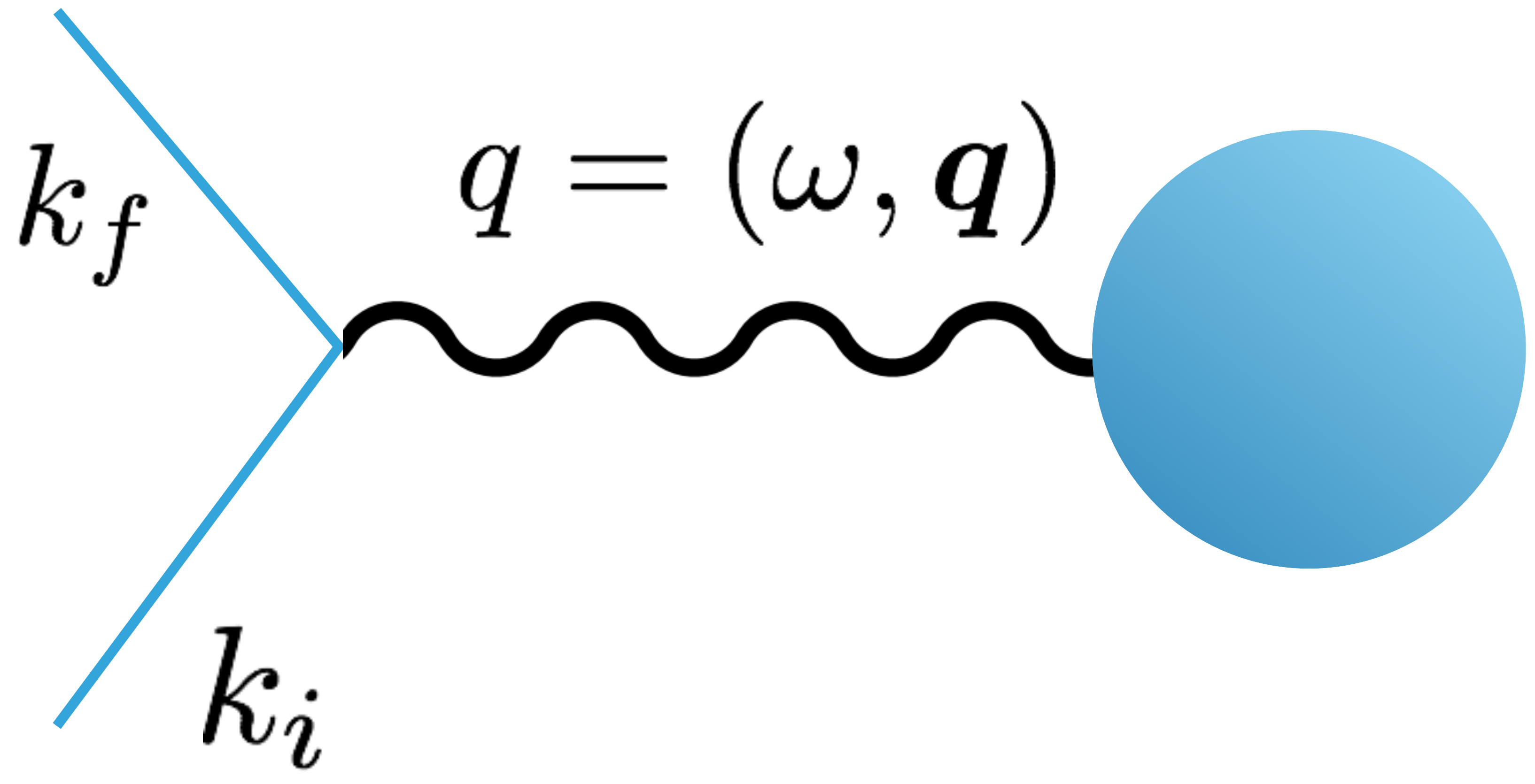
MICHAEL PAOLONE

NEW MEXICO STATE UNIVERSITY

FOR THE E05-110 COLLABORATION.

THE COULOMB SUM RULE IN NUCLEI

COULOMB SUM RULE



Inclusive electron scattering cross-section:

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

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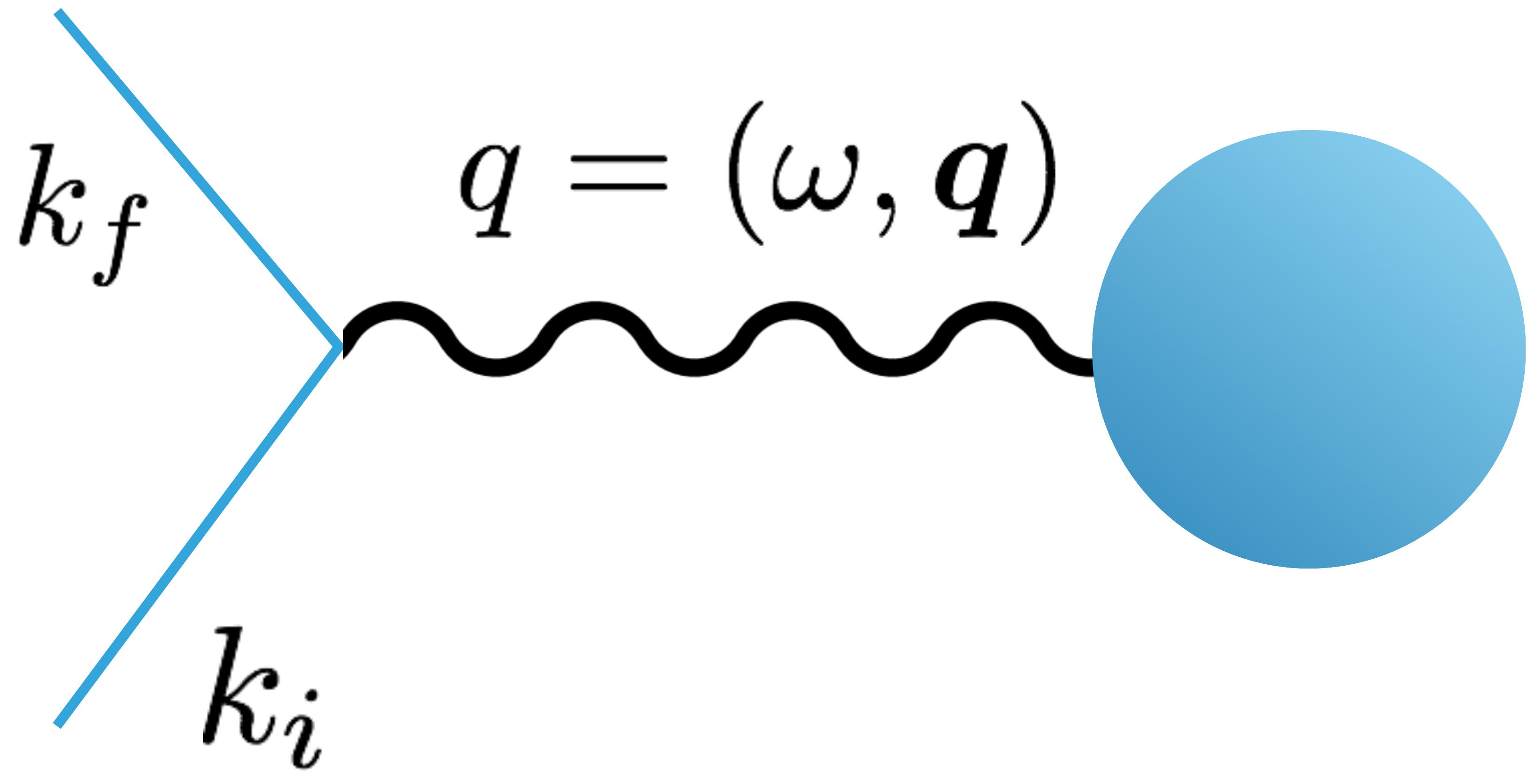

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Scattering response due to **charge** properties

Scattering response due to **magnetic** properties

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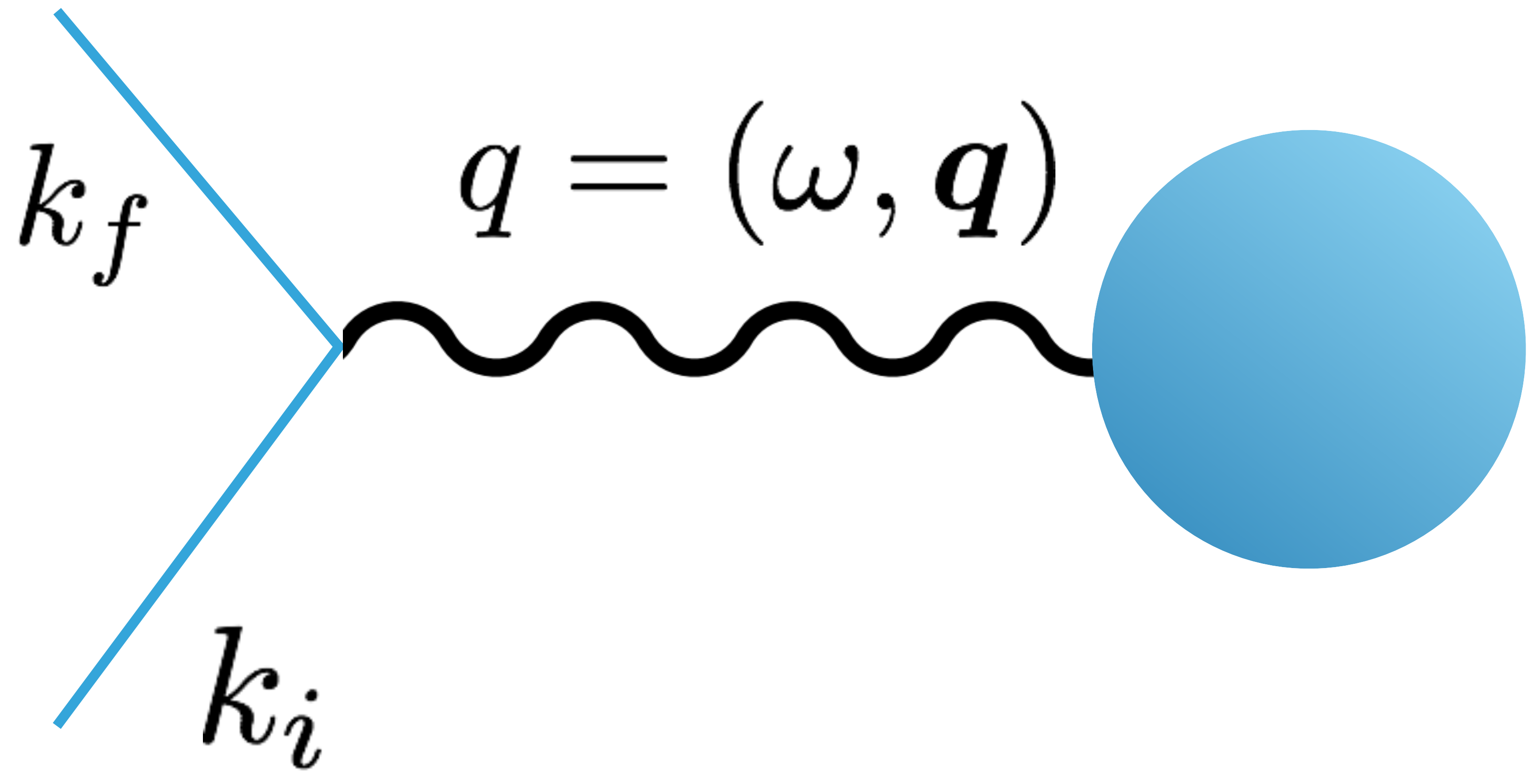

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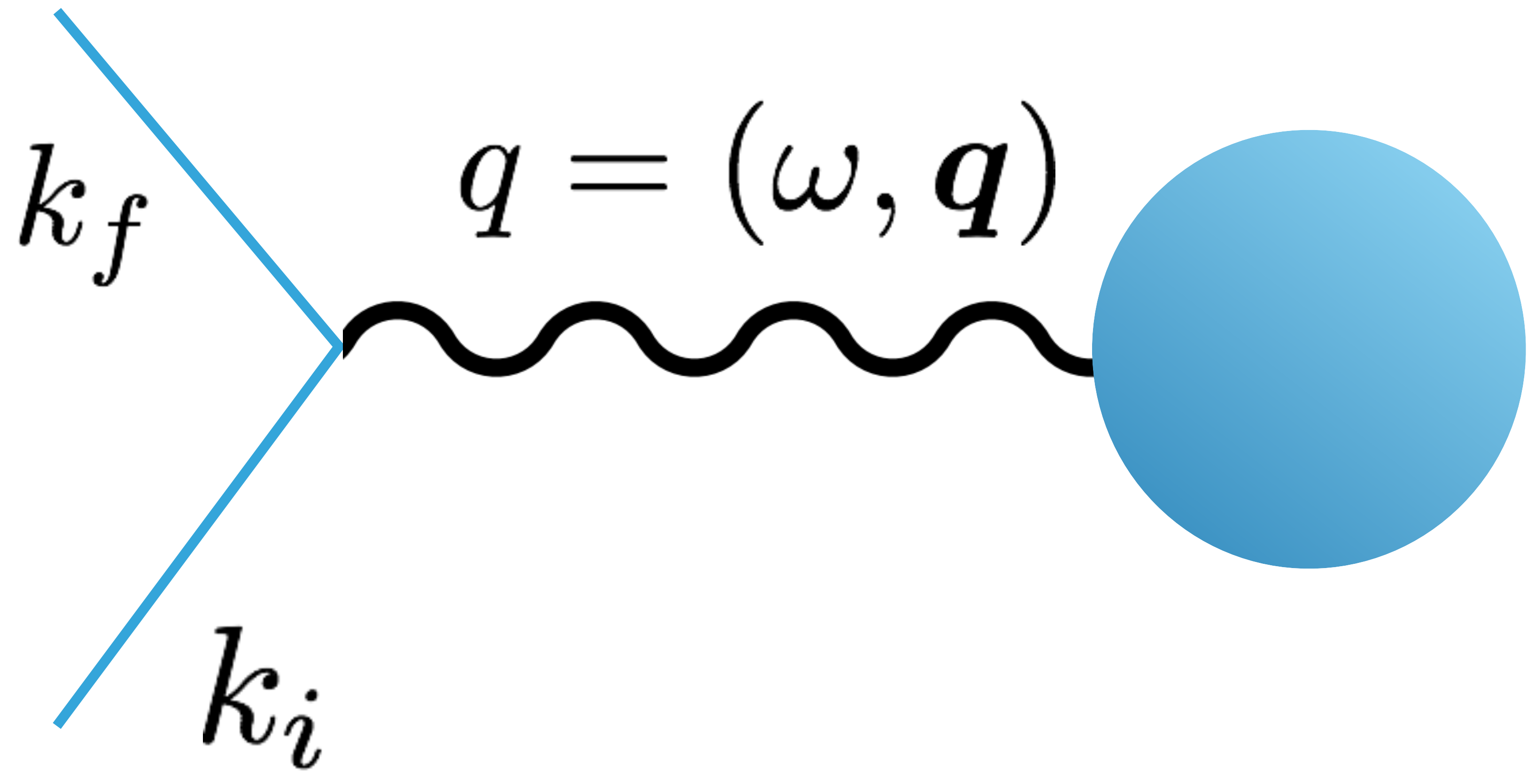

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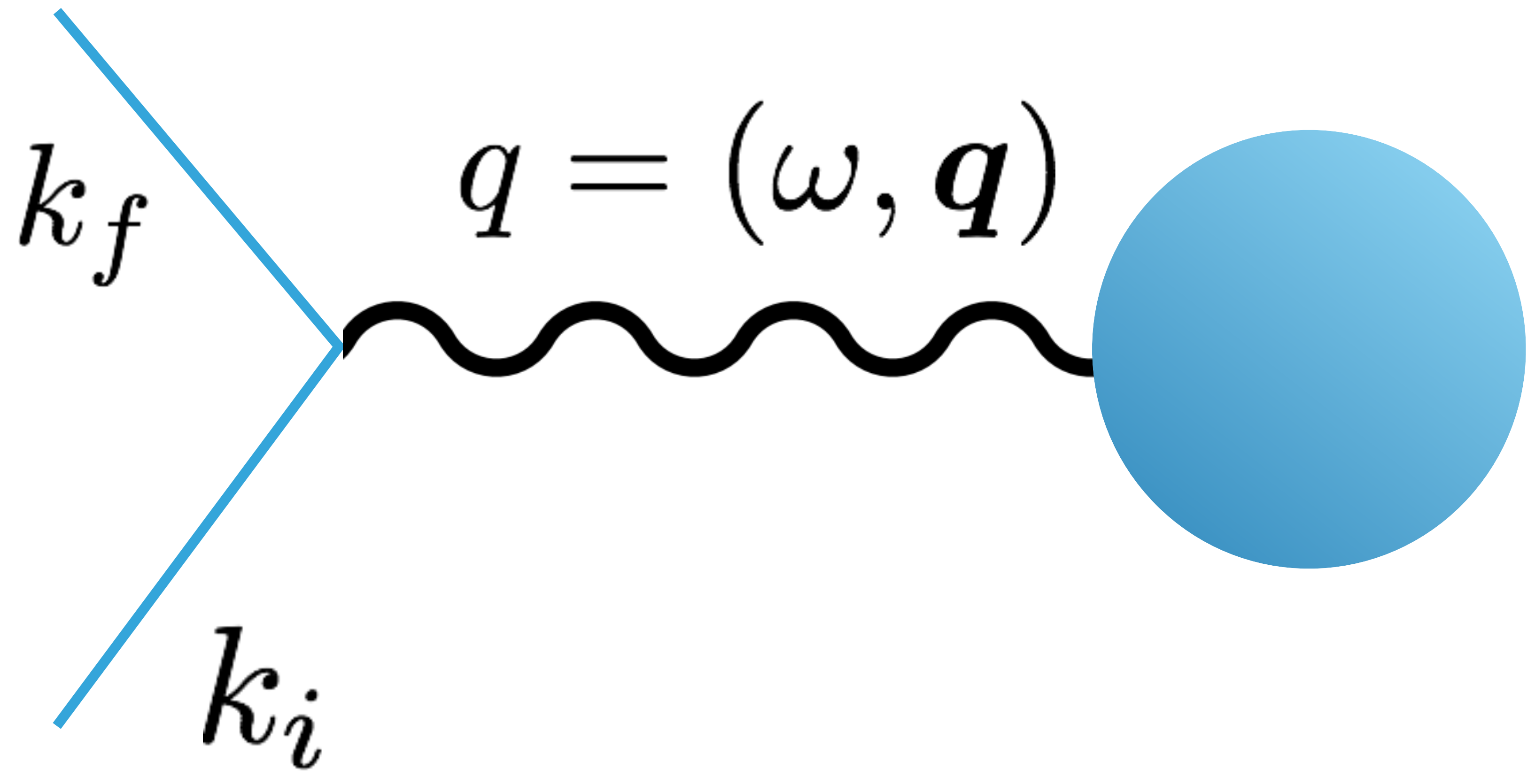

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This is calculated according to expected structure for unbound nucleons.

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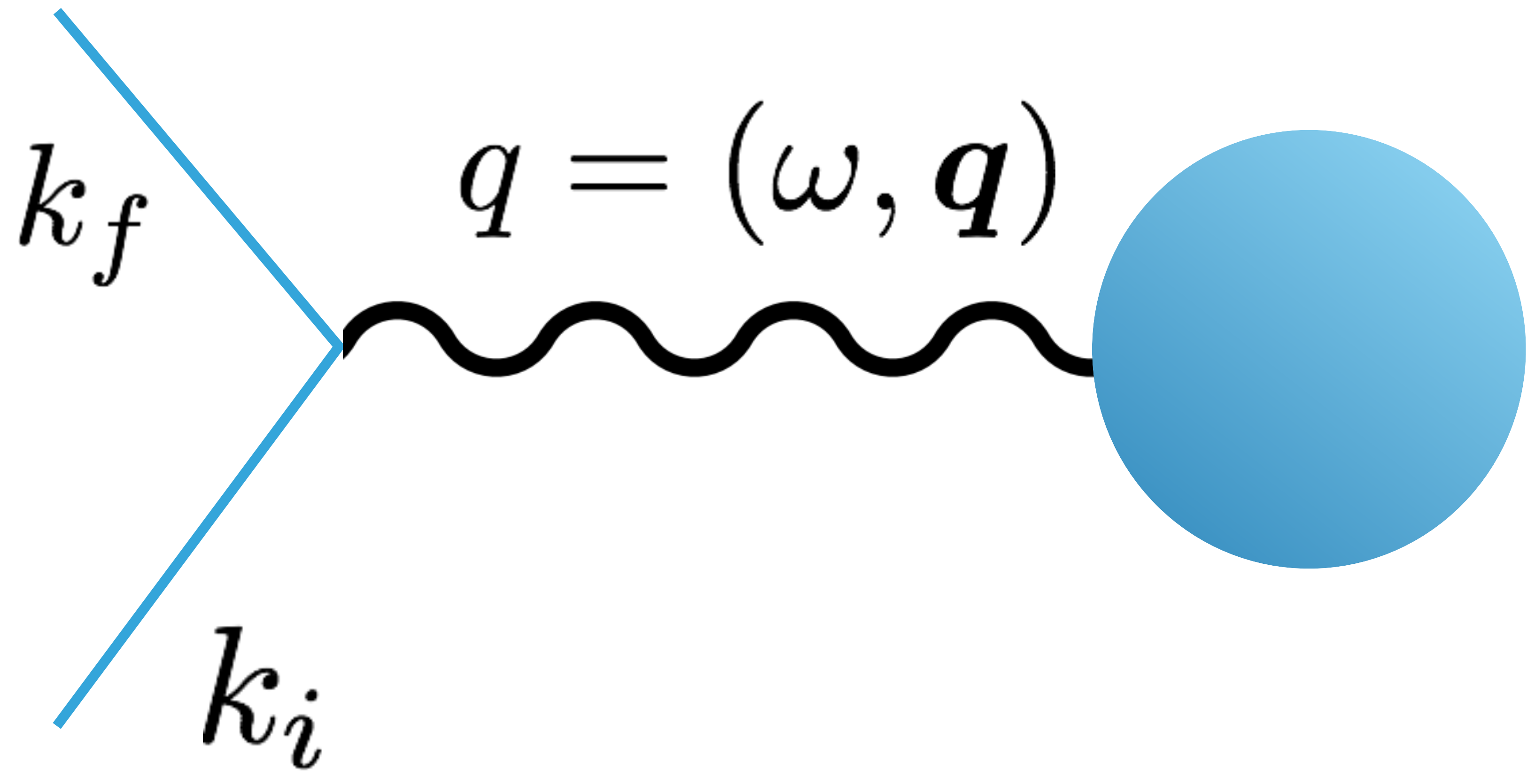

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If one integrates the charge response divided by the total charge form factor over all available virtual photon energies, naively one might expect the integral to go to unity.

