CHAPTER 2

ELECTRON-PROTON COLLISION

2.1 Electron-proton collision at HERA

The collision between electron and proton at HERA is useful to obtain the kinematical values of particle diffraction and interaction at high energy. When an electron strikes a proton which contains quarks and gluons, the electron will transfer part of its energy and momentum to one of the quarks through the emission of a photon carrying a certain wavelength. The wavelength of the photon basically will reflect the strength of the interaction whether it is a hard or soft interaction. At HERA, the common phenomena observed are the diffractive interactions where the constituent quarks in the proton remain intact, $ep \rightarrow Xp$, where X is the new particle produced in the interaction. If the photon exchange between the electron and the proton only transfers a little momentum, the photon will only observe the main components of the proton which are the three individual valence quarks. However, if a greater momentum involve in the interaction, the HERA microscope will able to observe the quarks, anti-quarks and gluons in the proton. A photon-proton kinematics parameter called Q^2 is usually used to describe the strength of the momentum exchange. The Q^2 and the rest parameters will be explained in detail the next section. The force between the quarks can also be determined based on a coupling constant, α. An accurate measurement was taken at ZEUS have shown that, the coupling constant will increase with increasing distance. In quantum electrodynamics theory (QED), the energy scale of the interaction, $\mu^2 = Q^2$ thus, the following behaviour is observed:

$$\alpha(Q^2) = \frac{\alpha_0}{1 - \frac{\alpha_0}{3\pi}\ln\frac{Q^2}{m_e^2}} \tag{1}$$

where m_e^2 is the mass of electron, and α_0 is the coupling constant at $Q^2 = m_e^2$ [4]. In this thesis, α will be calculated to determine the photon flux in the cross section equation.

2.2 Kinematics of electron-proton (*ep*) scattering

The kinematic variables of *ep* scattering are the basic quantities used in ZEUS analysis to describe the scattering process of the collided particles. The schematic diagram for the *ep* scattering $e(k)p(P) \rightarrow e(k')X$ is shown in the Figure 2.1. Below are the relevant Lorentz invariant variables:

- $s = (k+P)^2$, the square of the centre-of-mass energy. At HERA, the centre-of-mass energy for *ep* is defined in the square root value of s, $\sqrt{s} = 318$ GeV.
- $Q^2 = -q^2 = -(k-k')^2$, the negative squared four-momentum of the exchanged virtual photon;

- $y = \frac{P.q}{P.k} = \frac{W^2}{s}$, the fraction of the positron energy transferred to the photon in the proton rest frame;

- $x_{Bj} = \frac{Q^2}{2(P.q)}$, the Bjorken variable, which can be interpreted as the fraction of the proton momentum carried by the struck charged parton;

- $W = (P+q)^2 = 2E_p(E-P_z)$, the squared centre-of-mass energy of the photon-proton system where E is the energy and P_z is the longitudinal momentum.

2.3 Diffraction

The diffraction at high energy describes processes in which the quantum numbers of the vacuum are exchanged. This physics phenomenon is also used as an alternative approach to the problem of perturbative and non-perturbative physics and the saturation of parton densities in the proton. Moreover, diffractive event is significantly useful for two pre-QCD phenomenological frameworks, Regge phenomenology and the Vector Dominance Model (VDM). The combination of the VDM and Regge phenomenology can be applied to describe certain physics processes, for example diffractive events at HERA. Generally there are three common diffractive processes in hadron-hadron collisions to be seen at HERA.

- Elastic scattering ($A+B \quad A+B$)

- Single diffraction ($A+B \quad B+X$)

- Double diffraction ($A+B \quad X+Y$)

Where the quantum numbers of X and Y are related to the incoming particles.

