MICHAEL PAOLONE

TEMPLE UNIVERSITY

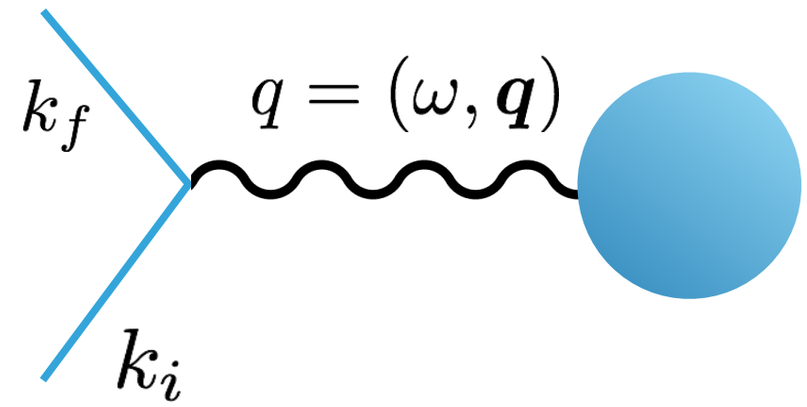
FOR THE E05-110 COLLABORATION.

UPDATE OF EXPERIMENT E05-110: MEASUREMENT OF QUASI-ELASTIC TRANSVERSE AND LONGITUDINAL RESPONSE FUNCTIONS IN THE RANGE $0.55 < |q| < 1.0\ GeV/c$

OUTLINE

- Experimental motivation
- Experimental procedure
- Recent developments
- Remaining work

COULOMB SUM RULE



Inclusive electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

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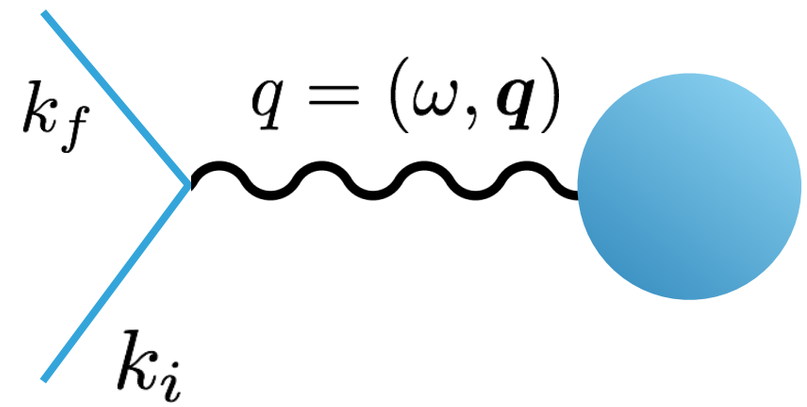

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Scattering response due to **charge** properties

Scattering response due to **magnetic** properties

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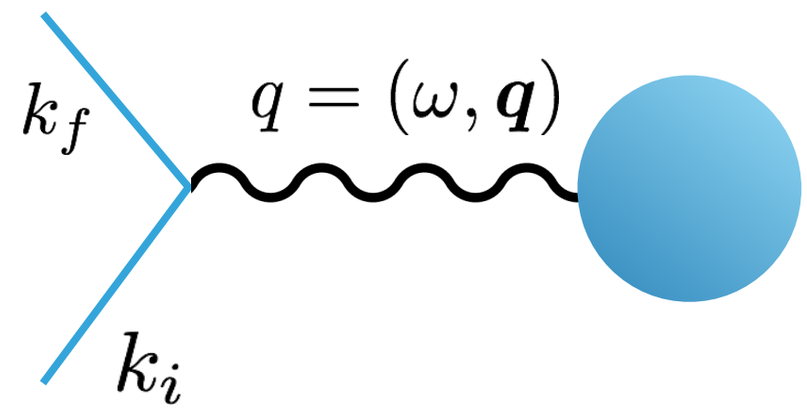

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$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

If one integrates the charge response divided by the total charge form factor over all available virtual photon energies, naively one might expect the integral to go to unity.

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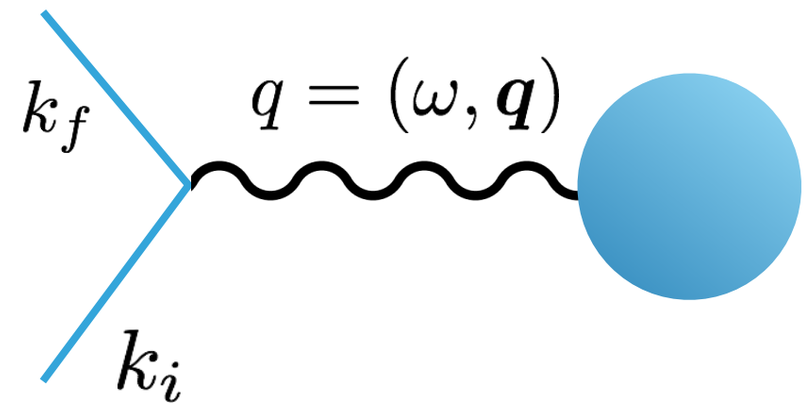

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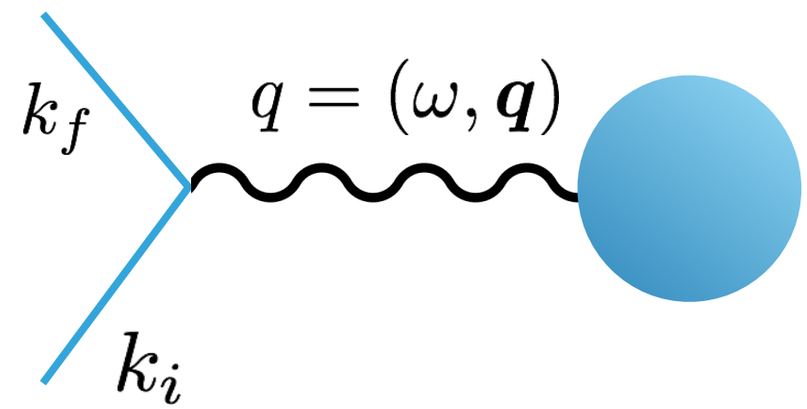

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At large |q| >> $2k_f$, S_L should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!

*Short range correlations will also quench S_L, but only by < 10%

COULOMB SUM RULE

PRL **116,** 032701 (2016) PHYSICAL REVIEW LETTERS week ending 22 JANUARY 2016

Relativistic and Nuclear Medium Effects on the Coulomb Sum Rule

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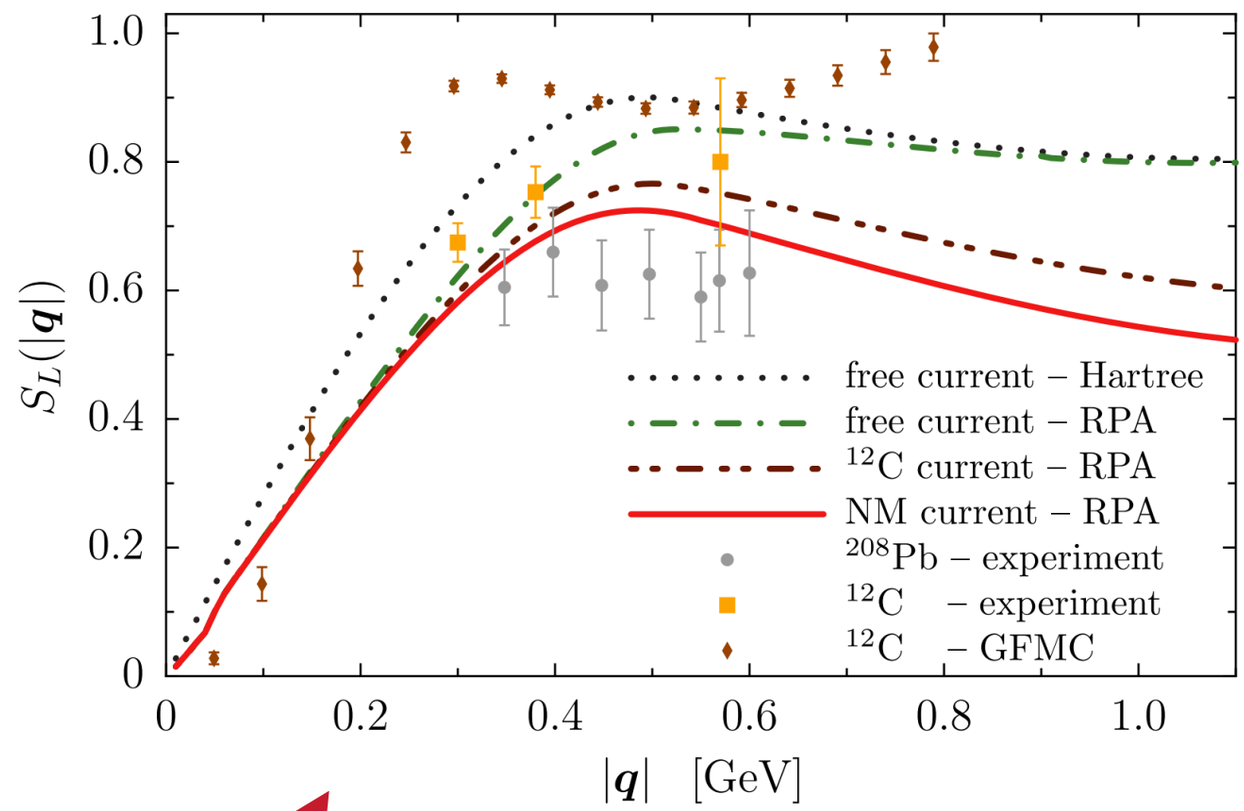
[2]*Department of Physics, School of Science, Tokai University, Hiratsuka-shi, Kanagawa 259-1292, Japan*
[3]*CSSM and ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide South Australia 5005, Australia*
(Received 23 June 2015; published 19 January 2016)

In light of the forthcoming high precision quasielastic electron scattering data from Jefferson Lab, it is timely for the various approaches to nuclear structure to make robust predictions for the associated response functions. With this in mind, we focus here on the longitudinal response function and the corresponding Coulomb sum rule for isospin-symmetric nuclear matter at various baryon densities. Using a quantum field-theoretic quark-level approach which preserves the symmetries of quantum chromodynamics, as well as exhibiting dynamical chiral symmetry breaking and quark confinement, we find a dramatic quenching of the Coulomb sum rule for momentum transfers $|q| \gtrsim 0.5$ GeV. The main driver of this effect lies in changes to the proton Dirac form factor induced by the nuclear medium. Such a dramatic quenching of the Coulomb sum rule was not seen in a recent quantum Monte Carlo calculation for carbon, suggesting that the Jefferson Lab data may well shed new light on the explicit role of QCD in nuclei.

DOI: 10.1103/PhysRevLett.116.032701



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Continuing theoretical interest!

At small |q| , S_L will deviate from unity
due to long range nuclear effects, Pauli blocking.
(directly calculable, well understood).

At large |q| >> $2k_f$, S_L should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!

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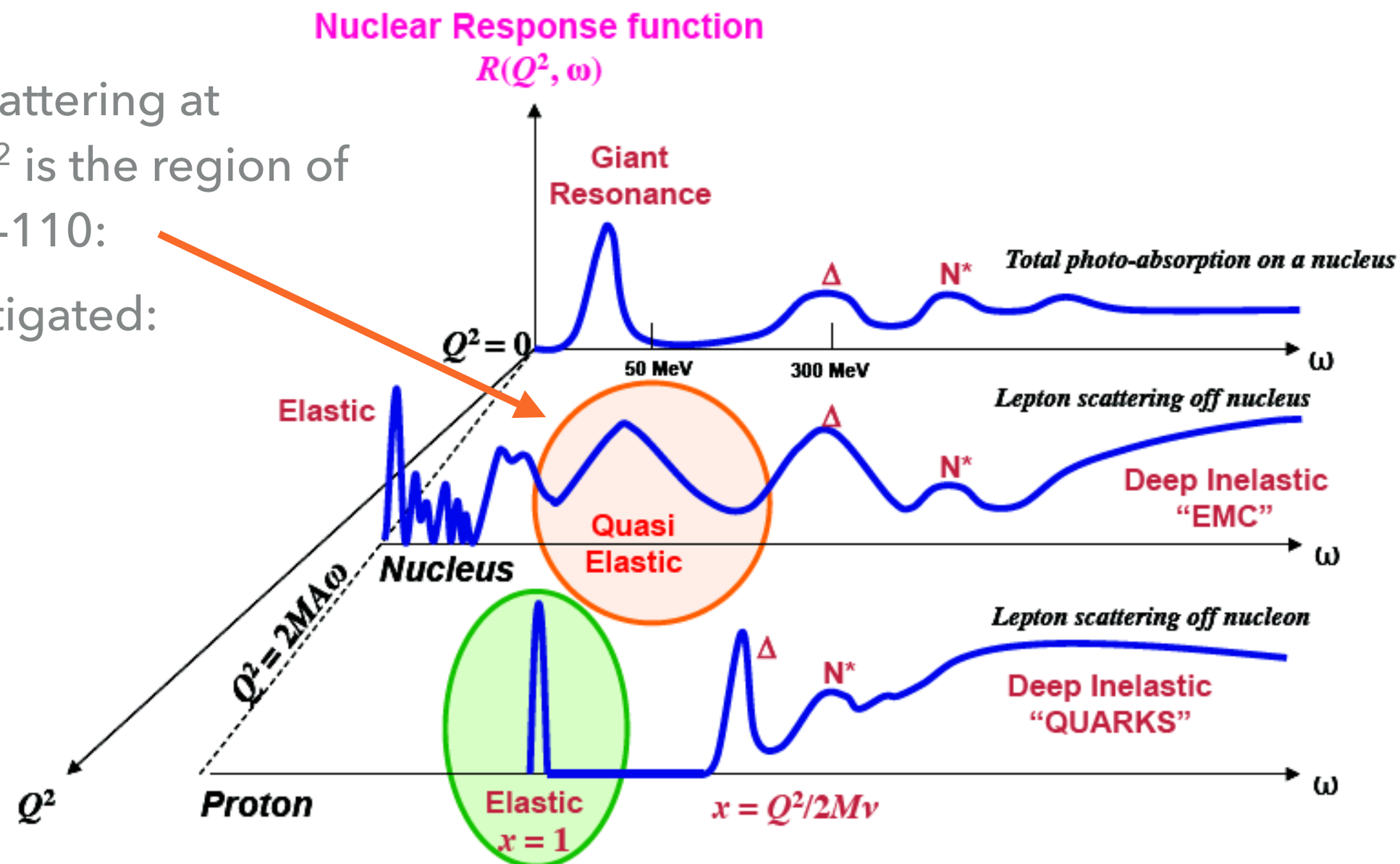
QUASI-ELASTIC SCATTERING

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

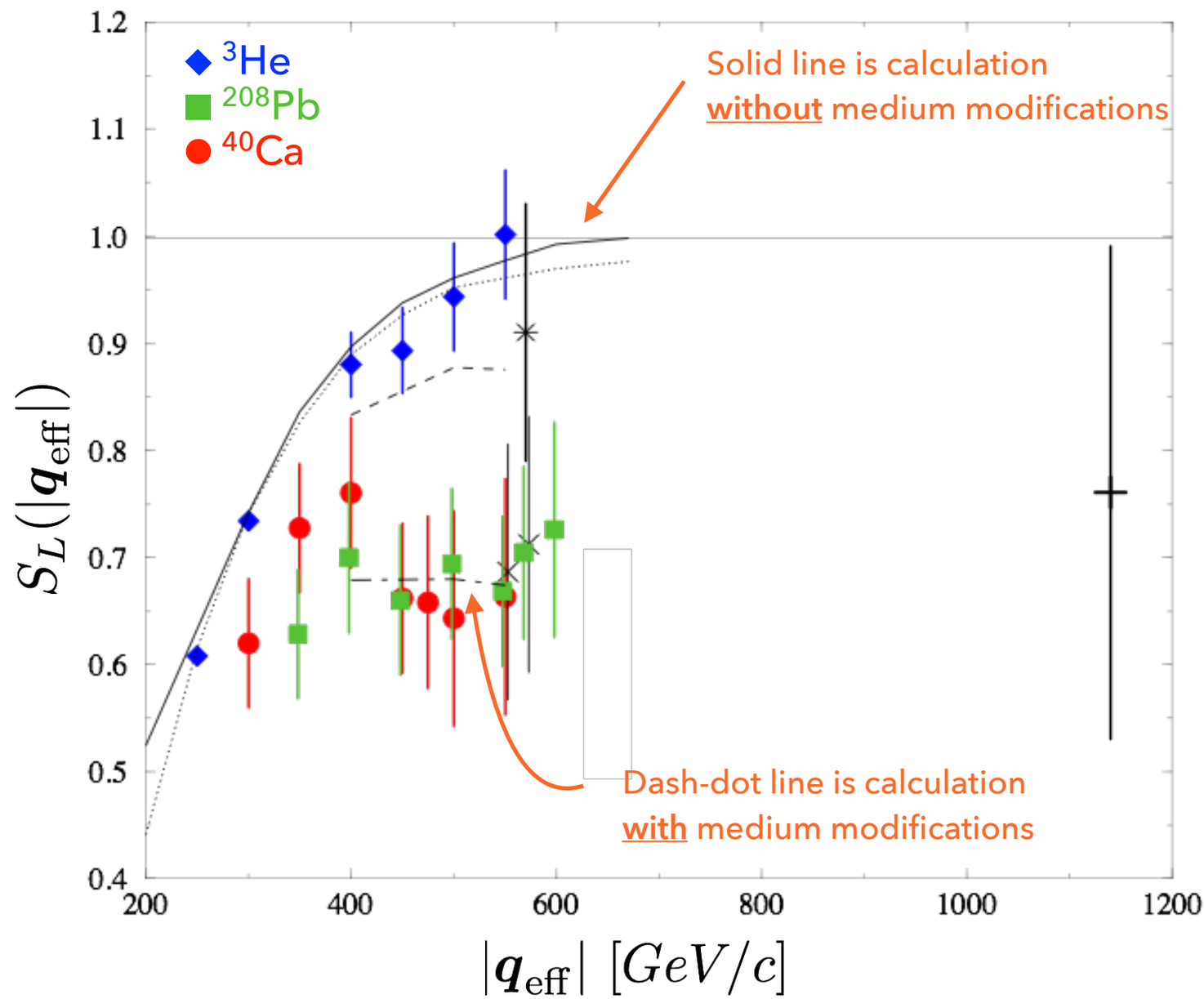
We want to integrate above the coherent elastic peak:
Quasi-elastic is "elastic" scattering on constituent nucleons inside nucleus.