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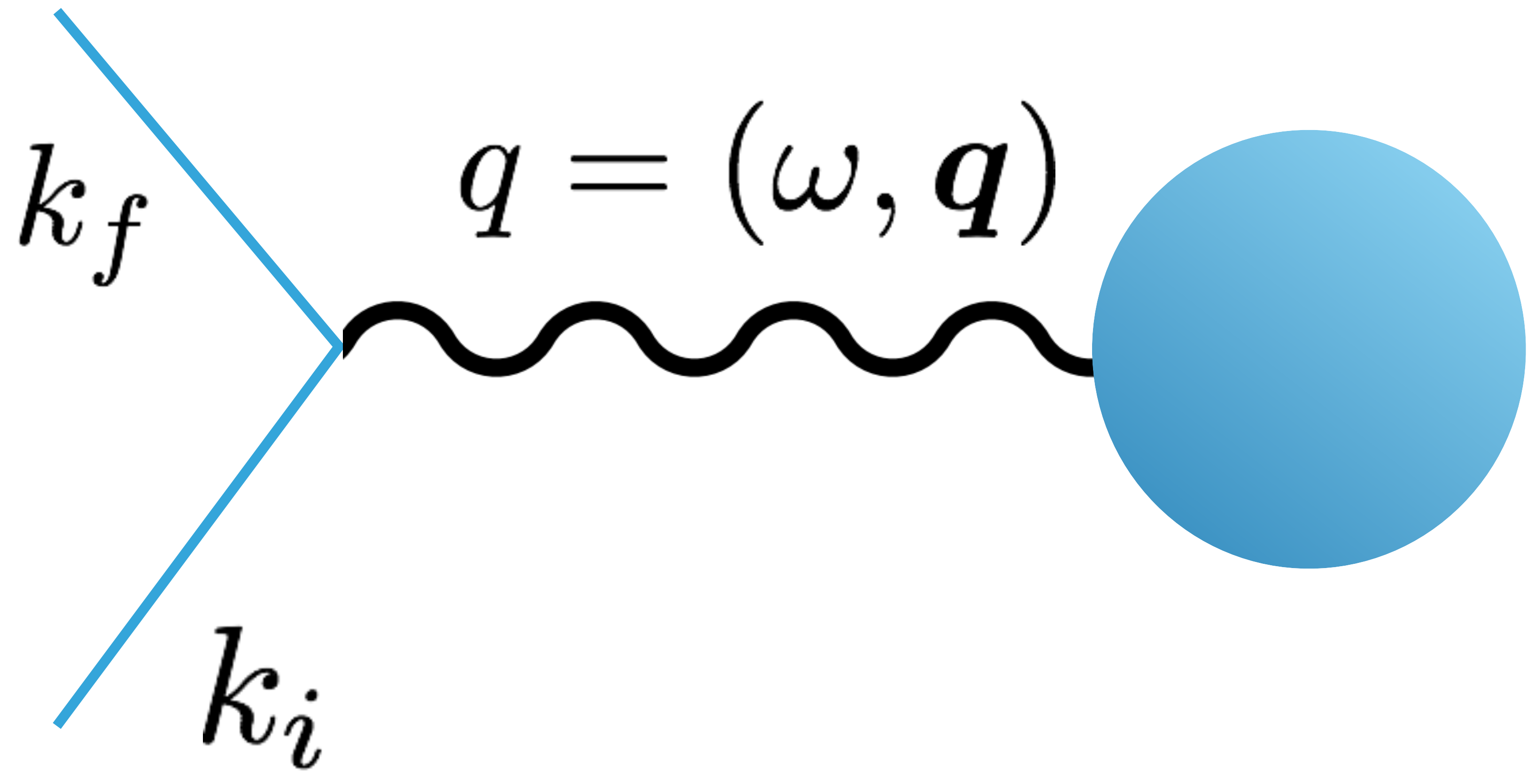

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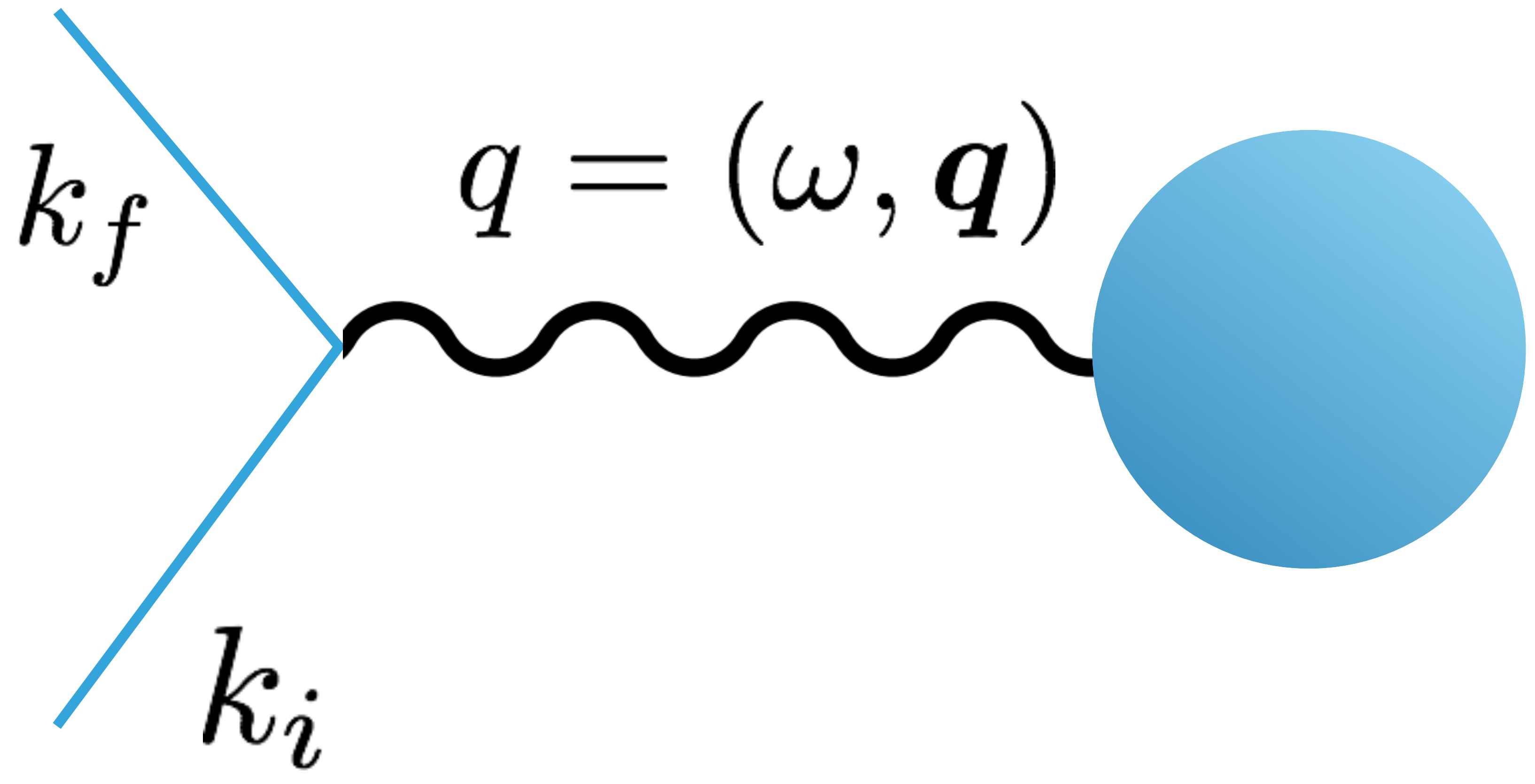

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At large |q| >> $2k_f$, S_L should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!

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

COULOMB SUM RULE

- Long standing issue with many years of theoretical interest.
- Even most state-of the-art models cannot predict existing data.
- New precise data at larger |q| would provide crucial insight and constraints to modern calculations.

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

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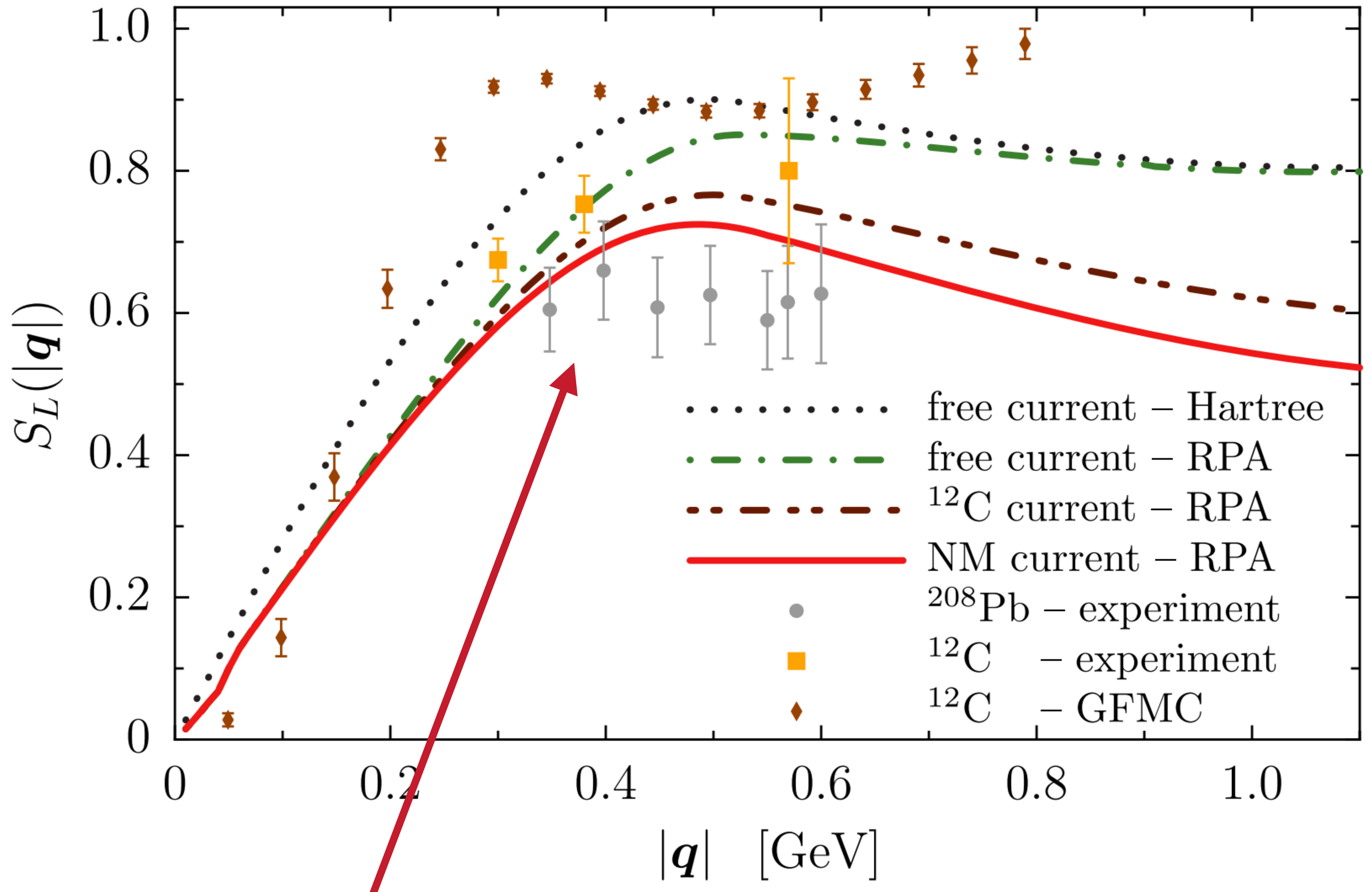
[2]*Department of Physics, School of Science, Tokai University, Hiratsuka-shi, Kanagawa 259-1292, Japan*
[3]*CSSM and ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide South Australia 5005, Australia*
(Received 23 June 2015; published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



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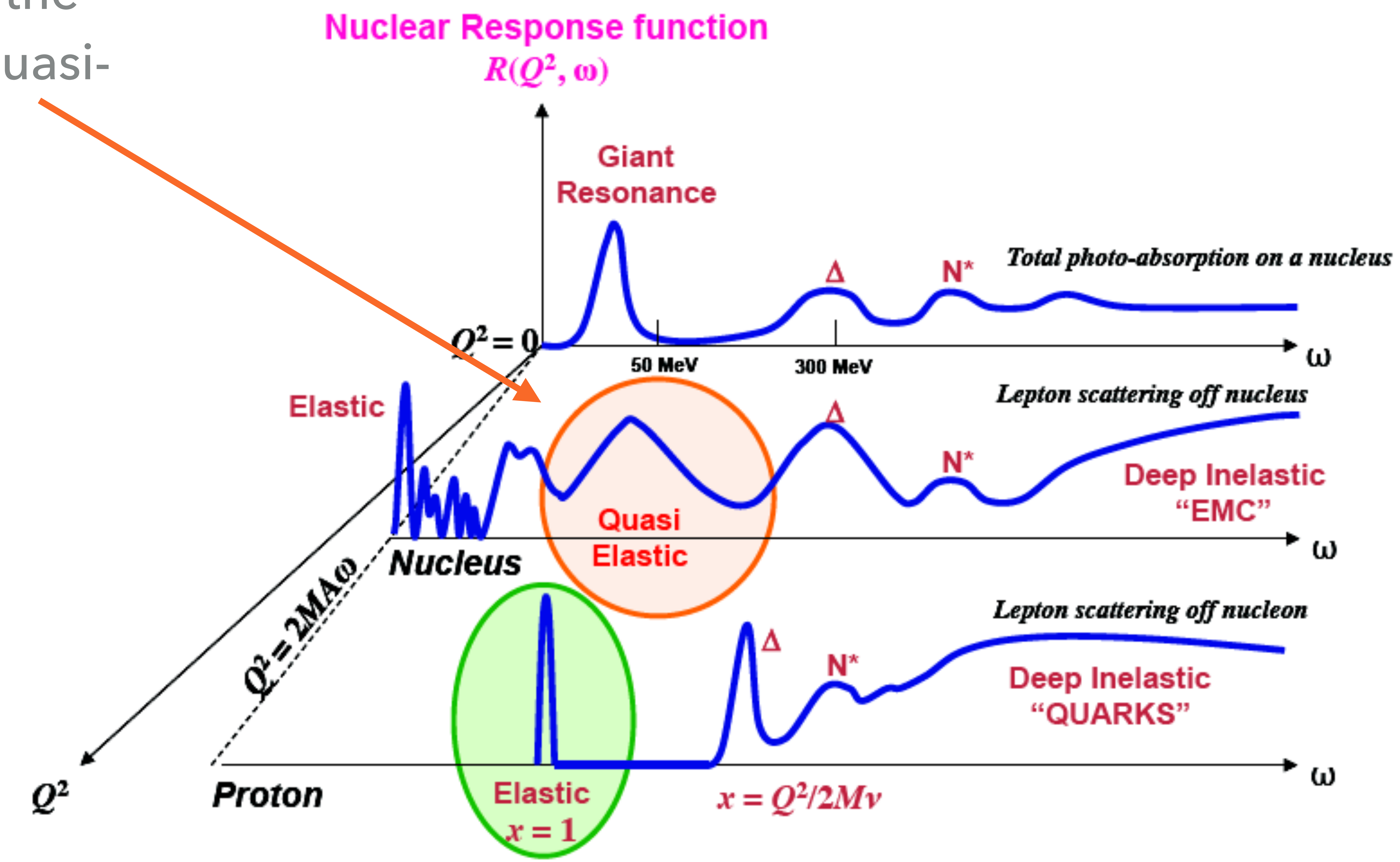
EXPERIMENTAL CONSTRAINTS ON INTEGRATION

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

- We consider the scattering on the constituent nucleons in the nucleus, and focus on the quasi-elastic to delta region.



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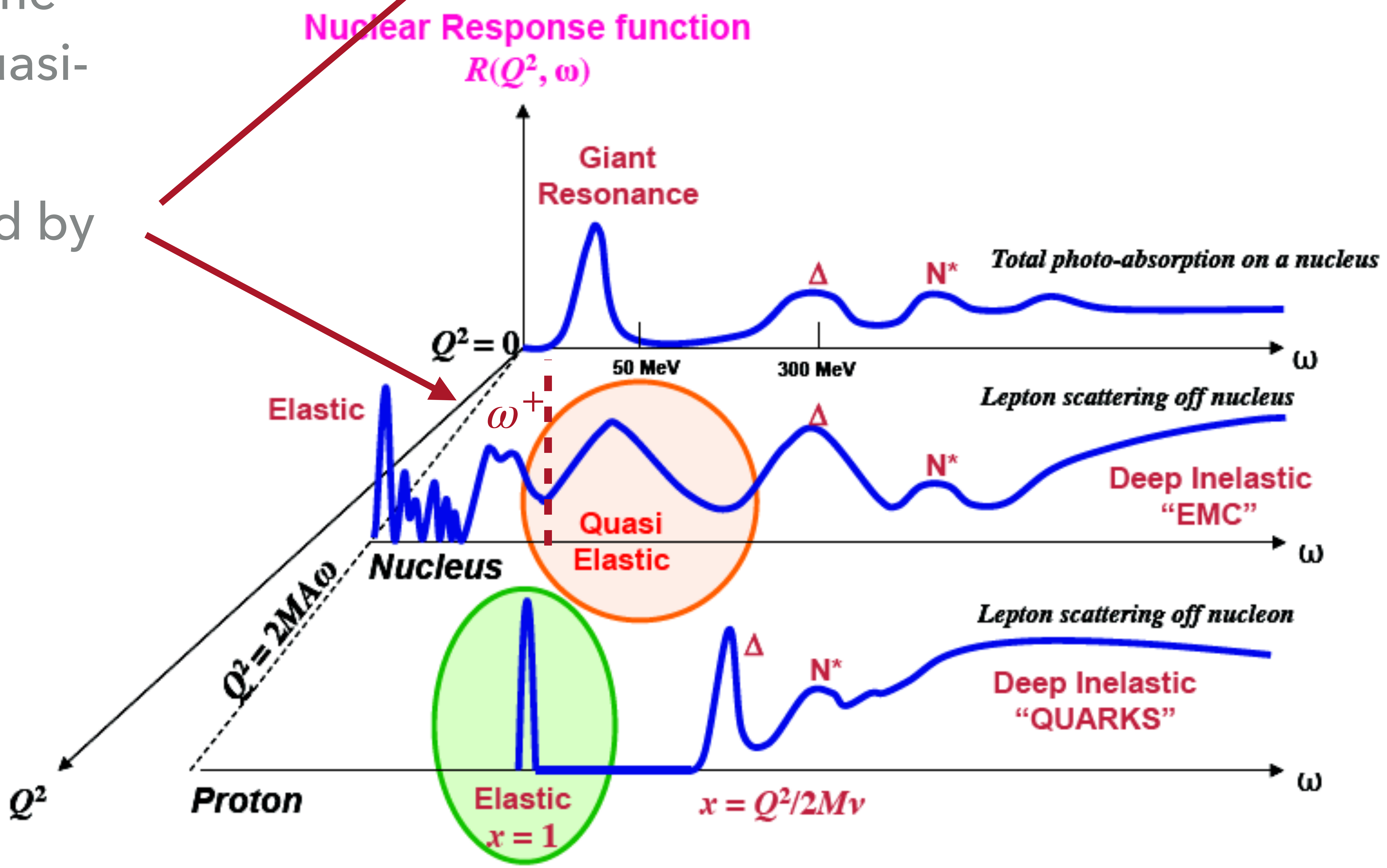

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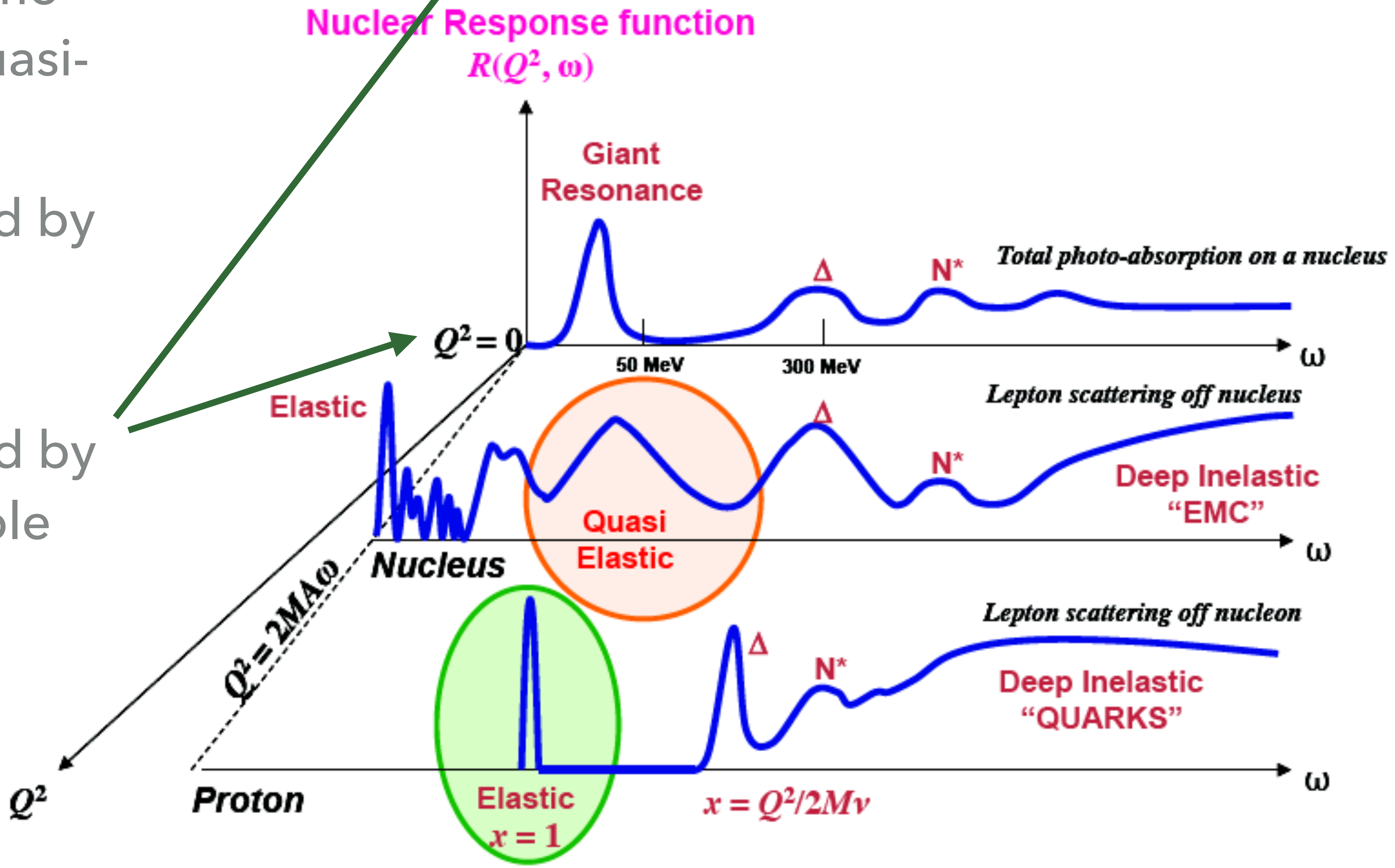
$$Q^2 = |\mathbf{q}|^2 - \omega^2$$

- We consider the scattering on the constituent nucleons in the nucleus, and focus on the quasi-elastic to delta region.
- The lower limit is constrained by avoiding the nuclear elastic contribution.
- The upper-limit is first limited by $Q^2 = 0$, and then by accessible experimental phase-space.



