Baryon-Omega Meson Electroproduction

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Abstract. The exclusive channels for the electroproduction of baryonic resonances as a function of Q^2 (the four momentum squared of the virtual photon) represent a sensitive tool to explore the QCD description of baryons. For this experiment, $Q^2 \sim 5.5$ (GeV/c)^2. Here the physics description changes from the relativistic Constituent Quark Model (CQM) to perturbative Quantum Chromo Dynamics (pQCD), through a region described by the Generalised Parton Distribution (GPD). In this experiment, the final state contains baryonic de-excitation channels with either a pion, the eta or the omega. This work focusses on the omega channel $p(e, e'\omega)p$. The measurements were performed in Jefferson Lab's Hall C. The unpolarised differential cross-sections are reported for the process, $\gamma^\star p \to p'\omega$. The extraction of the ω-meson differential cross-section follows the comparison of the full Monte Carlo simulation of the experiment to the measured data. The input signal and background cross sections are varied until the data is correctly modeled by the simulation. In addition, several algorithms were developed to select the kinematic region where the extraction of the cross section was robust in an unbiased way, on a bin by bin basis for various spectrometer settings. These data represent an extension of previous data into previously unmeasured territory for the Q^2. The strength of the measured cross section is greater than that predicted based on scaling using the Q^2 dependence of the dipole form factor.

1. Introduction

In this present work, our main goal is to extract the measured exclusive ω differential cross-section for the highest achievable Q^2 values in the valence quark region. This study has therefore provided data at the average Q^2 of 5.5 (GeV/c)^2. This Q^2 falls in the region where the transition from low Q^2, low t physics, where soft, non-pertubative QCD processes characterised by constituent quarks dominate, to the high Q^2, high t regime where hard processes characterised by current quark correlations are expected to play an increasingly important role [1].

2. Experimental setup

The data were acquired in Hall C at the Thomas Jefferson National Accelerator Facility (JLab) for the E01-002 experiment which was designed to study η and π^0 electroproduction in the reactions $p(e, e'p)\eta$ and $p(e, e'p)\pi^0$ respectively [1]. The experiment consists of an electron beam energy of 5.5 GeV incident on a cryogenic proton target, two spectrometers for detecting negative and positive particles, and electronics with software for reconstruction of events.

The scattered electrons are detected using the Short Orbit Spectrometer (SOS) [2][3], a resistive $QD\overline{D}$ (quadrupole, dispersive dipole, anti-dispersive dipole) spectrometer while the

High Momentum Spectrometer (HMS), $QQQD$ spectrometer, was used in detecting the recoil protons. The ω particles were identified using the missing mass method [1]. The instrumentation layout of the experiment can also be found in Ref. [1].

3. Selection of data

In other to capture as much of the decay cone as possible, the proton spectrometer was stepped in angle and momentum, with kinematics chosen such that adjacent settings overlapped in the mentioned two variables [4]. With such an approach, there is a reduction in systematic uncertainties associated with imperfect knowledge of the spectrometer acceptance. The kinematic settings of the experiment can be found in Ref [1].

The SOS was used to separate the electrons from the negatively charged pions. This was done by using a threshold gas C̃erenkov detector and a lead-glass calorimeter. In the HMS, protons were separated from positively charged pions using a combination of coincidence time (the di□erence between the trigger times of two the spectrometers) and particle velocity, or the time of flight β_{tof}.

The Hall C analysis code called ENGINE [1] was used for the o□ine data analysis of the collected raw signals. This analysis code, written in the Fortran computer language, reads each of the events, determines which detectors were fired, reconstructs trajectories, and also generates particle identification information for each event. In essence, the replay ENGINE converts raw data into calibrated physical quantities on an event by event basis. These physical quantities may include combinations of raw data quantities. Also developed were other codes making use of Perl and C++ in the Root Data Analysis framework which could perform ultimately the comparison of the simulated experiment based on signal and background cross sections and the measured data [1]. The simulation uses event generators for the signal (omega) and background (multi-pion) processes, and propagates the products from these reactions through the spectrometers on a Monte Carlo basis (SIMC [5]) .

