atomic mass of target
L : Length of the target

Elastic cross section (Monte Carlo Ratio Method)

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

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

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

Assuming acceptance and radiative contributions are correctly modeled:

$$\frac{d\sigma}{d\Omega}^{data}(\theta) = \frac{d\sigma}{d\Omega}^{mod}(\theta) . \frac{Y^{data}}{Y^{MC}} \longrightarrow (3)$$

Elastic cross section extraction procedure

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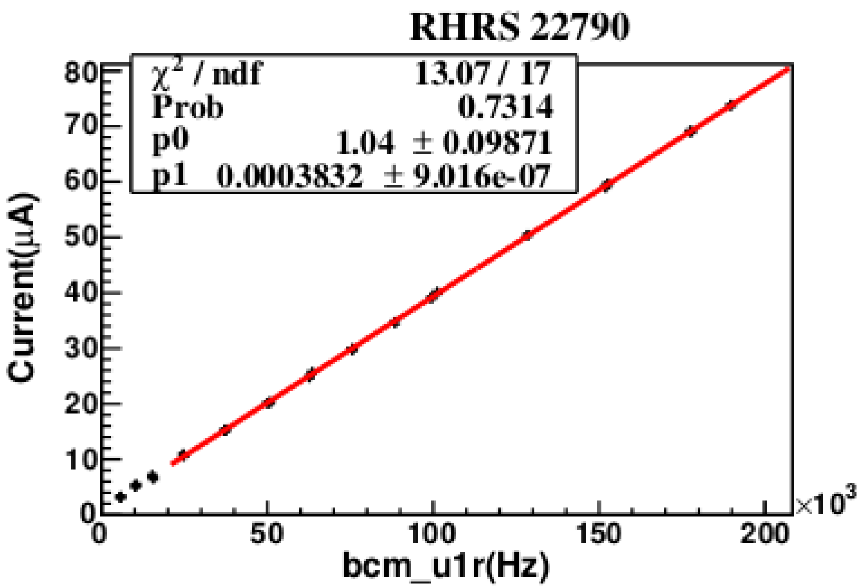
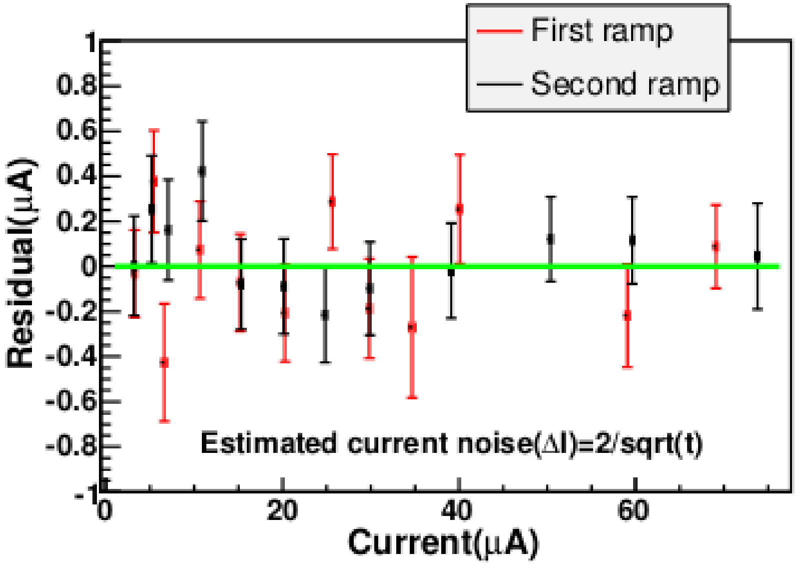
Beam charge calibration

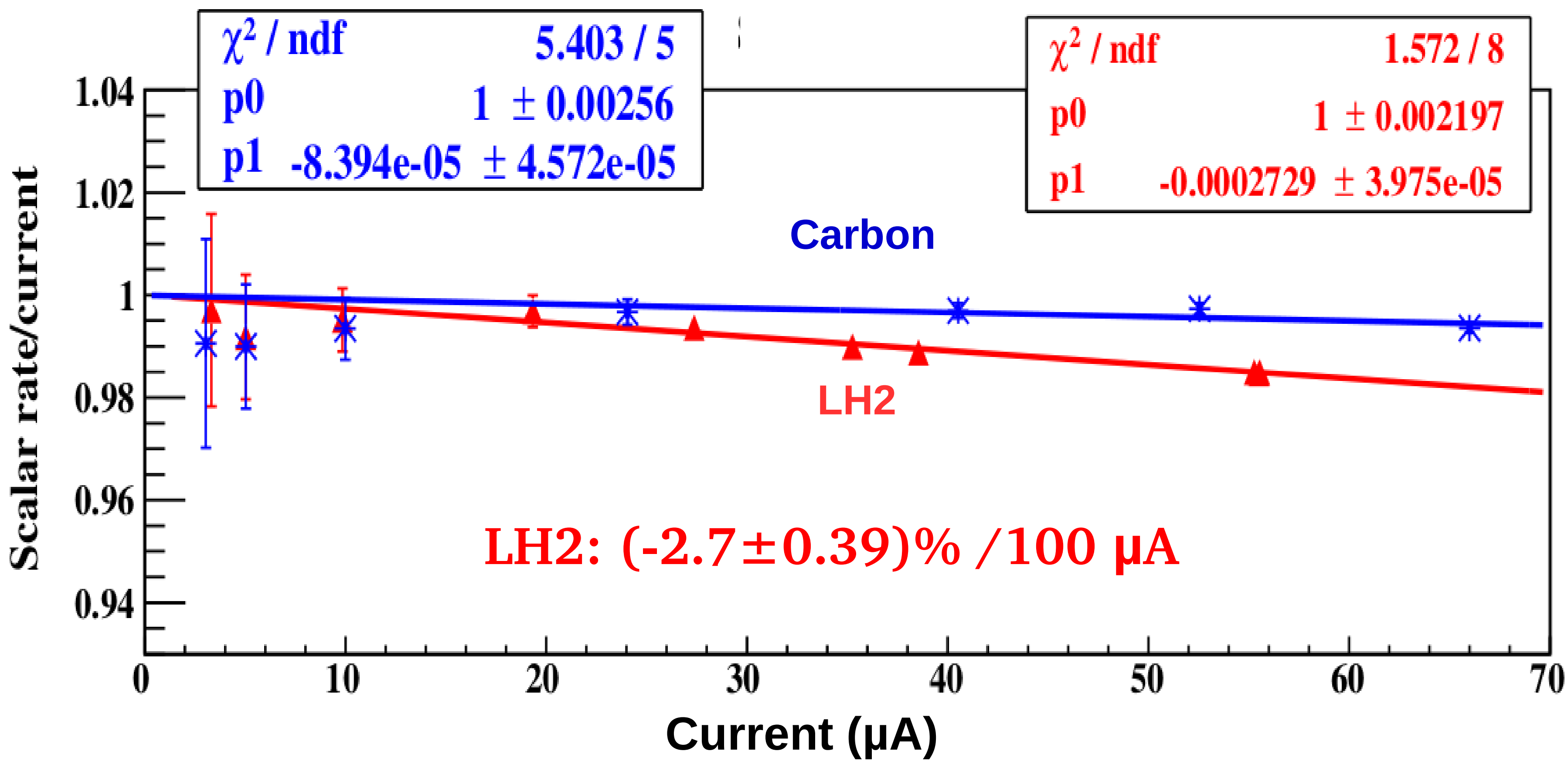
- Multiple instruments of charge measurement: Unser and two BCMs
- The Unser monitor were calibrated by using a precise current source and provided an absolute reference during BCM calibrations
- Calibration coefficients from multiple measurement have negligible drift within uncertainties
- Beam current determination is much better than 1%
- Estimated Current uncertainty in GMp experiment is ~0.06 μA





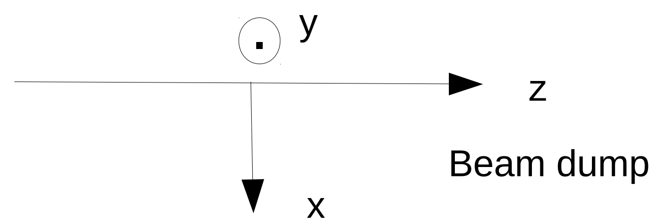
Target boiling studies

- Target used: 15 cm LH2 target in Loop2 and single foil carbon target
- Carbon target is used to separate possible rate systematic from boiling
  - → Range of beam current: 3-67 µA
  - → Raster size: 2×2 mm²