- Quasi-elastic scattering at intermediate Q^2 is the region of interest for E05-110:
  - Nuclei investigated:
    - ^{4}He
    - ^{12}C
    - ^{56}Fe
    - ^{256}Pb



PUBLISHED EXPERIMENTAL RESULTS

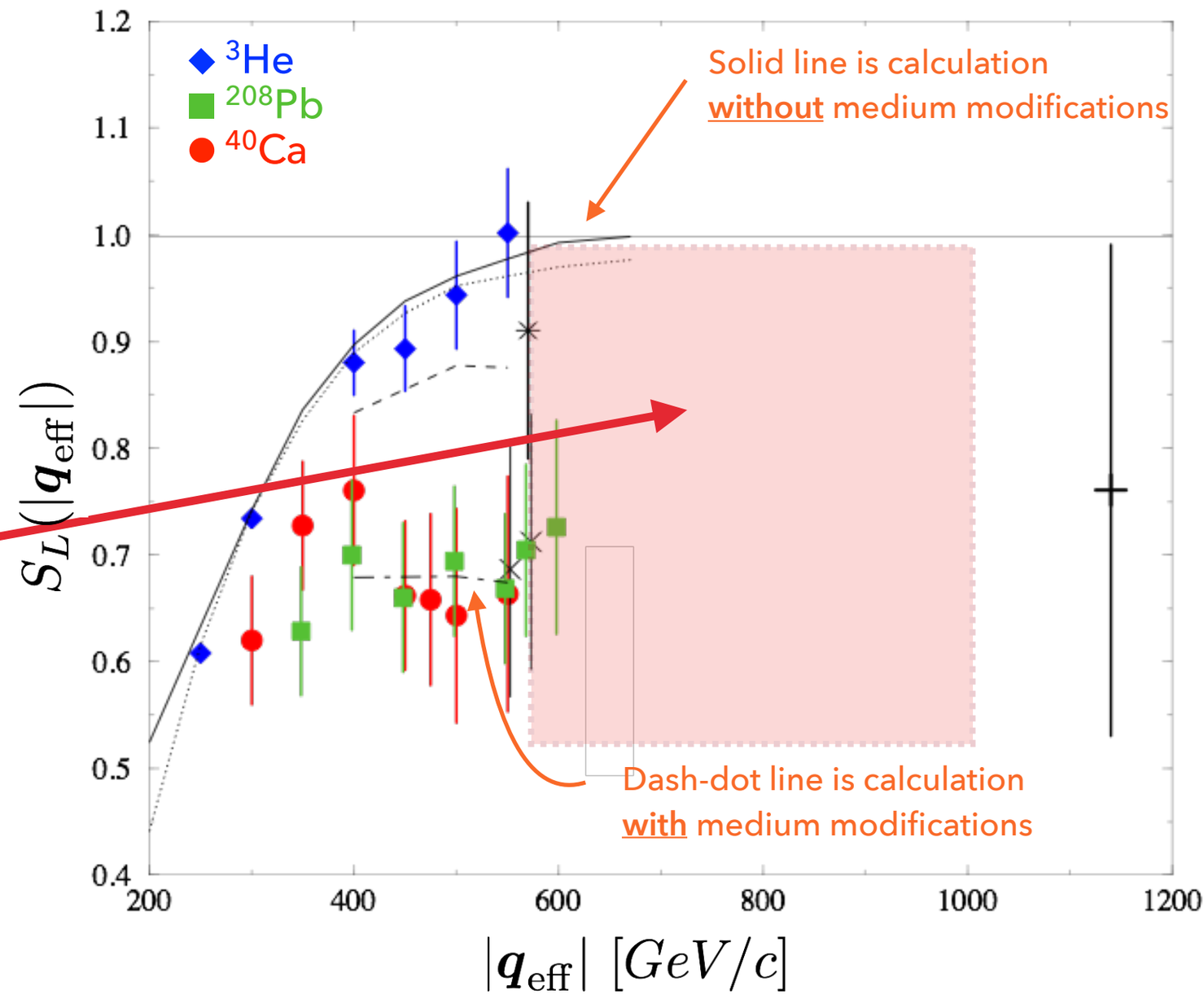
- First group of experiments from Saclay, SLAC, and Bates show a quenching of S_L consistent with medium modified form-factors.



$|q_{eff}|$ is $|q|$ corrected for a nuclei dependent mean coulomb potential. Methodology agreed on by Andrea Aste, Steve Wallace and John Tjon.

PUBLISHED EXPERIMENTAL RESULTS

- First group of experiments from Saclay, SLAC, and Bates show a quenching of S_L consistent with medium modified form-factors.
- Very little data above |q| of 600 MeV/c, where the cleanest signal of medium effects should exist!
  - Difficult to extract without large angle and energy coverage.



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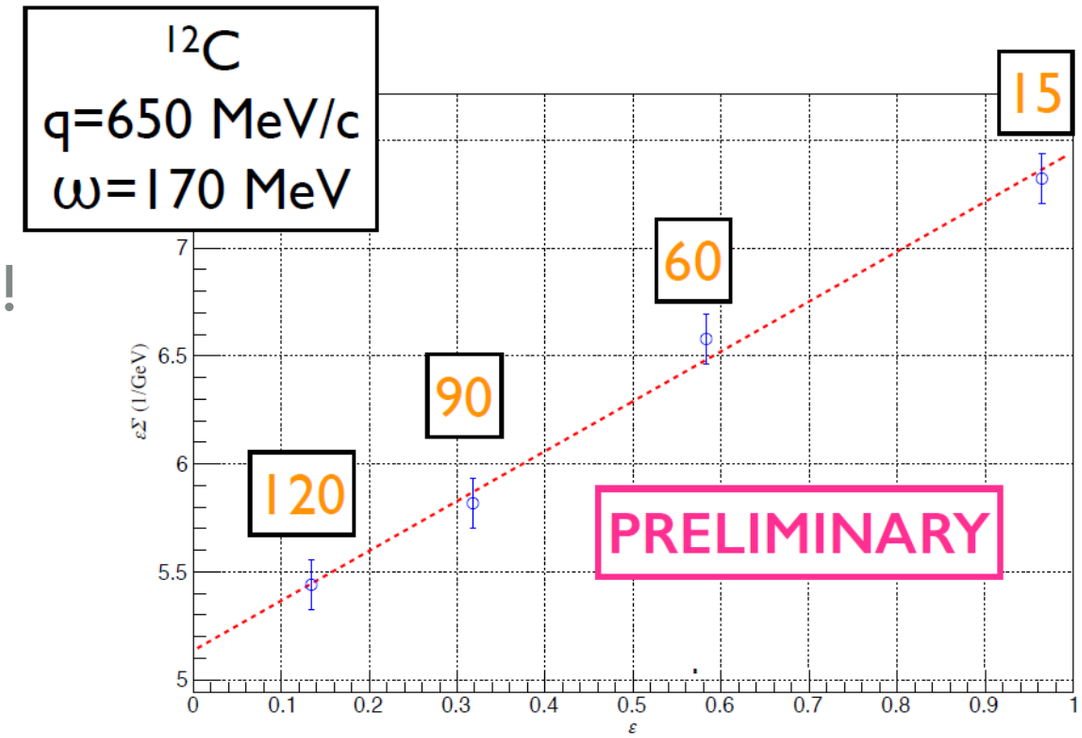
EXPERIMENTAL DESIGN

- Need R_L ⟶ Use Rosenbluth separation!

$$\text{Slope} = \frac{Q^4}{\vec{q}^4} R_L$$

$$\text{Intercept} = \frac{Q^2}{2\vec{q}^2} R_T$$

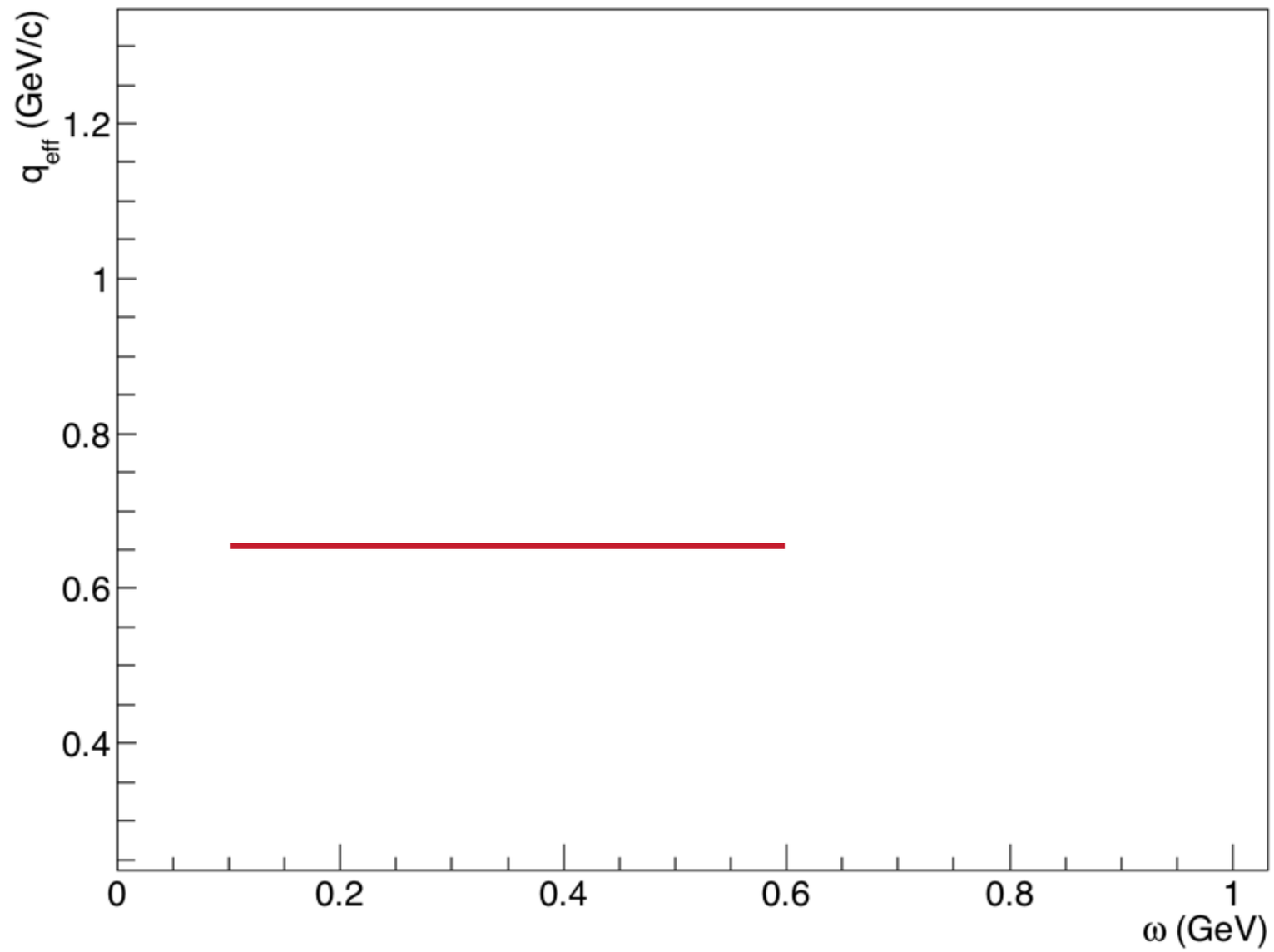


  - Experiment run at 4 angles per target: 15, 60, 90, 120 degs. Very large lever arm for precise calculation of R_L!

- Need data for each angle at a constant |q| over an ω range starting above the elastic peak up to |q|.
  - When running a single arm experiment with fixed beam energy and scattering angle, |q| is NOT constant over your momentum acceptance.
    - Need to take data at varying beam energies, and "map-out" |q| and ω space.

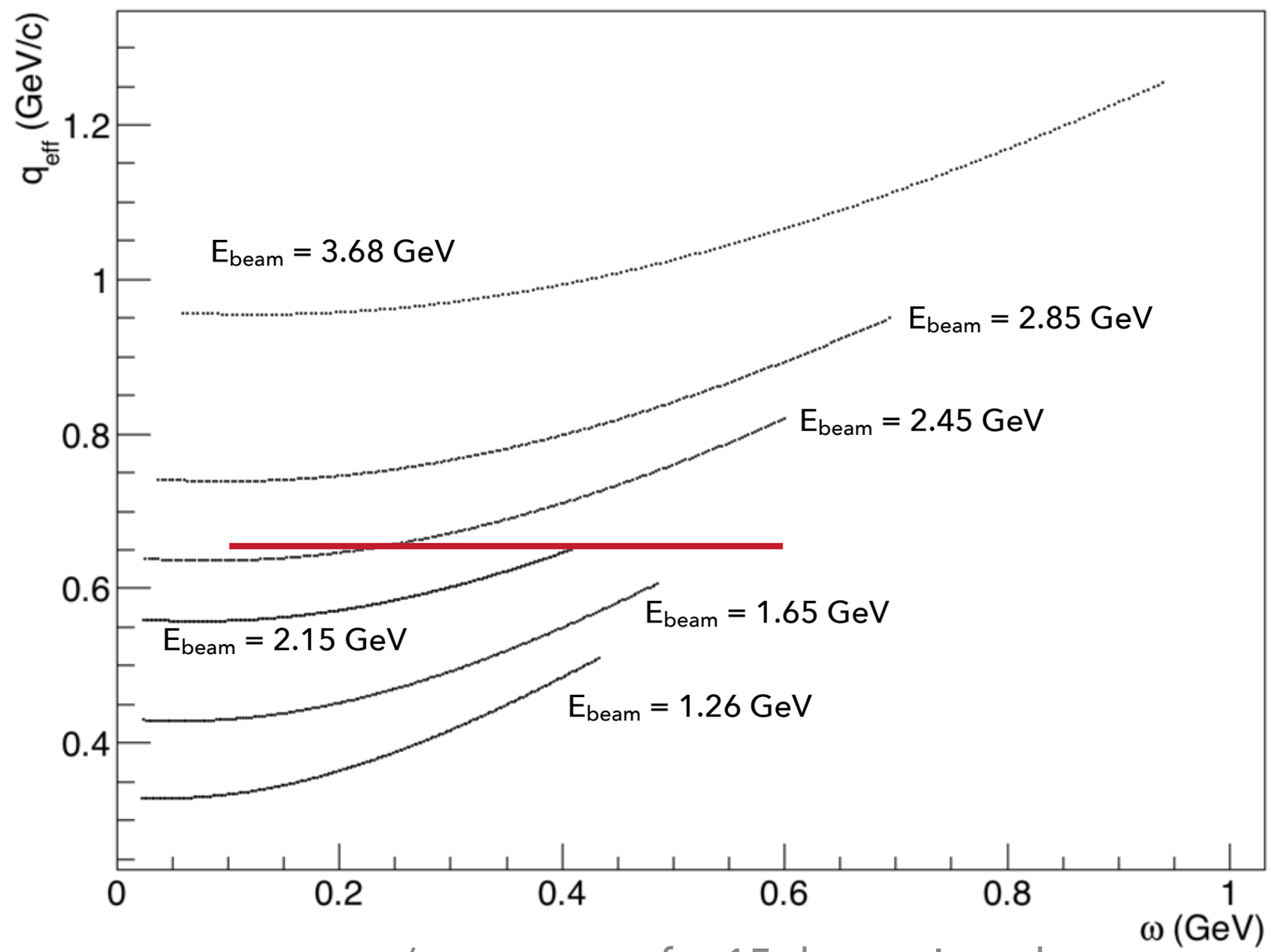
EXPERIMENTAL DESIGN

- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c



EXPERIMENTAL DESIGN

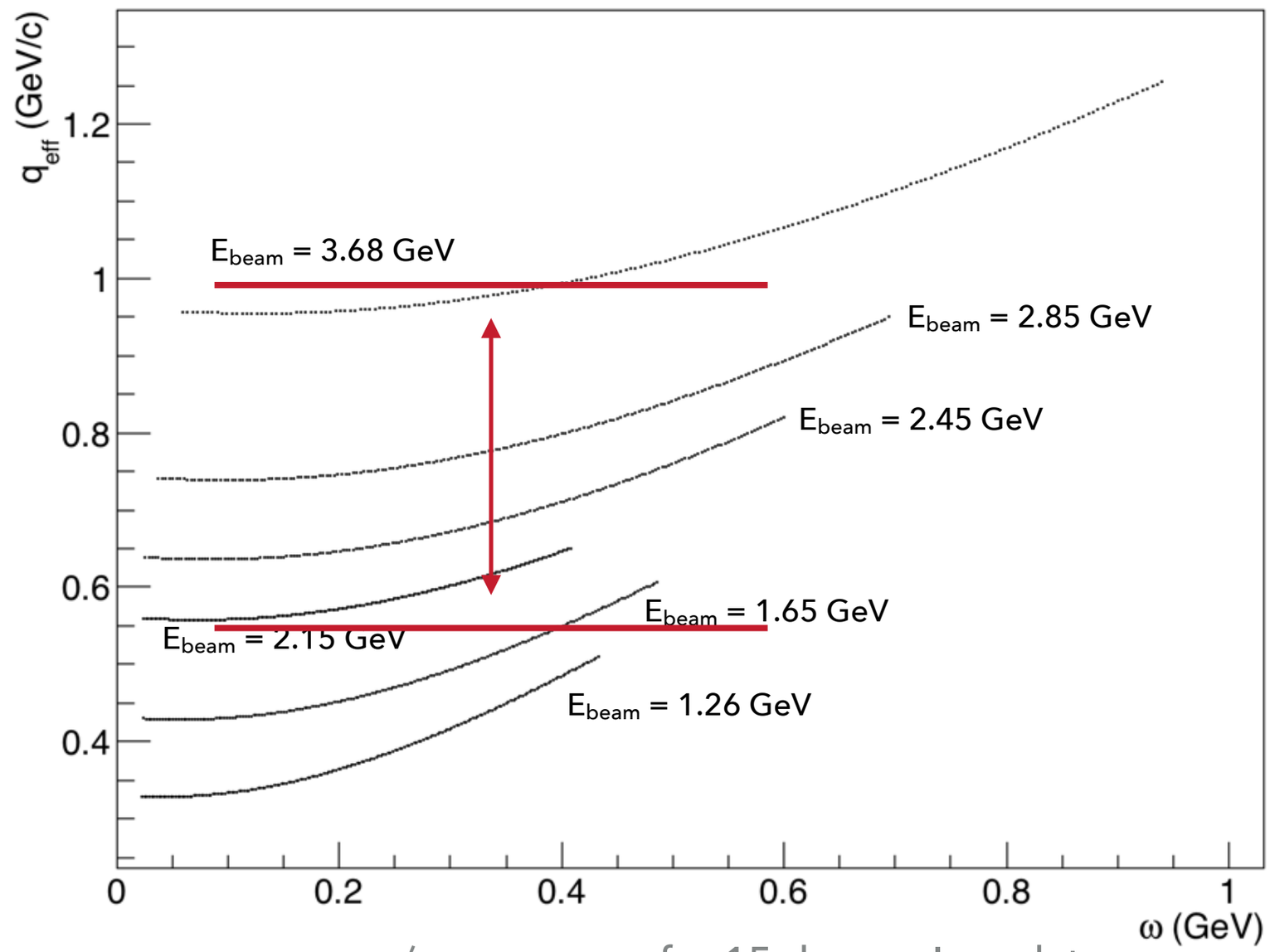
- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.