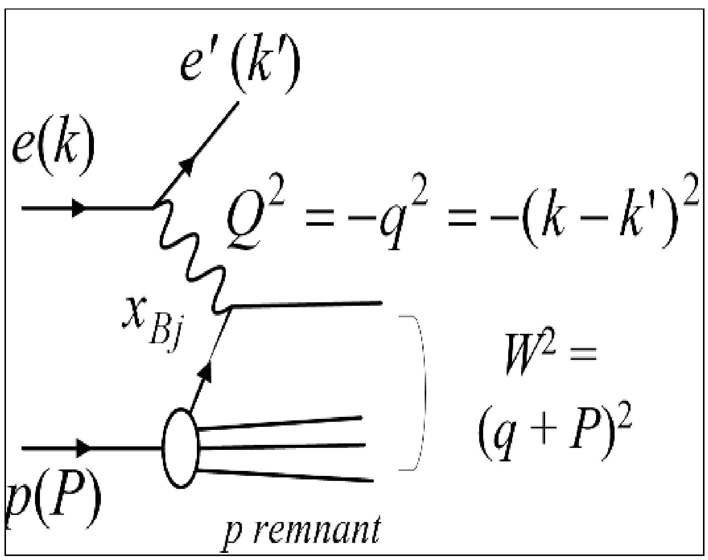


Figure 2.1: The picture shows a schematic diagram of *ep* scattering with the relevant kinematic variables.

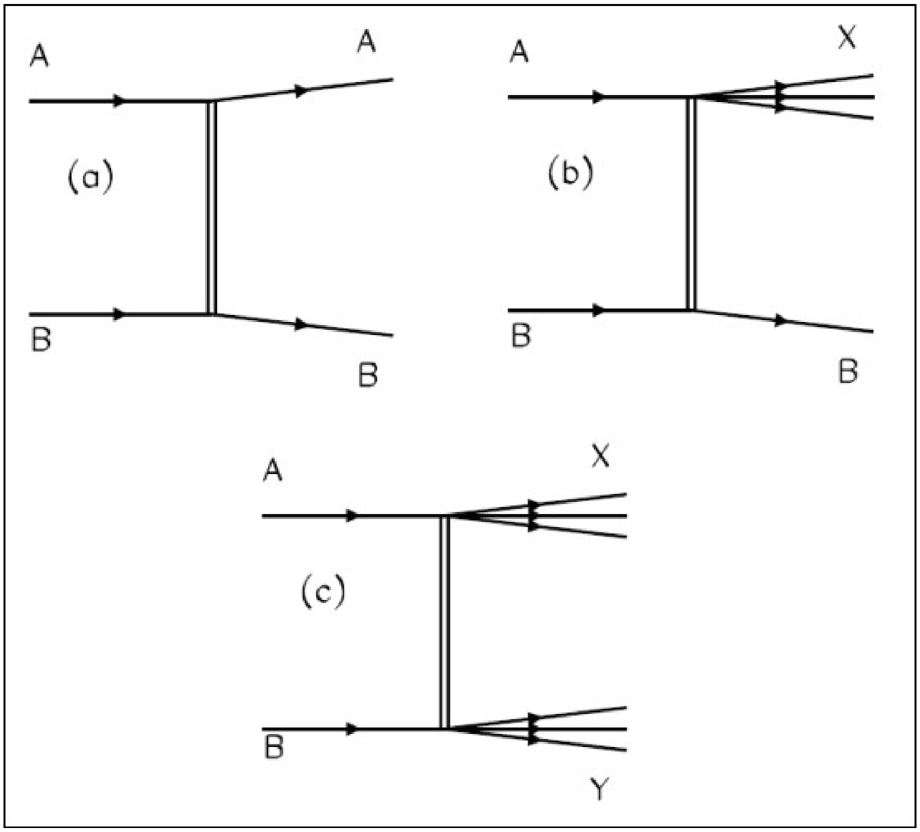


Figure 2.2: The classification of diffractive processes: (a) Elastic, (b) Single diffraction, (c) Double diffraction.

2.3.1 Regge Phenomenology

A simple spherically symmetric potential with discrete energy levels *k* and angular momentum *l* was defined in 1957 by Regge [5,6]. Then a complex value of *l* was recognized to obtain an interpolating function $a(l,k)$ which reduced to $a_l(k)$ for $l = 0,1,2,...$ n. The singularities of $a(l,k)$ turned out to be Regge poles [10] for Yukawa type potentials. It is located at values defined by a relation of the kind $l = \alpha(k)$ where $\alpha(k)$ is a function of the energy called the Regge trajectory. The Regge poles contributes to the scattering amplitude an asymptotically term (i.e for s and t fixed, where t is the four-momentum transfer between A and B) as

$$\lim(s \quad)A(s,t) \sim s^{\alpha(t)} \tag{2}$$

where $\alpha(t)$ is the Regge trajectory, assumed to be linear in t,

$$\alpha(t) = \alpha(0) + \alpha^{'} t \tag{3}$$

The intercept, $\alpha(0)$, and the slope, $\alpha^{'}$, of the trajectory are determined experimentally. The forward differential cross-section of the AB scattering is expressed by the following relations:

