

MICHAEL PAOLONE

NEW MEXICO STATE UNIVERSITY

FOR THE E05-110 COLLABORATION.

# THE COULOMB SUM RULE IN NUCLEI

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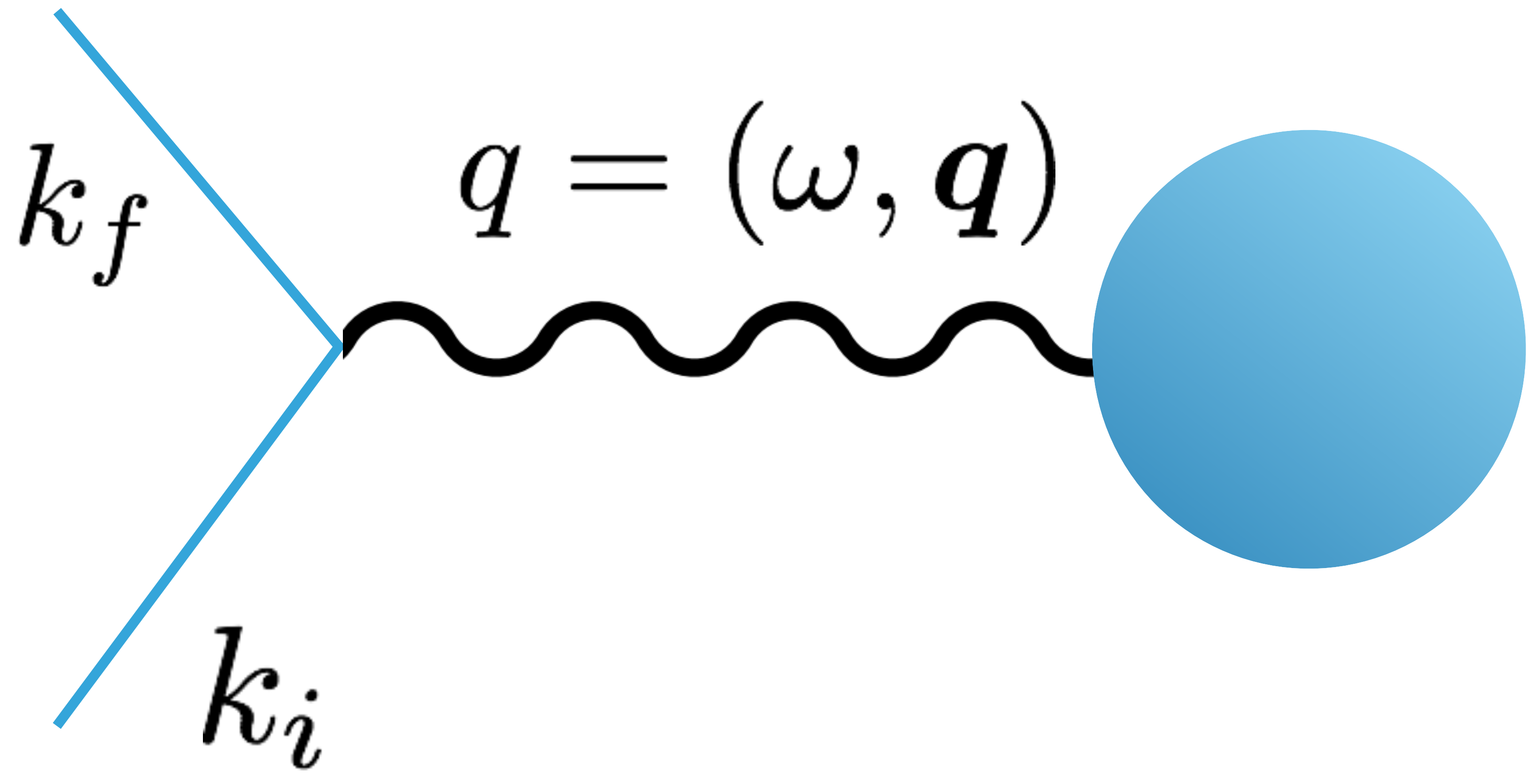


Inclusive electron scattering cross-section:

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

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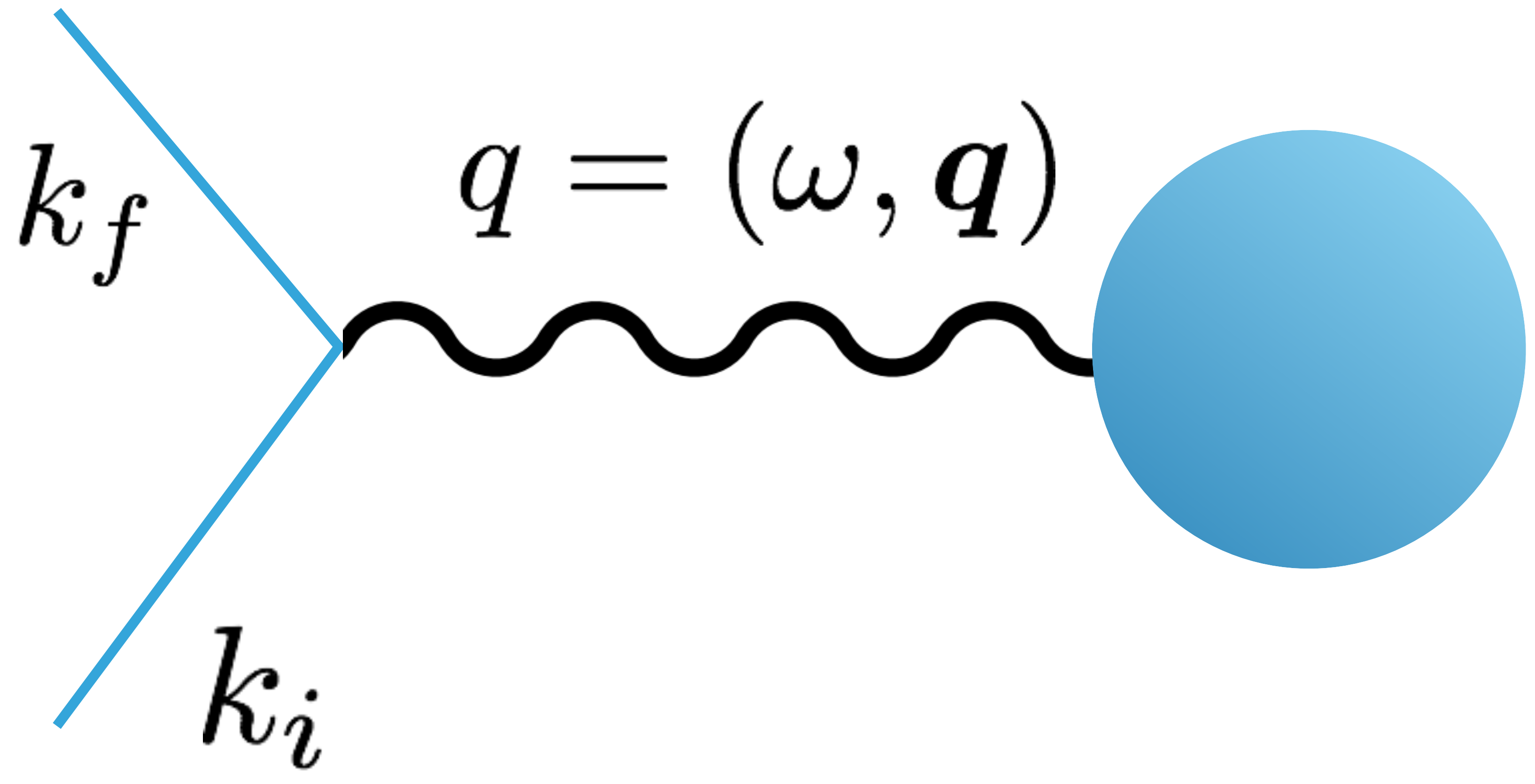


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$R_L$: Scattering response due to **charge** properties

$R_T$: Scattering response due to **magnetic** properties

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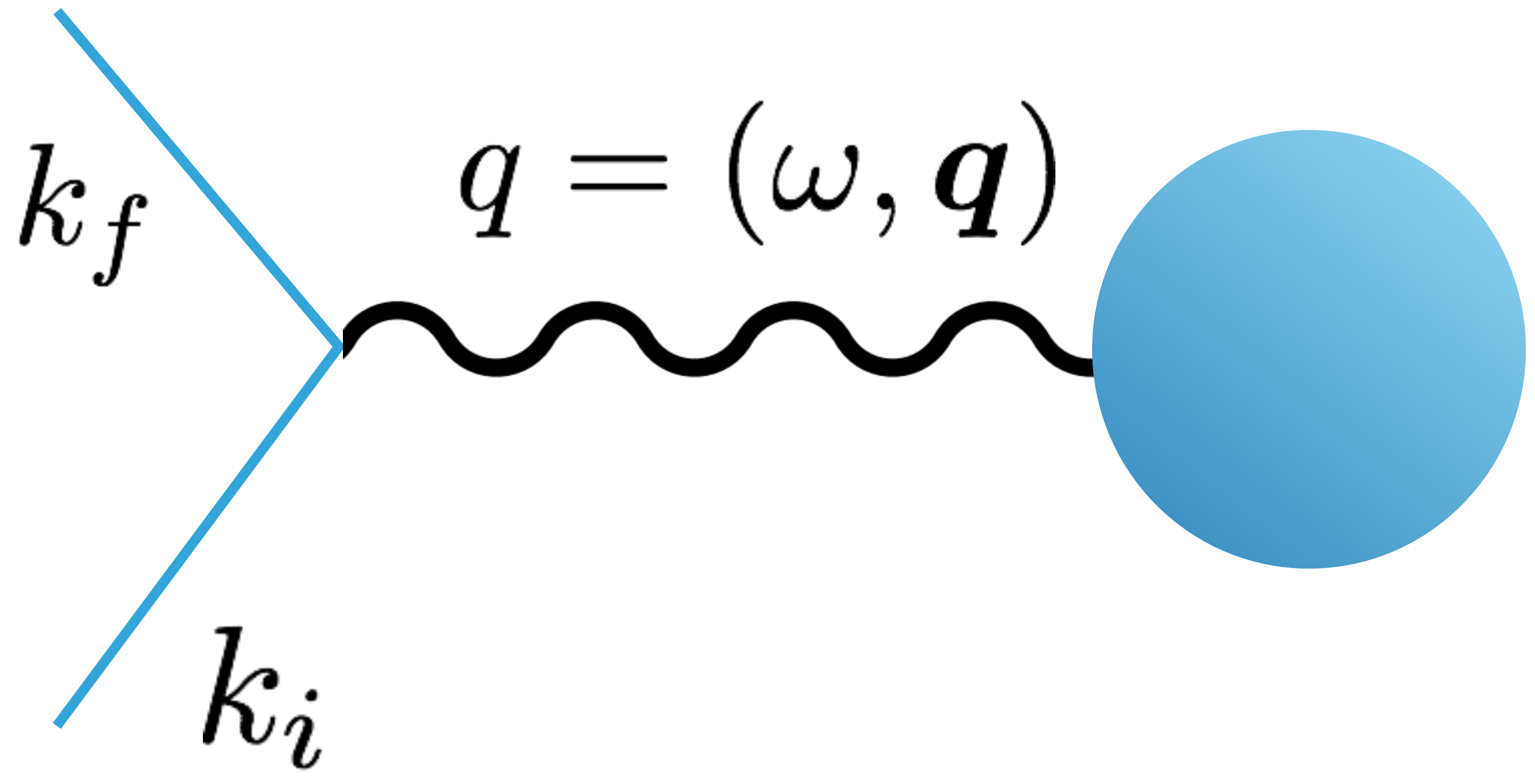


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Scattering response due to **charge** properties

Scattering response due to **magnetic** properties

Coulomb Sum Rule definition:

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

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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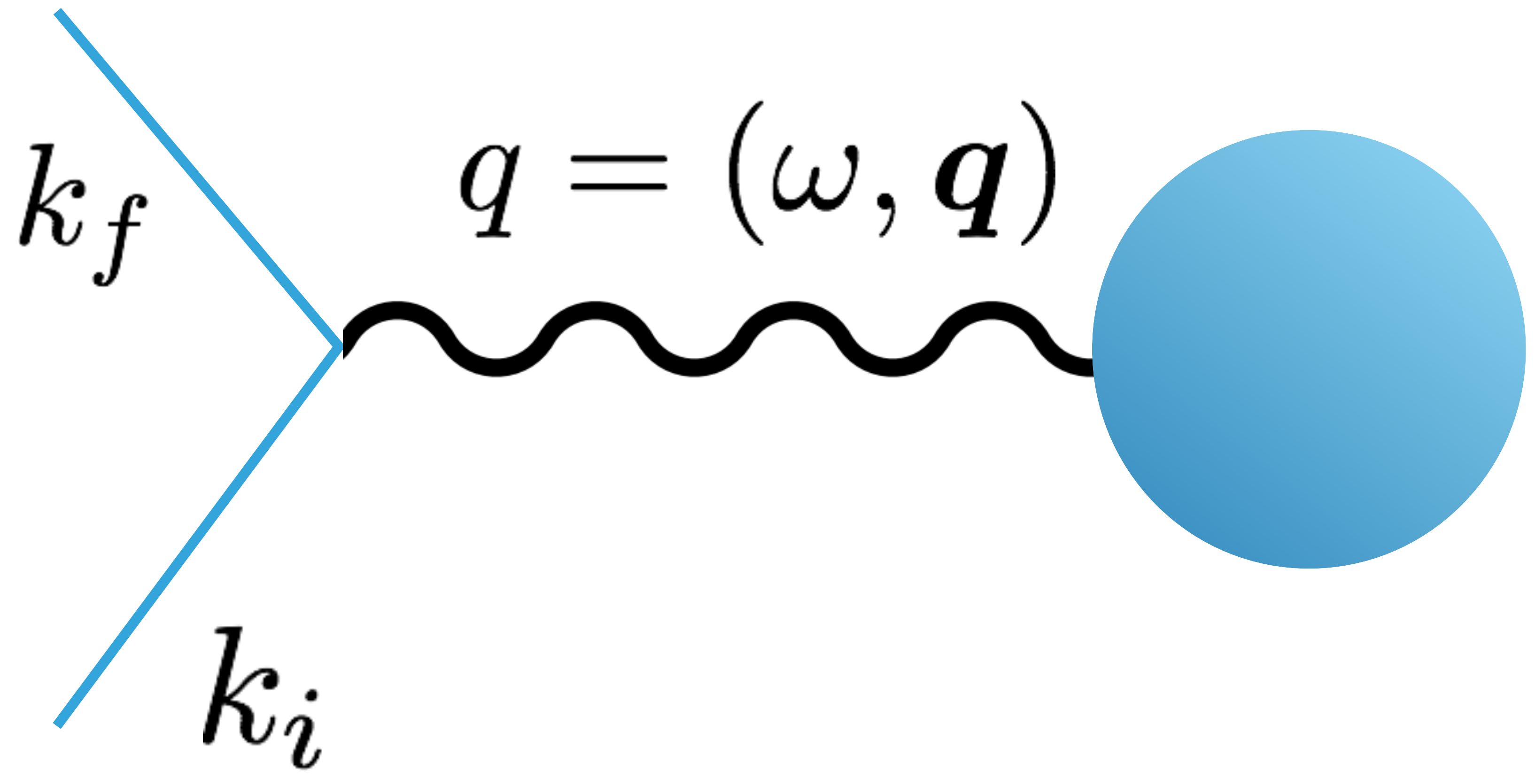


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At small |**q**| , $S_L$ will deviate from unity due to long range nuclear effects, Pauli blocking. (directly calculable, well understood).

