The JLab 12 GeV Program

Results and Future Perspectives

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Abstract. We review results from the Jefferson Laboratory (JLab) program with the 12 GeV Upgrade of the CEBAF accelerator, with a particular emphasis on processes involving mesons. We include associated efforts in theory and phenomenology. We also discuss expected results from future analyses and data taking, including new instrumentation, in particular SoLID and the planned 22 GeV Upgrade of CEBAF.

1 Introduction

A new era began at Jefferson Lab (JLab) in Fall 2017 when the 12 GeV upgrade to the Continuous Electron Beam Accelerator Facility (CEBAF) was completed [1]. High energy, high current electron beams with polarization close to 90% were delivered to a suite of new apparatus in the existing experimental Halls A, B, and C. In addition, a fourth experimental station, Hall D, was commissioned with an apparatus, GlueX, designed for precision meson spectroscopy using linearly polarized photon beams.

Figure 1 shows the current and future configurations of CEBAF and the four experimental end station halls. The original 6 GeV accelerator was upgraded to 12 GeV with the addition of new high-gradient accelerator sections in each of the two linacs, along with upgraded high-field arc magnets. A fourth experimental station, Hall D, was also included in the upgrade. New experimental equipment includes the Super Bigbite Spectrometer (SBS) system in Hall A, the CLAS12 detector in Hall B, the Super High Momentum Spectrometer (SHMS) in Hall C, and the GlueX spectrometer in Hall D.

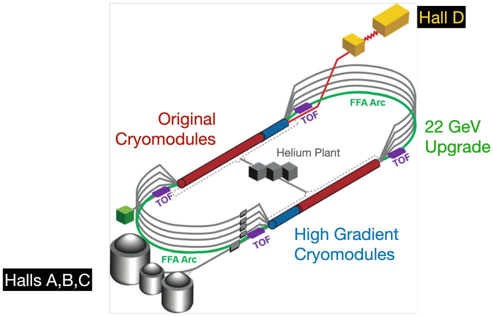

Figure 1. The current configuration of the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab, including the upgrade to 12 GeV from 6 GeV operation. New high gradient cryomodules and high field arc magnets made the 12 GeV upgrade possible. Recent work has shown that a 22 GeV accelerator will be possible using Fixed Field Alternating Gradient arc magnets which allow multiple beams to orbit in the same magnet.

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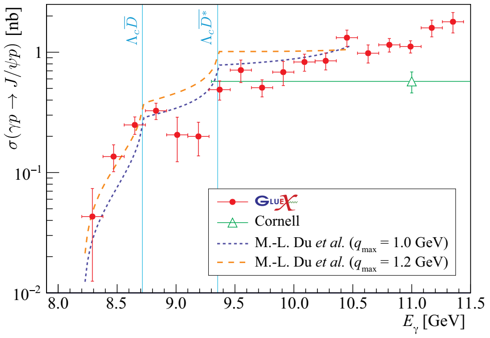

Figure 2. GlueX result on the total cross section for $\gamma p \to J/\psi p$ [2]. The thresholds for $\Lambda_c\bar{D}$ (8.71 GeV) and $\Lambda_c\bar{D}^*$ (9.35 GeV) production are shown as vertical lines. Also included is an old total cross section measurement from Cornell, and model calculations based on box diagrams with open charm channels.

This talk focusses on only a small fraction of the experiments done or in progress at the laboratory. I have concentrated on measurements that emphasize studies of meson properties, or the use of meson production as a tool for understanding hadron dynamics in general.

2 Photoproduction of J/ψ from the Proton (GlueX, Hall D)

The GlueX collaboration recently published [2] their measurements of the total and differential cross sections for $\gamma p \to J/\psi p$. This reaction has long been considered as a way to probe the gluonic content of the proton (see, for example, [3]) and more recently as a way to measure the proton's "mass radius." [4]. This interpretation, however, relies on the partial waves for the reaction being dominated by elastic $J/\psi + p$ scattering.

Figure 2 shows their result on the total cross section near threshold. The statistical precision is already good enough to suggest structure near production of open charm thresholds, which would challenge an interpretation dominated by elastic $J/\psi + p$ scattering [5]. See the talks by Matt Shepherd and Adam Szczepaniak in this conference for more details.

3 DVMP with π^0 at High Q^2 (Hall A)

An important goal of the CEBAF 12 GeV program is to map out the internal structure of the nucleon by measuring integrals of the Wigner function [1]. One of these integrals leads to Generalized Parton Distributions (GPD's) that describe various exclusive hard electron scattering processes. Exclusive meson production, aka Deeply Virtual Meson Production (DVMP), is one of these exclusive reactions that has received much attention.

