J/ψ Near-Threshold Photoproduction off the Proton and Neutron with CLAS12

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Abstract. Near-threshold J/ψ photoproduction is a key aspect of the physics program at the Thomas Jefferson National Accelerator Facility (JLab) 12 GeV upgrade due to the wealth of information it has to offer. J/ψ photoproduction proceeds through the exchange of gluons in the t-channel and is expected to provide unique insight about the nucleon gravitational form factors and the nucleon mass radius. The JLab based CLAS Collaboration, which uses the CEBAF Large Acceptance Spectrometer (CLAS12), aims to measure the J/ψ near threshold photoproduction cross section using both a proton and a deuteron target, from threshold up to 10.6 GeV. The deuteron target further offers the possibility of comparing the proton and neutron gluonic form factors and mass radii in a first measurement of the cross sections off a proton or neutron within the deuteron target. The analysis towards these measurements is ongoing and well advanced, with machine learning based techniques for particle identification already designed and validated with CLAS12 data.

1 Introduction

J/ψ, a $c\bar{c}$ meson, has played an important role in modern day particle and nuclear physics since its discovery in 1974 [1, 2]. As such it has been extensively studied in collider experiments with centre of mass energies well beyond the threshold energy required to produce J/ψ. However, theoretical developments at the start of the century has prompted renewed interest in J/ψ photoproduction near the 8.2 GeV threshold, which is close to the energy at which the CEBAF Large Acceptance Spectrometer (CLAS12) operates.

Currently-available measurements of the J/ψ photoproduction cross section off the proton in the near threshold region (SLAC [3], Cornell [4], GlueX [5]) span the energy range from threshold up to about 20 GeV [5]. Several existing theoretical calculations of the exclusive J/ψ photoproduction cross section off the proton [6–8] aim to describe the J/ψ photoproduction production mechanism. In particular, [7] implies a large gluonic contribution to the nucleon mass and the predicted cross section is in a very good agreement with the GlueX results [5] that have a similar energy range to that covered by CLAS12 data. This model is very interesting as it relates to other models within the framework of which the real part of the J/ψ-nucleon scattering amplitude contains the anomalous trace of the energy-momentum tensor [9]. These models are based on the assumption of a two gluon exchange as being the dominant production mechanism. Further evidence that the two gluon exchange is dominant over other production mechanisms comes from the fact that a two gluon form factor is shown to adequately describe the J/ψ differential cross section as a function of t [10]. The relation between the J/ψ photoproduction differential cross section and the trace anomaly of Quantum Chromodynamics (QCD) was also studied by means of a holographic QCD approach [11]. Furthermore, estimates of the b parameter that quantifies the magnitude of the contribution to the nucleon mass due to the trace anomaly can be extracted from VMD based models of J/ψ photoproduction [12, 13].

The matrix elements of the trace anomaly known as gravitational form factors (GFFs), which encode mechanical properties of the nucleon [14, 15], can then be directly related to J/ψ photoproduction [14, 15]. A scalar GFF is estimated from the J/ψ differential cross section as a function of t [14] by assuming a simple dipole form:

$$G(t) = M(1 - \frac{t}{m_s^2})^{-2}, \tag{1}$$

where m_s is a free parameter which relates to the rms mass radius of the nucleon as [14]:

$$< R_m^2 >= \frac{12}{m_s^2}. \tag{2}$$

The first estimate of the mass radius of the proton, shown in Figure 1 of [14], based on GlueX data [5], yields $m_s = 1.24 \pm 0.07$ GeV and $R_m = \sqrt{< R_m^2 >} = 0.55 \pm 0.03$ fm. Other estimates by the J/ψ-007 experiment carried out in JLab's Hall C are in good agreement [15]. The fact that the charge radius of the proton $R_C = 0.8409 \pm 0.0004$ fm is statistically significantly larger than the mass radius of the proton suggests that the quark radius of the proton is significantly larger than its gluon radius [14].