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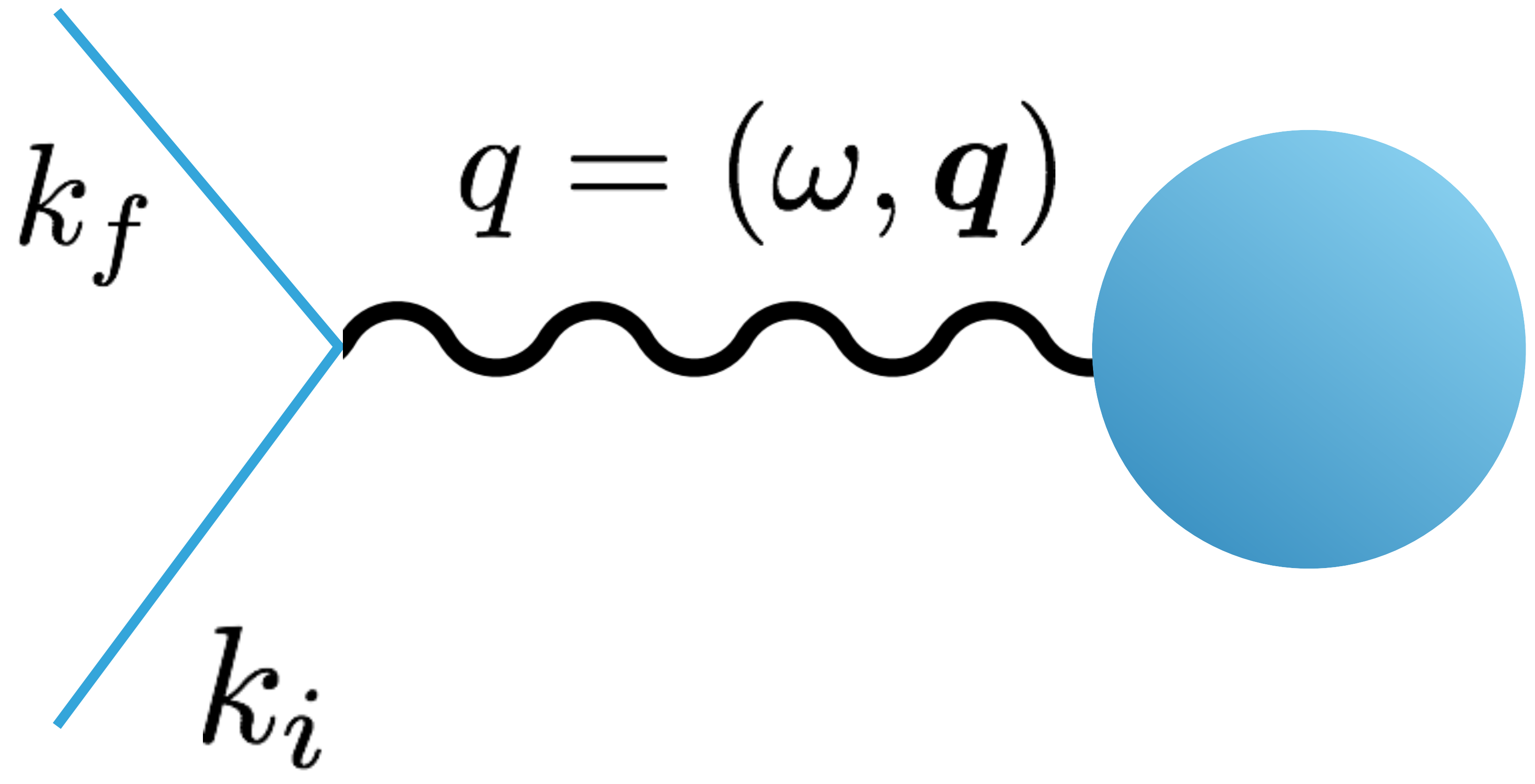


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**At large |q| >> 2k$_f$ , $S_L$ should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!**

*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.

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

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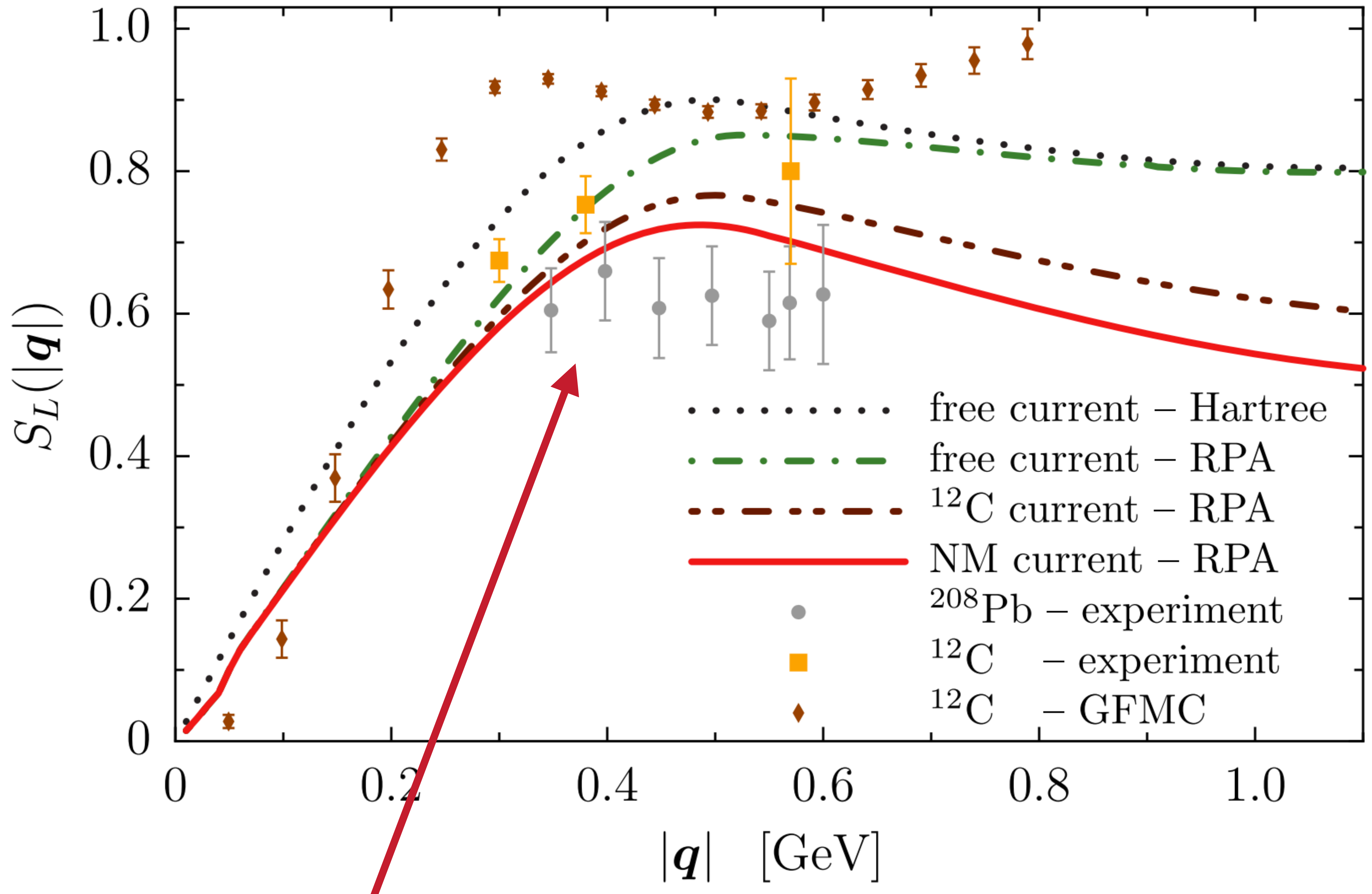
[2]*Department of Physics, School of Science, Tokai University, Hiratsuka-shi, Kanagawa 259-1292, Japan*
[3]*CSSM and ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide South Australia 5005, Australia*
(Received 23 June 2015; published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

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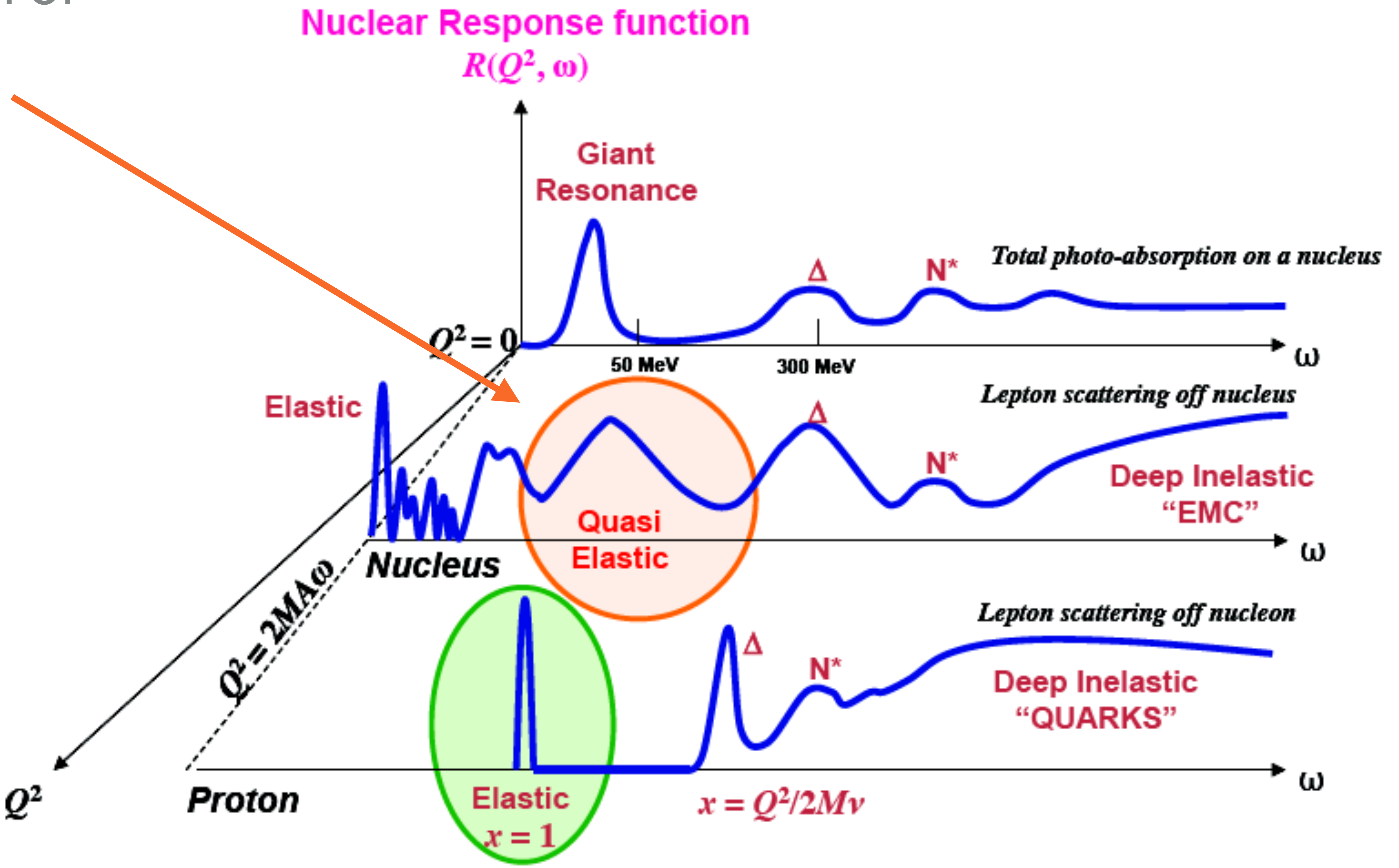
# QUASI-ELASTIC SCATTERING

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

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 our experiment:
  - Nuclei investigated:
    - $^{4}$He
    - $^{12}$C
    - $^{56}$Fe
    - $^{208}$Pb



# 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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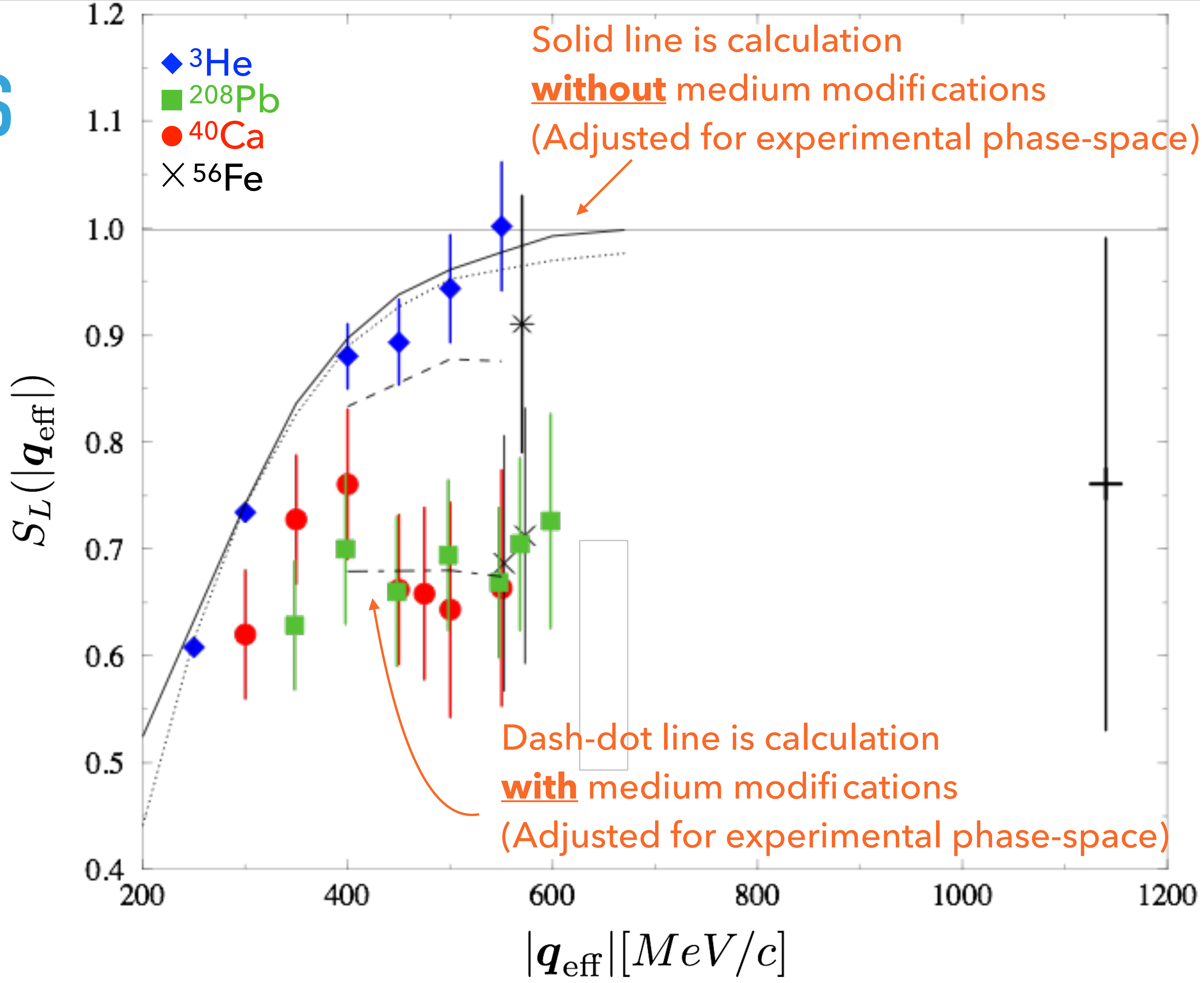
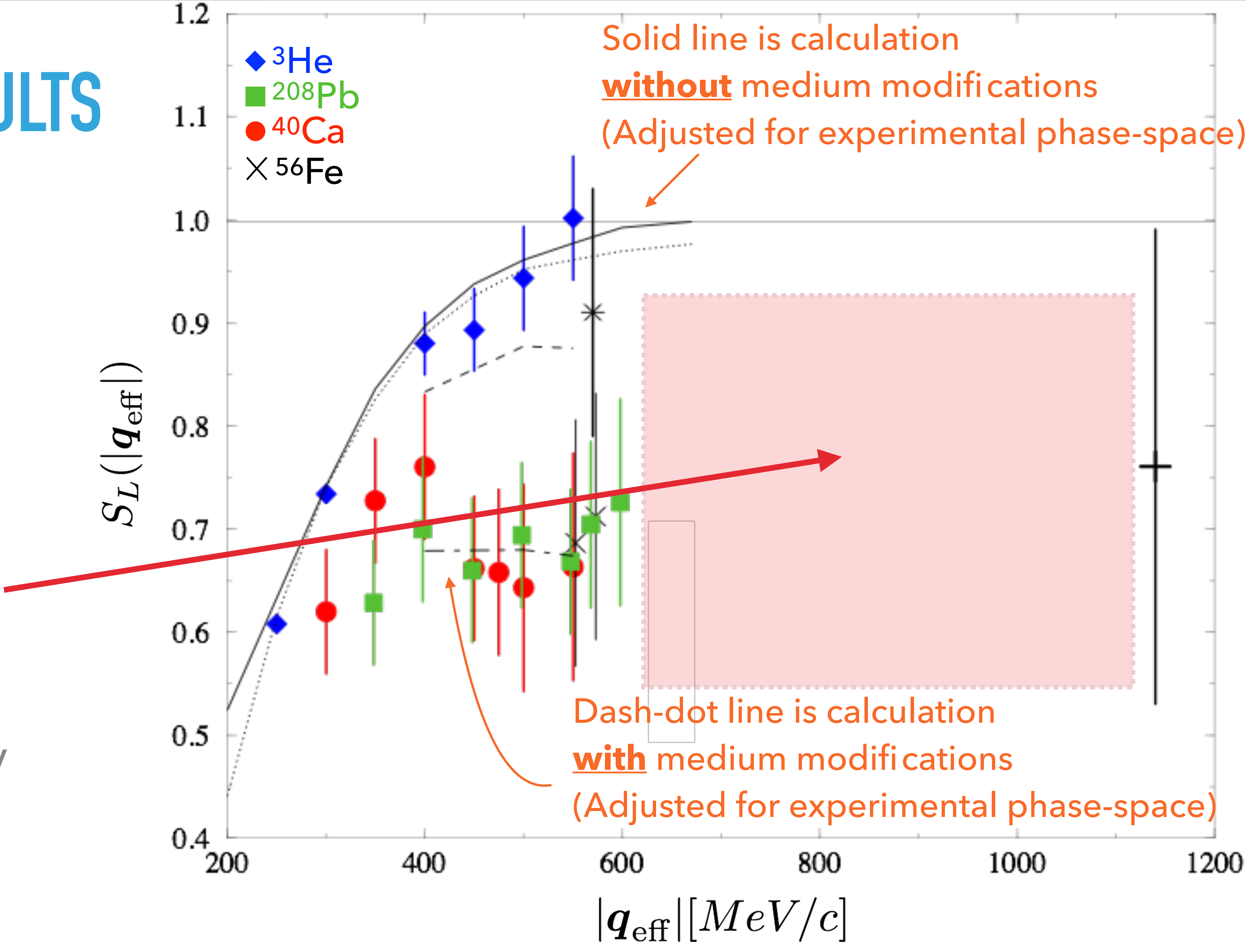



$|\boldsymbol{q}_{\mathrm{eff}}|$ is $|\boldsymbol{q}|$ corrected for a nuclei dependent mean coulomb potential. Methodology agreed on by Andreas Aste, Steve Wallace and John Tjon.