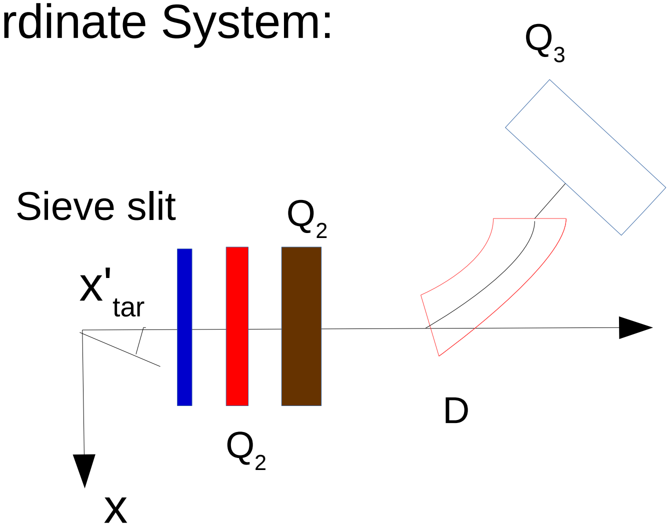


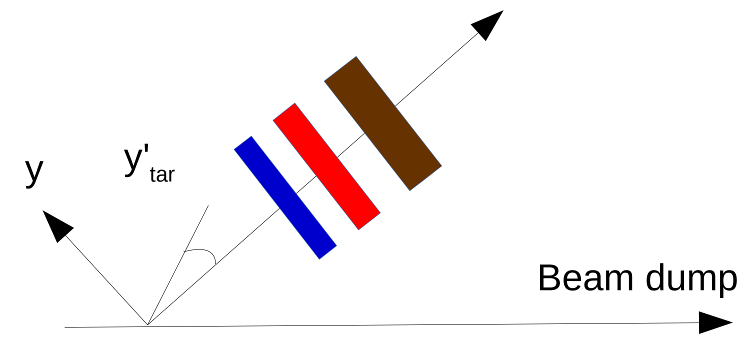
Coordinate systems

- Hall Coordinate System:

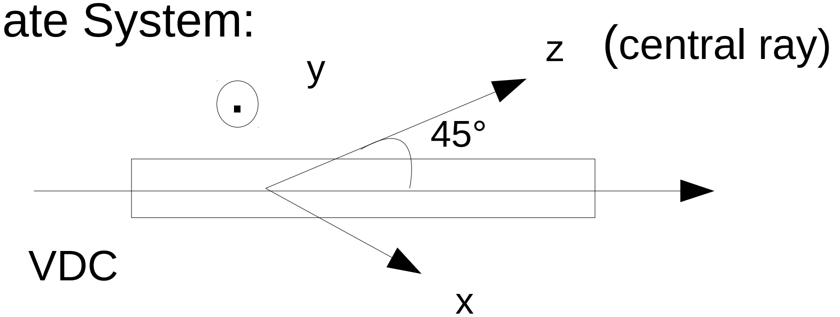


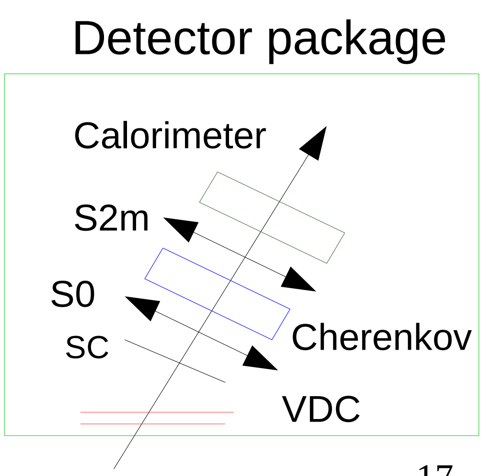
- Target Coordinate System:





- Transport Coordinate System:



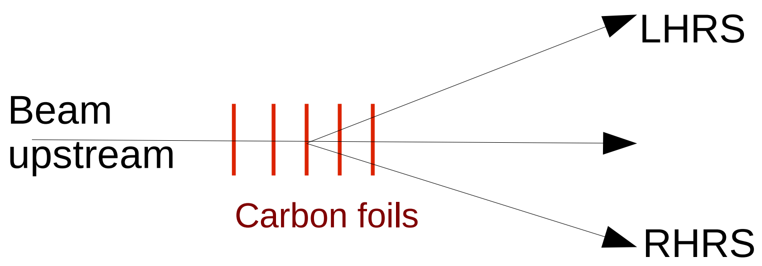


Optics Calibration spring 16 (LHRS)

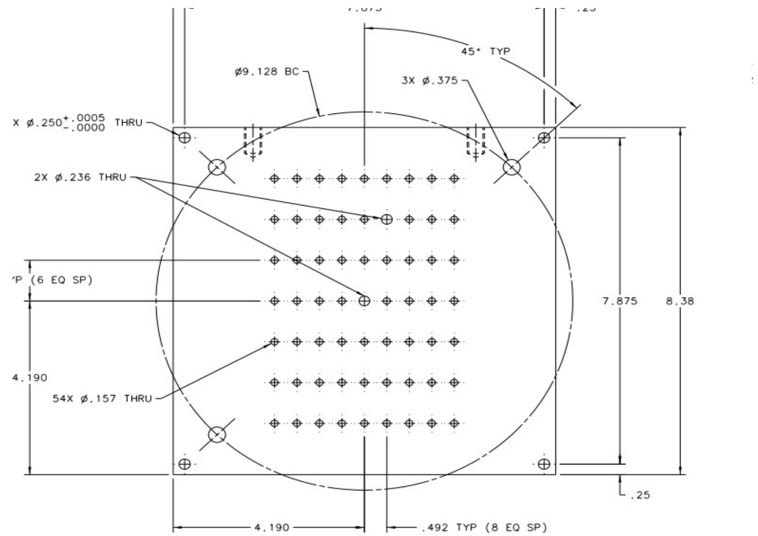
- Two data sets for optics calibration:
  - Multi-foil target + sieve: inelastic electron events, vertex and angle calibration

Run no: 12686, E = 2.305 GeV, ϴ = 16.632, P = 1 GeV

No. of rows = 7
No. of column =9



Multi-foil target



Sieve on LHRS spring 2016

  - LH2 target: elastic electron events for momentum calibration

Run no:	Delta (%)	P (GeV)
12755	-4	2.183
12759	-2	2.141
12763	0	2.099
12767	2	2.057
12788	4	2.015

Hole size:
big hole = 0.24 inch
small hole = 0.16 inch

Distance of sieve from target = 1.18 m

Optics optimization

- Process of finding a matrix that can reconstruct focal plane quantities into target quantities

$$W_{tg} = [\text{optics matirx}]\ W_{fp}$$

- Theoretical values are obtained form survey and geometry whereas, experimental values are obtained from focal plane quantities
- All target variables calculated from survey are assumed to be actual value of event (W^0)
- The experimental target variable: $W(x_{tg}, \theta_{tg}, y_{tg}, \phi_{tg})$