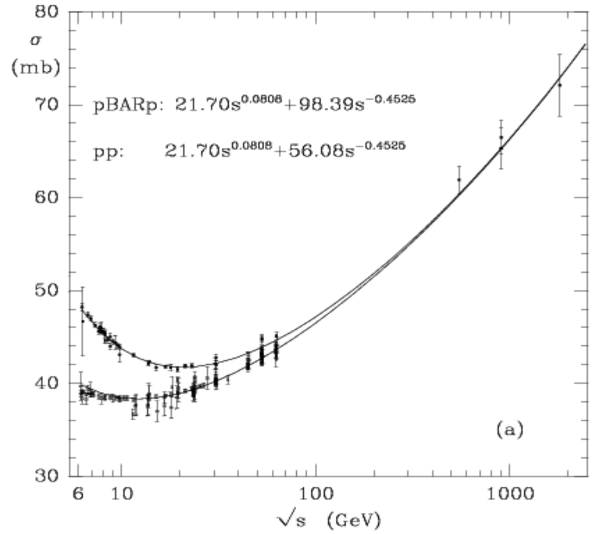
$$\frac{d\sigma_{el}}{dt}(t=0) \sim \frac{|A(s,t)|^2}{s^2} \sim e^{b(s)t}\left(\frac{s}{s_0}\right)^{2(\alpha(t)-1)} \tag{4}$$

where $b(s)$ is a parameters, which can be related to the transverse size of the interaction region similar to optical theorem,

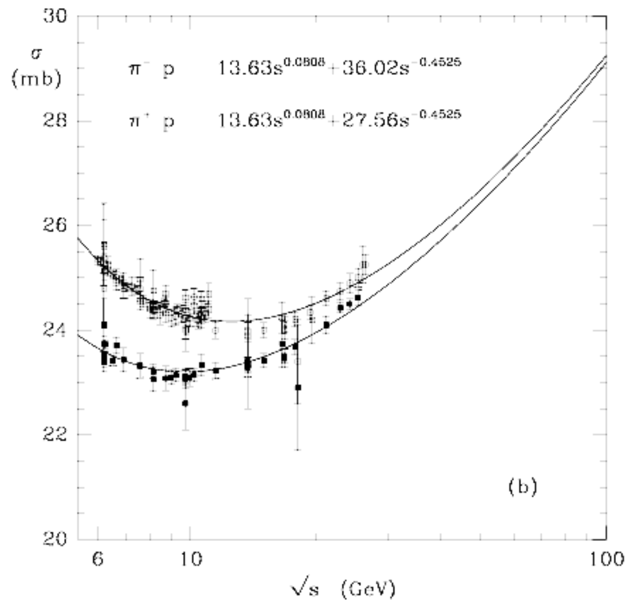
$$\sigma_{AB \quad X} \sim \operatorname{Im} A(AB \quad AB, s, t=0) \tag{5}$$

Hence the energy dependence of the total hadron-hadron cross-sections may be derived within the Regge theory (see Figure 2.3) and gives:

$$\sigma_{tot} \sim s^{\alpha(0)-1} \tag{6}$$



(a)



(b)

Figure 2.3: Total cross section measured in hadronic scattering as a function of centre-of-mass energy for (a) $pp, p\overline{p}$ and (b) $\pi\ \ p$ scattering. The total cross-sections drop at energy s < 10 GeV and increase consistently for higher energy level with the form of $\sigma \quad s^{0.08}$.

A global fit of hadron-hadron collisions was analysed by Donnachie and Lanshoff [7-9] to give the following relation,

$$\sigma_{tot} = Xs^{\alpha_R(0)-1} + Ys^{\alpha_P(0)-1} \quad (7)$$

where the first term corresponds to the exchange of all Reggeons dominating at low energies and the second terms accounts for the exchange Pomeron at high energies. Donnachie and Landshoff also performed fits to the |t| dependence of pp and $p\overline{p}$ cross sections following the parameterization. The result of the fits is given by the following trajectory:

$$\alpha_P(t) = 1.08 + 0.25t \quad (8)$$

where t is given in GeV/c^2, is often referred to as a Soft Pomeron.

