CHAPTER I
INTRODUCTION

This research was carried out using the ZEUS detector at the electron-proton collider HERA,[†] operating at a center of mass energy $\sqrt{s} = 296\text{GeV}$ in 1993, with the electron beam energy at 26.7GeV and proton beam energy at 820GeV. At collisions of such high center of mass energy, the Coulomb force between proton and electron accounts for only a small fraction of the observed cross section. Most of the observed cross section is attributed to scatterings between the proton and a transverse electromagnetic field, or quasi-real(almost transversely polarized) photons(emitted by the beam electron) in the language of quantum field theory. This γp process is known as photoproduction. In γp scatterings, the proton is usually broken by the large energy and momentum transfer. However, there exists a class of scatterings in which the beam proton remains intact and only slightly deflected, and the beam photon emerges as a neutral vector meson($\rho, \omega, \phi, J/\psi$). This process is called elastic photoproduction. This thesis investigates elastic photoproduction of J/ψ, a process whose Feynman diagram is shown in Figure 1. J/ψ is a neutral vector meson composed of $c\bar{c}$. It has the same quantum numbers as the photon($J^{PC} = 1^{--}$), but is heavy($m_{J/\psi} = 3.1\text{GeV}$) and shortlived(lifetime $\sim 10^{-20}\text{s}$).

It is a universal phenomenon in high energy scattering, in accordance with interacting field theory, that a fraction of the (fermion) beam energy is imparted to gauge bosons, and a gauge boson in turn may impart a fraction of its energy to fermion-antifermion pairs in the vacuum. Therefore the electron beam may

[†] The ZEUS detector and HERA, the Hadron Electron Ring Accelerator, will be described in Chapter III.

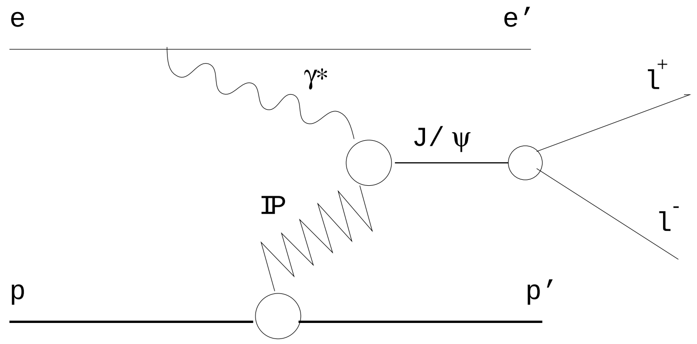

Figure 1: $ep \rightarrow epJ/\psi \rightarrow epl^+l^-$ process. J/ψ decays to $\mu^+\mu^-$ or e^+e^- each with 6.0% branching ratio. Beam electron and proton remain inside the beampipe. The dominant hard process is conceived to be $\gamma^* I\!\!P \rightarrow J/\psi$, with electron serving as the source of virtual photons, and proton the source of pomerons.

serve as a source of quasi-real photons, and the proton beam may act as a source of gluons and $q\bar{q}$ and photons in addition to a flux of valence uud quarks. While photon-photon and photon-parton† collisions can explain a wide range of electron-proton scattering, they are obviously not relevant to the topical process of this thesis, $ep \rightarrow J/\psi ep$. Photon-photon collision does not produce J/ψ because of the charge conjugation requirement. Photon-parton collision does not produce J/ψ because of color constraint. The particle that does excite a photon into a J/ψ must have the same quantum numbers as the vacuum. Such a particle, or rather pseudo-particle, was in demand to explain the diffractive hadron proton scattering phenomenology, and consequently had been conceived (more than 30 years ago) even before the discovery of J/ψ vector meson in 1974. The particle is called pomeron($I\!\!P$),[1] named after the Russian physicist Issak Pomeranchuk. As Figure 1 suggests phenomenologically, J/ψ is produced via a $\gamma I\!\!P$ fusion. Although the concept of pomeron has been fruitful in describing diffractive hadron proton scatterings, the connection between pomeron and perturbative QCD is far from