$$W = \sum C_W^{jkl} . x_{fp}^i . \theta_{fp}^j . y_{fp}^k . \phi_{fp}^l$$

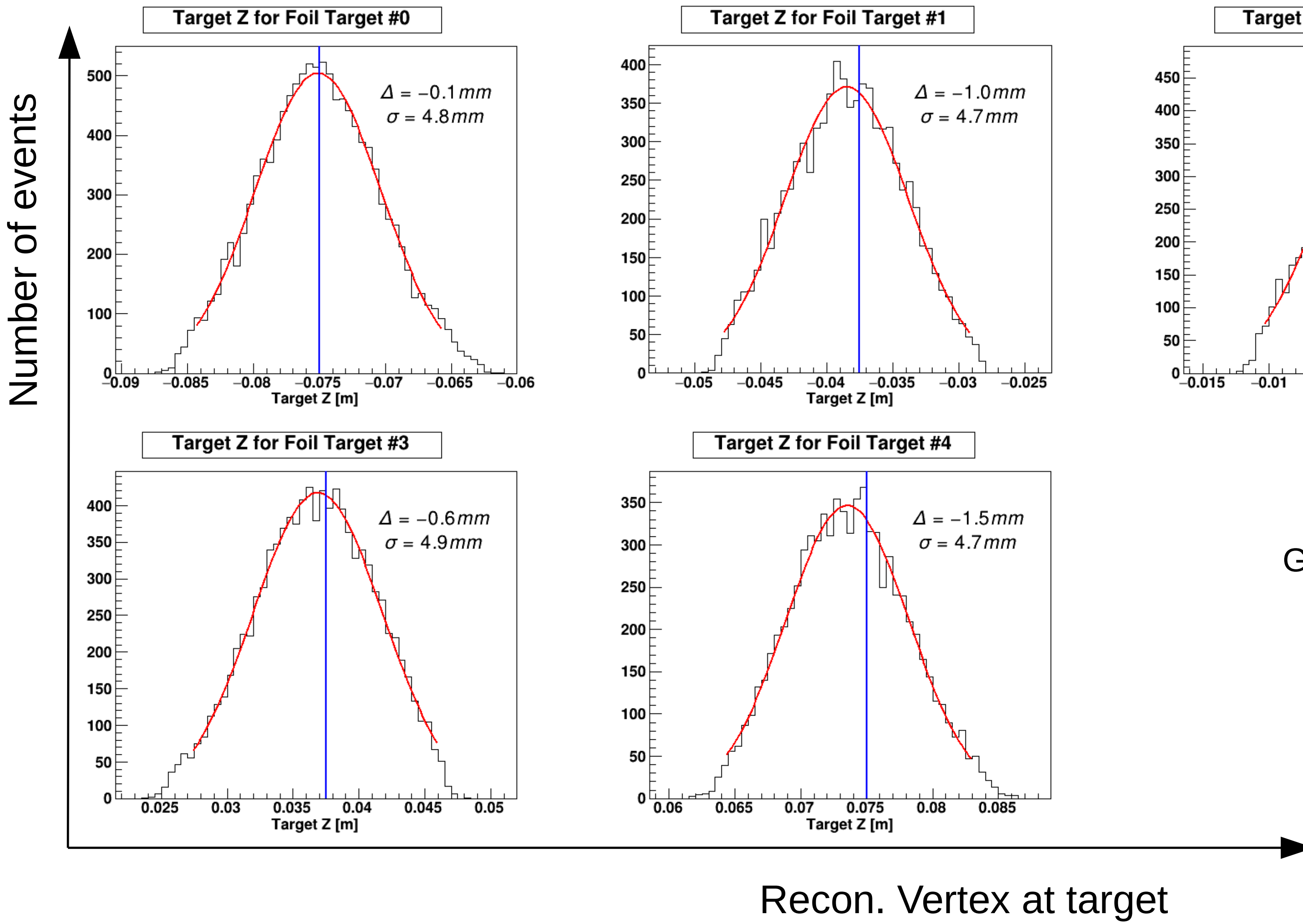
And,

$$\chi^2 = \sum_s \left[\frac{W - W^0}{\sigma_w^s}\right]^2$$

- The optics tensor C_{jkl}^w are determined from a χ^2 minimization in which events are reconstructed as close as possible to the known position of the corresponding foil target

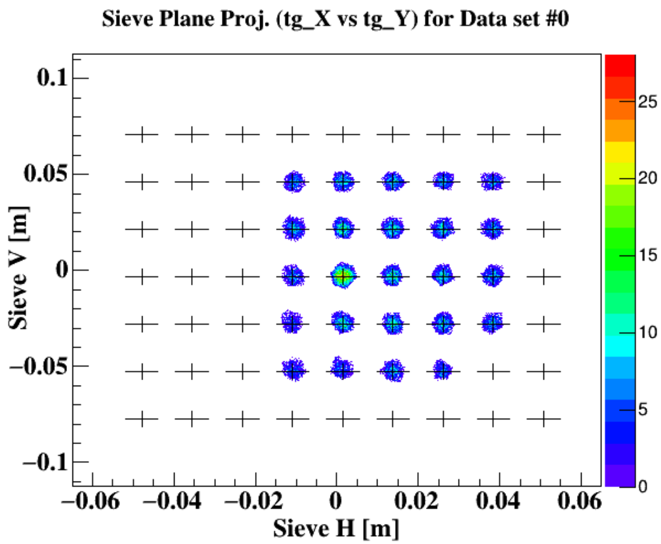
Vertex Calibration:

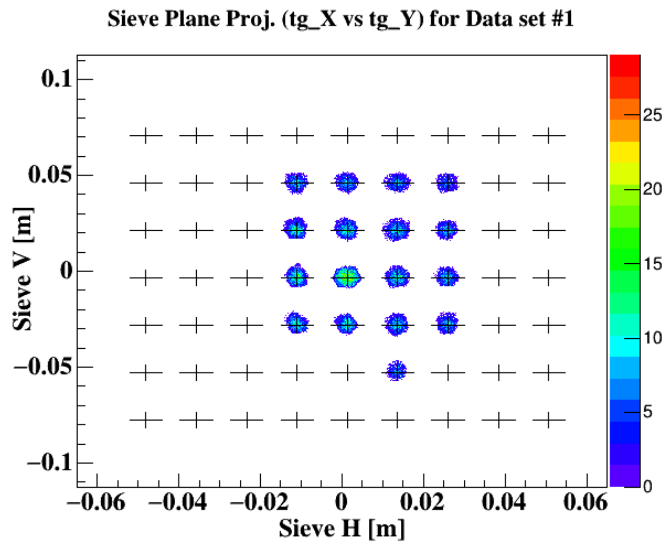
- Blue lines indicate the real foil target positions
- Δ shows the difference between the data Gaussian fitting center and real position