# 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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# EXPERIMENTAL DESIGN

- Need $R_L$ ⟶ Use Rosenbluth separation!

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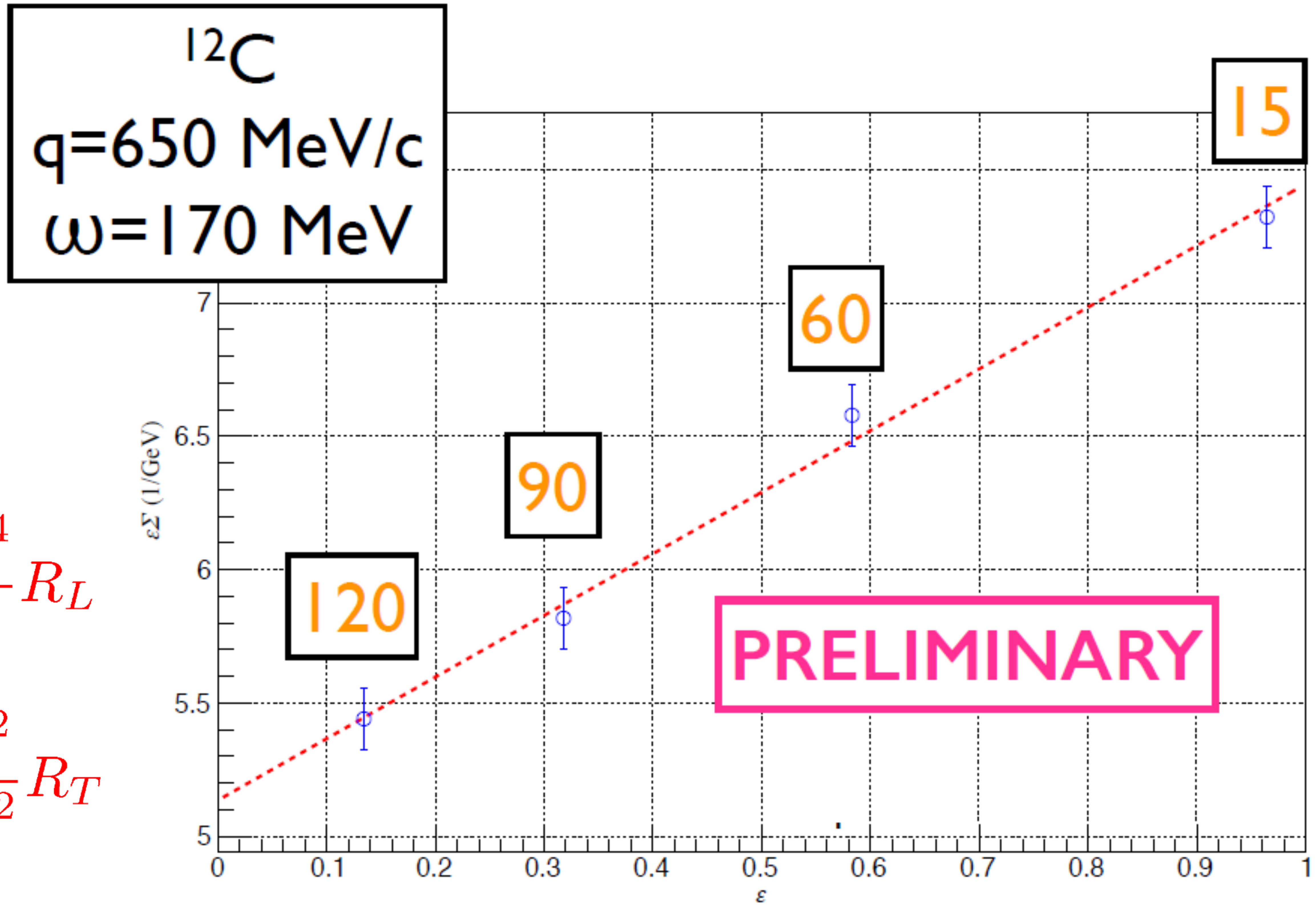
Slope = $\frac{Q^4}{\vec{q}^4} R_L$

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



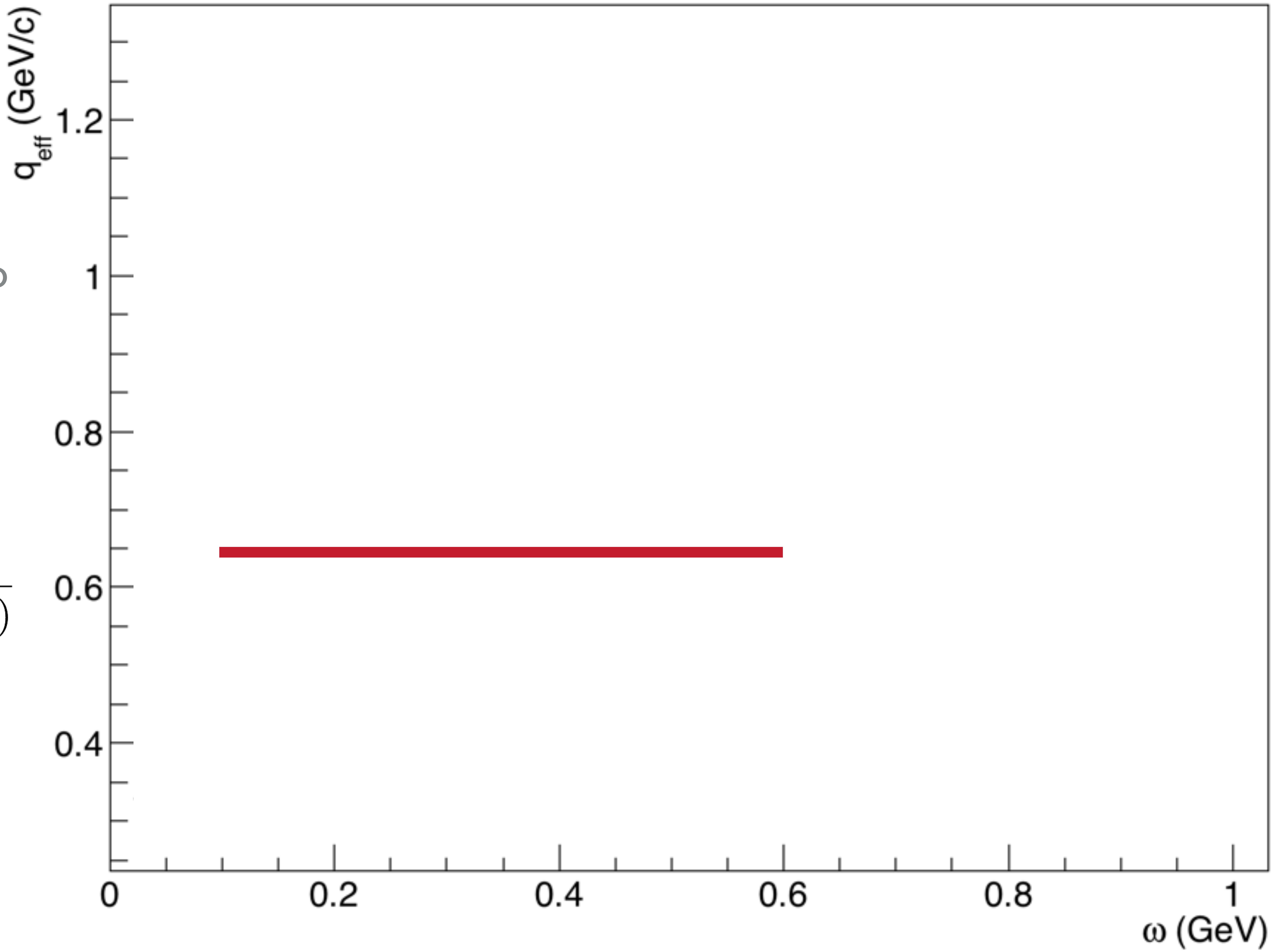

- Experiment run at 4 angles per target: 15, 60, 90, 120 degs. Very large lever arm for precise calculation of $R_L$!
- Need data for each angle at a constant |q| over an ω range starting above the elastic peak up to |q|.
  - When running a single arm experiment with fixed beam energy and scattering 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**| !!

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



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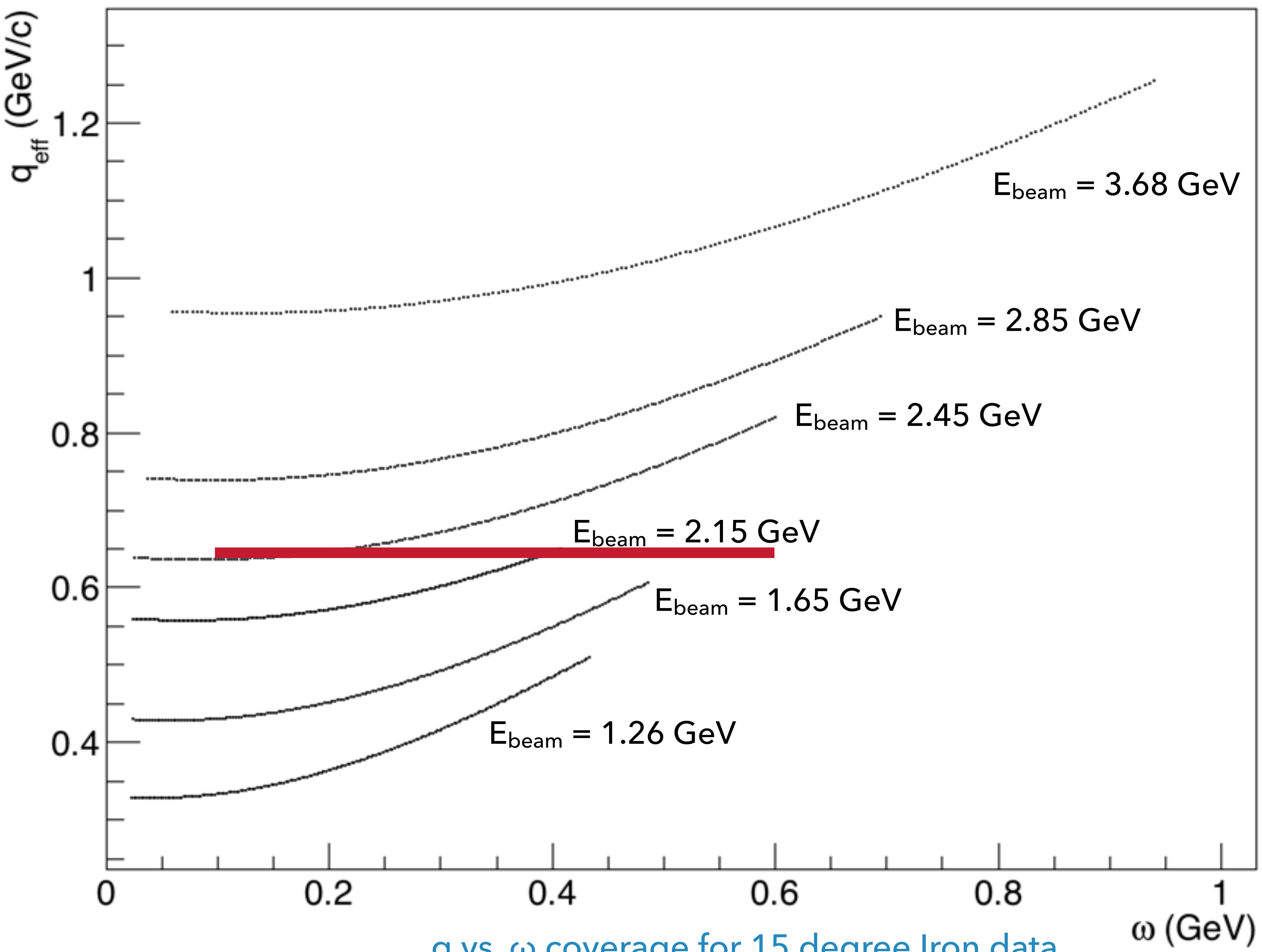
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.




q vs. ω coverage for 15 degree Iron data

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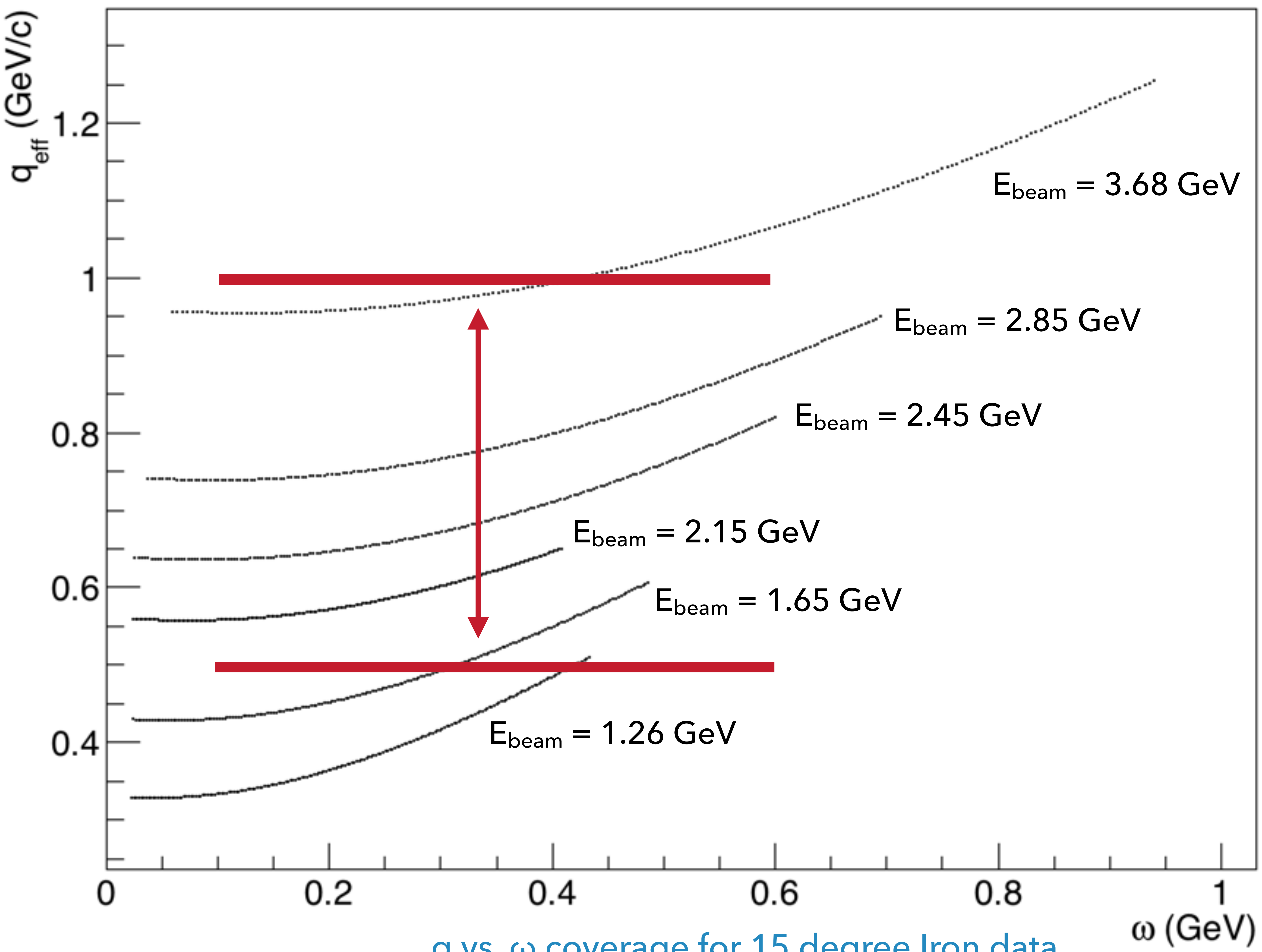
  - |q| can be selected between 550 and 1000 MeV/c