2.3.2 Vector Dominance Model (VDM)

In VDM, a photon is a superposition of a QED photon and a hadronic component. This statement supports the appearance of a hadronic structure of the photon which was interpreted through the similarity of the measurement of the total cross section energy dependence in photon-hadron and hadron-hadron collisions. The hadronic component arises due to the quantum fluctuations ruled by the uncertainty principle. In the original VDM, the hadronic component is assumed to be a superposition of light vector mesons (VMs), which are ρ, ω and ϕ particles. In the Generalized VDM (GVDM) [11], when $Q^2 >> M_v^2$ (where M_v is the mass of a particular VMs) the higher mass states are included as well. In some events, the photon fluctuates into VM long before it interacts with the proton. In this case, a hadron-hadron type of interaction occurs between the VM and the proton. The similarity of energy dependence for hadron-hadron and photon-hadron interaction can be observed in Figure 2.4.

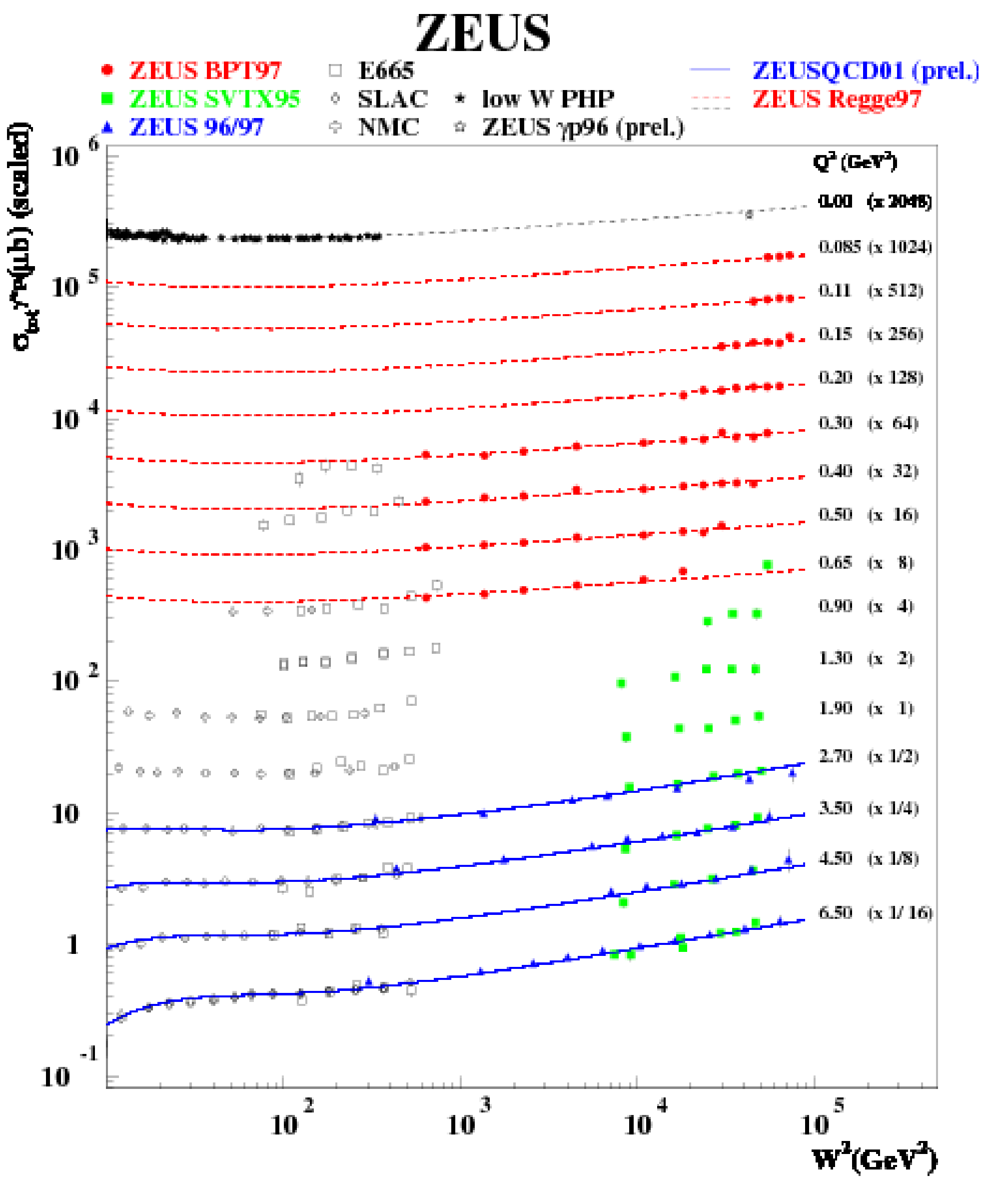


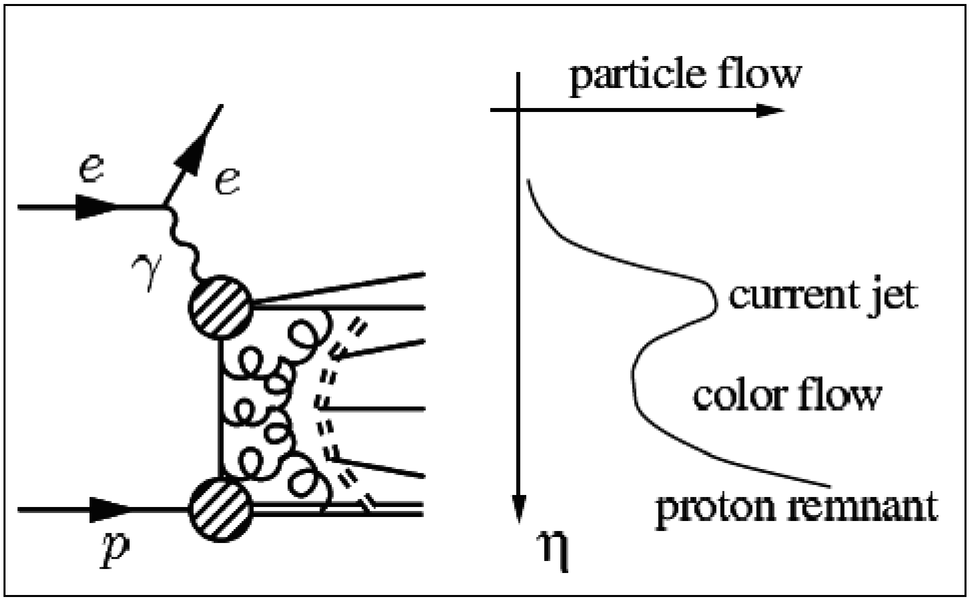
Figure 2.4: The total cross-section of photon-hadron scattering, σ_{tot}, as a function of different W^2 and Q^2.

2.4 Photon-proton collisions

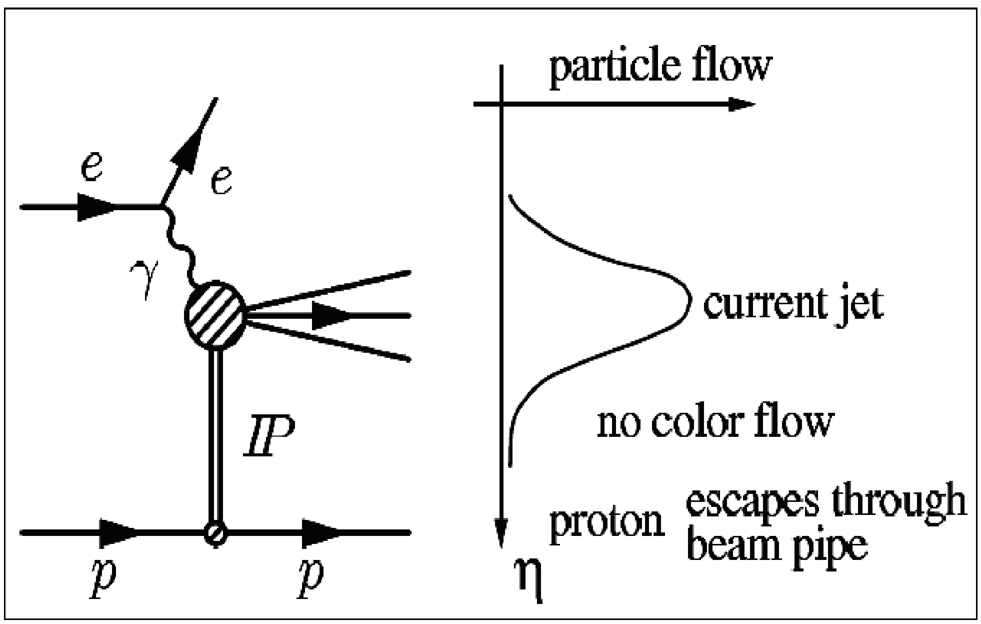
A combination of VDM and Regge phenomenology can be applied to describe the diffractive physics processes at HERA. Photon-proton interaction at HERA can be categorized in four processes;