Before moving on, it is worth emphasising that the assumption of a dominant two gluon exchange for J/ψ photoproduction sees two spin-1 gluons exchanged, mimicking a spin-2 system such as a graviton [11, 16]. Due to the extreme weakness of the gravitational field of the proton and the fact that graviton-proton scattering is currently off

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limits [14], the theoretical framework described above offers new opportunities in hadron physics whereby the mass and mechanical properties of the nucleon can be measured from J/ψ photoproduction. Although the mass radius of the proton has already been quantified, CLAS12 will provide the first estimates of the mass radius of the bound neutron and proton in deuteron.

2 Methodology

CLAS12 [17] is a large acceptance spectrometer located in Hall B at JLab where the Continuous Electron Beam Accelerator Facility (CEBAF) [18] was recently upgraded to produce a 12 GeV electron beam, with beam energies up to 11 GeV delivered to CLAS12. CLAS12, shown in Figure 1, has a forward detector covering polar angles of 5 to 35 degrees and a central detector covering the range 35 to 125 degrees. Both have full azimuthal coverage. Only the forward detector is used in the measurement of J/ψ photoproduction off the free and bound nucleon, motivating a short description of its main components. The High Threshold Cherenkov Counter (HTCC) is used to identify electrons [17]. The Drift Chambers (DC), in combination with the solenoid magnet, allow to determine the charge and momentum of final-state particles [17]. The Forward Time Of Flight (FTOF) counters were designed to identify charged hadrons by measuring their speed [17]. The Electromagnetic Calorimeters (PCAL and EC) are used to detect neutrals and identify electrons and muons by measuring their energy deposition [17].

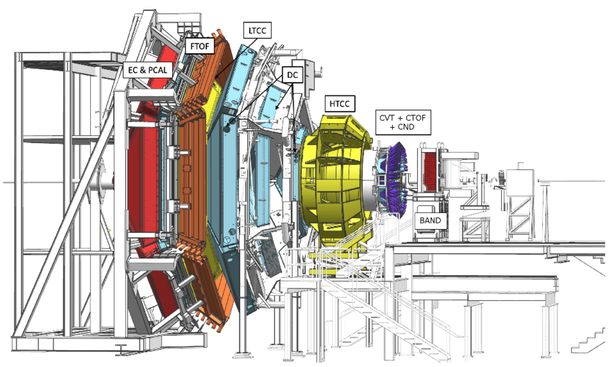

Figure 1. The CEBAF Large Acceptance Spectrometer (CLAS12) pictured with its main subsystems highlighted. In the forward detector, magnetic spectrometry is carried out by means of a superconducting solenoid magnet. CLAS12 is comprised of six identical sectors covering the full azimuthal-angle range, with three of these visible here.

In recent years, CLAS12 took data with both proton and deuteron targets, which means that data on several J/ψ reaction channels is available. On a hydrogen target, J/ψ is produced in the interaction of the electron beam with a free proton. The interaction is mediated by a quasi-real photon. With a deuteron target, J/ψ is produced off either the bound proton or neutron, and the selection of the reaction channel requires the detection of the final-state proton or neutron. The scattered electron is undetected by CLAS12 and J/ψ is identified by detecting the lepton pair (electron-positron or di-muon) to which it decays. The recoil nucleon on which J/ψ was produced is also detected to select exclusive photoproduction events.

