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.

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This talk focuses 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 $J/\psi$ from the Proton (GlueX, Hall D)

The GlueX collaboration recently published [2] their measurements of the total and differential cross sections for $\gamma p \rightarrow J/\psi p$. 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 $\pi^0$ 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 $e^- p \rightarrow e^- p \pi^0$. 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 $\phi$ between the electron scattering and $p\pi$ reaction planes. These are referred to as $\sigma_{LT}$ (which has a cos $\phi$ dependence), $\sigma_{TT}$ (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 $\pi^+$ at High $Q^2$ (CLAS12, Hall B)

The CLAS12 collaboration has also carried out a measurement of DVMP [8], for the reaction $e^- p \rightarrow e^- n\pi^+$ with the neutron identified using the missing mass technique. As is the case with the Hall A measurement of $e^- p \rightarrow e^- p\pi^0$, the polarized electron beam was used to measure “Beam Spin Asymmetries” that allowed the extraction of different interference terms
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the nucleon by measuring integrals of the Wigner function [1]. One of these integrals leads
to waves for the reaction being dominated by elastic
of heavy hadrons in this model implies a very shallow
dependence of the total cross section near the open-charm
thresholds that can be interpreted as the cusps ex-
ploited 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 \( \gamma p \rightarrow pe^+e^- \), where the
final state \( e^+e^- \) mass is selected to be between the \( \phi \) and \( J/\psi \) 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 \( A_{\phi U} \) 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 \( \xi \) is the momentum im-
balance on the incoming and outgoing struck quark. These data, taken for photon energy


$E_y \approx 7$ 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 $\pi^+$ (Hall C)

The elastic electromagnetic form factor $F_+(Q^2)$ of the charged pion is a fundamentally important quantity in hadronic physics (Here, $-Q^2$ is the squared mass of the virtual photon.) The $\pi^+$ 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 $\pi^+$ 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 $e^+e^- \rightarrow \pi^+\pi^-$ 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 $e^- p \rightarrow e^- \pi^+ n$ in kinematics designed to extract $F_+(Q^2)$ at large spacelike $Q^2$. In this case, the “target” is the virtual $\pi^+$ 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 $F_+$ 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 focusing 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 $\pi^+$ (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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a $\pi^-$ 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 $e^- p \rightarrow e^- X(p)$ for the $\pi^0$ structure function, or $e^- d \rightarrow e^- X(p)$ for the $\pi^-$. 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 $e^- p \rightarrow e^- \pi^- X$ at high

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$Q^2$ 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 $J/\psi$ 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 $J/\psi$ 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.

References

[5] D. Winney et al. (2023), 2305.01449
[13] A. Accardi et al. (2023), 2306.09360