Coulomb Sum Rule Experiment

Seonho Choi
Seoul National University

July 24, 2014
6th Workshop on Hadron Physics in China and Opportunities in US

Overview

- Probing nucleons in nuclei with electrons
- Quasi-elastic scattering and Coulomb Sum Rule
- One of the long standing puzzles in nuclear physics
- New experiment at JLab
- Preliminary results and summary

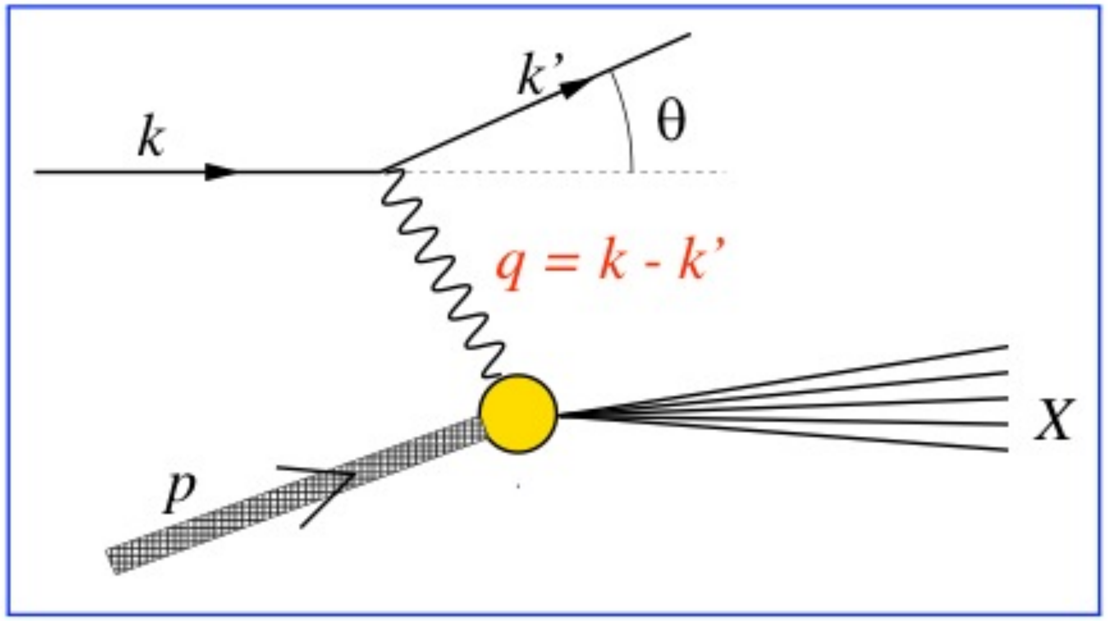
Electrons as a Probe

- Electron scattering has been an excellent tool to study properties of nucleons, nuclei etc.
  - Charge/Magnetization distribution of various nuclei
  - Elastic form factors of nucleons free or inside nuclei
    - Surprises from JLab on $\mu G_E^p / G_M^p$
    - Polarization transfer from ^{4}He

QE Scattering

- Elastic scattering on bound nucleons
- We can study the nucleon properties inside the nucleus
- Scattering on the moving nucleons
- Response functions instead of Form Factors

Response Functions



- Momentum Transfer

$$q = |\mathbf{k} - \mathbf{k}'|$$

- Energy Transfer

$$\omega = E - E'$$

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[\frac{Q^4}{q^4} R_L(q,\omega) + \frac{Q^2}{2q^2} \frac{1}{\varepsilon} R_T(q,\omega) \right]$$

$$\varepsilon = \left[1 + \frac{2q^2}{Q^2} \tan^2 \vartheta \right]^{-1}$$

Response Functions

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[\frac{Q^4}{q^4} R_L(q,\omega) + \frac{Q^2}{2q^2} \frac{1}{\varepsilon} R_T(q,\omega) \right]$$

- Roughly R_L corresponds to $G_E{}^2$
- One complication: the separation of quasi-elastic and inelastic scattering is not a clear cut.
- Fortunately, inelastic scattering contributes mainly to R_T, leaving R_L mostly from quasi-elastic

Coulomb Sum

- Integral of R_L to be compared to G_E

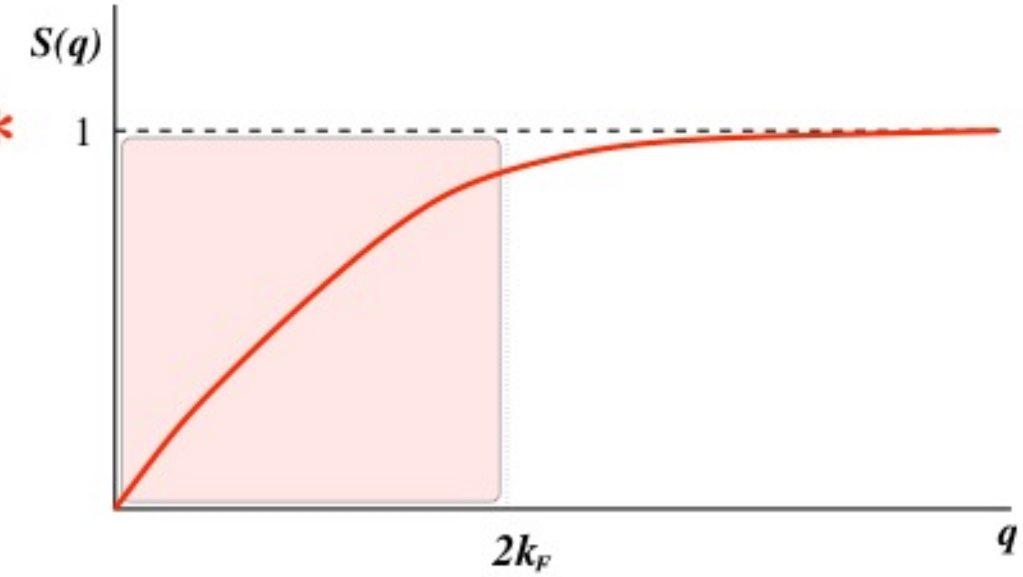
$$S_L(q) = \int_{\omega_{\rm el}^+}^{\infty} d\omega \frac{R_L(q,\omega)}{Z\tilde{G_E}^2(Q^2)}$$

- Denominator = contribution from electric form factors of protons and neutrons

$$\tilde{G_E}^2(Q^2) = \left([G_E^p(Q^2)]^2 + (N/Z)[G_E^n(Q^2)]^2\right) \frac{1+Q^2/4M^2}{1+Q^2/2M^2}$$

Coulomb Sum Rule in One Page

- Coulomb Sum Rule
  - $S_L(q) \to 1$ at sufficiently large q*
- Deviation from unity
  - at small q
    - Pauli blocking
    - NN long range correlations
  - at large $q (>> 2k_F)$
    - Short range correlations
    - Nucleon properties in the nuclear medium



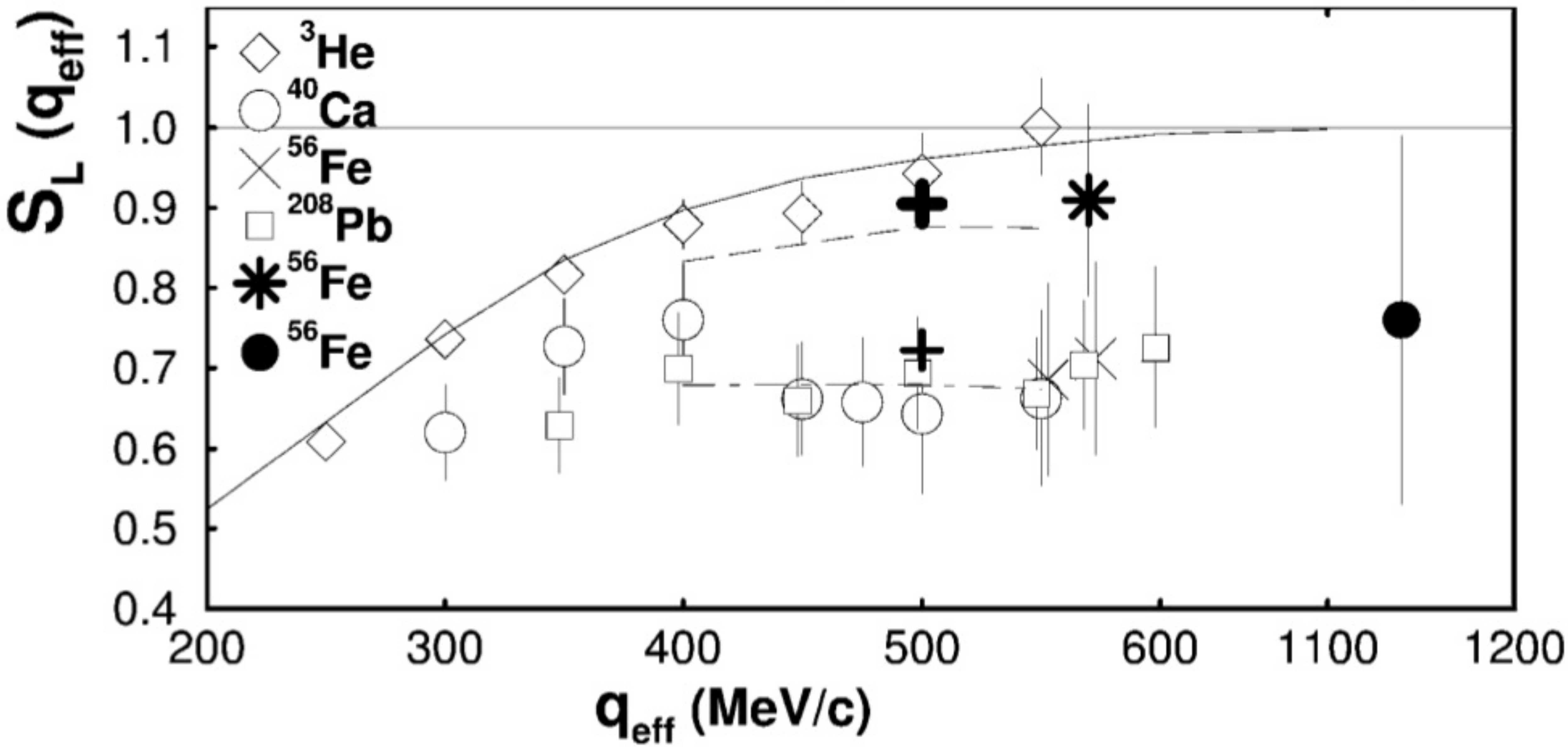
* McVoy and Van Hove, Physical Review 125, 1034 (1962)

Previous Measurements

- For the past 30 years, a large experimental program at Bates, Saclay and SLAC
- Saturation of the Coulomb sum still a puzzle
- Limited kinematic coverage in q and ω due to machine limitations
- Unresolved issue on the control of systematics
    - background events for backward scattering
    - Coulomb corrections

Existing Data for CSR

Morgenstern & Meziani PLB 515 (2001) 269



CSR Puzzle

- Early data show significant quenching of the CSR
- With the addition of forward angle data, some analysis claims no significant quenching
  - Jourdan NPA 603, 117 (1996)
- Other, new analysis claims that quenching persists
  - Morgenstern & Meziani, PLB 515, 269 (2001)

Major Issues of the CSR Experiments

- Coulomb Corrections
  - Effect of the nuclear Coulomb field to the incoming and outgoing electrons
  - Actual incident & scattered energy inside the nucleus are modified
  - Corrections are necessary before the comparison of elastic & quasi-elastic
- Experimental Systematics
  - Machine limitations (too low or too high)
  - Relatively small lever arm for LT separation
  - Control of background events in the detector

Coulomb Corrections

- Up to now, two methods have been suggested
  - Approximated Distorted Wave Impulse Approximation (DWIA) calculations
    - Leading to LEMA(Local EMA)
    - Jourdan, PLB 353(1995) 189, NPA603(1996) 117
  - Approximate corrections via Effective Momentum Approximation (EMA)
    - Morgenstern & Meziani, PLB 515, 269 (2001)
- To make things more complicated
  - MIT/Bates experiments have used LEMA
  - Saclay experiments used EMA

What is EMA?