PUBLISHED EXPERIMENTAL RESULTS

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

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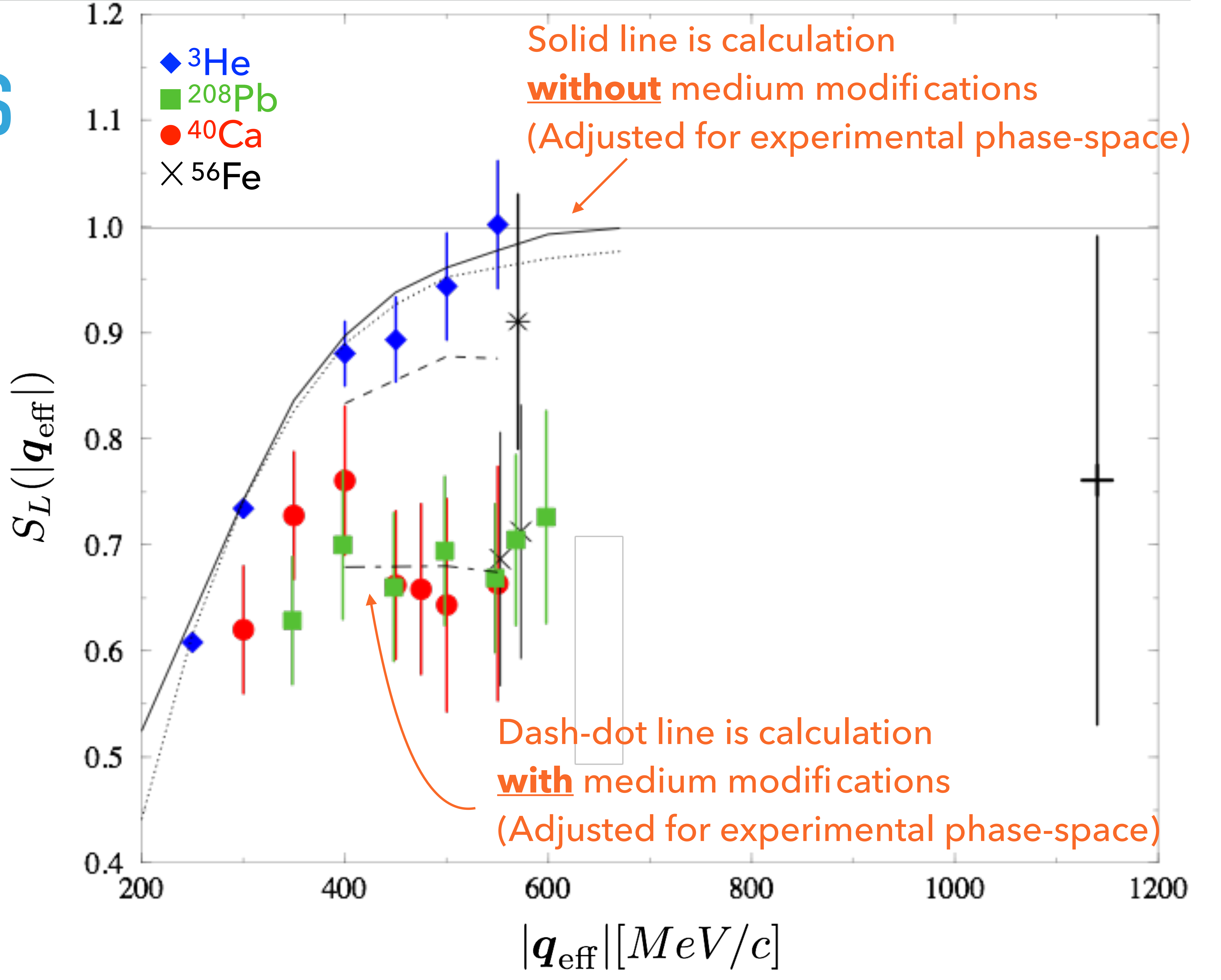
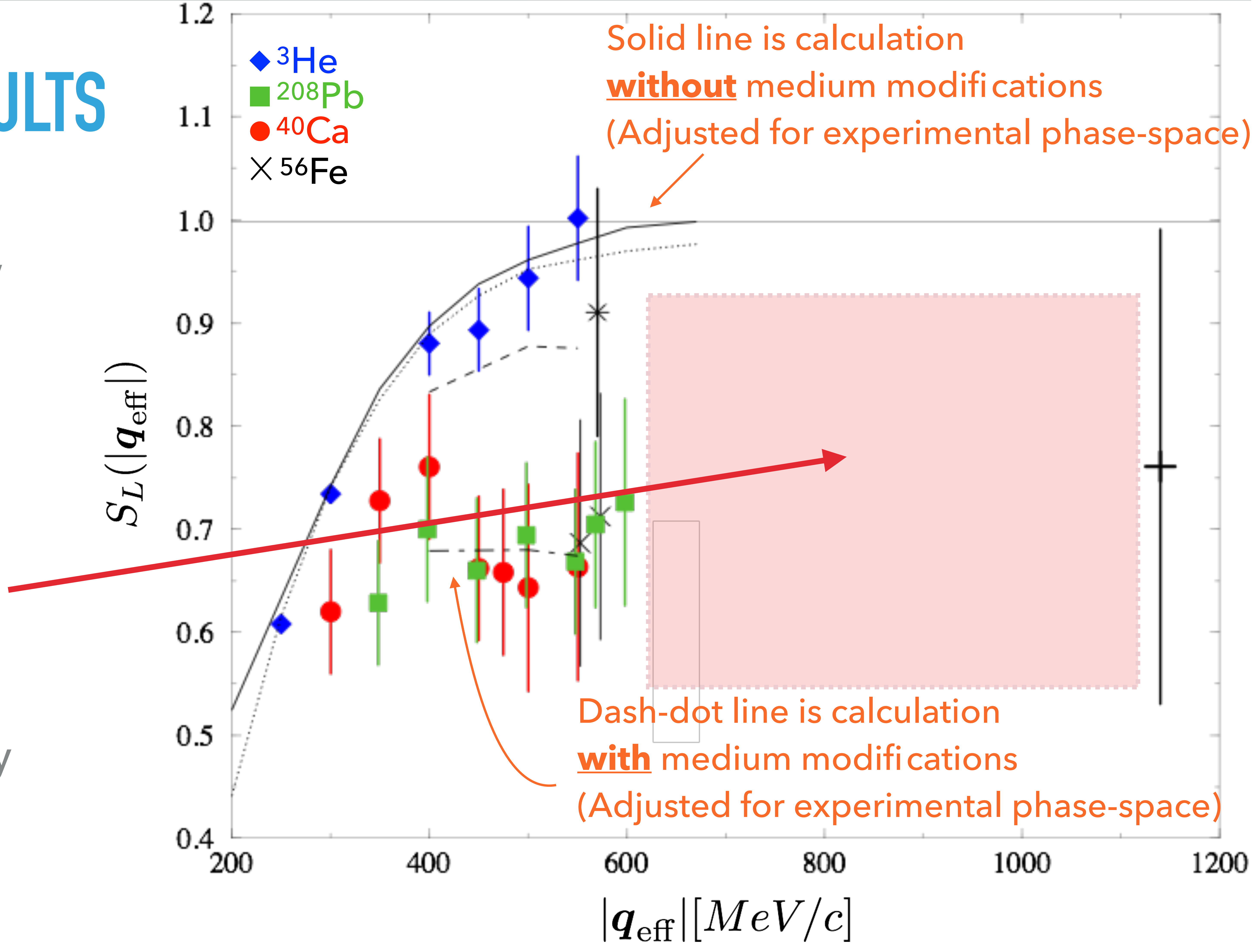


$|\boldsymbol{q}_{\rm eff}|$ is $|\boldsymbol{q}|$ corrected for a nuclei dependent mean coulomb potential. Methodology agreed on by Andreas Aste, Steve Wallace and John Tjon.

PUBLISHED EXPERIMENTAL RESULTS

- First group of experiments from Saclay, Bates, and SLAC 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!
    - Saclay, Bates limited in beam energy reach up to 800 MeV.
    - SLAC limited in kinematic coverage of scattered electron at |q| below 1150 MeV/c.



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THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

- Located in Newport News, Virginia
- Four main experimental halls
- Recently completed upgrade allows electron beam energies up to 12 GeV

Jefferson Lab Accelerator Site

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

EXPERIMENTAL DESIGN

- Need R_L ⟶ Use Rosenbluth separation!

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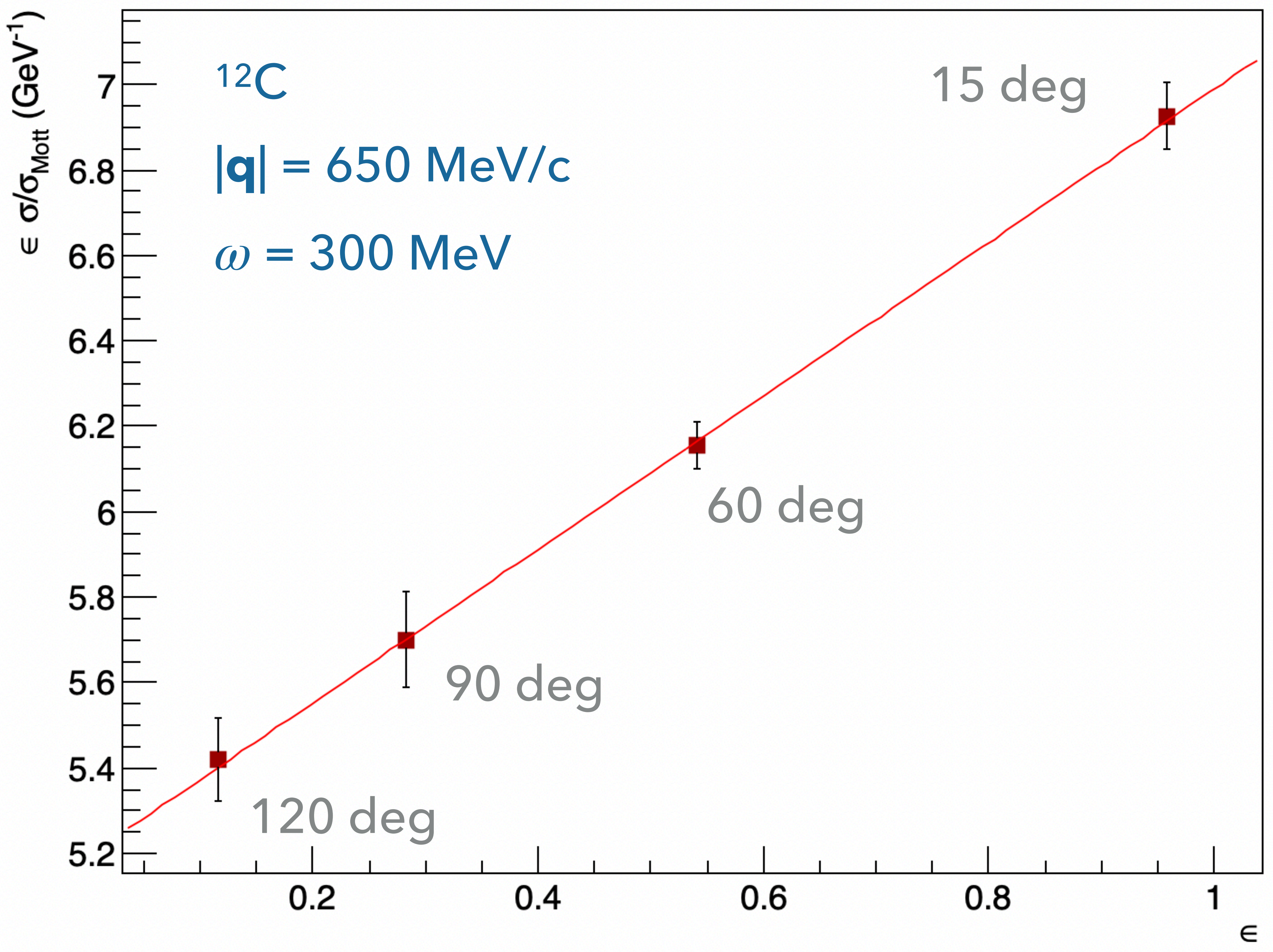
Slope = $\frac{Q^4}{\vec{q}^4} R_L$

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

CSR calculated at constant |**q**| !!

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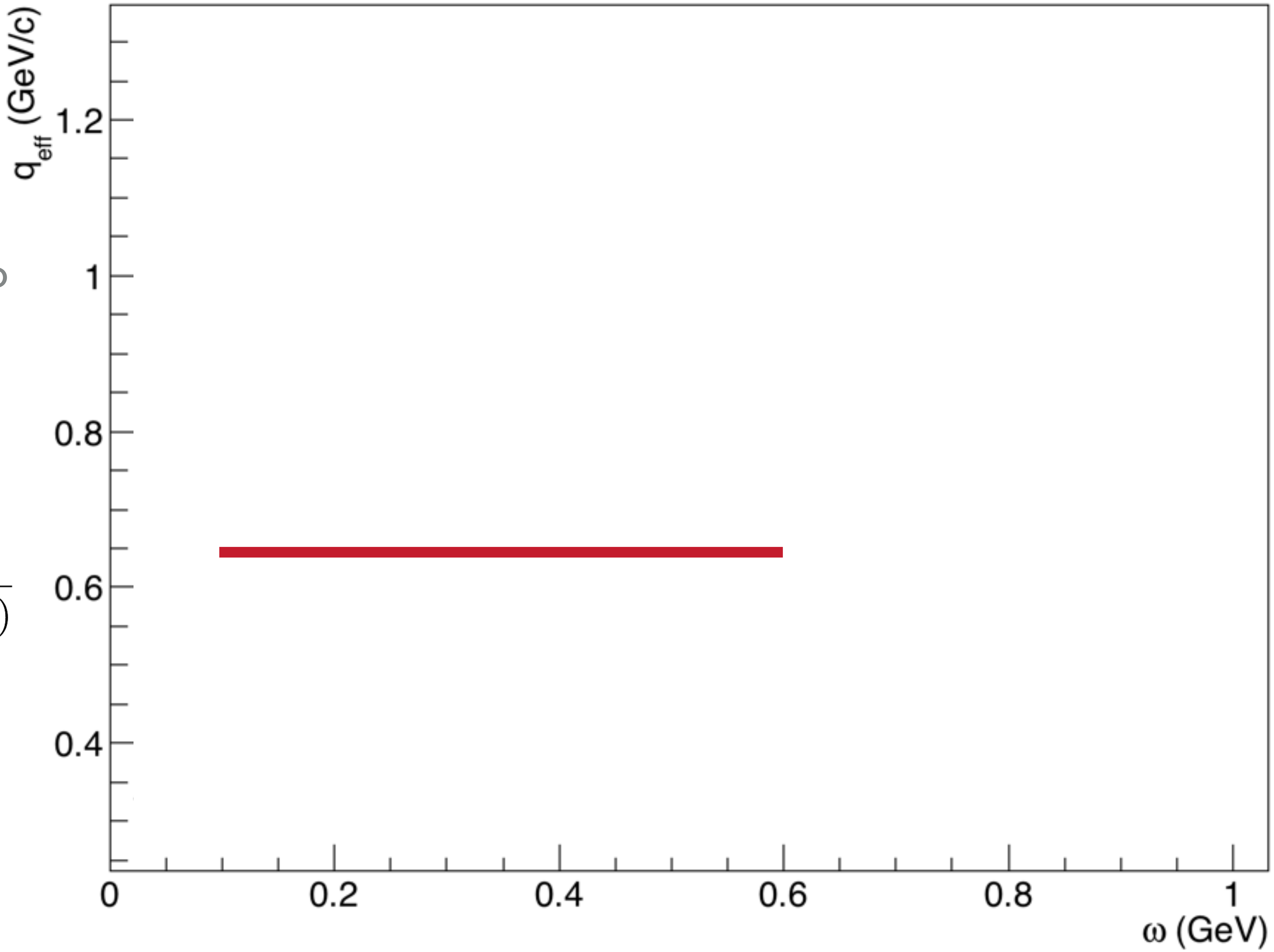

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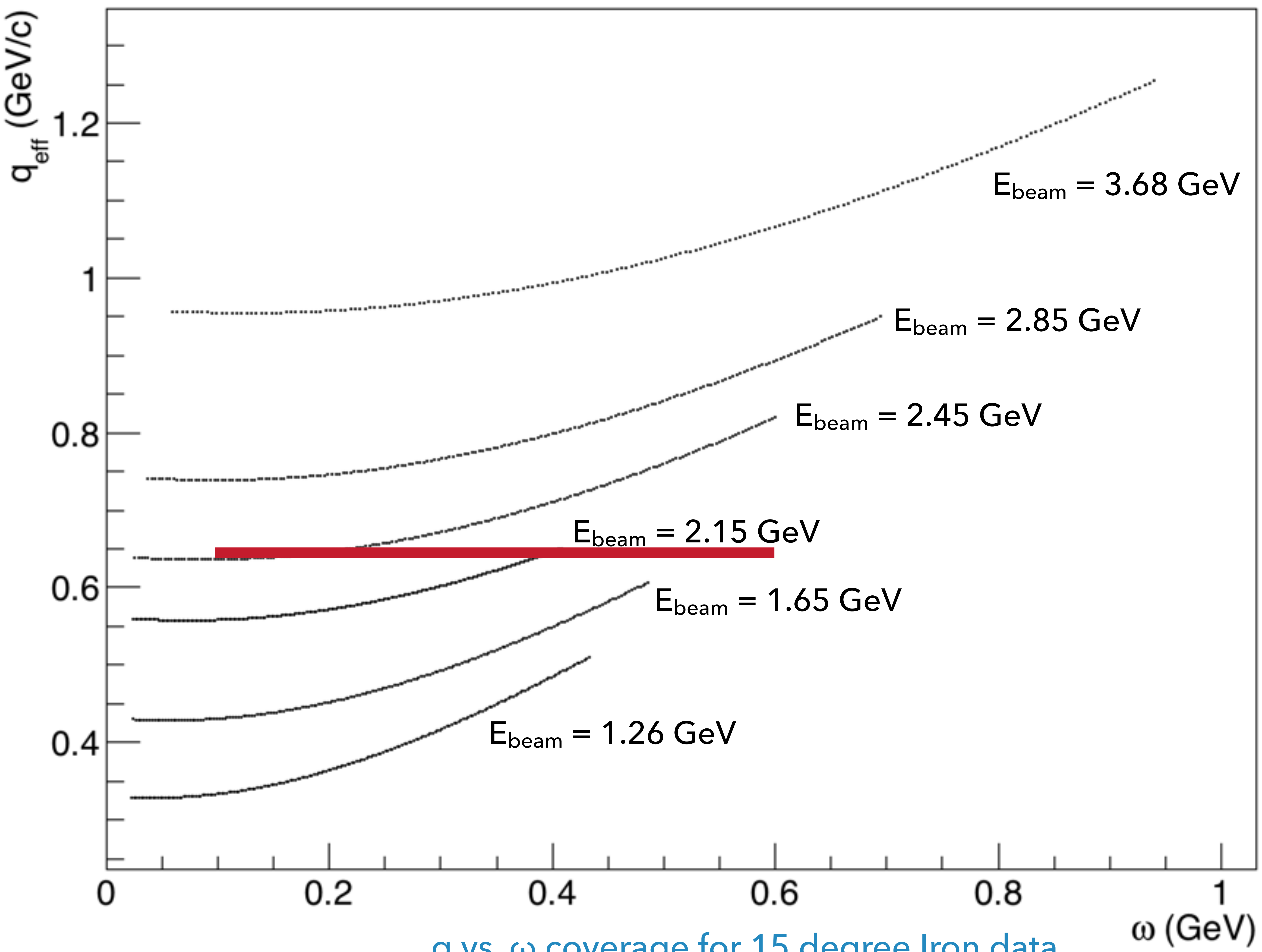
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.



q vs. ω coverage for 15 degree Iron data

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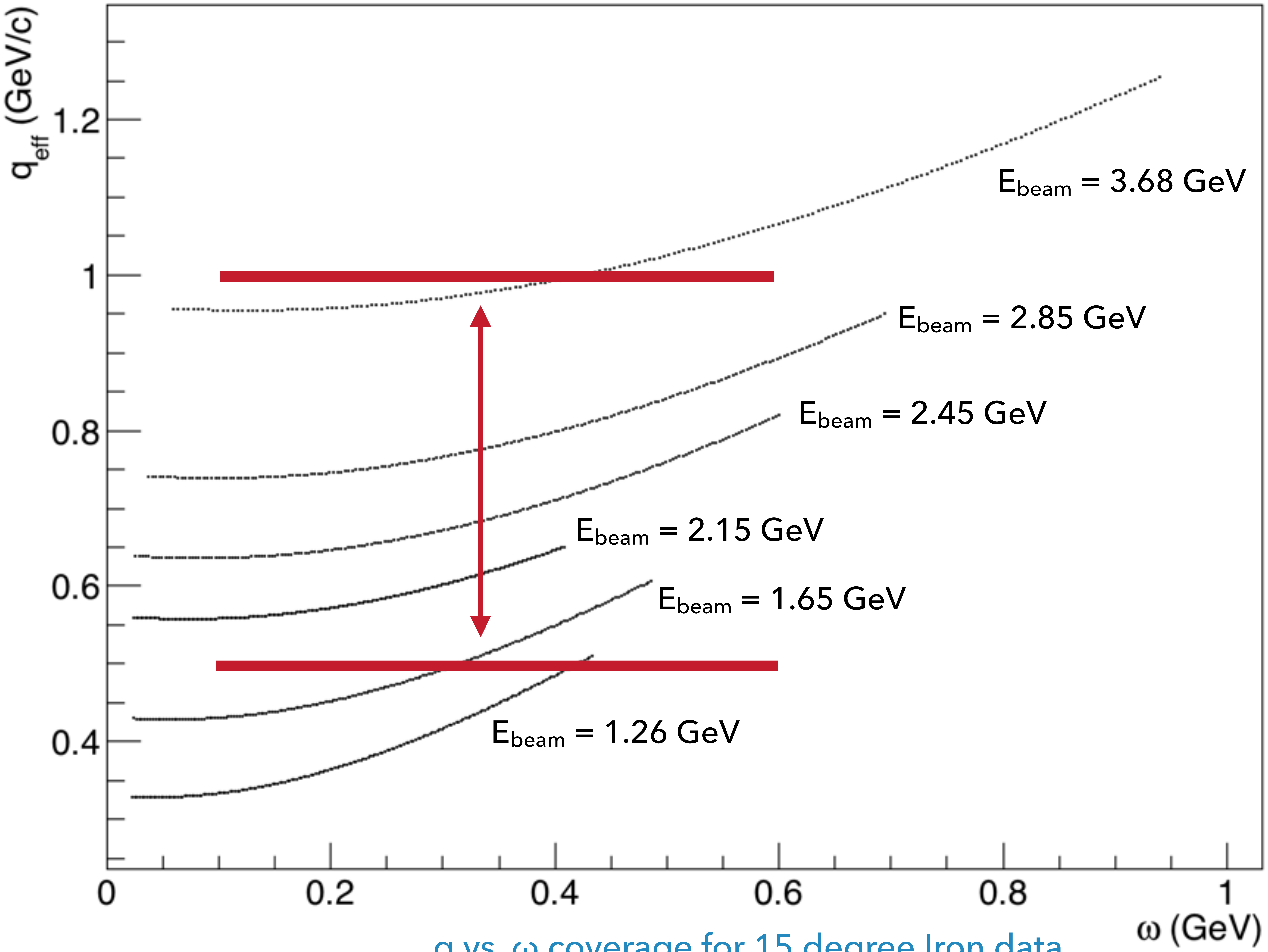
- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.
  - |q| can be selected between 550 and 1000 MeV/c



