APS talk notes to myself

1. Hi, I am Zihao Lin, a first year from University of Rochester. Today, 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. The diagram shows Electron-Nucleon, 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) $\boldsymbol{\sigma_L}$and $\boldsymbol{\sigma_T}$.

   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 ν (or excitation energy Ex) and square of 4-momentum transfer, Q^2. Alternatively, instead of Q2, they can be constructed by 3-momentum transfer **q**.

3. The quantities I mentioned can have different names across nuclear and particle physics communities, so here I summarize what we used in our analysis:

   ν is the energy transfer.

   Q^2 (Q2) is the 4-momentum transfer squared.

   W^2 (W2) is the final state invariant mass squared.

   $\boldsymbol{q}$ (lower q) is 3-momentum transfer. I call them "qv".

   E_x is excitation energy.

   RL is longitudinal response function.

   RT is transverse response function.

4.

   We have initiated a program to extract RL and RT values on various nuclei using all available data of entire world. Today we are reporting our extraction for Carbon. Aluminum will be our next target.

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 **Rosenbluth** fit to extract RL RT, which require cross section measurements at different angles for the same values of Q^2 and ν, so we did analysis based on bins in Q^2 and ν.

We chose 18 values of fixed Q2, from 0 to 3.45 GeV^2.

Similarly, we chose 18 fixed **qv** values, from 0.1 to 2.78 GeV, so to do analysis in **qv**.

We start the extraction at $\nu = 0\ GeV$, and extend to the end of resonance region where $W = 2.0\ GeV$, to make sure covering the entire range of interest

For Carbon, there're around 16k electron scattering cross section measurements till today. We also include photo-production data, which corresponds to those with $Q^2 = 0\ GeV^2$.

Goals:

Our extracted RL RT will be useful in these ways:

To test first-principle nuclear theories.

To validate 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 hope this analysis will be more comprehensive.

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

5. We are using this fit by Prof. Christy and Prof. Bodek published in 2022 as reference. It's also 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.

6. What's new in our analysis today is the Rosenbluth extraction of RL and RT with Coulomb corrections and bin-centering corrections.

   We firstly bin the cross-section data in bins of Q2 and apply the corrections using our universal fit.

In each Q2 bin, the data is then binned again in small bins of ν. After that we apply Rosenbluth linear fit to these small subsets of the data versus ϵ, the virtual photon polarization, as the figure demonstrated.

The RL and RT is proportional to the Slope and Intercept of Rosenbluth fit. In this way, we can extract the RL RT at specified values of Q2 and ν, namely, the center value of Q2 bins and ν bins.

A similar procedure is done for **qv** bins in contrast to Q2.

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.

What's more, for low ν, the bin centering-corrections are minimized if we extract RL RT as functions of Ex. For higher ν, the bin centering-corrections are minimized if we extract the RL RT as functions of W2.

Thus for $\nu < 50MeV,$ the ν bins are converted to Ex bins, while for $\nu > 50MeV$, they are converted to W2 bins. The bin-centering corrections are done for Ex and W2 accordingly, later all converted back to ν.

7. Theory comparison:

   These are sample plots of RL (on the left) and RT (on the right) versus ν for three **qv** bins: 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 dashed lines respectively. The QE predictions are reasonable, but not perfect.

   Notice that for fixed **qv** bin the curve stops at $\nu = \mathbf{qv}$, 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.

8. MC comparison:

   We now compare our data to MC generator NuWRo's QE prediction, in green dashed lines. Notice that 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.

9. Previous studies comparison **qv**:

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

10. Previous studies comparison Q2:

    Barreau also extracted RL RT for Q2 bin: 0.16. We are in good agreement with him. However, here we don't have as many points as he has, because 25% of Barreau's cross section data is still under analysis. We will include them here soon.

11. Conclusion:

    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 over the entire kinematic range of interest.

    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.

Thanks!

12. Back up slides starts here.

    There're other plots of extracted RL, RT for different bins in Q2 or **qv**.