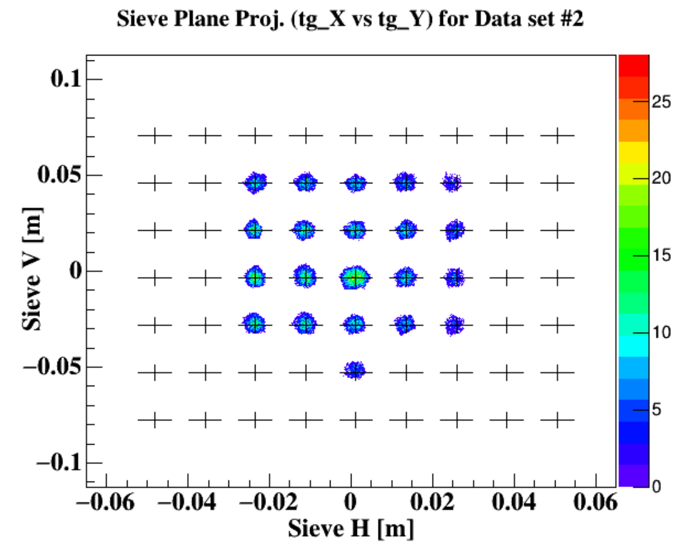


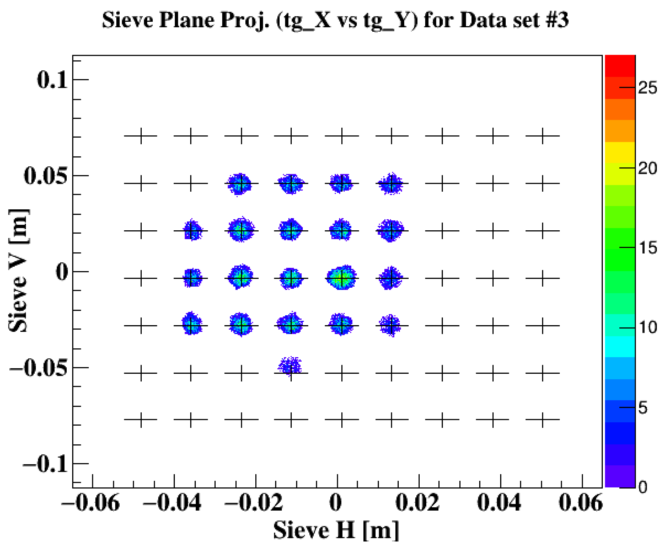
GMp requirement:
Δ = 0.75 mm

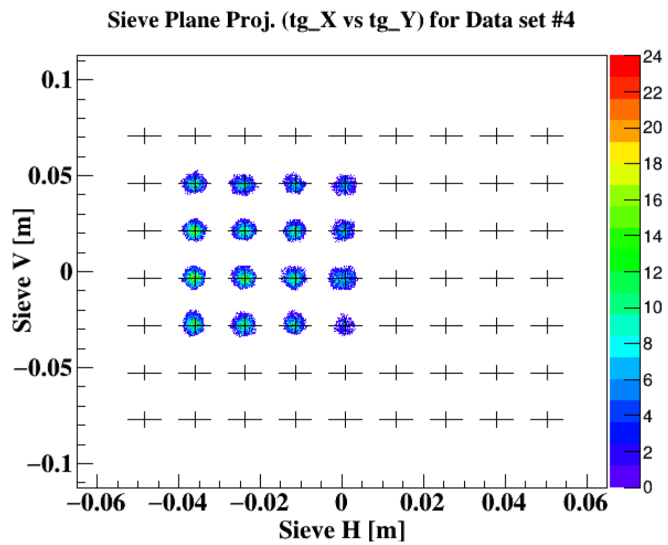
Angle Calibration











Observed:
$|D|_H$ = 0.42 mm
$|D|_V$ = 0.6 mm

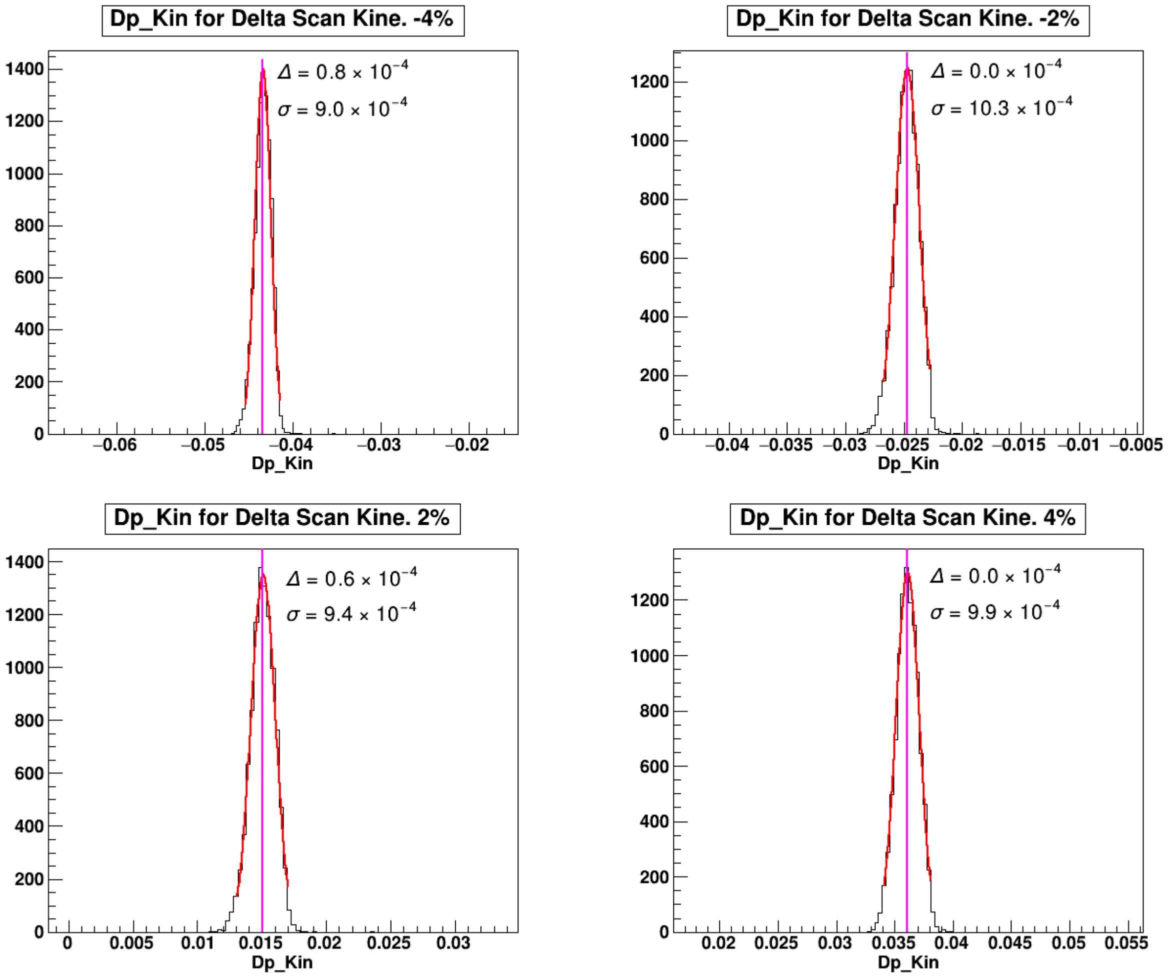
Gmp requirement:
$|D|_H$ = 0.18 mm
$|D|_V$ = 0.35 mm

D = Ave. of the absolute value of the difference between the men of Gaussian fit and corrected hole position

→ Crosses indicate the reconstructed average track center
→ Positions at the sieve plane are reconstructed by θ_{tar} and Φ_{tar}

Momentum Calibration

- We took delta scans at ±4%, ±2% and 0% dipole setting
- Clearly, the optimization readout is in the order of 10^{-4}



$$DpKin_{Real} = \frac{P_{\theta_{HRS}} - P_{Central}}{P_{Central}}$$

$$DpKin = dp - \frac{(P_{\theta} - P_{Loss}) - P_{\theta_{HRS}}}{P_{Central}}$$

$$DpKin - DpKin_{Real} = dp - \frac{(P_{\theta} - P_{Loss}) - P_{Central}}{P_{Central}}$$

Elastic cross section extraction procedure

- Cross section $$\frac{d\sigma}{d\Omega}^{data}(\theta) = \int dE' \frac{N^{data}(E',\theta) - N_{BG}(E',\theta)}{\mathcal{L}^{data}\epsilon LT} \cdot \frac{RC^{data}}{A^{data}(E',\theta)}$$
- Reduce Cross section: $$\sigma_{\text{red}} = \frac{d\sigma}{d\Omega}\frac{\epsilon(1+\tau)}{\sigma_{\text{Mott}}} = \frac{4E^2\sin^4\frac{\theta}{2}}{\alpha^2\cos^2\frac{\theta}{2}}\frac{E}{E'}\epsilon(1+\tau)\frac{d\sigma}{d\Omega}$$
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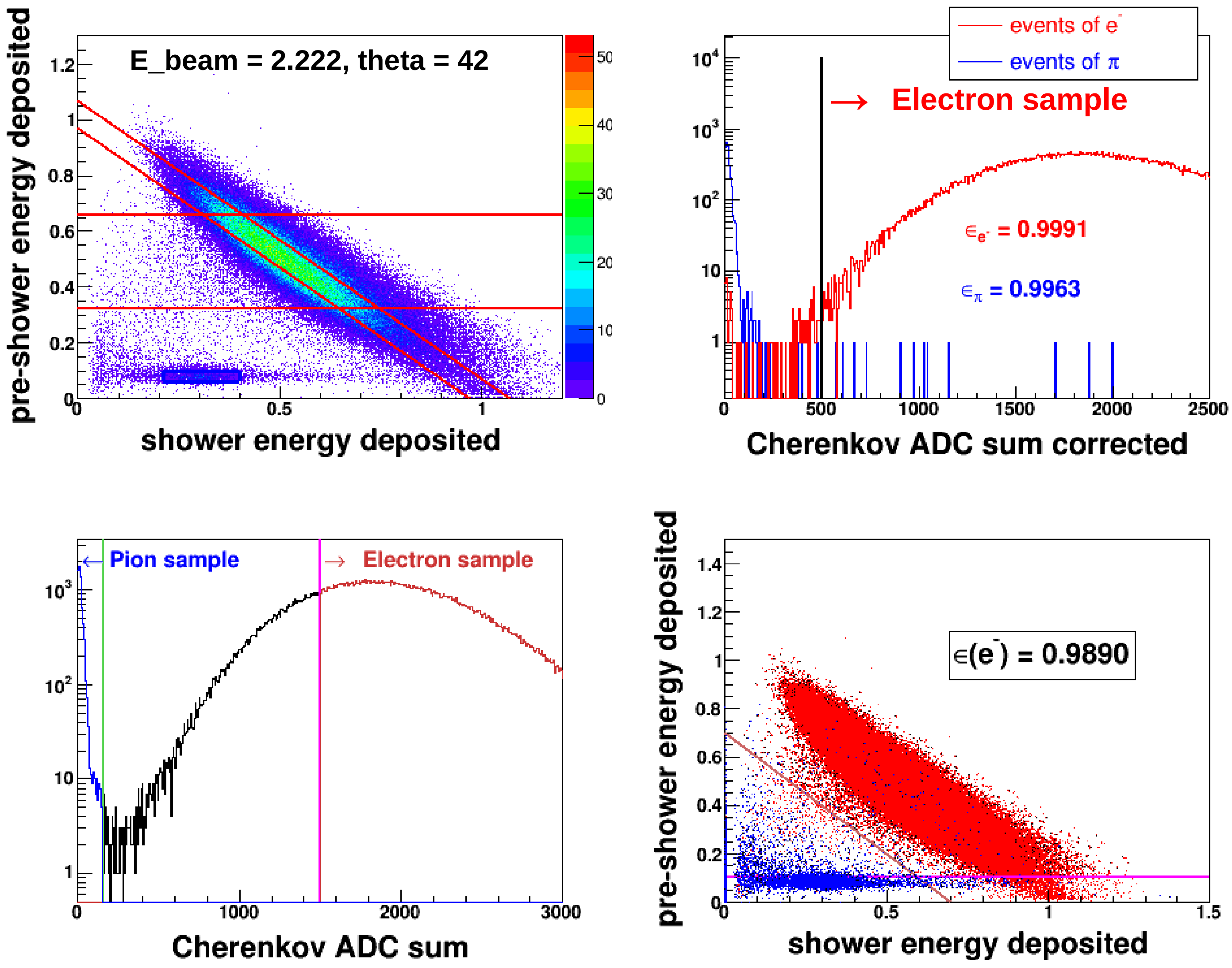
Particle identification analysis

→ We did particle identification studies using Cherenkov and calorimeter

→ Got preliminary PID efficiency at one pass and the cuts were set to select good electrons