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

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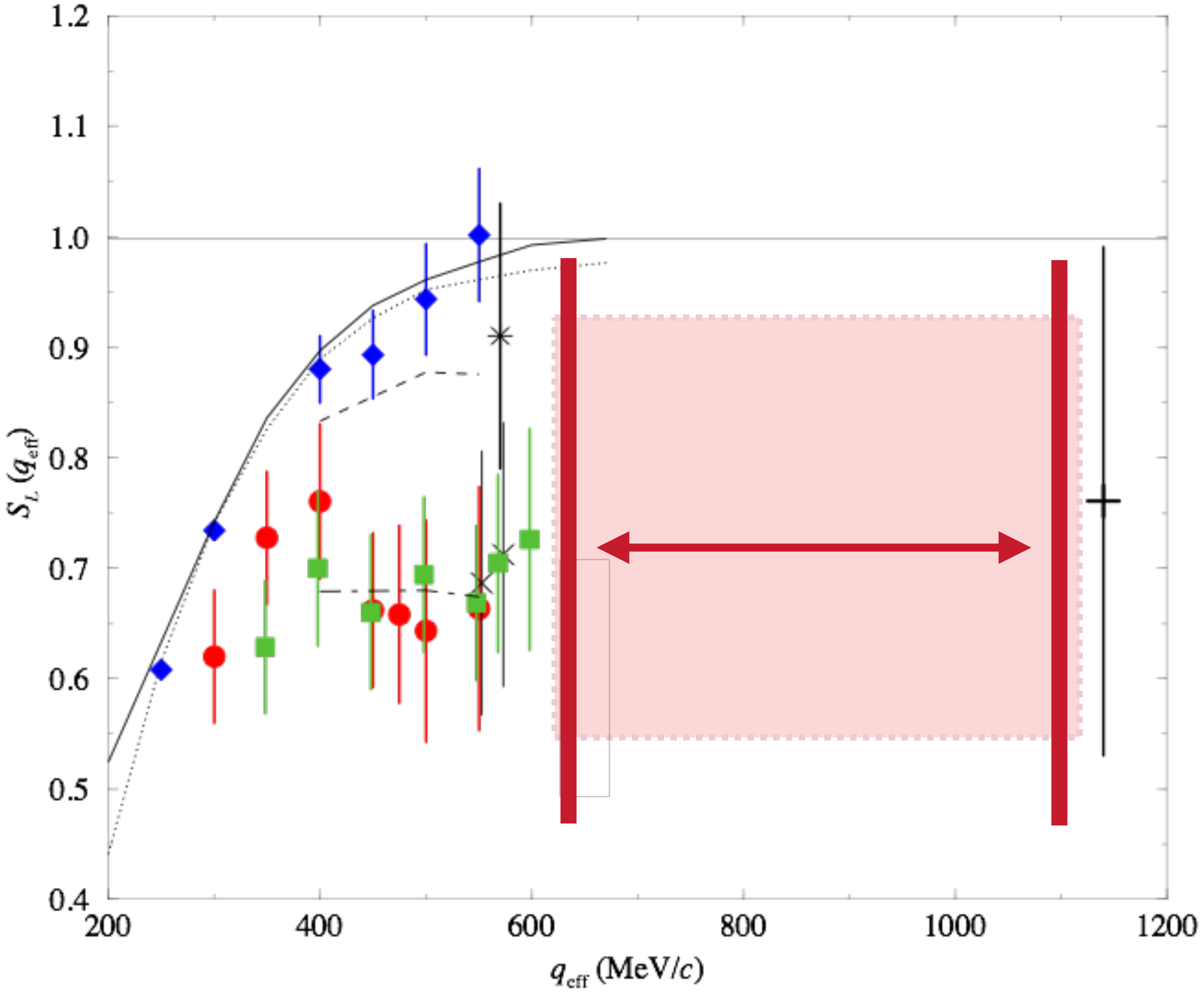

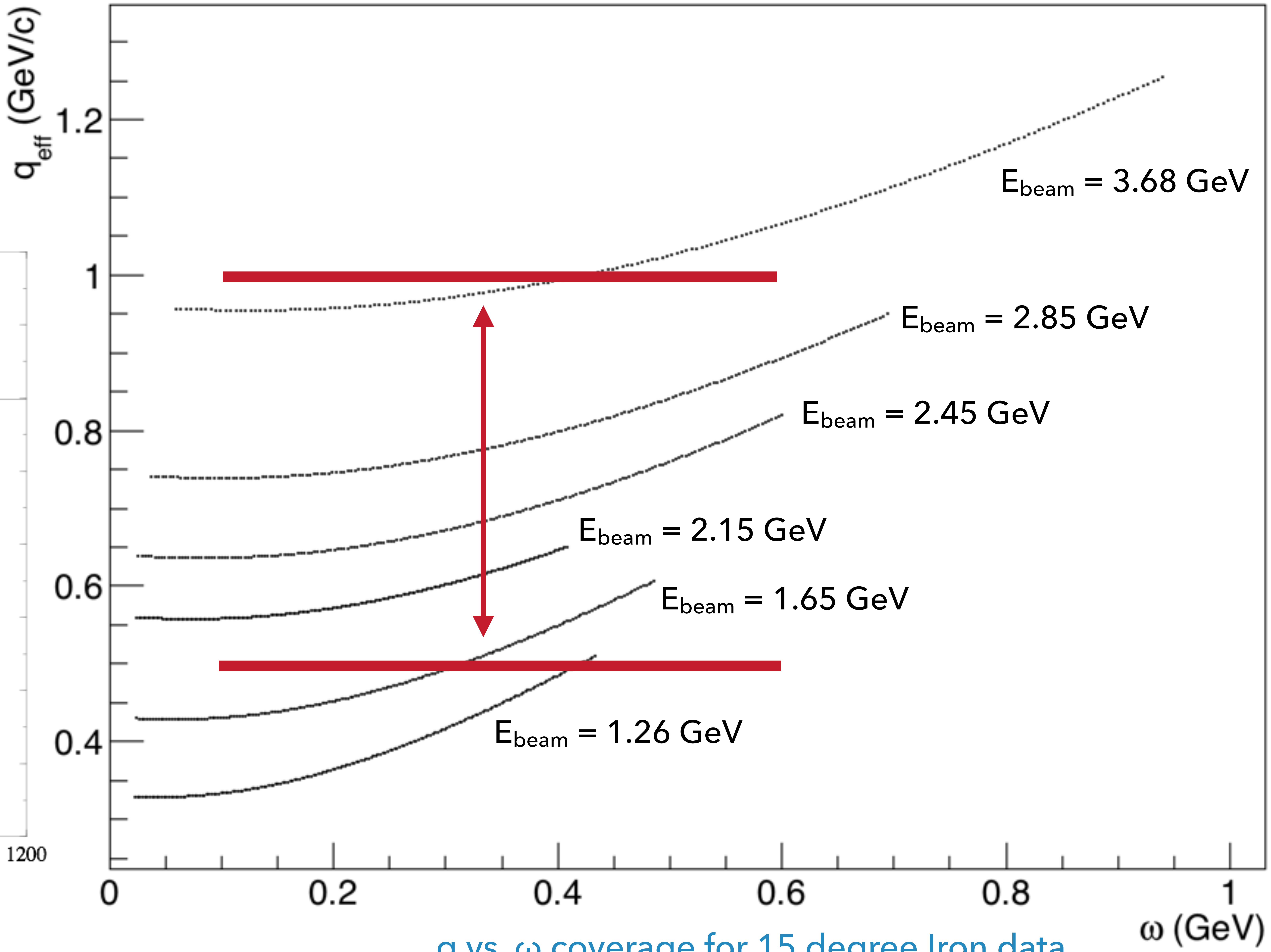

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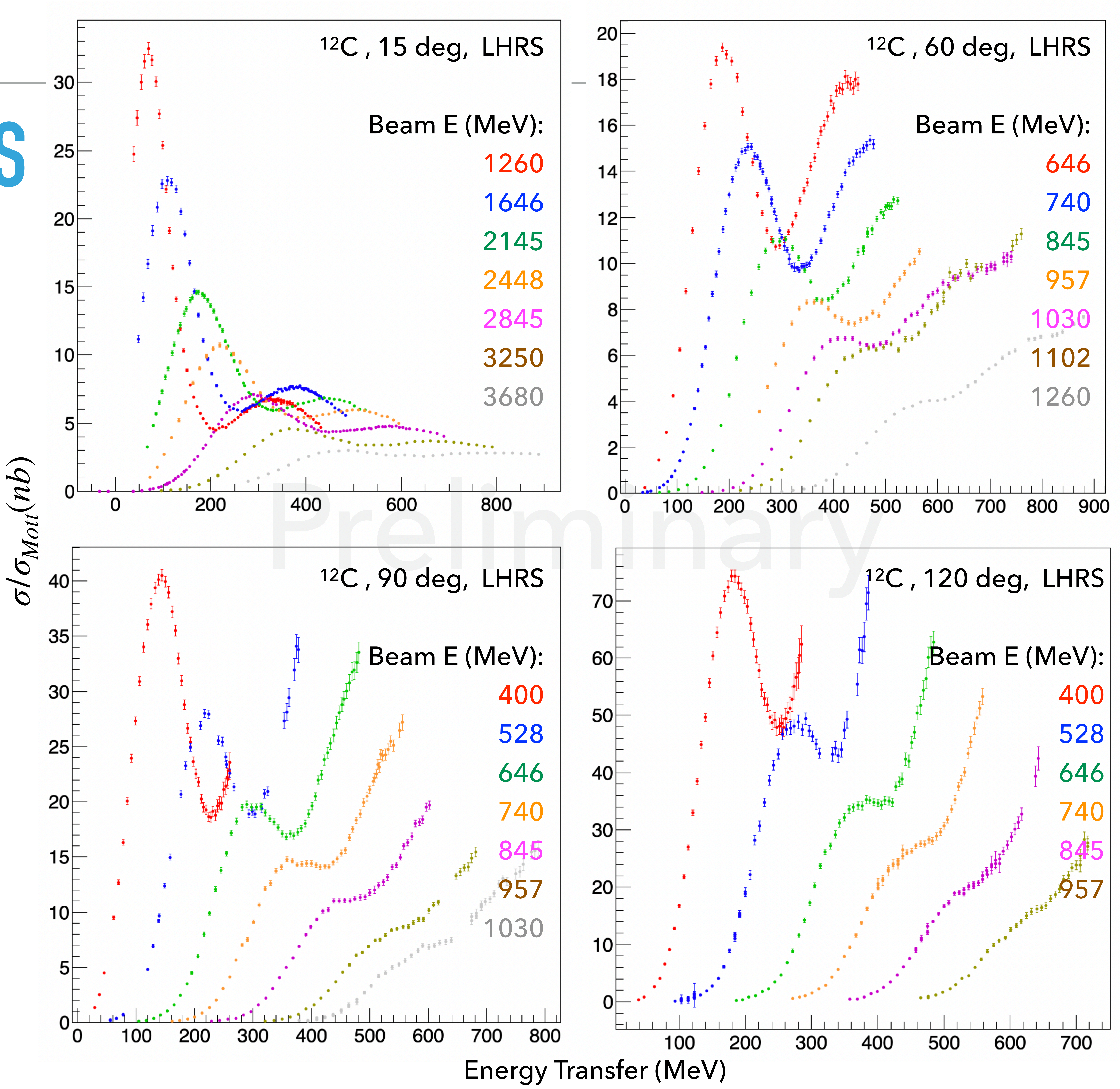
EXPERIMENTAL SPECIFICS

- 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, ^{208}Pb.



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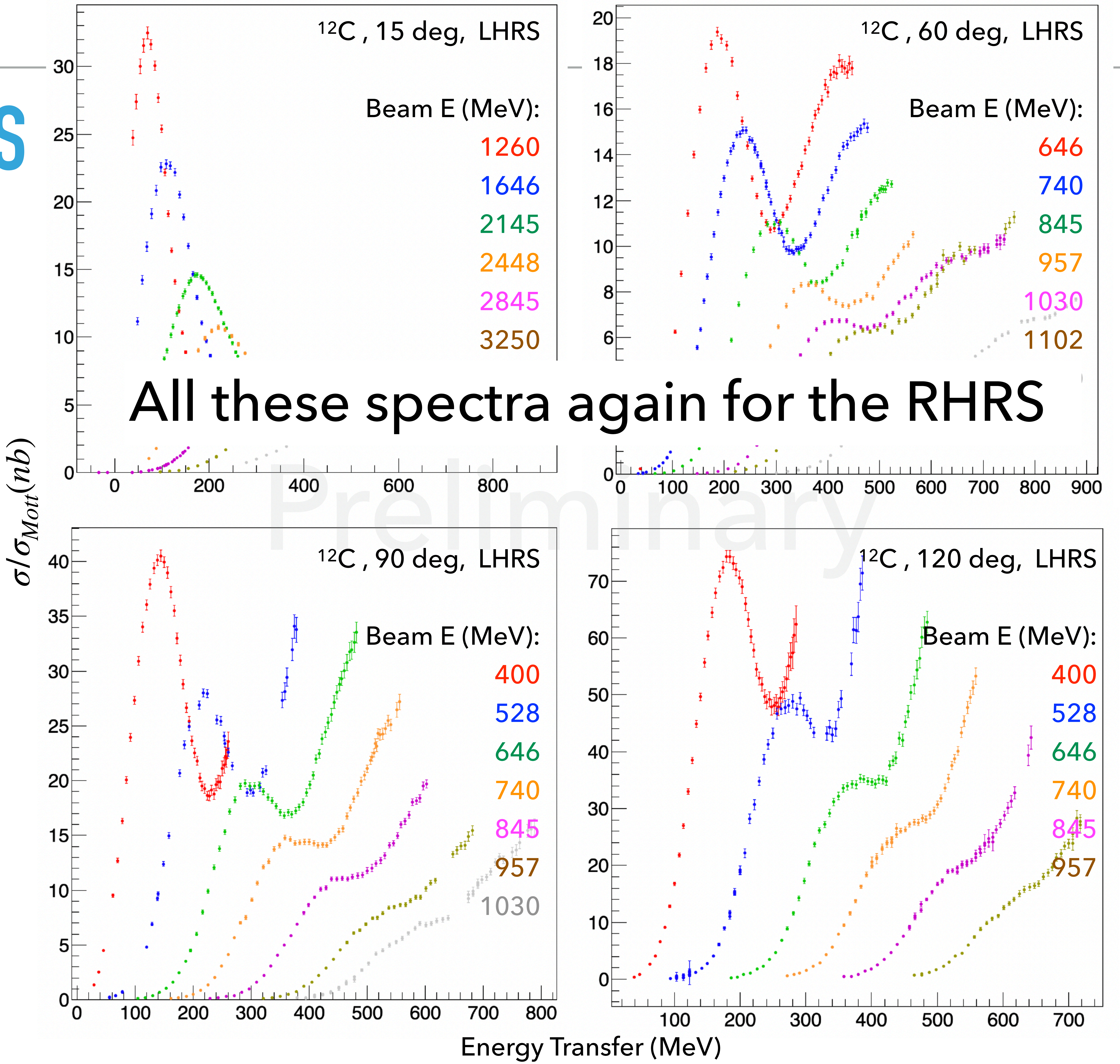

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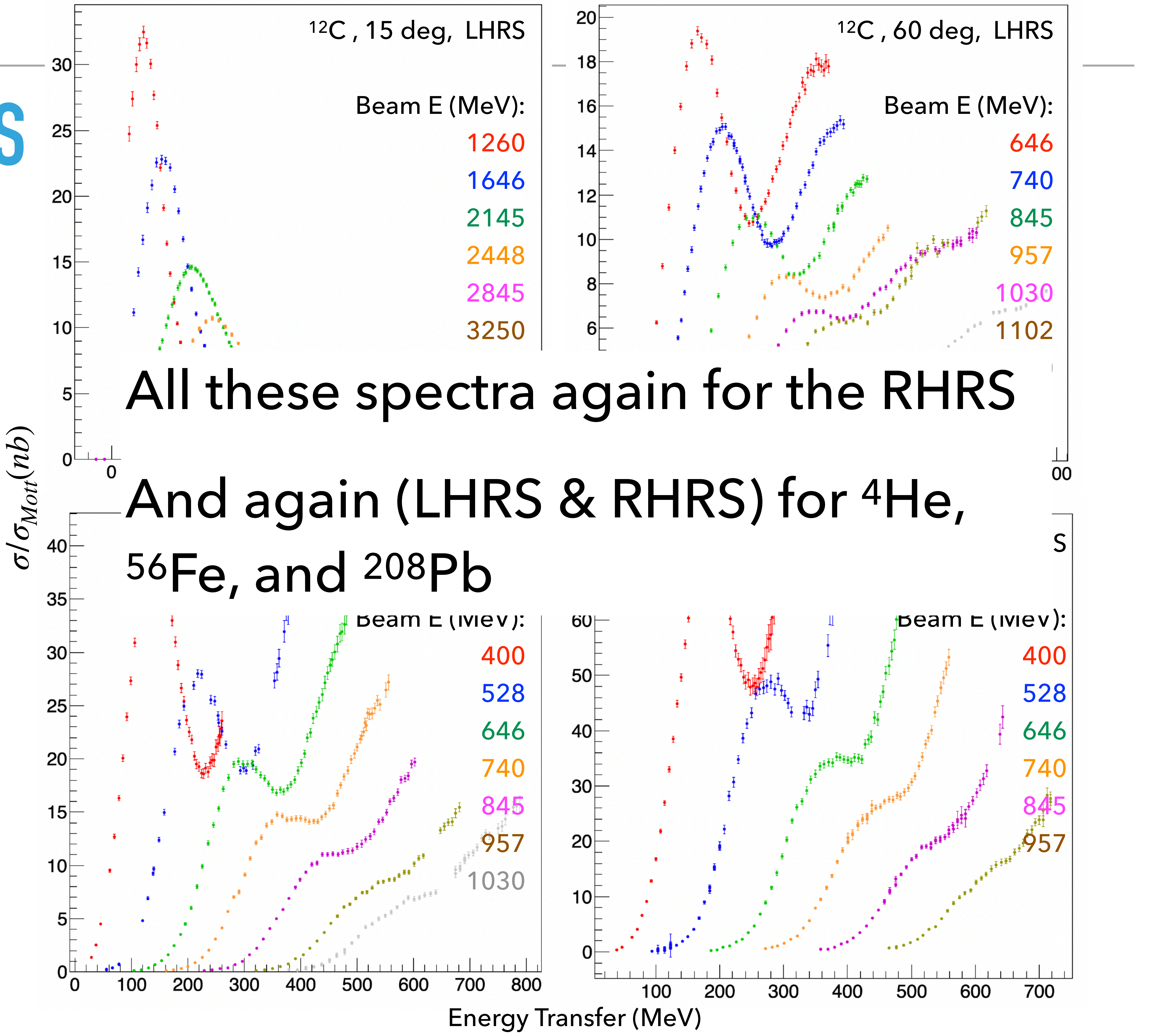

All these spectra again for the RHRS

And again (LHRS & RHRS) for ^{4}He, ^{56}Fe, and ^{208}Pb

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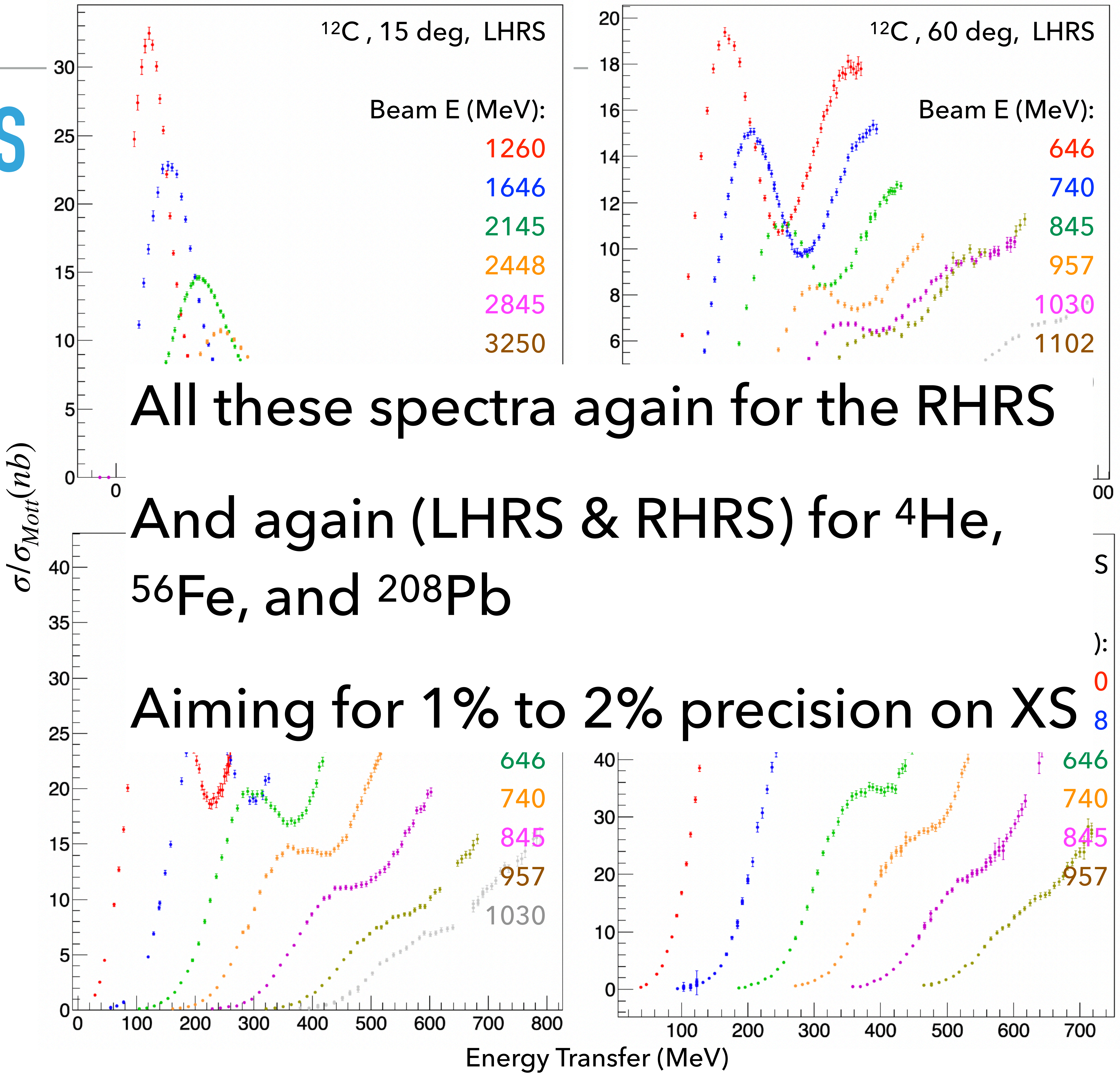