The final state particles are identified in the first step of this analysis. Electrons and positrons are required to produce a signal in the HTCC and have a ratio of the energy deposition to momentum around 0.25. Muons are minimum ionising particles selected with cuts on their energy deposition in the calorimeters. The lepton particle identification (PID) is refined by training a machine learning classifier on variables from several CLAS12 detector subsystems, such as the energy deposition and cluster information in the calorimeters and the number of photoelectrons produced in the HTCC. The type of classifier used here is a boosted decision tree [19]. The training sample contains simulated pions, the main background in di-lepton identification in CLAS12 data, and simulated positrons or muons. The classifier learns to distinguish between these particle types. The PID process is then reduced to a cut on the response of the classifier. The J/ψ and background yields as a function of the cut on the response are shown in Figure 2, for J/ψ produced on a hydrogen target and decaying to a di-muon pair. For protons (and charged hadrons in general) a cut is made on the β versus momentum parametrization. For neutrons, only a neutral charge is required. No further cuts are applied as there is not any strong evidence of photon contamination. Some corrections are then applied to the detected particles. When a photon has also been detected within a small angular range from the final-state electron or positron, the photon energy is added to the lepton energy. This method recovers electron (positron) energy loss due to bremsstrahlung. Neutrons produce secondary clusters that are reconstructed as independent neutral tracks and give rise to a non-physical background in the neutron sample. These are removed by taking the earliest neutral in a given sector. The reconstructed path length for neutrons is corrected by comparing the reconstructed to expected path length in exclusive reactions producing a neutron. This leads to a more accurate estimate of the neutron momentum. Fiducial cuts are applied to remove electron or positron hits close to the edges of the PCAL where the shower is not fully contained within the calorimeter. Fiducial cuts in the drift chambers are applied to electrons, positrons, protons, and muons by removing hits at the edge of the layers.

The next step of the analysis is to select J/ψ photoproduction events. First, to ensure quasi-real photoproduction events, the invariant mass Q^2 of the virtual photon mediating the interaction between the electron beam and the target must be close to zero. An upper limit of 0.3 GeV^2 on Q^2 restricts the virtuality of the photon and ensures the selection of quasi-real photoproduction events. Next, the invariant mass of the state X in the reaction $eN \rightarrow l^+l^-NX$ should be consistent with the electron rest mass as the scattered electron is not detected, as mentioned previously. For all reactions of interest discussed here, the assumption is made that the target nucleon N is at rest. At GeV energies, m_X is essentially zero, with the Fermi motion of the bound proton and bound neutron in deuteron decreas-

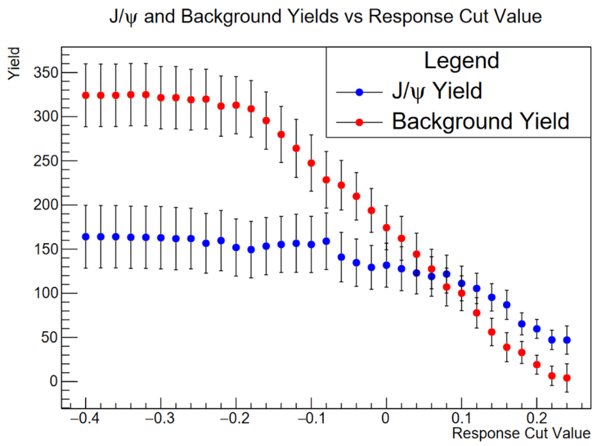

Figure 2. The J/ψ and background yields as a function of the cut on the muon machine-learning classifier response, for J/ψ produced on a hydrogen target and decaying to a di-muon pair. The background yield drops off faster than the J/ψ yield. This allows for an improved identification of muon pairs with a cut at 0.1, for example.