q / ω coverage for 15 degree Iron data

EXPERIMENTAL DESIGN

- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.
  - |q| can be selected between 550 and 1000 MeV/c



q / ω coverage for 15 degree Iron data

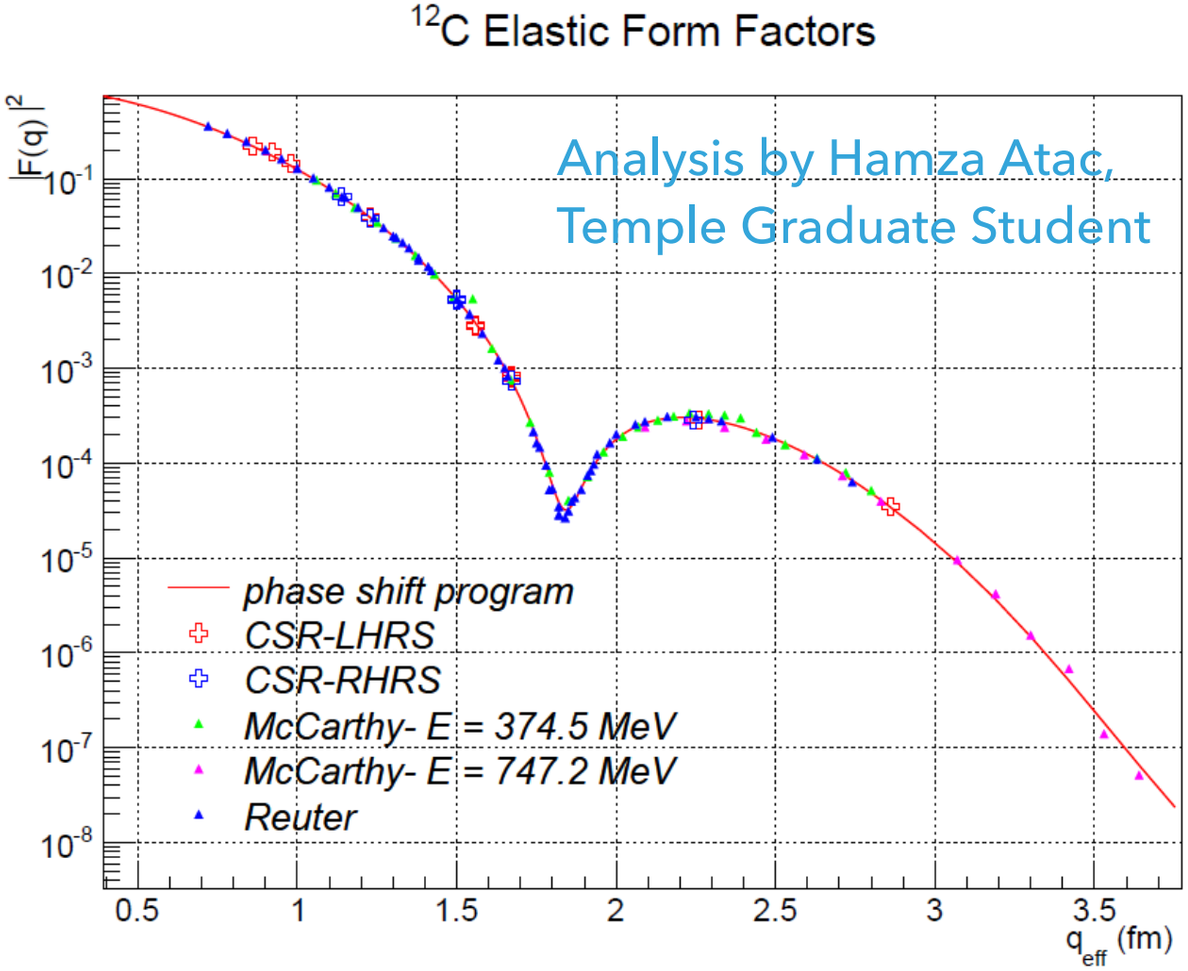
Repeat this "mapping" for 60, 90, and 120 degree spectrometer central angles.

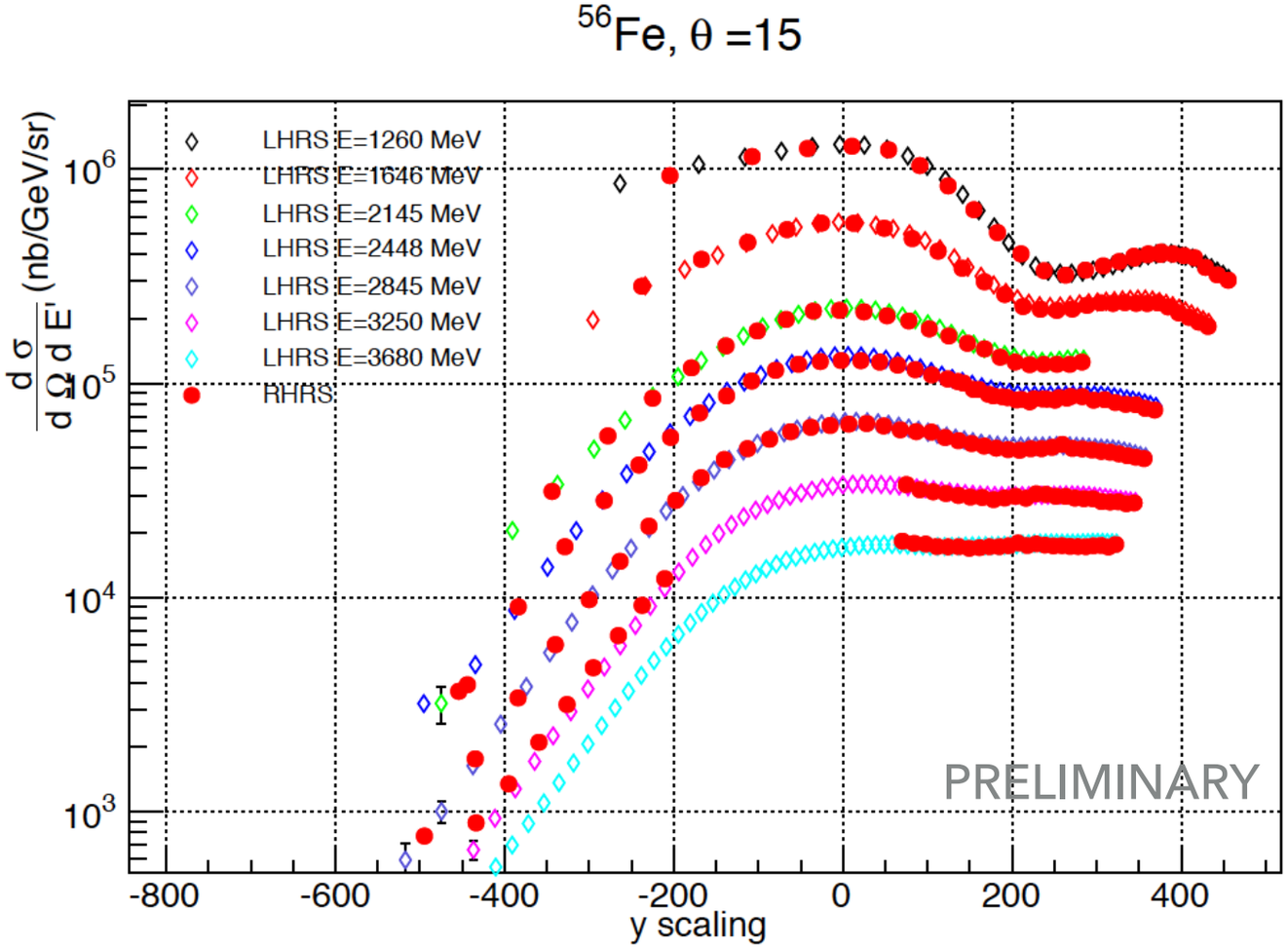
EXPERIMENTAL SPECIFICS

- E05-110:
  - Data taken from October 23rd 2007 to January 16th 2008
  - 4 central angle settings: 15, 60, 90, 120 degs.
  - Many beam energy settings: 0.4 to 4.0 GeV
  - Many central momentum settings: 0.1 to 4.0 GeV
  - LHRS and RHRS independent (redundant) measurements for most settings
  - 4 targets: ^{4}He, ^{12}C, ^{56}Fe, ^{256}Pb.

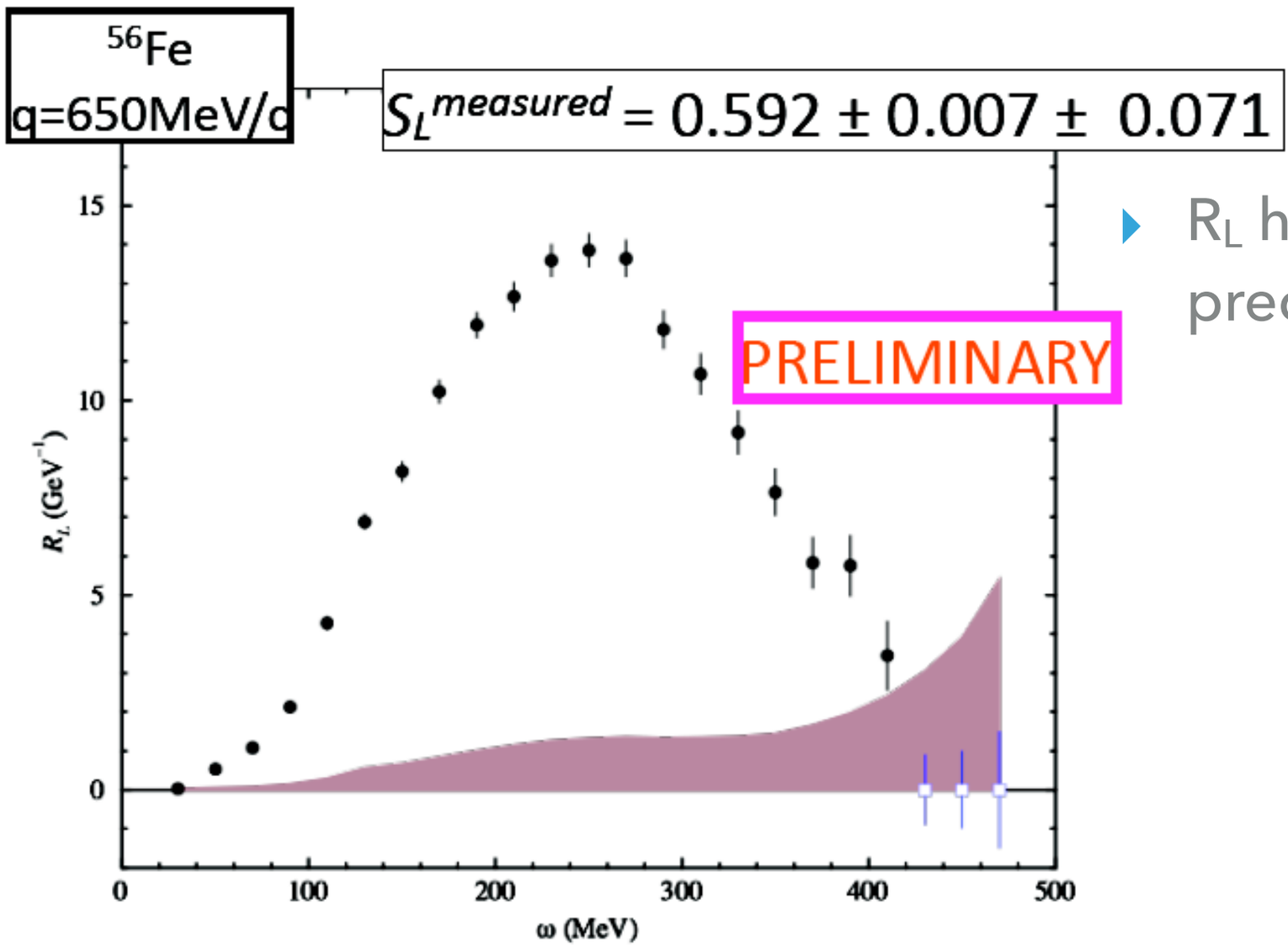
PRELIMINARY RESULTS: LHRS AND RHRS AGREEMENT

- Both LHRS and RHRS agree well :
  - with world data on ^{12}C elastic form factors
  - with each other for ^{56}Fe quasi-elastic cross-section.
- Each spectrometer arm is an independent measurement.
  - Agreement shows a good handle on acceptance and radiative corrections.





PRELIMINARY RESULTS
^{56}FE LONGITUDINAL RESPONSE FUNCTION



- R_L has been calculated with precision at low ω.

Analysis by Dr. Yoomin Oh
PhD Graduate of Seoul National University

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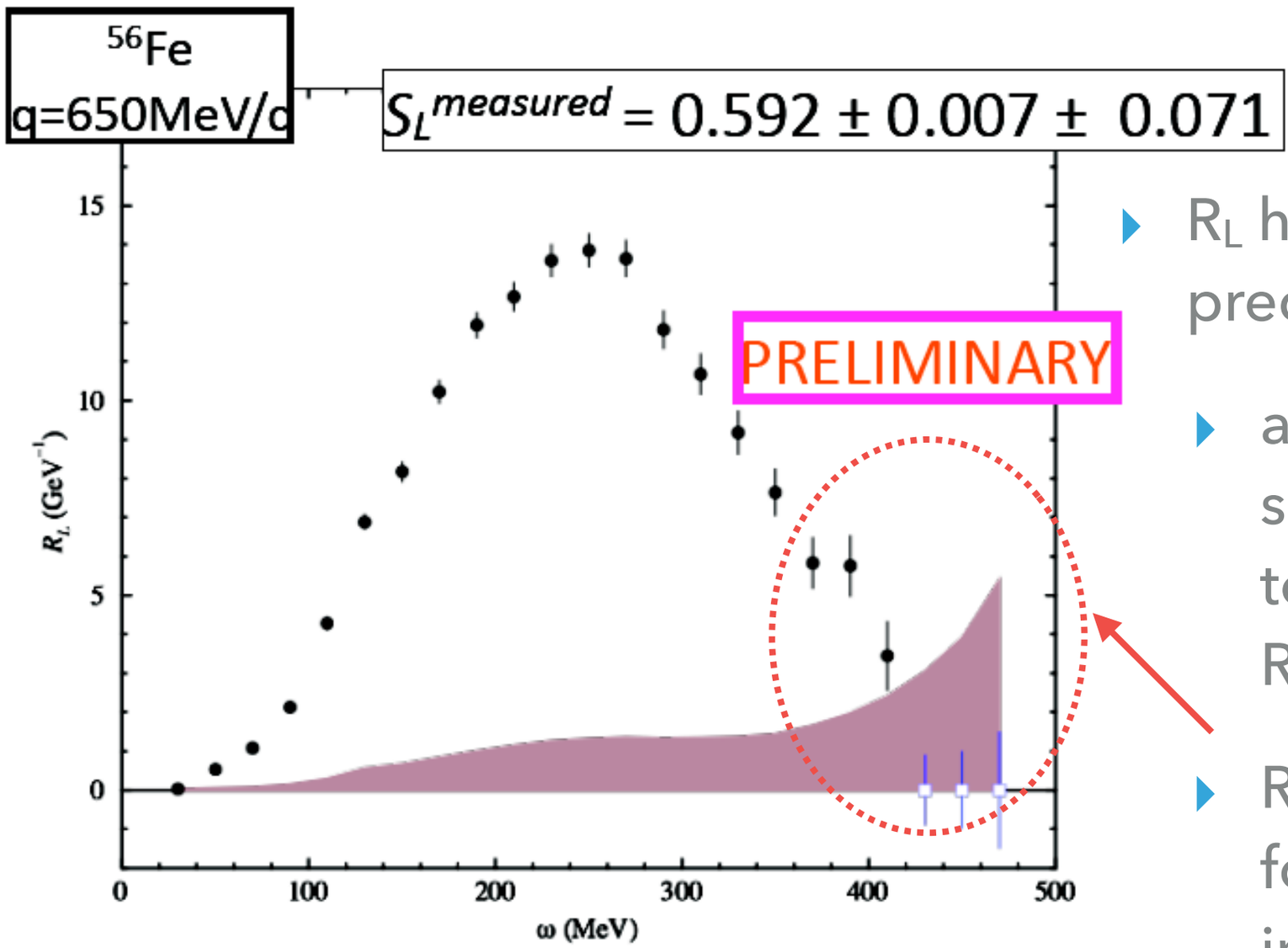

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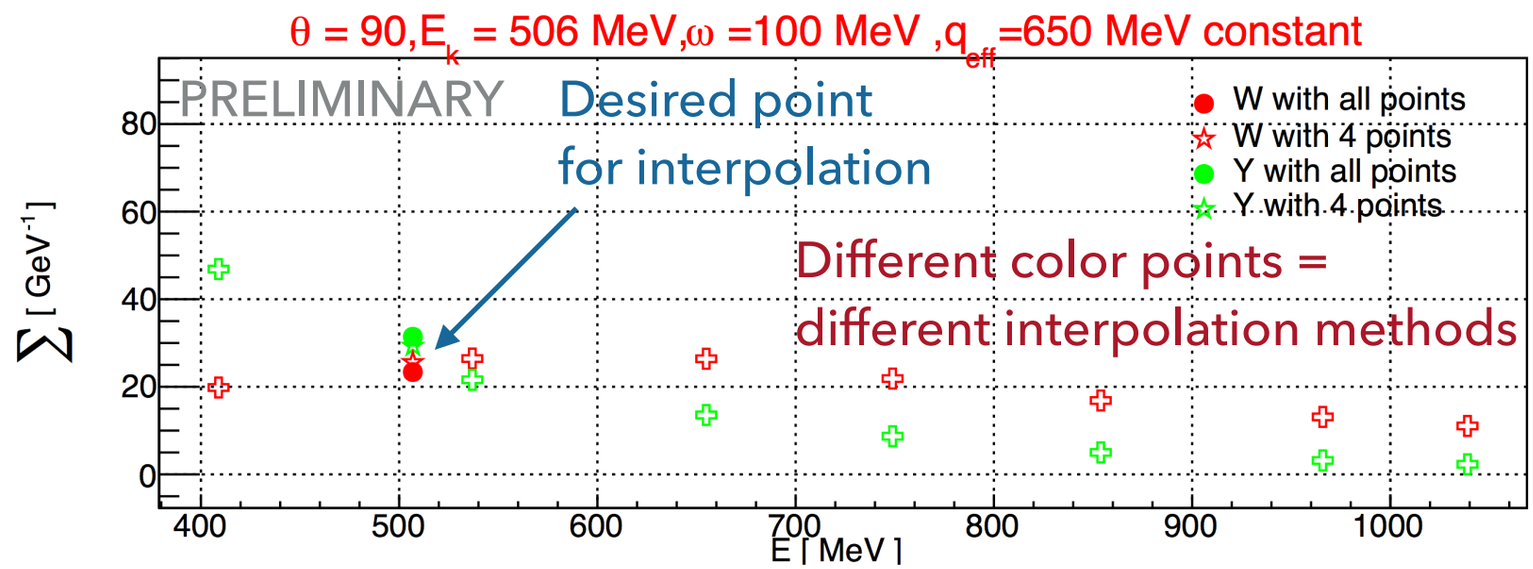
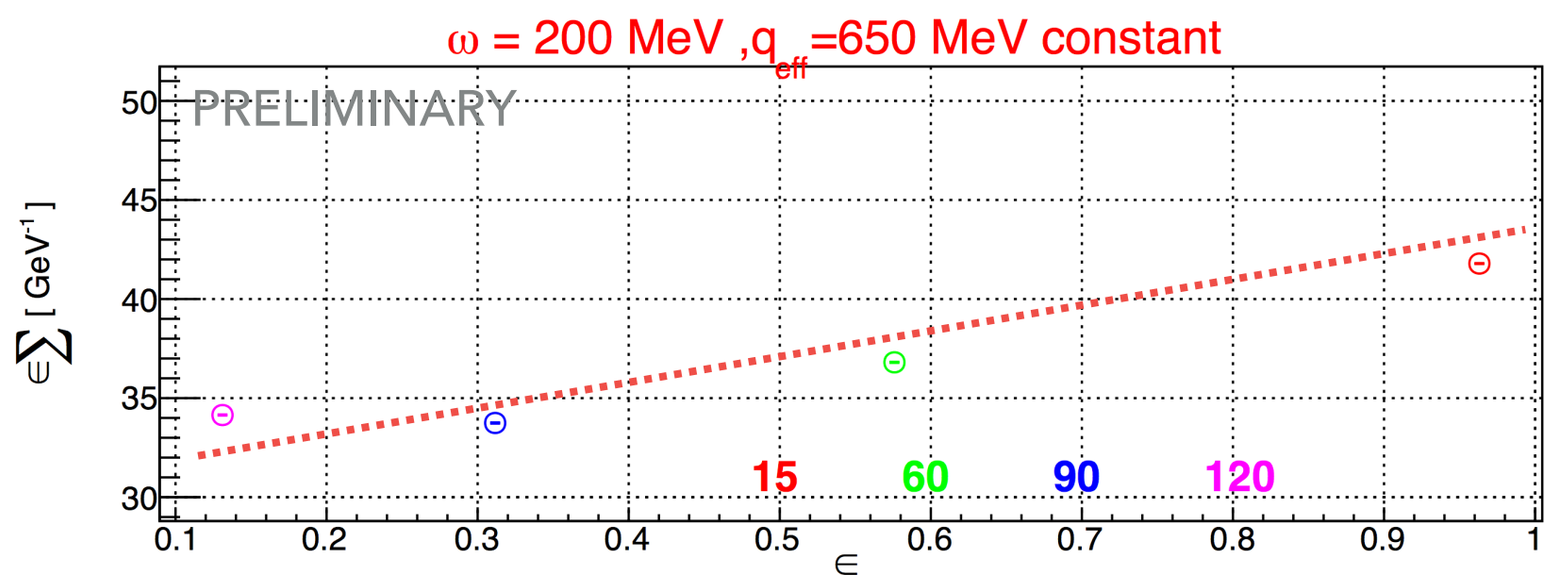
- R_L has been calculated with precision at low ω.
- at larger ω, where R_L becomes small, there is a high sensitivity to the quality of the linear fit for Rosenbluth separation.
- Recent efforts have been focused at systematically investigating these large ω bins.