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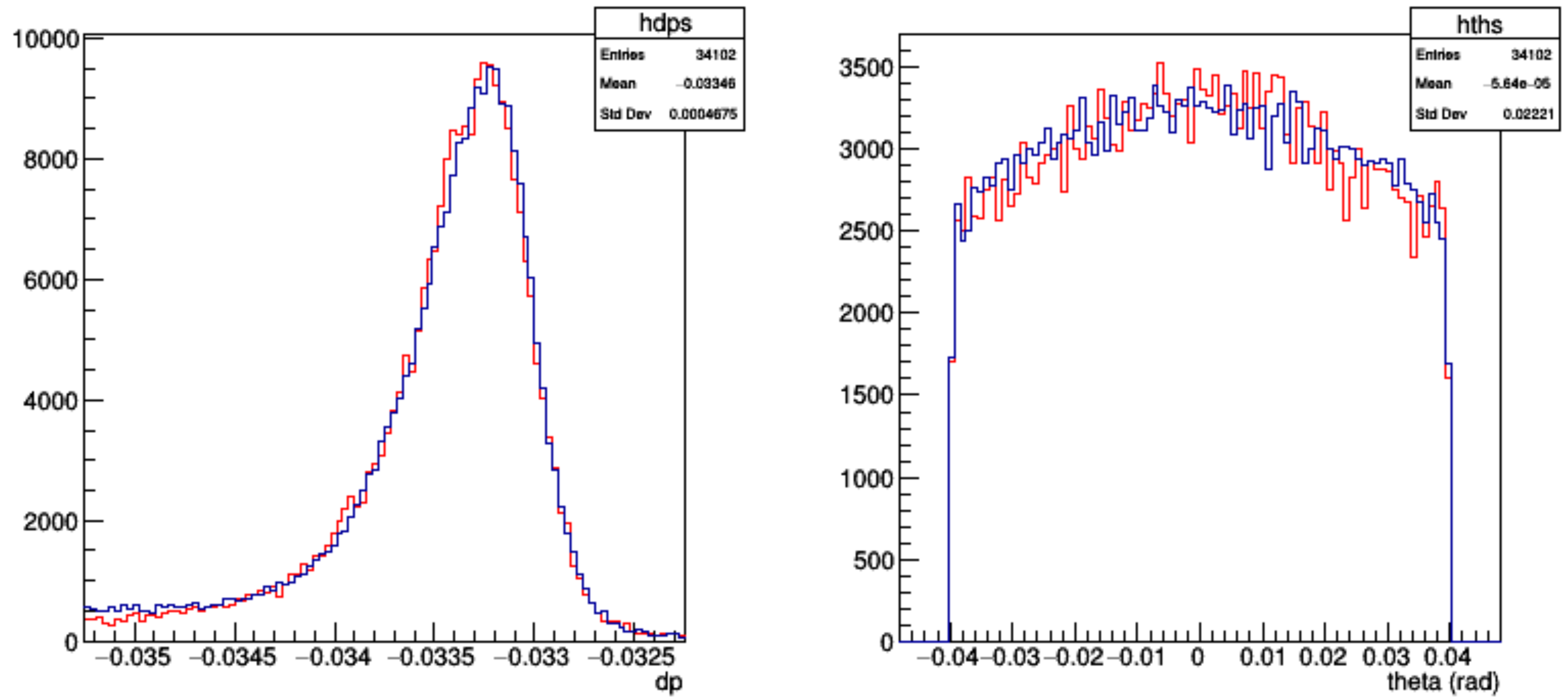
Aiming for 1% to 2% precision on XS

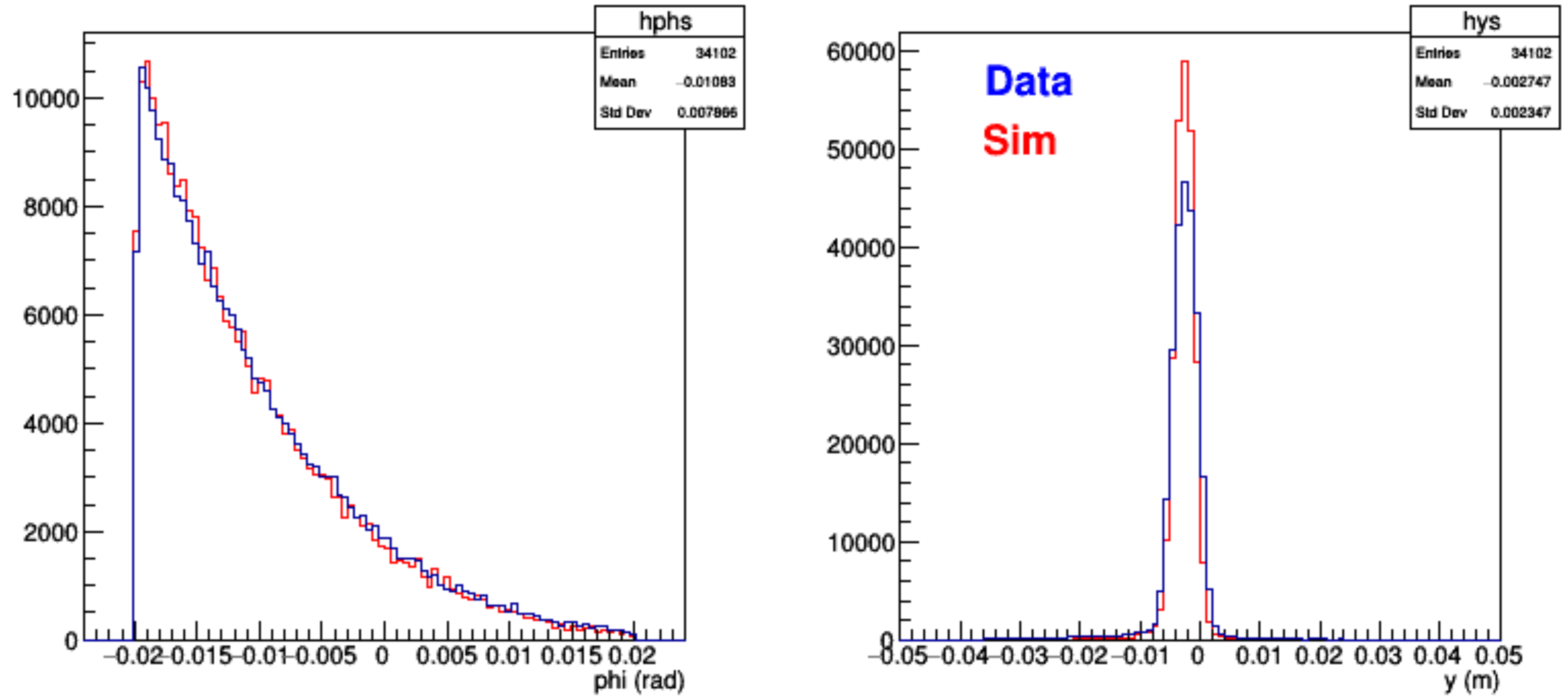
EXPERIMENTAL CHALLENGES

- Data collection for many different settings!
  - Special calibration data needed to be strategically scheduled.
    - Elastic runs and optics runs could not be reasonably done for all settings, so improved algorithms needed to be developed to apply calibrations to all run-settings.
  - Very low momentum settings push the limits of the HRS spectrometers.
    - Negligible effects in high momentum settings must be considered with care.
      - Hysteresis effects and magnetic field read-back on the central momentum of the spectrometer
      - Backgrounds from magnet-rescattering.
      - Extra care needed for calculations of multiple-scattering and radiation loss.
  - Accurate interpolation routines needed to be developed for both radiative corrections and general analysis.
  - Systematic uncertainty analysis of each spectrometer arm independently.

ELASTIC XS CALCULATIONS, AND ELASTIC TAIL CORRECTIONS



^{12}C elastic XS at 1260 MeV, 15 degrees



- Blue histograms are reconstructed data.
- Red histograms are monte-carlo:
  - Event sample generated from expected XS calculations (Fourier-Bessel fit to world data)
  - Radiative effects (internal, external, vertex) are handled, including exact bremsstrahlung distributions.
  - Resolution effects are applied by calculating the expected material effects of tracks passing through the VDC chamber materials.

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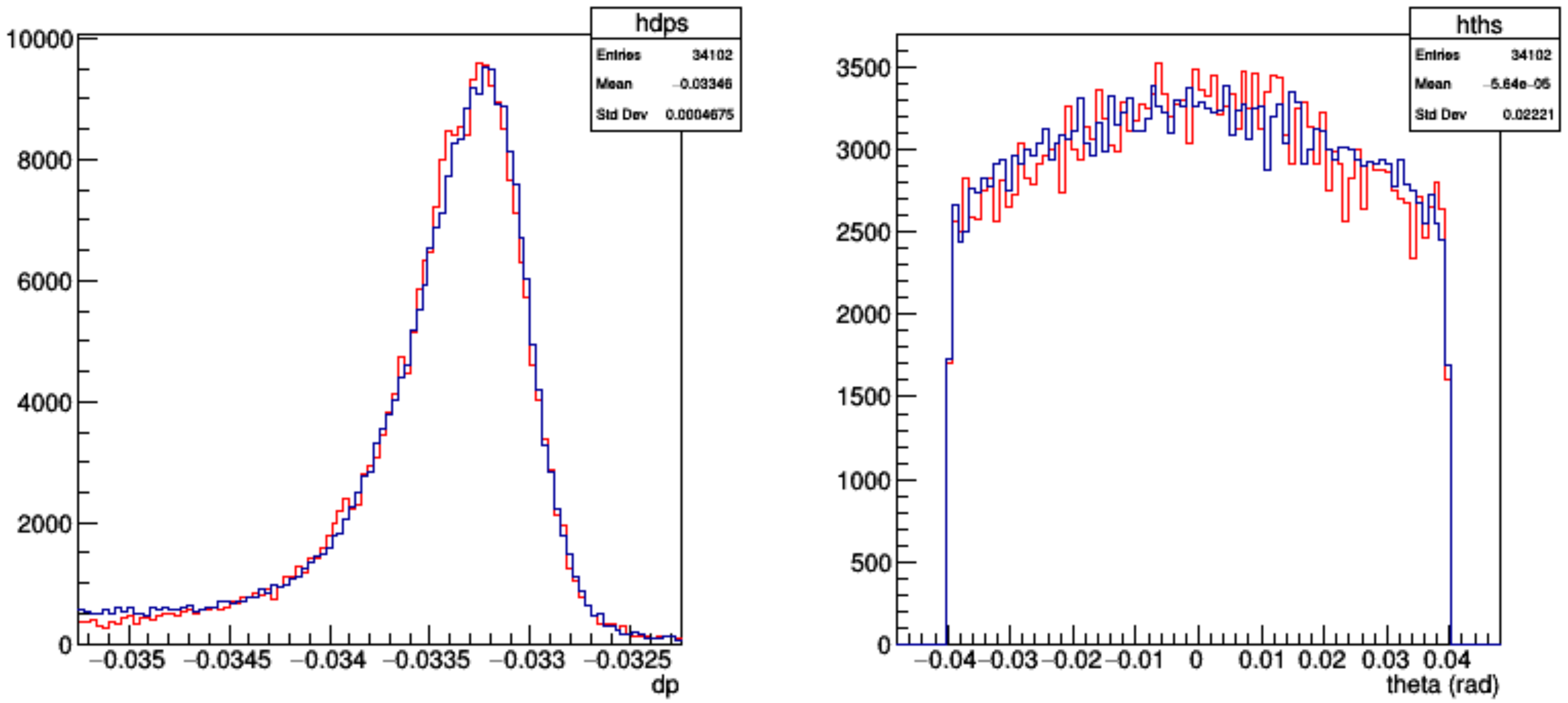

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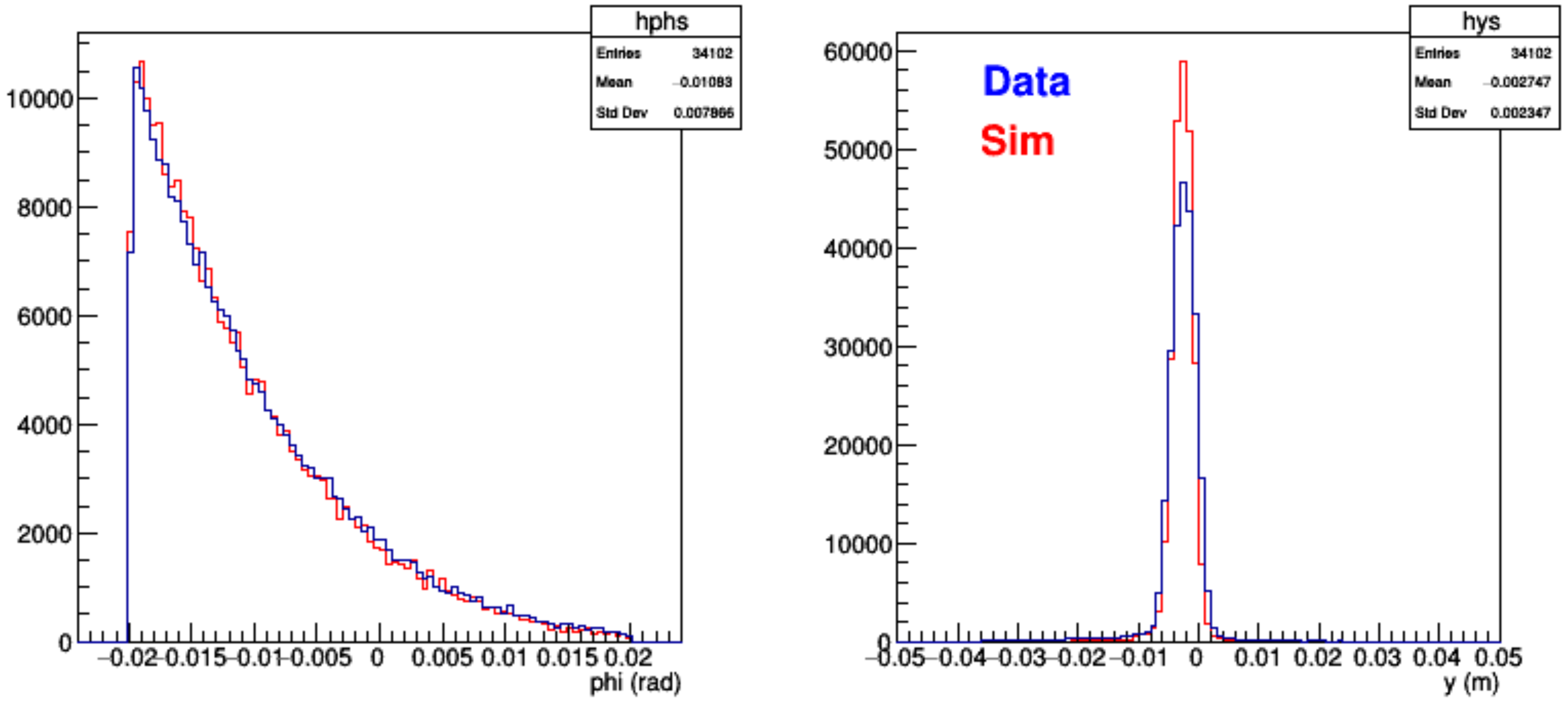