† Colored constituents of a nucleon, i.e. quarks, antiquarks and gluons, are collectively called partons.

being established.[1] Elastic photoproduction of J/ψ was recently recognized as a preferred test process for perturbative QCD calculations.[90]

In this thesis, we make a distinction between the terms diffractive scattering and elastic scattering, although they are often used interchangeably in literatures of diffractive scattering. Elastic scattering refers to the process where both beam particles are unbroken, although particle identity and mass may change (e.g., the photon becomes a vector meson) and therefore the process is actually inelastic. In a (single-)diffractive scattering, one of the beam particles is unbroken and is deflected only slightly, hence the term (single-)diffractive. There is no color exchange in either elastic or diffractive scattering. In the 1993 ZEUS experiment, as in many other experiments, the distinction between elastic scattering and diffractive scattering was not fully observable, since beam protons were not tagged.[†]

During the short space-time interval of ep scattering, the proton flux is equivalent to a mixture of flux of all kinds of partons. The *proton structure function* is a quantitative description of this mixture. Proton structure functions have been relatively well measured in previous experiments and in experiments at HERA.

The concept of the photon structure function and pomeron structure function can be introduced in a similar way. Structures of photon and pomeron have drawn intense interest in recent years. However, at present there is no significant degree of knowledge of photon and pomeron structure functions, either from theoretical calculations or from experimental data. In fact, no consensus has been reached on whether the seed of the pomeron(the pomeron as seen in longer space-time interval) is a colorless configuration of gluons or of quark-antiquark pairs.[2−3]

A basic class of measurements that may lead to a better understanding of the photon and pomeron is the measurement of the cross section of elastic photoproduction of neutral vector mesons V^0 over a wide range of the photon-proton center-of-mass energy ($\sqrt{s_{\gamma p}}$), where V^0 can be ρ, ω, ϕ, J/ψ and Υ. All of these neutral vector mesons are closely related to the photon since they have the same

† Beam protons were tagged in part of the 1994 runs.

quantum numbers. In previous fixed target experiments, the highest available energy of the photon beam was less than 400 GeV, corresponding to $\sqrt{s_{\gamma p}}$ less than 28 GeV. At HERA, upper limit of $\sqrt{s_{\gamma p}}$ is extended to 296 GeV, corresponding to photon beam energy of 47 TeV in the proton rest frame.

Figure 2 shows the inclusive and exclusive photoproduction cross sections measured by fixed target experiments[4−11] and by the ZEUS experiment. It is clear from this figure that $\sigma_{\gamma p \to J/\psi p}$, and its dependence on $\sqrt{s_{\gamma p}}$, differ from that of photoproduction of the light vector mesons. The low energy data and theoretical predictions of elastic photoproduction of J/ψ are quite divergent. Theoretical models will be described in Chapter VI. Here we only note that the photoproduction cross section is expected to increase more rapidly with $\sqrt{s_{\gamma p}}$ if the scattering is in the perturbative QCD regime and slower if in the nonperturbative regime. The J/ψ meson is composed of heavy quarks and may well be produced in a more perturbative region. However, cross section measurements at higher energy are needed to support this prediction.

HERA, the world's first ep collider, is kinematically advantageous for the study of $ep \to epJ/\psi$ over fixed target experiments. First, in a colliding γp facility, a much higher $\sqrt{s_{\gamma p}}$ can be reached without requesting higher energy of the photon beam. In fact, at HERA, E_γ is less than 26.7 GeV(electron beam energy). Given the geometrical coverage of $10°$–$170°$ in polar angle of the tracking chambers of the ZEUS detector, the accessible $\sqrt{s_{\gamma p}}$ range for $ep \to epJ/\psi(\to l^+l^-)$ is 20–240 GeV (for the 1993 ZEUS data, the analyzable range is $\sqrt{s_{\gamma p}} = 40$–140GeV). Second, the electron beam is a source of a wide energy band quasi-real photon flux. The energy spectrum of the equivalent photons is fixed by the dynamics. Therefore, when comparing $\sigma_{\gamma p \to V^0 p}$ measured at different $\sqrt{s_{\gamma p}}$, errors in the luminosity measurement at different $\sqrt{s_{\gamma p}}$ are correlated, and normalization is less of a concern at HERA. Third, in fixed target experiments, the photon beam energy is almost entirely converted into the J/ψ's kinetic energy during a diffractive photoproduction process by definition(diffractiveness is defined as $E_{J/\psi}/E_\gamma$ in the fixed target frame). This high boost results in decay leptons and beam electron

