CHAPTER II
THEORY I: KINEMATICS

Theoretical materials are presented separately in this chapter and Chapter VI according to their pertinence to the measurement. This chapter addresses the following questions which one has to deal with in the design stage of an experiment:

(1) How do we recognize an $ep \to epJ/\psi$ event in the detector?

(2) How many such events do we expect to collect in the 1993 runs?

(3) In order to measure this process, what special requirements do we have for the detector?

(4) With these events, what kinds of physics analysis are feasible?

Kinematics and equivalent photon approximation, instead of detailed information of the detector hardware and sophisticated Monte Carlo simulations, form the theoretical basis of this discussion. Lately developed QCD theoretical models on diffractive scattering† will be described in Chapter VI together with description of Monte Carlo simulations, before presentation of data analysis.

† Much of theoretical interest and progress were inspired by recent results of the ZEUS and H1 experiments at HERA.

2.1 Classification of J/ψ photoproduction

The J/ψ vector meson can be recognized in its leptonic decay into a pair of e^+e^- or $\mu^+\mu^-$, each by 6.0% branching ratio,[12] with an invariant mass of 3.1GeV. It should be noted that a branching ratio at percent level is unusually large for pure leptonic decays, since heavy flavor mesons tend to decay hadronically through strong interaction.

Elastic photoproduction of J/ψ, the process of interest to this analysis, is one of the several known mechanisms of J/ψ production in electron-proton scattering at HERA.[15] Theoretical classification of the production mechanisms is based on event topology of the first order Feynman diagrams and kinematical region in the phase space, as illustrated in Figure 4.

The distinction between *elastic* production and *inelastic* production of J/ψ is based on event topology—whether particles other than the J/ψ meson is produced. Processes represented by Figure 4(b)-(e) are collectively called inelastic J/ψ production. A further classification of inelastic processes is made according to rapidity distribution of the hadrons other than the J/ψ. In a *diffractive* J/ψ production, all other particles are crowded into narrow cones around the beam electron and proton. Diffractive production can be further divided into proton diffractive and photon diffractive processes as shown in Figure 4(c) and (d). An interesting process within inelastic J/ψ production, if can be detected experimentally, is shown in Figure 4(e), which is resolved photon process where both photon and proton are broken.

Another classification is based on value of Q^2 which is a function of energy and deflection angle of the scattered beam electron. *Deep inelastic*(DIS) production and *photoproduction* of J/ψ correspond to two extreme cases—very large value of Q^2 and nearly zero value of Q^2. Nearly zero Q^2 corresponds to the case where the beam electron emitts a quasi-real photon which then hits the proton. Physics in the vast volume of phase space between these two extremes has not been fully explored either experimentally or theoretically. For theoretical purposes, an operational distinction between DIS and photoproduction is often made,

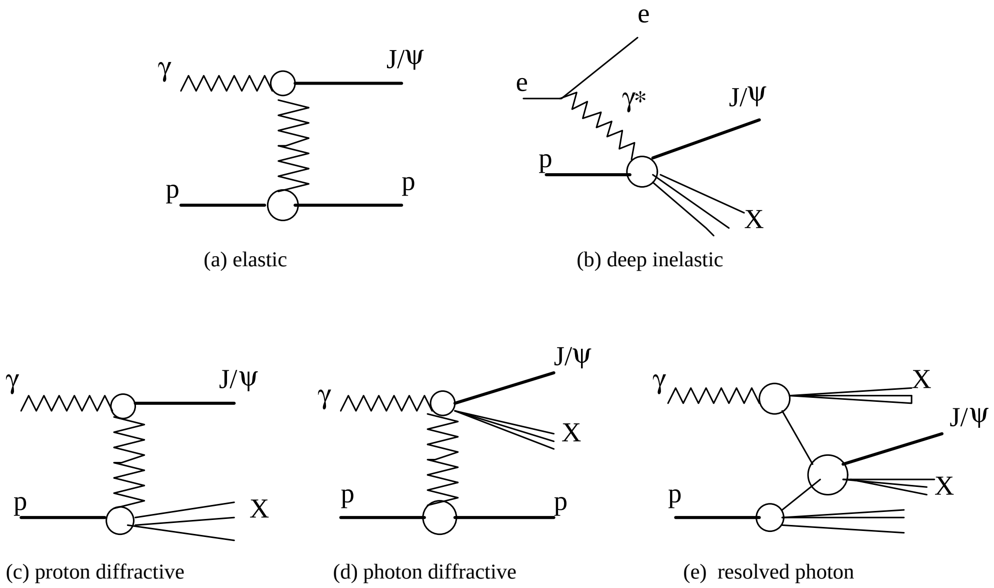

Figure 4: Classification of J/ψ productions. (a) Elastic photoproduction of J/ψ, the process of interest to this thesis. (b)-(e) are collectively called inelastic production of J/ψ. (b) Deep elastic production of J/ψ, where the beam electron may be scattered into the main detector due to large Q^2 of the photon. (c) Proton diffractive photoproduction of J/ψ, where the beam electron and unspecified hadrons X travel down the beam pipes in opposite directions. (d) Photon diffractive photoproduction of J/ψ, where the beam electron and unspecified hadrons X travel down the beam pipes in the same direction. (e) Resolved photon J/ψ production where both the proton and photon are broken.

quite arbitrarily, according to whether Q^2 is greater or lesser than one or a few GeV^2. Experimentally, the distinction between DIS and photoproduction is made according to the energy and deflection angle of the scattered beam eletron.

The ZEUS detector detects and discriminates e, μ, γ and stable(longlived) charged and neutral hadrons in nearly 4π solid angle. At ZEUS, experimental signature of elastic J/ψ photoproduction is that a pair of oppositely charged leptons(e or μ) with an invariant mass 3.1GeV are detected in the main detector and the beam proton and electron escape through the forward and rear beampipes, respectively.[†]

2.2 Kinematics

In this section, studies of kinematics for elastic photoproduction of J/ψ is made in context of general J/ψ production. In our experiment in 1993, without detection of the beam electron and proton, the kinematical measurements are incomplete, as shown in the next subsection. This complicates the relation between the Lorentz invariant variables of theoretical interest and laboratory measurements. In this section, a thorough investigation of the kinematics is made to clarify what assumptions and approximations are essential for kinematical reconstruction of J/ψ photoproduction at ZEUS and the reconstruction formulae are derived and presented in a most precise form.

2.2.1 Degrees of freedom and kinematical variables

A final state is defined by a set of kinematic variables. A differential cross section, which is the integrand in the following equation,

$$\sigma = \int \frac{d^n\sigma}{dx_1 dx_2 \cdots dx_n} dx_1 dx_2 \cdots dx_n \tag{1}$$

is the probability for each final state$(x_1, x_2, \cdots, x_n)$ to occur. It is preferred to write the differential cross section with respect to a set of Lorentz invariant variables. These Lorentz invariant variables can be reconstructed from 4-momenta of the final particles measured in the laboratory.

Following symbols are used for 4-momenta of particles (refer to Figure 5):

[†] Due to finite resolution of the tracking chamber, and energy loss by Bremsstrahlung radiation in the case of e^+e^- decay, the measured invariant mass is a continuous distribution peaked near 3.1GeV.