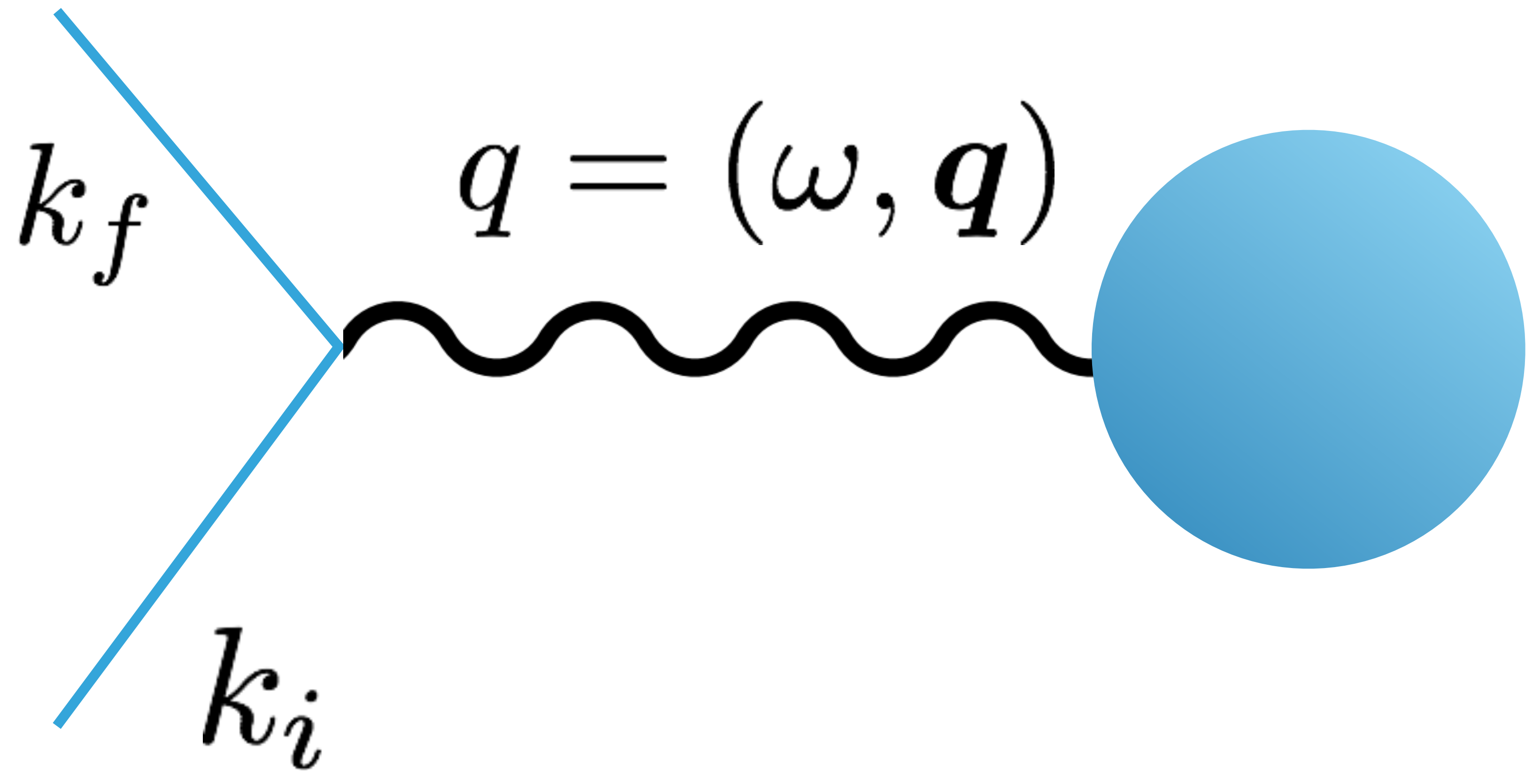
MICHAEL PAOLONE

TEMPLE UNIVERSITY

FOR THE E05-110 COLLABORATION.

COULOMB SUM RULE IN THE RANGE $0.55 < |q| < 1.0\ GeV/c$

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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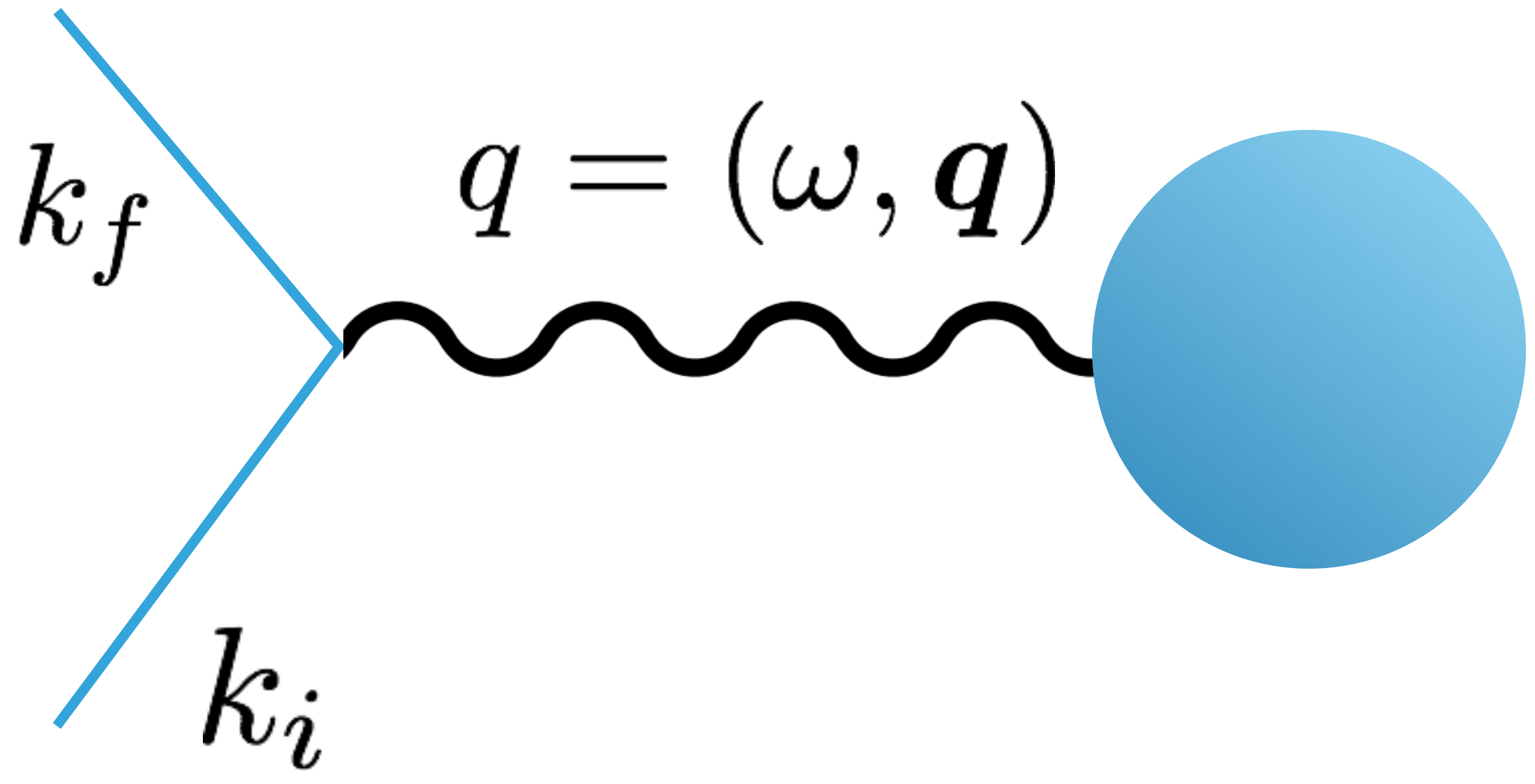

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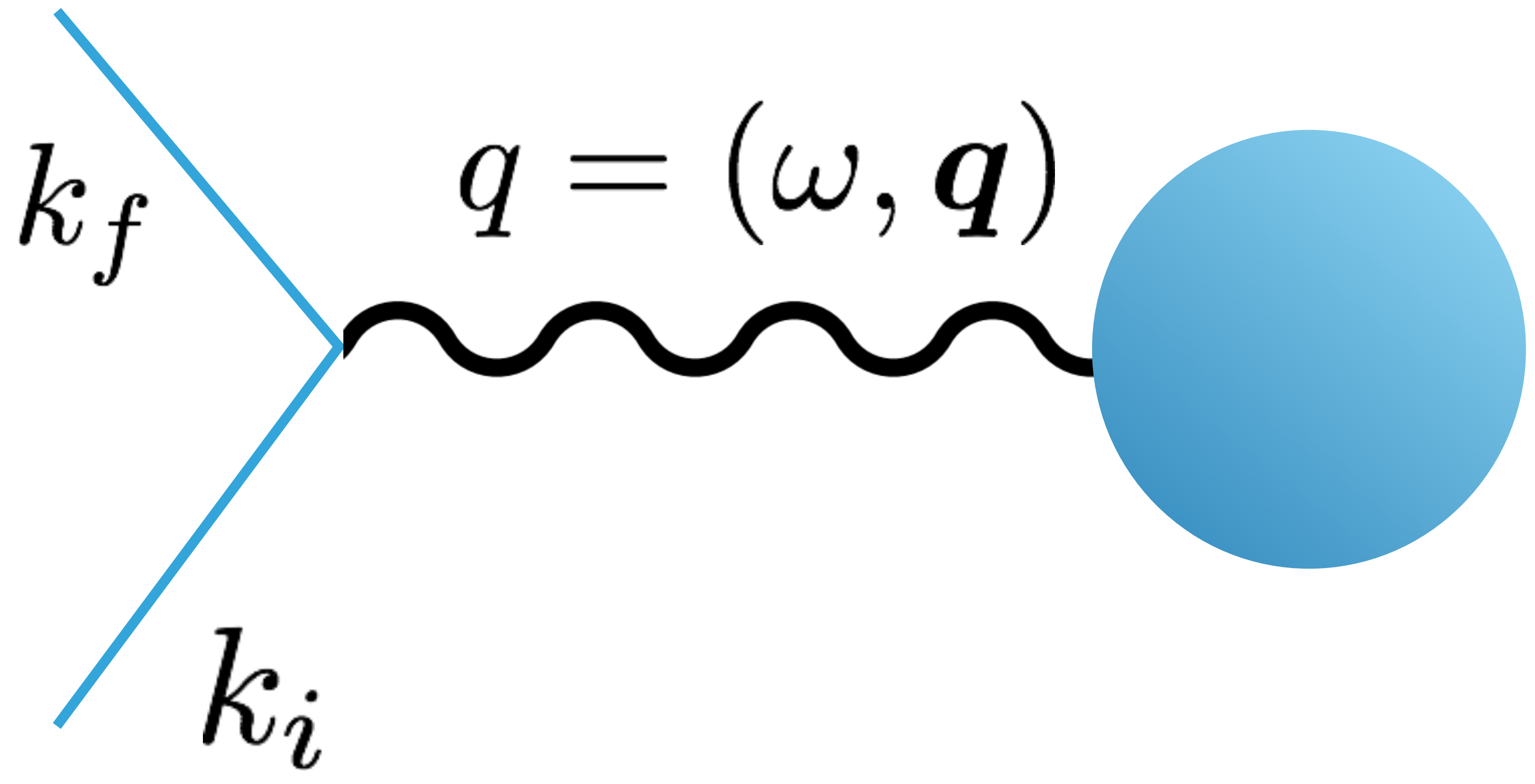
Scattering response due to **charge** properties (R_L)

Scattering response due to **magnetic** properties (R_T)

COULOMB SUM RULE



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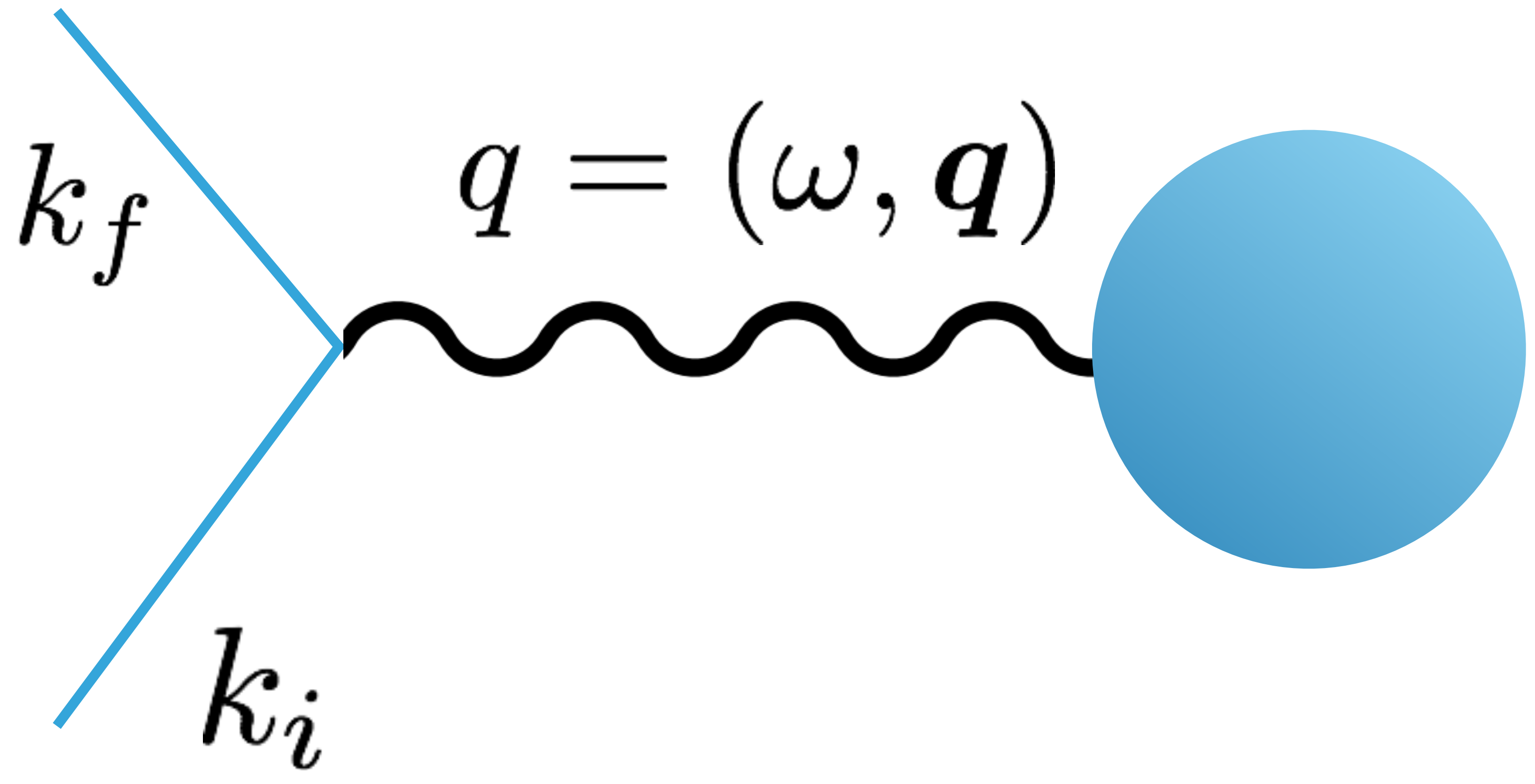
Scattering response due to **magnetic** properties

Coulomb Sum Rule definition:

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

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.