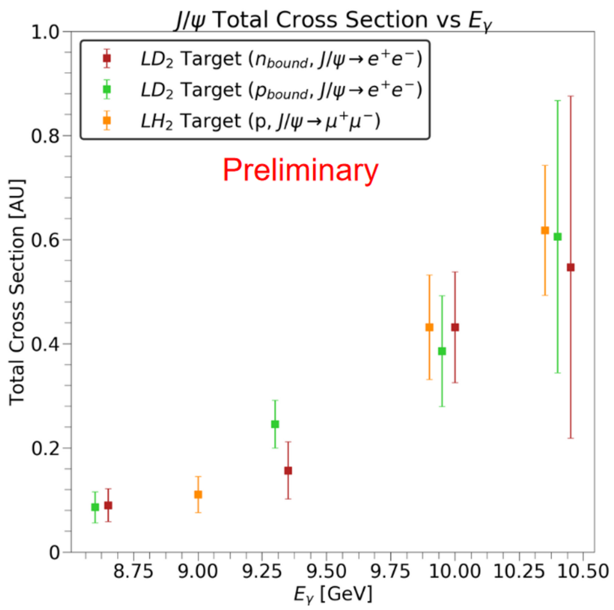

Figure 3. The J/ψ total cross section for J/ψ produced exclusively off a hydrogen (LH_2) target decaying to a di-muon pair (orange), J/ψ produced exclusively off the bound proton (green) or bound neutron (red) in the deuteron target (LD_2) decaying to an electron positron pair (blue). The cross section is given in arbitrary units as these results are still preliminary. Only statistical uncertainties are shown here, with the data points reported at the centre of the E_γ bin. The uncertainty increases as a function of E_γ due to the decreasing photon flux (taken as the sum of the real and quasi-real fluxes).

ing the resolution on the invariant mass of X. The invariant mass squared m_x^2 is referred to as the missing mass squared of the event, and is typically restricted to a range from -0.3 to 0.3 GeV^2. Cuts on the missing mass squared and Q^2 allow to select quasi-real photoproduction of di-lepton pairs. Such pairs can be produced in the decay of J/ψ, ρ, ω or ϕ, Bethe Heitler photoproduction, or Time-like Compton Scattering [20]. The number of J/ψ events in the data sample is then measured by fitting the di-lepton invariant mass.

3 Results and Outlook

Once the final state particles have been identified and corrected and the final states of interest have been selected, the total and differential cross sections can be extracted from the experimental yields. The total cross section for the $ep \rightarrow (e')J/\psi p$ reaction, where J/ψ is reconstructed by means of its di-muon decay, as for the $ep_{bound} \rightarrow (e')J/\psi p$ and $en_{bound} \rightarrow (e')J/\psi n$ reactions, where J/ψ is reconstructed by means of its electron-positron decay, is shown in Figure 3. Here, p_{bound} and n_{bound} denote the bound proton and neutron in deuteron, respectively. The absolute normalisation is yet to be evaluated and, thus, the cross section is given in arbitrary units. As these results are still preliminary, they are not compared to previous data. Work is ongoing to better understand the normalisation. However, some interesting observations can be derived from Figure 3. First, the cross section off the free and bound proton agree within the statistical uncertainties, suggesting that any contributions due to final-state interactions in the quasi-free sample are smaller than the statistical precision of the measurement. The cross section off the bound proton and neutron also agree with one another within their uncertainties, which suggests that if there are any isospin violation effects, they are smaller than the precision on these cross sections. Two- and three-gluon exchange mechanisms are isospin conserving and if they dominate the reaction dynamics, one would expect the same cross sections off the proton and neutron. Finally the estimate of the total cross section in the di-muon decay channel is the result of the first CLAS12 analysis using muons. This demonstrates the viability of carrying out muon physics with CLAS12 when machine learning techniques are employed. While not shown here, very preliminary estimates of the differential cross sections of the three final states of interest are consistent with each other within their uncertainties. These estimates will enable a quantitative comparison of the mass radii of the free and the bound proton, and the bound neutron.

The near-threshold exclusive J/ψ photoproduction total and differential cross sections are sensitive to the J/ψ production mechanism and the nucleon gravitational form factors. The J/ψ differential cross section as a function of t can be directly connected to the nucleon mass radius. CLAS12 is aiming for a first measurement directly comparing the J/ψ photoproduction cross section off the free proton, bound proton, and bound neutron. This will constitute a first measurement of the bound proton and bound neutron mass radii. AI based improvements in the tracking reconstruction at CLAS12 show an average 40% increase in the efficiency for 3 charged particles. The data already taken at CLAS12 is about to be reprocessed with the new tracking improvements. The experiment aiming for the measurements of J/ψ photoproduction on deuterium still

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has about 40% of beam time left to run. Both of these increases in statistics will enable higher precision estimates of the exclusive total and differential cross sections. Future luminosity upgrades at JLab and CLAS12 will enable a further increase in statistics of J/ψ photoproduction at CLAS12. An energy upgrade of the accelerator at JLab would provide complementary studies of higher mass charmonium states.

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