q vs. ω coverage for 15 degree Iron data

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

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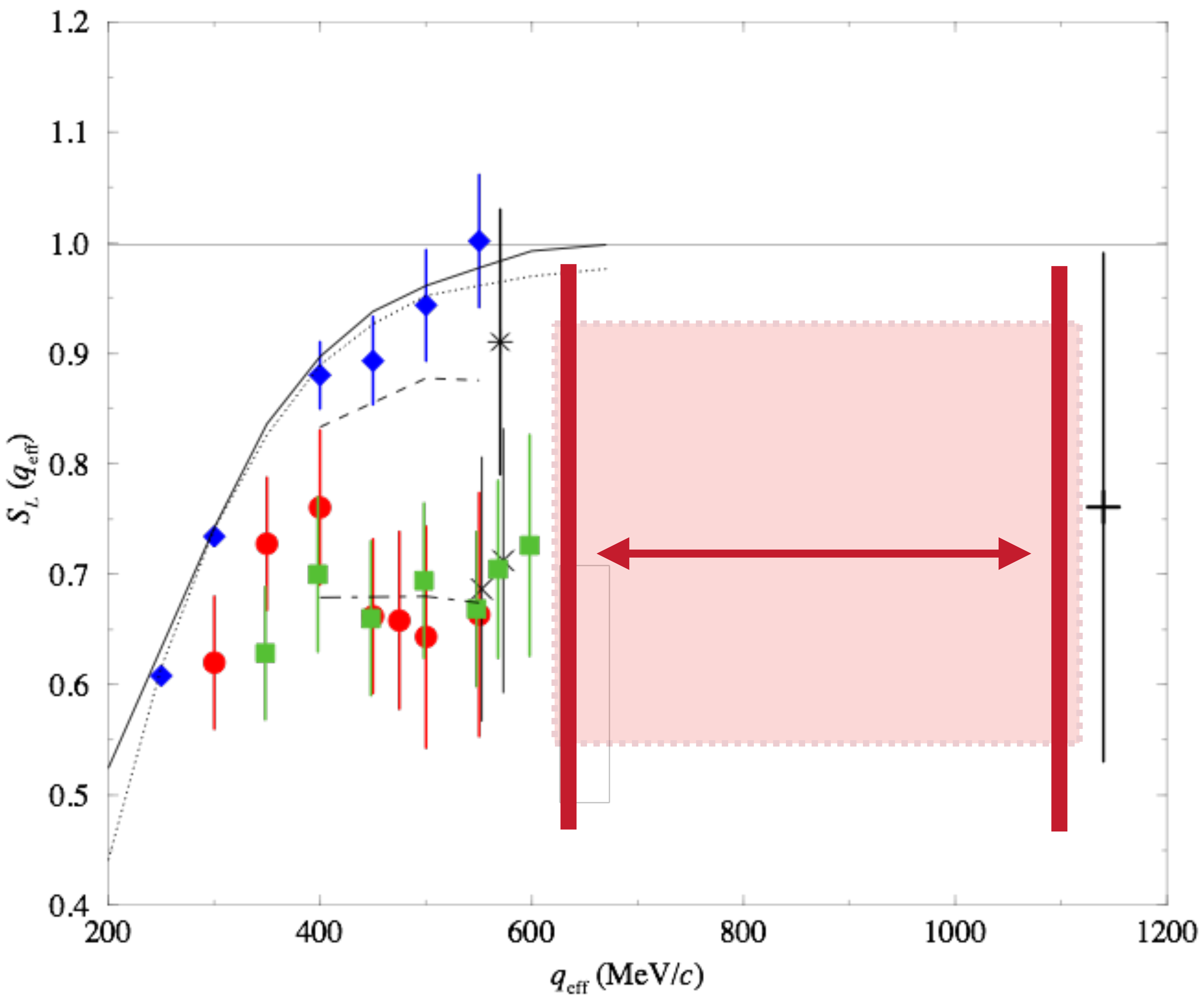


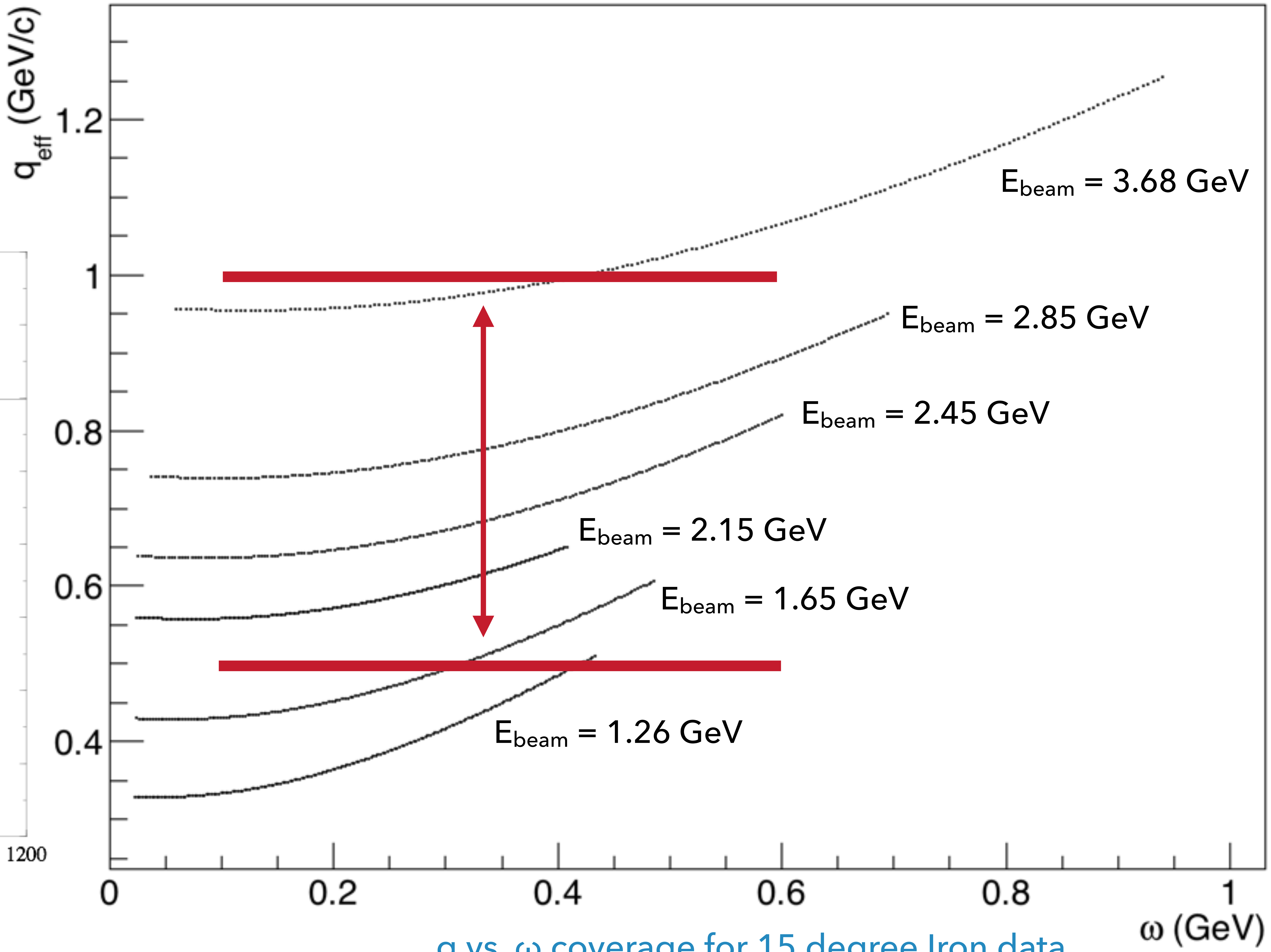


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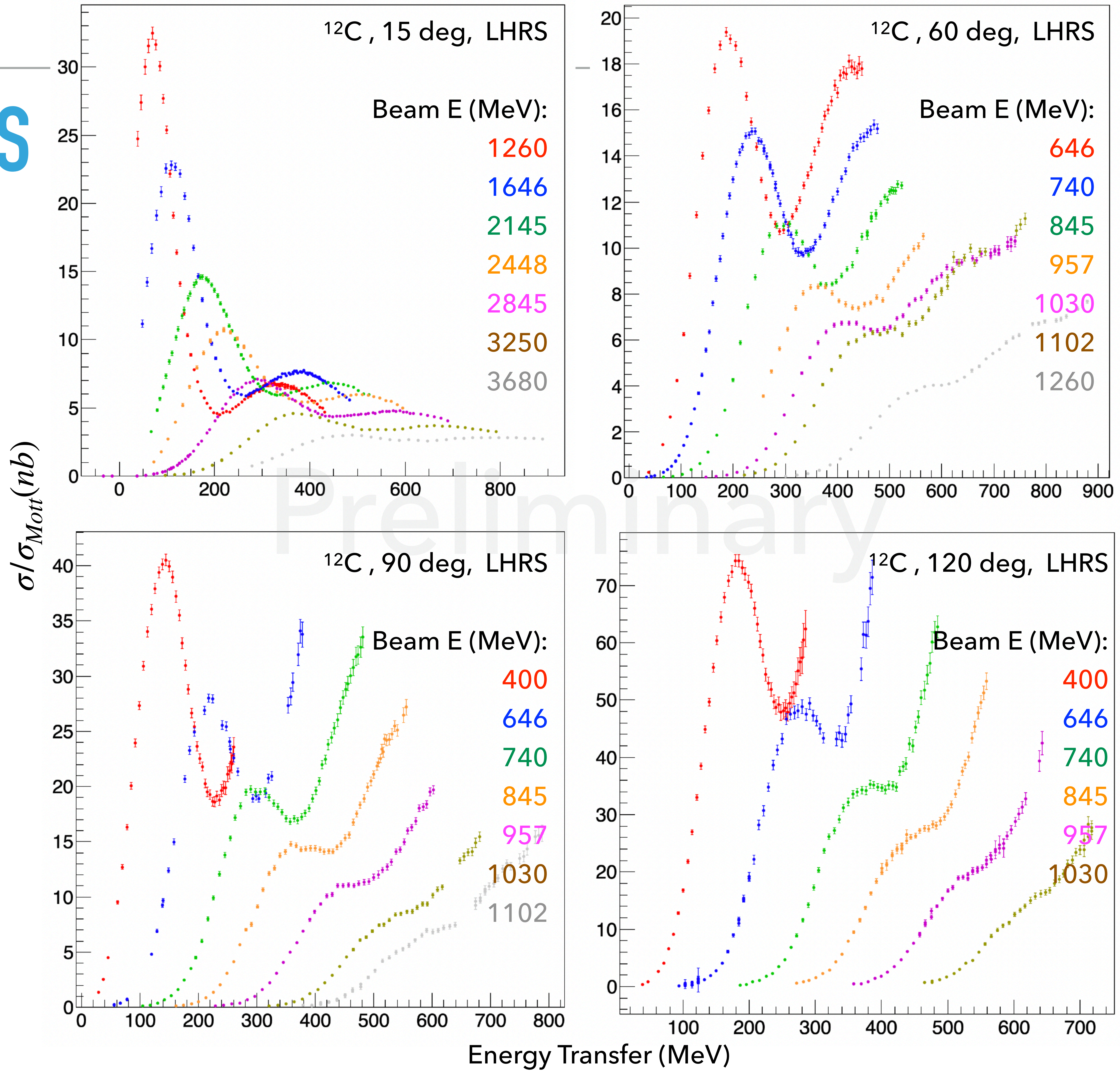
# EXPERIMENTAL SPECIFICS

- 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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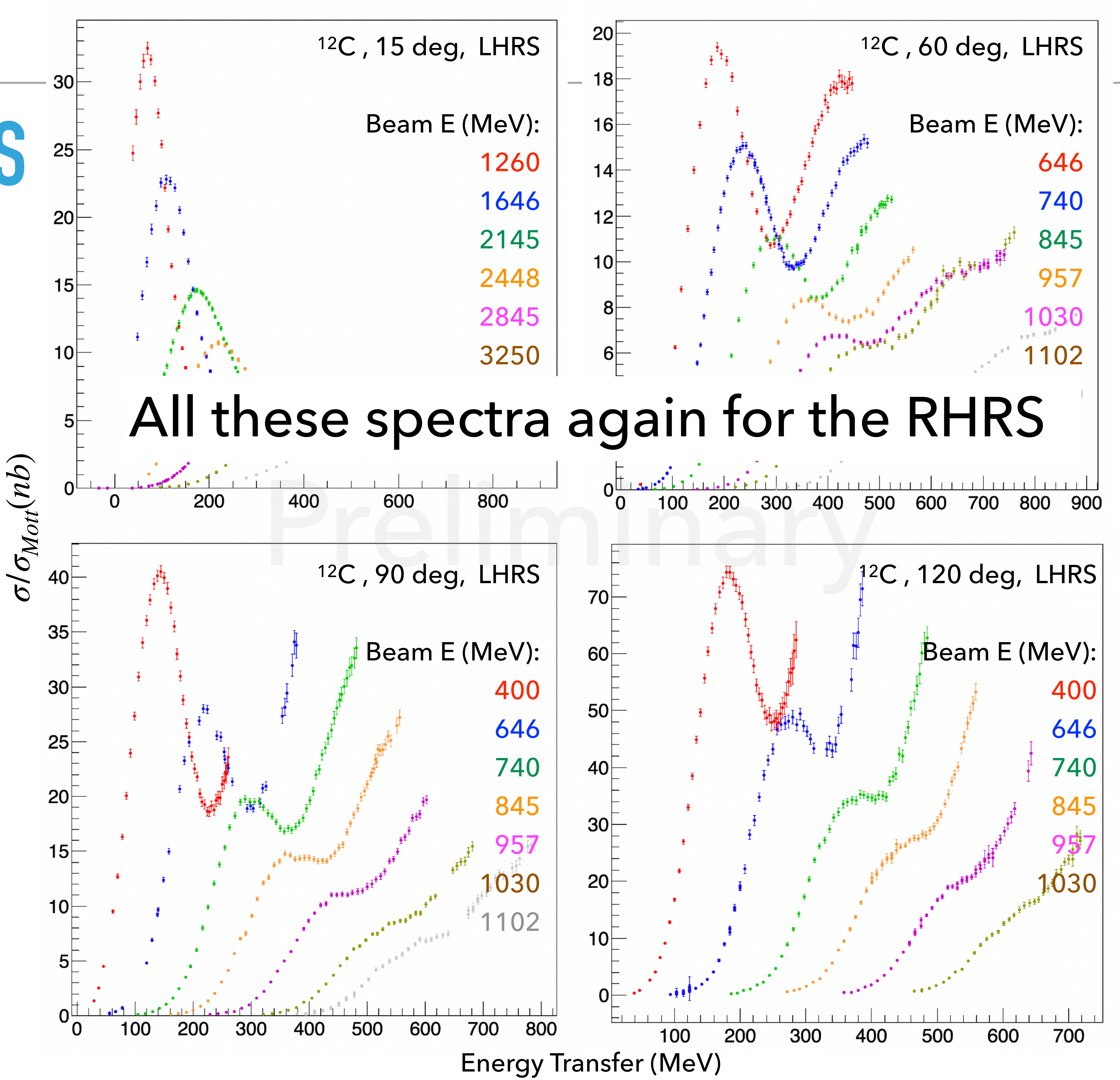