COULOMB SUM RULE



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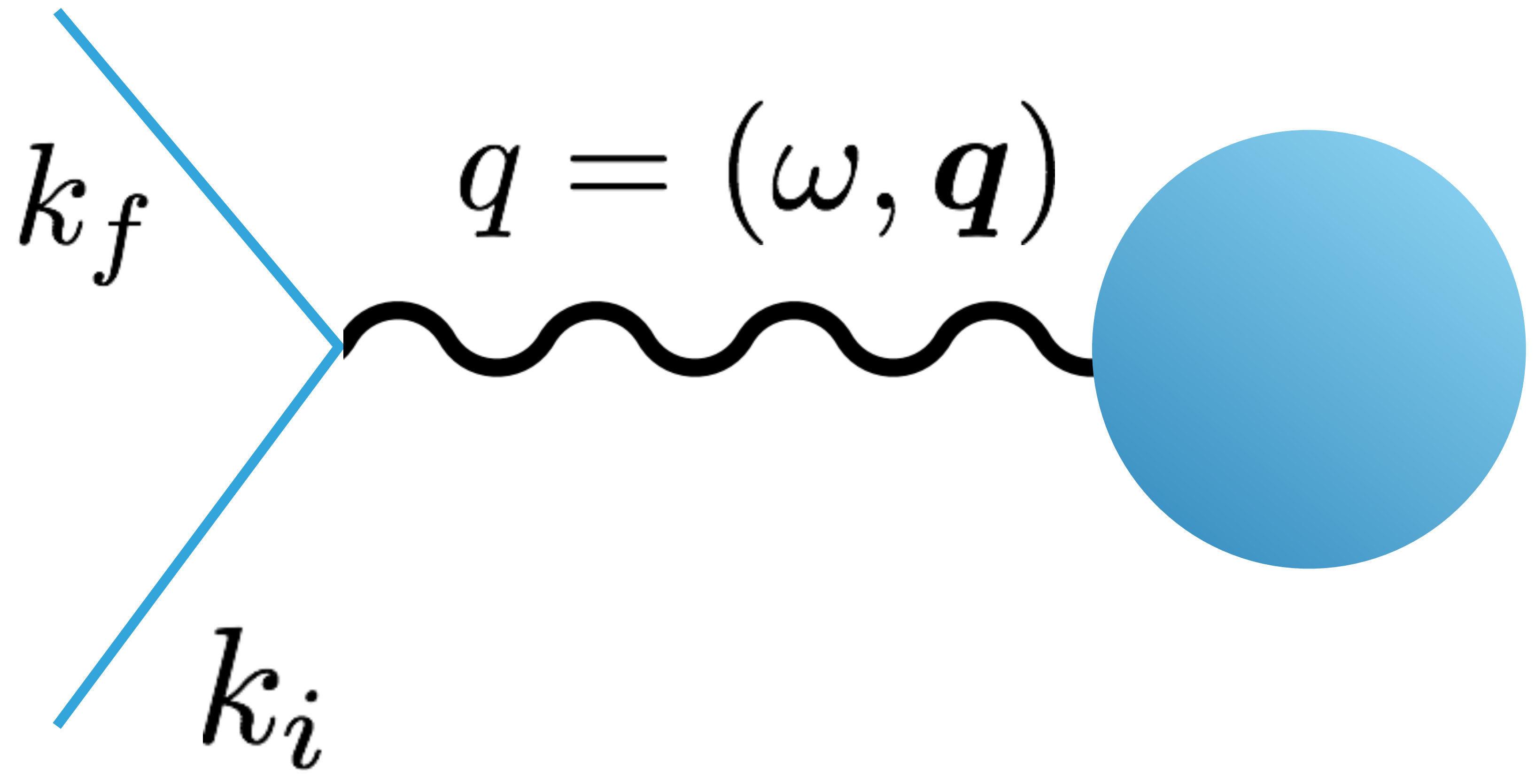

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At large |q| >> $2k_f$, S_L should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!

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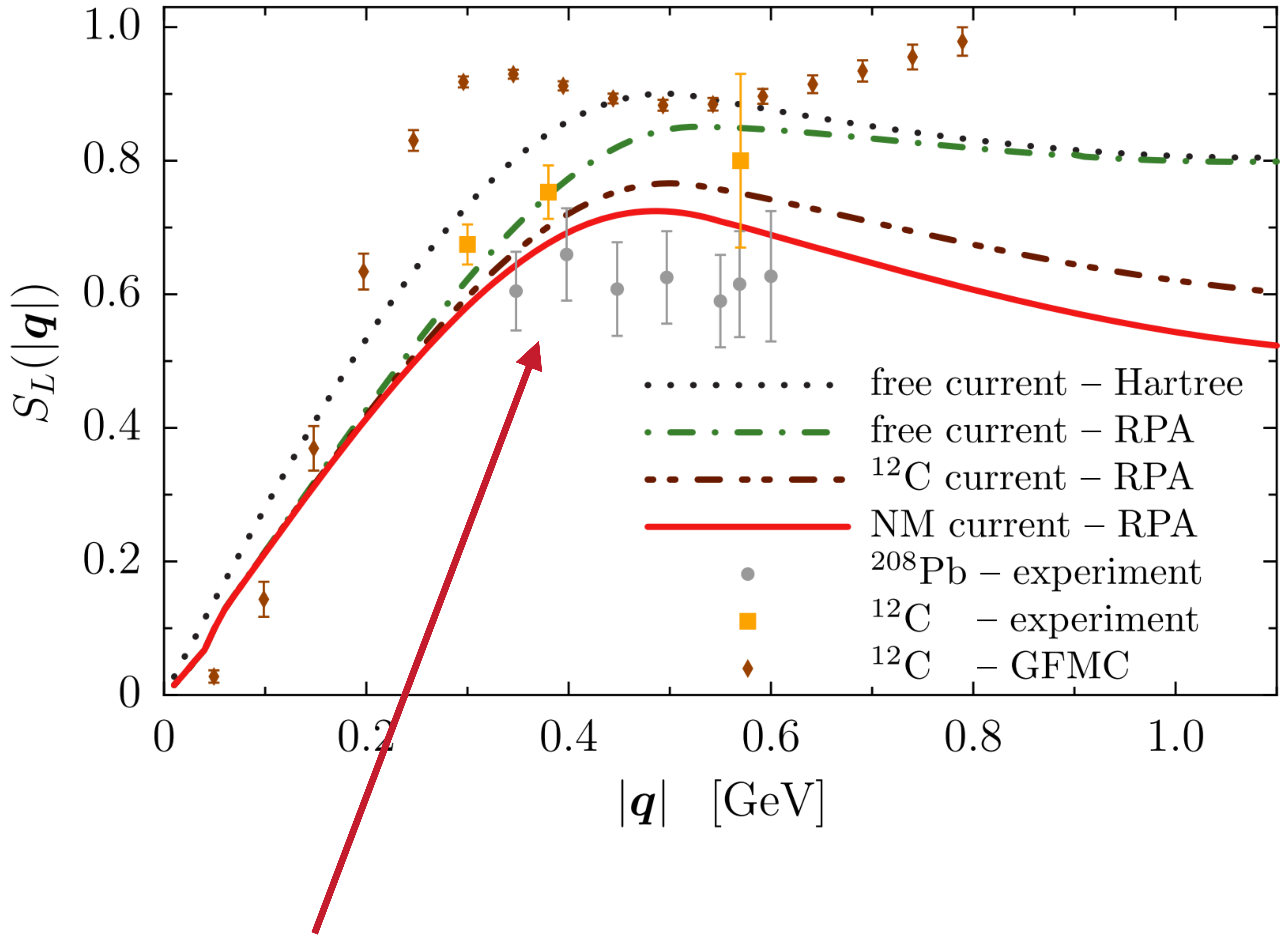
[2]*Department of Physics, School of Science, Tokai University, Hiratsuka-shi, Kanagawa 259-1292, Japan*
[3]*CSSM and ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide South Australia 5005, Australia*
(Received 23 June 2015; published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



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!

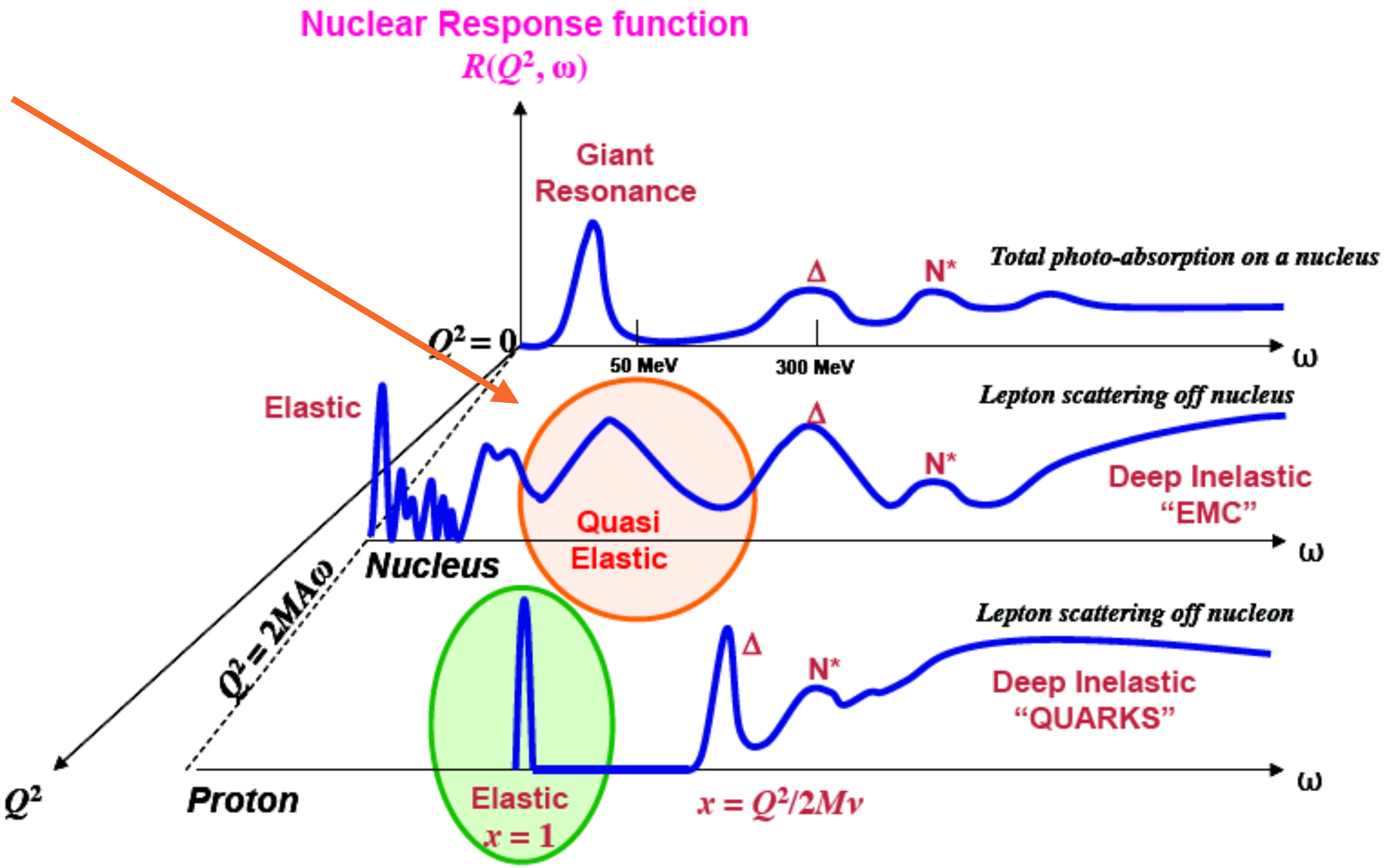
*Short range correlations will also quench S_L, but only by < 10%