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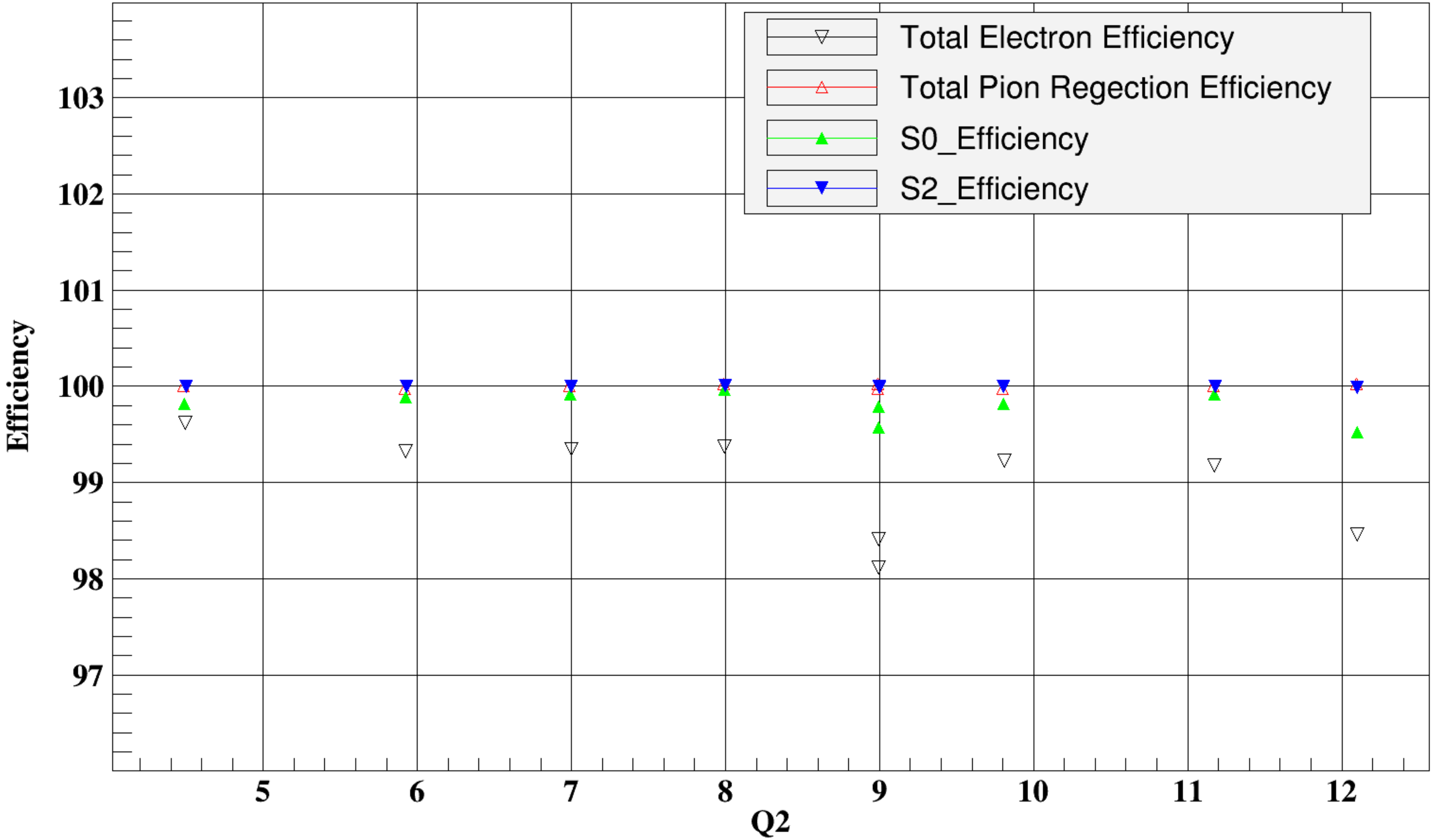

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Spectrometer acceptance

- The acceptance function is calculated generating Monte Carlo events and taking the ratio of the number of detected to the number of generated in each bin in phase space:

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

$$\theta=\arccos[\cos(x'_{tg})\cos(\theta_0-y'_{tg})]$$

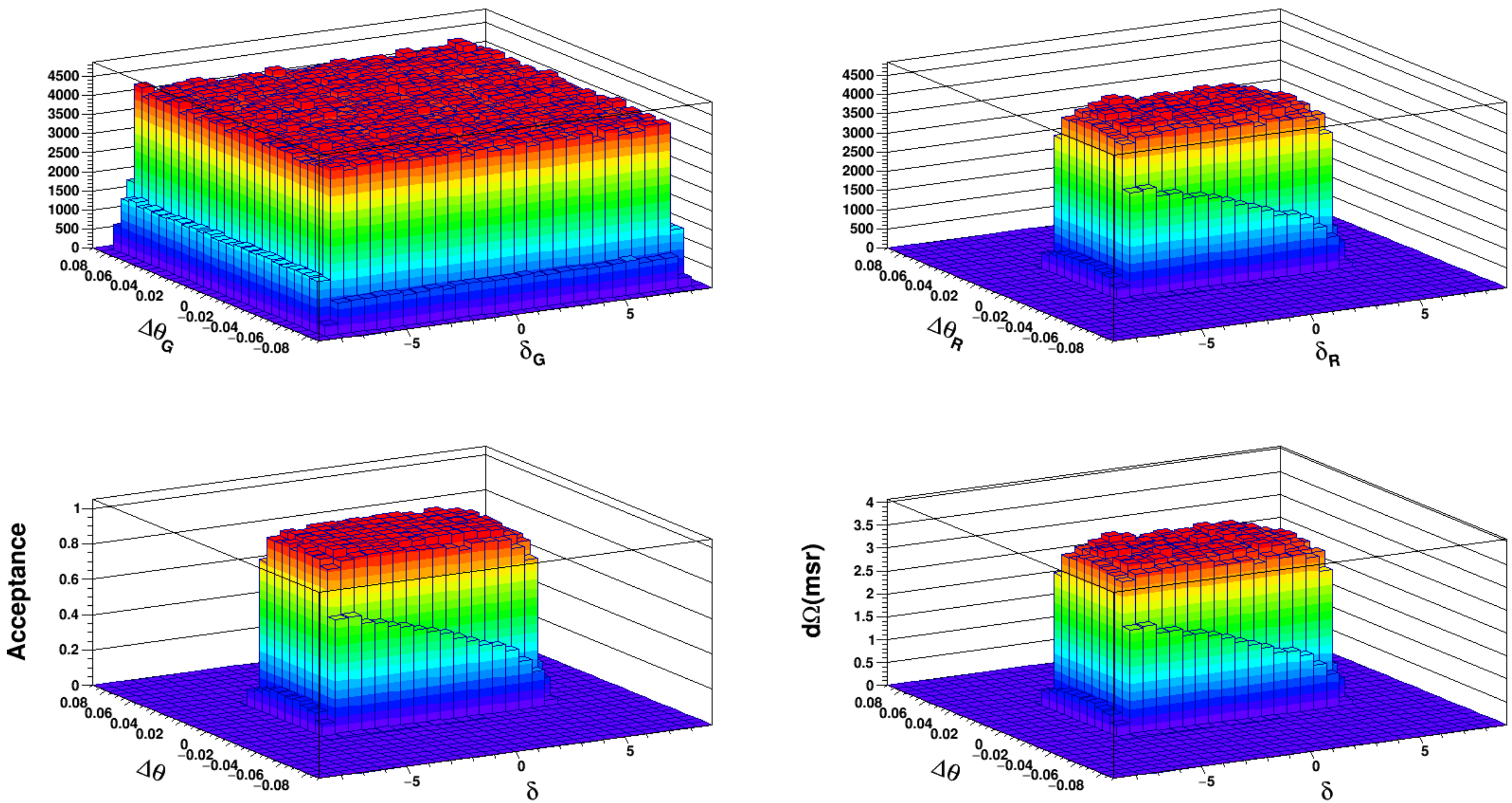
$$\delta=\frac{P-p_0}{P_0}$$

- The effective solid angle for uniform generation is given by:

$$\Delta\Omega_{eff}(\delta,\theta)=N_{rec}(\delta,\theta)\frac{\Delta\Omega^{tot}(\delta,\theta)}{N^{tot}_{gen}}=A(\delta,\theta)\,\Omega_{gen}(\delta,\theta)$$

- Both generated and reconstructed data were binned in small δ and θ bins. For HRS, a δ range of ±6% was used and binned in 30 bins and θ is of (-37,37) mrad was binned in 30 bins. The acceptance correction is applied in bin by bin basis in (δ,θ).

Spectrometer acceptance



$$\Delta\theta = \theta - \theta_0$$

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Radiative Correction

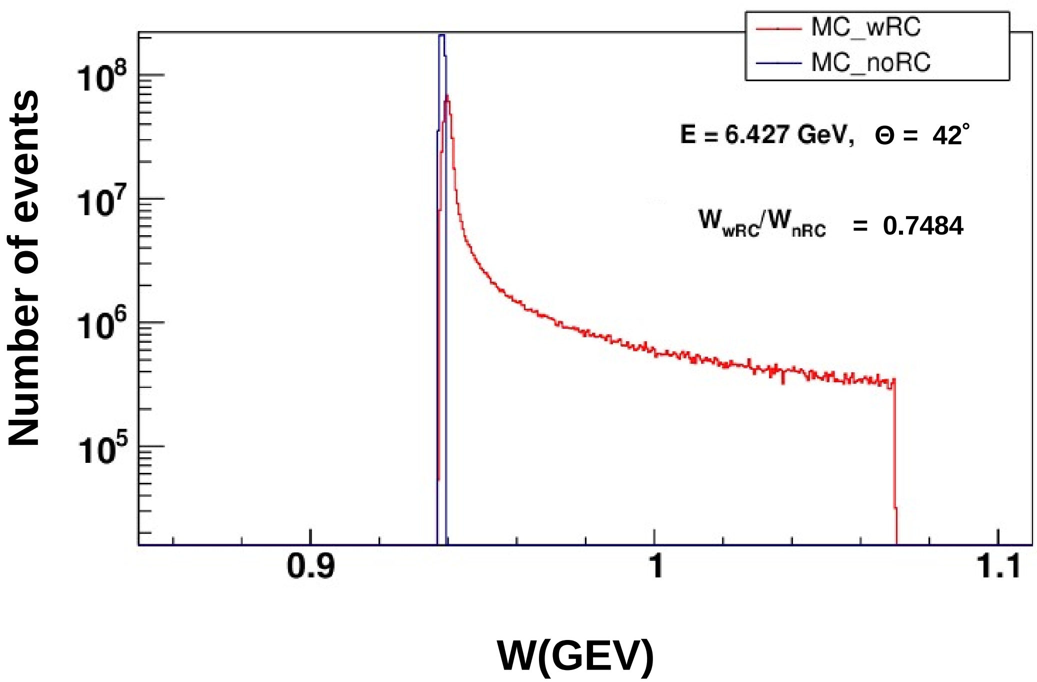
- Internal: Occur inside actual scattering vertex such as vaccum polarization, vertex and internal Bremsstrahlung during collisions
- External: Caused by secondary scattering from the rest of the material in the target, such as Bremsstrahlung and straggling effect due to ionization