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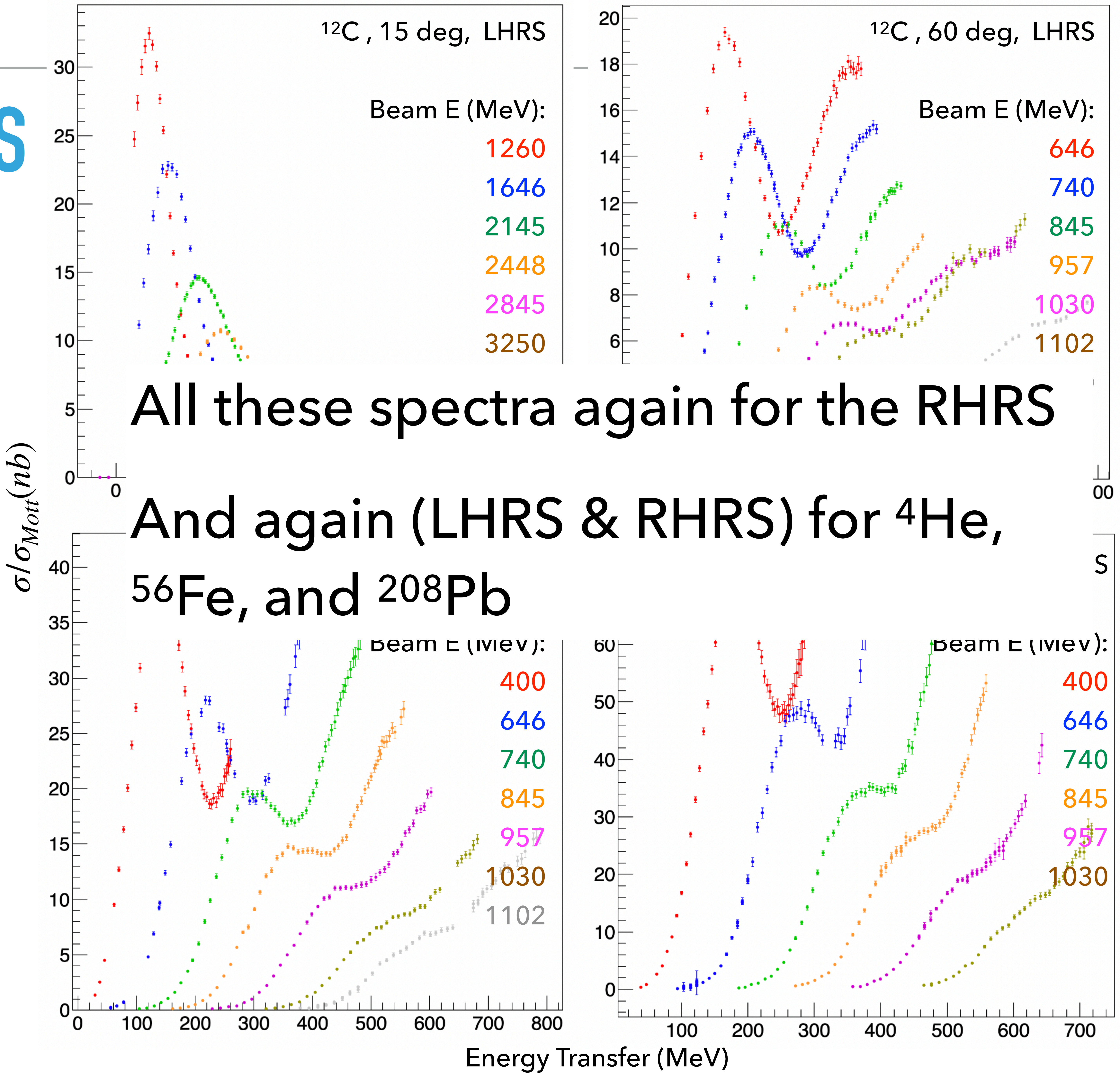


All these spectra again for the RHRS

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

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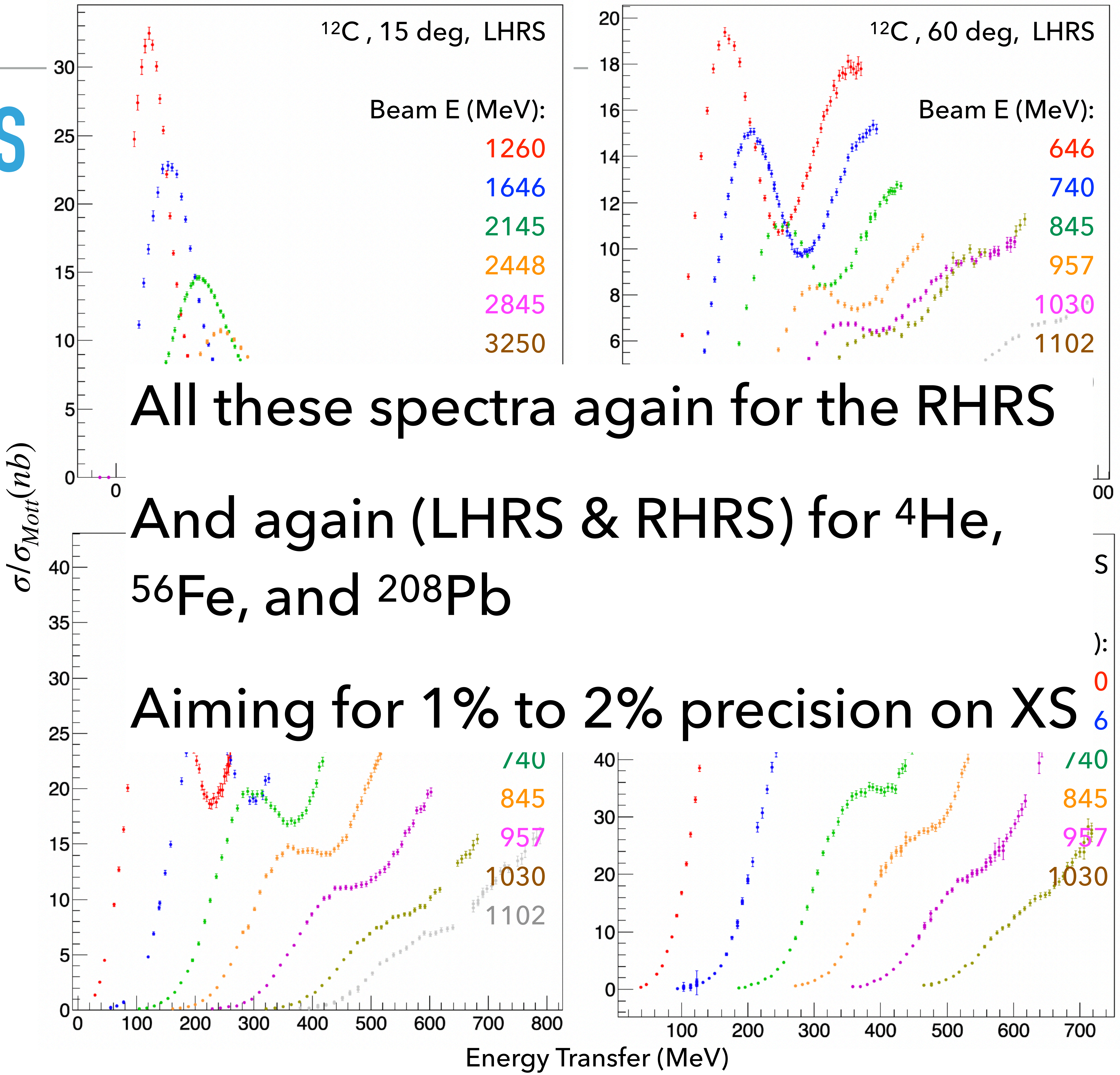


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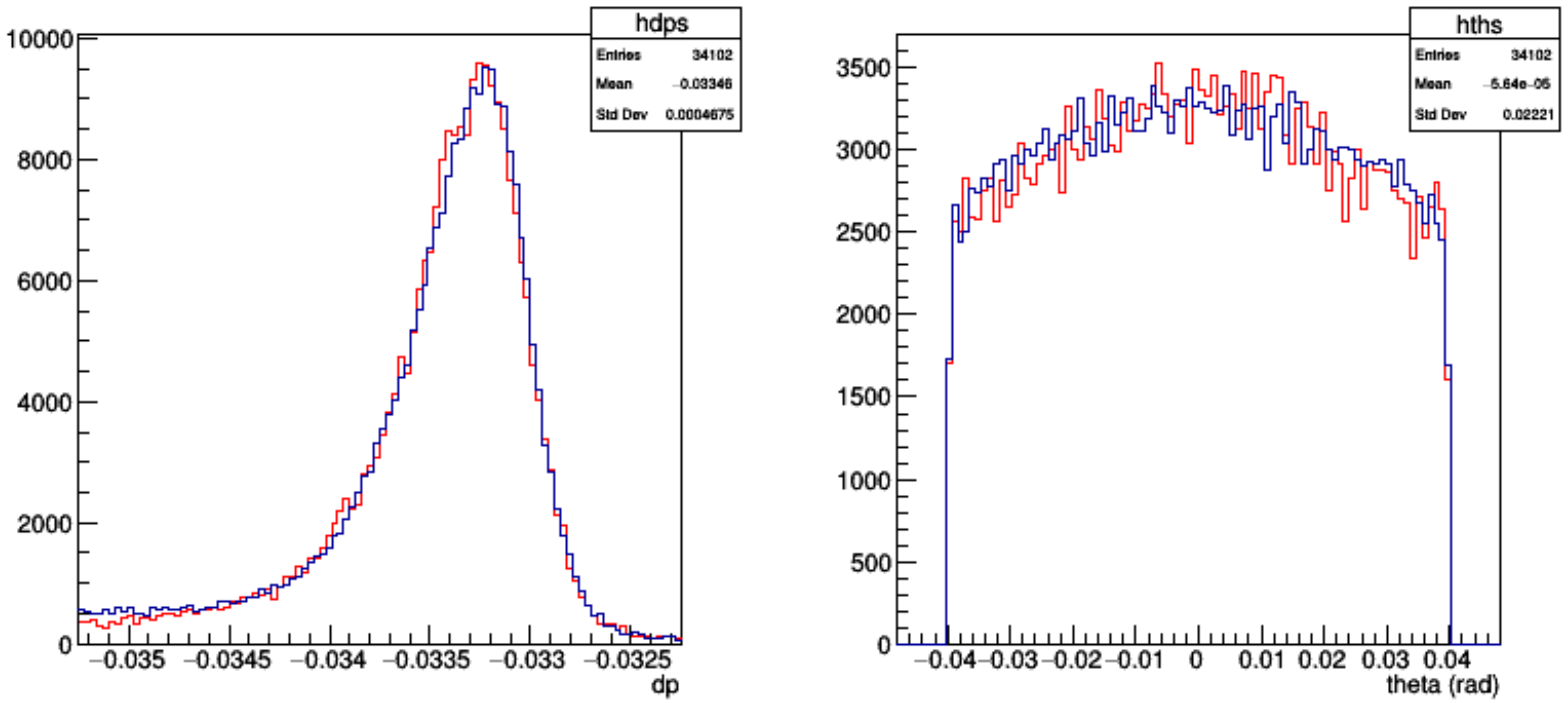
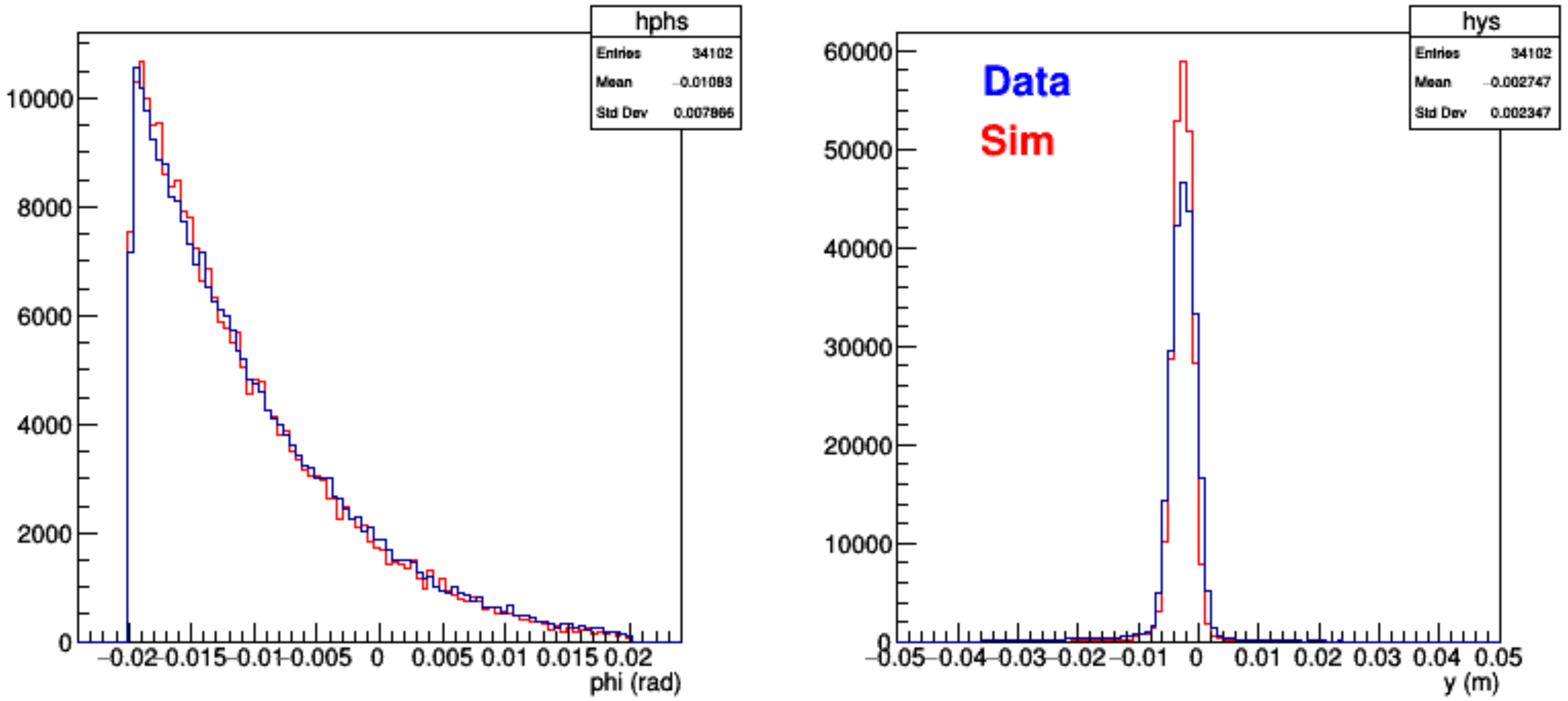
Aiming for 1% to 2% precision on XS

# 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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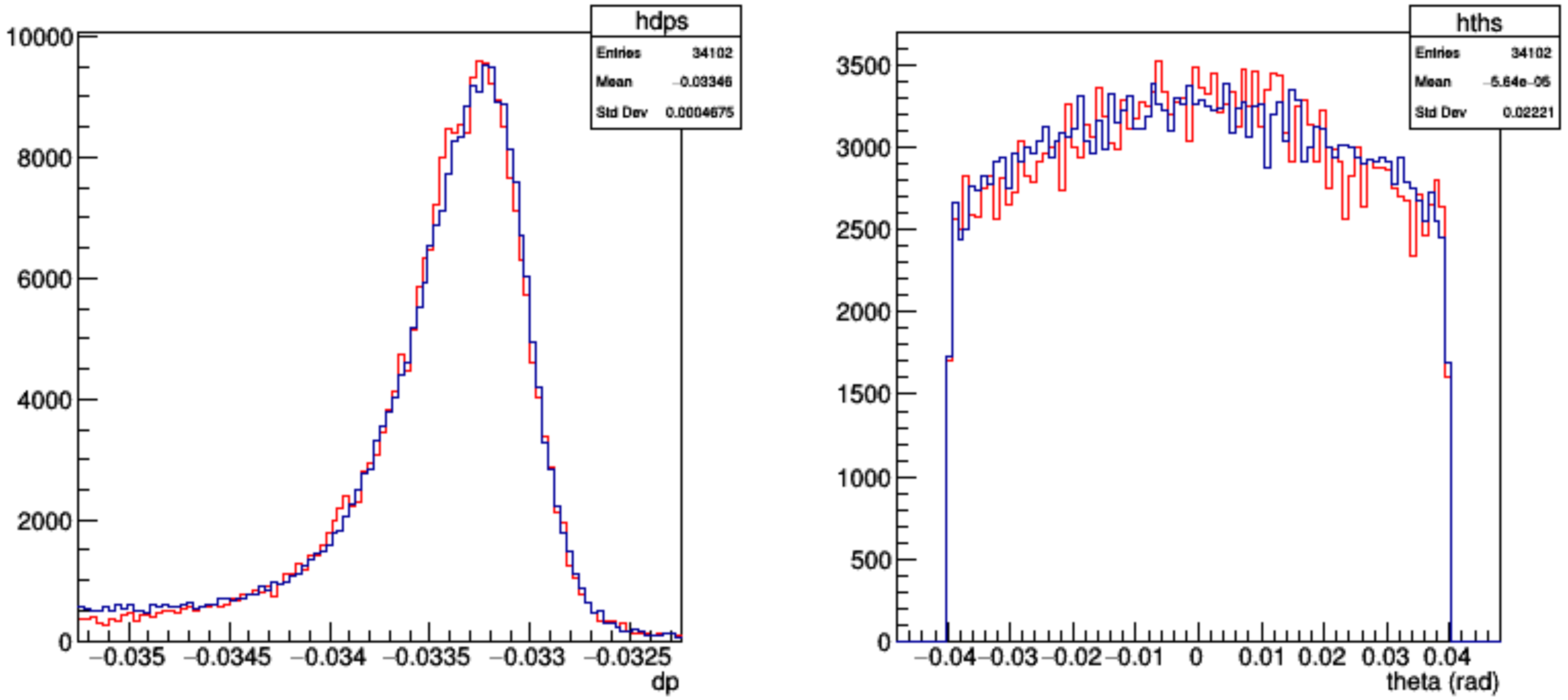