- Corrections to incident and scattered electron energies by average potential $\overline{V_C}$

$$\left.\begin{array}{ccc} E & \rightarrow & E_{\rm eff} = E - \overline{V_C} \\ E' & \rightarrow & E'_{\rm eff} = E' - \overline{V_C} \end{array}\right\} \longrightarrow \mathbf{q}_{\rm eff}, Q^2_{\rm eff}$$

- Response functions after EMA corrections are

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\rm Mott}(E, E', \theta)\left[\frac{Q^4_{\rm eff}}{q^4_{\rm eff}} R_L(q_{\rm eff}, \omega) + \frac{Q^2_{\rm eff}}{2q^2_{\rm eff}}\frac{1}{\varepsilon_{\rm eff}} R_T(q_{\rm eff}, \omega)\right]$$

- Comparison of positron vs electron scattering on Pb nuclei
  - P. Gueye et al., Physical Review C 60 044308 (1999)

New Development on Coulomb Corrections

- 4 independent theory groups have worked on the subject
  - A. Aste (Basel), K. Kim (Korea), J. Tjon (Maryland), J. Udias (Madrid), S. Wallace (Maryland), L. Wright (Ohio)
- Workshops organized by Jefferson Lab and College of William & Mary
  - Mini-workshop on Coulomb Corrections (Mar. 2005)
  - A session during JLab/INT workshop (Aug. 2005)

New Conclusions

- EMA is a reasonable approximation, especially
  - for medium-light nuclei
  - for incident electron energies higher than 500 MeV
  - EMA should be a reasonable approximation for Coulomb corrections up to ^{56}Fe
- How good is EMA for R_L in the case of ^{208}Pb?
  - For different nucleus, the effect goes roughly as $\left(1 - \frac{V(0)}{E}\right)^2$
  - Coulomb corrections significant
  - Have to work with theorists

References for CC

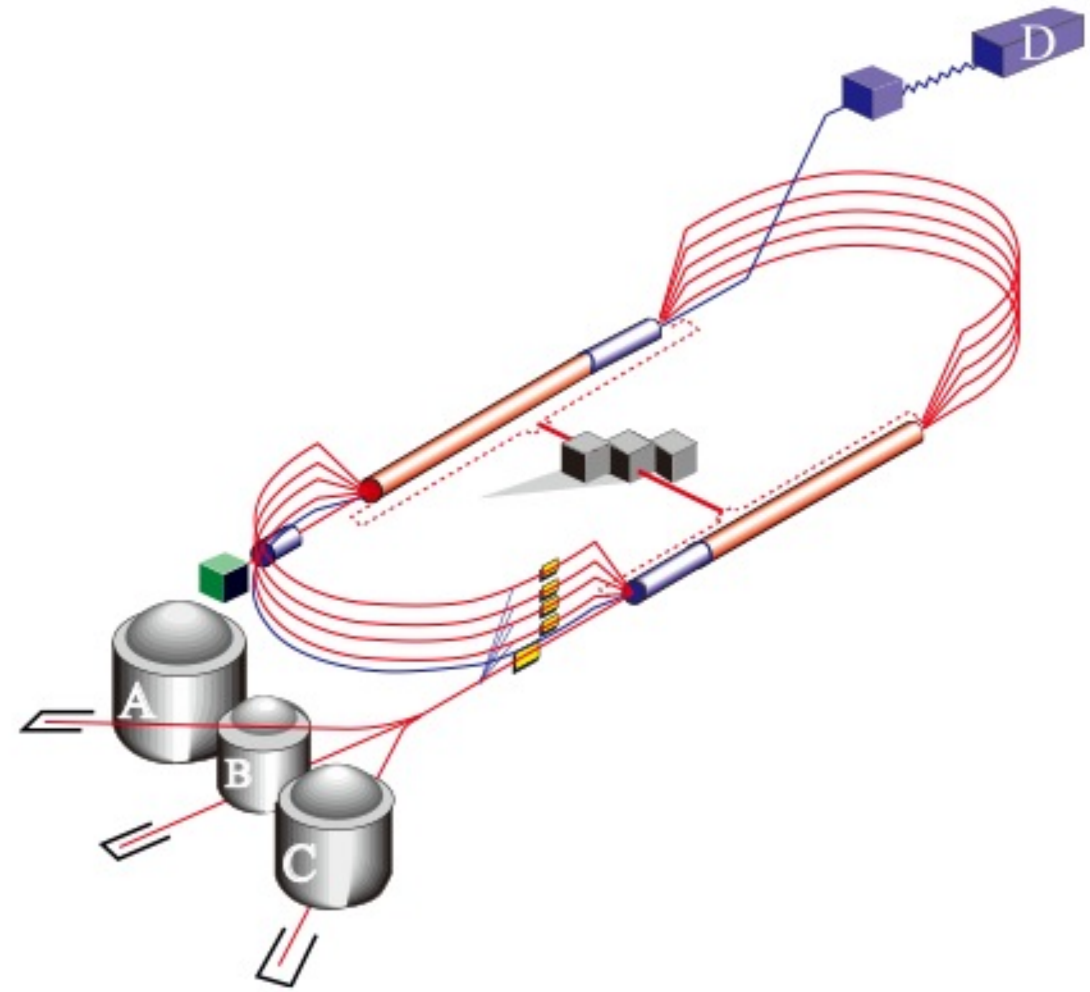
- Wallace & Tjon, PRC78, 044604 (2008)
- Aste, NPA806, 191 (2008)
- Benhar, Day & Sick, RMP 80, 189 (2008)
- Aste & Trautmann, EPJA33, 11 (2007)
- Tjon & Wallace, PRC74, 064602 (2006)
- Kim & Wright, PRC72, 064607 (2005)
- Aste, von Arx & Trautmann, EPJA26, 167 (2005)

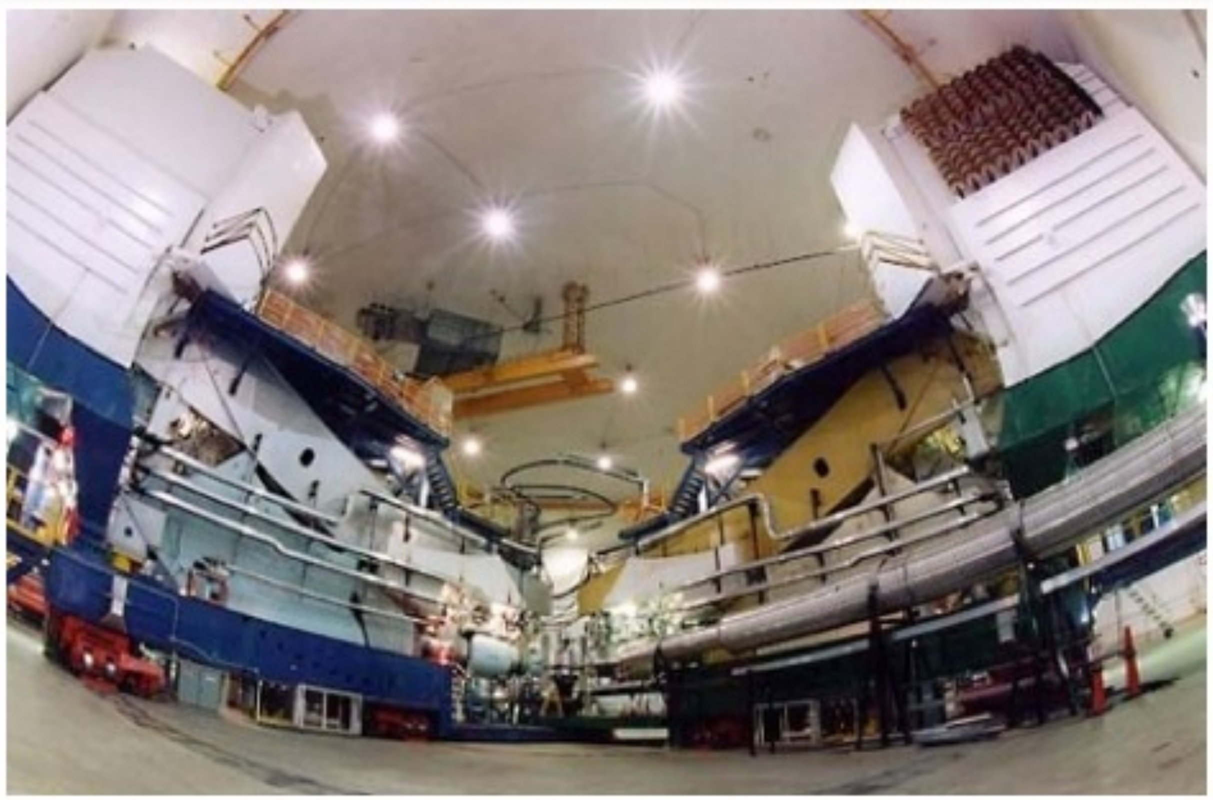
* References only after 2005 CC Workshop have been listed.

New Experiment at JLab

- Beam: 16 energies from 0.4 to 4.0 GeV
- Scattering angles: 15°, 60°, 90°, 120°
- Targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb
- Spectrometer momenta range from 4 GeV down to 100 MeV
- Covers q from 550 to 1000 MeV/c