QUASI-ELASTIC SCATTERING

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

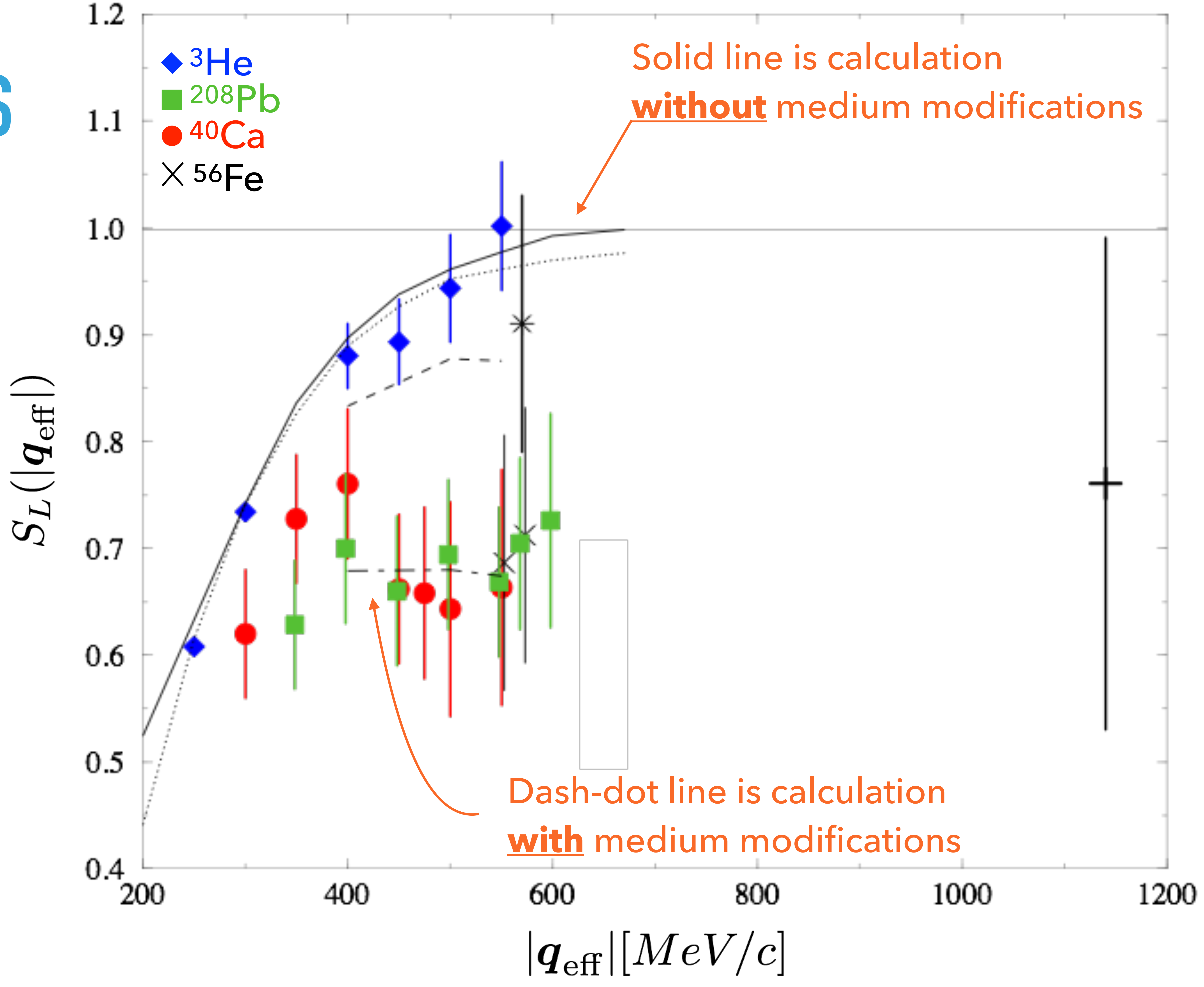
We want to integrate above the coherent elastic peak:
Quasi-elastic is "elastic" scattering on constituent nucleons inside nucleus.

- Quasi-elastic scattering at intermediate to low Q^2 is the region of interest for our experiment:
  - Nuclei investigated:
    - ^{4}He
    - ^{12}C
    - ^{56}Fe
    - ^{208}Pb



PUBLISHED EXPERIMENTAL RESULTS

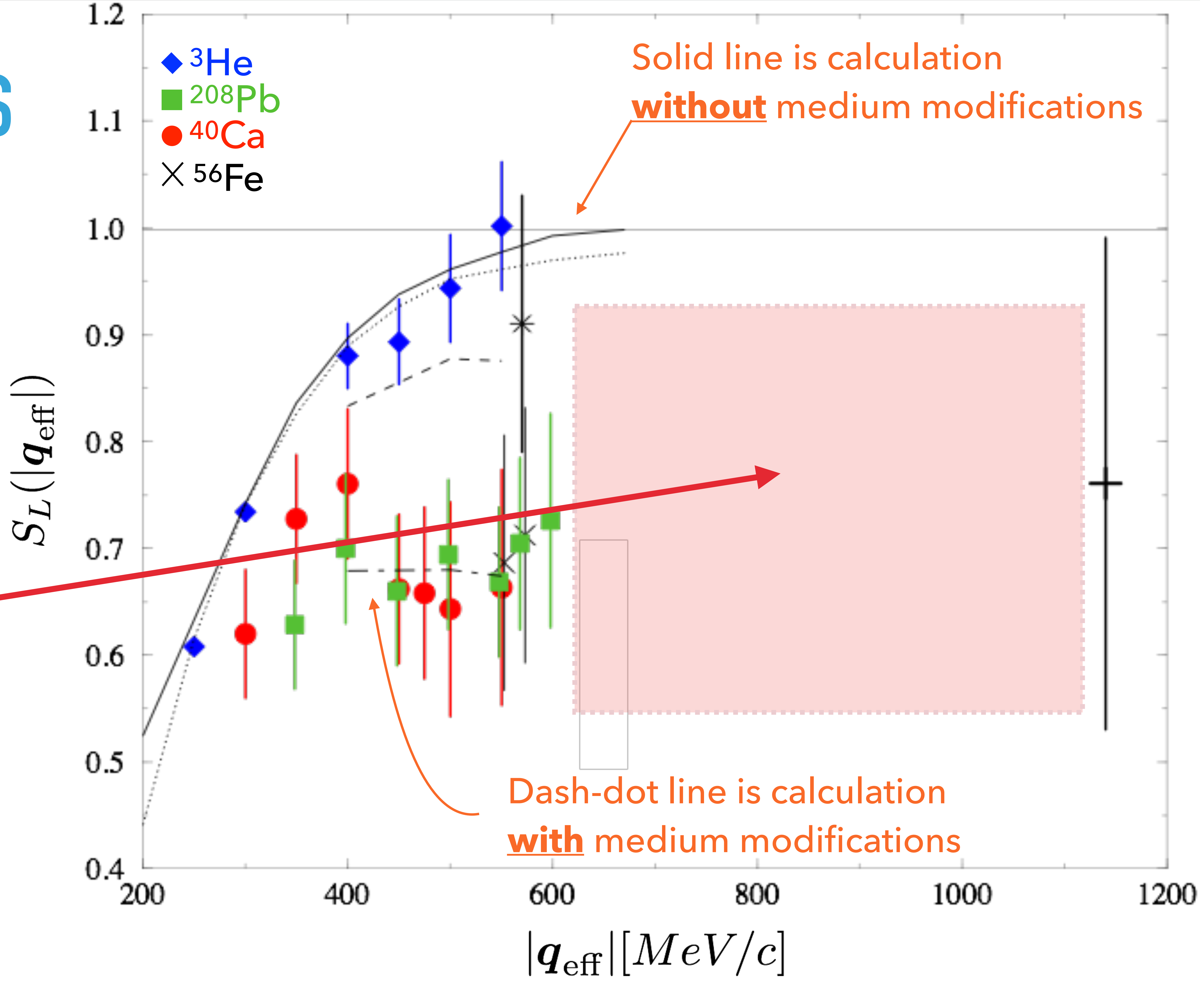
- First group of experiments from Saclay, Bates, and SLAC show a quenching of S_L consistent with medium modified form-factors.



$|\mathbf{q}_{eff}|$ is $|\mathbf{q}|$ 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, 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!
  - Sarclay, Bates limited in beam energy reach up to 800 MeV.
  - SLAC limited in kinematic coverage of scattered electron at |q| below 1150 MeV/c.



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

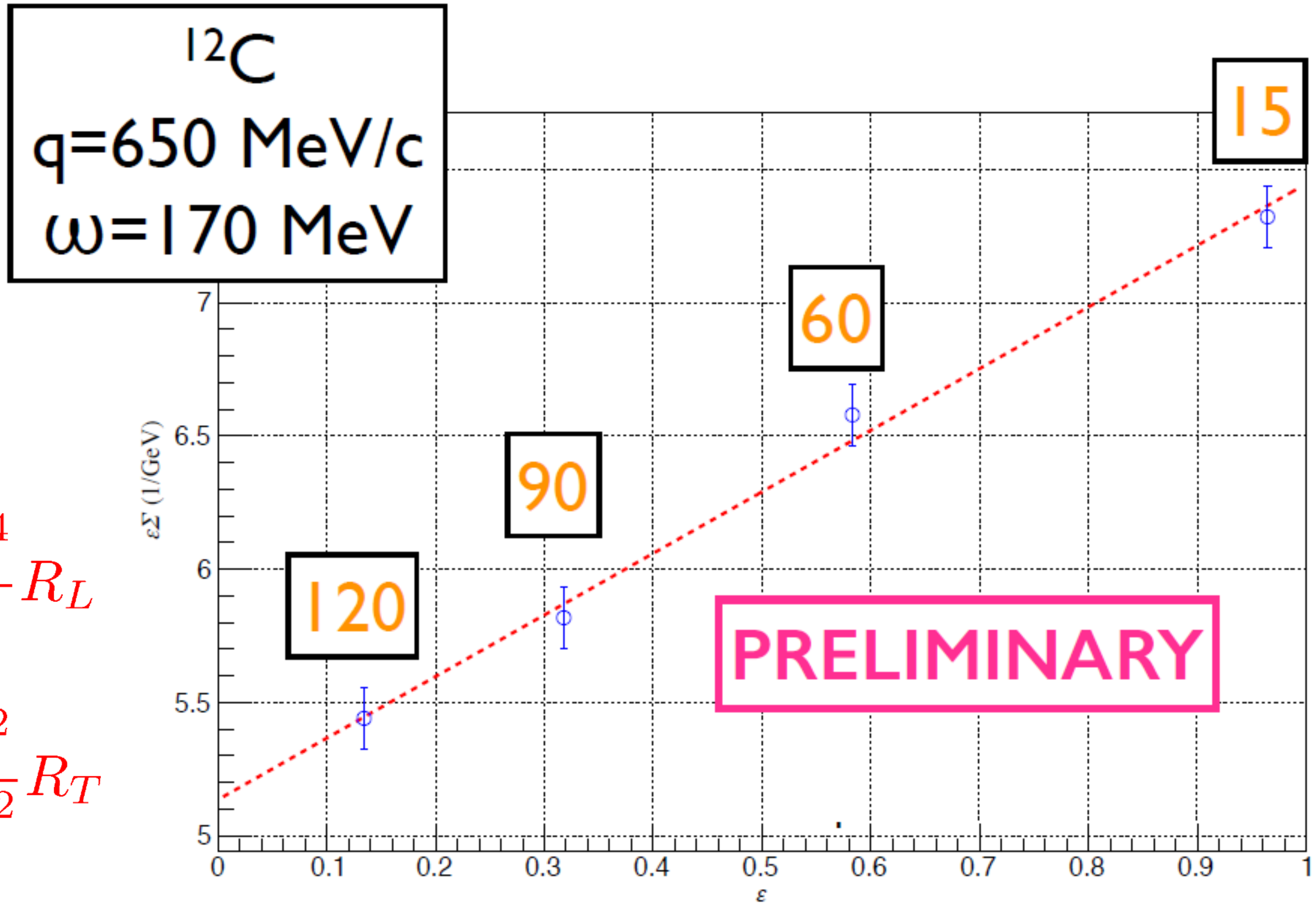
EXPERIMENTAL DESIGN

- Need R_L ⟶ Use Rosenbluth separation!

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

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

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



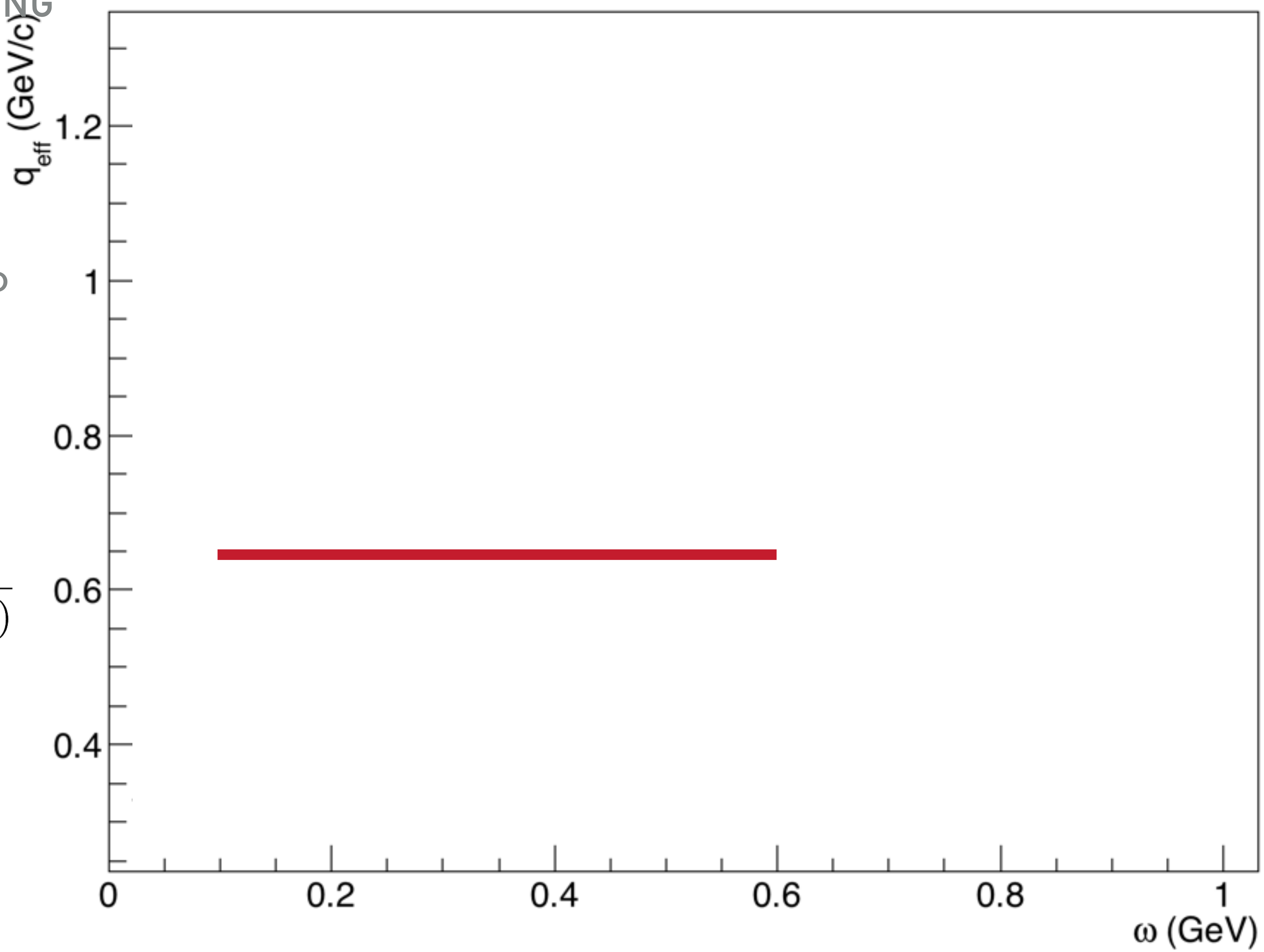
- Experiment run at 4 angles per target: 15, 60, 90, 120 degs. Very large lever arm for precise calculation of R_L!
- Need data for each angle at a constant |q| over an ω range starting above the elastic peak up to |q|.
  - When running a single arm experiment with fixed beam energy and scattering angle,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