The Hall A collaboration recently measured [6] differential cross sections for the reaction $e^-p \to e^-p\pi^0$. These measurements used a longitudinally polarized electron beam, which allowed the separation of various components of the cross section, from their dependence on the angle ϕ between the electron scattering and $p\pi$ reaction planes. These are referred to as σ_{LT} (which has a $\cos\phi$ dependence), σ_{TT} ($\cos^2\phi$), and $\sigma_{LT'}$ ($\sin\phi$).

Results for a subset of their (Bjorken) x and Q^2 values are shown in Figure 3. Data from other kinematic points show similar levels of agreement.

4 DVMP with π^+ at High Q^2 (CLAS12, Hall B)

The CLAS12 collaboration has also carried out a measurement of DVMP [8], for the reaction $e^-p \to e^-n\pi^+$ with the neutron identified using the missing mass technique. As is the case with the Hall A measurement of $e^-p \to e^-p\pi^0$, the polarized electron beam was used to measure "Beam Spin Asymmetries" that allowed the extraction of different interference terms

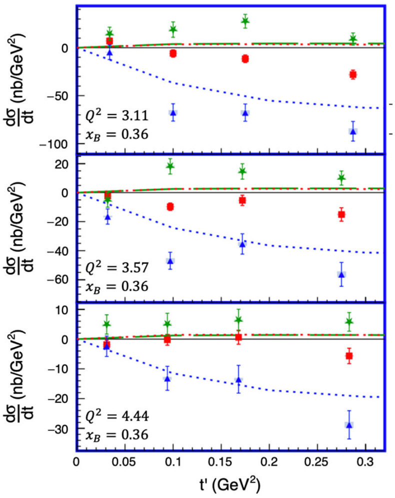

Figure 3. Deeply Virtual Meson Production in the reaction $e^- p \to e^- p\pi^0$ in Hall A at CEBAF for a subset of kinematics from [6]. Extracted differential cross sections for σ_{LT}, σ_{TT}, and $\sigma_{LT'}$ are shown in red square, blue triangles, and green stars, respectively. The dashed curves refer to model calculations. [7]

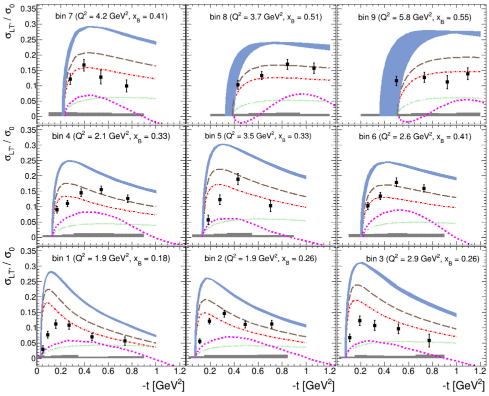

Figure 4. The interference cross section $\sigma_{LT'}$, relative to the unpolarized cross section $\sigma_0 = \sigma_T + \epsilon\sigma_L$, from Deeply Virtual Meson Production in the reaction $e^- p \to e^- n\pi^+$ using CLAS12 in Hall B at CEBAF [8]. The different curves represent alternate models of the GPD's for the nucleon. The dotted green curve shows the theory result under the assumption that no pion pole term is contributing.

in the cross section. The results of the measurement, with comparison to various GPD model calculations, are shown in Figure 4.

5 Timelike Compton Scattering (CLAS12, Hall B)

CLAS12 has also carried out the world's first measurement [9] of polarization observables in so-called Timelike Compton Scattering (TCS), using the reaction $\gamma p \to pe^+e^-$, where the final state e^+e- mass is selected to be between the ϕ and J/ψ signals. This cross section will of course have a large component from QED, that is Bethe-Heitler, processes. However, polarization observables will once again allow an extraction of terms that are sensitive to nucleon structure. In fact, as opposed to DVMP, there is no additional complication to the cross section from the meson distribution amplitude. Furthermore, the nucleon structure components will be sensitive to different combinations of GPD's.