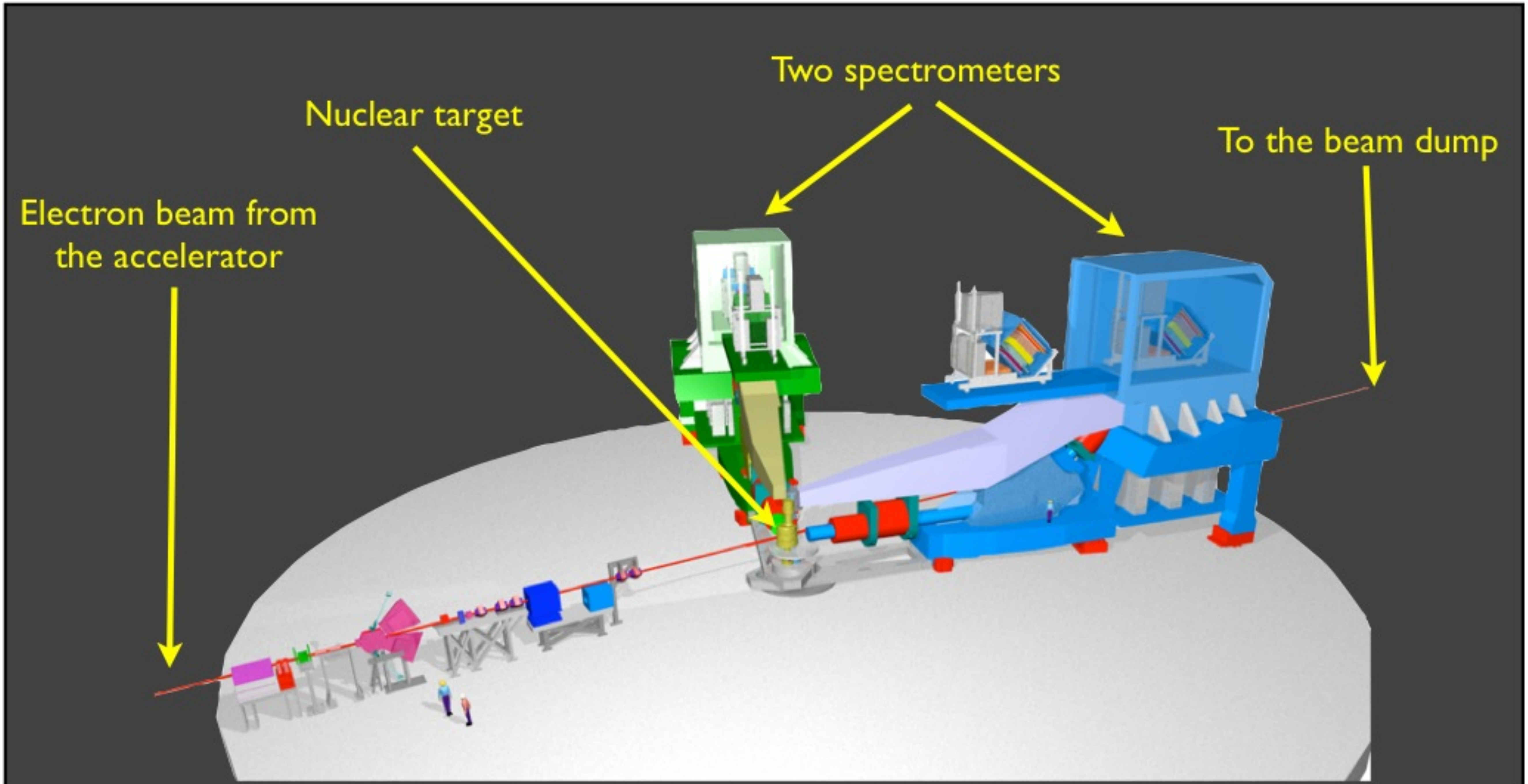
Jefferson Lab / Experimental Hall A



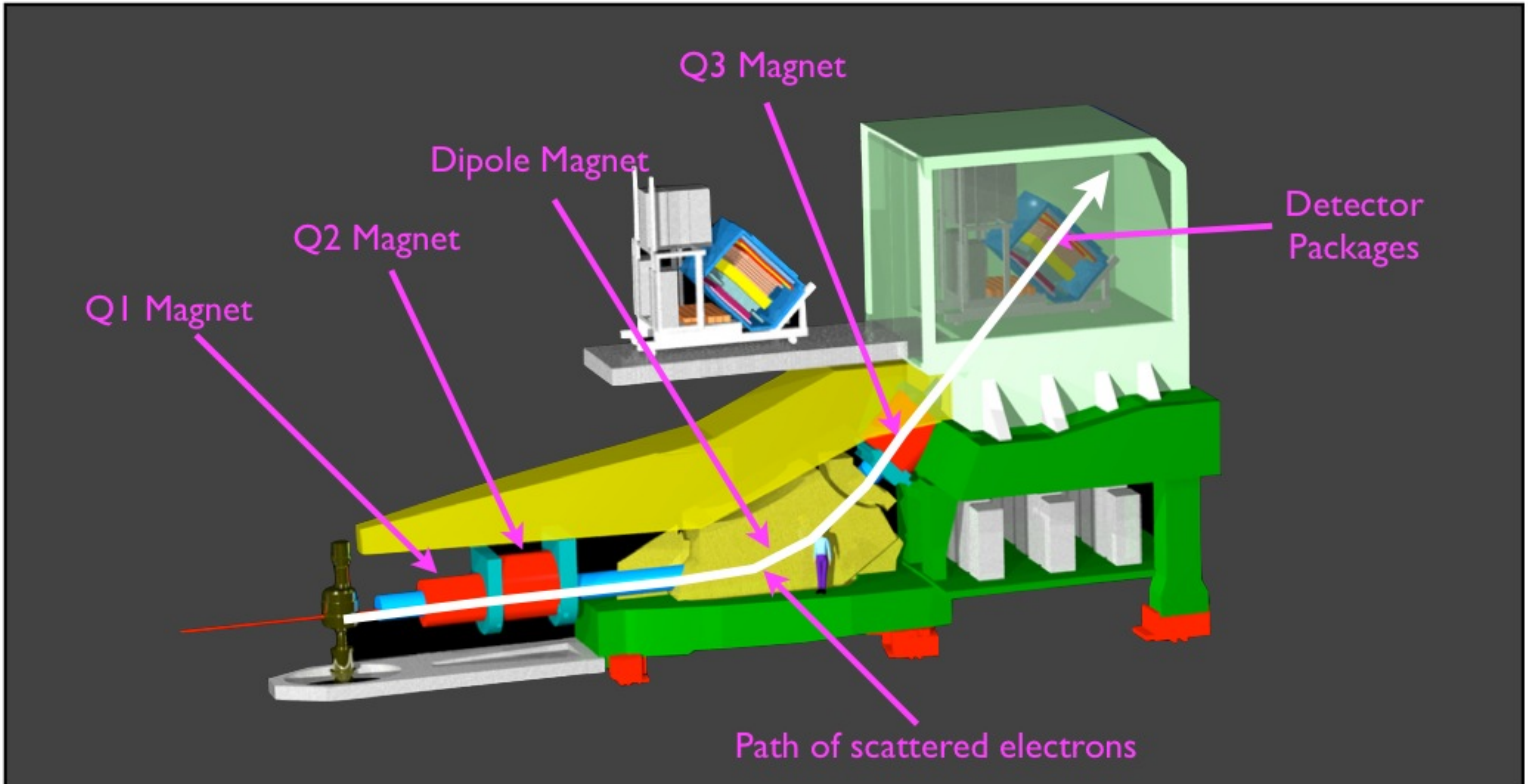


- Up to ~6 GeV polarized electron beam
- 100 μA for Hall A / C
- Now under 12 GeV upgrade with Hall D construction

Jefferson Lab Hall-A



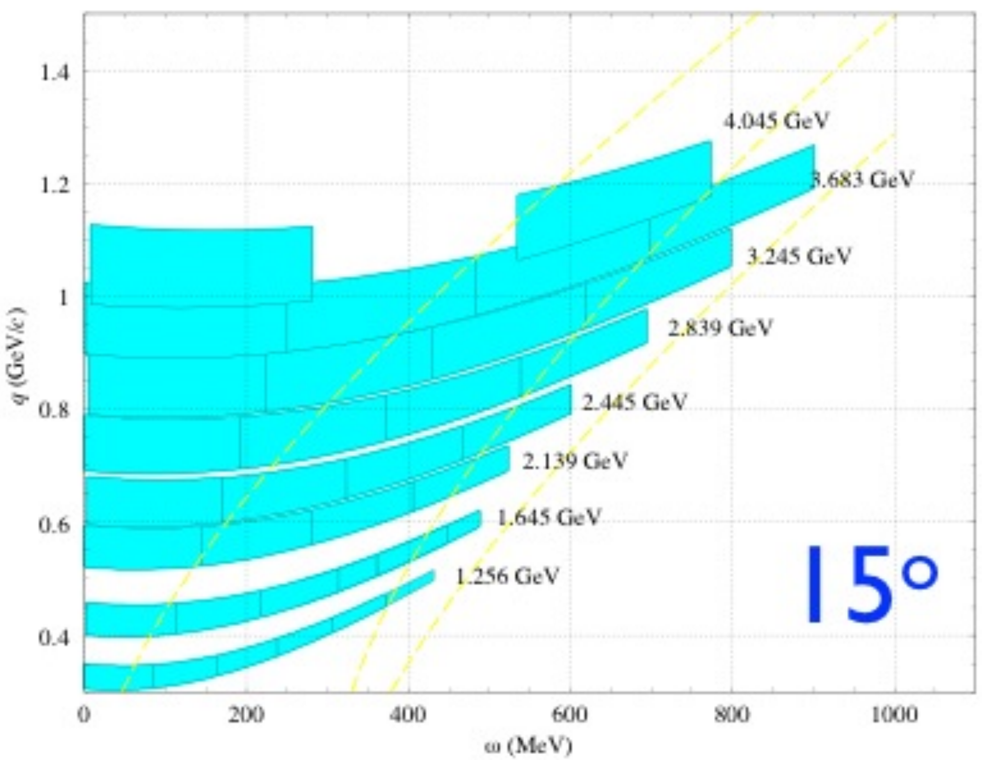
Spectrometer

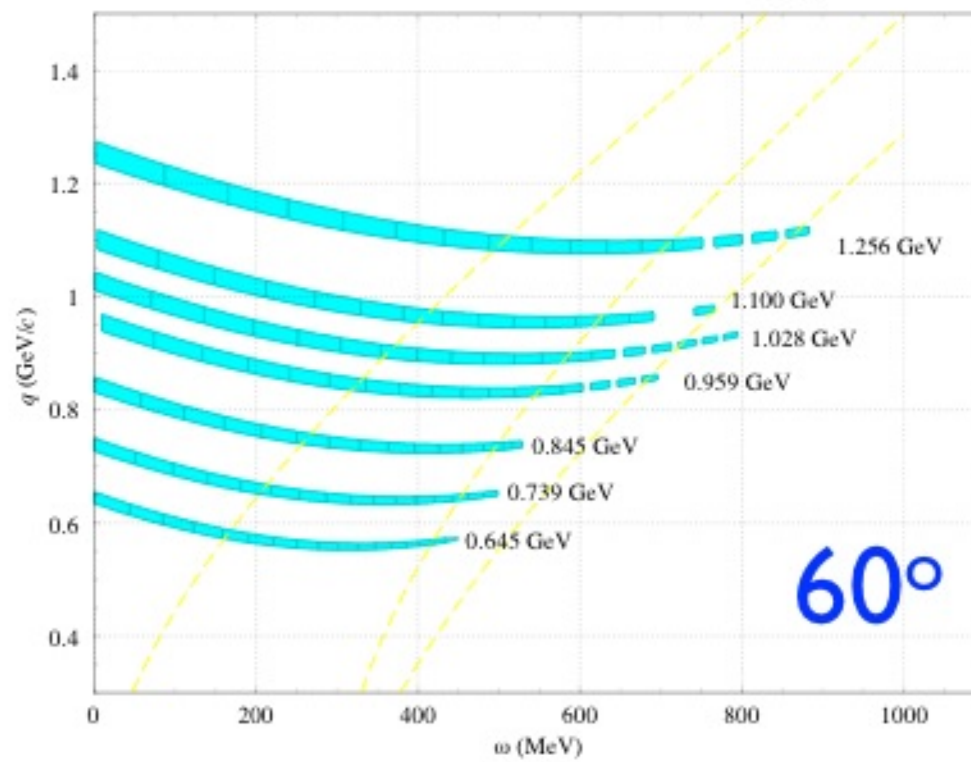


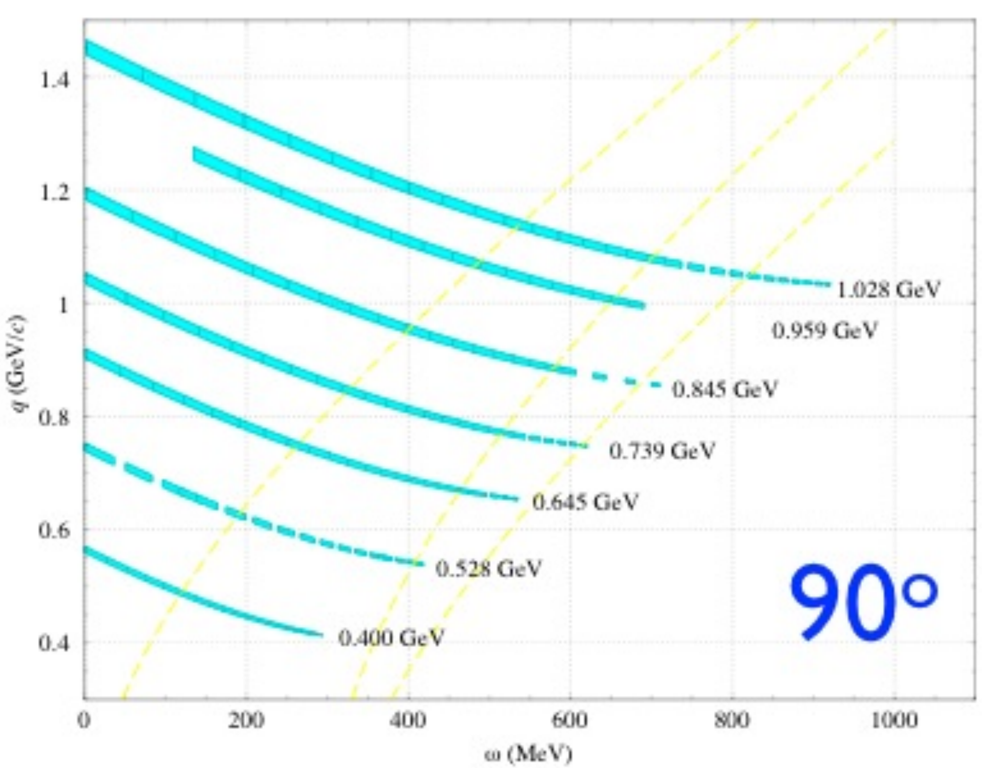
What's New?