In this experiment, $p(e, e'p)\omega$, the scattered electron and the recoil proton are detected and the emitted ω particle is not directly detected. Instead, the rest mass of the undetected particle is reconstructed by calculating the missing mass squared m_x^2 from the conservation of the four-momentum. The extraction of ω resulted in applying a cut on m_x^2 around the omega peak and subtracting the background.

Shown in Table 1 are the set of standard cuts applied to the data. Cuts such as the particle momentum deviation at both the SOS and HMS (δ_h and δ_s) were applied to ensure that only particles within the understood region of the spectrometer momentum acceptance were used. Also used, but not listed in Table 1, were cuts on the collimators at both spectrometers. These were to ensure that the path of the reconstructed track of a detected particle traced back through acceptable regions of the collimator slits.

The data was binned in $\{W$, cosθ_ω, $\phi_{cm}\}$ for the purpose of extraction of the cross section as in indicated in Table 2. W represents the invariant mass of the baryonic resonance, and the angles represent the polar angle of the ω with respect to the virtual photon and the azimuthal angle of scattering plane of the proton and ω with respect to that of the scattered electron and the virtual photon. The bins were retained for analysis if they passed the following two criteria. Firstly, the simulation is required to have predicted that the number of entries in the maximum bin of the signal region should be more than 10. Secondly, the simulation needed to predict the percentage of non-overlap of the signal and background distributions of at least 10%. This is because if the signal and background have the same shape, the fitting method (presented below) will not converge.

Table 1. Set of standard cuts applied to the data and to the simulation where applicable. The particle identification cuts (†) were not applied to the simulation.

Quantity	Cut	Purpose
†Coincidence time	$\mid t_{coin} - t_{cent} \mid \leqslant 1.5$	Selecting proton
HMS particle momentum deviation, $\delta_h = \dfrac{P - P_{HMS}}{P_{HMS}}$	$\mid \delta_h \mid \leqslant 9\%$	HMS acceptance
SOS particle momentum deviation, $\delta_s = \dfrac{P - P_{SOS}}{P_{SOS}}$	$-15\% \leqslant \delta_s \leqslant +20\%$	SOS acceptance
SOS x position focal plane, $X_{SOS,f.p}$	$-20cm \leqslant X_{SOS,f.p} \leqslant +22cm$	SOS acceptance
†SOS shower counter sum, E_{norm}	$E_{norm} \geqslant 0.7$	selecting electron
†SOS Čerenkov number of photons, $N_{p.e.}$	$N_{p.e.} \geqslant 0.5$	selecting electron
Missing mass squared m_x^2	$0.56\ \text{GeV}^2 \leqslant m_x^2 \leqslant 0.66\ \text{GeV}^2$	selecting ω particle

Table 2. The ω analysis binning for Experiment E01-002.

Variable	Range	Bins
W (GeV)	$1.72 \leq W \leq 1.92$	10
$\cos\theta_\omega$	$-1.0 \leq \cos\theta_\omega \leq 1.0$	6
ϕ_ω (rad)	$0 \leq \phi_\omega \leq 2\pi$	5

4. Simulation of events

In order to extract reliable results from our data, corrections were made on a run-by-run basis, on the track reconstruction inefficiencies, dead times and offsets. All the corrections applied to the data are shown in Table 3.

The entire set of kinematic offsets that were use during the replay of our present data is listed in Table 4.

A 4 % correction due to proton absorption is done for the trigger efficiency. The condition for a proton to cause a trigger in the HMS is that it had to deposit enough energy to create above-threshold signals in at least three out of four scintillator planes in the detector stack. A trigger inefficiency for proton detection in the HMS is produced by protons which are not detected in their interaction with the scintillator and by protons that do not make it through all the scintillators due to absorption.

The radiative corrections for our experiment were calculated within the SIMC Monte Carlo framework. The size of the radiative corrections implemented by SIMC is evaluated by running

Table 3. Corrections applied to the data. Indicated by the parentheses are the range of correction sizes applied on a run-by-run (†) or a bin-by-bin basis (‡).