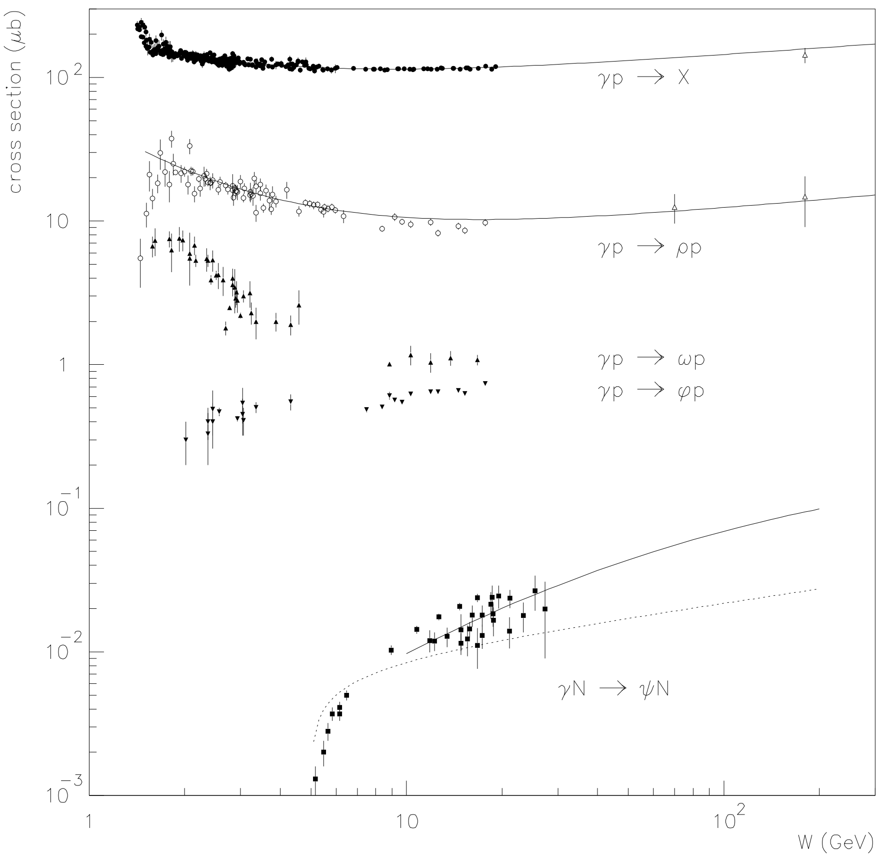

Figure 2: Compilation of photoproduction cross section data. The maximum $\sqrt{s_{\gamma p}}$ accessible before HERA is about 28GeV. HERA allows $\sqrt{s_{\gamma p}}$ to reach 296GeV. The inclusive photoproduction cross section data appear at the top of the figure. The theorectical prediction that fits pre-HERA and ZEUS measurements is based on Donnachie-Landshoff. Next to the top are cross section data for elastic photoproduction of the ρ meson. The theoretical prediction is based on a nonperturbative model. At the bottom of the figure are previous measurements for elastic photoproduction of J/ψ. The solid curve is the prediction by a perturbative QCD model. The dotted curve is the prediction by a nonperturbative model.

and proton all crowded into a narrow cone along the beam direction, presenting difficulties in measurement of each particle. In particular, it is usually uncertain whether the J/ψ is produced elastically or inelastically. At HERA, the energy of the observed J/ψ is typically less than 5 GeV. Large angular separation of beam electron, proton and decay leptons makes it easy to distinguish elastic and inelastic processes. The phenomenology and kinematics will be discussed in more detail in Chapter II.