RECENT DEVELOPMENTS

- Interpolation of |q|
  - Rosenbluth separation can be sensitive to the results of the interpolation*.



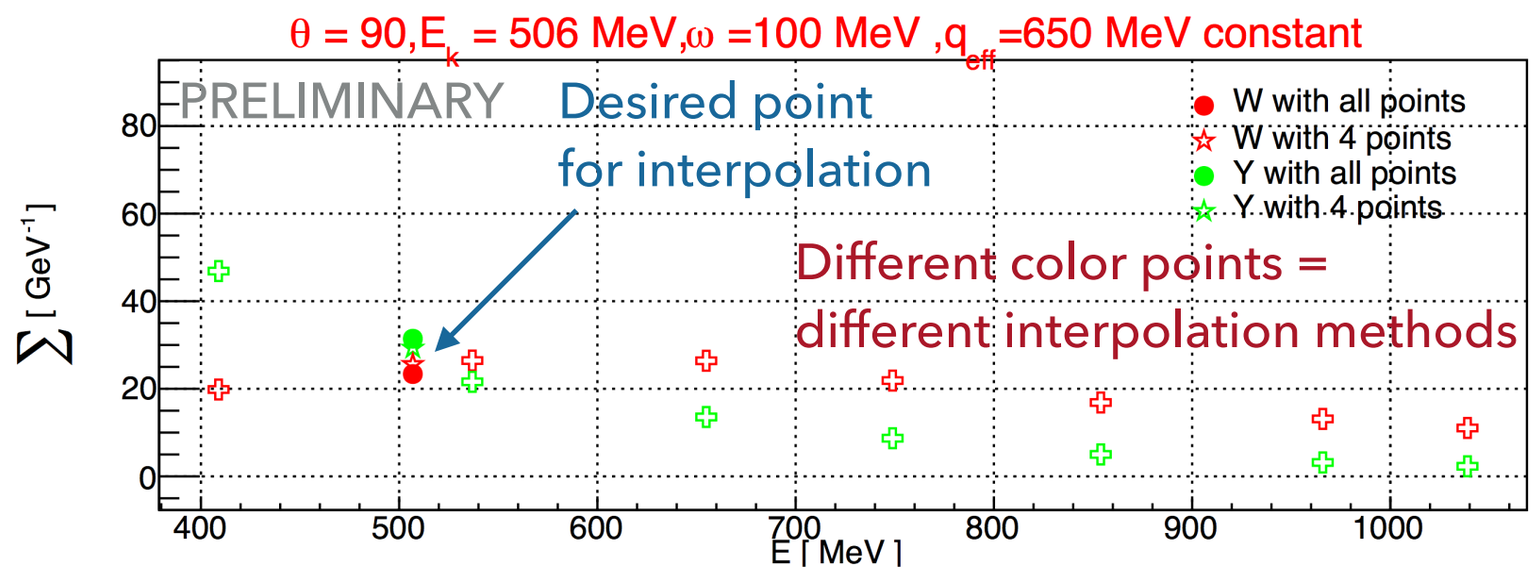


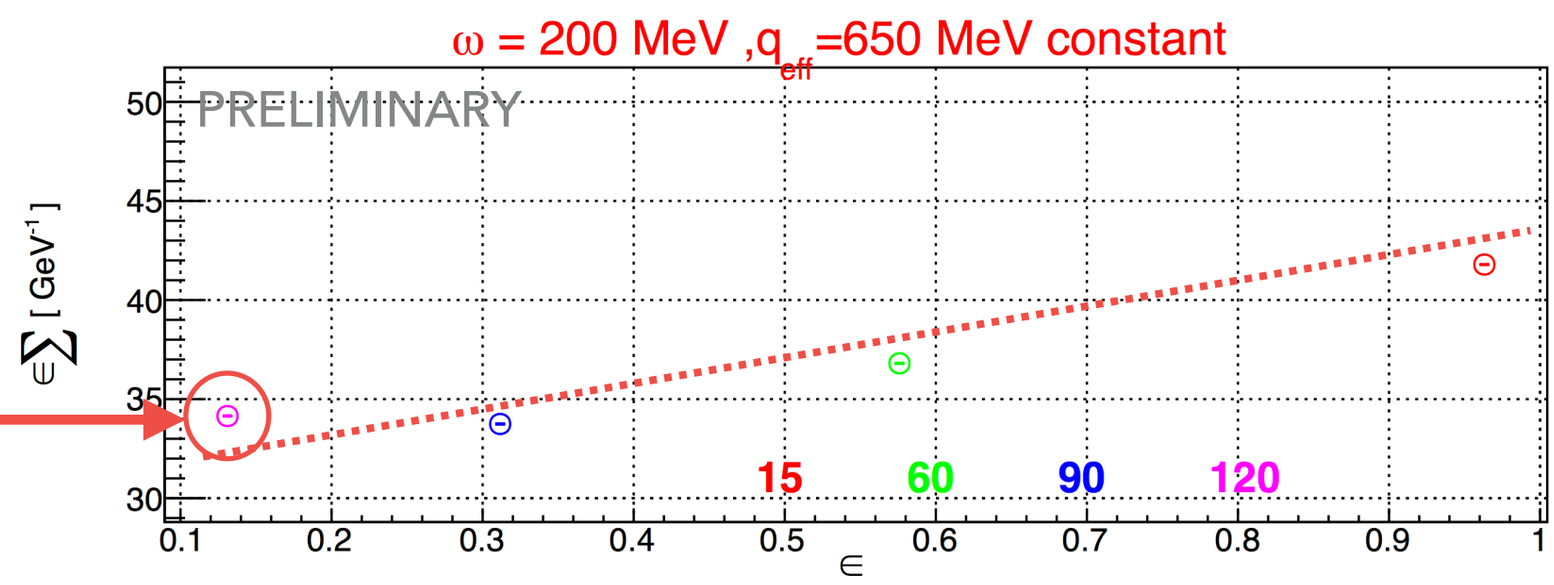
Analysis by Hamza Atac, Temple Graduate Student

Note: The radiative corrections also use interpolation techniques, but are not very sensitive to the method used.

RECENT DEVELOPMENTS

- Interpolation of |q|
  - Rosenbluth separation can be sensitive to the results of the interpolation*.
  - Currently investigating 120 degree data where Rosenbluth looks most non-linear.





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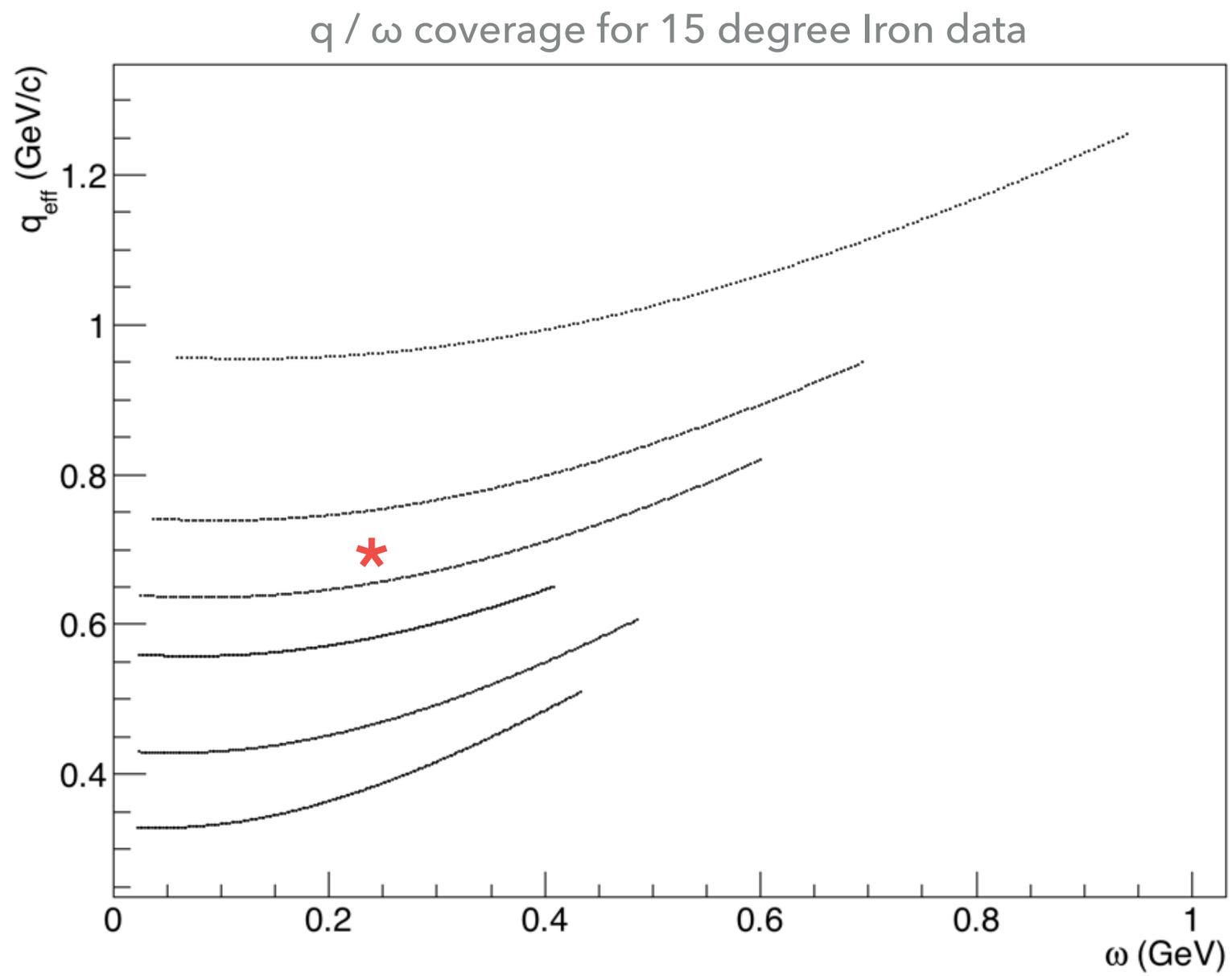

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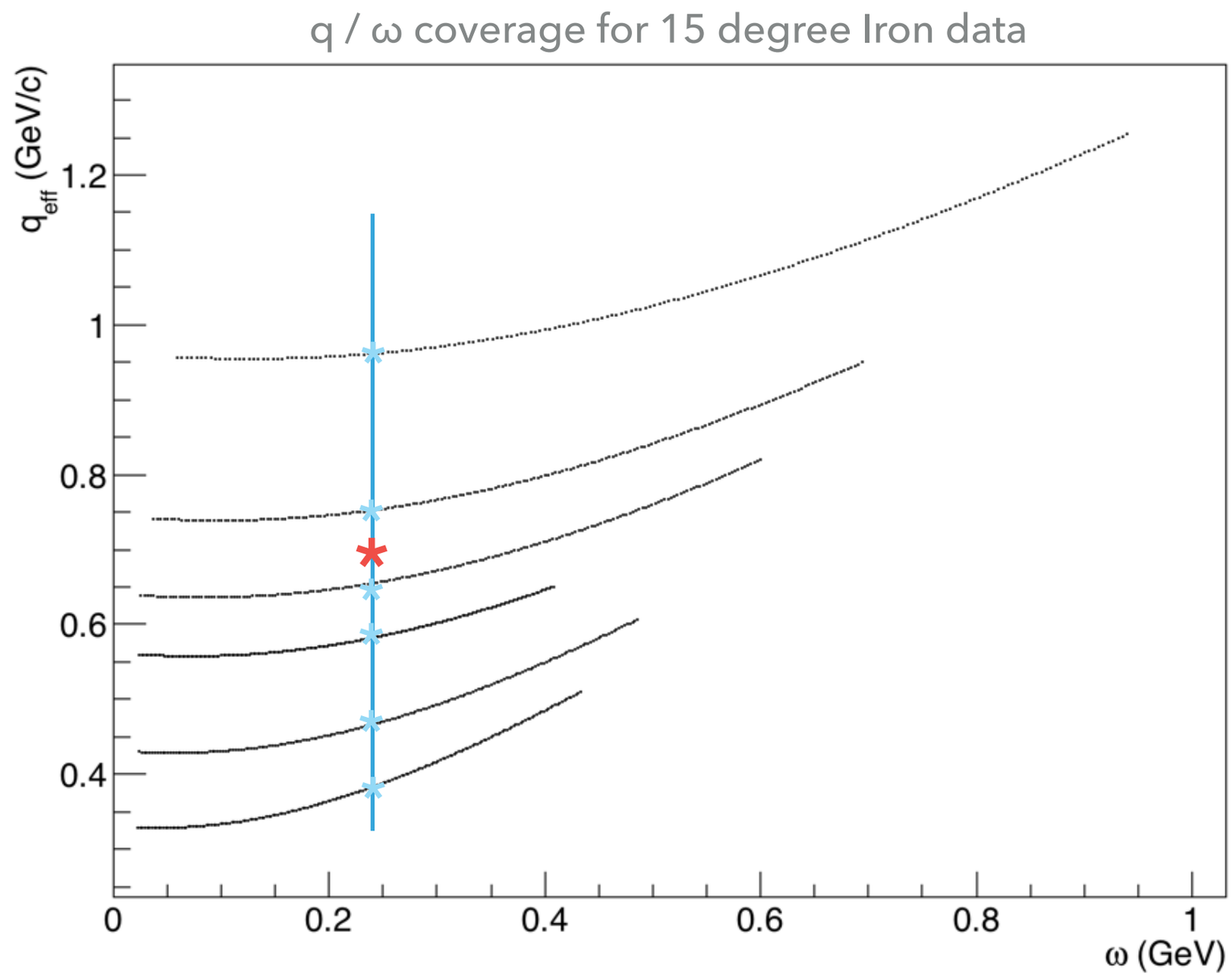
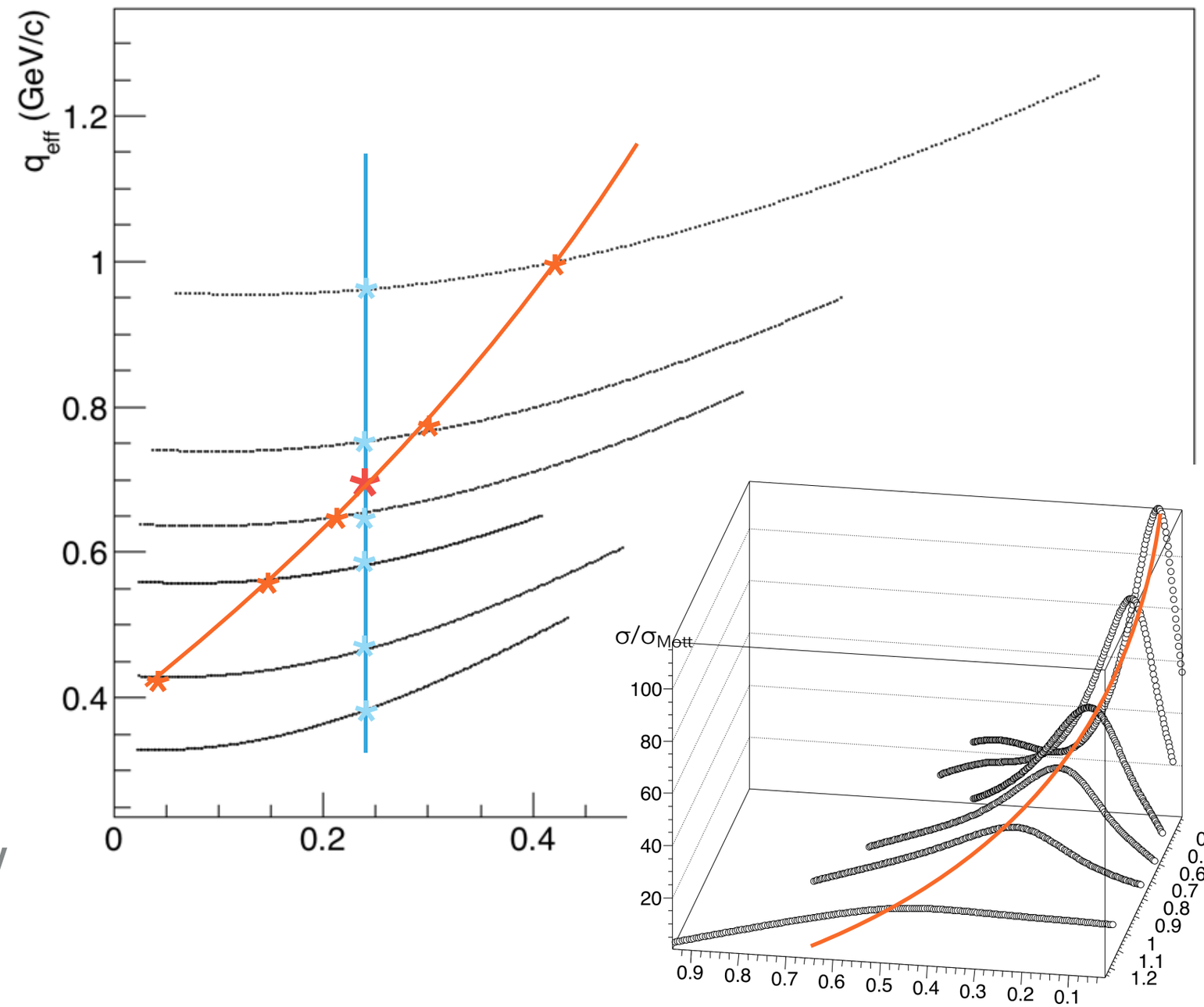
  - Could go along a constant ω line. Not very useful.