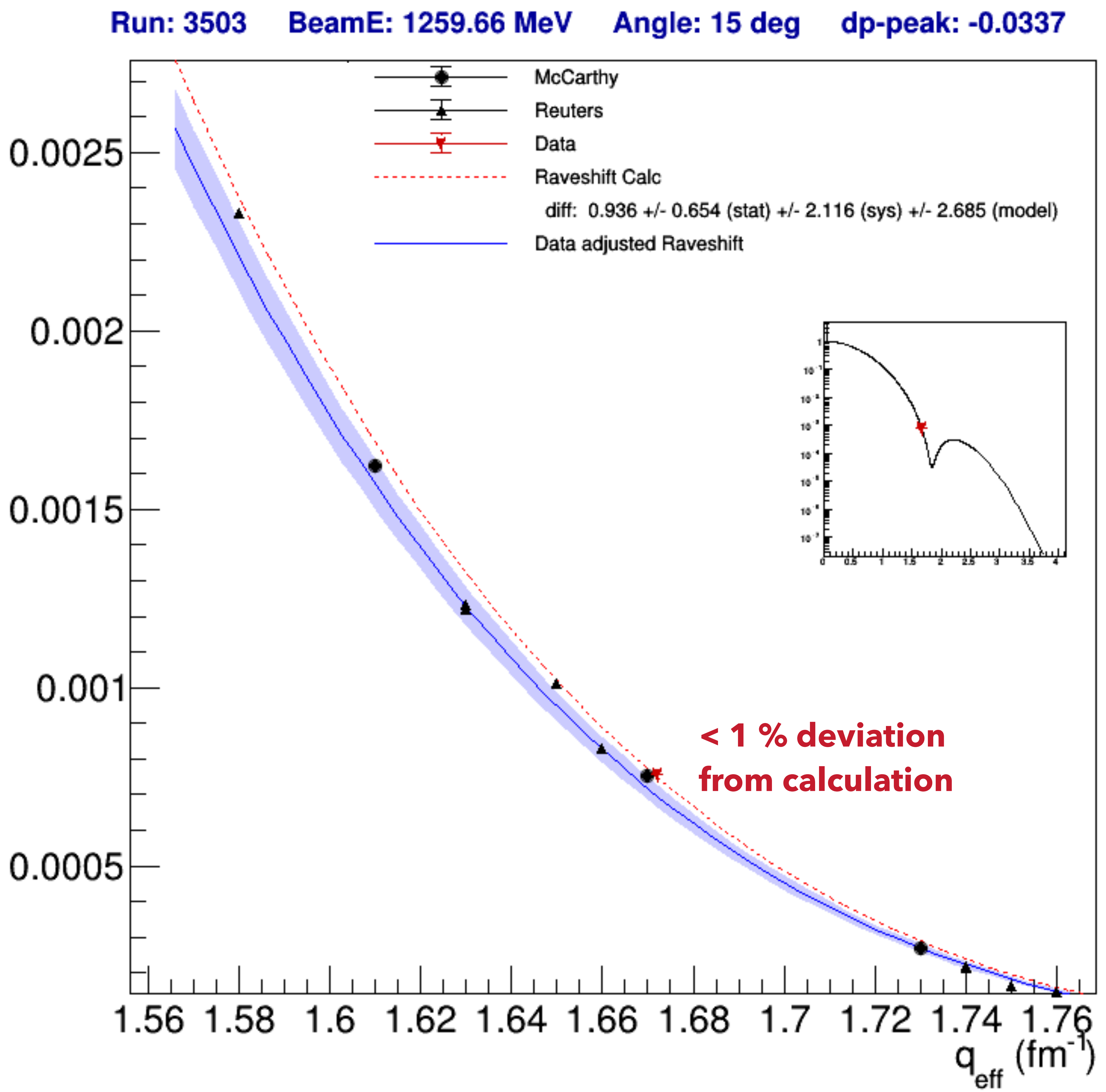

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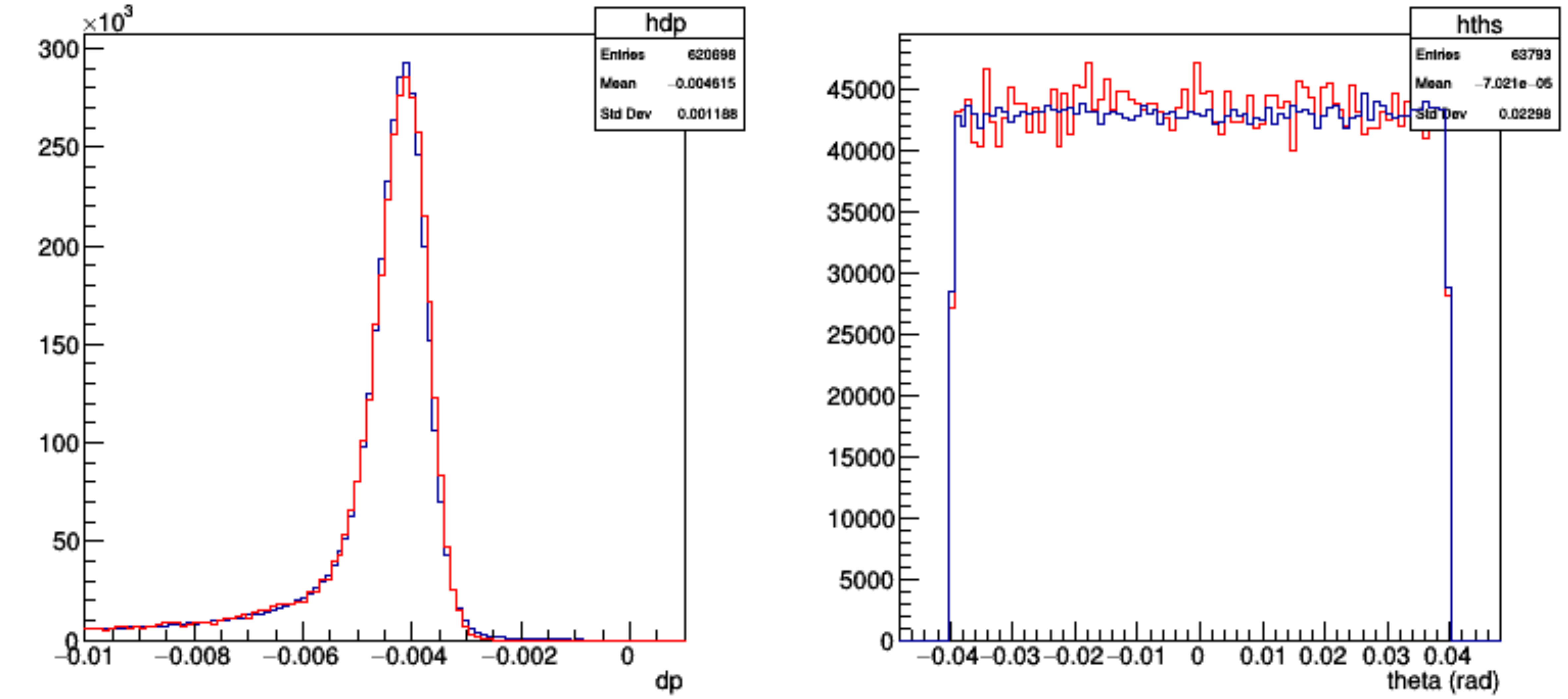
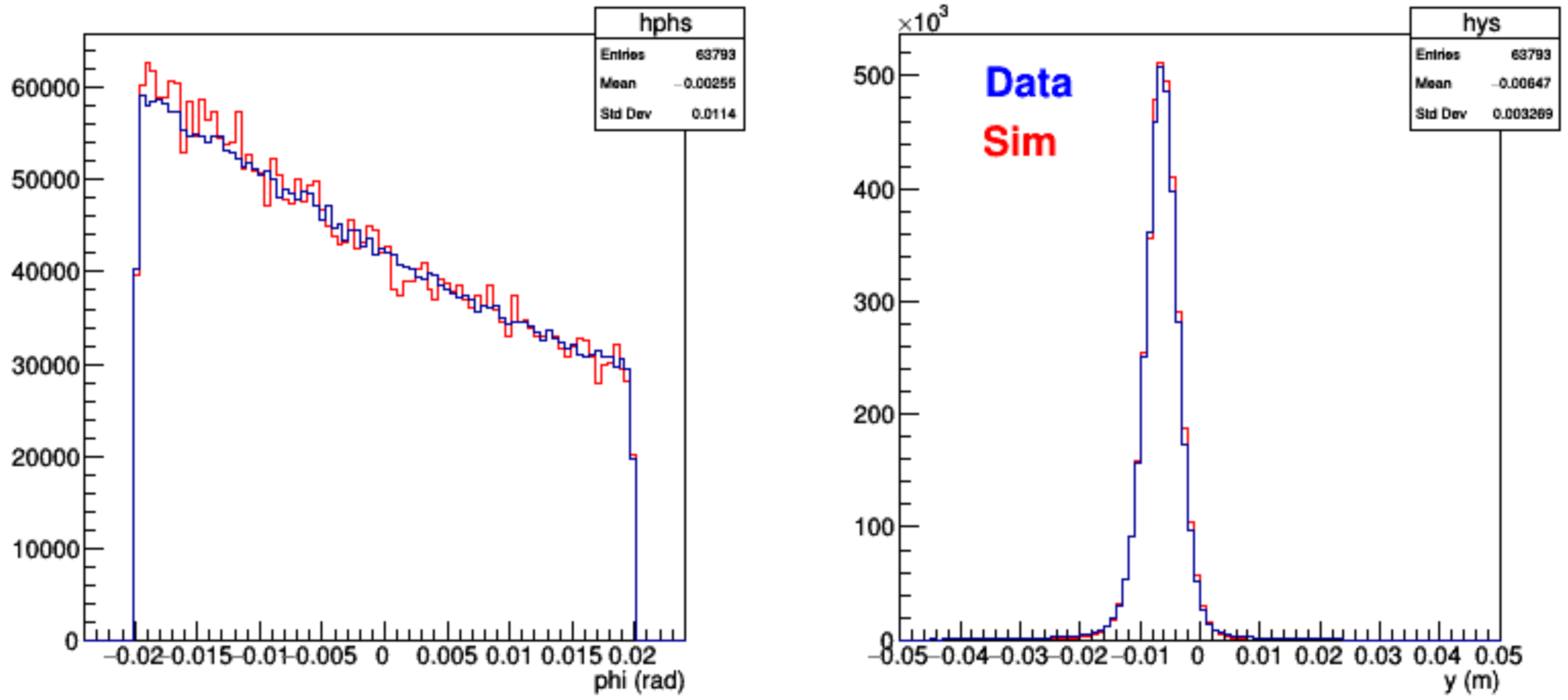
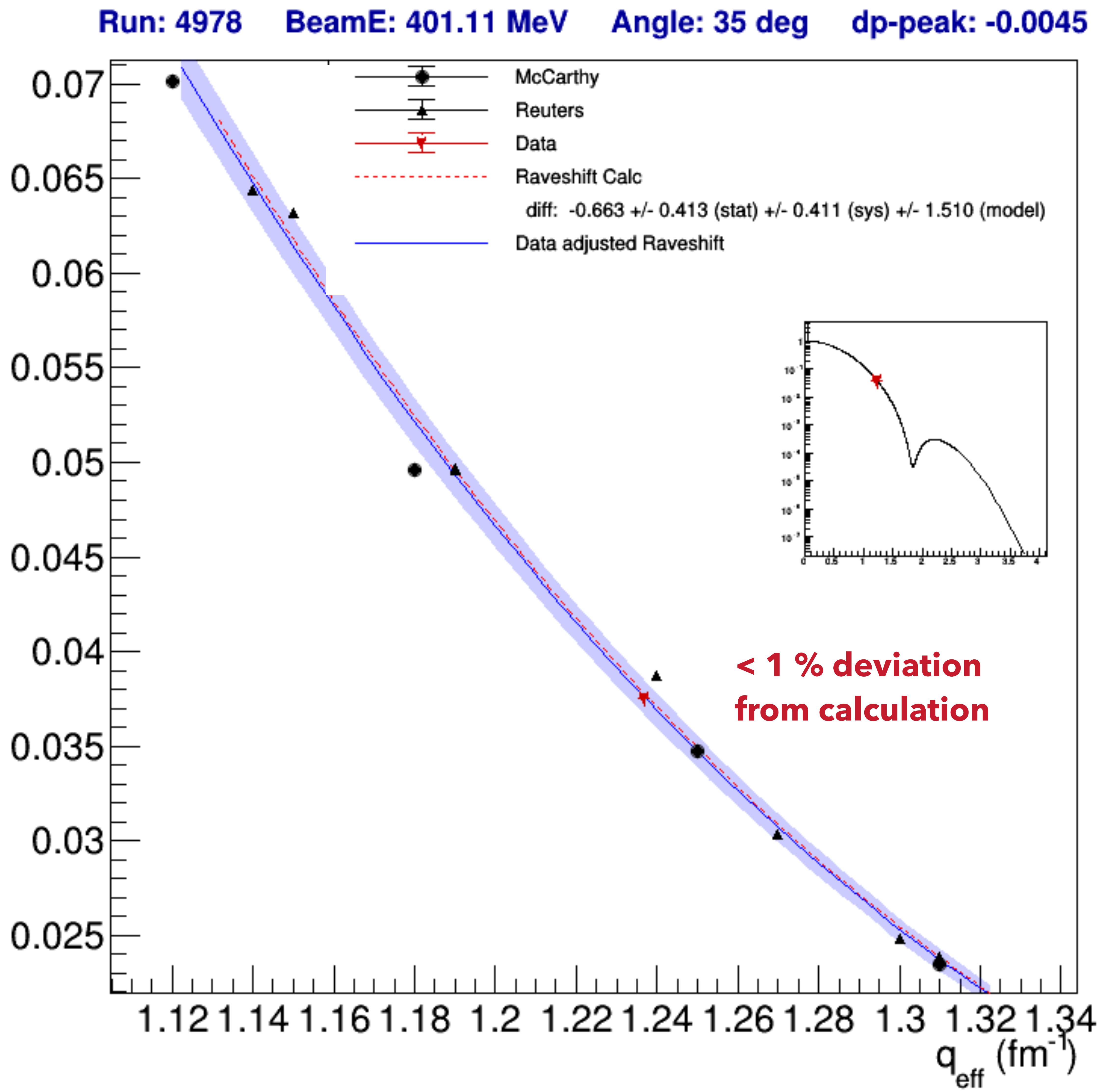
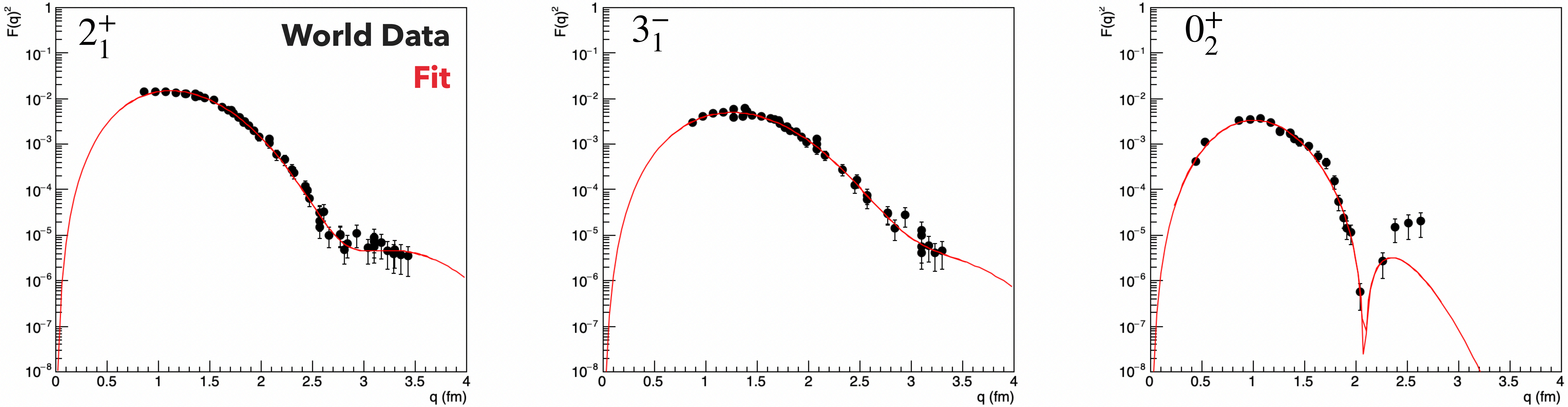


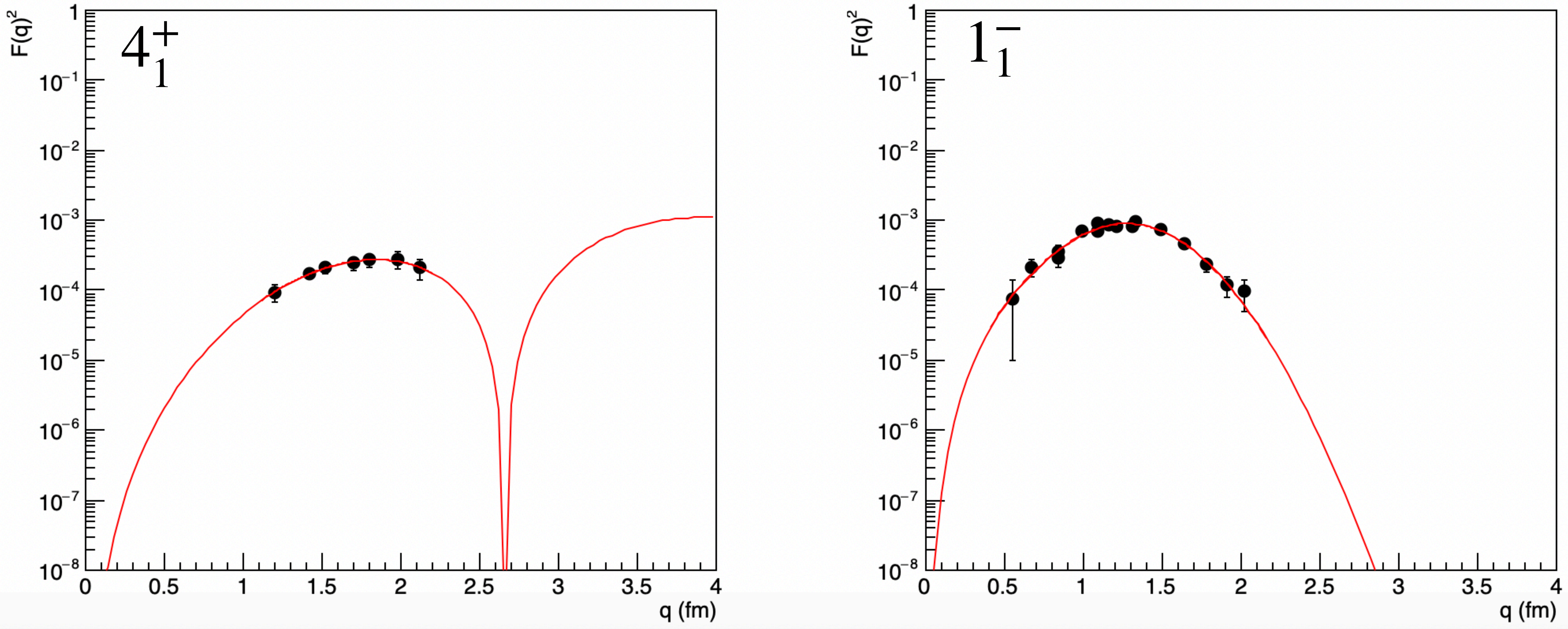
^{12}C elastic XS at 400 MeV, 35 degrees





EXCITED ELASTIC STATES





Extractions of excited elastic states based on fit of transition form-factors to world data.

Functional form follows an analytic, global, and model-independent analysis introduced recently* (mostly in the study of the 0_2^+ "Hoyle" state)

$$F(q) = \frac{1}{Z} e^{-\frac{1}{2}(bq)^2} \sum_{n=1}^{n_{\max}} c_n (bq)^{2n}$$

* M. Chernykh, *et al*. Phys. Rev. Lett. 105

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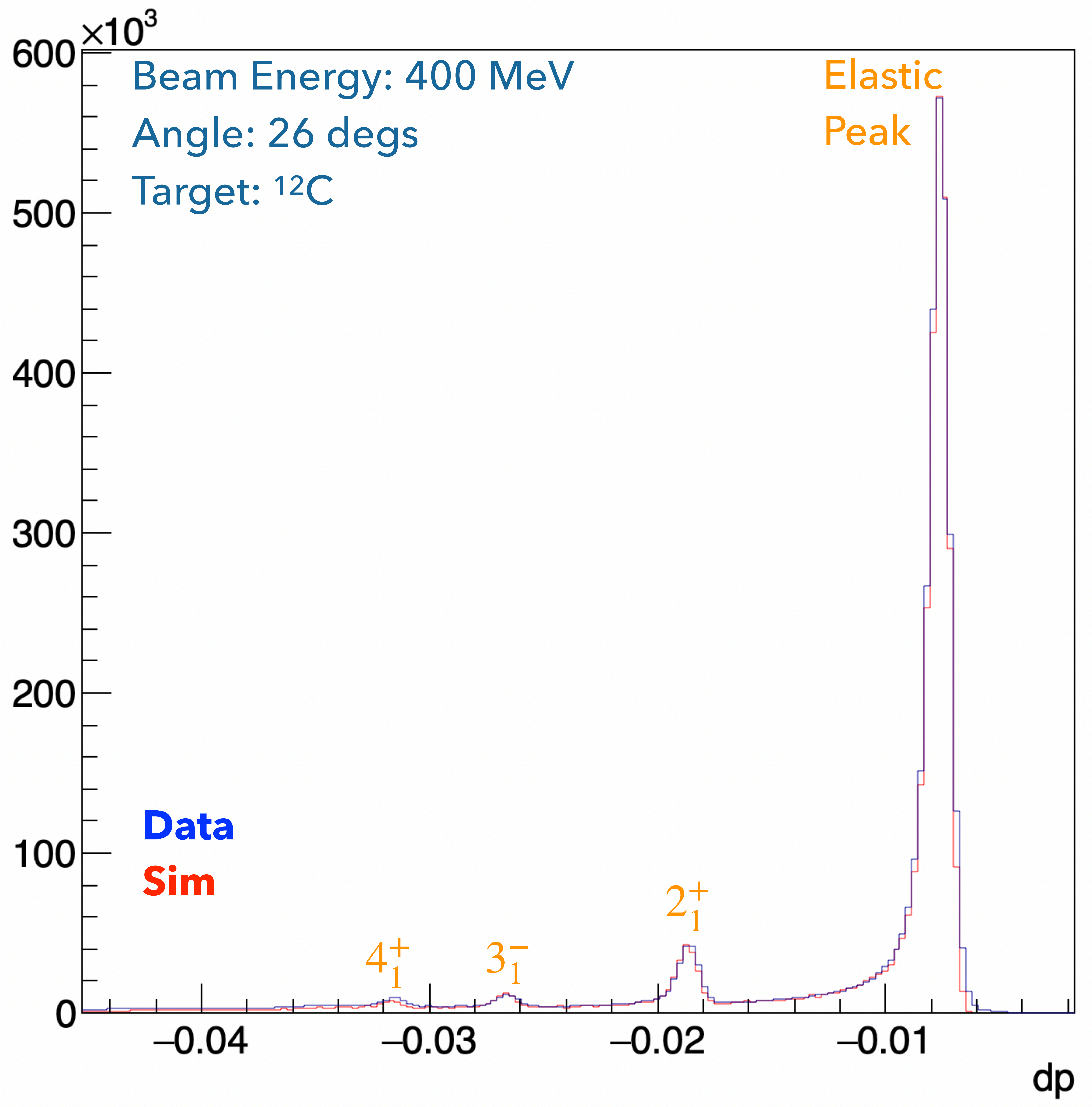
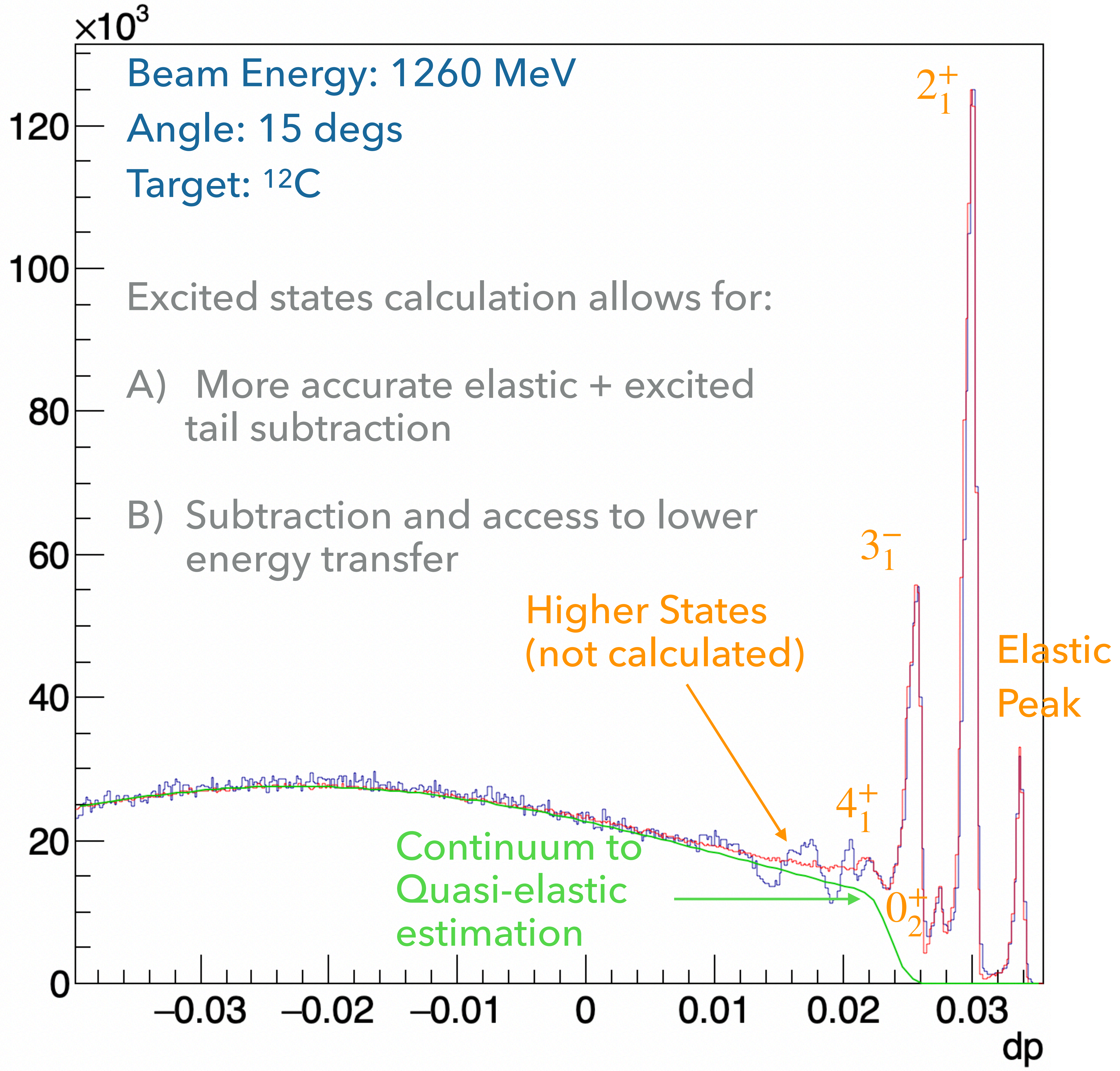
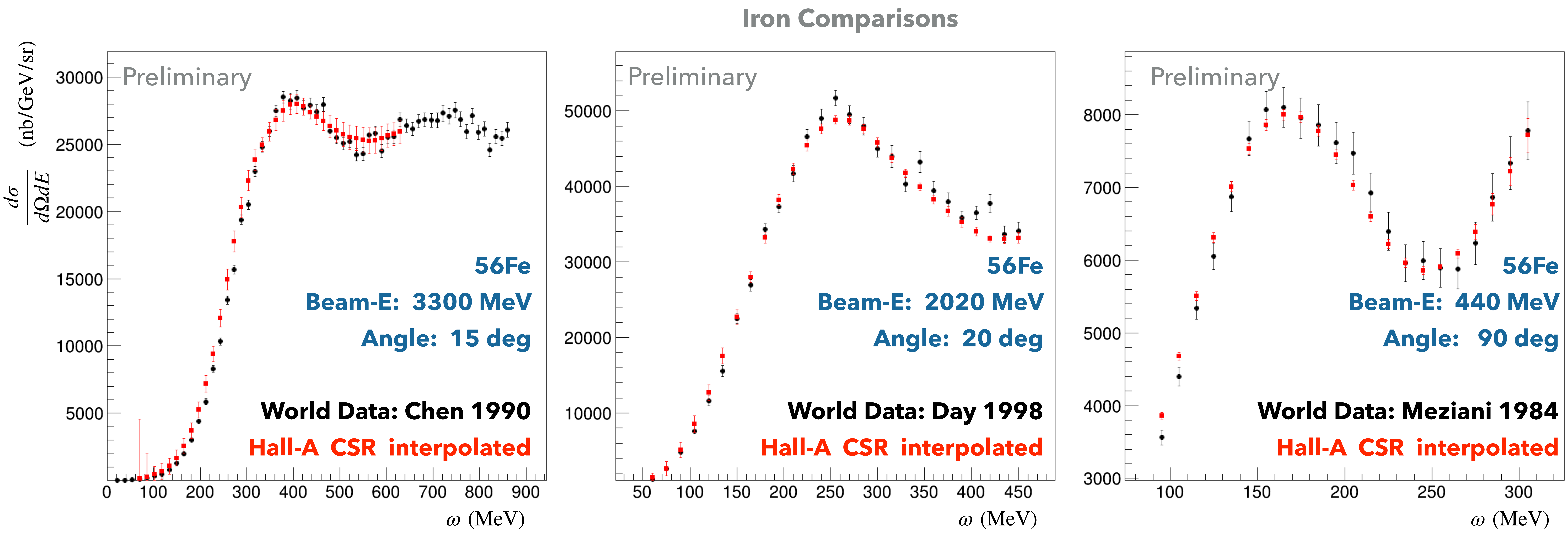




* M. Chernykh, *et al*. Phys. Rev. Lett. 105

COMPARISON TO WORLD DATA

- By using our available ω / |q| space over 4 angles, we can interpolate to any ω / |q| , and use Rosenbluth fits to calculate at a given angle.