Figure 5 shows results for the photon polarization asymmetry $A_{\odot U}$ and the forward-backward asymmetry A_{FB} for a particular set of kinematics representing a subset of the data. The sensitivity to GPD's is imbedded in the real and imaginary parts of the Compton Form Factor $\mathcal{H}(t, \xi)$, where t is the momentum transfer to the proton, and ξ is the momentum imbalance on the incoming and outgoing struck quark. These data, taken for photon energy

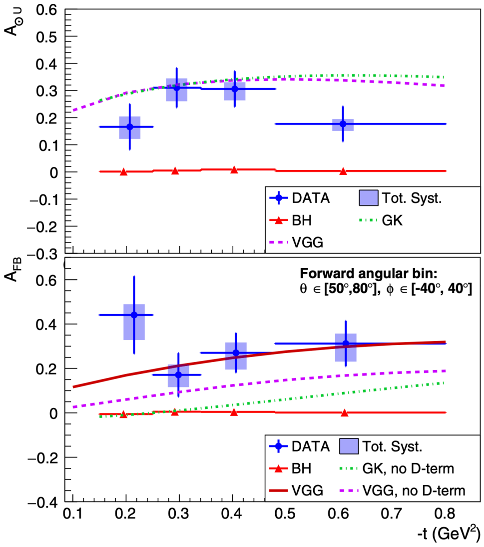

Figure 5. Measurement from CLAS12 [9] of the photon polarization asymmetry $A_{\odot U}$ (top) and the forward-backward asymmetry A_{FB} (bottom) in Timelike Compton Scattering from the proton compared to models. The Bethe-Heitler process predicts only very small asymmetries, clearly inconsistent with the data. Good agreement with models is obtained for $A_{\odot U}$, which is primarily sensitive to the imaginary part of the Compton Form Factor $\mathcal{H}$. On the other hand, good agreement with A_{FB}, which is sensitive to the real part of $\mathcal{H}$, requires inclusion of the so-called D-term which has recently gained relevance for its links to the mechanical properties of the nucleon.

$E_\gamma \approx 7$ GeV and $M_{e^+e^-} \approx 1.8$ GeV, are clearly inconsistent with pure QED, and appear to favor a model which includes the so-called "D-term" in the Compton Form Factor.

6 Elastic Form Factor of the π^+ (Hall C)

The elastic electromagnetic form factor $F_\pi(Q^2)$ of the charged pion is a fundamentally important quantity in hadronic physics (Here, $-Q^2$ is the squared mass of the virtual photon.) The $\pi^\pm$ is the simplest hadronic system, and its form factor should behave like $1/Q^2$ in the limit of perturbative QCD. It is not clear, however, what is the relevant Q^2 scale for the onset of perturbative behavior. Of course, there is no possibility of an isolated $\pi^\pm$ target, so the only ways to measure the reaction directly is using a pion beam on atomic electrons (which restricts Q^2 to very small values) or $e^+e^- \to \pi^+\pi^-$ which only reaches timelike Q^2 and which is severely rate limited at high Q^2 values.

One priority for the JLab 12 GeV program is to measure the reaction $e^-p \to e^-\pi^+n$ in kinematics designed to extract $F_\pi(Q^2)$ at large spacelike Q^2. In this case, the "target" is the virtual π^+ surrounding the proton, and the longitudinal part of the differential cross section must be separated from the transverse part. A model incorporating both the off-shell pion and the recoil nucleon effects is then used to extract F_π from the magnitude and t-dependence of the longitudinal component. This requires a large body of data with tight control of systematic uncertainties so that the separations and extrapolations can be precisely performed.

This measurement is the goal of JLab Experiment E12-19-006[1] which in fact has taken its complete data set in Fall 2019, Fall 2021, and Summer 2022. The electron and pion were detected separately in the two focussing magnetic spectrometers in Hall C, with the final state neutron identified using missing mass. Figure 6 shows the statistical quality of results expected in 2025.

7 Deep Inelastic Scattering from the π^+ (Hall C)

Another fundamentally important measurement in QCD is the valence quark momentum distribution in the pion. This distribution has been extracted from the Drell-Yan process with

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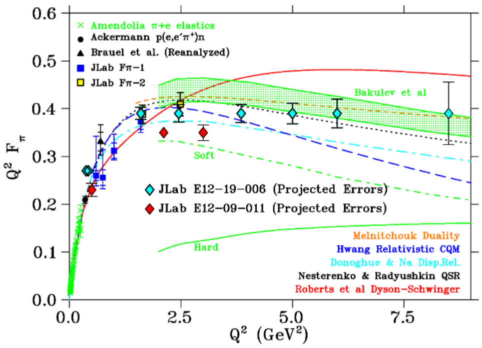

Figure 6. Expected statistical and systematic uncertainties on the pion elastic form factor from Hall C, from the reaction $e^- p \to e^- \pi^+ n$. The analysis requires that the longitudinal and transverse components of the cross section be separated, and a model used to extract F_π from the magnitude and t-dependence of the longitudinal component. This difficult measurement will extend the Q^2 range by more than a factor of two over existing data, owing to the high reach afforded by 12 GeV CEBAF.