Effects	Correction in %
Proton absorption	+4 $\pm$ 1
†Computer dead time	+(1.0 – 19.1)
†HMS tracking	+(2.3 – 14.3)
†SOS tracking	+(0.3 – 0.9)
†Electronic dead time	+(0.0 – 2.4)
‡Random coincidence	-(0.0 – 7.6)

Table 4. Kinematic offsets applied to the data during the replay phase.

Quantity	HMS	SOS
θ	0.0 $\pm$ 0.5 mrad	0.0 $\pm$ 0.5 mrad
ϕ	+1.1 $\pm$ 0.5 mrad	+3.2 $\pm$ 0.5 mrad
p	-0.13 $\pm$ 0.05 %	-1.36 $\pm$ 0.05 %
E_e	0.00 $\pm$ 0.05 %	0.00 $\pm$ 0.05 %

the full simulation with and without including radiative effects. The uncertainty in the radiative corrections was estimated to be 2%.

The main source of background is from events with more than one undetected particle, mainly multiple pions. In that case, we observe that the missing mass does not correspond to any physical mass, resulting in a continuous background in the missing mass spectrum. The treatment of the background was implemented by simulating the m_x^2 spectra of the background using SIMC with an input model where the MAID software [1] was used as an event generator for SIMC for the multi-pion events. The SIMC output was subjected to the same processing and binning as the data. Consequently, these yielded our approximation to the shape of the multipion background without an absolute normalisation. As an absolute multipion cross section was not being extracted, the shape with a fitted scale factor was sufficient to subtract it from the data.

5. Principle of the measurement

The signal ω contribution was simulated in a similar way using an event generator which was isotropic in the centre of mass system. The background and signal contributions were estimated with a two-parameter fit in each (W, cosθ_ω, ϕ_ω) bin. Assuming the signal and background shapes given by the model are correct, the fit parameters are the normalization of the signal and background. However, in some cases (out-of-plane ϕ bins), the multipion background and the omega m_x^2 spectra are too similar to have a reliable result from the fit. The is due to the decrease in acceptance. In some of these cases, a constraint could be added to restrict the background normalization parameter to be constant with respect to the azimuthal angle ϕ.

Figure 1 shows the result of this procedure for just one selected bin from about one hundred similar examples for the full kinematic coverage that was measured. The data is represented in blue, while the simulated points after the fit are shown in red. The agreement between the simulated and the measured spectra is good in this case. The multipion background contribution is shown in green, and the ω signal in pink. We note that the shapes are well modeled. The systematic errors were extracted with a variational procedure based on the most likely sources of such errors. The cross section was thus extracted as a function of the variation of certain spectrometer positioning parameters and the missing mass squared cut. The systematic error in the cross-section was propagated in this way from the systematic errors in these quantities. The total error was then evaluated from summing in quadrature the systematic error and the statistical error.

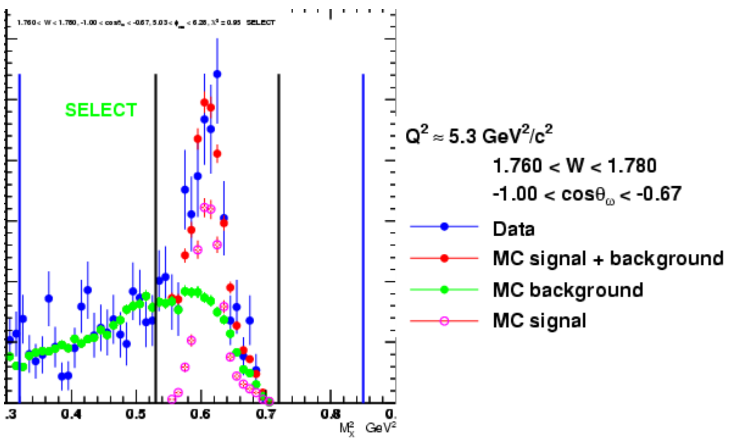

Figure 1. (Colour online) Missing mass spectrum. Data is shown in blue, while the Monte Carlo (signal + background) is shown in red. The components of the Monte Carlo distribution are shown after fitting in green (multipion background) and pink (ω signal). The black lines indicate the region within which the background fit is done, while the blue lines indicate the region within which the cross-section is measured.