The measurement in this thesis was made using the ZEUS detector. The ZEUS detector will be described in Chapter III. In 1993, the second year of HERA operation, when the central tracking drift chamber of ZEUS was fully commissioned, the first data sample of J/ψ, detected in its leptonic decay modes, was collected. 1993 also saw a 20 times increase in luminosity ($\sim 600\text{nb}^{-1}$ as collected by the ZEUS detector, as compared to $\sim 30\text{nb}^{-1}$ in 1992). The successful collection of diffractively photoproduced J/ψ, in e^+e^- and $\mu^+\mu^-$ decay modes, is a demonstration that the ZEUS detector is capable of measuring higher order physics processes with small cross sections and low activity(a few GeV energy deposition in the calorimeter) as well as deep inelastic scatterings of very high activities(a few hundred GeV energy).

J/ψ data were collected in both e^+e^- and $\mu^+\mu^-$ decay modes. This thesis describes the work done for $J/\psi \to e^+e^-$ measurement. Chapter IV describes the special online triggers developed for elastic $J/\psi \to e^+e^-$ collection. Chapter V describes the offline selection of elastic $J/\psi \to e^+e^-$ candidates. Theoretical models and Monte Carlo simulations are described in Chapter VI. Chapter VII presents the physics analysis. The most significant result is the measurement of $\sigma_{\gamma p \to J/\psi p}$ and its dependence on $\sqrt{s_{\gamma p}}$.

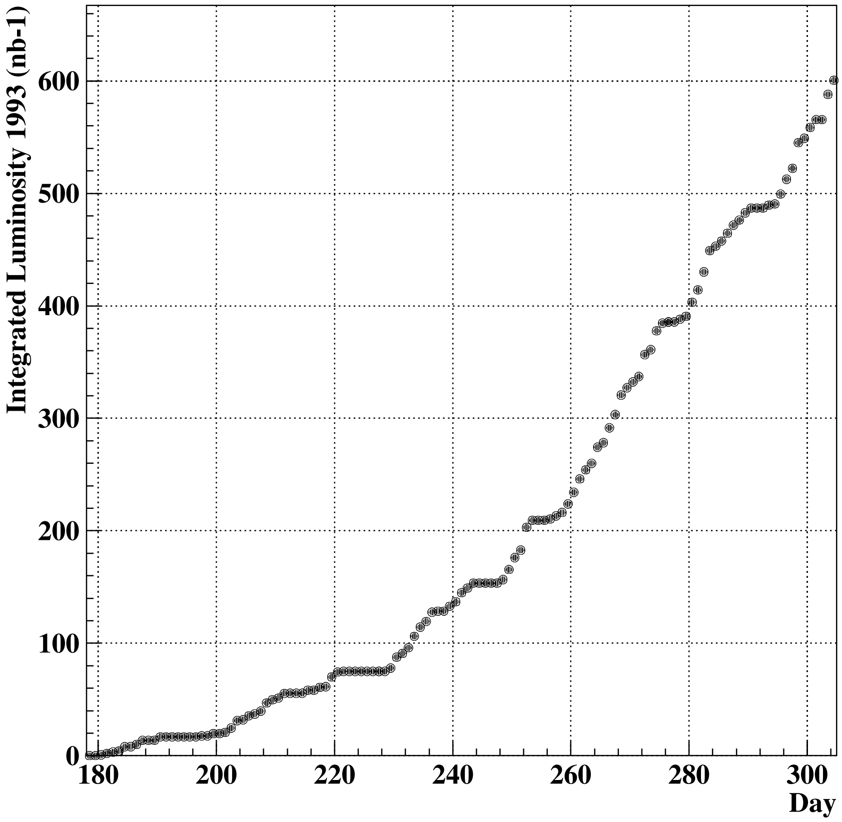

Figure 3: Integrated luminosity as recorded by the ZEUS detector during the 1993 runs.