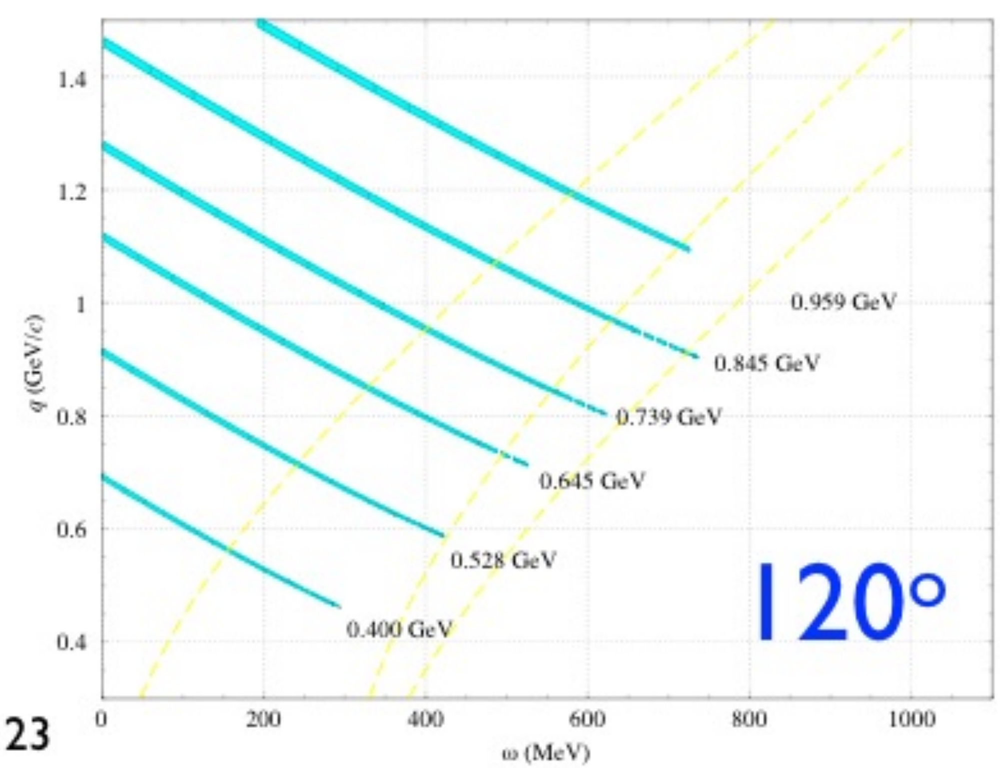
- Comfortable high values of *q*
  - From 550 MeV/*c* to 1000 MeV/*c*
  - High enough for clean observation of CSR
  - Previously unexplored region
- Comprehensive single experiment
  - Largest lever arm
  - Measurement at 4 angles
- Better control of background with NaI detector

Kinematic Coverage

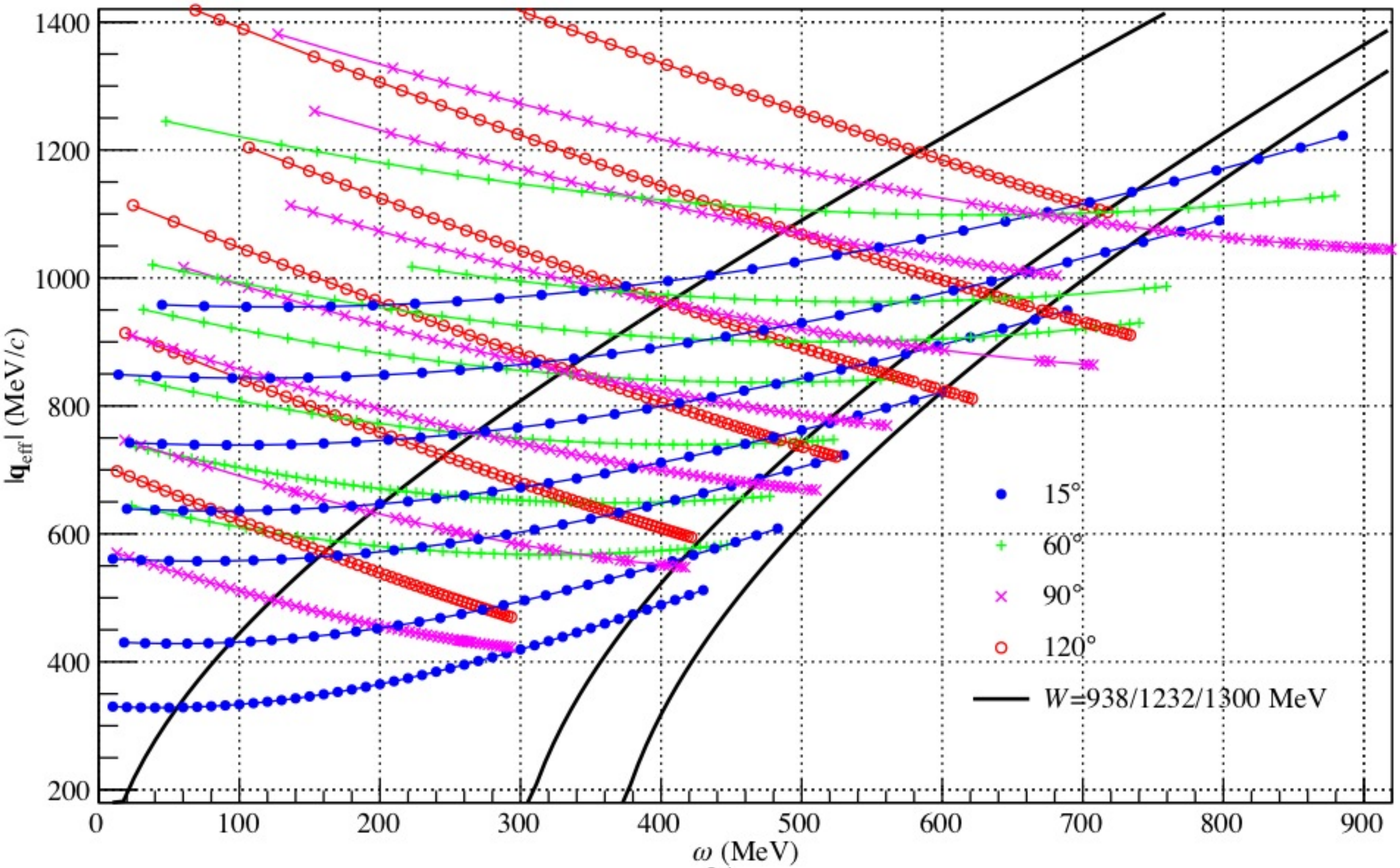




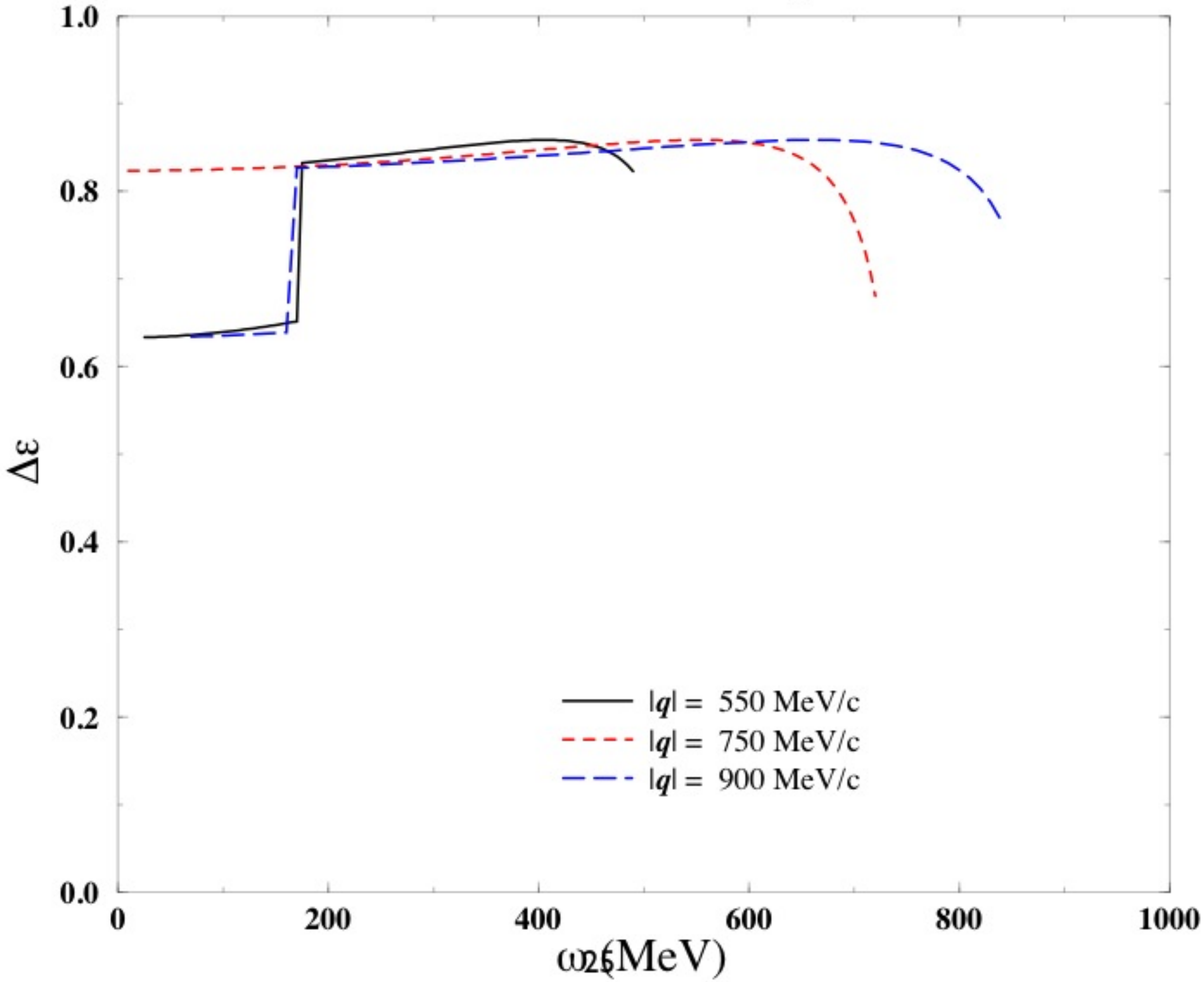




Kinematic Coverage



Lever arm for Rosenbluth Separation



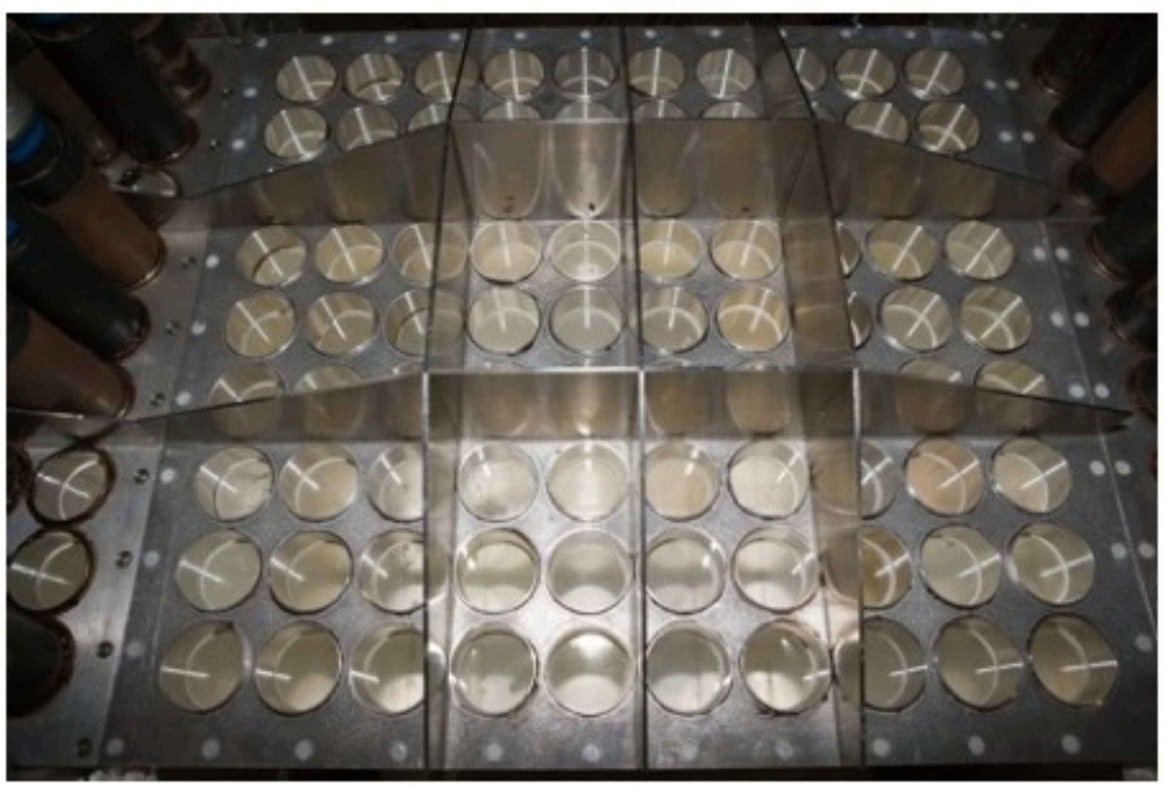
NaI Detector

- Electrons reflected inside the spectrometer
  - Source of background at low energy backward angle
- Reduction of the background
  - Careful geometry cut at the focal plane
  - Independent energy measurement of the electrons using NaI detector