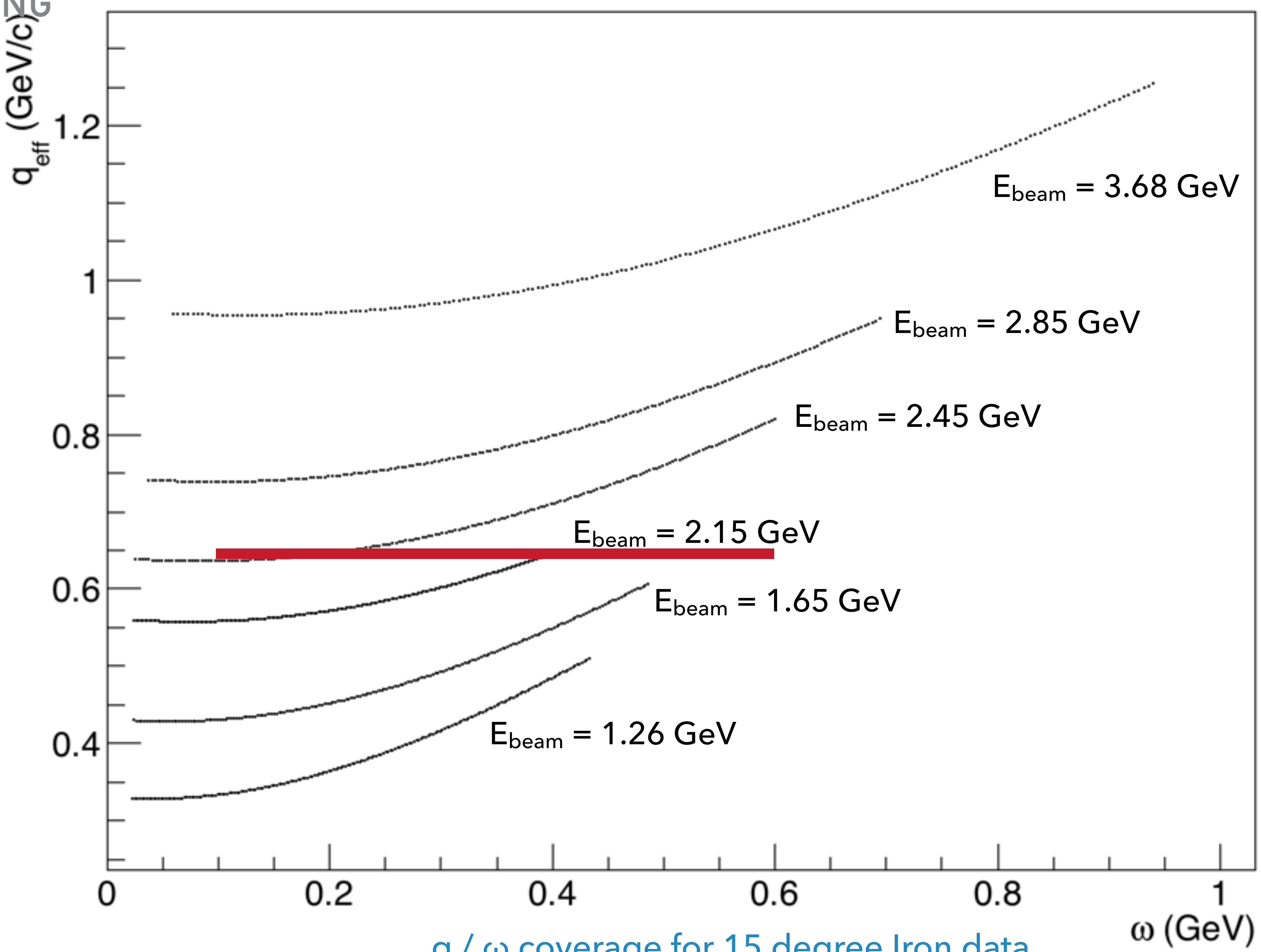
CSR calculated at constant |**q**| !!

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



EXPERIMENTAL DESIGN

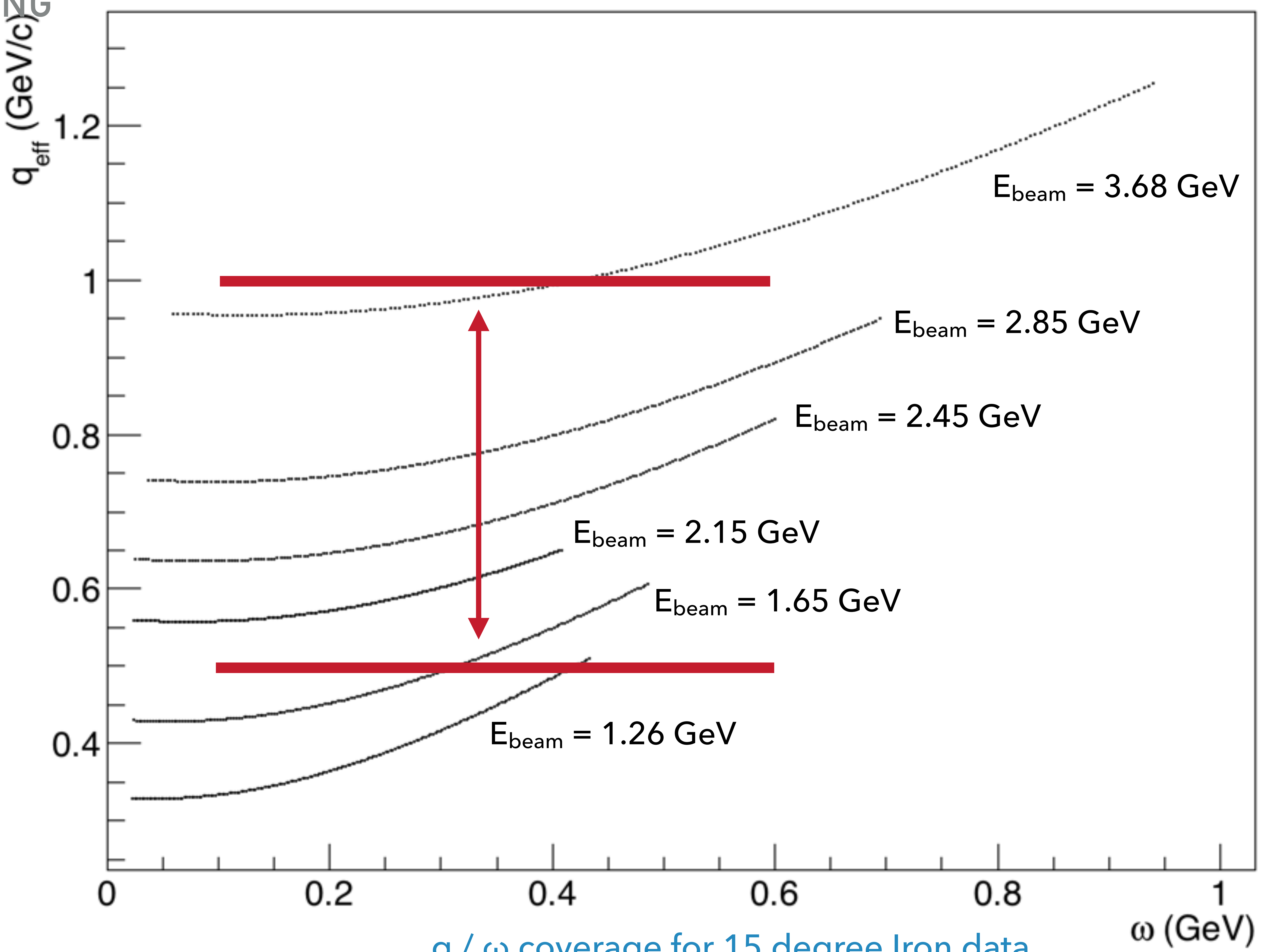
- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.



