Hadronic Multi-Particle Final State Measurements with CLAS at Jefferson Lab

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Precision measurements in the neutrino sector are becoming increasingly feasible due to the development of relatively high-rate experimental capabilities. These important developments command renewed attention to the systematic corrections needed to interpret the data. Hadronic multi-particle final state measurements made using CLAS at Jefferson Lab, together with a broad theoretical effort that links electro-nucleus and neutrino-nucleus data, will address this problem, and will elucidate long-standing problems in intermediate energy nuclear physics. This new work will ultimately enable precision determinations of fundamental quantities such as the neutrino mixing matrix elements in detailed studies of neutrino oscillations.

1. Introduction

Neutrino physics has evolved over the past three decades from a niche area with limited experimental exposure to a forefront field having important applications to numerous fundamental studies. The impact of the observation of neutrino oscillations has been profound, since it is a clear example of physics that may be unknown to the Standard Model. The modern revolution in astrophysics has been powerfully shaped by neutrinos as their potential role in supernovae and dark matter has clarified. These points of progress have stimulated intensive improvements in neutrino experiments, such as high rate, long-baseline experiments designed to characterize neutrino oscillations.

A concomitant of achieving high fluxes, however, is that the understanding of systematic uncertainties in the measurements must be revisited. In particular, since most experiments use nuclear targets as a partial means of attaining higher rates, a better understanding of the lepto-nuclear response becomes critical in interpreting statistically precise data from neutrino detectors. Symbiotically, an improved understanding of leptonuclear physics in the neutrino sector is likely to emerge, particularly in combination with data from *electro-nuclear* experiments.

Electron scattering experiments have exerted an important influence on nuclear and particle physics for over half a century. From the discovery in the 1950's that protons are not pointlike, to the discovery of 'scaling' in deep inelastic scattering (DIS) that pointed to the existence of quarks, to the precise mapping of form factors of nuclei and nucleons, to the understanding of the spin structure of the proton, electron scattering has been the 'microscope of choice' for understanding the structure of composite systems.

However, these achievements have been based on inclusive measurements, detecting only the scattered electrons. Studies of other particles emerging from the interactions has historically been badly hampered by low rates relative to hadron beams, which have much higher cross sections. The essential technical limitation on rates was the very low duty factor of accelerating cavities operating at high gradient, due to thermal limitations; experimental rates were therefore constrained by peak pulse intensities. The breakthrough technology of superconducting accelerat-

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ing structures has removed this limitation, bringing the advent of accelerators with 100% duty cycle ('continuous wave', or 'cw'). The first institution to implement a large-scale cw accelerator was the Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Newport News, Virginia, USA, which houses the Continuous Electron Beam Accelerator Facility (CEBAF)[1]. CEBAF began operation in 1995.

CEBAF provides a 100 micron diameter electron beam of more than 100 microamperes with energies in the range 0.5-5.7 GeV to three experimental areas simultaneously. Beam bunches arrive at the targets every two nanoseconds, permitting high-luminosity coincidence measurements. Of the three experimental areas, Hall A and Hall C provide multiple high-resolution magnetic spectrometers with momentum acceptances ranging from 5% to 20% and angular acceptances ranging from 5 to 10 millisteradians, while Hall B houses a moderate resolution, large acceptance spectrometer. This instrument, the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B[2], is capable of detecting multiple final-state charged and neutral hadrons over a wide range of angles and momenta. In the following sections, a description of the experimental capabilities of CLAS and its potential role in interpreting data from neutrino facilities is presented.

2. Description of CLAS

The primary instrument in Jefferson Lab's Hall B, CLAS was constructed by the CLAS collaboration, an international alliance of 160 scientists from 39 academic institutions. Data taking began at the end of 1997. The scientific program centered around CLAS is exceptionally broad in scope, including:

- a comprehensive investigation of the properties of excited nucleons, with emphasis on searching for new resonances
- an epic study of the neutron magnetic form factor
- polarized structure functions of the proton and deuteron
- deep virtual Compton scattering and its connection to generalized parton distributions
- quark/hadron propagation through nuclear systems
- semi-inclusive deep inelastic scattering on nucleons and nuclei
- exotic meson searches
- elementary and nuclear hyperon production
- two-nucleon correlations in light nuclei

The experimental requirements to satisfy this broad program include a few common elements