RECENT DEVELOPMENTS

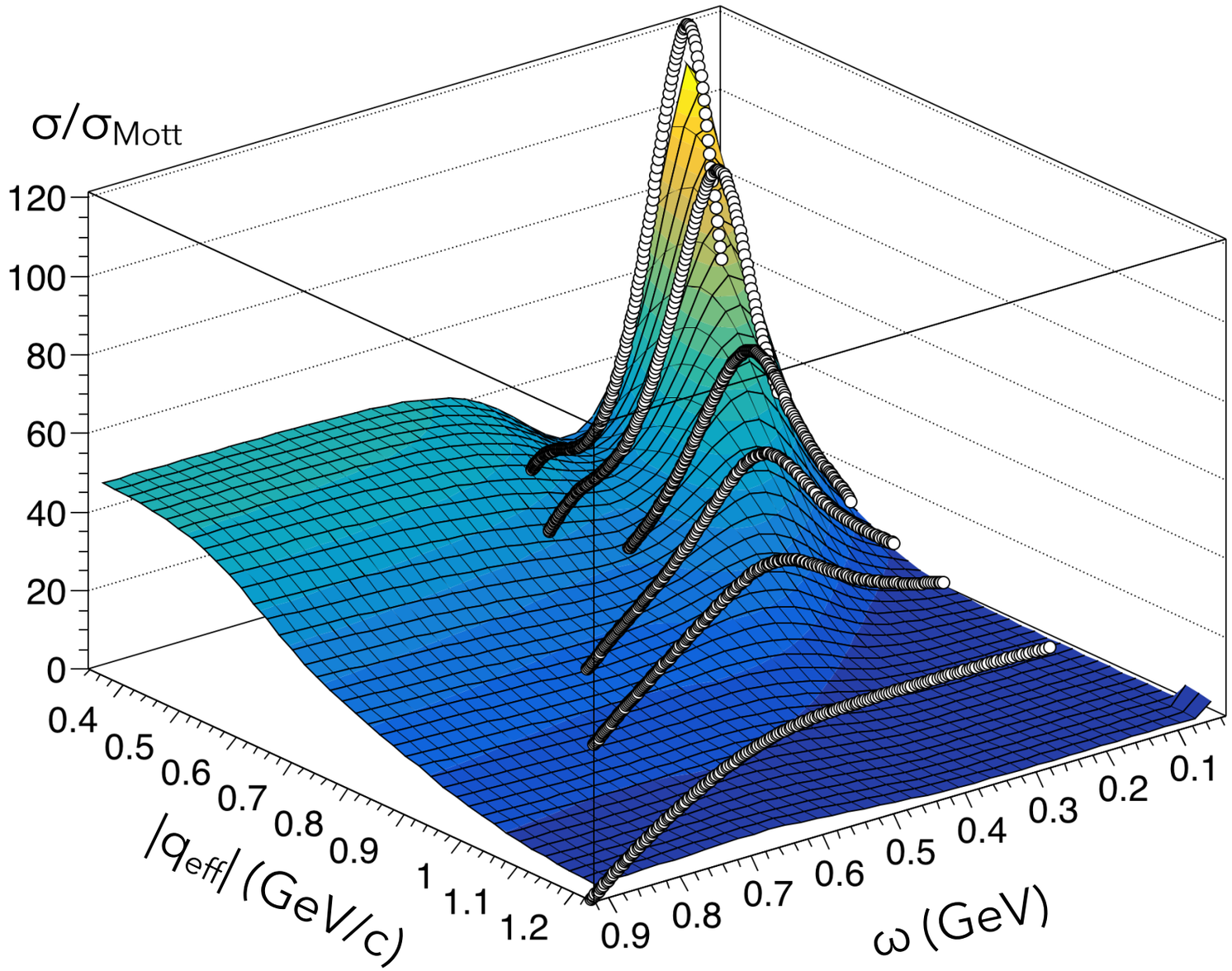
- Interpolation of |q|
  - Could go along a constant ω line. Not very useful.
  - Better: use a constant y line, which will follow the trend of quasi-elastic peak.
  - Alternative: use a constant W line, which should follow the Δ peak.
    - or even a combination of y and W.

q / ω coverage for 15 degree Iron data



RECENT DEVELOPMENTS

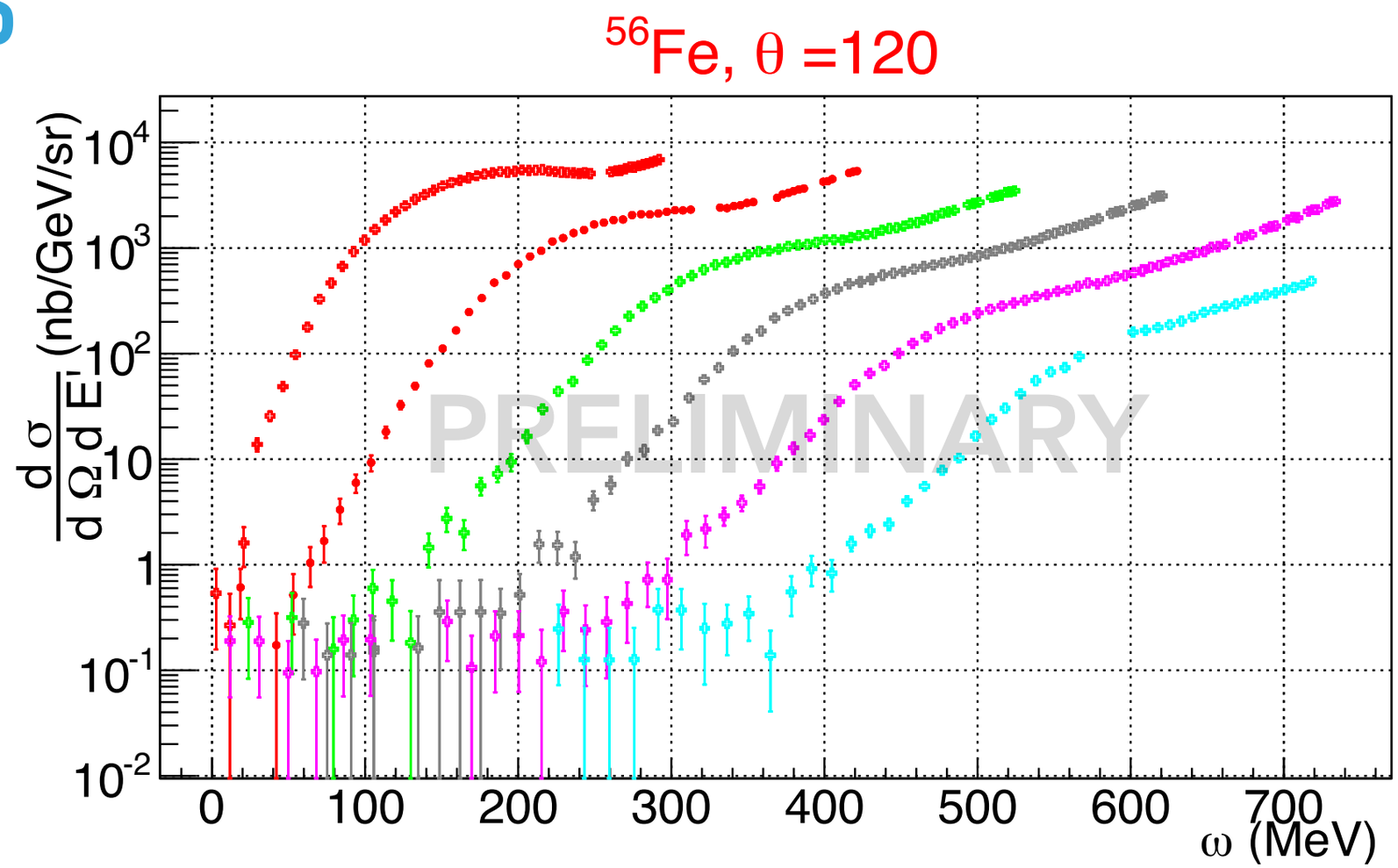
- Alternative methods for interpolation of |q|:
  - Neural Network can predict cross-section based on training sample and relevant kinematic variables like |q|, ω, y and W.
  - "Kriging" statistical estimator, useful for mapping of 2D of trends.



Sample neural network map from data

RECENT DEVELOPMENTS

- Backward angle data:



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RECENT DEVELOPMENTS

- Backward angle data:
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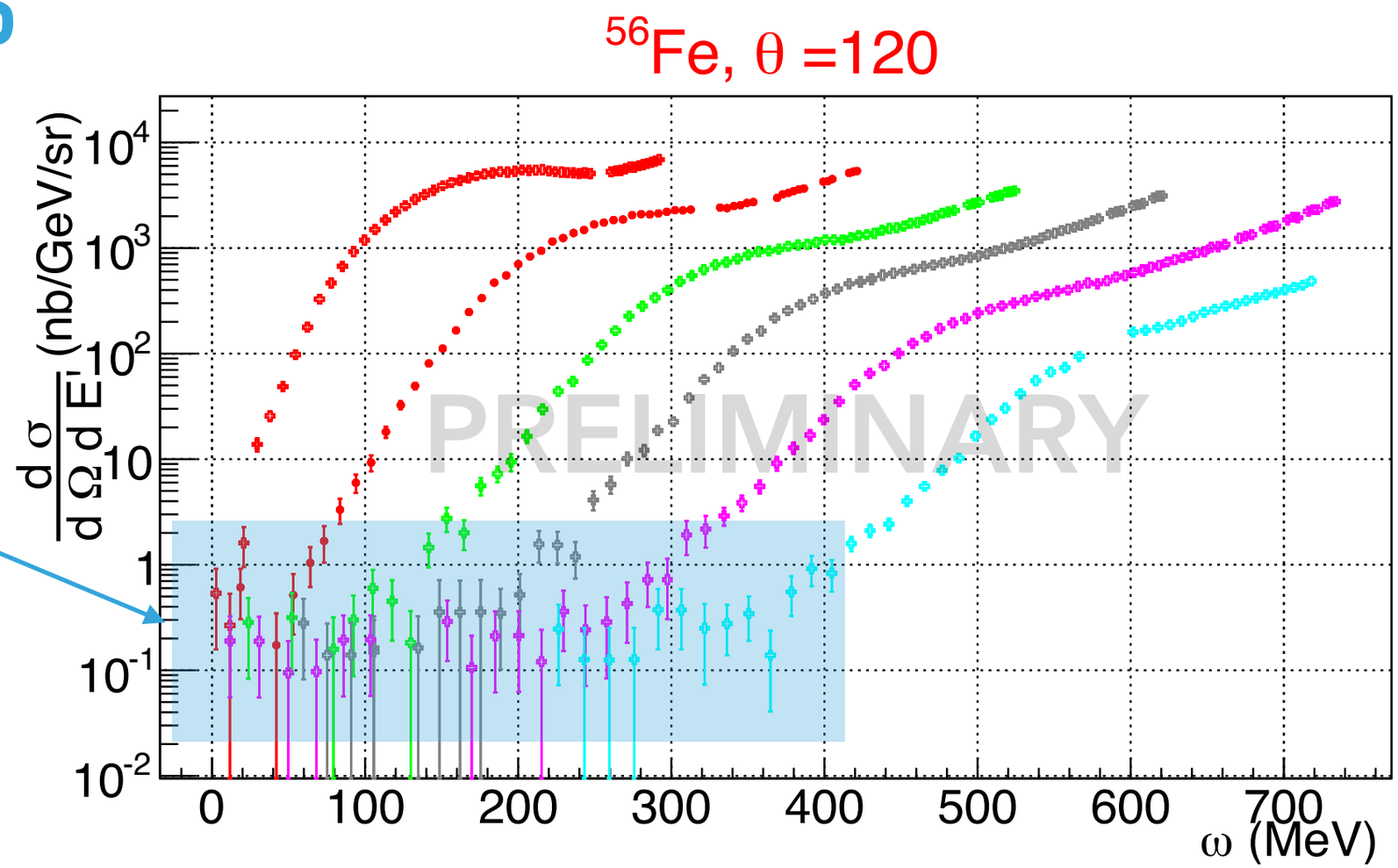

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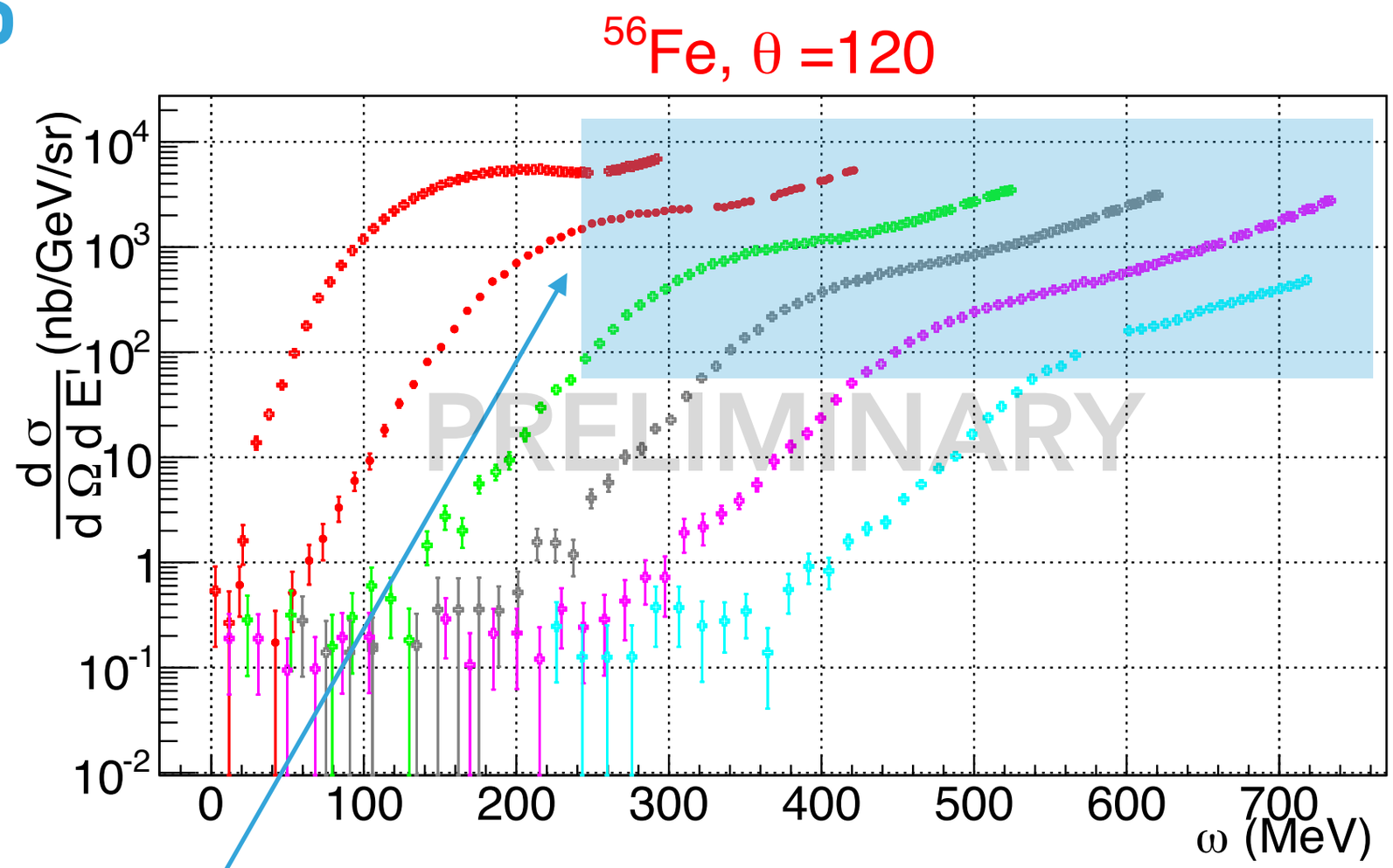