The experimental cross section:

$$\frac{d\sigma}{d\Omega}^{expt} = C_{rad} \frac{d\sigma}{d\Omega}^{born}$$

Where, for $0.67 < C_{rad} < 0.78$

$$C_{rad} = \exp(\delta_{int} + \delta'_{int} + \delta_{ext})$$



Kinematic	RC Direct	RC from SIMC
K3-6	0.7461	0.7484
K3-7	0.7510	0.7518
K3-8	0.7579	0.7697
K3-9	0.7695	0.7936
K4-9	0.7165	0.7276
K4-10	0.7191	0.7304
K4-11	0.72584	0.7373
K4-12	0.7322	0.7582

Elastic cross section (Monte Carlo Ratio Method)

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

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

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

Assuming acceptance and radiative contributions are correctly modeled:

$$\boxed{\frac{d\sigma}{d\Omega}^{data}(\theta) \quad = \quad \frac{d\sigma}{d\Omega}^{mod}(\theta) . \frac{Y^{data}}{Y^{MC}}} \longrightarrow (3)$$

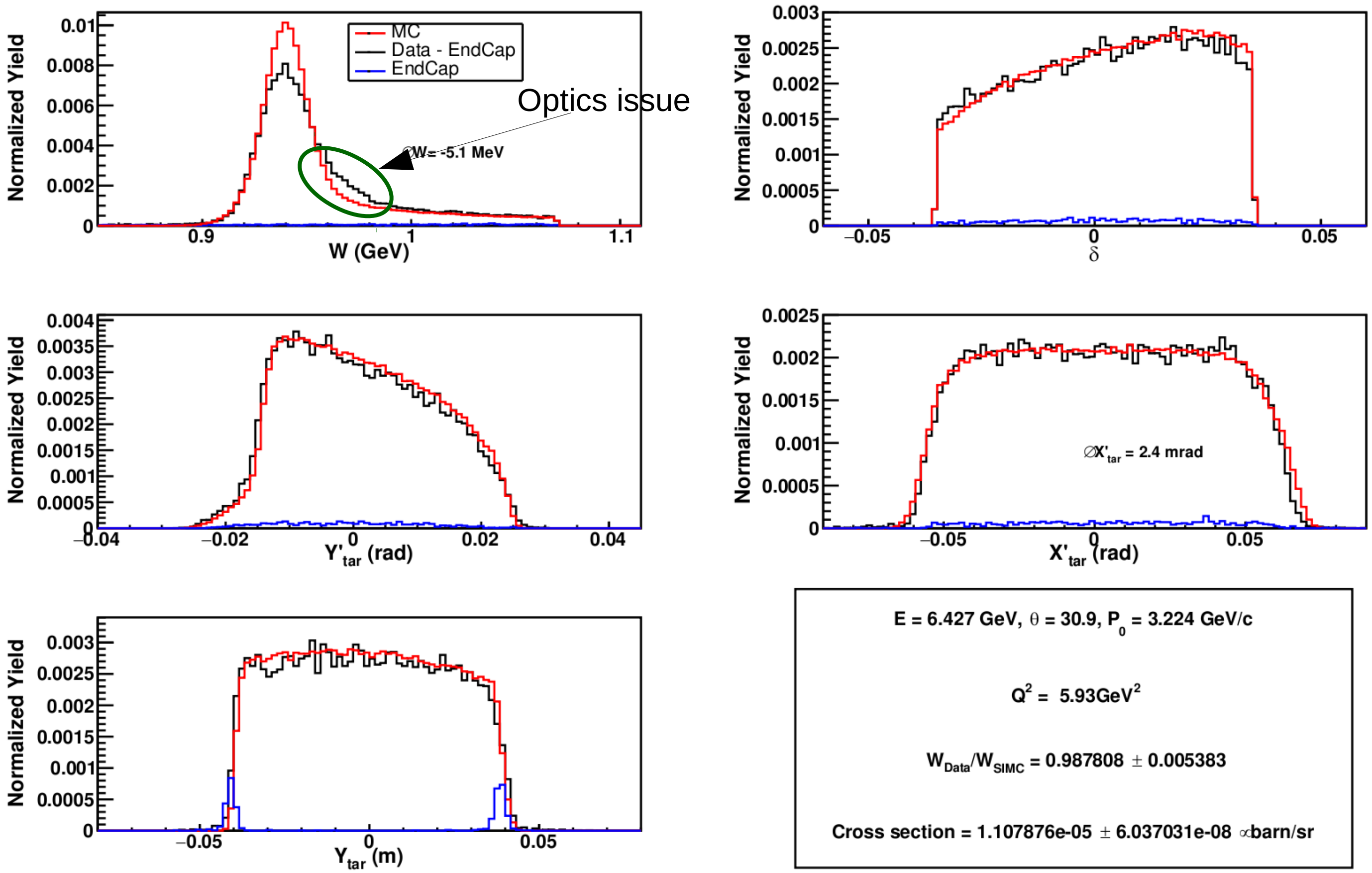
e-p Data vs Monte Carlo

→ In MC the transport function generated by the program COSY infinity were used to model the particle trajectory

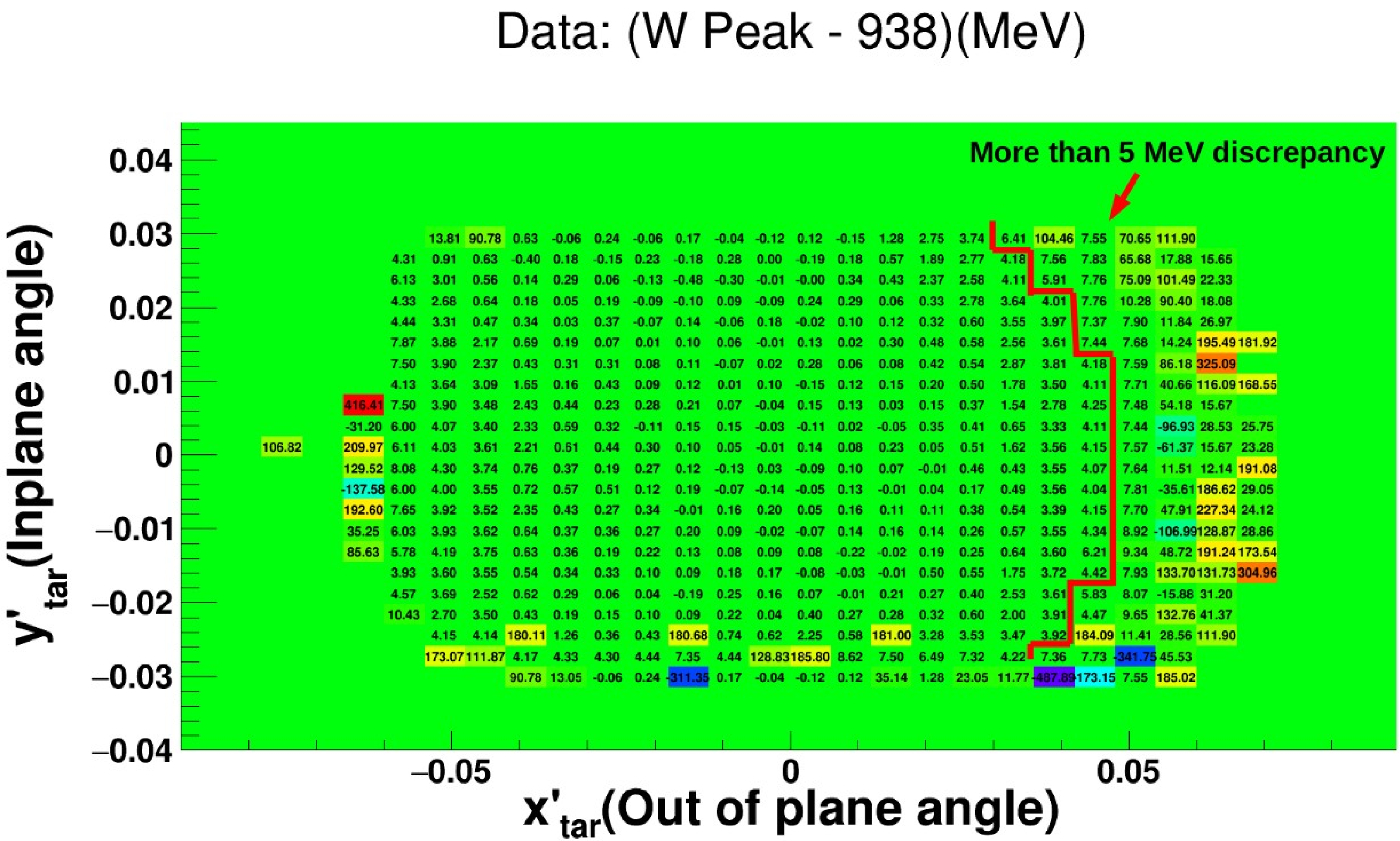
→ The hit positions at each aperture plane were checked and a flag was set if the particle is blocked