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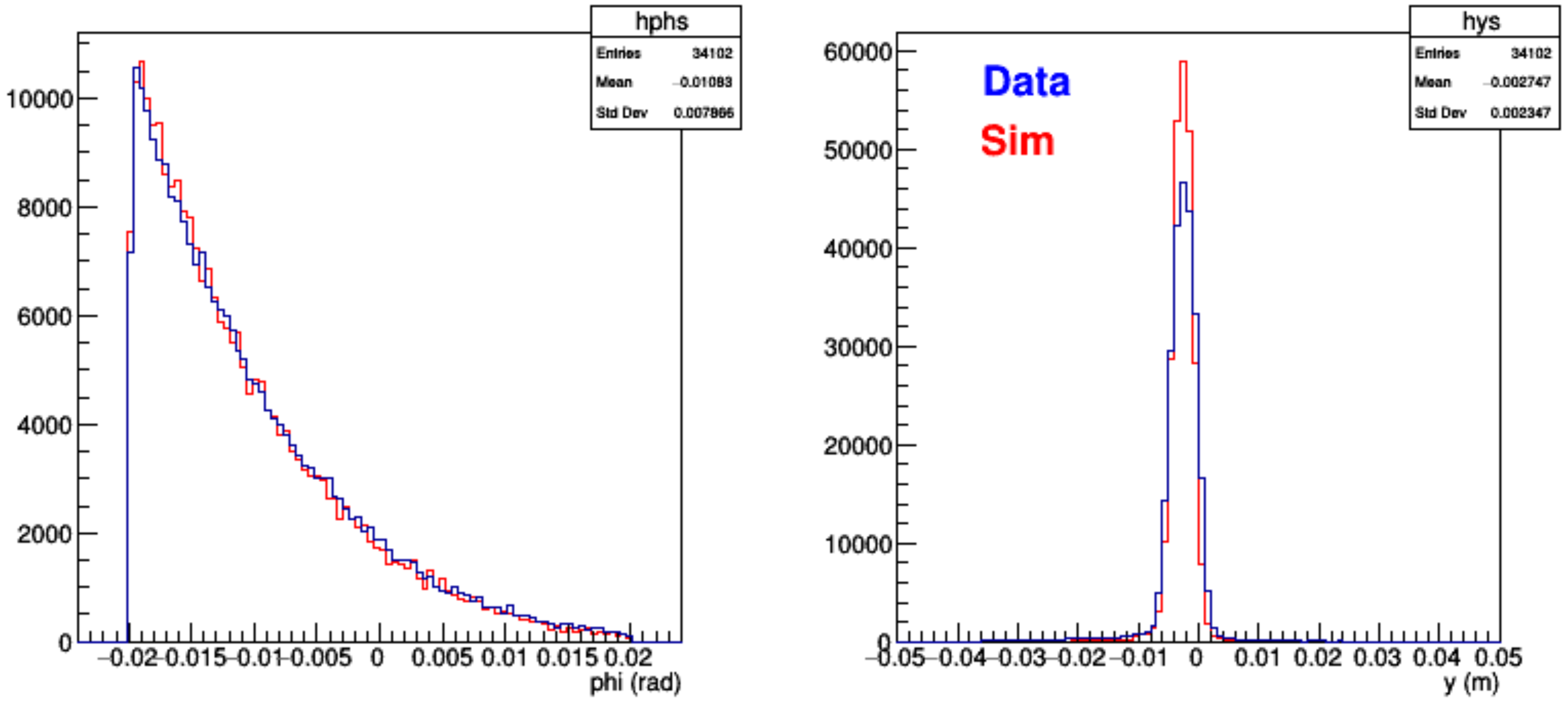


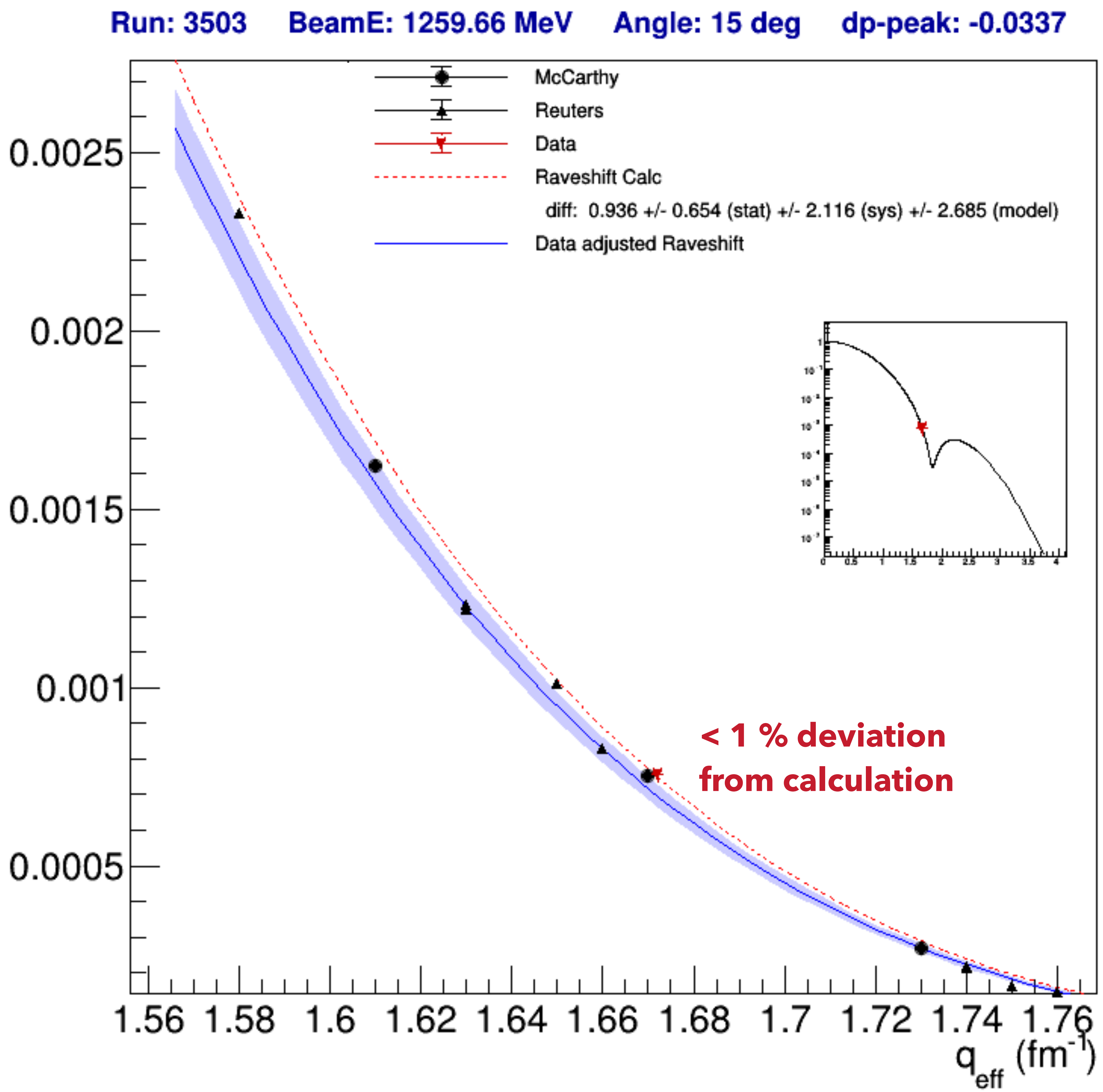

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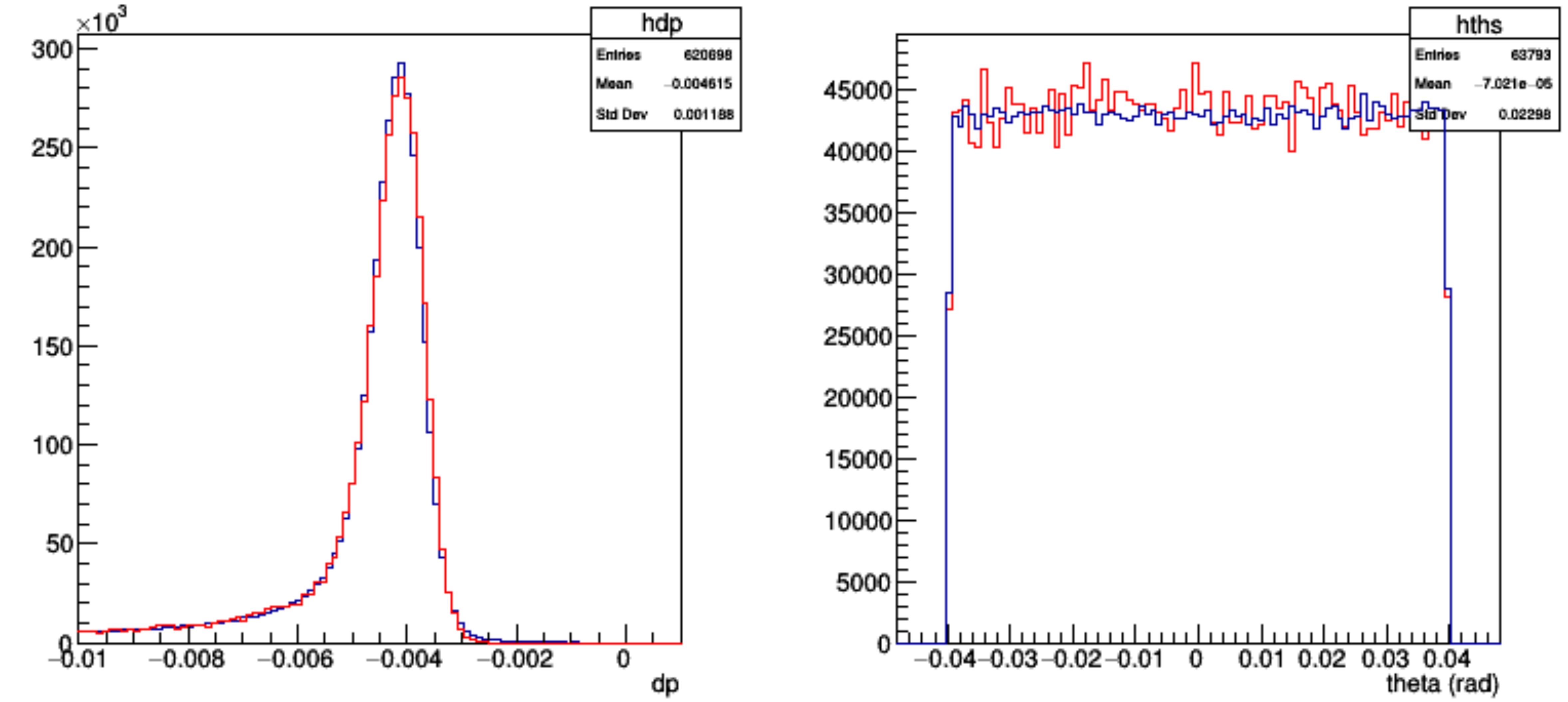
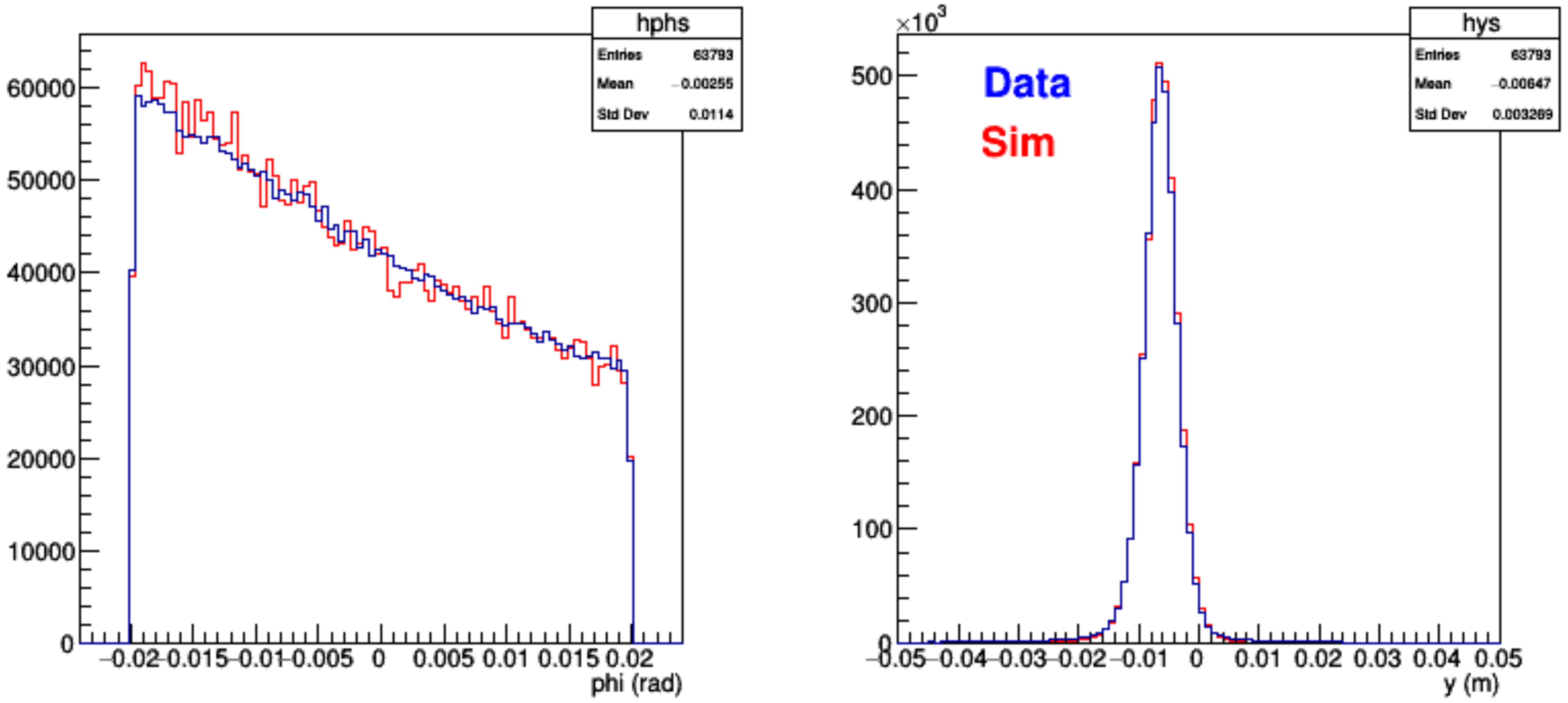
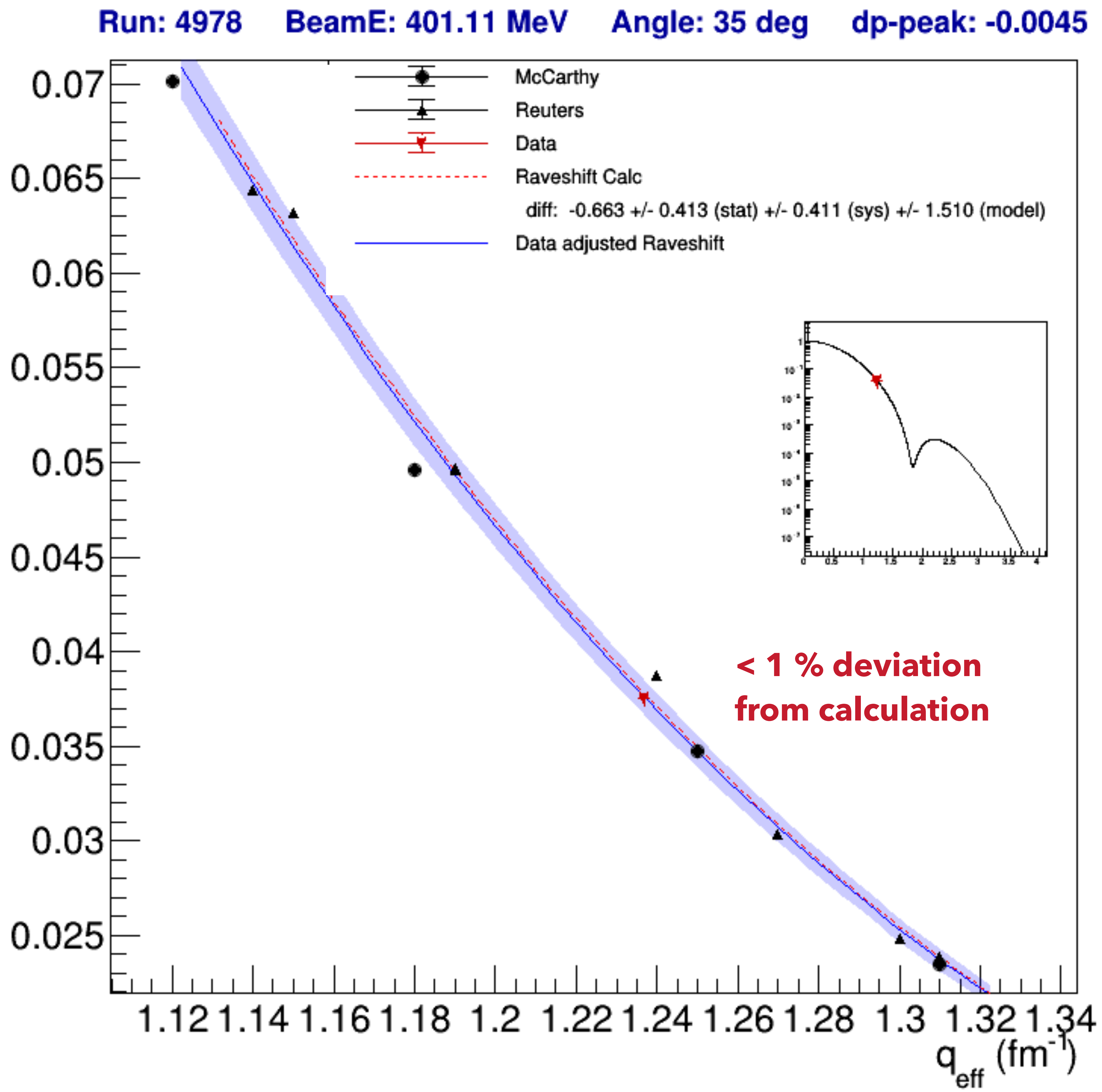
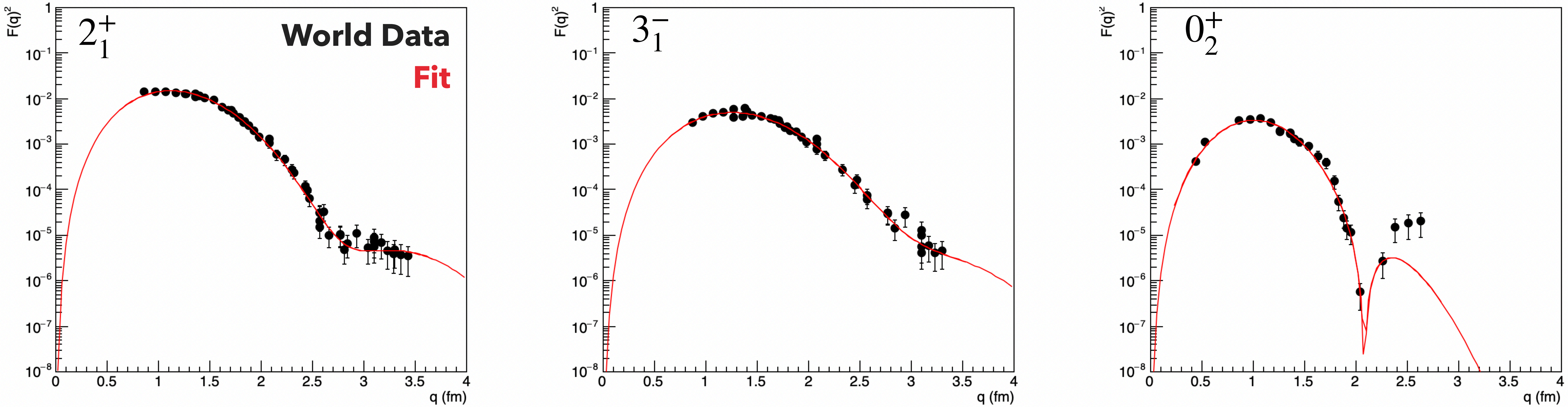