6. Results and Conclusion

The measurement for the cross section of the reaction $p(e, e'p)\omega$ was extracted by comparing simulated data to measured data. The input cross-sections for the event generators were scaled until the simulated data fitted the measured data.

Figure 2 shows the computed centre-of-mass differential cross-sections for the process $p(e, e'\omega)p$ process on an average Q^2 of 5.5 GeV^2 at the invariant mass range $1.72 \leq W \leq 1.92$ GeV with full coverage of cosθ_{cm} and ϕ_{cm}. The cross section was computed in six cosθ_{cm} and five ϕ_{cm} bins. This dataset forms an extension to the kinematic region in Q^2 to studies from CLAS [6][7]. In fact, our input model cross section for the ω electroproduction was developed by scaling the cross section measured there to our Q^2 value of 5.5 GeV^2 using the dipole form factor variation of $G = (1 + \frac{Q^2}{0.71})^{-2}$. For this work, where $W \leq 1.92$ GeV, we neglected the ρ meson interference, which would broaden the peak at larger missing mass, creating an asymmetry.

Our extracted cross-section seems larger than the input model cross-section extrapolated to $Q^2 \sim 5.5$ GeV^2 using the dipole form factor. Both our cross section and the input model peak are more or less similar for $W \leq 1.86$ GeV. However, at higher W and more backward angles ($-1.0 \leq \cos\theta_{cm} \leq -0.6$), our extracted cross section is stronger.

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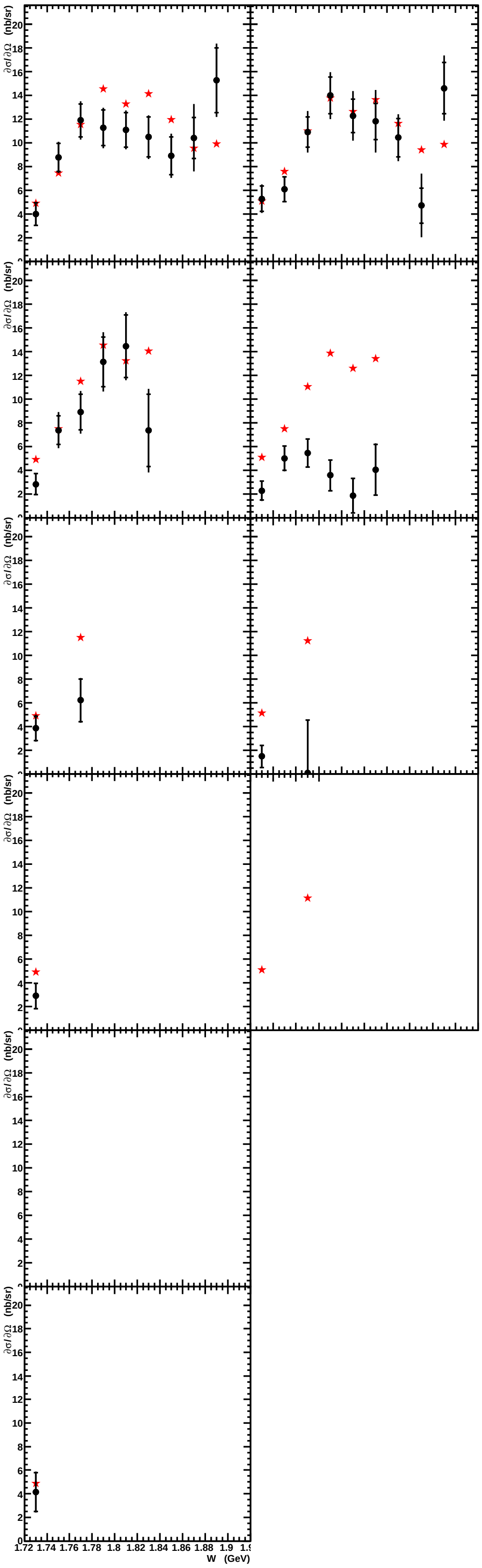

∂σ/∂Ω (nb/sr)
W (GeV)