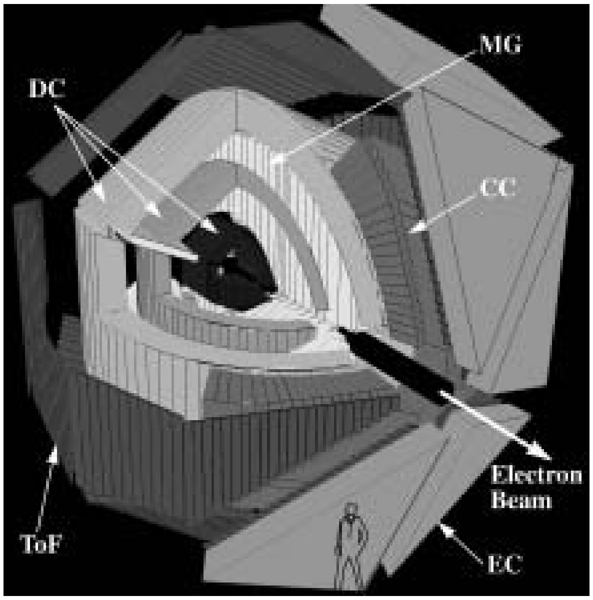

Figure 1. A three-dimensional representation of the CEBAF Large Acceptance Spectrometer, CLAS. The cutaway reveals a view of the interior of the spectrometer. The five major subsystems are indicated in the figure: the superconducting torus magnet (MG), the three regions of drift chambers (DC), the time-of-flight counters (ToF), the Cerenkov counters (CC), and the electromagnetic shower calorimeters (EC).

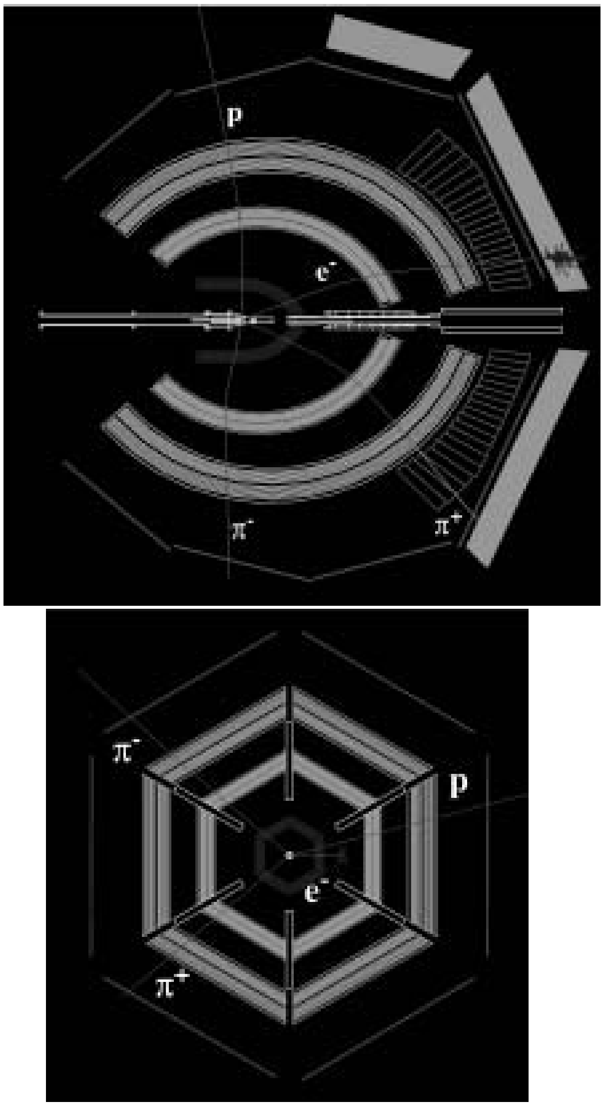

Figure 2. Two projected views of CLAS. The upper panel shows a horizontal cross section of CLAS containing the target region, viewed from above. The lower panel shows a view along the beamline in a plane containing the target. Charged particle tracks can be seen in these views: with the nominal torus polarity, negatively charged particles bend toward the beamline while positive particles bend away.