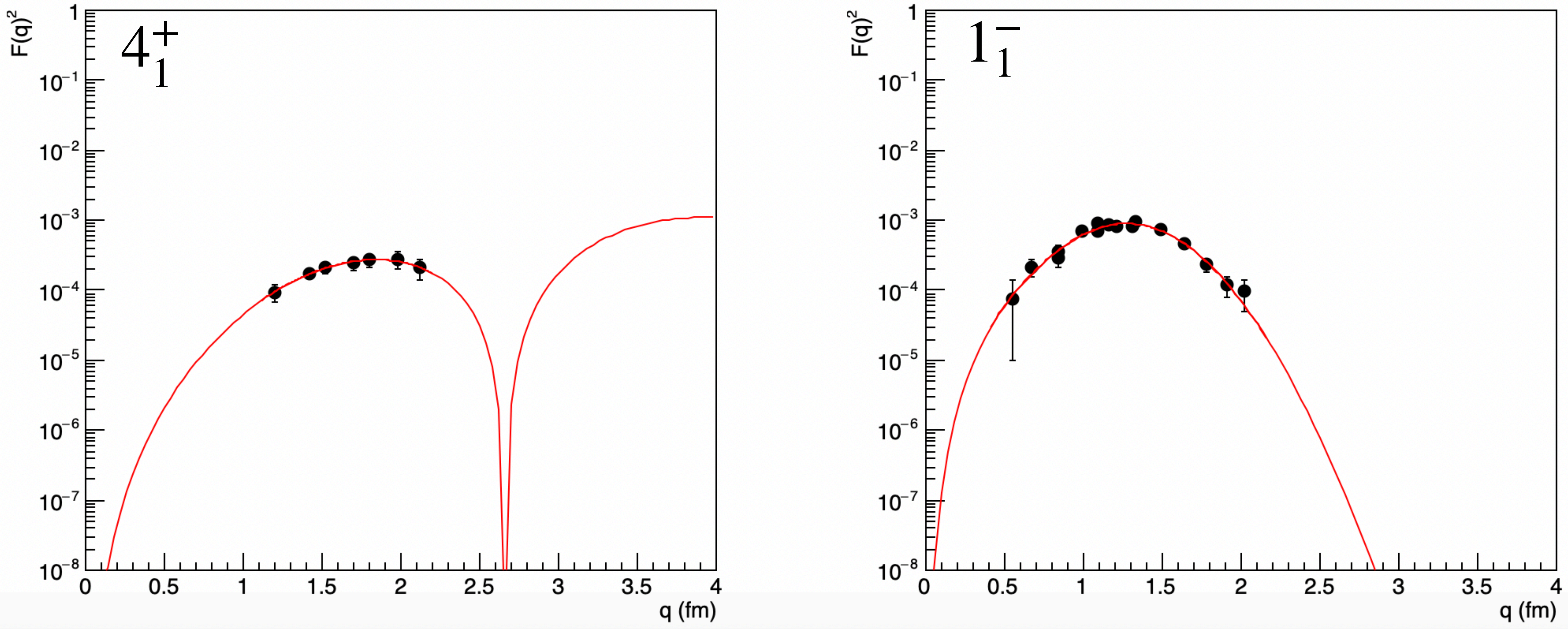

$^{12}$C elastic XS at 400 MeV, 35 degrees



# 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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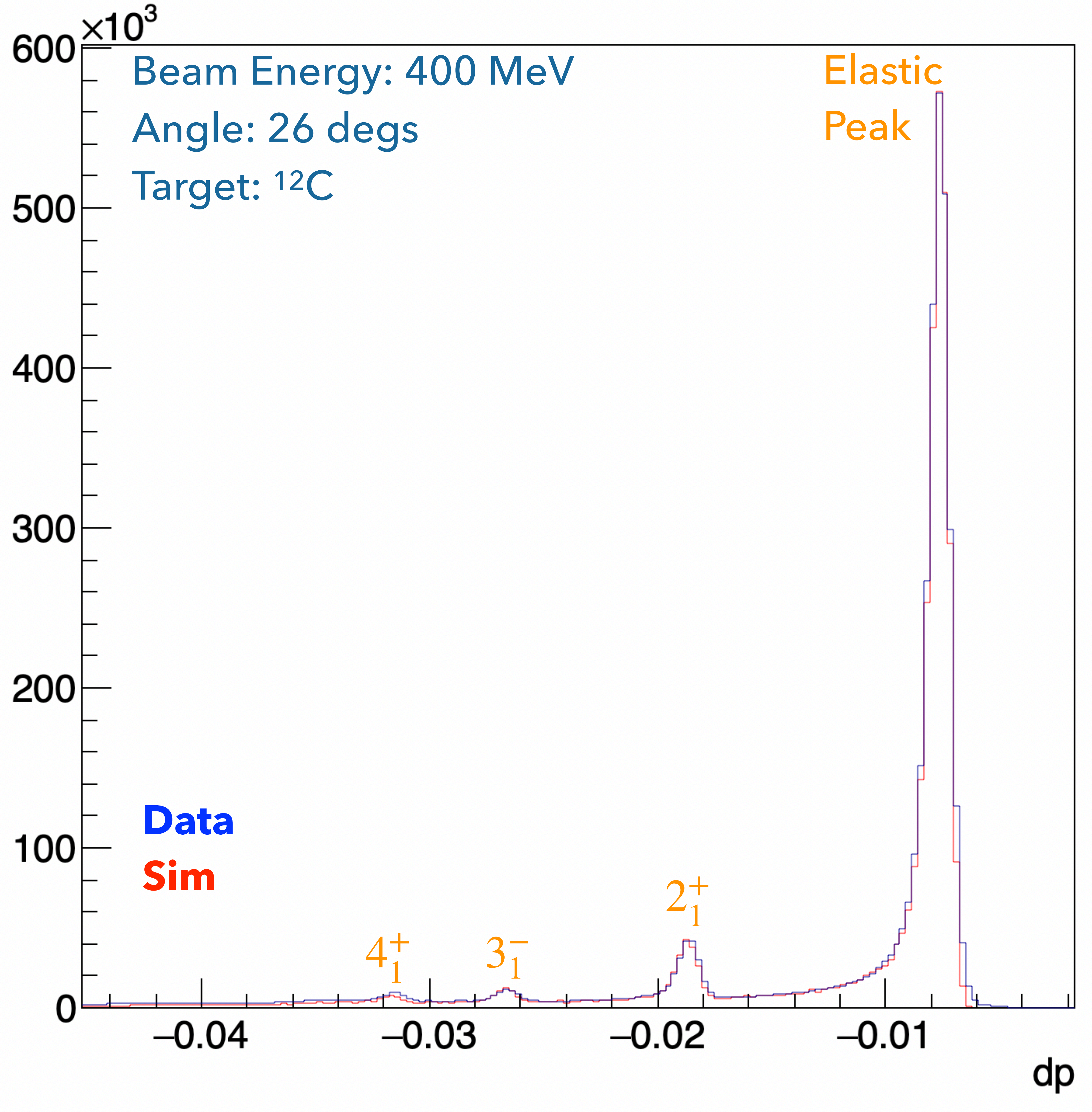


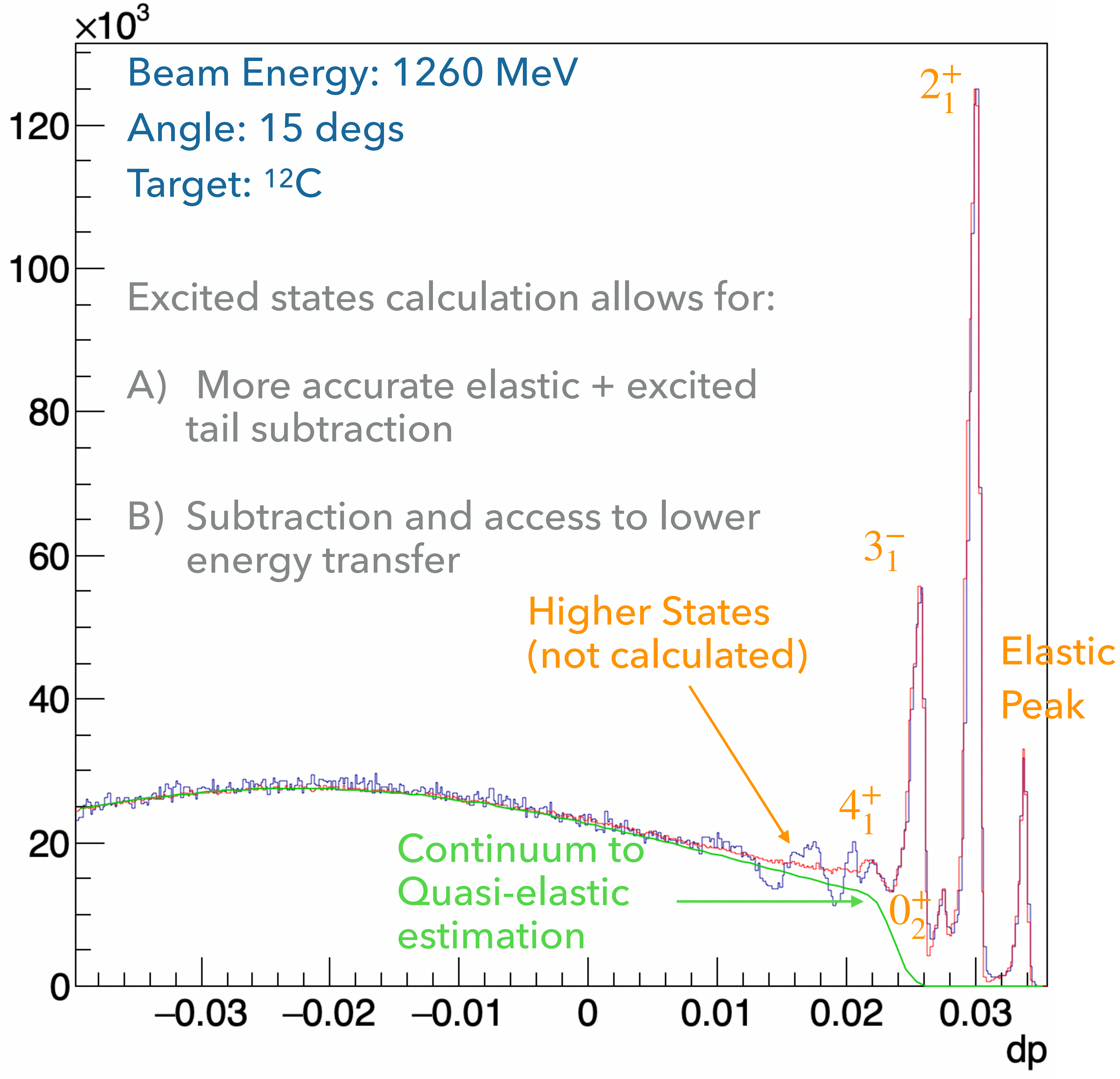


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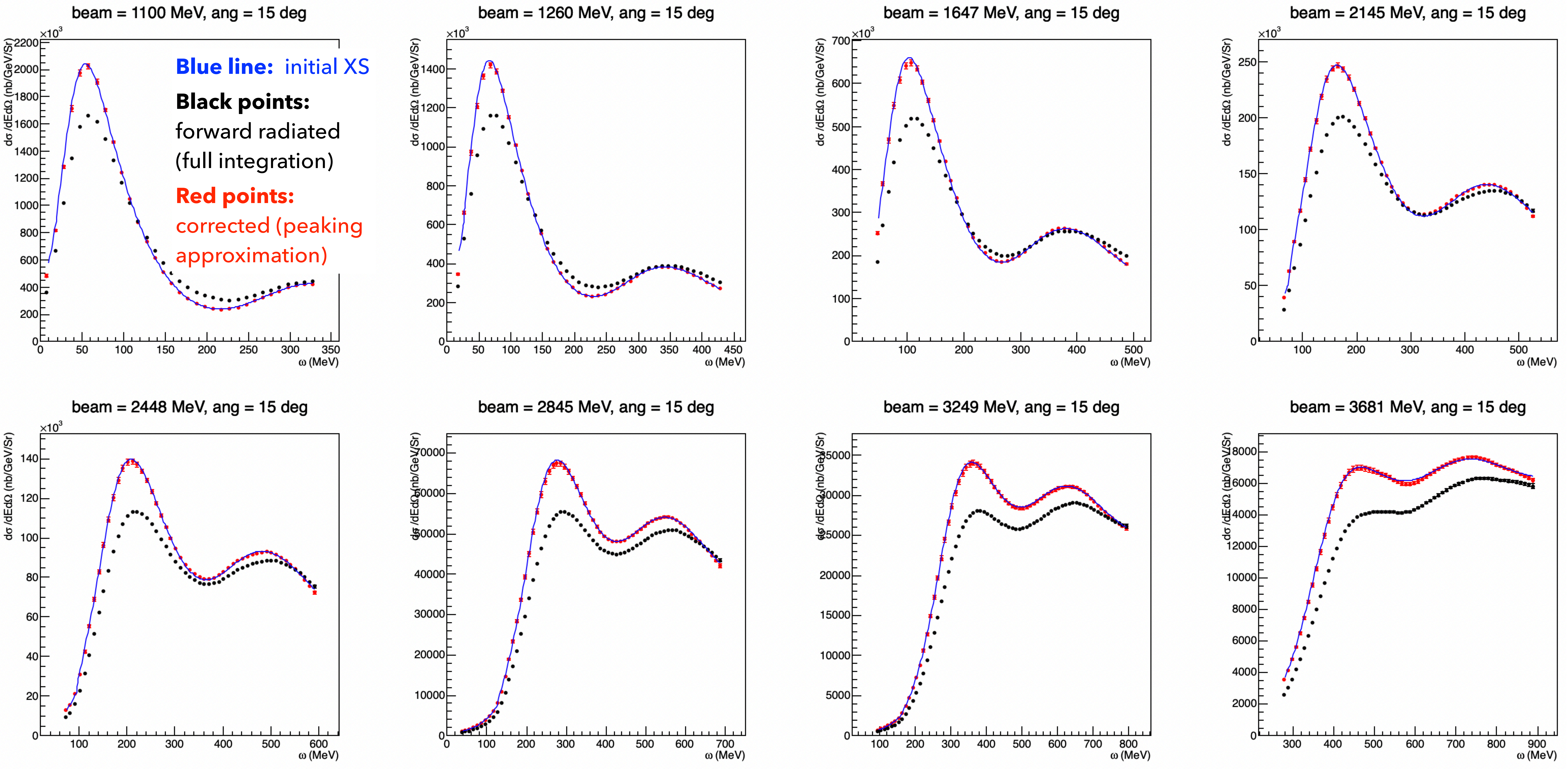
# MAGNET RESCATTERING

- At low central momentum, magnet-rescattered events may be present.