→ The simulated events were generated uniformly in the phase space and then weighted by the physics cross section

→ Improvement of optics and model of spectrometer are ongoing



Data vs MC Comparision



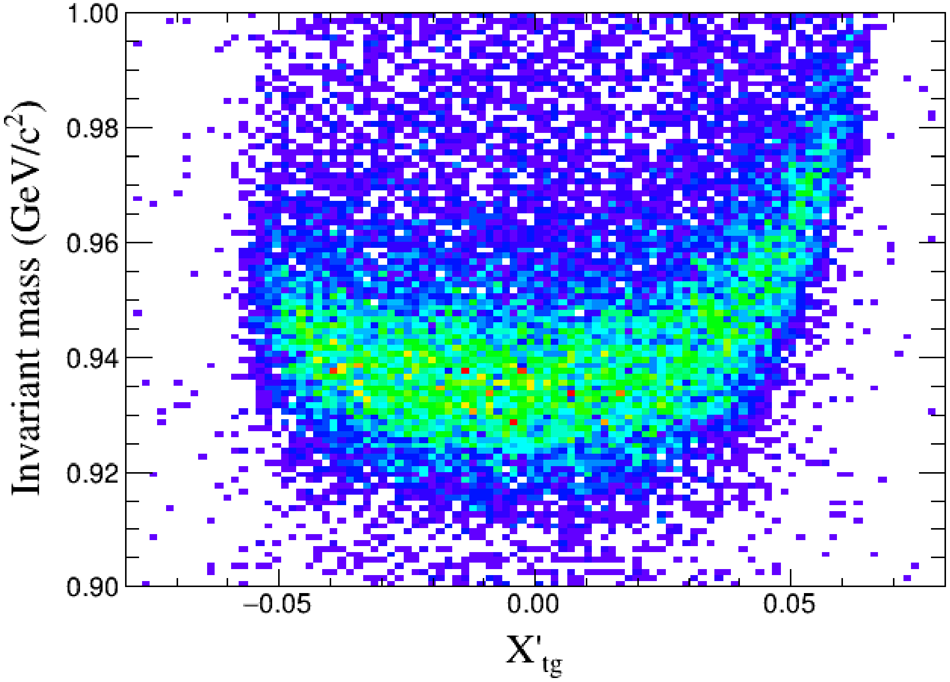
→ $\Delta W = 5$ MeV ➡ $\Delta\theta \sim 2.3$ mrd

$\Delta E' \sim -3.2$ MeV

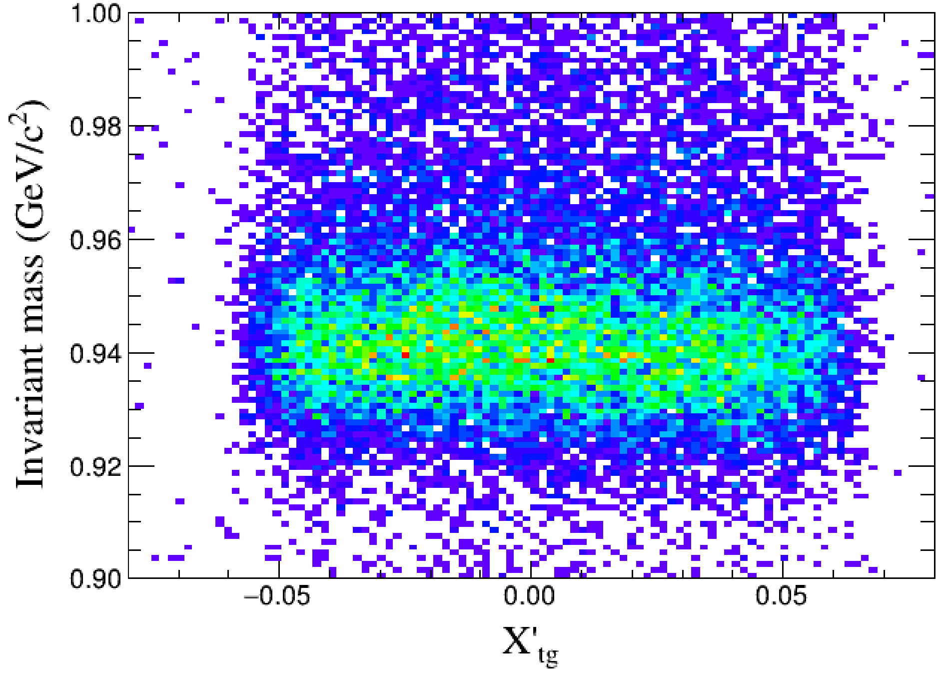
$\Delta E \sim 7.8$ MeV

Improvement of Optics Calibration (Fall 2016)

E=6.42 GeV, θ=44.5 degree, E'=2.15 GeV



Before improvement



After improvement

^{12}C Fall 2016 (Inelastic)

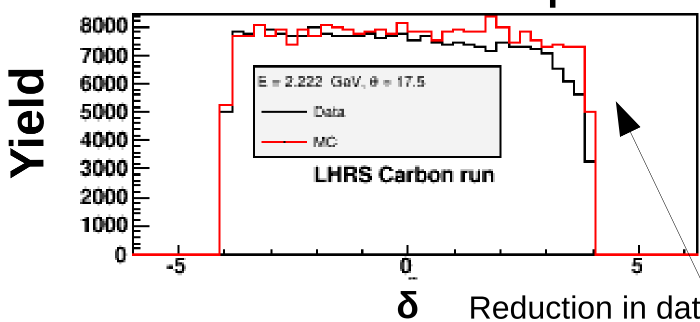
→ Took data on single foil carbon target to study the acceptance of the spectrometer

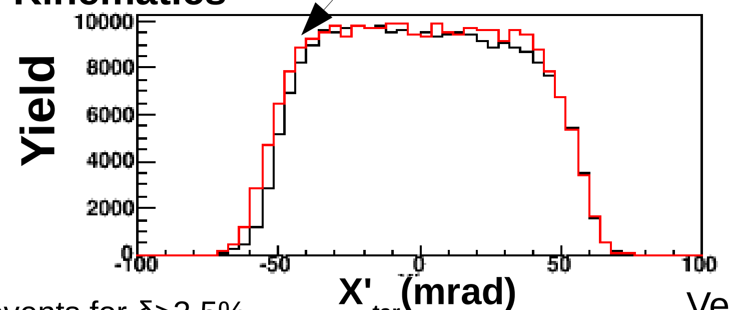
→ Used single arm simulation which gives an uniformly distributed phase space for carbon target without physics weighting

→ Used external code to get physics weighting which is the ratio of born cross section to radiative correction factor