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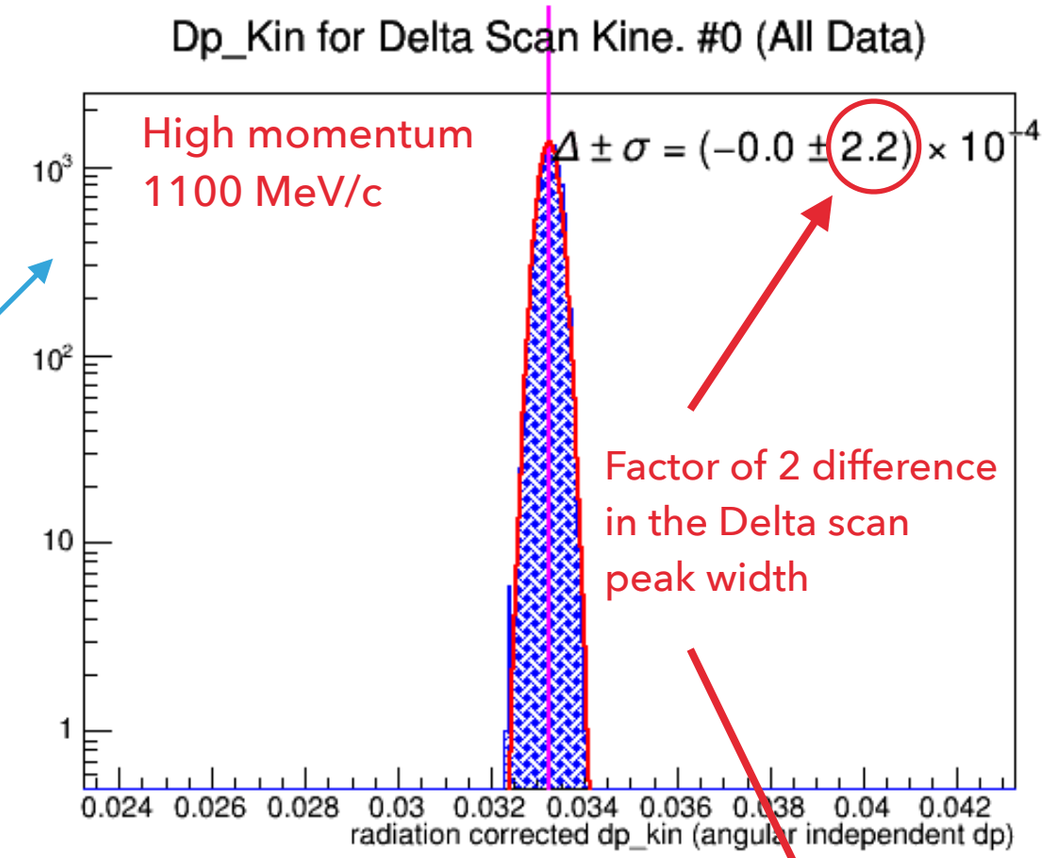
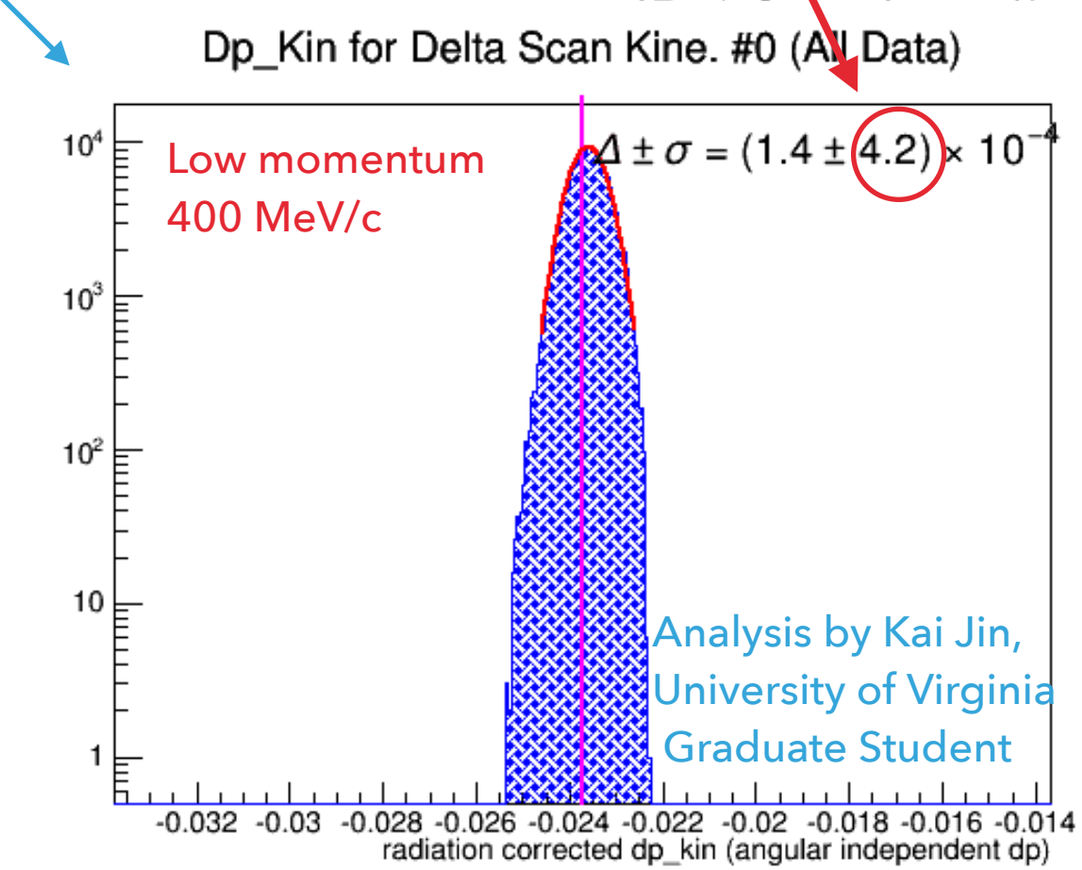
Still, largest uncertainties in R_L calculation come from high ω region.

RECENT DEVELOPMENTS – OPTICS

- A large range of central-momentum settings for spectrometer arms was used.
  - **High momentum optics** (1100 MeV/c) were well optimized using standard procedures.
  - **Low momentum optics** (400 MeV/c) are proving difficult to calibrate:
    - No pointing survey information (surveys were not performed for every new spectrometer setting because of the large number of setting changes)
    - NMR probe doesn't work well below 450 MeV/c, and gaussmeter has larger uncertainties.
  - **Intermediate momentum optics** runs:
    - No pointing survey information.
    - Raster was on!





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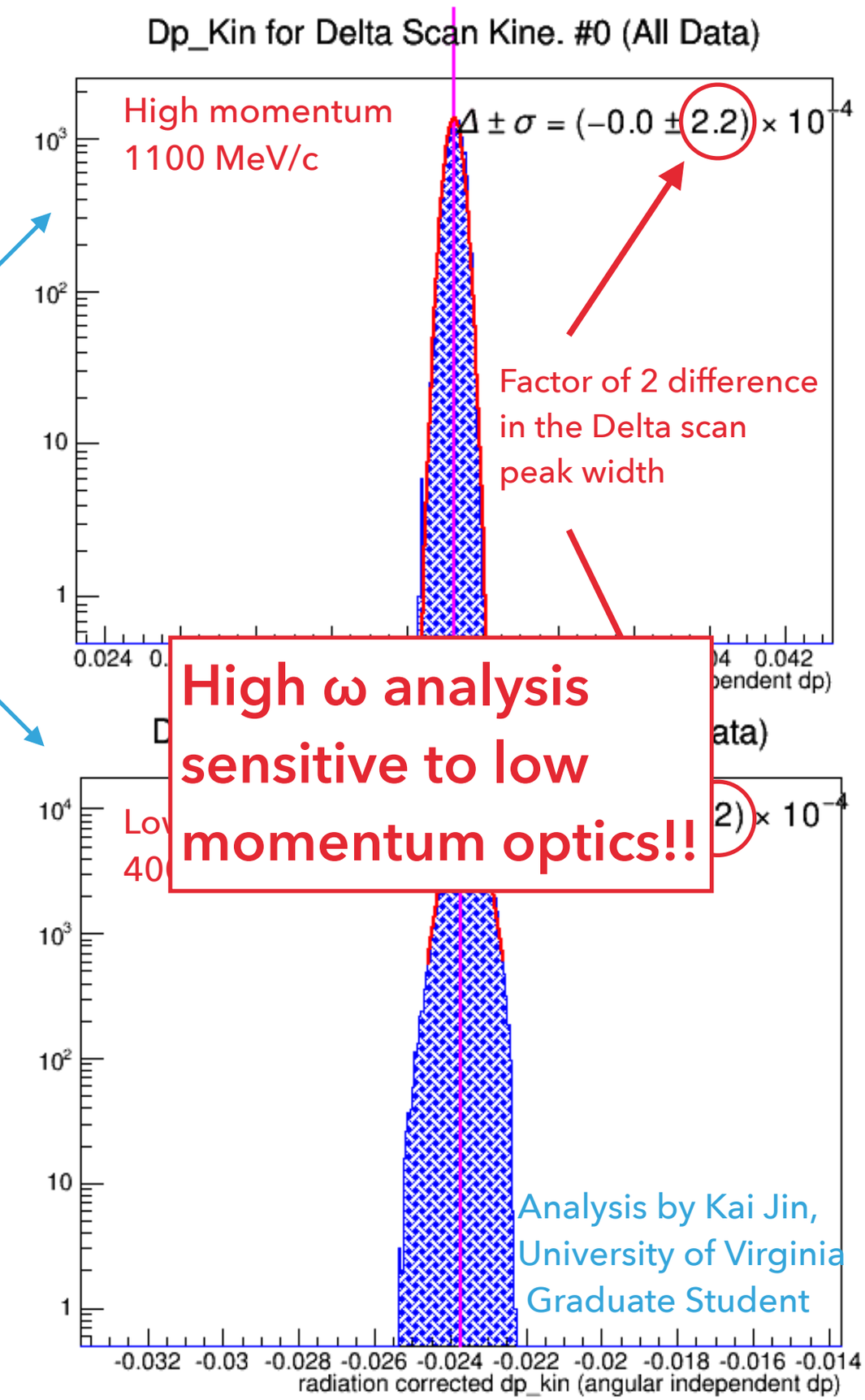
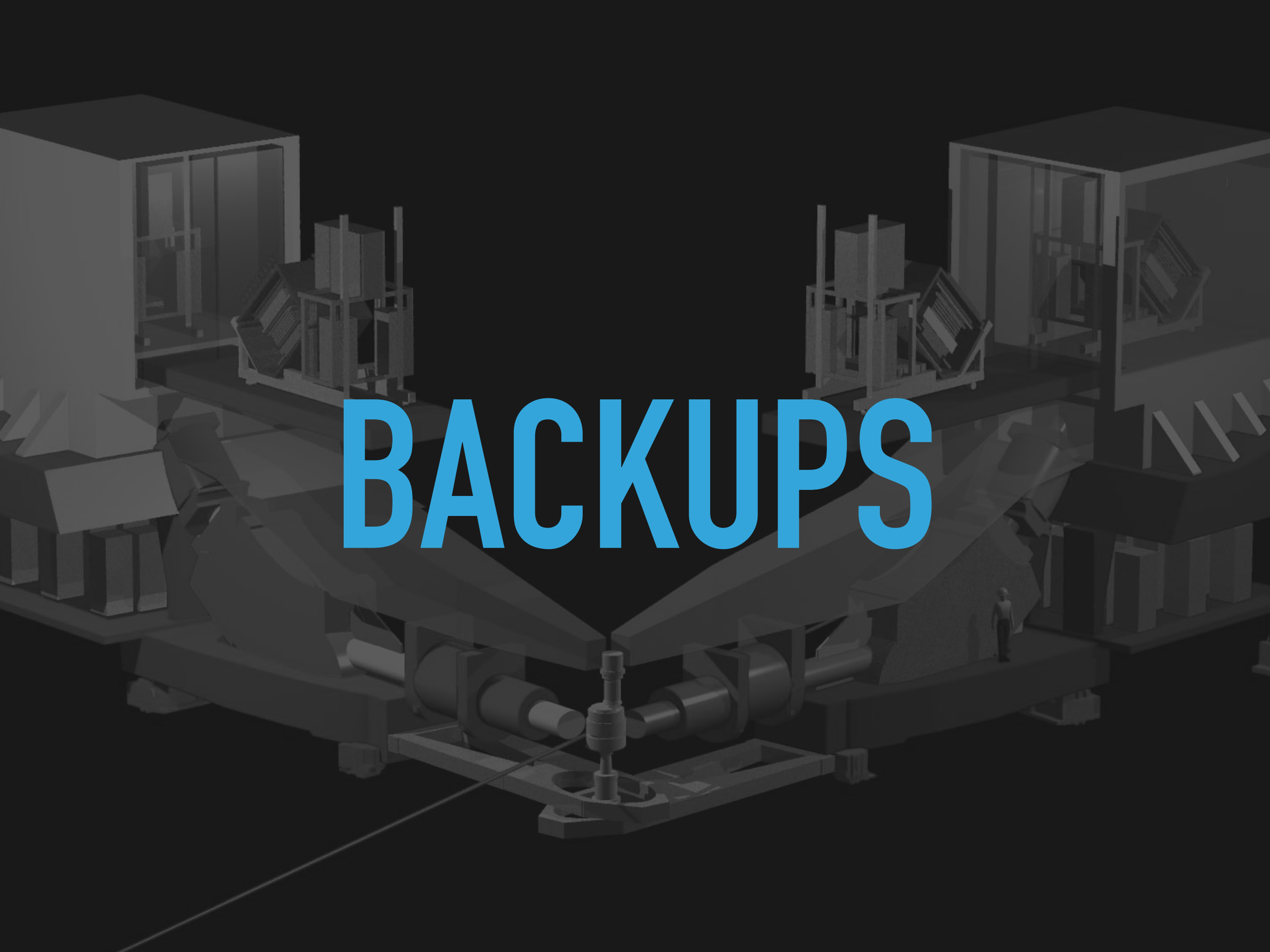


CONCLUSIONS AND WORK LEFT:

- Most regions of S_L calculation are well understood.
  - Working systematically through all contributions to R_L
    - carefully investigating the large ω region where Rosenbluth separation is most sensitive.
  - Completing studies and calibration of low and intermediate momentum optics.
- Final results are just around the corner (fingers crossed).



BACKUPS

VARIOUS DEFINITIONS AND CORRECTIONS

Basic kinematic definitions:

$$\epsilon(|\boldsymbol{q}|,\omega,\theta) = \left[1 + \frac{2\boldsymbol{q}^2}{\boldsymbol{q}^2 - \omega^2}\tan^2\frac{\theta}{2}\right]^{-1}$$

$$\frac{d\sigma}{d\Omega}_{\text{Mott}} = \frac{\alpha^2\cos^2(\theta/2)}{4E^2\sin^4(\theta/2)}$$

$$Q^2 = \boldsymbol{q}^2 - \omega^2$$

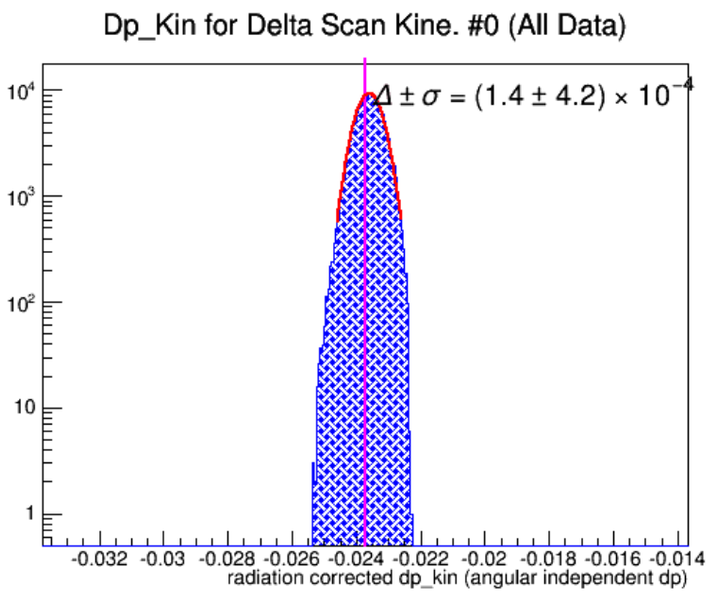
$$W^2 = M_N^2 + 2M_N\omega - Q^2$$

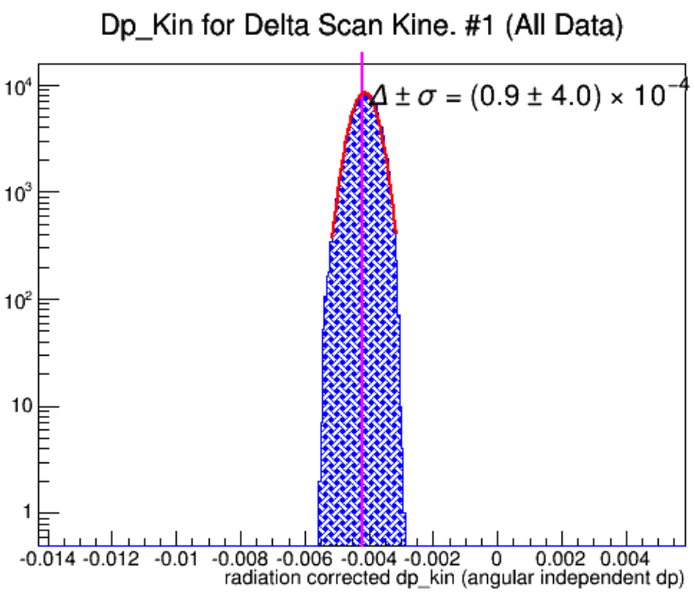
Relativistic correction to nucleon form-factor:

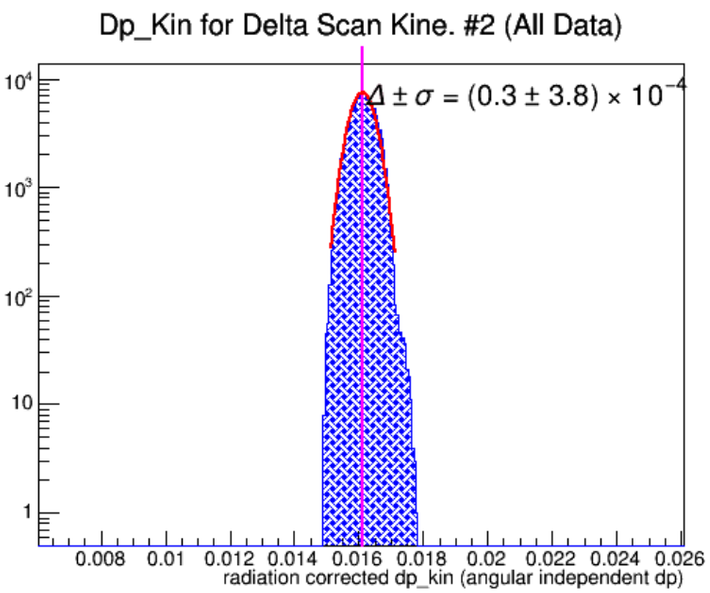
$$\tilde{G}_E^2 = G_E^2\frac{1 + Q^2/4M^2}{1 + Q^2/2M^2}$$