NaI Detector

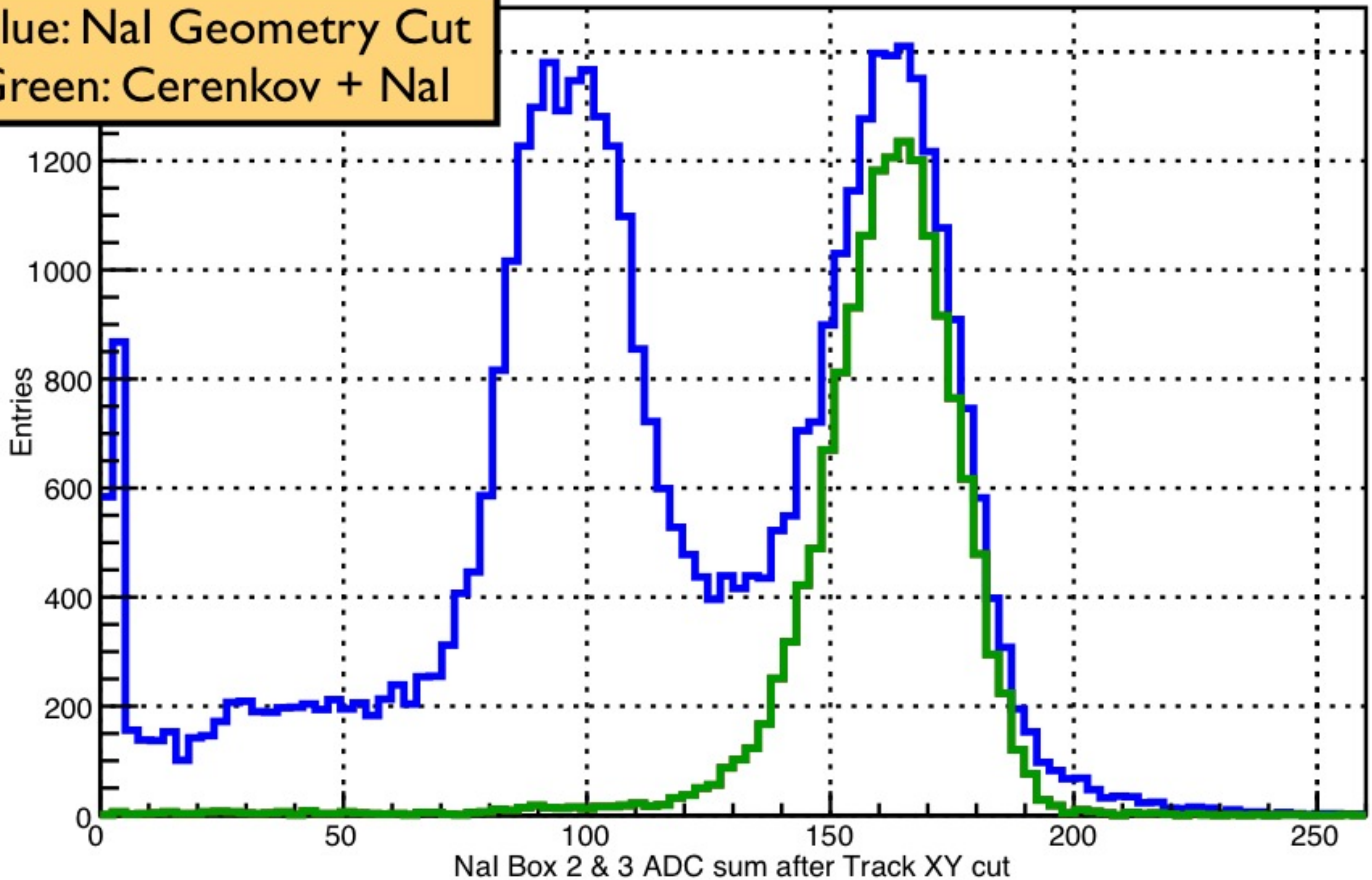
- NaI Crystal given from BNL
- About 400 crystals of 2.5"x2.5"x12"
- Refurbished at JLab: polishing, assembly in new boxes, sealing
- Final product: 3 boxes of 90 crystals (9x10 arrangement) each
- Covers whole focal plane of L-HRS

Installation of NaI detector



Performance

- Blue: NaI Geometry Cut
- Green: Cerenkov + NaI



People

Kalyan Allada, Korand Aniol, John Arrington, **Hamza Atac**, Todd Averett, Herat Bandara, Werner Boeglin, **Alexandre Camsonne**, Mustafa Canan, Jian-Ping Chen, Wei Chen, Khem Chirapatpimol, Seonho Choi, Eugene Chudakov, Evaristo Cisbani, Francesco Cusanno, Raffaele De Leo, Chiranjib Dutta, Cesar Fernandez-Ramirez, **David Flay**, Salvatore Frullani, Haiyan Gao, Franco Garibaldi, Ronald Gilman, Oleksandr Glamazdin, Brian Hahn, Ole Hansen, Douglas Higinbotham, Tim Holmstrom, Bitao Hu, Jin Huang, Florian Itard, Liyang Jiang, Xiaodong Jiang, Hoyoung Kang, Joe Katich, Mina Katramatou, Aidan Kelleher, Elena Khrosinkova, Gerfried Kumbartzki, John LeRose, Xiaomei Li, Richard Lindgren, Nilanga Liyanage, Joaquin Lopez Herraiz, Lagamba Luigi, Alexandre Lukhanin, Maria Martinez Perez, Dustin McNulty, Zein-Eddine Meziani, Robert Michaels, Miha Mihovilovic, Joseph Morgenstern, Blaine Norum, **Yoomin Oh**, Michael Olson, Makis Petratos, Milan Potokar, Xin Qian, Yi Qiang, Arun Saha, Brad Sawatzky, Elaine Schulte, Mitra Shabestari, Simon Sirca, Patricia Solvignon, **Jeongseog Song**, Nikolaos Sparveris, Ramesh Subedi, **Vincent Sulkosky**, Jose Udias, Javier Vignote, Eric Voutier, Youcai Wang, John Watson, Yunxiu Ye, **Xinhu Yan**, **Huan Yao**, Zhihong Ye, Xiaohui Zhan, Yi Zhang, Xiaochao Zheng, Lingyan Zhu

and

Hall-A Collaboration

Students **Post-docs** Run Coordinators Collaborators Spokespersons

Data Taking

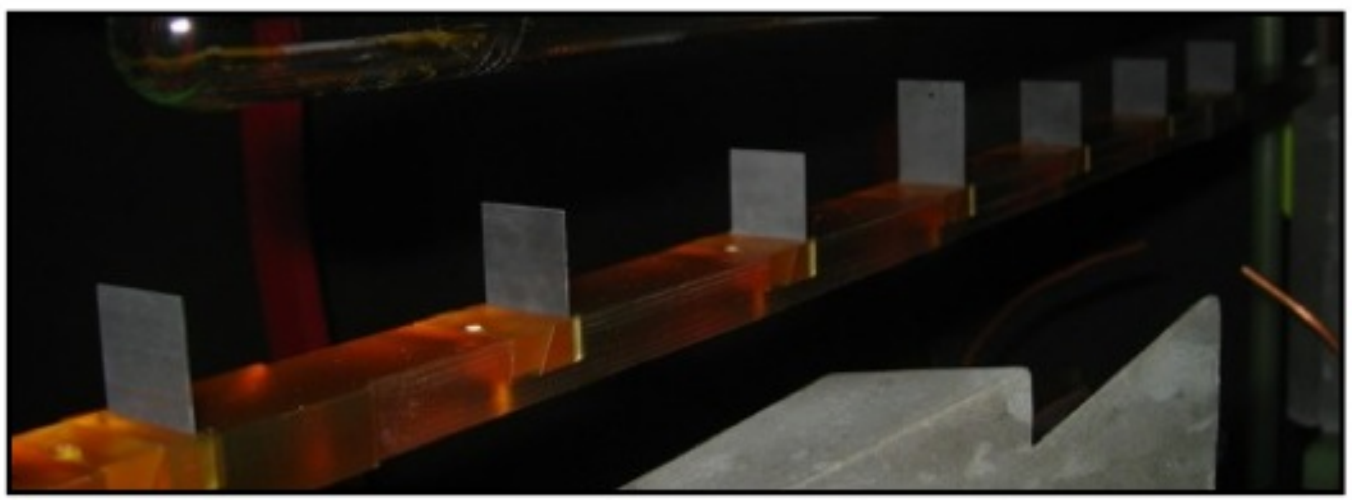
- Dates: Oct. 23, 2007 - Jan. 16, 2008
  86 calendar days - 2 holiday shutdowns
- Data taken: about 3TB over 7000 runs
- Most of the runs are 5 minutes long
  - Frequent changes of target and spectrometer momentum

Analysis

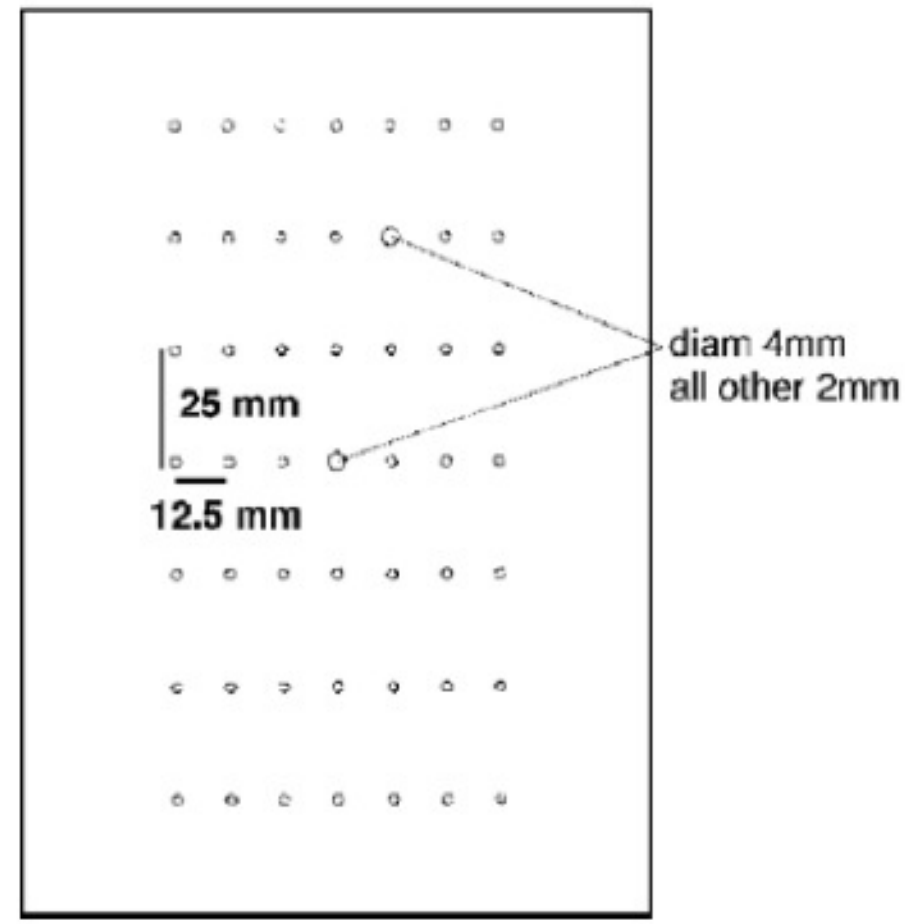
- Measurement of absolute cross sections
- Comparison of two absolute cross sections for two different kinematic conditions
  - Forward vs backward angle
  - High vs low beam energy
  - Almost two extremes of spectrometer momentum configuration
- Finally subtraction of two large numbers to find the small difference