Couple of mrad shift

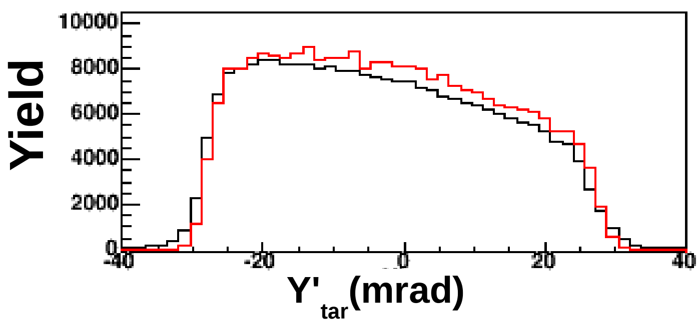
Deep Inelastic Kinematics

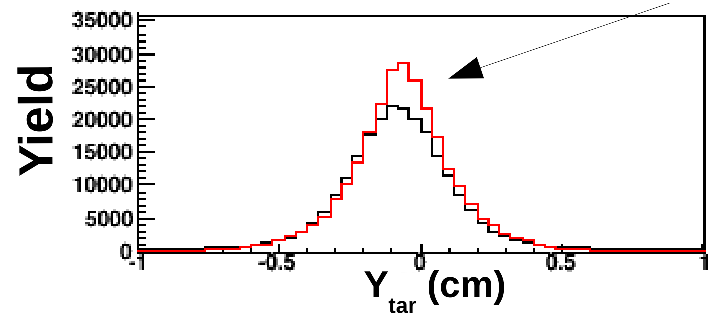


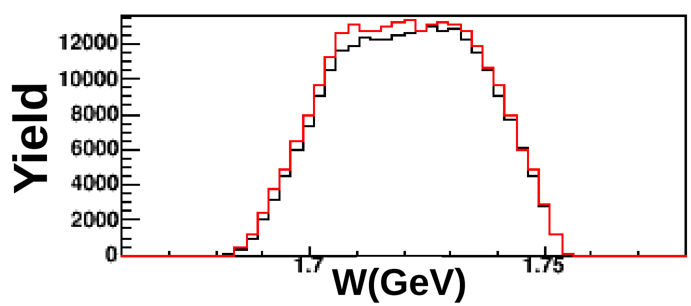


Reduction in data events for δ>3.5%

Vertical aperture shift







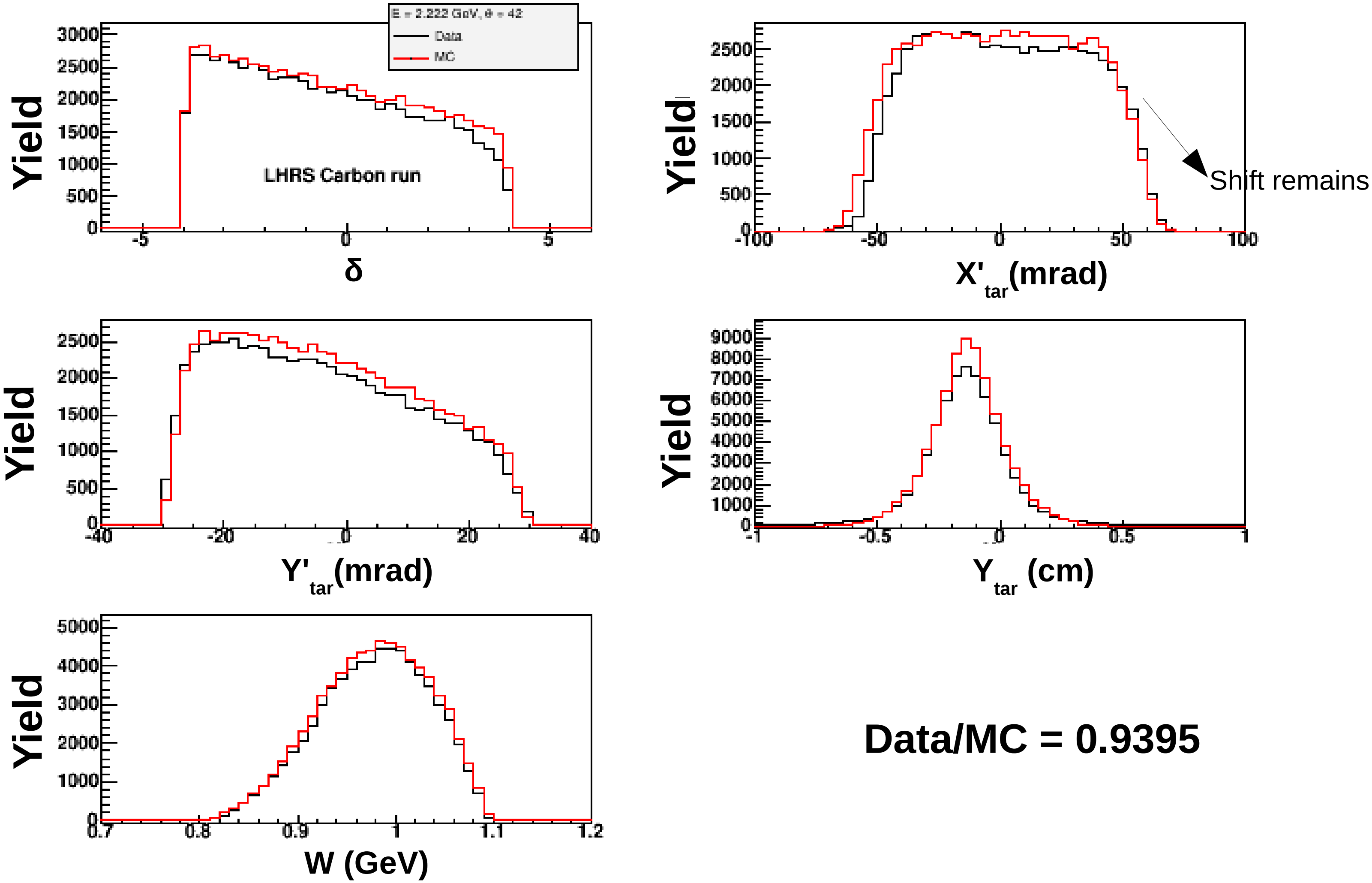
Data/MC = 0.9525

e-p Data vs Monte Carlo

→ Shapes are consistent at very different kinematics

→ The discrepancy observed in high delta probably comes from spectrometer model

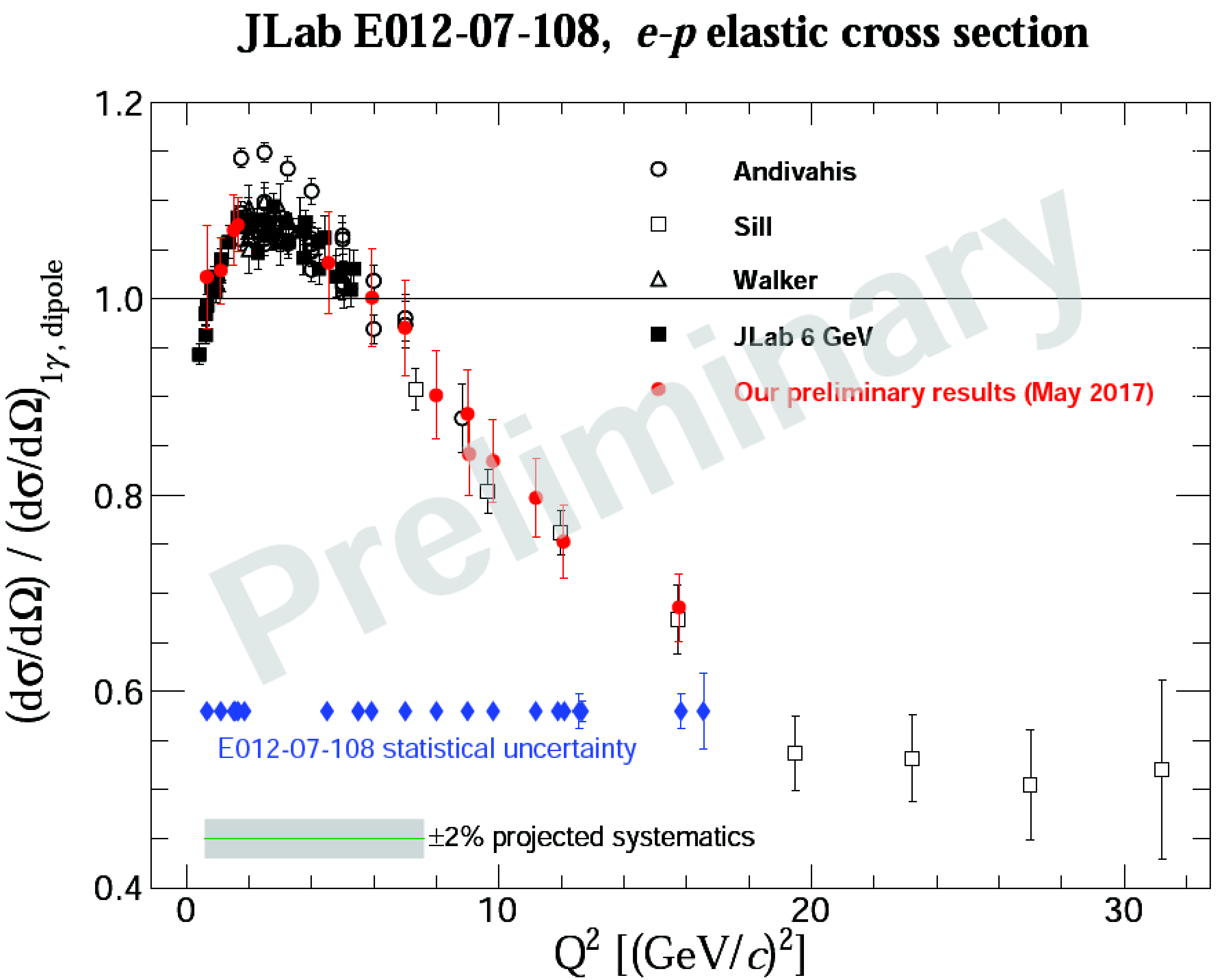
Quasi elastic Kinematics



Data/MC = 0.9395

Preliminary Results (Data/MC method)

- Preliminary cross-section results presented below with 5% uncertainty (total)



Summary

- 12 GeV GMp experiment data taking completed successfully
- Equipment operated stably and satisfactorily
- First pass data replay is close to completion
- First iteration of optics is ongoing
- Projected milestones:

  → First publication to be submitted by the end of 2017

GMp collaboration

- Hall A collaboration, physics staff, technical staff, accelerator team and shift taker
- Spokesperson: J. Arrington, E. Christy, S. Gilad, V. Sulkosky, B. Wojtsekhowski (contact)
- Postdoc: Kalyan Allada (MIT)
- Graduate students: Thir Gautam (Hampton U.), Longwu Ou (MIT), Barak Schmookler (MIT), Yang Wang (W&M)

Thank you everybody!