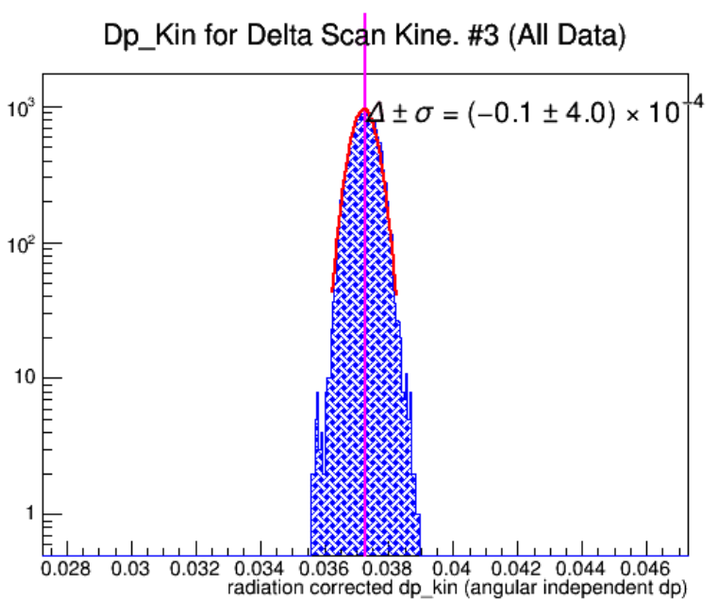
MORE OPTICS COMPARISONS

All Delta scans - momentum - 400 MeV/c



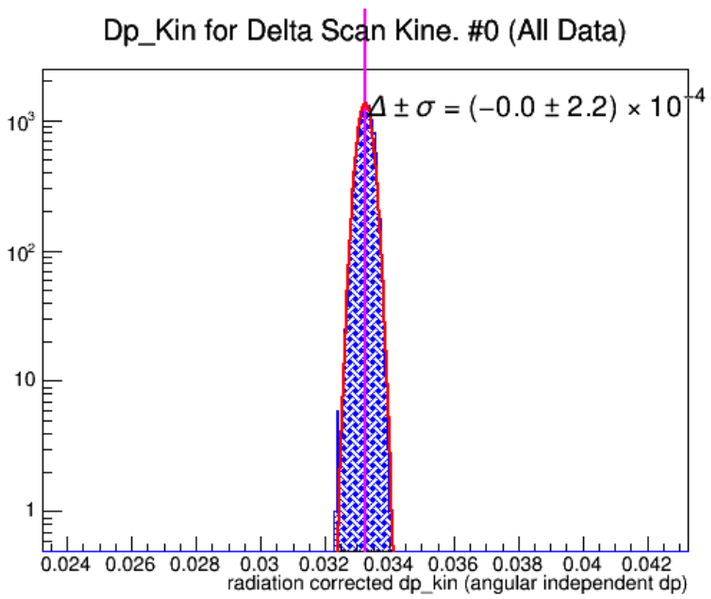


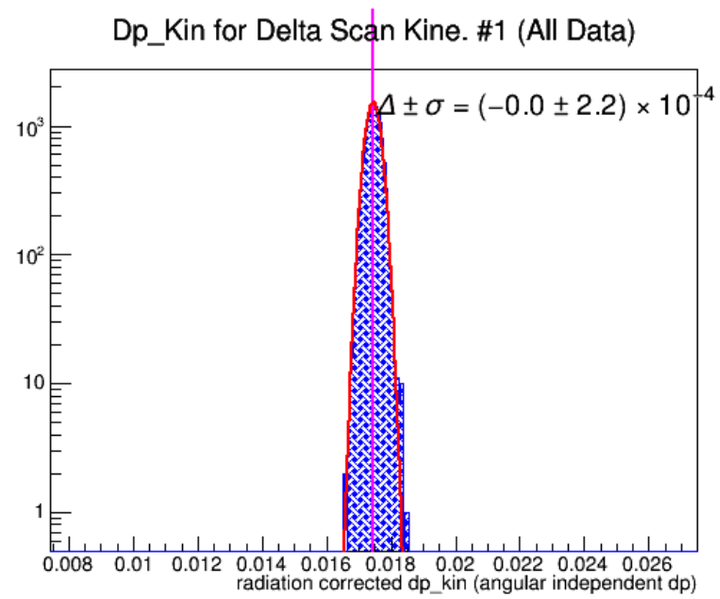


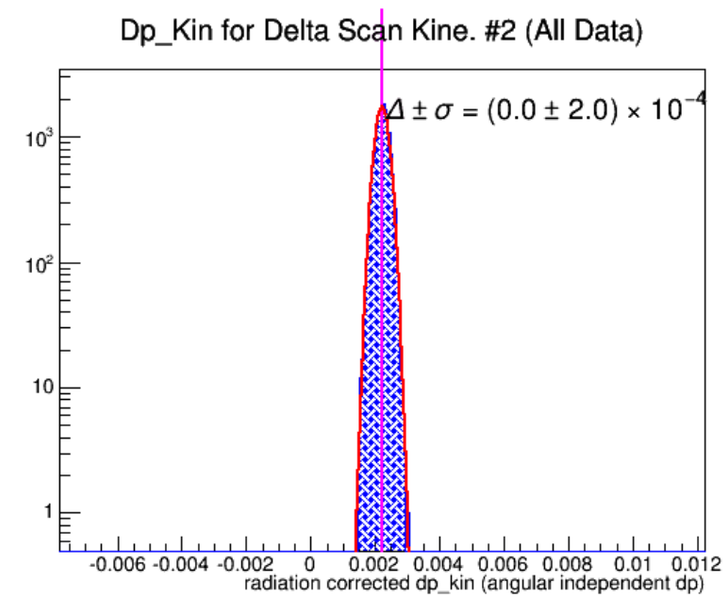


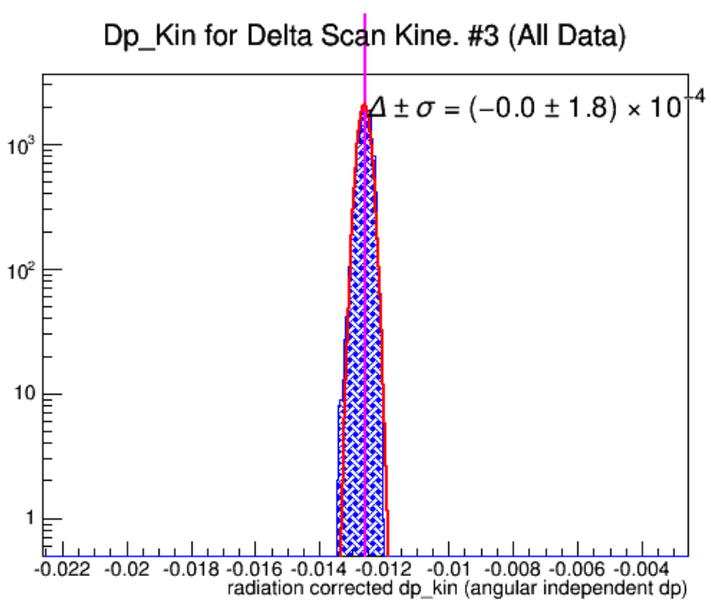
MORE OPTICS COMPARISONS

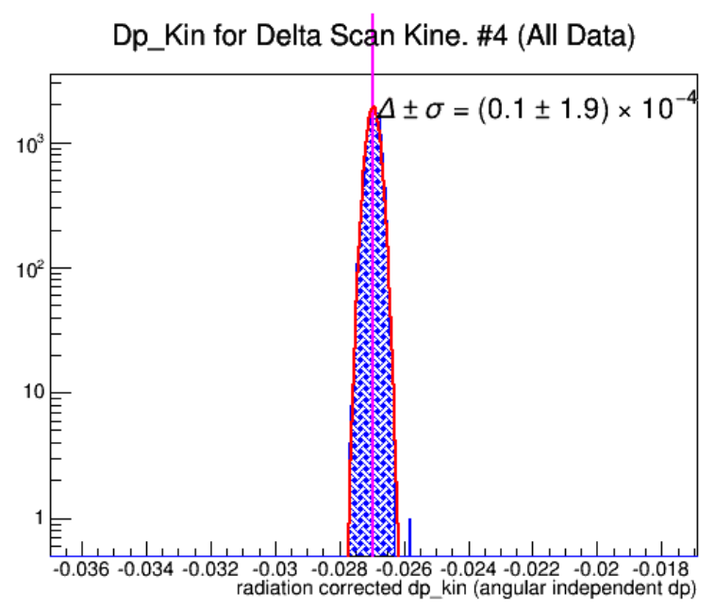
All Delta scans - momentum - 1100 MeV/c

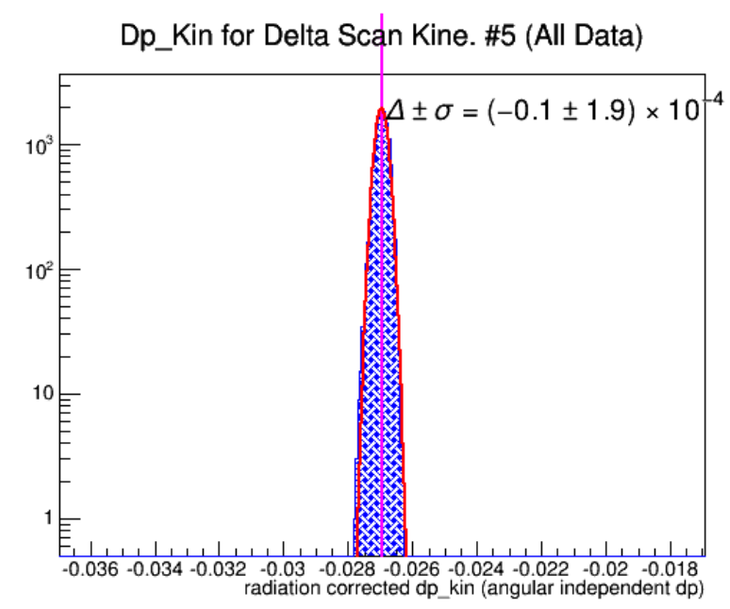






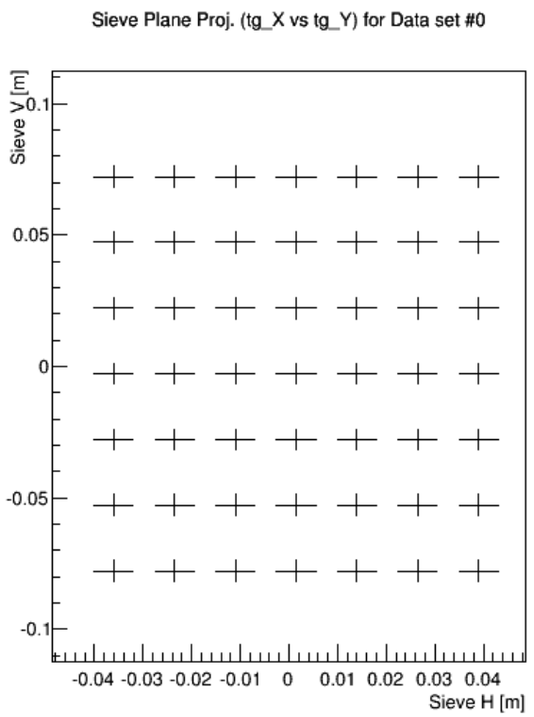


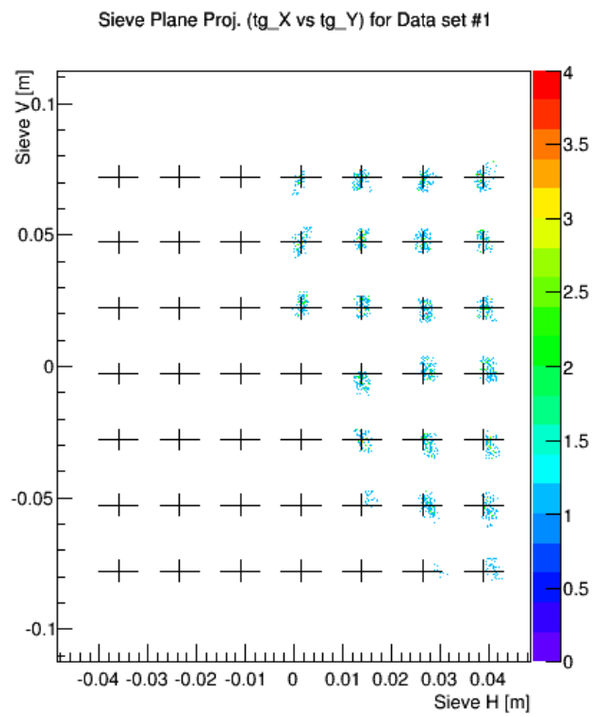


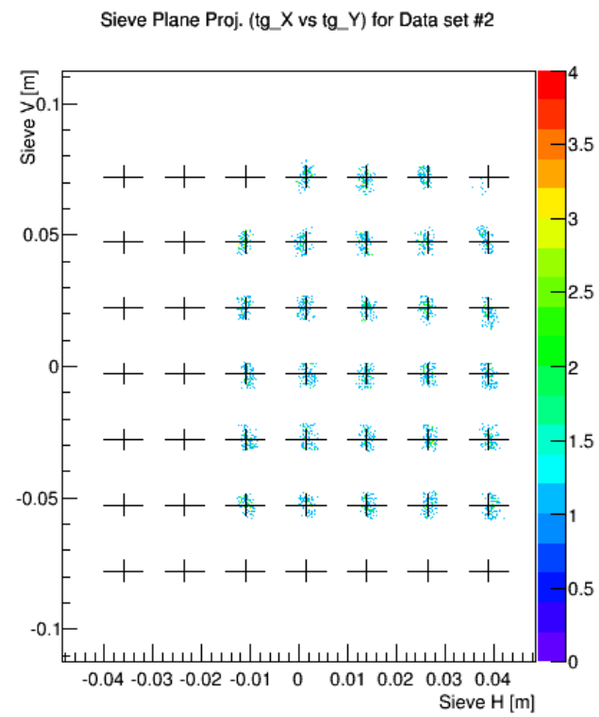


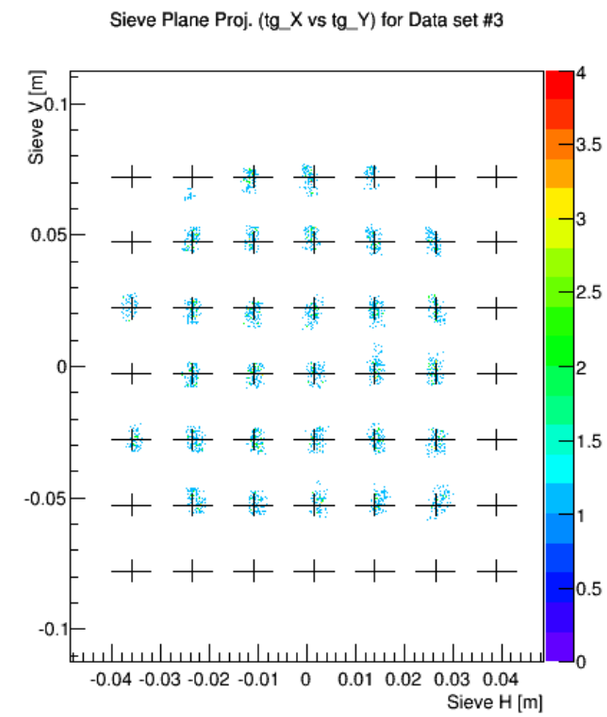
MORE OPTICS COMPARISONS

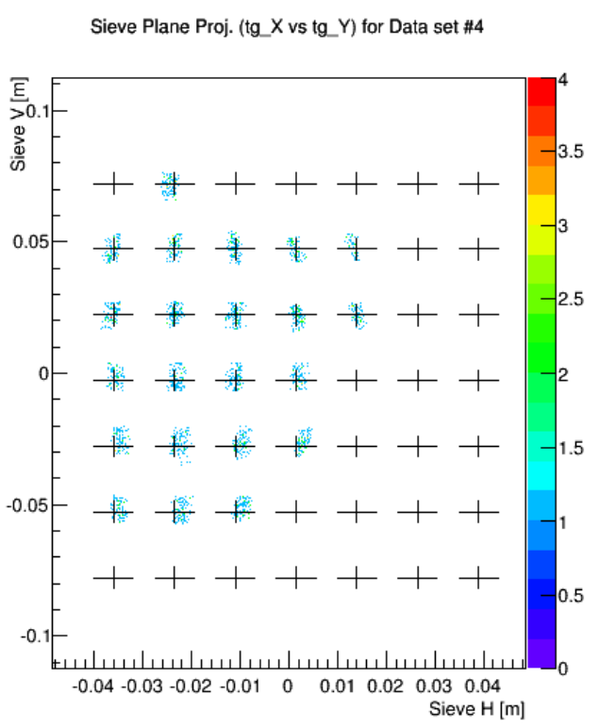
All Delta scans - Sieve / angle - 400 MeV/c