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



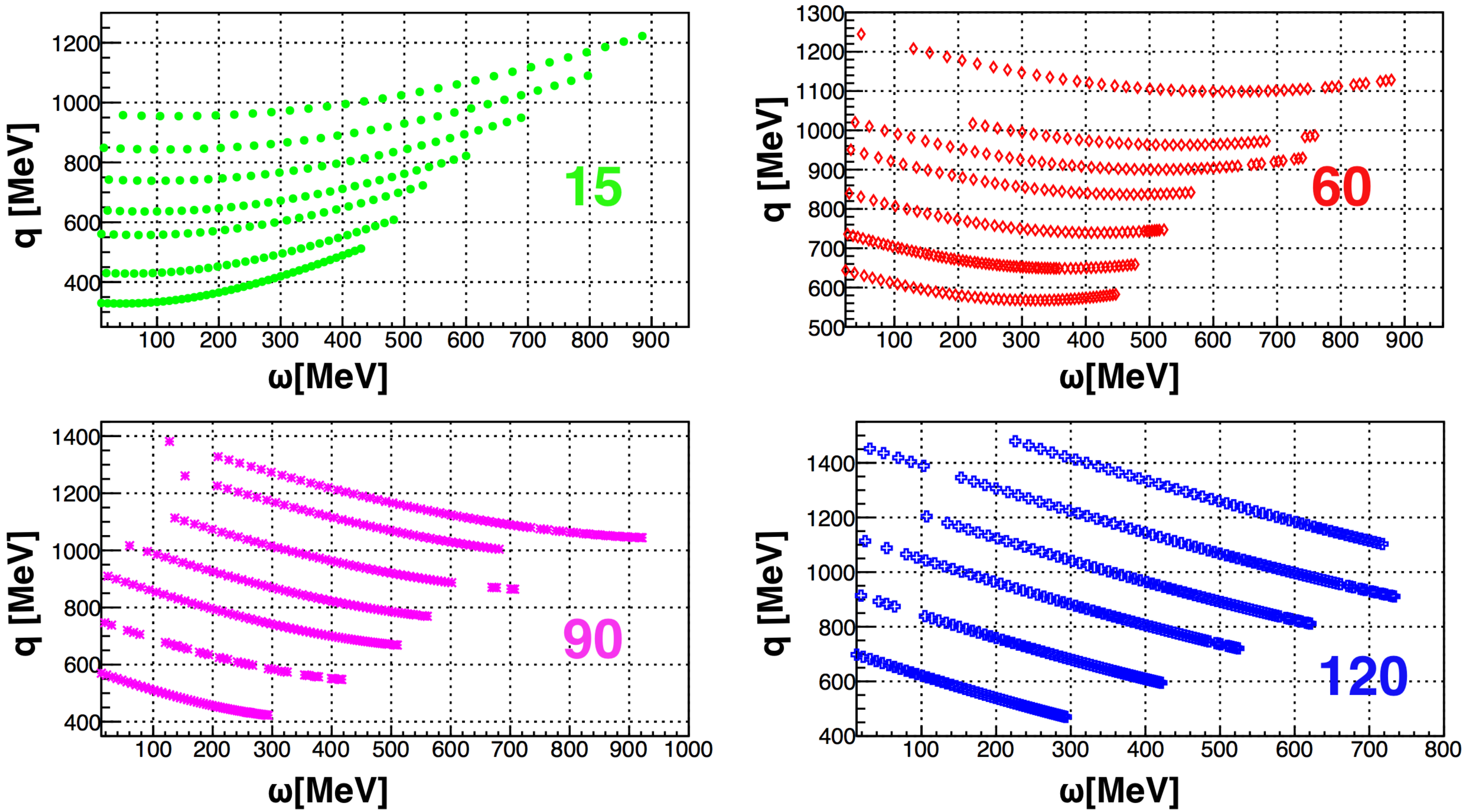
q / ω coverage for 15 degree Iron data

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

EXPERIMENTAL SPECIFICS

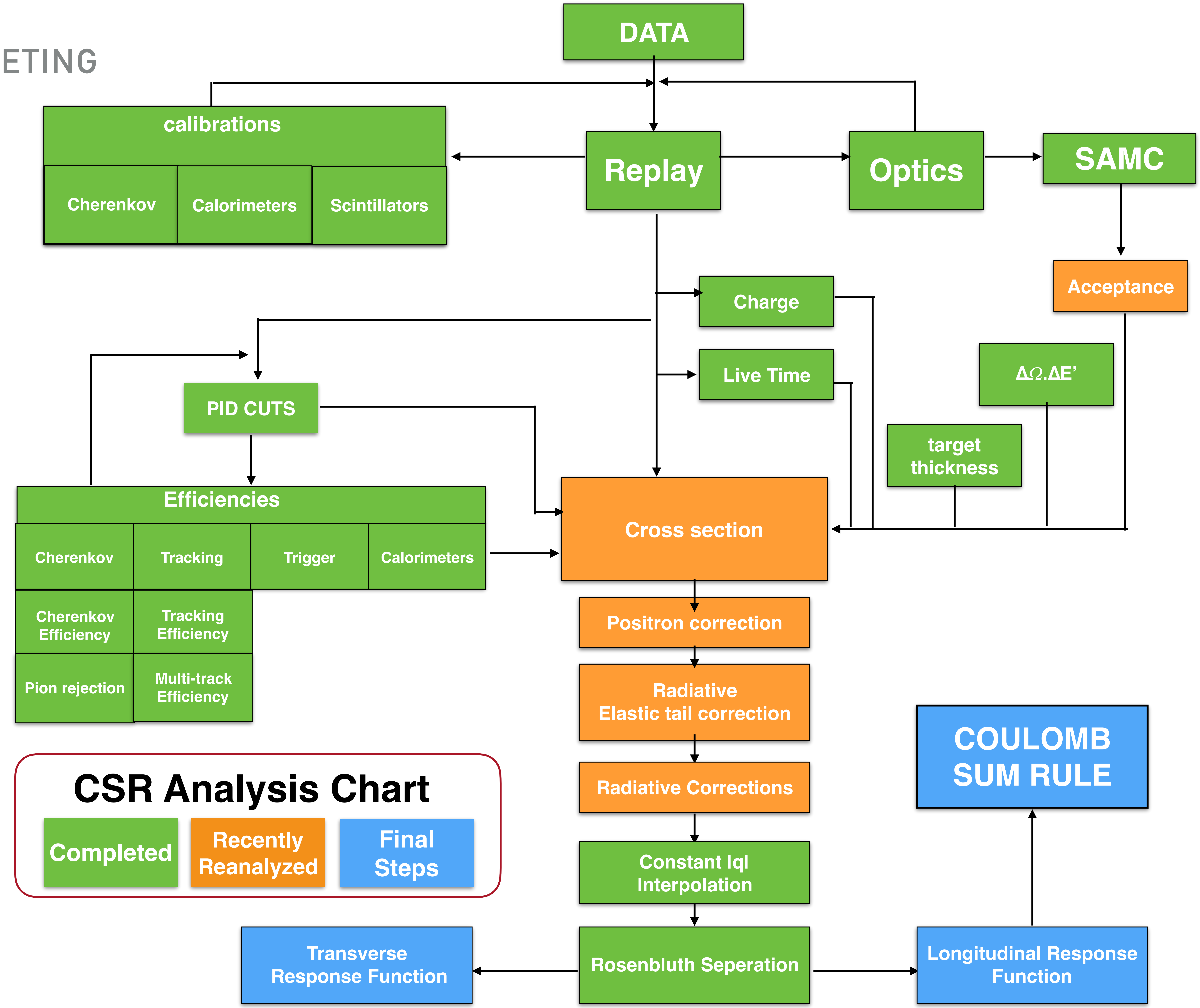
- E05-110:
  - Data taken from October 23rd 2007 to January 16th 2008
  - 4 central angle settings: 15, 60, 90, 120 degs.
  - Many beam energy settings: 0.4 to 4.0 GeV
  - Many central momentum settings: 0.1 to 4.0 GeV
  - LHRS and RHRS independent (redundant) measurements for most settings
  - 4 targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb.

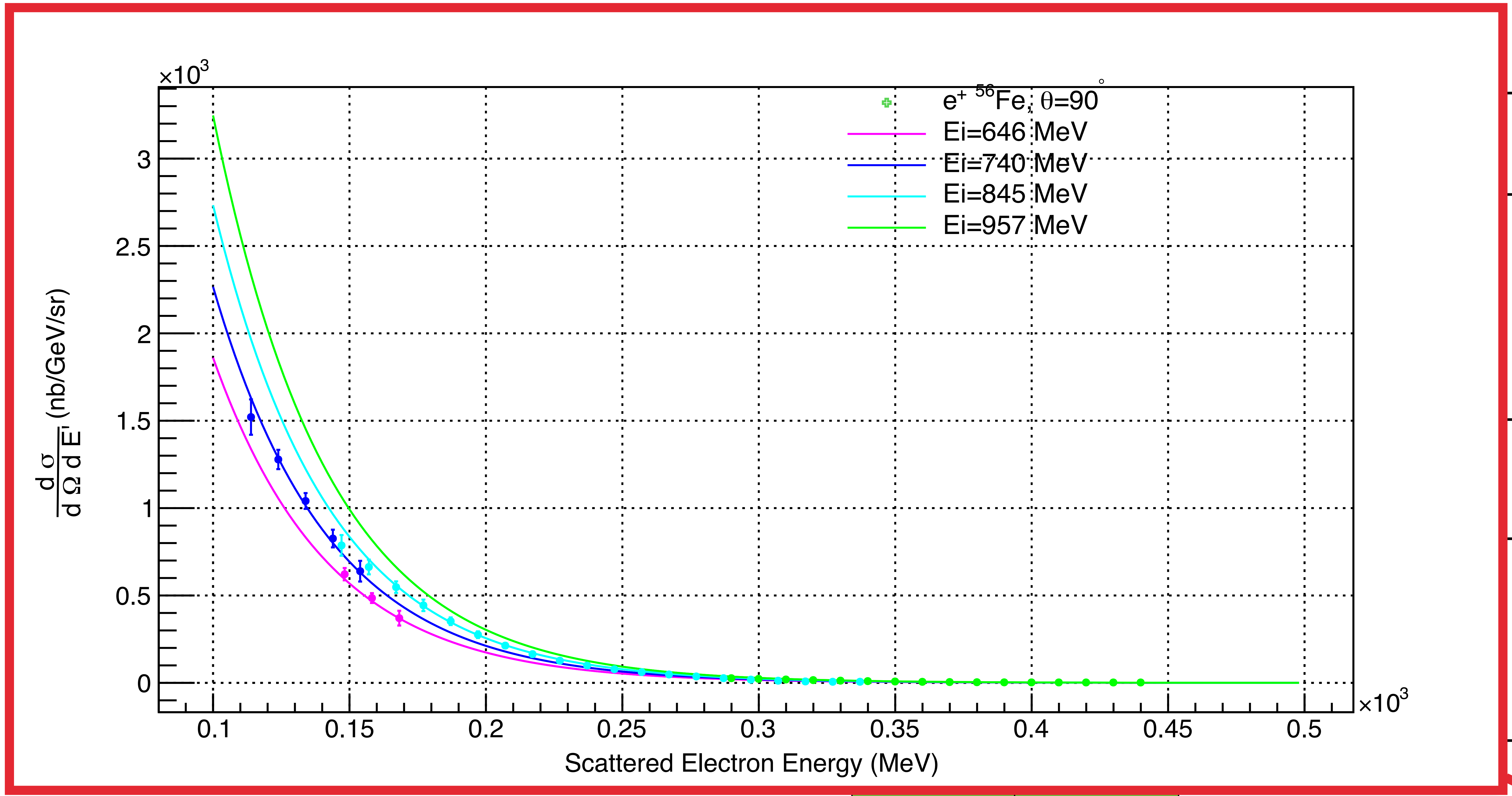
Each data line represents a constant beam-energy



RECENT EFFORTS

- Re-analysis of positron correction.
- Re-analysis elastic tail subtraction.
- Much work on acceptance procedure.
- Cross-checks on radiative effects in MC and radiative corrections of data.

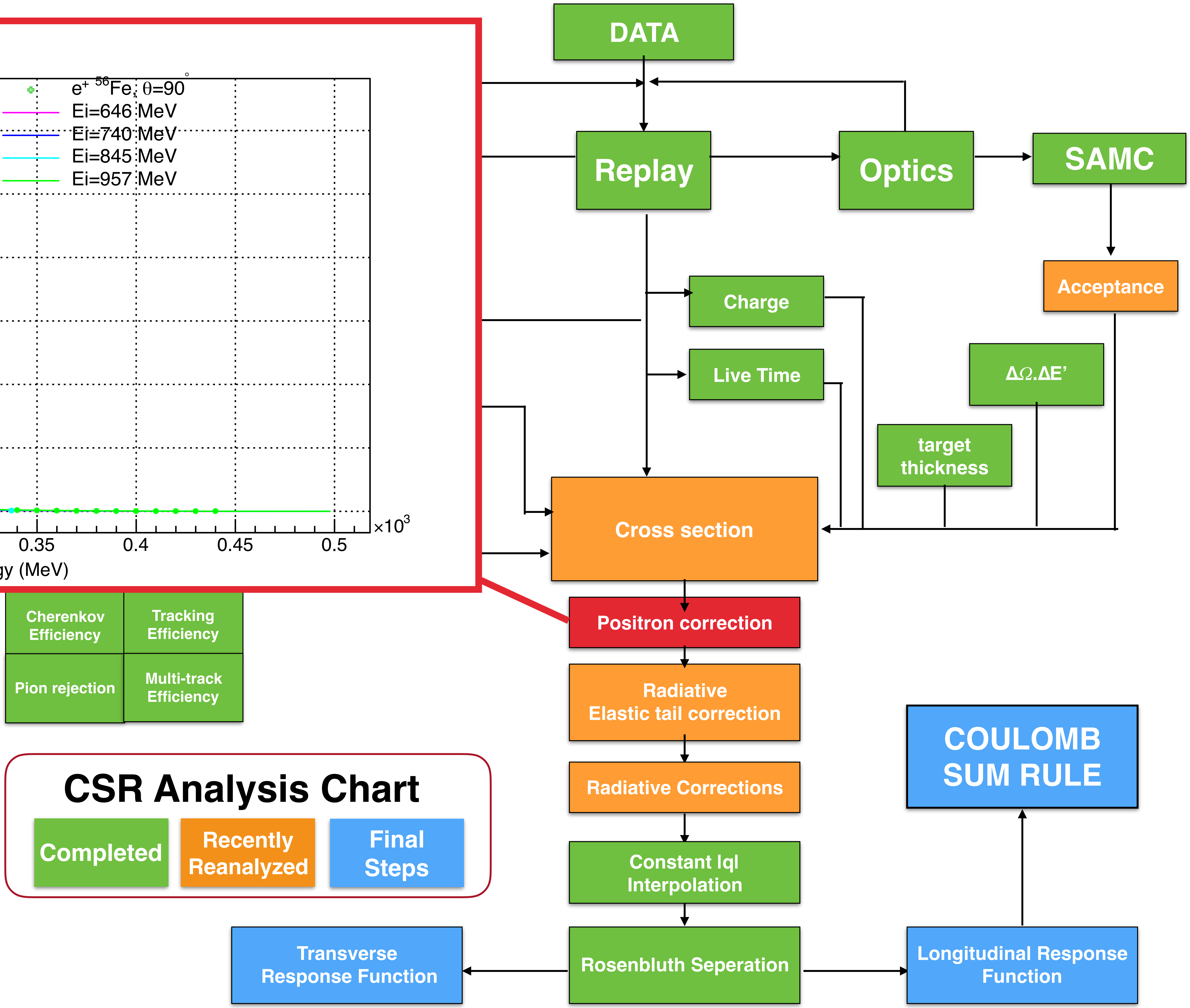




Calculating the positron cross-section allows us to subtract electron contributions from pi0 decays.

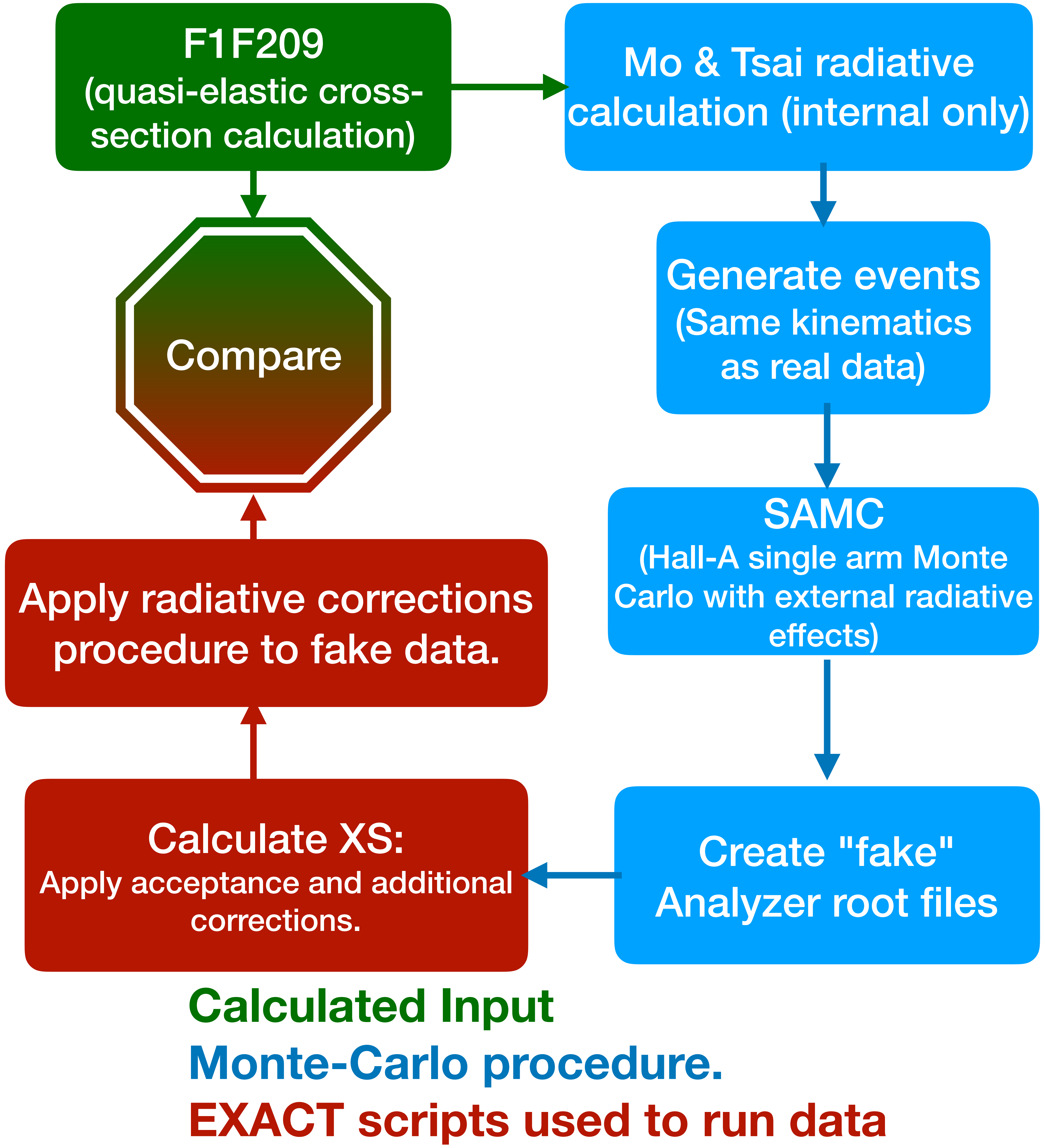
New fits to the positron data were recently performed.