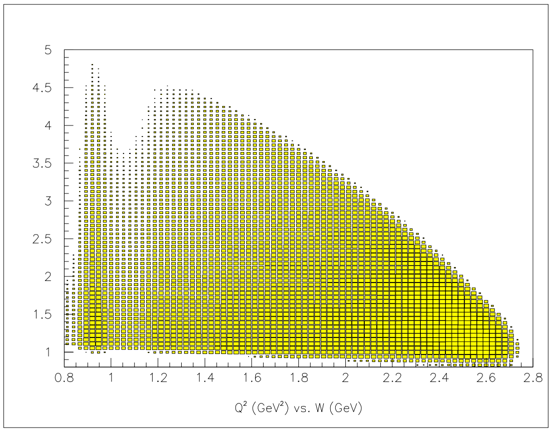

Figure 3. A plot of the electron variables from the CLAS E5 run. The plot shows a sample of 50 million electrons acquired with a beam energy of 4.232 GeV. The cutoff in Q^2 is a function of beam energy and magnetic field settings; the lower practical limit is approximately 0.1 GeV^2.

that mandate employing a large acceptance spectrometer. These elements include the capability of measuring final states with multiple, nearly uncorrelated particles; or measurements that intrinsically require low beam current. Examples of the latter include polarized target experiments, and photon beam experiments using Bremsstrahlung photons that are energy-tagged by the associated electron.

The technical solution chosen to achieve large acceptance in an electron beam environment was a toroidal magnetic field, where the incident electron beam is directed along the toroidal axis of symmetry. This field configuration offers several advantages over solenoid or dipole fields: for instance, it has full acceptance over a wide range in scattering angle, and is field-free at the target location, which is critical for polarized target operation. A three-dimensional view of CLAS is depicted in Fig. 1, where the cutaway reveals details of the inner detector configuration. The field is produced by six kidney-shaped superconducting magnet coils sheathed in six thin stainless steel cryostats. This choice naturally segments the detector volume into six sectors. Three drift chamber layers sample the charged particle trajectory before, during, and after the bend in the magnetic field. In the forward direction, electron identification is obtained at the trigger level by a combination of gas Cerenkov counters and an electromagnetic shower calorimeter, which subtend scattering angles from 8 to 45 degrees from the nominal target location, while the drift chambers span the range 8 to 142 degrees in scattering angle. This angular range is matched by an array of 5 centimeter thick scintillators which are optimized for precision time measurements; for many of the charged hadrons of interest, the time-of-flight technique can determine the hadron mass, thus distinguishing charged pions, kaons, protons, and deuterons. There are also calorimeters at larger angles in two sectors. In addition to electron and positron detection and pion rejection, all calorimeters are used for neutron and neutral pion detection. Two-dimensional 'slices' through the detector are shown in Fig. 2. In the upper panel, the electron beam is incident from the left; the trajectories of charged particles may be seen through the drift chambers and magnetic field volume. The electron track can also be seen to interact with the forward electromagnetic shower calorimeter. In the lower panel of this figure, the acceptance in the azimuthal angle for this four-track event is evident.

The field-free central region of the spectrometer offers great flexibility in the selection of targets. Cryogenic liquid hydrogen, deuterium, ^{3}He and ^{4}He have all been used, as well as solid targets of carbon, iron, and lead. Cryogenic polarized solid NH_3 and ND_3 targets with superconducting Helmholtz coils have also been used for double polarization measurements.

3. Description of CLAS Data

For electron beam experiments, the spectrometer is usually operated at its design luminosity of $10^{34}\ cm^{-2}s^{-1}$; this produces nominally a megahertz rate of hadronic interactions and a gigahertz rate of Møller electrons. The drift chambers are protected from the latter by a small toroidal magnetic shield produced by a normal-conducting magnet located inside the innermost drift chamber. A highly-configurable fast trigger preferentially selects events where a scattered electron intercepts all three drift chambers, reducing the accepted event rate to 3-4 kilohertz. More restrictive triggers are used occasionally for specialized measurements. The data transfer rate can exceed 20 megabytes per second, or approximately a terabyte per day when operational efficiencies are taken into account. Depending on the experiment configurations, from 10 to 30 billion triggers are collected annually.

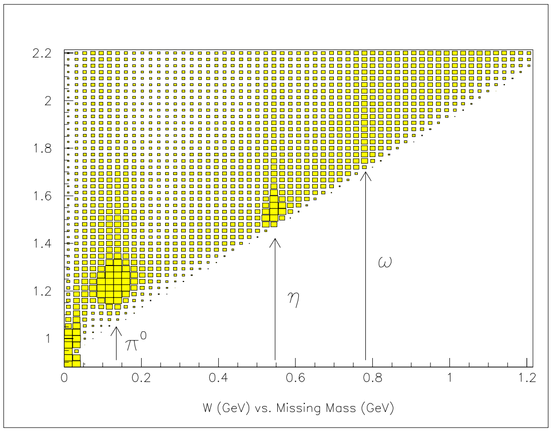

Figure 4. The invariant mass W vs. the missing mass of the unmeasured particles in electron scattering from a hydrogen target, where one proton is detected in coincidence with the electron. The coupling of many of the resonance states to particular hadronic decay channels is visible by eye.