Spectrometer Optics Calibration

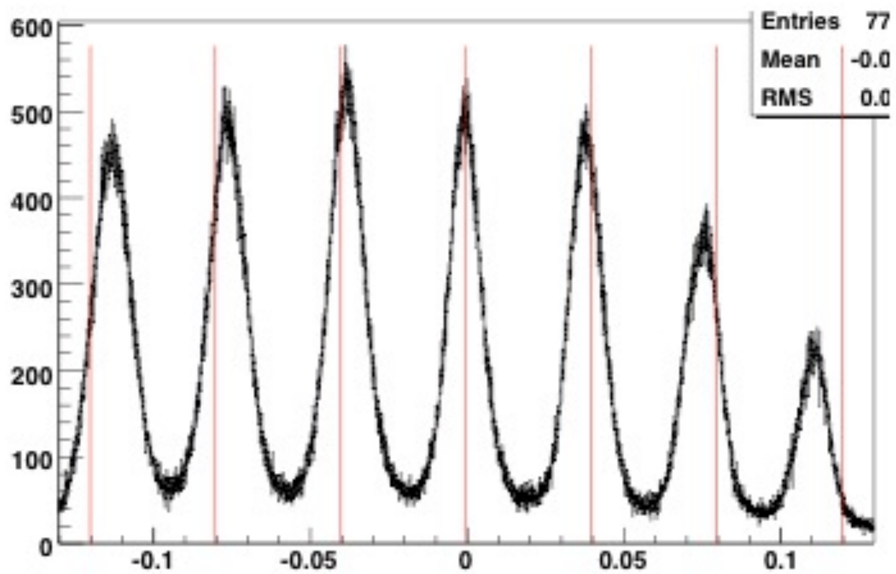
7-foil Carbon target

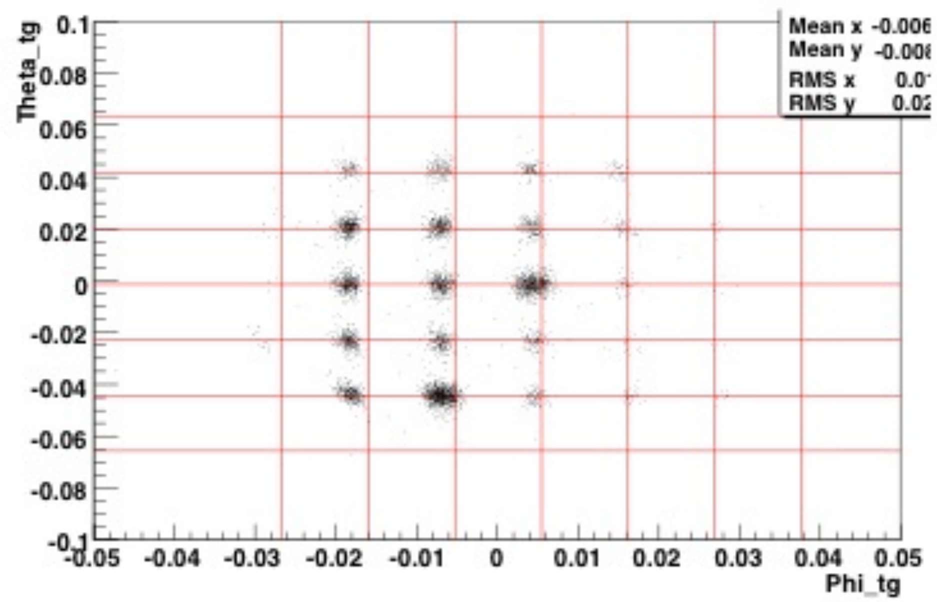


Sieve Slit



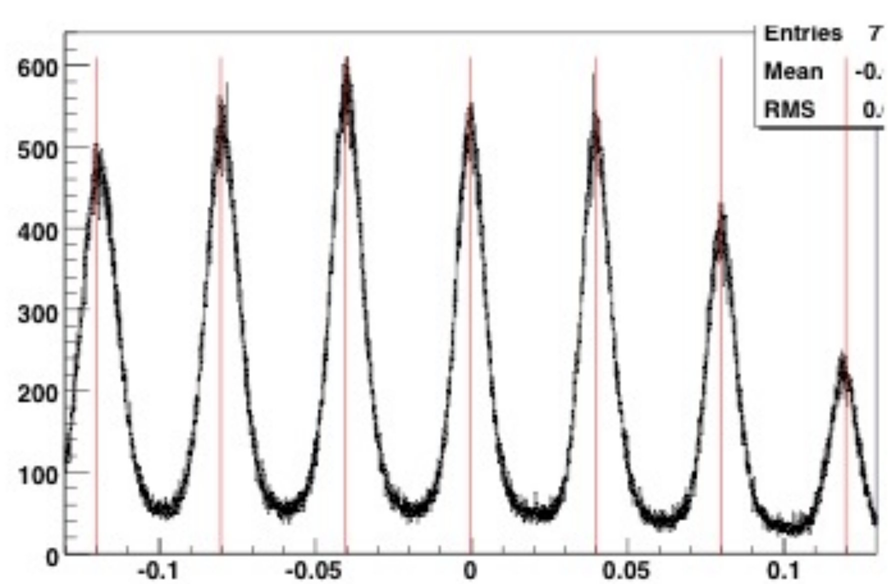
Spectrometer Optics

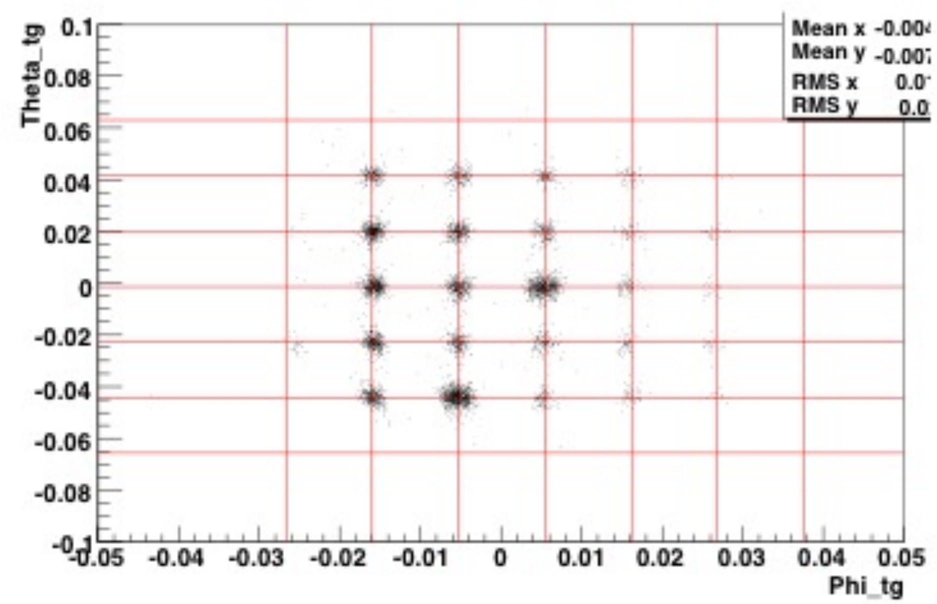




Before Optimization

Red lines: Surveyed positions and angles of the target and slit holes



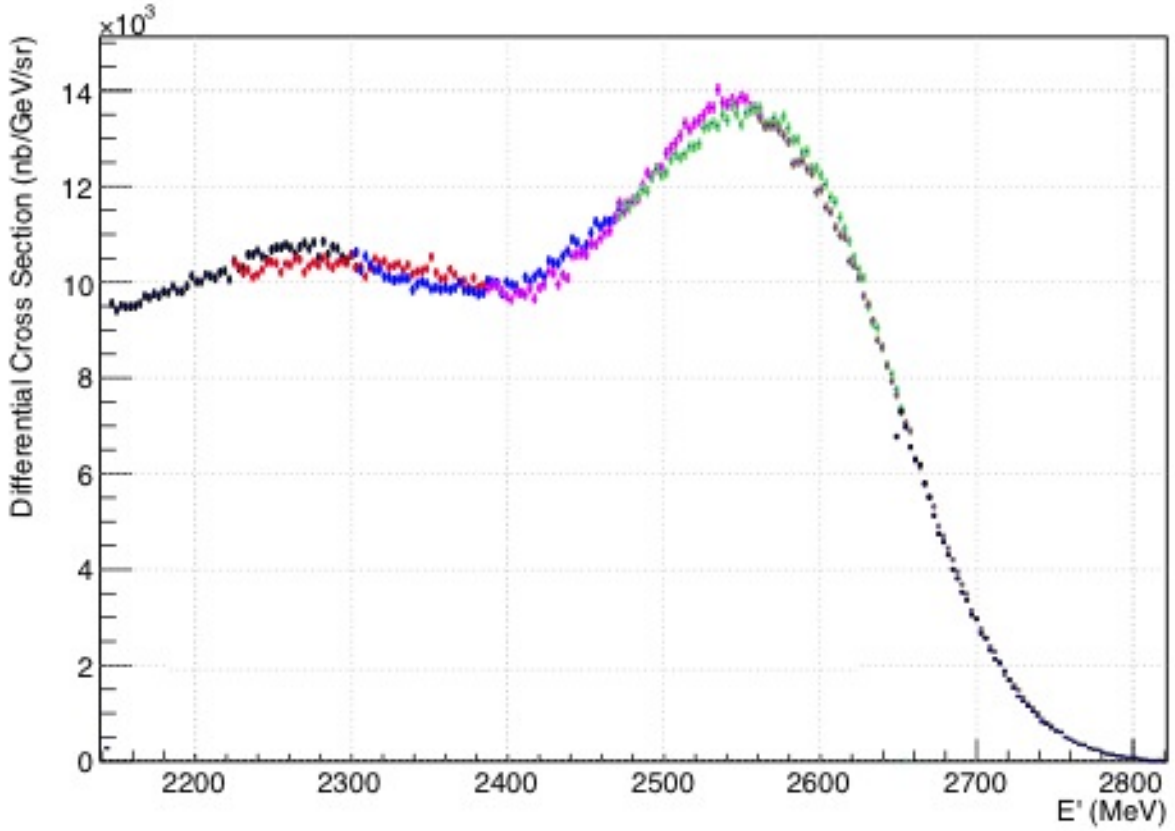


After Optimization

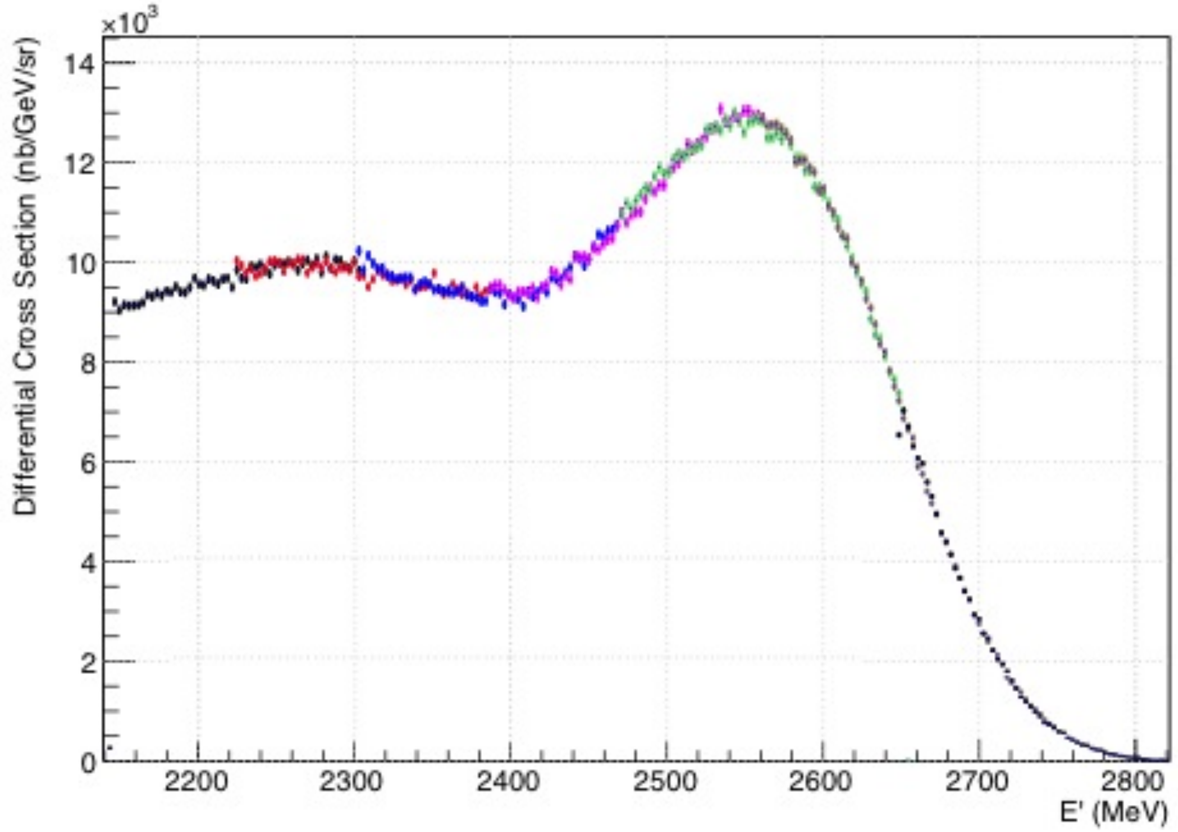
Spectrometer Acceptance

- Realistic acceptance with full simulation considering
  - Effect of energy loss
  - Multiple coulomb scattering
  - Detector resolutions