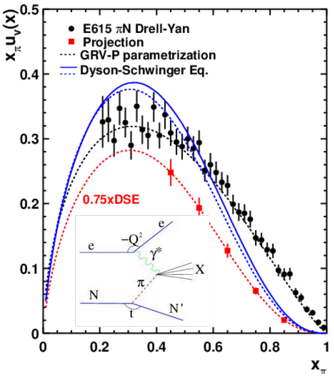

Figure 7. Data on the π^- valence quark distribution function from the reaction $\pi^- A \to \mu^+ \mu^- X$ on a Be target [10] compared to models based on the Dyson-Schwinger Equations [11] and next to leading order QCD resummation [12]. The inset shows a different experimental approach based on the Sullivan process, where one carries out deep inelastic scattering on the pion cloud of the nucleon. This approach is the basis of the Tagged Deep Inelastic Scattering (TDIS) experimental program planned for CEBAF, as well as the Electron Ion Collider (EIC).

a π^- beam [10], but a different approach would be to scatter a high energy electron beam from the pion cloud surrounding the nucleon. This is all depicted in Figure 7 including two different theoretical approaches [11, 12], both of which disagree with the Drell-Yan data at high x. The need for a new experiment is clear.

The Tagged Deep Inelastic Scattering (TDIS) experiment[2] is in the planning stages at CEBAF. This measurement would make use of a cylindrical time projection chamber (TPC) in a solenoidal field to tag the spectator nucleon in the reaction $e^- p \to e^- X(p)$ for the π^0 structure function, or $e^- d \to e^- X(p)$ for the π^-. This TPC is in the design stages. This pioneering experiment would also serve as a proof-of-principle for future experiments at the EIC and for 22 GeV beams from CEBAF.

8 The Future: SoLID and 22 GeV

The Solenoidal Large Intensity Device (SoLID)[3] is a large acceptance forward scattering spectrometer with full azimuthal angular coverage capable of handling luminosities up to 10^{39}/cm^2/s with a variety of polarized and unpolarized targets. This will allow the full capabilities of CEBAF to be exploited for several different kinds of measurements that are impossible to carry out elsewhere. The design has been thoroughly reviewed and is awaiting funding to begin construction.

The anticipated experimental program for SoLID covers three general areas. One is Semi-Inclusive Deep Inelastic Scattering (SIDIS), that is reactions such as $e^- p \to e^- \pi^- X$ at high

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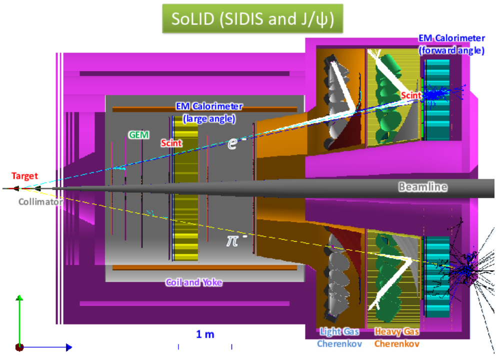

Figure 8. Detailed drawing of the SoLID detector as set up for measurements of SIDIS and J/ψ production, allowing for targets polarized in arbitrary directions. For PVDIS measurements, the target is moved into the center of the solenoid, and baffles are installed to restrict the kinematic range of the scattered electrons. The superconducting magnet, with the iron yoke, is in hand, from the CLEO-III collaboration at Cornell. Particle detector configurations will change based on the measurement.

Q^2 with polarized beam and targets, which will be used to disentangle more details of the nucleon Wigner function through extraction of Transverse Momentum Distributions (TMDs). A second area is J/ψ production using photon and electron beams, similar to what GlueX has achieved (Sec. 2) but with much higher statistics. Thirdly, in a modified configuration, SoLID will be used for precision parity violation measurements in deep inelastic scattering (PVDIS) for testing the Standard Model through the *eq* couplings.

Still other measurements are possible, including Double Deeply Virtual Compton Scattering (DDVCS) which is similar to TCS (Sec. 5) but using an incoming electron and virtual photon. This would allow additional tuning of the relevant kinematics.

An elevation view of SoLID as configured for SIDIS and J/ψ production is shown in Figure 8. The superconducting magnet is at Jefferson Lab, undergoing tests. The plan is for SoLID to begin construction and installation in Hall A when the MOLLER experiment is decommissioned, likely some time in 2028.

The design of a 22 GeV CEBAF (See Sec. 1) is progressing and a wide ranging program of experiments is anticipated [13]. SoLID will play a key role in exploiting this unique high energy and high intensity accelerator, as well as the existing instrumentation in the other experimental areas. The future of CEBAF and Jefferson lab is a bright one, with lots of exciting physics yet to come.

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