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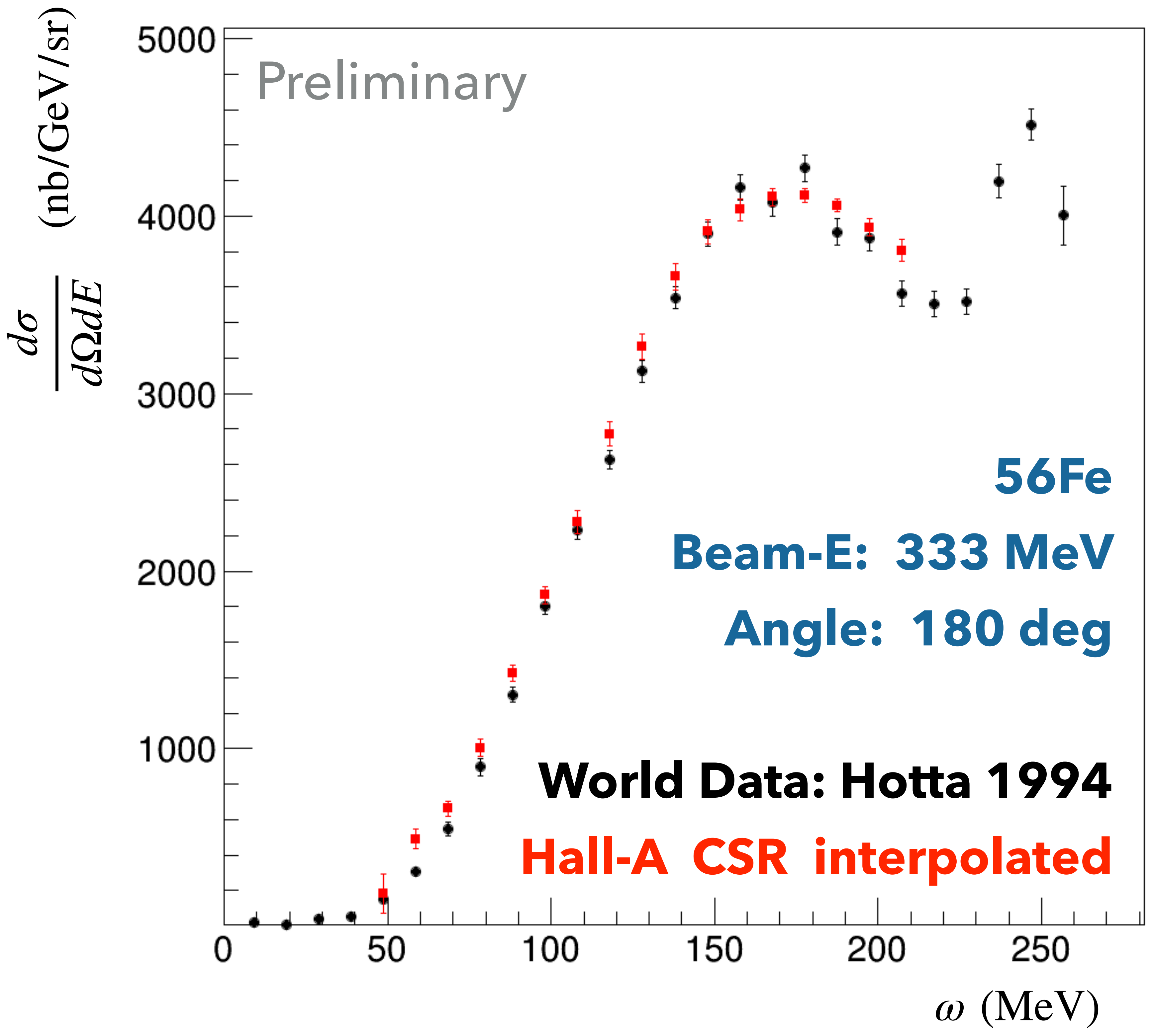
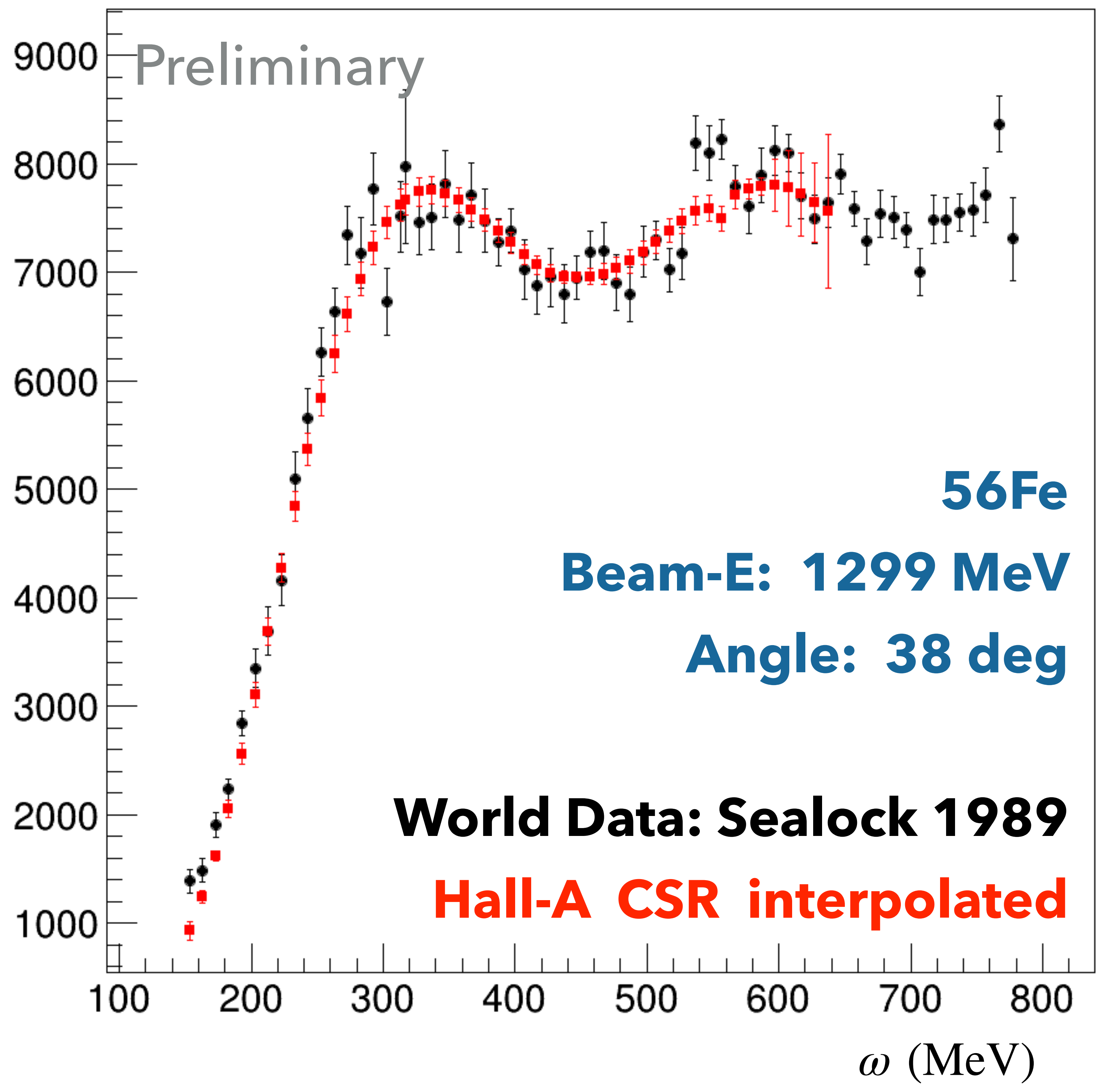
More Iron Comparisons





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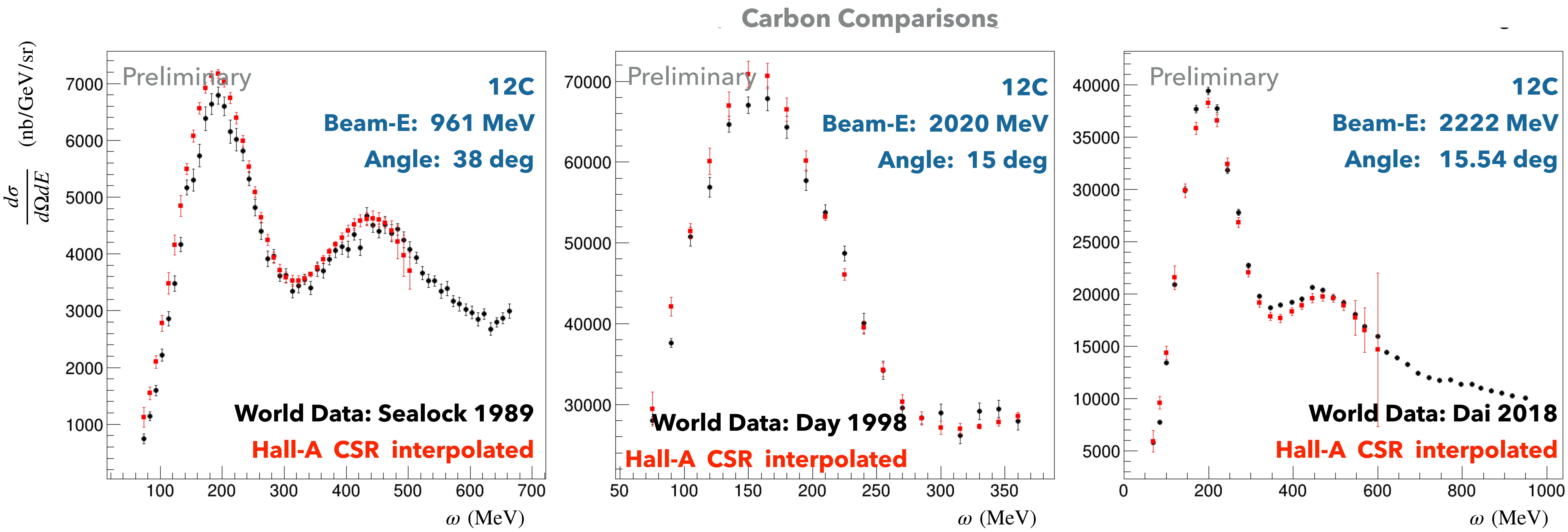

SOME RESULTS

- Three of the four targets (^{12}C, ^{56}Fe) have been analyzed extensively.
  - ^{208}Pb and ^{4}He need extended target analysis (preliminary results exist for ^{4}He, but are not shown here)
  - ^{208}Pb needs analytic calculations for the Coulomb Correction, plus proper LH2 subtraction
- Large ω is the region where sensitivity to systematics is most pronounced. This is especially true in the region above the quasi-elastic peak (the "dip" and Δ region where R_T dominates).
  - This area needs higher order corrections to reduce systematic uncertainty. Some of these studies are ongoing.

COMPARISONS TO EXISTING SUM-RULE CALCULATIONS

- We have some coverage at the lowest end of $|q|$ to compare results at $|q|$ = 550 MeV/c with prior calculations.
  - Note: This is on the edge of our available phase space. Most slopes are calculated with only 2 or 3 angles.

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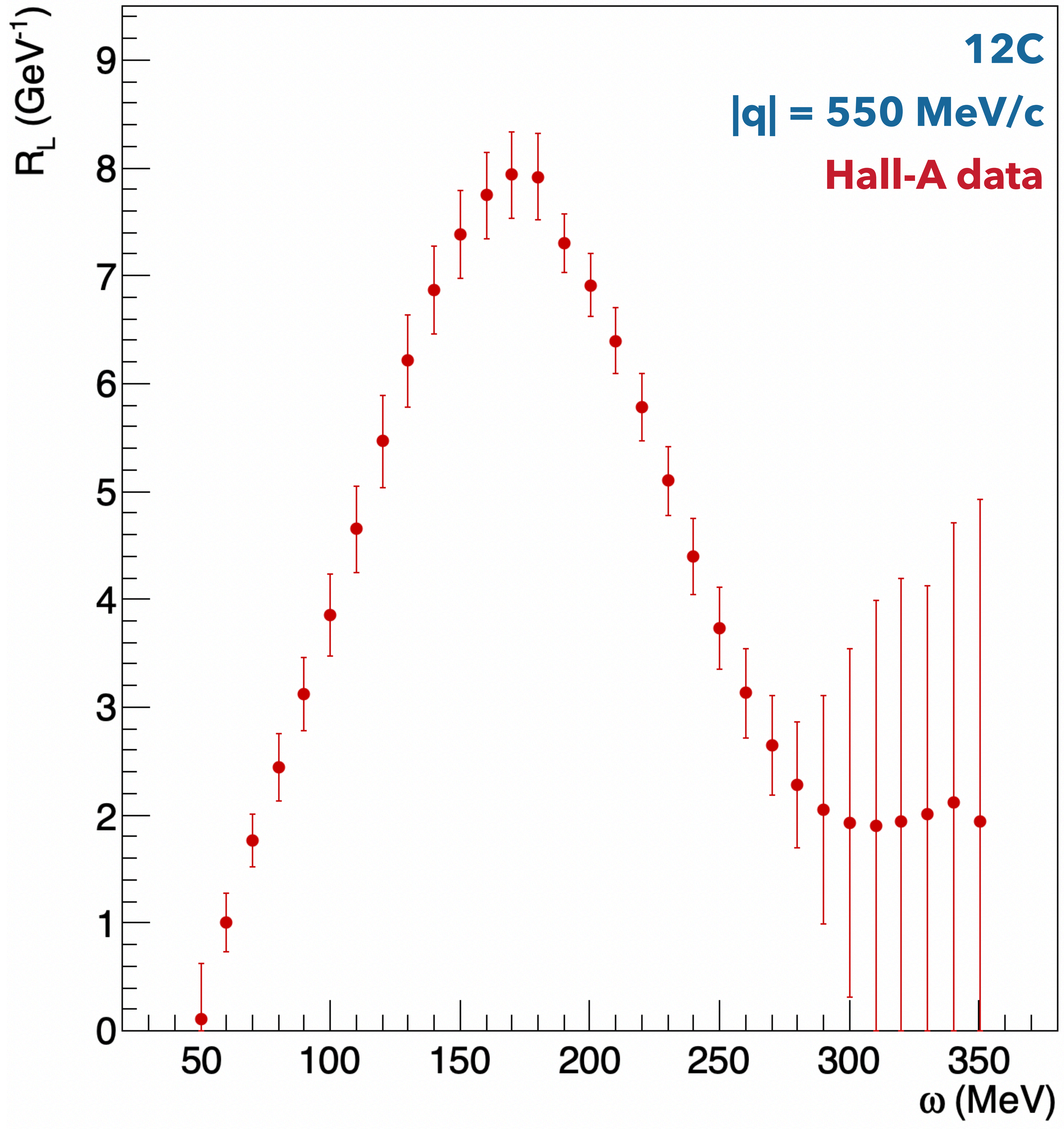

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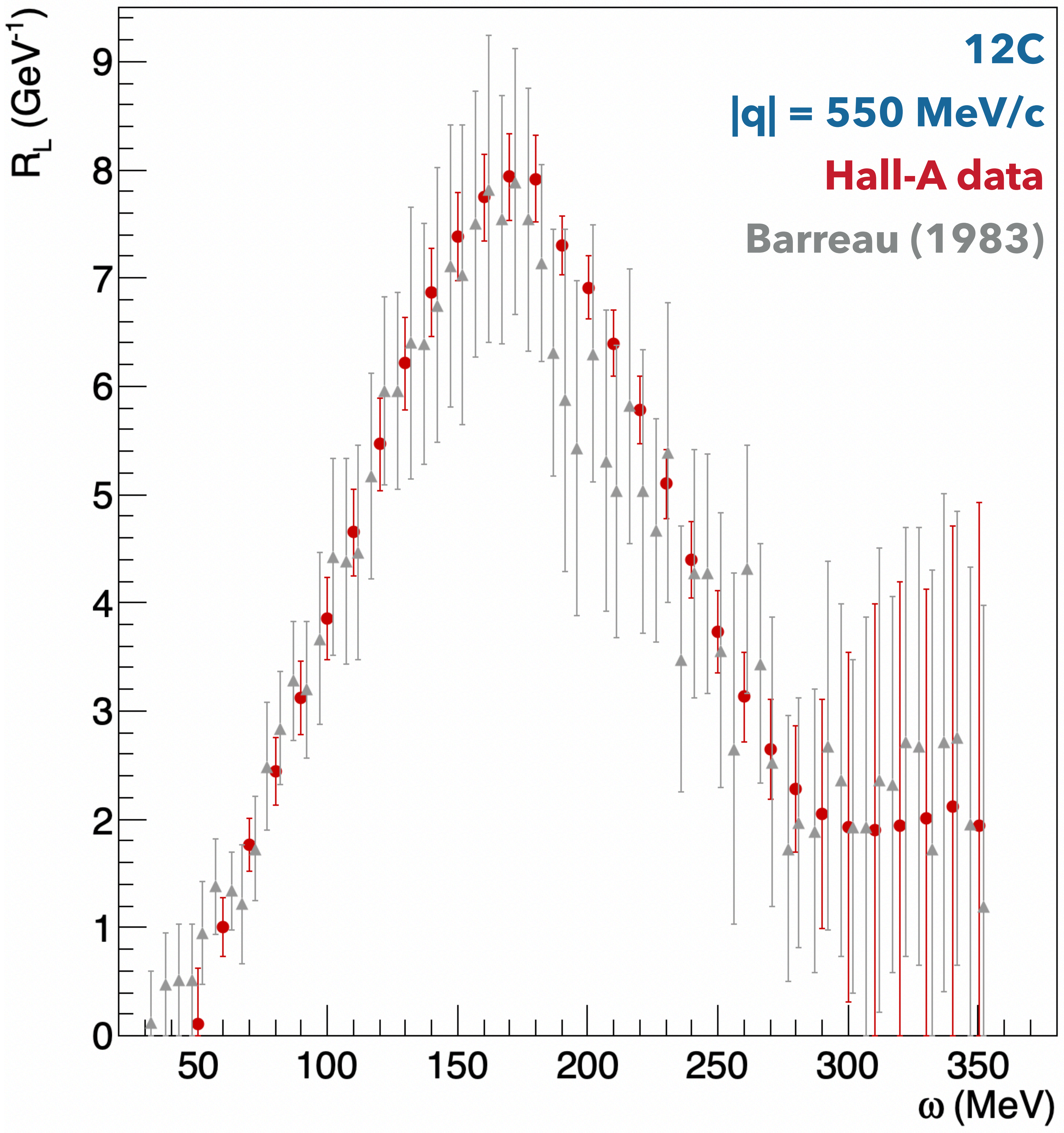

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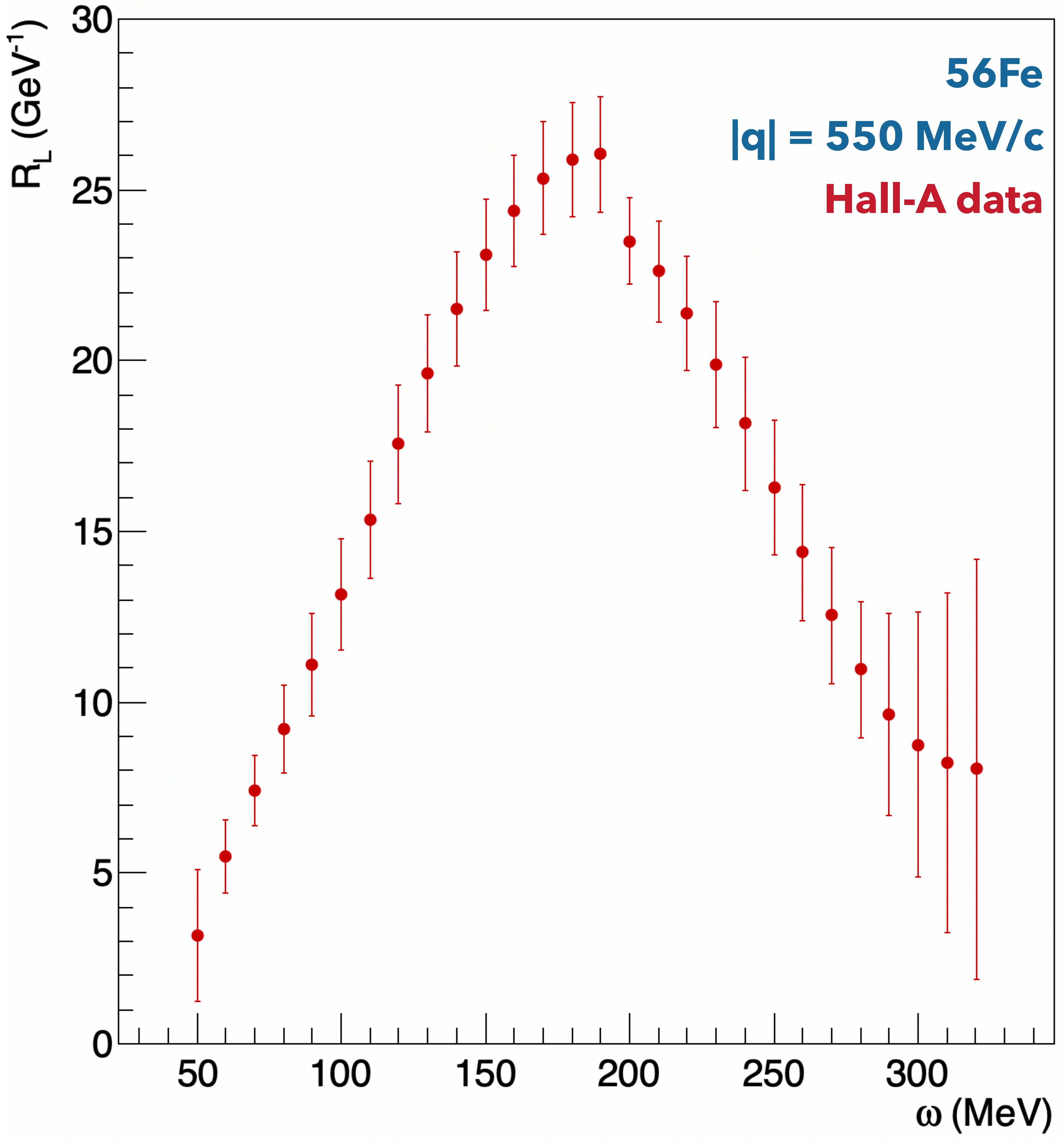