Analysis by Dr. Hamza Atac,
Recent Temple Ph.D. Graduate



RECENT EFFORTS

- Cross-check on methodology.
  - Multi-step analysis procedure can be checked through simulating data.
  - Checks:
    - Cross-section calculation from Analyzer input.
    - Acceptance procedure.
    - Comparison of radiative calculations from Mo & Tsai to event-by-event MC generation with bremsstrahlung probability distribution.
    - Final radiative correction procedure (requires many data points over different beam energies and central momentum settings)



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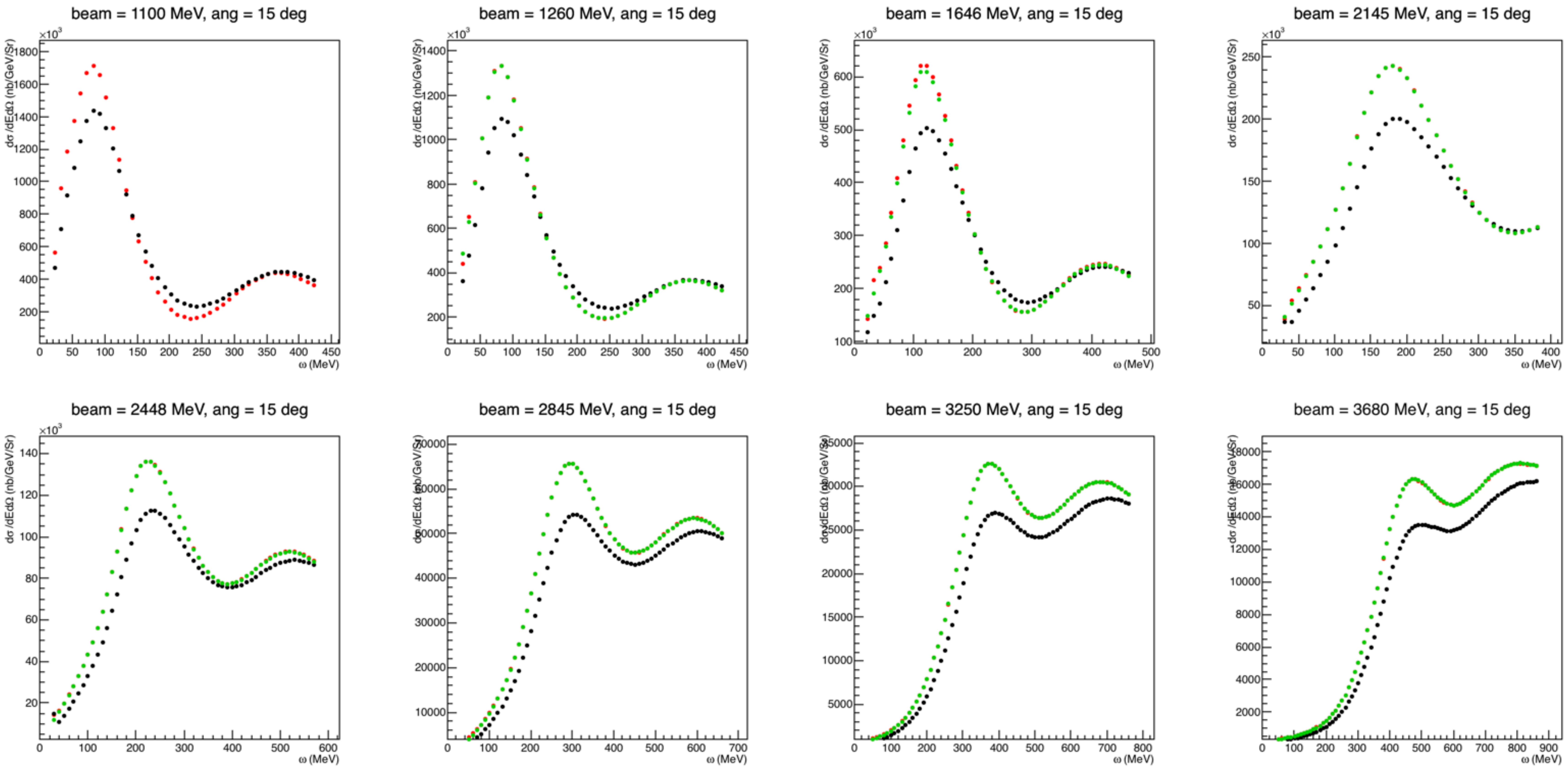
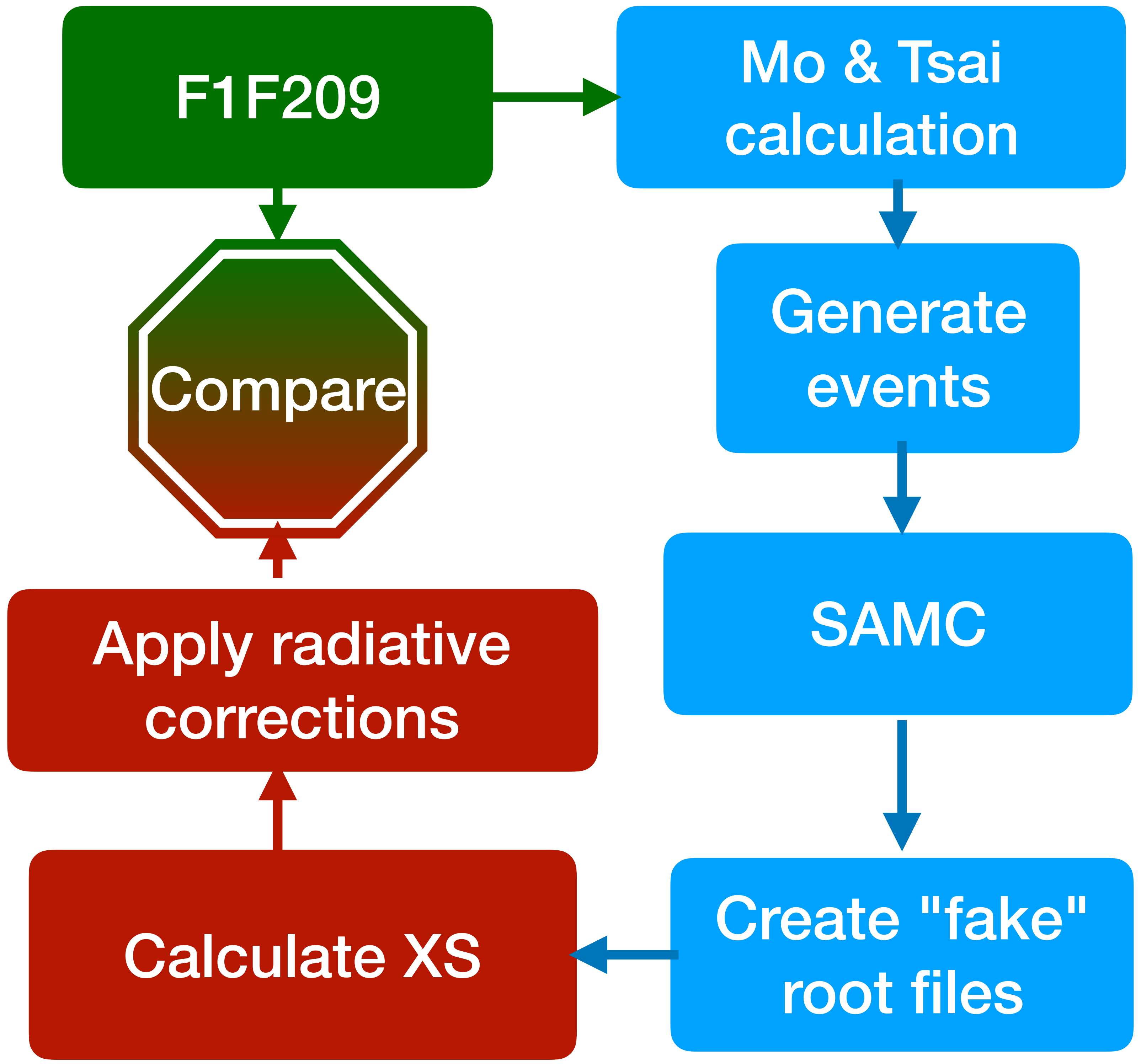


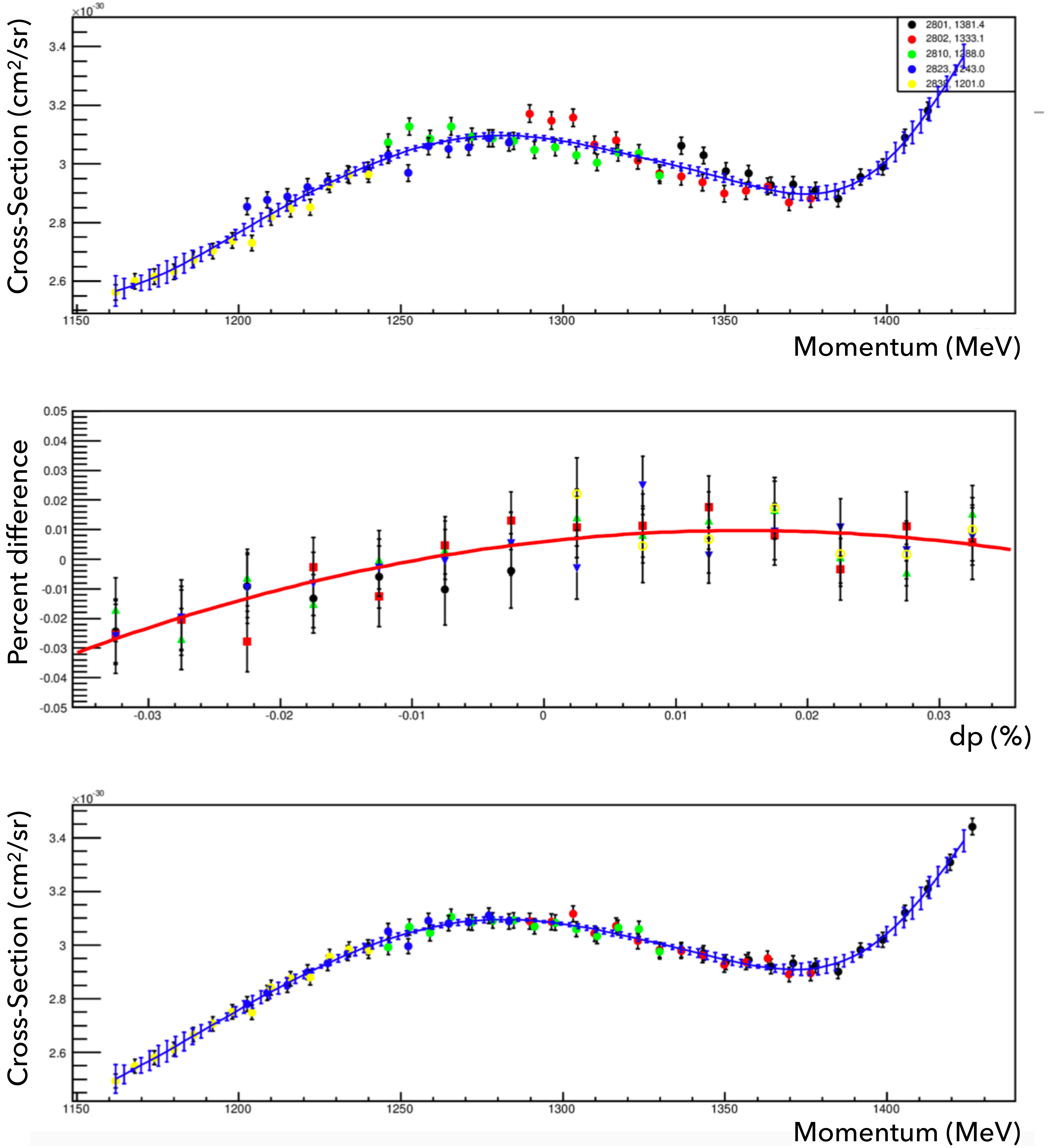


Green is original un-radiated F1F209
Black is radiated through Mo & Tsai calculation
Red is final corrected "data"