# RADIATIVE CORRECTIONS

- The radiative corrections are calculated via peaking approximation from Mo & Tsai formalism. Using multiple energy spectra, the corrections are unfolded.
- As a test to the radiative correction peaking approximation, a full forward-radiating Monte-Carlo was developed using the equivalent radiator method for internal radiation calculation.
- Test procedure: Use $^{54}$Fe XS predictions (F1F2 Bosted program) for test:
  - Radiate forward, with full integration over target length, radiated incident energy, and scattered electron energy. Vertex level corrections and ionization effects are also applied.
    - Use identical energies, angles, and measurement spacings as seen in data.
  - Use radcor fortran code to do peaking calculations and unfolding for radiative corrections.
    - Then compare input to output (ideally identical)

# RADIATIVE CORRECTIONS

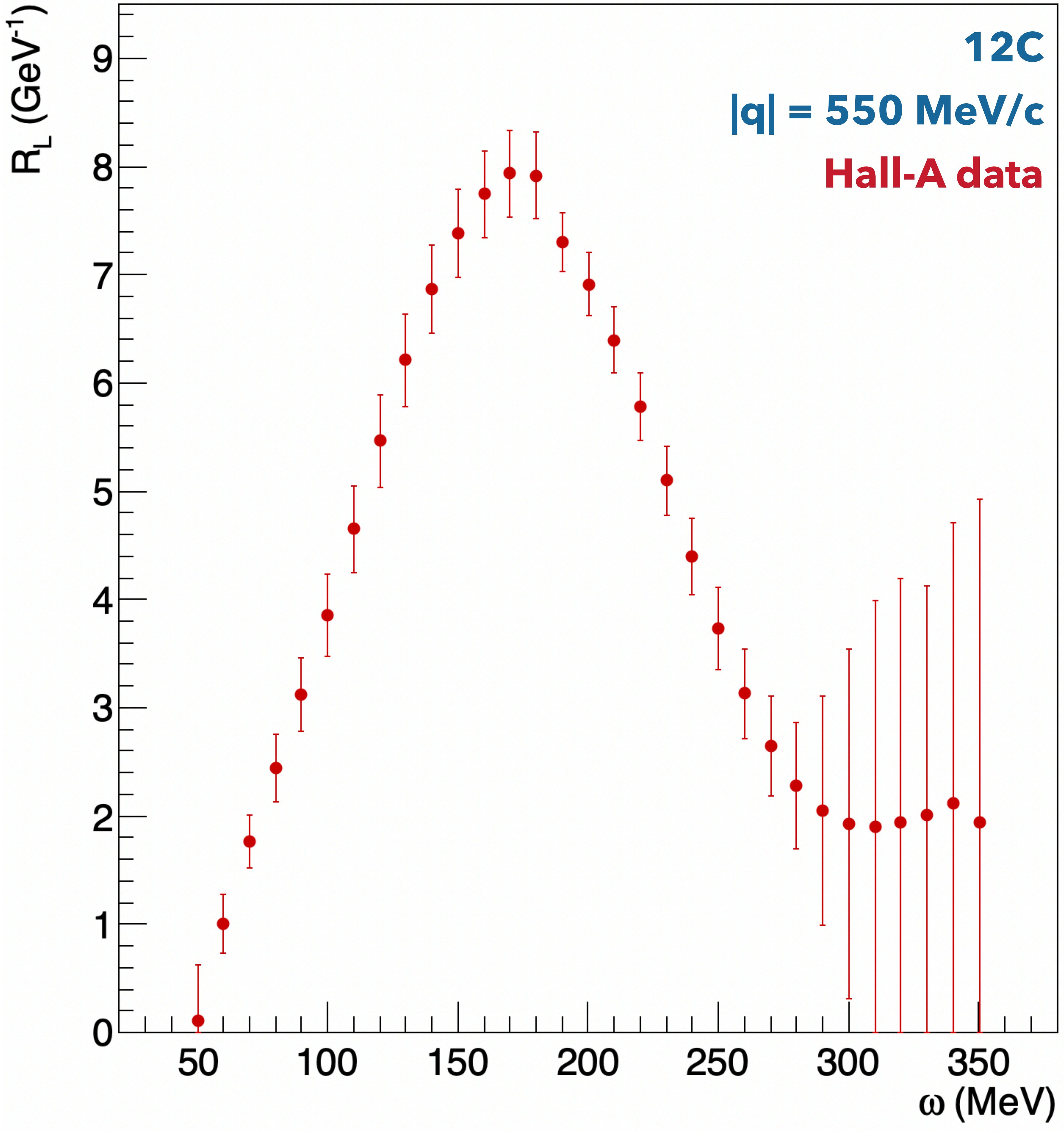


# RADIATIVE CORRECTIONS

Difference mostly at the < 1% level

# 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.
- For Carbon:



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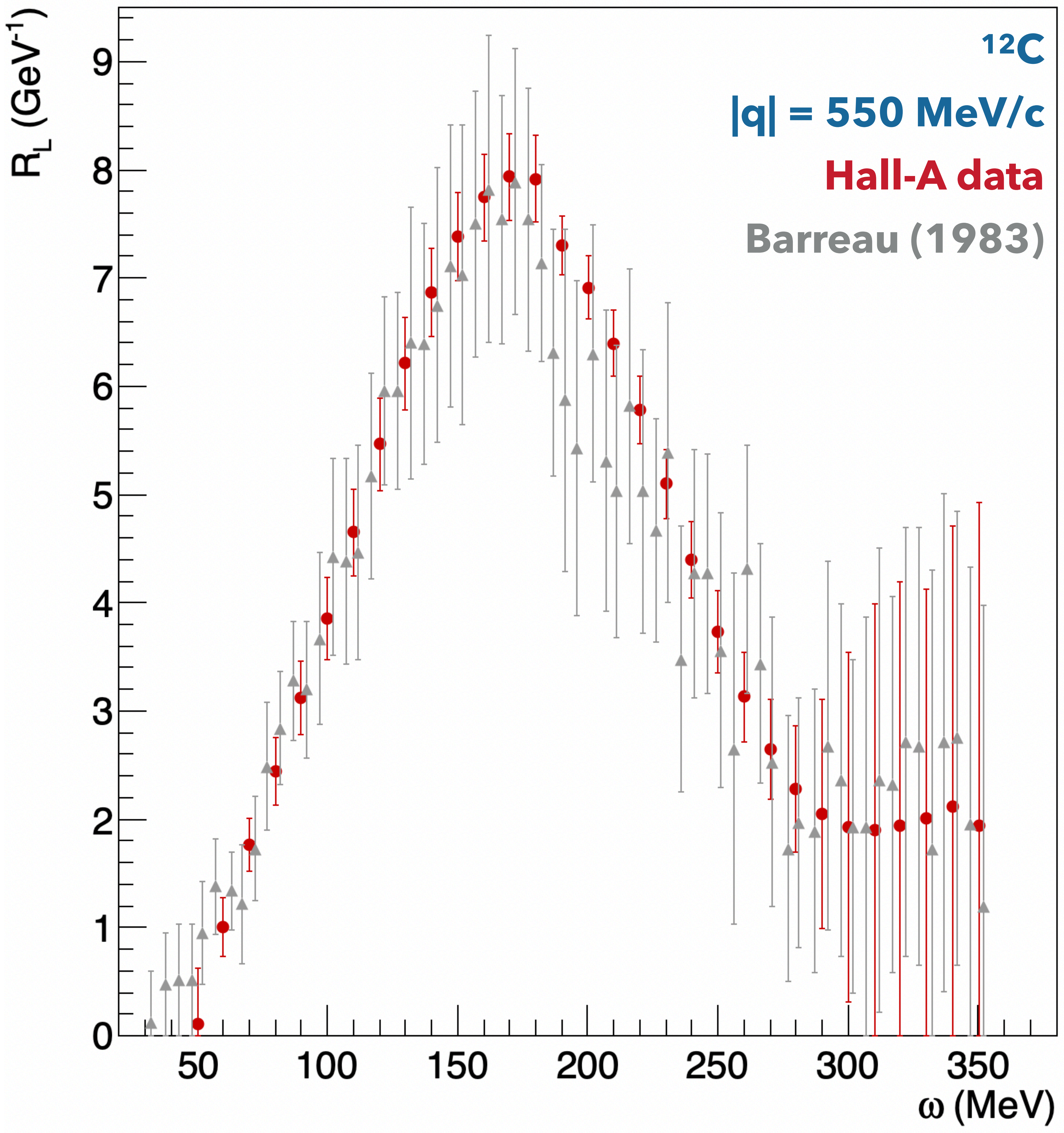

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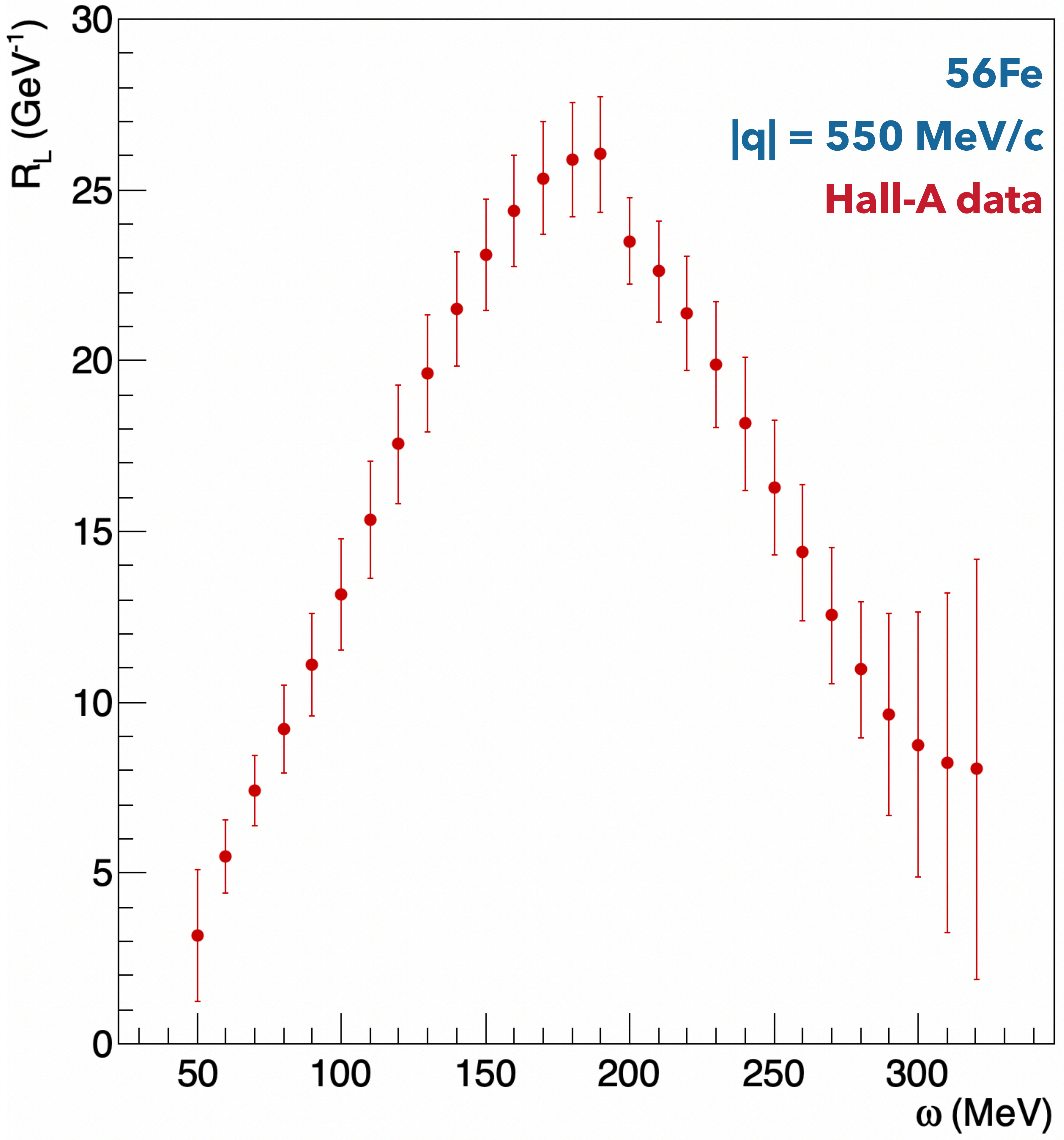

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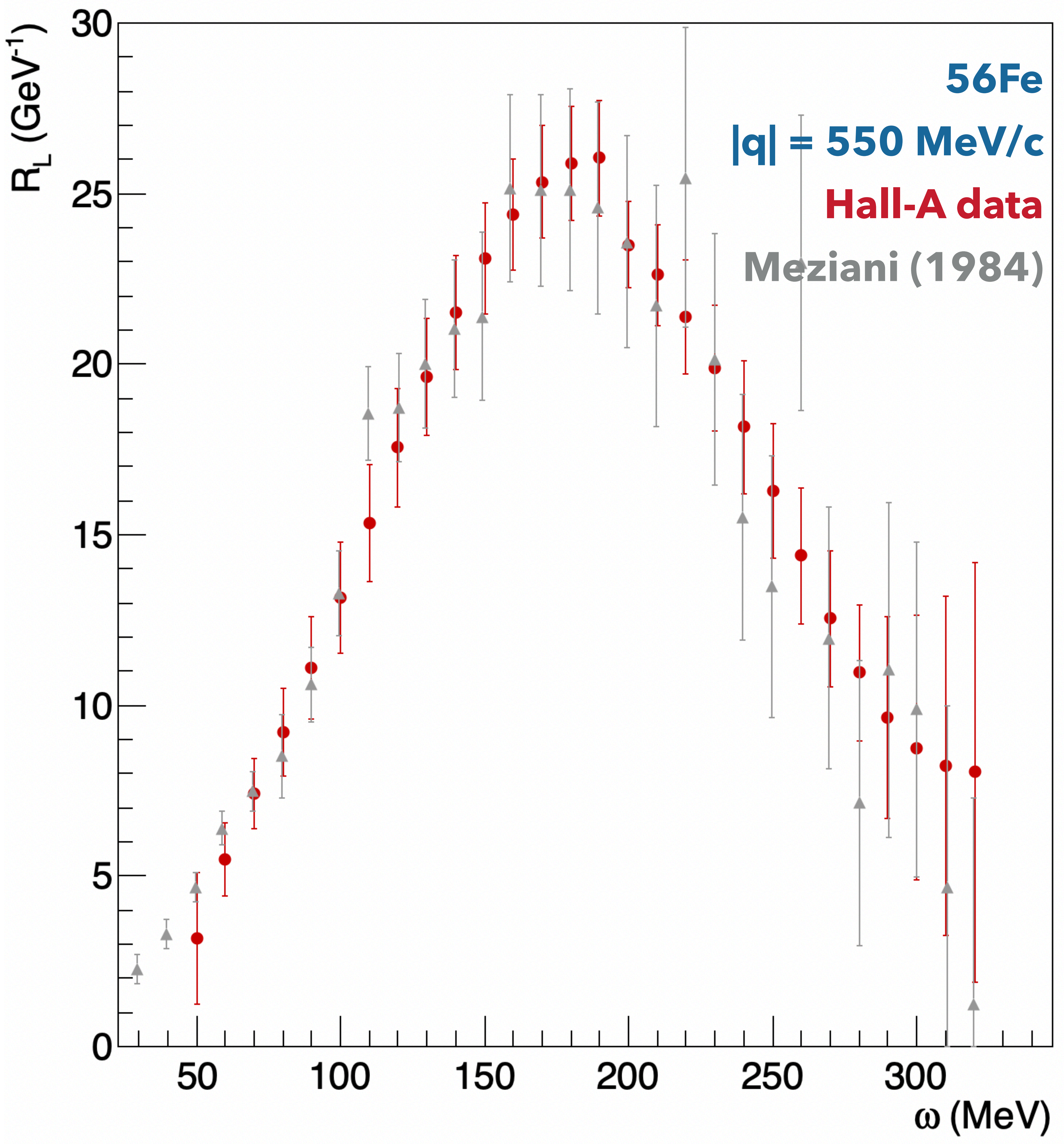
- For Iron: we also have nice agreement with Meziani, et. al.



# SUMMARY / LOOKING AHEAD

- Recent efforts:
  - Confirmation of radiative correction technique
  - Comparison to existing CSR data.
- Up next:
  - Systematic studies:
    - Comparison of Left to Right arm data.
  - Publish (a draft is in the works).

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