In distinction to traditional electron scattering measurements, in CLAS a wide range of angles and momenta are reconstructed simultaneously at given beam energy. As a result, continuous spectra are obtained for 4-momentum transfer squared (Q^2), invariant mass of the hadronic system (W), and hadron kinematic variables. An example is shown in Fig. 3, which illustrates the range of Q^2 and W obtained from a 4 GeV beam.

A typical event reconstruction begins by identifying the scattered electron for a given event using information from the Cerenkov detector and the electromagnetic shower calorimeter. Subsequently, hadrons are identified by calculating the time-of-flight (TOF) of other charged tracks in the event and deriving their mass from the TOF and the measured momentum. Neutral particles can be measured directly, or can also be inferred using the missing mass technique. As an example, in the reaction $e + p \rightarrow e' + p + X$ where a scattered electron and proton are measured, the mass of the unmeasured system X can be calculated. With the typical resolution of 10-20 MeV, missing hadrons can easily be identified. An illustration of this can be seen in Fig. 4, in which W is plotted against missing mass. Here the decay of resonances with masses in the range 1.2-2.2 GeV into π^0, η, and ω mesons is easily identified. A further illustration of this technique applied to successively more complex events is shown in Fig. 5, where up to four hadrons are measured in addition to the scattered electron.

4. Neutrino Connection

Now that the basic phenomenon of neutrino oscillations has been established, a program of measurements is needed for its characterization.

For instance, determination of the mass differences and elements of the mixing matrix can be carried out with a combination of high-statistics, accelerator-based long-baseline experiments; such experients are planned in the U. S. and Japan. The maximal probability of observing neutrino oscillations for the relevant experiments occurs for neutrino energies ranging from 0.5 - 3.0 GeV.

Neutrino and electron interactions with hadronic matter in this energy range typically produce multi-hadron final states via complex interaction mechanisms. The elementary production mechanisms on protons and neutrons include elastic scattering, resonance production, and deep inelastic scattering. These mechanisms are modulated in lepto*nuclear* interactions by Fermi motion, Pauli blocking, coherent pion production, hadron absorption and propagation through nuclei, nuclear form factors, and hadron formation length effects. While some of these topics have been thoroughly studied in the electron sector, much less is known from neutrino measurements. Because neutrino detectors are of necessity based on simple, integrating measurement schemes, such as Cerenkov light emission in water, the precise details of the final state are unknown and must be simulated. The complexity of the neutrino-nuclear response, coupled to integrating detection technologies, translates into uncertainties in the interpretation of neutrino data.

However, electron scattering and neutrino scattering are closely connected. The differences in the lepton tensor are trivial, and much is known about the relationships between the hadronic currents interacting with the two types of probes. A systematic theoretical treatment that describes hadron production in electro-nuclear interactions can in turn be used to predict hadron production in neutrino-nuclear interactions, beginning with the elementary production, and continuing with nuclear targets. Because CLAS offers multi-hadron final state measurements for few-GeV electrons that can constrain such a theoretical effort, a new and unique opportunity for a cross-disciplinary study of leptonuclear physics now exists for the first time.

A full program of this type would involve developing or adapting models to describe the elementary reactions on protons and neutrons. The models should be designed so that they can describe both electron beam and neutrino beam interactions. These could be tested against the large body of existing CLAS data for hydrogen and deuterium targets. This data has been acquired for a number of beam energies and experimental conditions; elastic, resonance, and DIS data are essentially always taken together in the same dataset, although the high W cutoff varies slightly depending on trigger thresholds. While there already exist models for such interactions, the requirements here are somewhat different than the typical purpose for developing descriptions of the data, and will therefore involve different choices. For instance, the specification of the higher resonance contributions may be adequate at a more phenomenological level than would be true of, e.g., a search for small contributions from missing resonances, a typical motivation for CLAS measurements. At the same time, attaining a good description of the data