RECENT EFFORTS

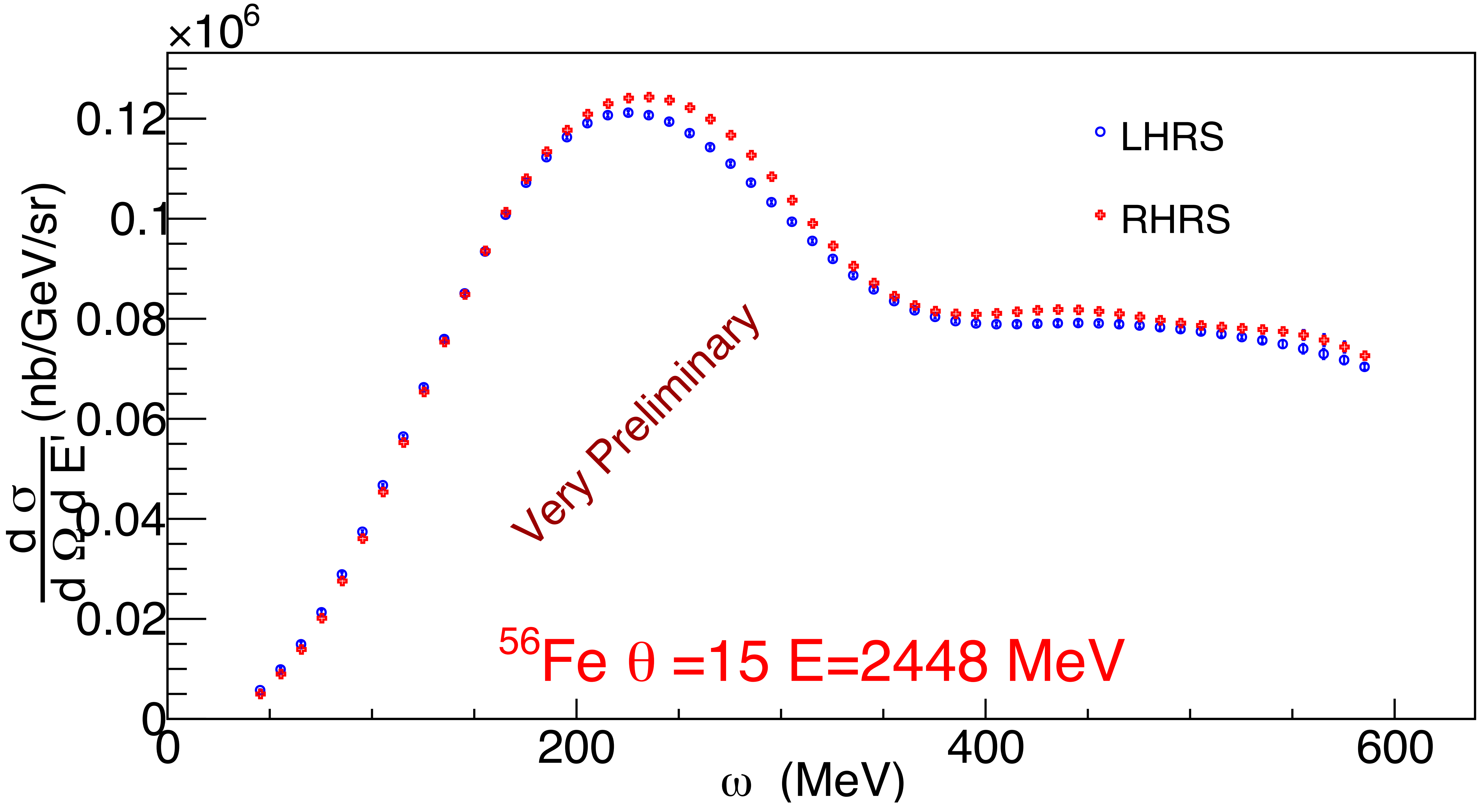
- After acceptance is applied, there remains some systematic discrepancy between overlapping data sets:
  - A gaussian reduction method ("kriging") is used to determine and remove the systematic effect.

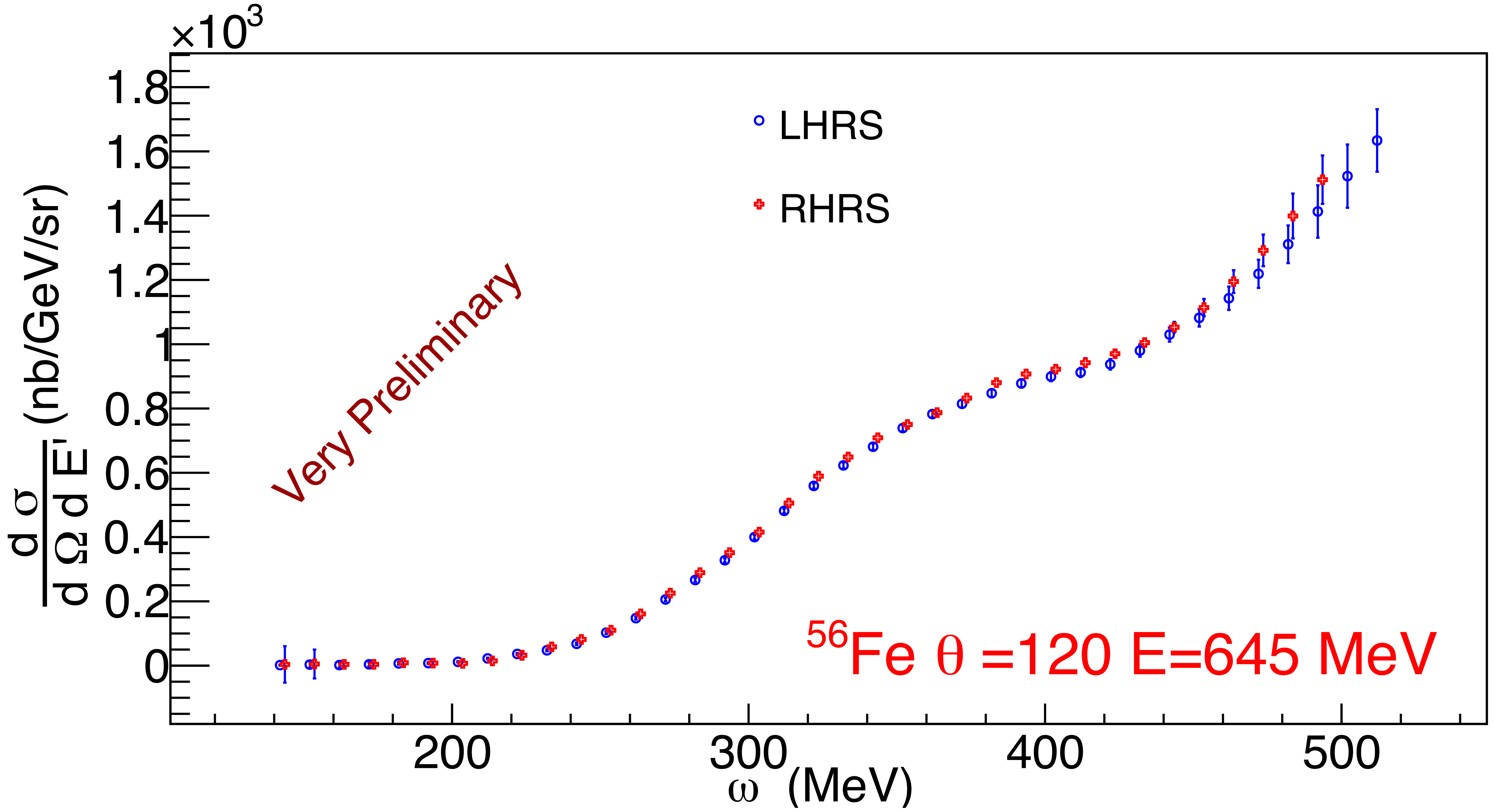
Analysis by Kai Jin,
University of Virginia
Graduate Student



RECENT EFFORTS

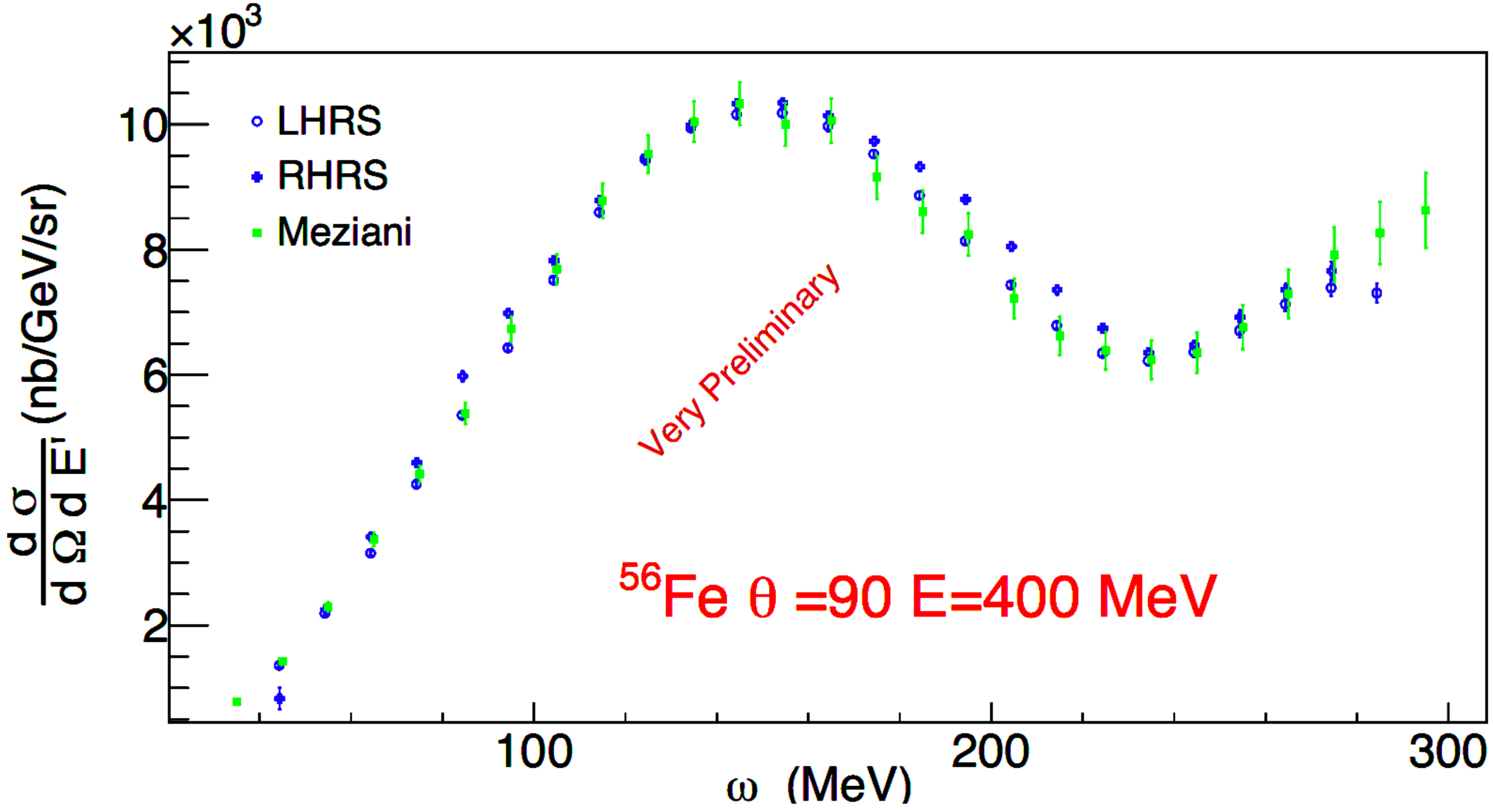
- Comparison of left arm and right arm cross-sections.
  - Low central momentum data agrees to within uncertainties.
  - High central momentum data still has disagreement of up to 5%.
    - Acceptance procedure is likely over-correcting for some bin-migration in theta and phi.





PRELIMINARY RESULTS: AGREEMENT WITH PREVIOUS MEASUREMENTS

- Not much world-data for Iron-targets at kinematics overlapping with E05-110.
- We do have one set of data at 90 degrees and 400 MeV from Saclay that we can directly compare to.
    - Good agreement between both arms and prior data.



CONCLUSIONS

- Recent work:
  - Verification of analysis procedure.
  - Acceptance studies.
  - Post-acceptance corrections.
  - Positron and elastic tail subtraction.
- Work left:
  - Completing acceptance procedure and assigning systematics.
  - Revisiting elastic cross-section calculation with updated methods.
  - Recover data from right arm that has partial interference from target frame (good test of radiative procedures).

This work is supported in part by the U.S. Department of Energy Grant Award DE-FG02-94ER4084.