- Elastic scattering $(\gamma^* p \to Vp)$ - the photon fluctuates into a vector meson, which scatters quasi-elastically off the proton
- Photon dissociation $(\gamma^* p \to Xp)$ - the photon fluctuates into a vector meson, which dissociates into a higher mass state, X, while the proton stay intact
- Proton dissociation $(\gamma^* p \to VY)$ - the photon fluctuates into a vector meson, which remain intact, while the proton dissociates into a higher mass state, Y
- Double dissociation $(\gamma^* p \to XY)$ - the photon fluctuates into a vector meson, which dissociates into a higer mass state, X, and the proton dissociates into a higher mass state, Y.

A typical signature of diffractive events at high energies is a large rapidity gap. The schematic presentation of energy flow for non-diffractive and diffractive events is shown in Figure 2.5 below.



(a) non-diffractive event



(b) diffractive event

Figure 2.5: The schematic presentation of energy flow in non-diffractive and diffractive event with large rapidity gap at HERA.

2.5 Relation between *ep* and $\gamma^* p$ scattering

In the one photon exchange (Born) approximation the electron-proton scattering may be regarded as a scattering of the virtual photon off the proton. The inclusive double differential *ep* cross section may be described in terms of two absorption cross sections, $\sigma_T^{\gamma^* p}$ and $\sigma_L^{\gamma^* p}$, corresponding to the transverse and longitudinal polarisations of the virtual photon:

$$\frac{d^2\sigma^{ep}}{dQ^2 dy} = \Gamma_T \sigma_T^{\gamma^* p} + \Gamma_L \sigma_L^{\gamma^* p} = \Gamma_T (\sigma_T^{\gamma^* p} + \in \sigma_L^{\gamma^* p}), \tag{9}$$

where Γ_L and Γ_L are the longitudinal and transverse photon fluxes [12]:

$$\begin{aligned} \Gamma_L(y, Q^2) &= \frac{\alpha}{2\pi Q^2} \frac{2(1-y)}{y}, \\ \Gamma_T(y, Q^2) &= \frac{\alpha}{2\pi Q^2} \left(\frac{1+(1-y)^2}{y} - \frac{2(1-y)}{y} \frac{Q^2_{\min}}{Q^2} \right) \end{aligned} \tag{10}$$

Where

$$Q^2_{\min} = m_e^2 \frac{y^2}{1-y} \tag{11}$$

is the minimum of Q^2 kinematically allowed and $\in$ is the ratio of the fluxes

(0< $\in$ <1):

$$\in = \frac{\Gamma_L}{\Gamma_T} = \frac{2(1-y)}{1+(1-y)^2} \tag{12}$$

The total $\gamma^{*}p$ cross section:

$$\sigma^{\gamma^{*}p} = \sigma_T^{\gamma^{*}p} + \sigma_L^{\gamma^{*}p} \tag{13}$$

is related to the inclusive *ep* cross section as follows:

$$\frac{d^2\sigma^{ep}}{dQ^2dy} = \Gamma_T\left(\frac{1+\in R}{1+R}\right)\sigma^{\gamma^{*}p}(y,Q^2) \tag{14}$$

where R is the ratio of cross sections for the longitudinally and transversely polarised virtual photons:

$$R = \frac{\sigma_L^{\gamma^{*}p}}{\sigma_T^{\gamma^{*}p}} \tag{15}$$

The proton structure functions are related to $\gamma^{*}p$ cross sections by the following relations:

$$\begin{aligned} F_2(x,Q^2) &= \frac{Q^2}{4\pi^2\alpha}\sigma^{\gamma^{*}p}(x,Q^2), \\ F_L(x,Q^2) &= \frac{Q^2}{4\pi^2\alpha}\sigma_L{}^{\gamma^{*}p}(x,Q^2) \end{aligned} \tag{16}$$

2.6 Exclusive Vector Meson Photoproduction

Photoproduction (PHP) process mainly describe the interaction of photon to proton after the *ep* collision at low energy of Q^2 <1 GeV. At this energy level, the scattered electron, *e'* shall remain undetected in the beampipe of the detector as well as the scattered proton or hadrons. These features are the main signature of PHP events. The illustrated picture of this interaction can be seen in the schematic diagram shown in Figure 2.5. Meanwhile, the word ‘exclusive’ refers to the elastic scattering which means, the interaction between photon and proton does not yield any inclusive processes inside the proton and the photon will fluctuate into a vector meson (VM), which scatters elastically off the proton. This terminology also due to the underlying two-body scattering process $\gamma^{*} p \quad Vp$, in which the proton stays intact and the VM holds the quantum number of the incident γ^{*}. The process area only primarily concurred at the photon-proton vertex which holds a precise number of particle produced. More specific explanations will be given in Chapter 5.

