1.

Hi, I’m Zihao Lin, a first year from University of Rochester.

I am presenting our study on extracting Longitudinal and Transverse Nuclear Electromagnetic Response Functions from electron scattering measurements of Carbon12:

in short, RL and RT extraction.

The analysis includes all the available Carbon differential electron scattering and photo-absorption cross-section measurements data.

This extensive dataset spans a broad range of energy and momentum transfers.

Therefore, our goal is using them to provide a platform for testing nuclear theory predictions and verifying electron and neutrino Monte-Carlo generators across the entire kinematic range of interest.

2.

As an introduction:

the diagram here shows Electron-Nucleon and Electron-Carbon-nucleus scattering cross-sections versus energy transfer.

The nuclear correction effects enhance the Transverse response and quench the longitudinal response in Quasi-elastic (QE) scattering.

There’re three formalisms in the academia characterizing these two responses: (1) RL and RT, (2) F1 and FL, (3) and .

In this analysis, we use RL and RT. They describe the electron scattering cross sections on nuclear targets completely.

They are functions of energy transfer (or excitation energy) and square of 4-momentum transfer. Alternatively, they can be constructed by 3-momentum transfer.

3.

As we are mining data sets from both nuclear physics and particle physics communities, we noticed that the quantities I mentioned can have different names across the two comunities.

Here I summarize what we used in our analysis:

is the energy transfer. Nuclear physicists call it omega instead.

(Q squared) is the 4-momentum transfer squared.

(W squared) is the final state invariant mass squared.

(lower q) is 3-momentum transfer. I called it “q3”.

Ex is excitation energy.

Most importantly,

is longitudinal response function.

is transverse response function.

4.

As an overview,

**We have initiated a project to extract RL and RT values on various nuclei using all available data of entire world**.

Today we are reporting our extraction for Carbon.

For Carbon, there’re around 16k electron scattering cross section measurements till today. We are including them all.

We also include photo-production data, which corresponds to those with .

The RL and RT extraction is done in all regions of interest: nuclear elastic, nuclear excitations, quasielastic, resonance region and inelastic continuum.

These regions are characterized by W, the final state invariant mass.

We are using a technique called **Rosenbluth** **linear fit** (will be introduced later) to extract RL RT, which require cross section measurements at different angles for the same values of and ,

so we did analysis based on bins in as functions of .

We chose 18 values of fixed Q square, from 0 to 3.45

Similarly, we chose 18 fixed **q3** values, from 0.1 to 2.78 GeV, so to do analysis in **q3** as functions of .

We start the extraction at , extending to the end of resonance region where , to make sure covering the entire range of interest.

5.

**Our Goals are** that the extracted RL RT will be useful in:

testing first-principle nuclear theories.

validating MC generators.

The previous RL RT extraction studies were done for a limited sets of kinematic regions using a few cross-section measurements.

By covering all kinematic regions, we have an advantage that this analysis will be more comprehensive.

**Where there is no data**, we provide the values from our universal fit to all electron scattering data.

6.

Part 1 of our study:

We are using this fit by Prof. Christy and Prof. Bodek done in 2022 as a reference. It’s updated to include all the available data of entire world.

We fit for these regions: QE scattering, resonance and pion production, DIS (deep inelastic scattering), nuclear excitation, elastic scattering.

The fit parametrizes the enhancement of Transverse QE cross section and quenching of Longitudinal QE cross section, also provides the most precise extraction of “Coulomb sum rule”.

The fit alone is also a tool to evaluate MC predictions, (for example, for e-H, e-D and e-12C and e-1O cross sections)

7.

Part 2:

What’s new in our analysis today is a technique called **Rosenbluth** extraction of RL and RT with Coulomb corrections and bin-centering corrections.

It is essentially a linear fit to small subset of data.

H is what I called the “Rosenbluth quantity”. When you fit H verses epsilon, the virtual photon polarization, to a linear model:

the Slope will be proportional to RL, and the intercept will be proportional to RT.

8.

The analysis of fixed **q3** runs this way:

We firstly bin the cross-section data in bins of **q** and then apply the 2 corrections using our universal fit.

Then In each **q** bin, the data is binned again in small bins of .

Finally we apply Rosenbluth linear fit to these small subsets of the data versus , the virtual photon polarization.

In this way, we can extract the RL RT at specified values of **q** and , namely, the center value of q bins and bins.

Our fixed q bin-centers are these guys:

A similar procedure can be done for Q2 bins in contrast to **q** and the corresponding bin centers are these guys.

There’s a little subtlety here: for low , the bin centering-corrections are minimized if we extract RL RT as functions of Ex.

For higher , the bin centering-corrections are minimized if we extract the RL RT as functions of W2.

Thus for the bins are converted to Ex bins, while for , they are converted to W2 bins.

The bin-centering corrections are done for Ex and W2 accordingly, later all converted back to .

It’s important to point out that the bin-centering-correction uses our universal fit as a reference,

because it fits for all the data spanning extended ranges of kinematic and angles, while the Rosenbluth fit is done in small subsets of data.

9.

Here’s our sample plots comparing to nuclear theories:

RL (on the left) and RT (on the right) versus 𝜈 for three q values: 0.30, 0.38, 0.57.

Our extraction, in big red dots, are in good agreement with the Christy-Bodek Universal Fit, which is in black solid line.

The Christy-Bodek Fit for QE is in black dashed line.

We are using Yamaguchi’s RL and RT measurement in 1971, so we put his data when available, in blue dots.

The theoretical prediction GFMC (Green’s Function Monte Carlo – First Principle)

and ED-RMF (Energy Dependent Relativistic Mean Field) of QE 1p1h process are in purple and green lines respectively.

The QE predictions are reasonable, but not perfect.

Notice that for fixed q bin the curve stops at 𝜈=𝐪, where RT can also be extracted from photoproduction data (in big Green triangles).

The Delta peak (𝑊=1.23𝐺𝑒𝑉) is only seen in RT, because Delta resonance is mostly transverse.

10.

We now compare our data to MC generator NuWRo’s QE prediction. The prediction with FSI is in green dashed lines, and that without FSI is in purple dashed lines.

Notice that NuWRo doesn’t model nuclear excitations. NuWRo is too large in RL and too small in RT,

because they didn’t include Transverse enhancement/MEC (Meson exchange currents) in electron mode.

The comparison with MC generator GENIE will be available soon.

11.

Here's our comparison with Previous studies at fixed **q**:

RL RT extraction was done by Jordan in 1995 (in green dots) and Barreau in 1981 (in yellow dots) for **qv** = 0.30, 0.38, 0.57. We are in good agreement with them.

12.

Here’s another comparison with Previous studies at fixed Q2:

Barreau also extracted RL RT for Q2 equals to 0.16. We are in good agreement with him.

13.

The 18 RL and RT extractions cover a large kinematic range.

The values are in excellent agreement with the Christy-Bodek Universal fit to all cross-section values.

The universal fit covers an even larger kinematic range.

The RL and RT measurements as well as the universal fit provide a simple way to validate electron and neutrino MC generators.

They are in good agreement in the QE region with nuclear theory for 3 values of **qv** (Predictions for all other values of **qv** not yet available).

Our data, fits, and codes will be made available to the public.

14.

Thank you! Any questions?

15.

We are using electron carbon scattering data from various experiments, so our reference list is long…

16.

…

17.

Backup slides start here. We have extracted RL RT plots of all 18 q / Q2 values.

18.

Here’re the datasets and their normalization

…

Huge thanks to Professor Arie Bodek. This is my first in-person talk, and I learnt everything about this project from him. He’s a legend.