Spectrometer Acceptance

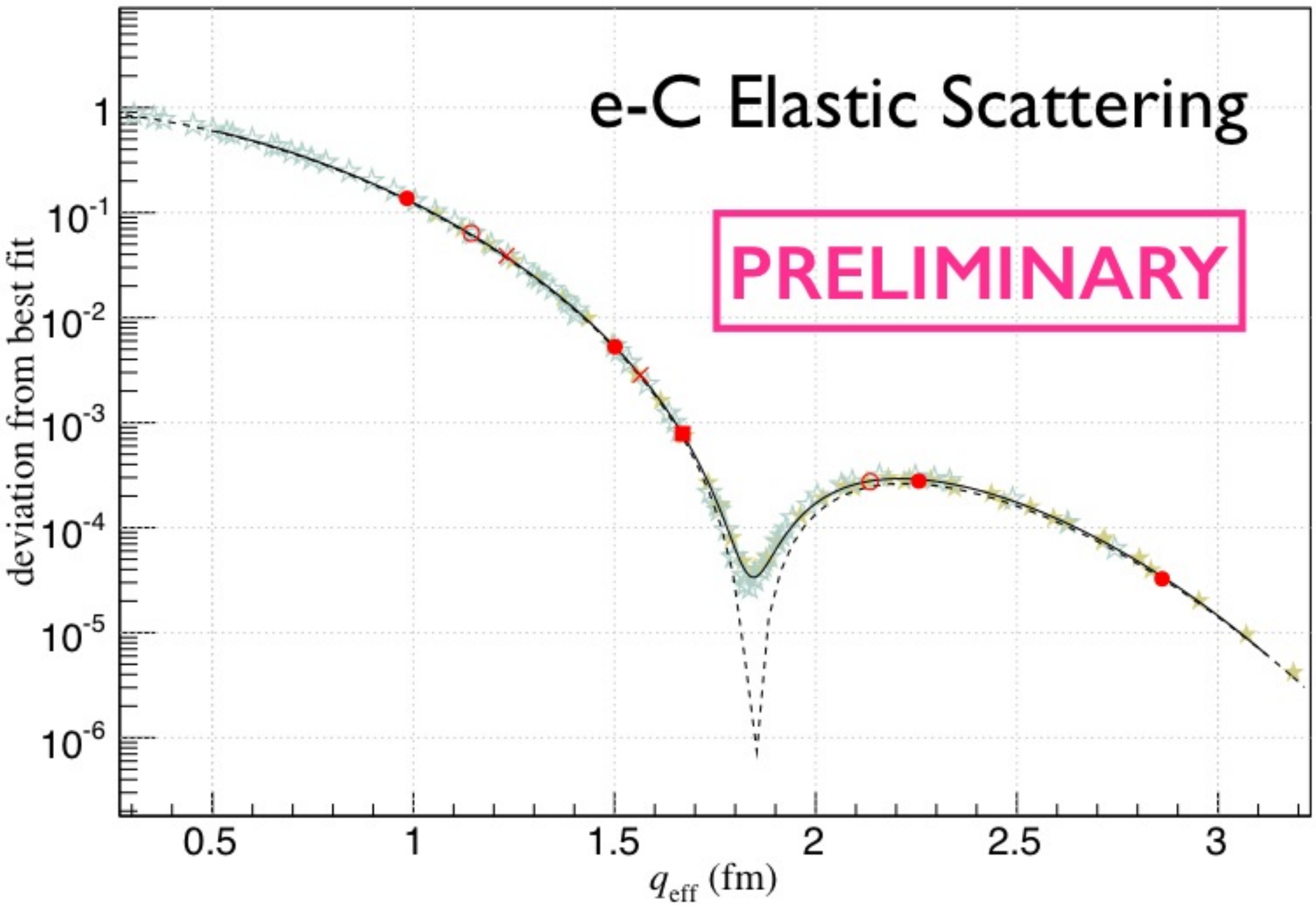


With
Geometrical Acceptance



With
Realistic Acceptance

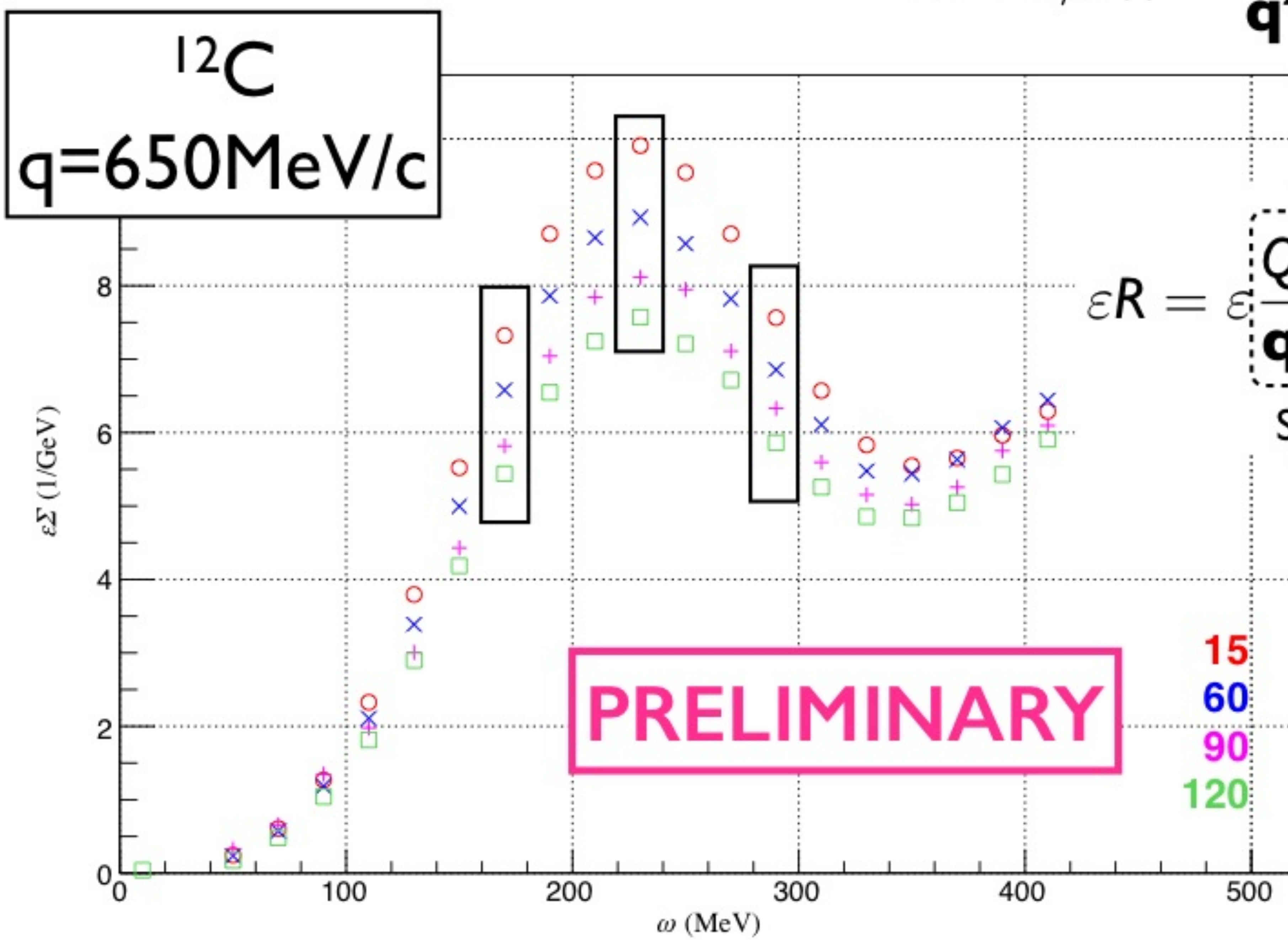
Elastic Cross Sections



LT Separation

$$R \equiv \sigma/\sigma_{\mathrm{M}} = \frac{Q^4}{\mathbf{q}^4} R_L + \frac{Q^2}{2\mathbf{q}^2} \frac{R_T}{\varepsilon}$$

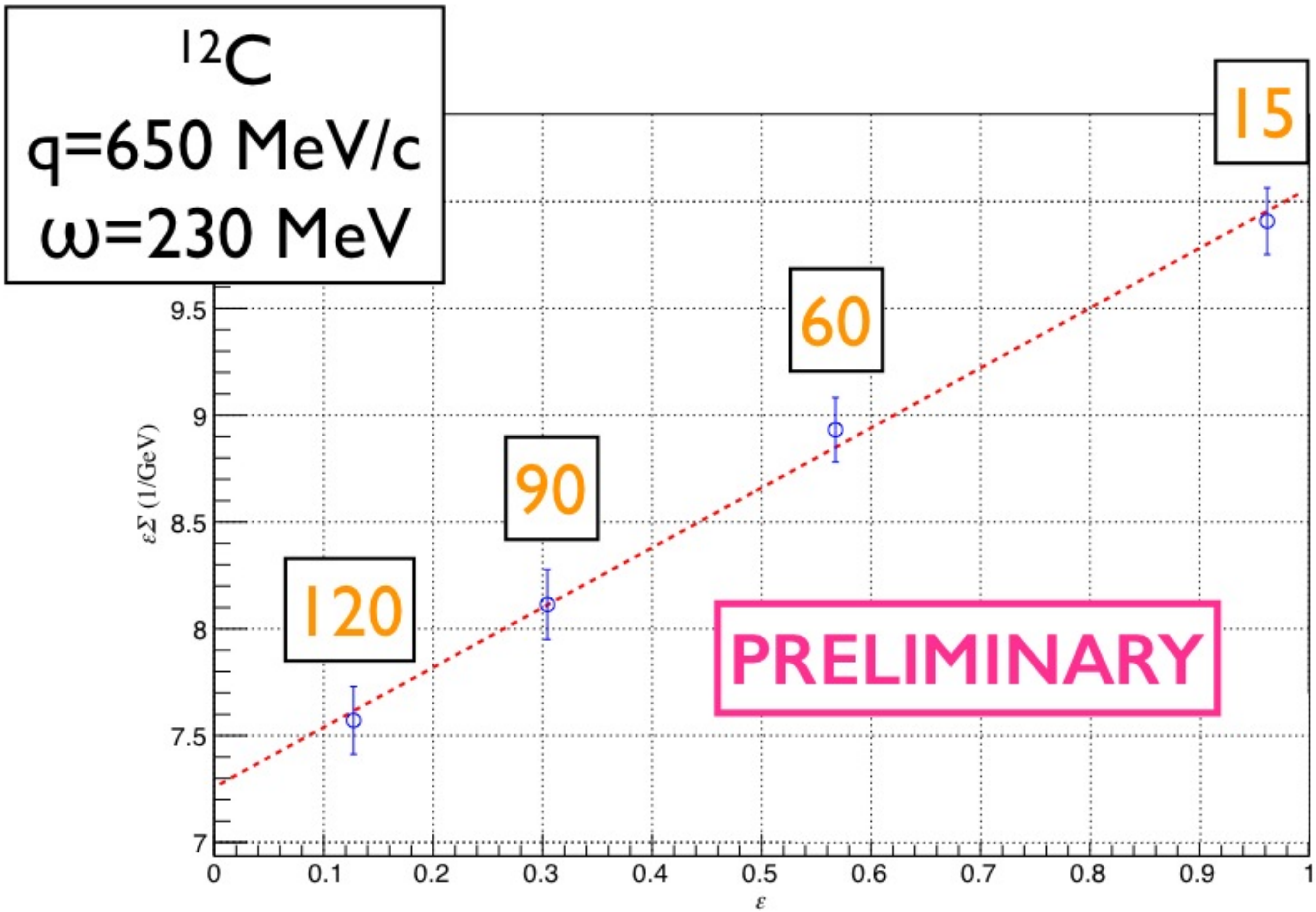
$$\varepsilon = \left[1 + \frac{2\mathbf{q}^2}{Q^2} \tan^2(\theta/2)\right]^{-1}$$