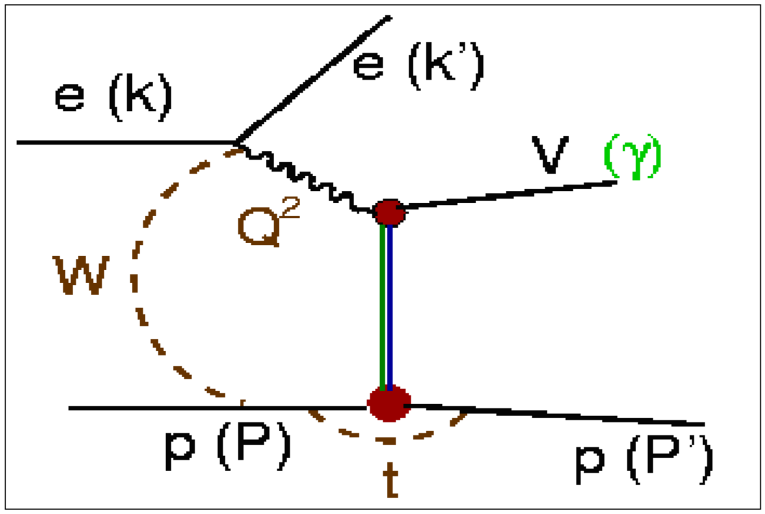


Figure 2.6: Schematic diagram of VM production.

2.7 Acceptance and γp Cross Section

The acceptance (A) and particle cross-section (σ) are the variables used to determine the production rates of the particular search particle and the likelihood of interaction between particles. Calculations and results of this analysis are shown in chapter 5 of this thesis.

2.7.1 Acceptance Calculation on Monte Carlo (MC)

The acceptance or production rate of a particle can be determined based on the ratio of the particle entries in the signal compared to the particle generated number using MC. The number of reconstructed particle N_p, is determined by calculating the particle entries of the signal which usually done by graph fitting procedure. The fitting algorithm will be describe later in analysis part of this thesis.

Acceptance (A) can be obtained from the following relation;

$$A = \frac{N_P}{N_G} \tag{17}$$

Where N_P is the number of particle produced in the signal and N_G is the number of particle generated in events.

2.7.2 γp Cross-Section Calculation

The γp cross-section defines as the ratio of *ep* cross-section over the effective photon flux in the specific value of W and Q^2 measured in the range of W(min:max) and Q^2(min:max).

The calculation can be done using the formula:

$$\sigma(Q^2, W) = \frac{\sigma_{ep}}{\Phi} \tag{18}$$

Where Φ is the effective photon flux and σ_{ep} is the cross section for *ep* interaction.

The σ_{ep} can be obtained by,

$$\sigma^{ep \to \psi(2S)p} = \frac{N_{\psi(2S)}}{ABL} \tag{19}$$

Where *A* is the acceptance, *B* indicates the branching ratio of the decay channel and *L* is the luminosity measured in the experiment.

$$\sigma^{\gamma p \to \psi(2S)\,p} = \frac{\sigma^{ep \to \psi(2S)\,p}}{\Phi} \tag{20}$$

And the effective photon flux, Φ can be calculated using following formula [12];

$$\Phi_{eff}^{\gamma p \to \psi(2S)\,p} = \int \Phi(y, Q^2)\, dy dQ^2 \tag{21}$$

$$\Phi(y, Q^2) = \frac{\alpha}{2\pi Q^2}\left[\frac{1+(1-y)^2}{y} - \frac{2(1-y)}{y}\left(\frac{Q^2_{\min}}{Q^2} - \frac{Q^2}{M^2_{\psi(2S)}}\right)\right]\left(1+\frac{Q^2}{M^2_{\psi(2S)}}\right)^{-2} \tag{22}$$

Where, $y = \frac{W^2}{s}$ and $Q^2_{\min} = M^2_{el}\frac{y^2}{(1-y)}$.

These equations will be implemented in the analysis part of this thesis and the results are shown in chapter 5.