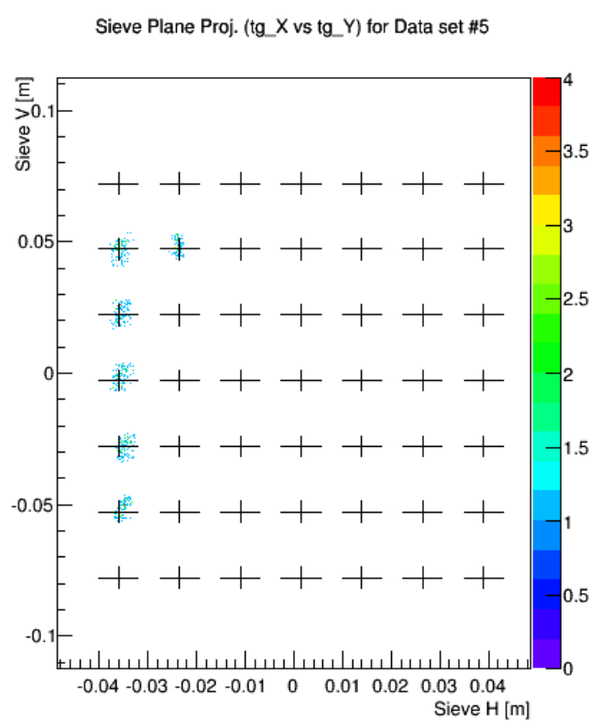


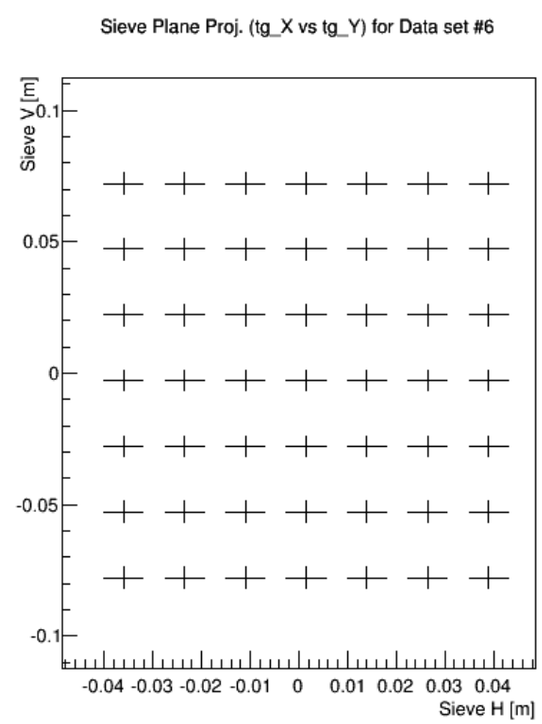






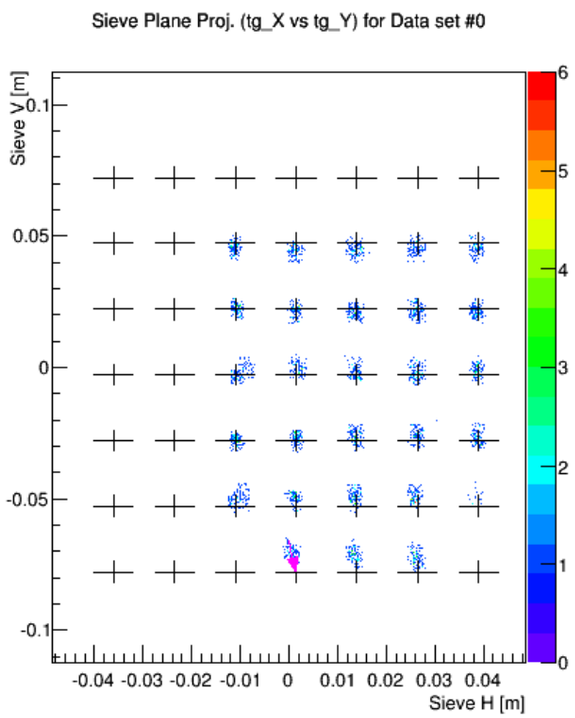


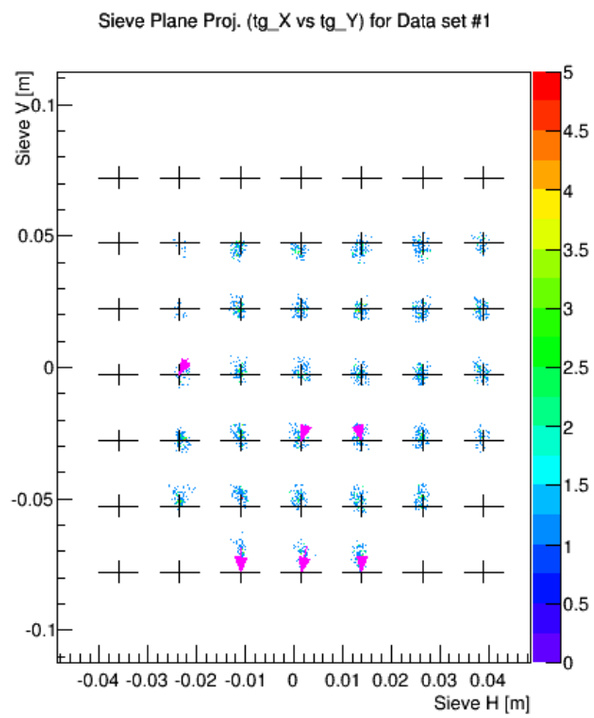


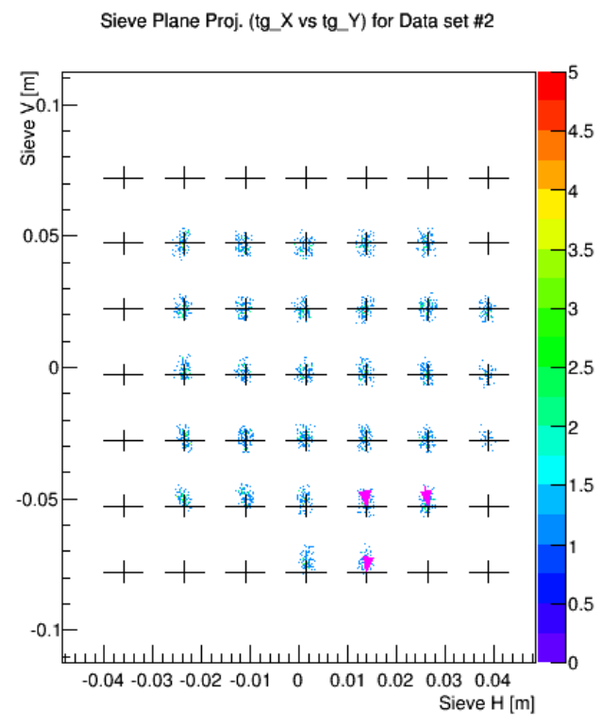


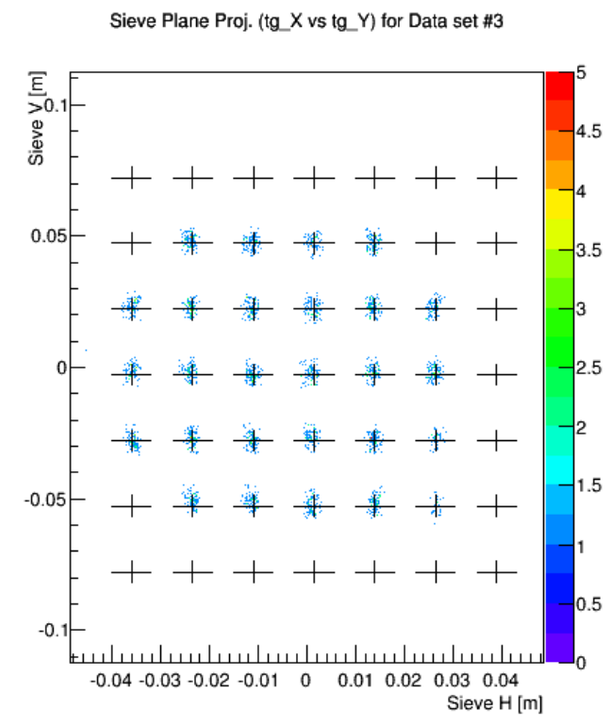
MORE OPTICS COMPARISONS

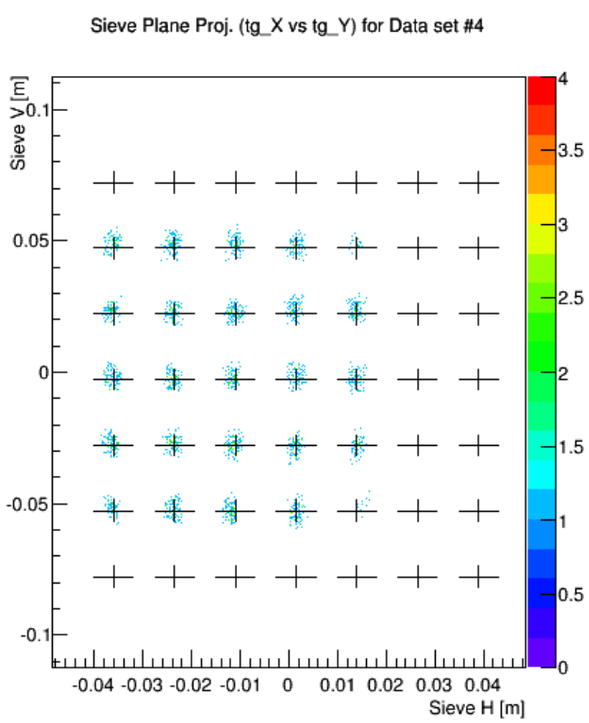
All Delta scans - Sieve / angle - 1100 MeV/c

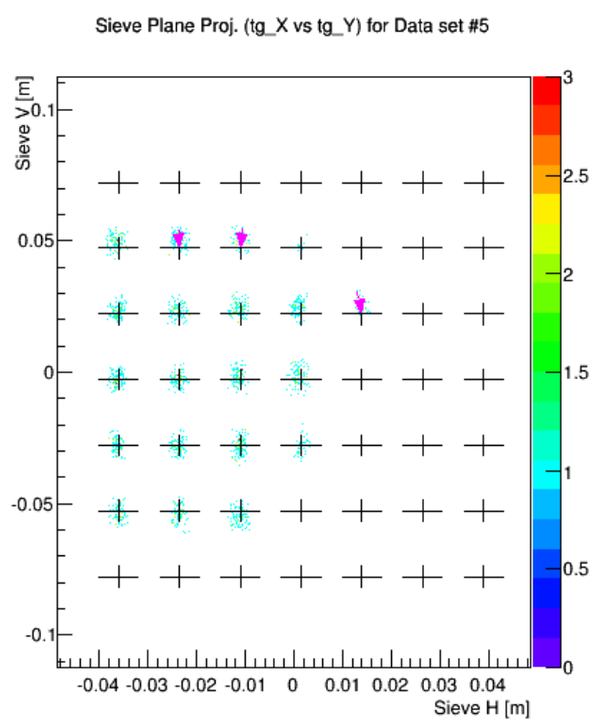


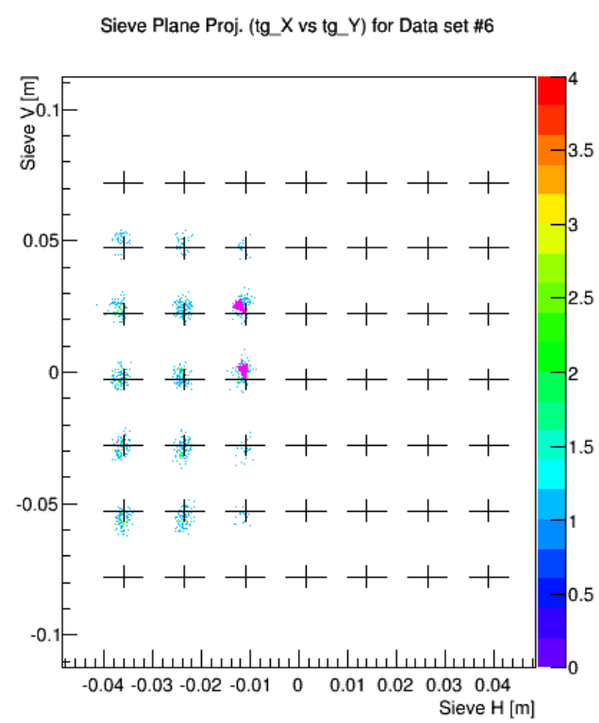




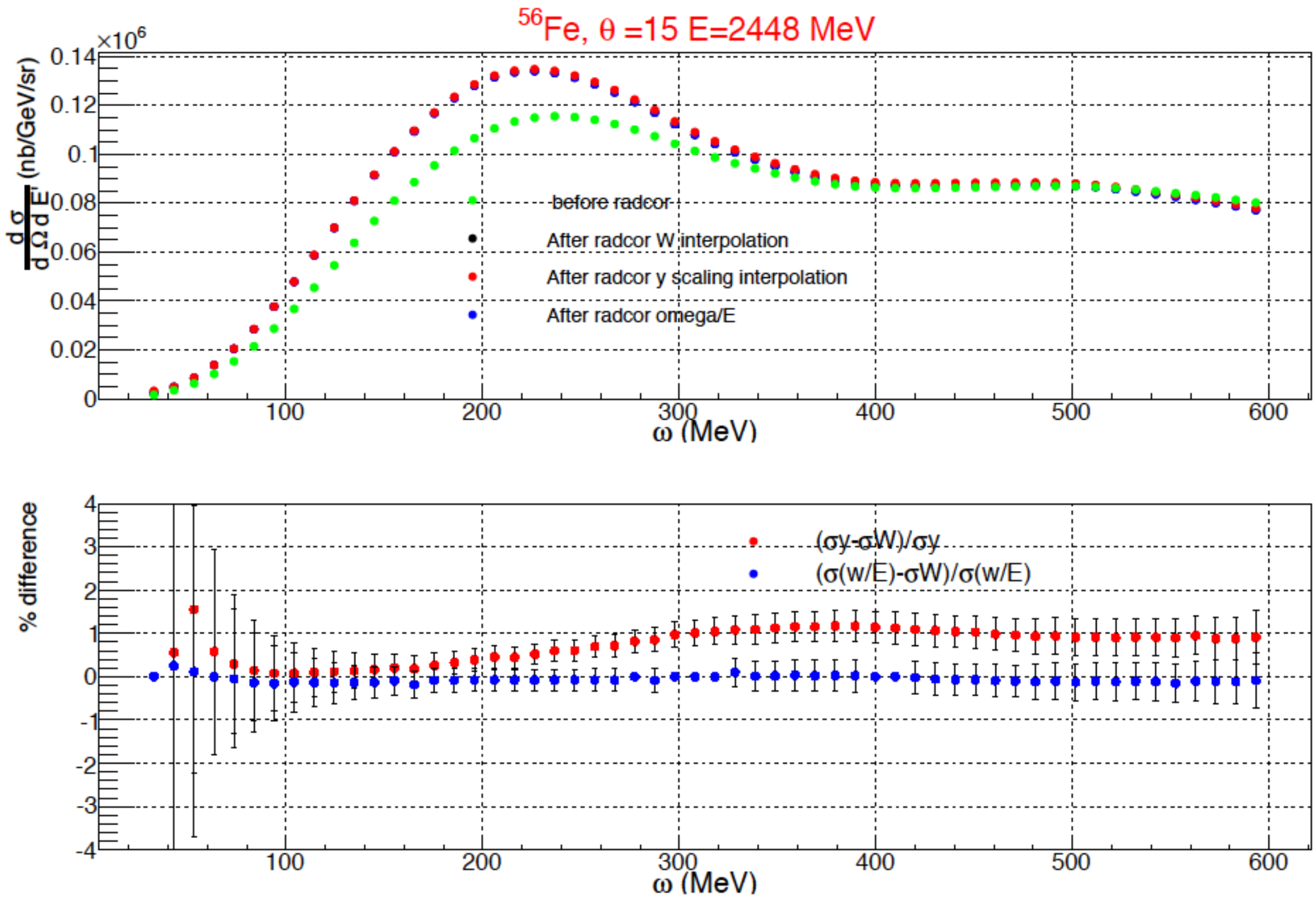




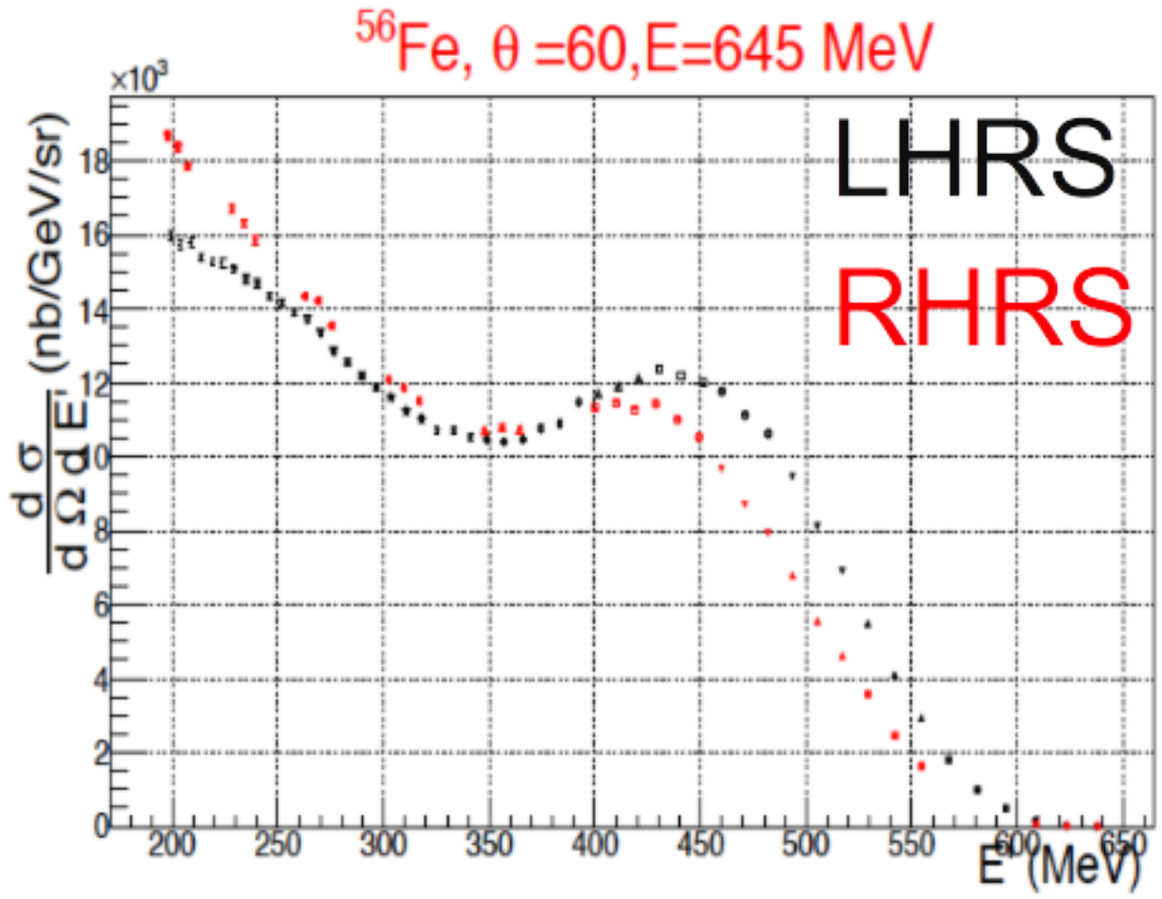


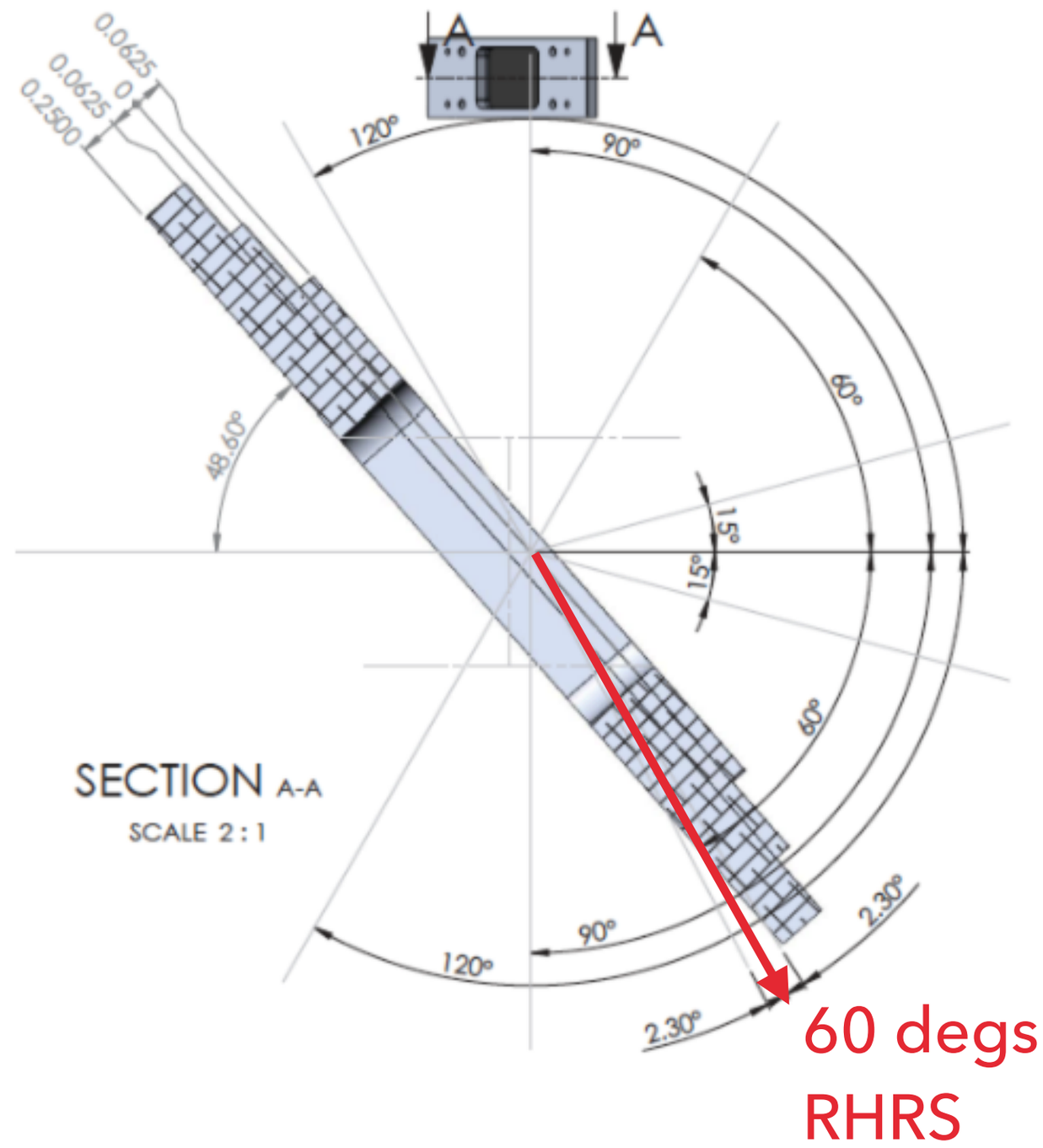


VERIFICATION OF RADIATIVE CORRECTIONS



TARGET FRAME ISSUES AT 60 DEGS





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