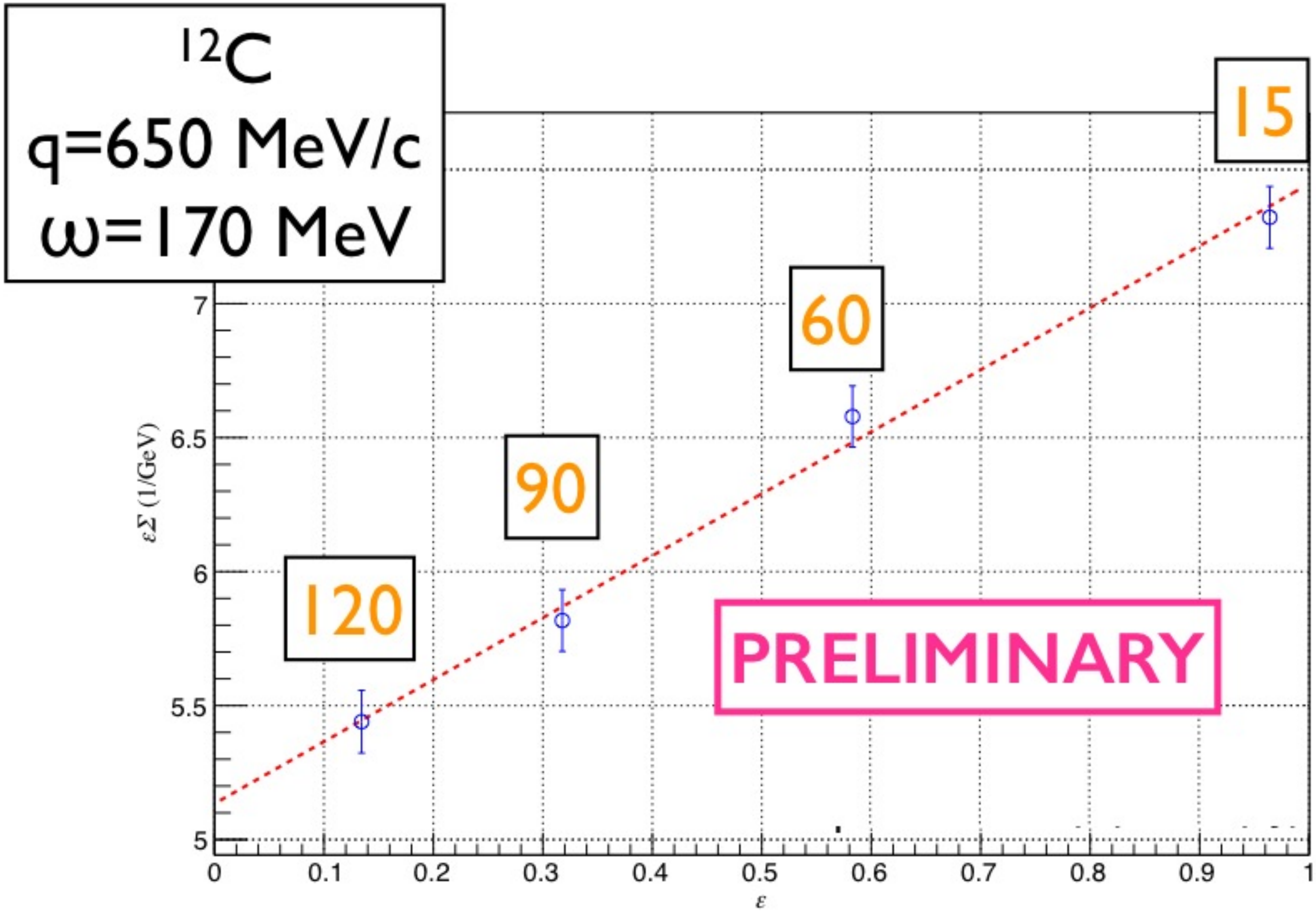
$$\varepsilon R = \varepsilon \frac{Q^4}{\mathbf{q}^4} R_L + \frac{Q^2}{2\mathbf{q}^2} R_T$$

Slope Intercept

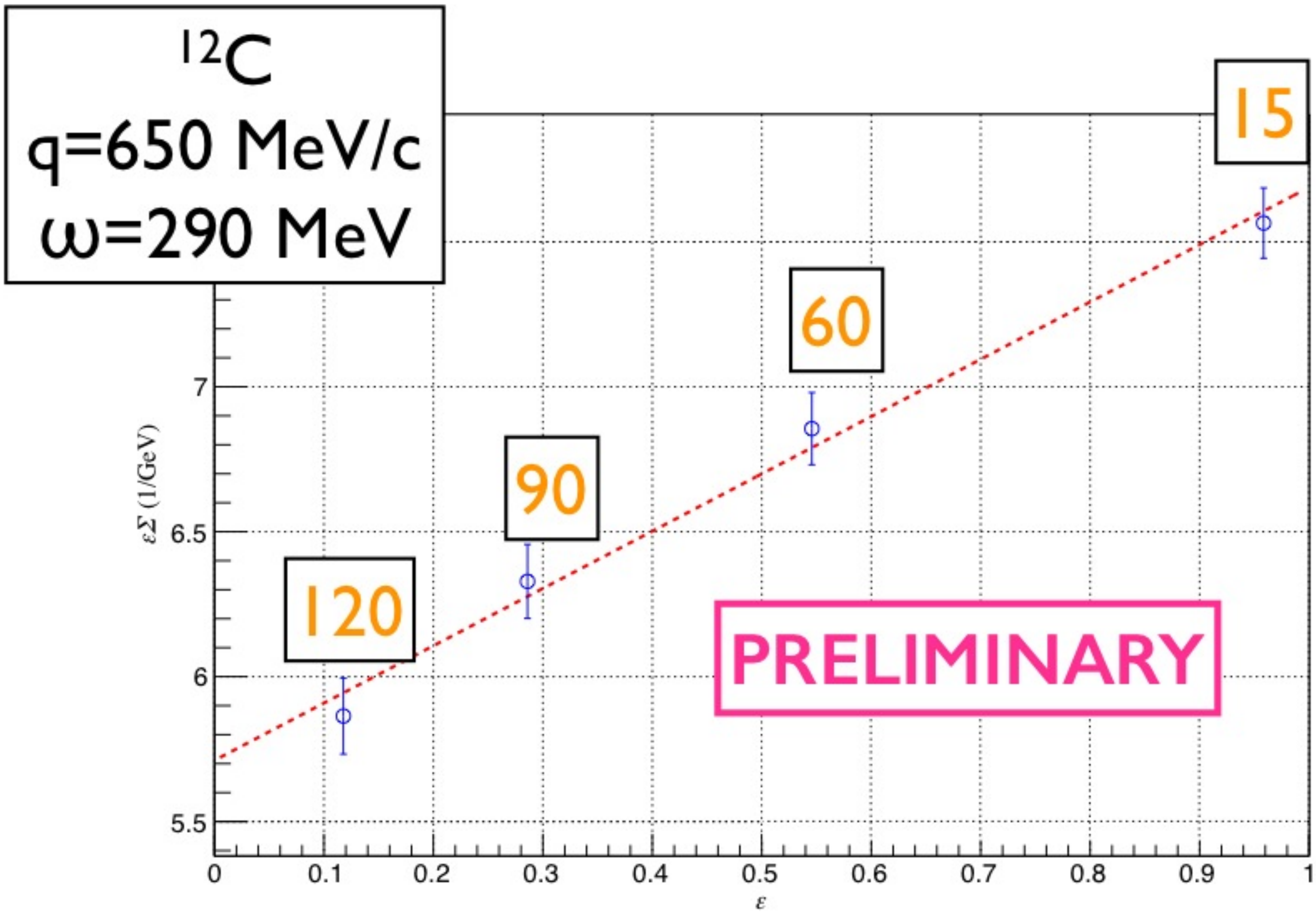
LT Separation



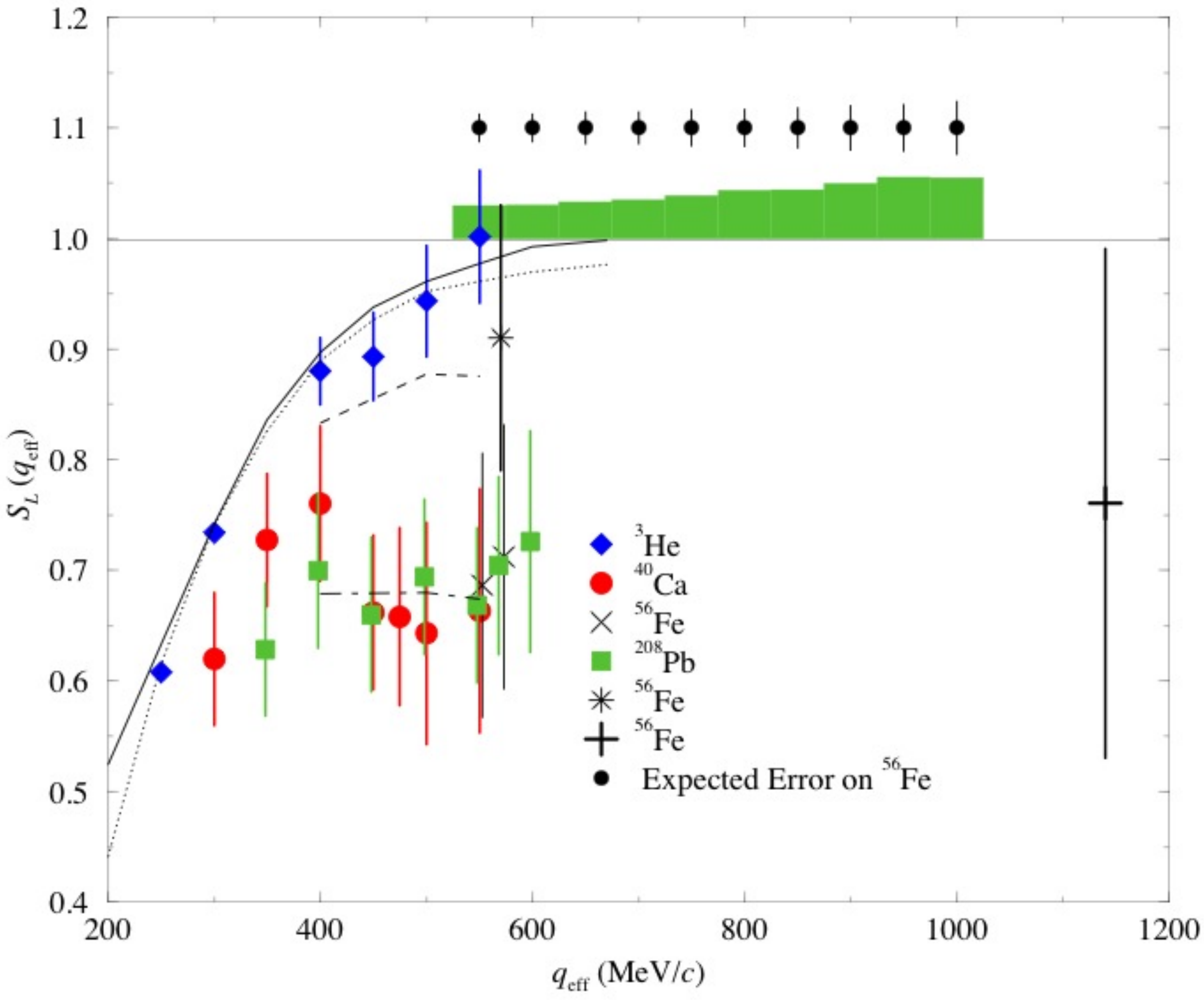
LT Separation



LT Separation



Expected Error



Summary

- Precision measurement of R_L and R_T over the QE scattering range
  - Momentum transfer: 550 MeV/c - 1000 MeV/c
  - On four nuclei: ^4He, ^{12}C, ^{56}Fe and ^{208}Pb
- Analysis in the final stage
  - Checking systematic errors etc
  - Cross check from two independent analyses
- Absolute cross section measurement
  - Cross check with e-C elastic etc
- Help solve the puzzle on Coulomb Sum Rule
  - Learn properties of nucleon inside the nuclear medium