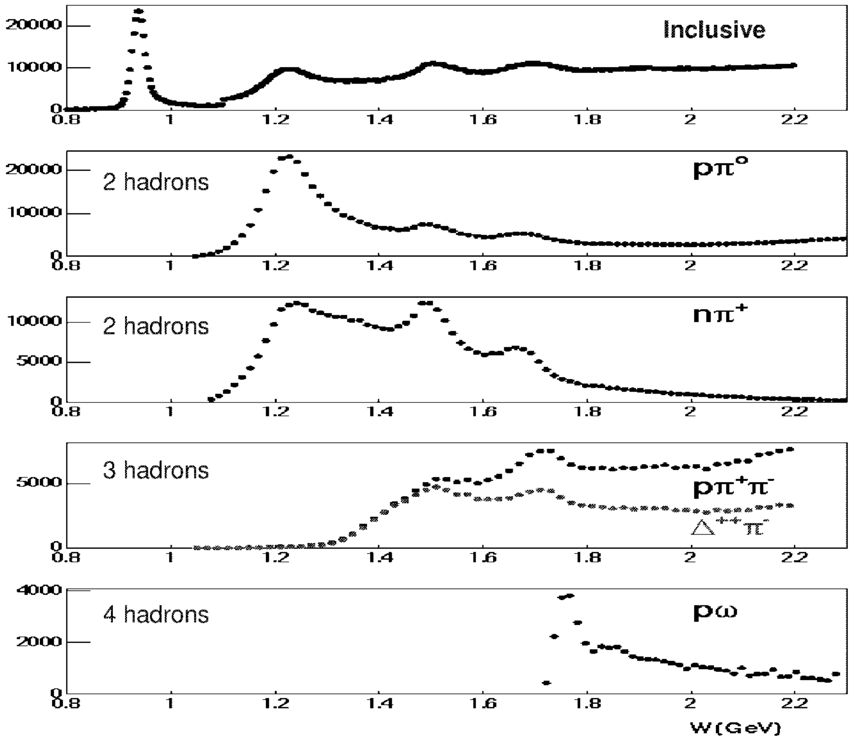

Figure 5. An example demonstrating the multi-hadron reconstruction capability of CLAS. The top plot shows the inclusive W spectrum; the successive plots show the W spectra when two, three, and four hadrons are detected. In the lower four plots, one of the hadrons is inferred by the missing mass technique while the other hadrons are detected directly.

over a wider range in W may be more critical for neutrino studies than, for instance, studying the properties of a particular resonance in exhaustive detail, another typical motivation of CLAS measurements. Above the two-pion threshold, the multi-hadron production mechanisms for resonances may have to be treated with a more phenomenological approach because of the complexity involved, but the many-fold differential cross sections can be constrained well by testing against CLAS data, even for two and three pion production.

Once the models for elementary interactions are constructed and tested, they can be turned to predict the interactions with nuclear systems. Here a host of new effects must be considered, as were listed above. At low energies and low momentum transfers, Pauli blocking, coherent pion production, and nuclear form factors will measurably alter the observed hadron yields. In the DIS regime, the formation lengths of hadrons will come into play; the determination of these formation lengths is a subject of one CLAS program involving nuclear targets[3][4]. The effects of hadron absorption and propagation through nuclei, as well as Fermi motion, have a strong impact on the data at all relevant energies. Existing CLAS data on carbon and iron targets, as well as ^2H, ^3He, and ^4He, can be used to study the A dependence of these effects; to access kinematic regions not yet measured in CLAS, new data can be acquired. A particularly important effect is the final state interaction influencing the reaction products in the nucleus; since this large effect is nearly identical for neutrino beams and electron beams, it can be predicted with confidence for neutrinos once the electron beam data is well-described. Needless to say, there are excellent prospects, not only for studying neutrino-nucleus interactions, but also for improving our understanding of the nuclear physics involved at a more fundamental level. This cross-disciplinary, symbiotic motivation holds the promise to involve a wider pool of talent and expertise in these compelling studies.

5. Conclusions

The advent of cw electron-beam accelerators, together with advances in detector and magnet technology, now permit measurements of multi-hadron final states with high statistical precision in many-fold differential cross sections. The combination of electron beam data from CLAS and a broad-based theoretical effort connecting these data to neutrino scattering holds great promise for advances in both neutrino science and in nuclear physics. This new work will enable precision determinations of fundamental quantities such as the neutrino mixing matrix elements in detailed studies of neutrino oscillations.

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