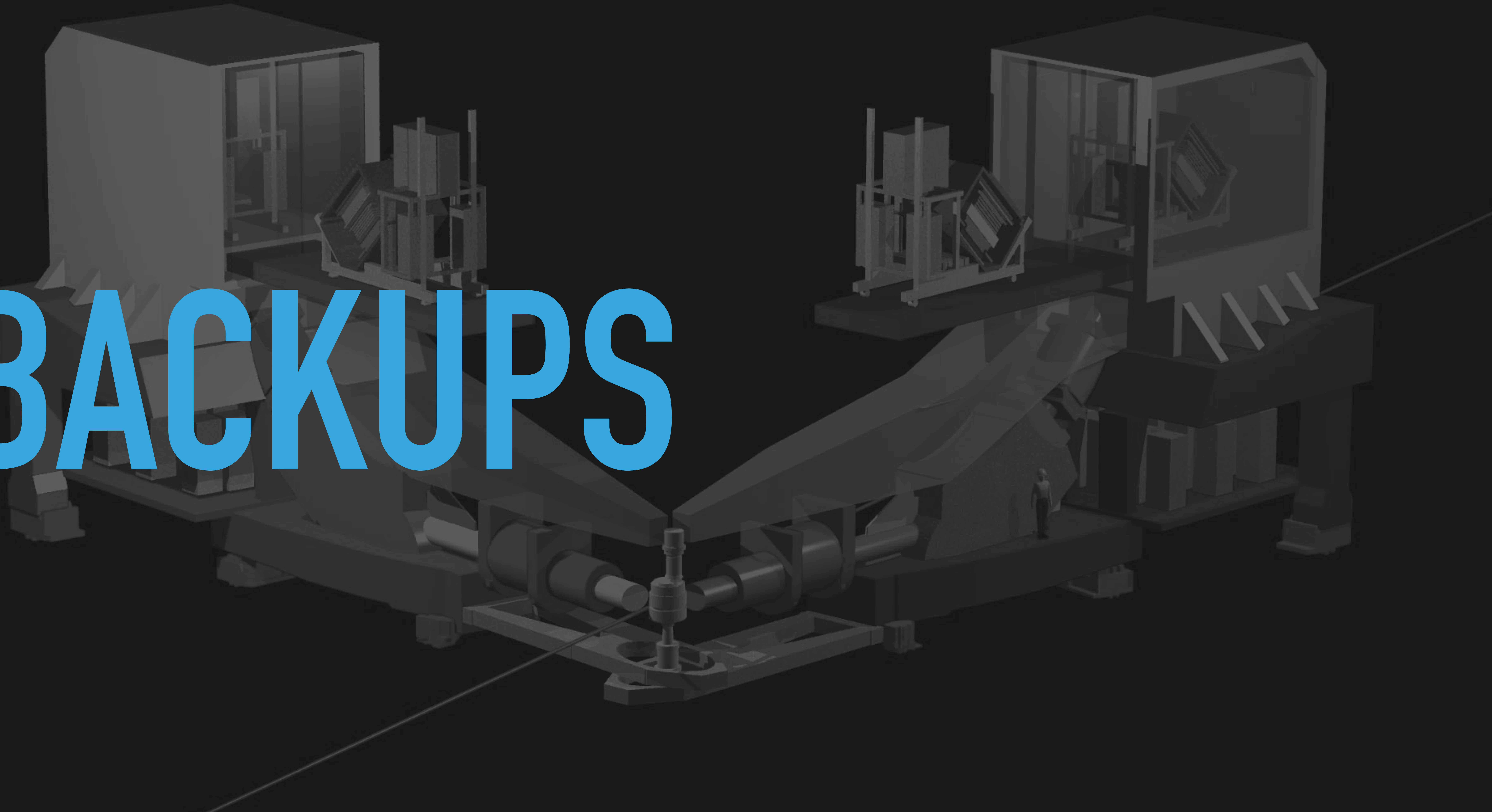
PEOPLE

Kalyan Allada, Korand Aniol, Jon 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, Rafelle 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, Yan Huang, Florian Itard, Liyang Jiang, Xiaodong Jiang, Kai Jin, 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, Michael Paolone, 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

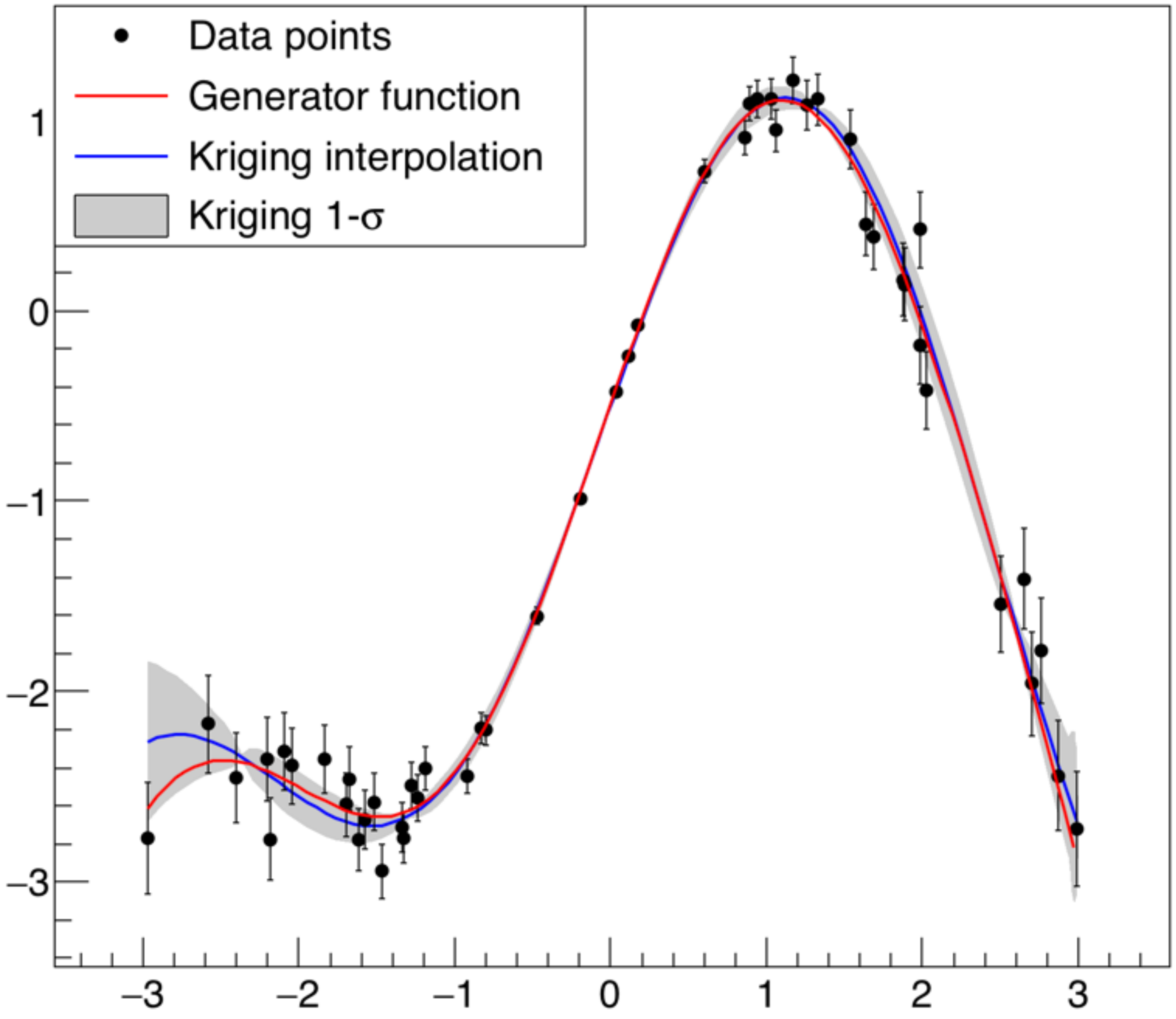
Spokespersons **Run Coordinators**

BACKUPS

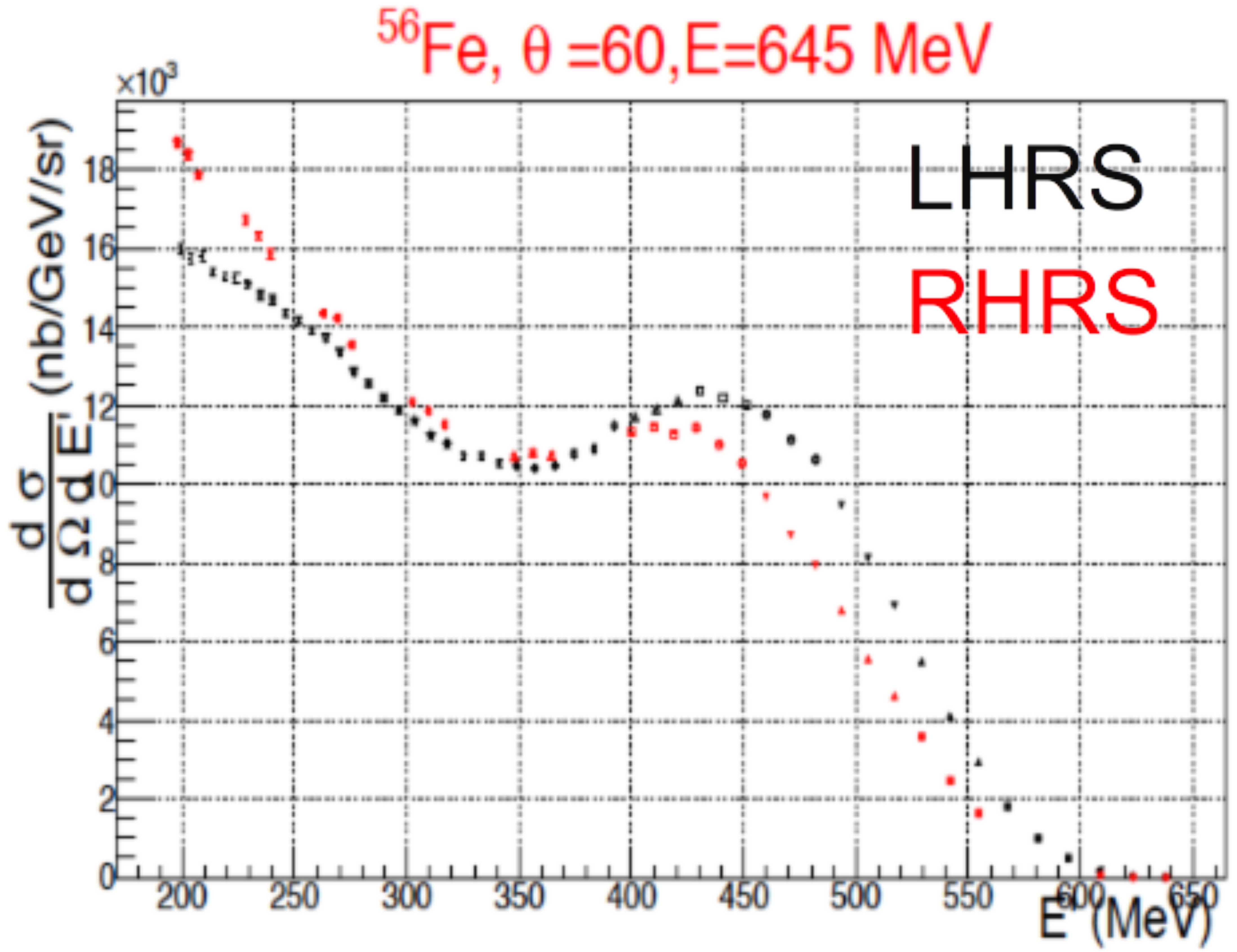


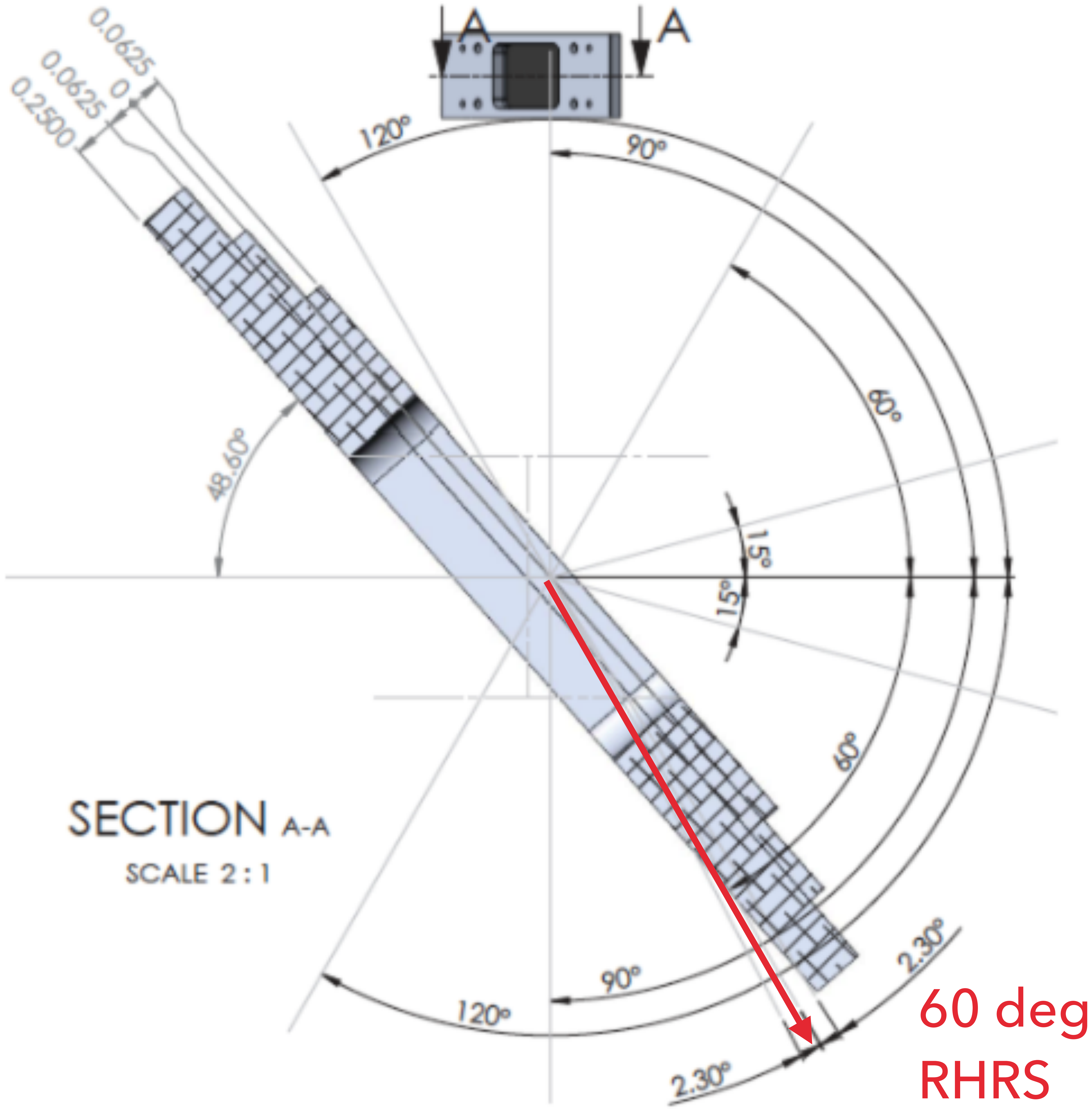
KRIGING

- Supervised machine learning technique that uses a gaussian reduction to calculate probable solutions.
  - Good for "smoothing data".
  - Best at interpolating, not as good at extrapolating.
  - Can easily be extended to 2D and higher.



TARGET FRAME ISSUES AT 60 DEGS





60 degs
RHRS