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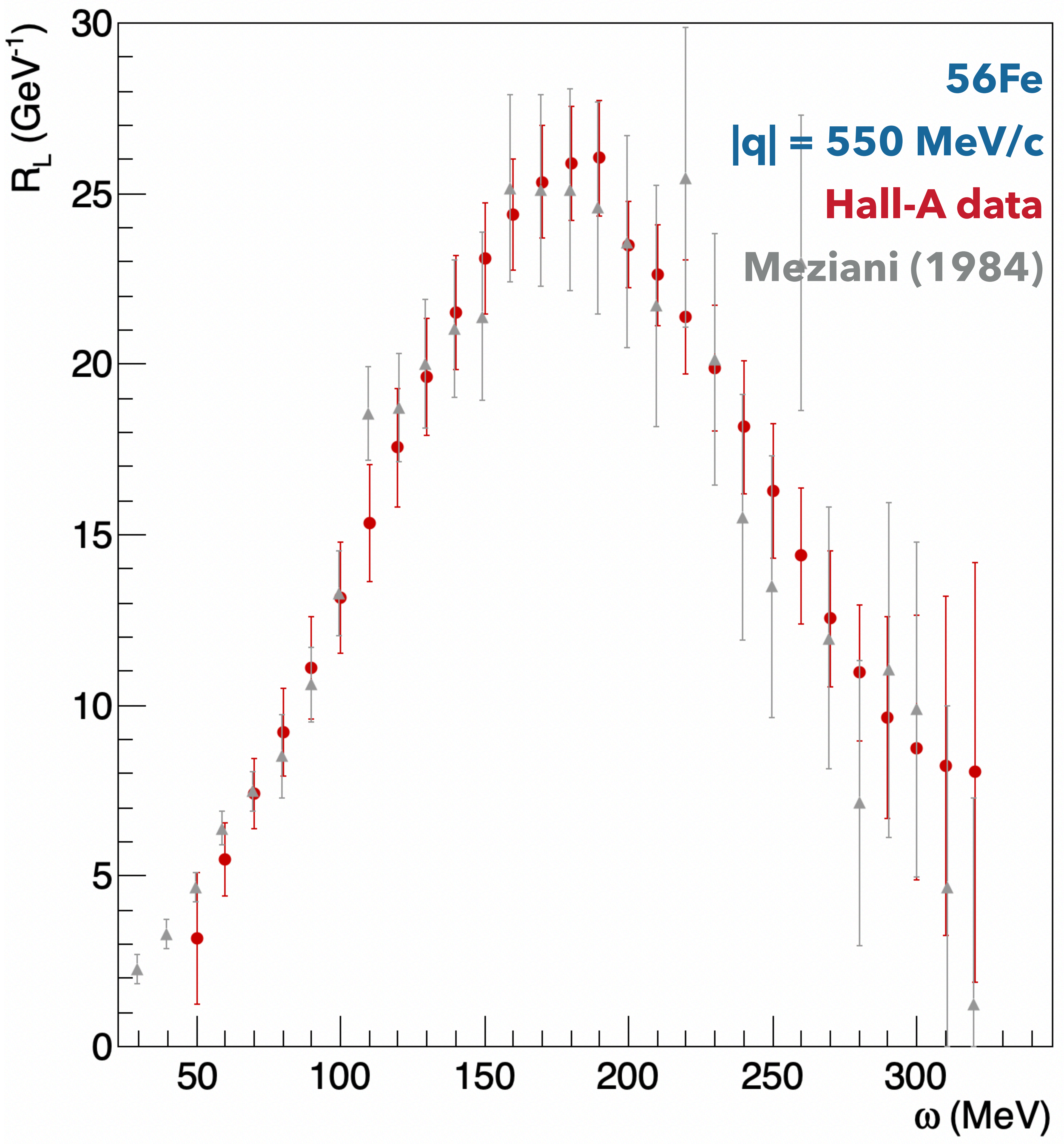
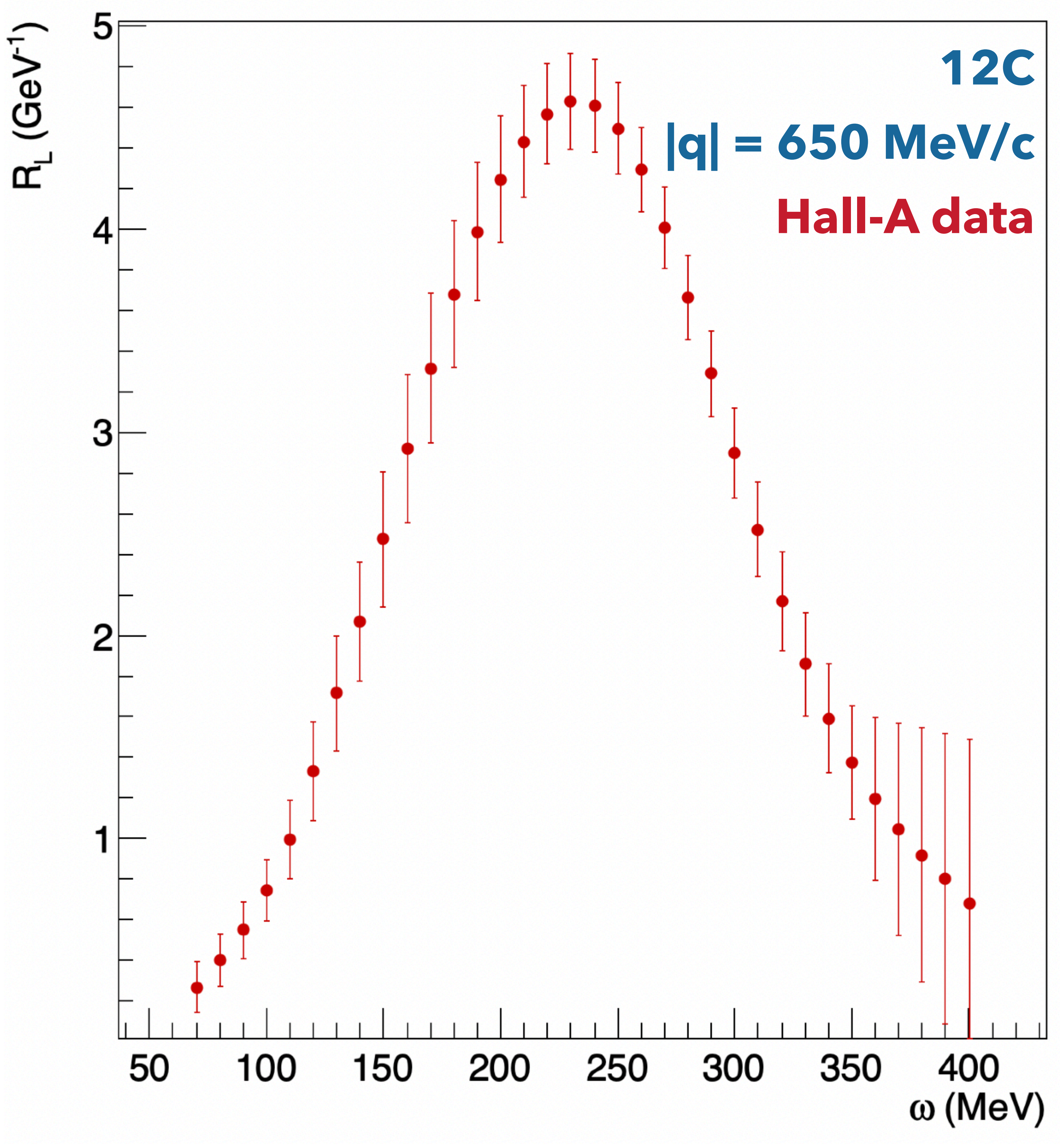
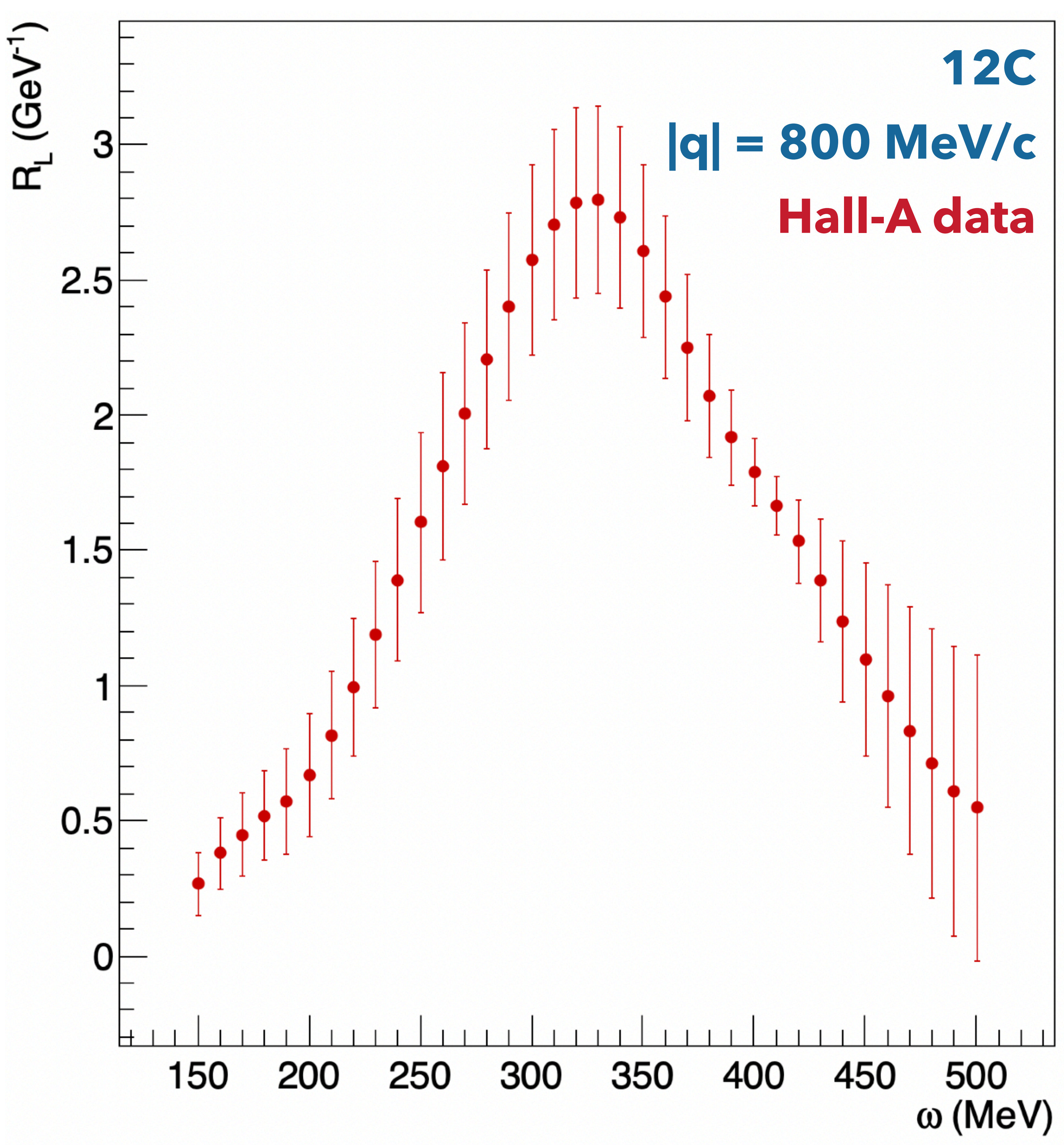
- For Iron: we also have nice agreement with Meziani, et. al.

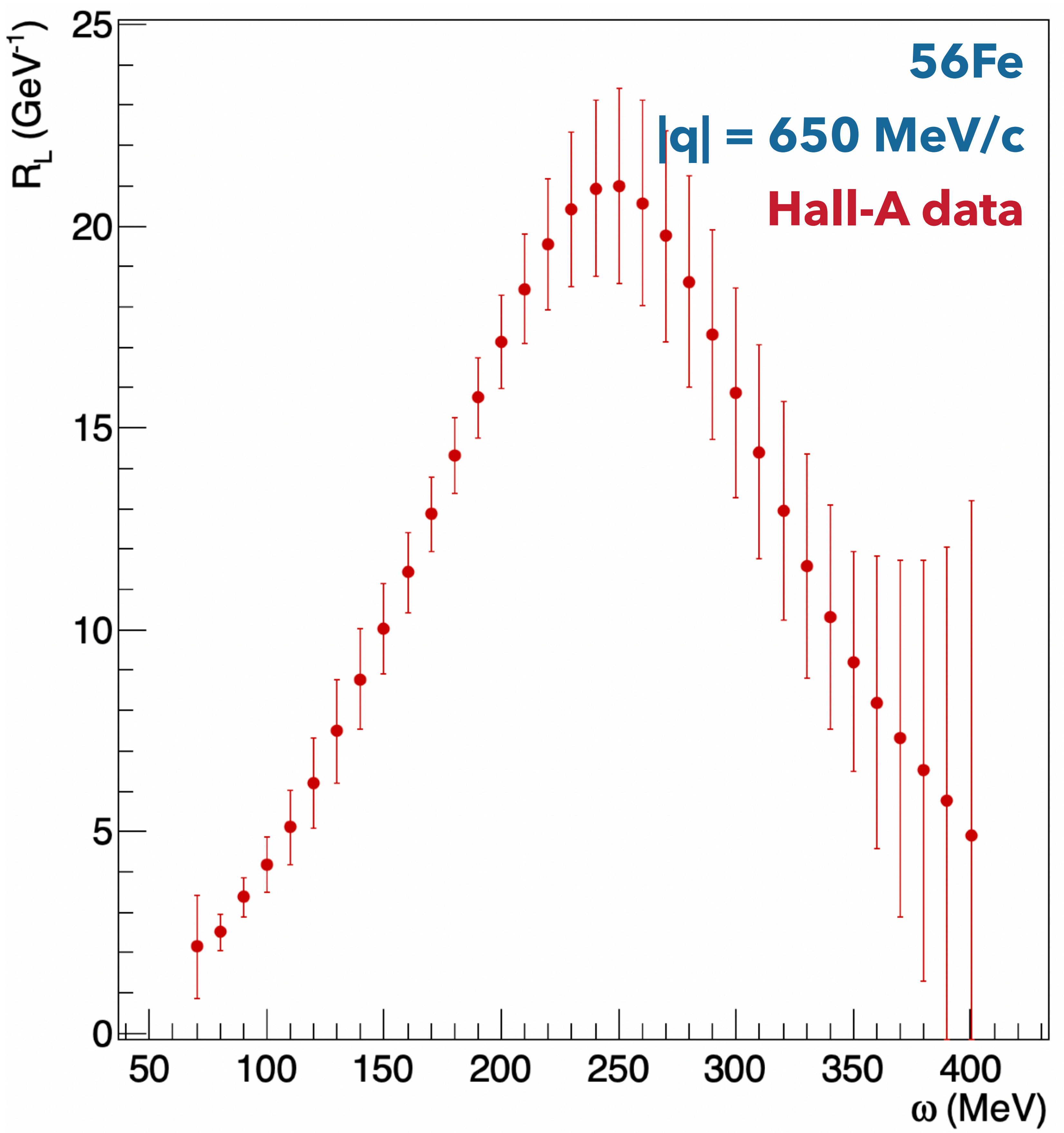


LONGITUDINAL RESPONSE AT LARGER MOMENTUM TRANSFER

- We can look at various larger |q| values, here I will discuss |q| = 650 MeV/c and |q| = 800 MeV/c







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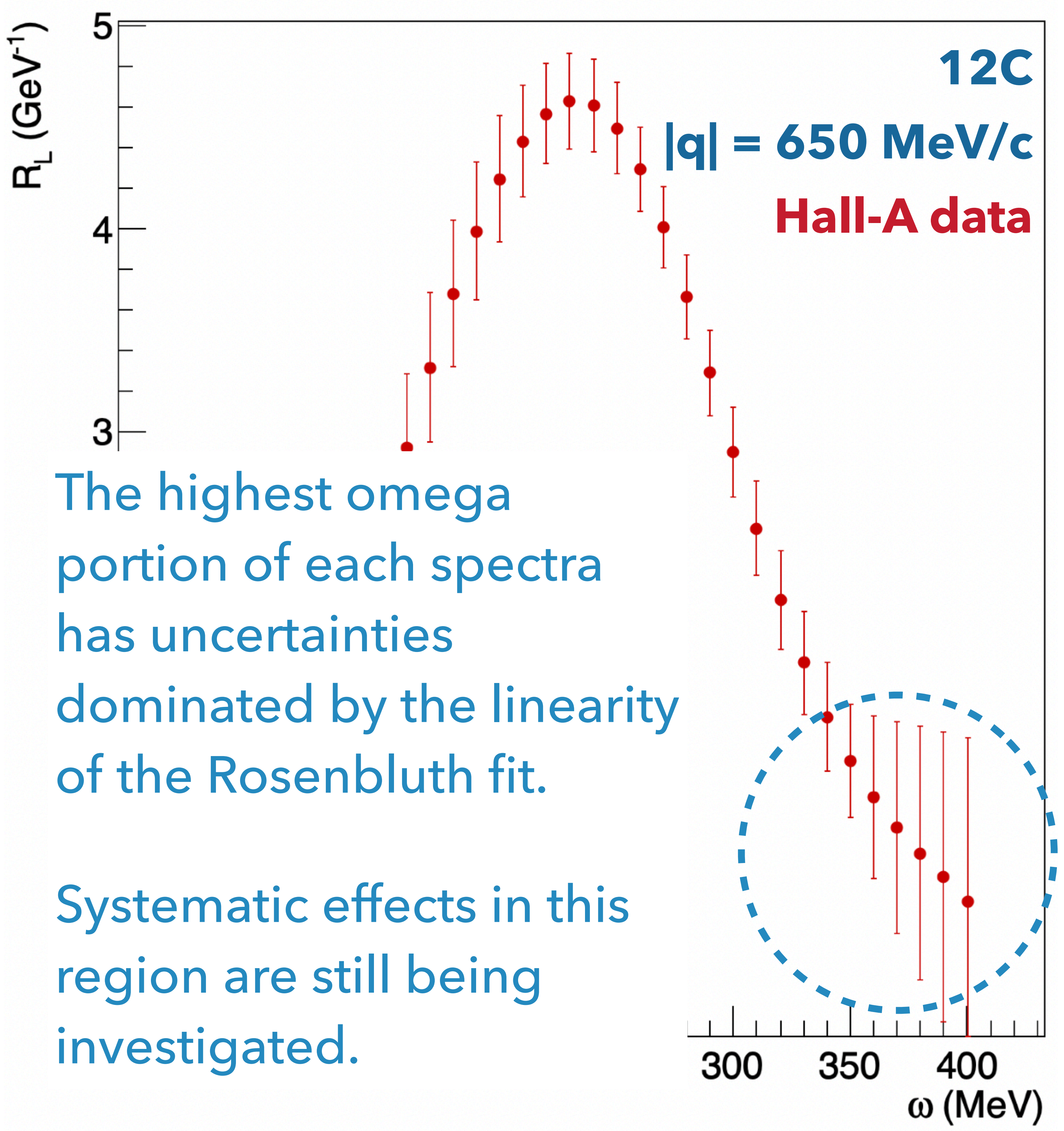
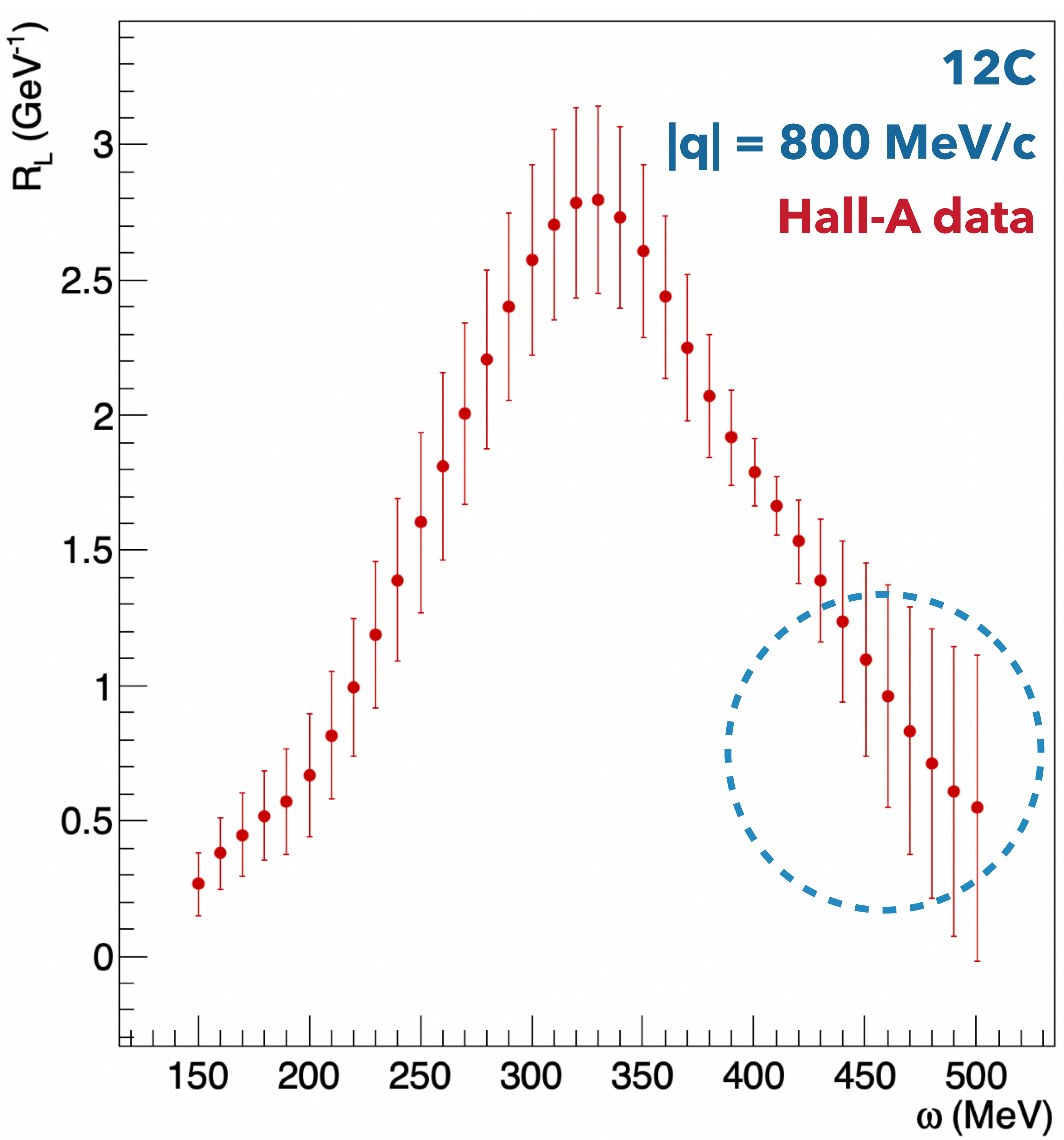
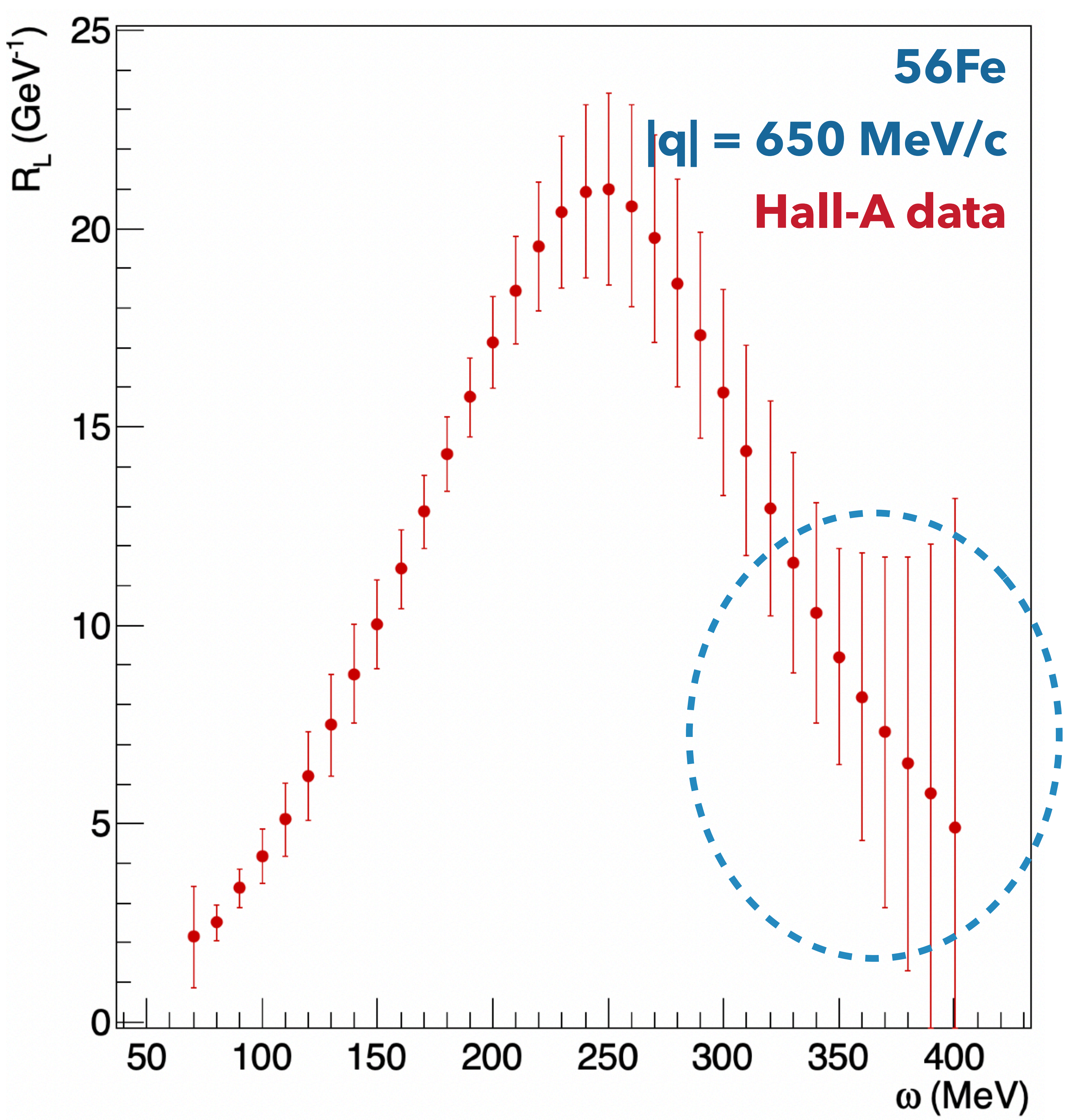


The highest omega portion of each spectra has uncertainties dominated by the linearity of the Rosenbluth fit.

Systematic effects in this region are still being investigated.





SUMMARY

- The Coulomb Sum Rule can be used to directly compare the integrated electric response of nucleons bound in a nucleus to the expected incoherent sum of electric structure of unbound nucleons:
  - In this way, we get a model independent test of medium-modification of nucleon structure with a purely electromagnetic probe.
- Early experiments reported a quenching of the CSR in heavy nuclei, since then theoretical interest has remained high.
- Experiment E05-110 was run at Jefferson Lab to investigate a critical region of $|q|$ where no world data existed.
- Latest results show an agreement with earlier calculations at $|q|$ = 550 MeV/c.
- The longitudinal response for larger $|q|$ have been measured, but the especially sensitive large omega region of the response is still being investigated with hopes of correcting systematic effects and reducing the uncertainty of the total sum.

THANK YOU!!!

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PEOPLE

and
Hall-A collaboration

PhD Students **Spokespersons** **Run Coordinators** **Special Contributors**