PHYSICS WITH THE VERY HIGH ENERGY e-p COLLIDER

Yoshitaka Kimura and Fumihiko Takasaki
National Laboratory for High Energy Physics, Ōho-machi, Tsukuba-gun, Ibaraki

Yoshimitsu Shimizu and Yoshio Yamaguchi
Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo

ABSTRACT

Physics with an e-p collider of several TeV CM energy is briefly discussed. Unique features of this collider are emphasized.

1. INTRODUCTION

Choosing a specific electron-proton (e-p) collider of

$$\begin{array}{lll} \text{the electron beam energy} & E_e & = 140 \text{ GeV} \\ \text{the proton beam energy} & E_p & = 20 \text{ TeV} \\ \text{the luminosity} & L & = 1\times10^{31} \text{ cm}^{-2}\text{sec}^{-1} \\ \text{the centre of mass energy} & \sqrt{s} & = 3.35 \text{ TeV,} \end{array} \qquad (1.1)$$

we shall discuss physics with this facility. Hereby we like to stick to experimentalists' view point rather than to follow the current theoretical fashion.

Such a facility will allow to study various e-p reactions,

$$e + p \rightarrow e + X \qquad (1.2)$$

$$e + p \rightarrow \nu + X \qquad (1.3)$$

notably,

$$\begin{array}{l} e + p \rightarrow Z^\circ + X \\ e + p \rightarrow W^\pm + X \end{array} \qquad (1.4)$$

and also multi-weak boson production processes.

Feasibility to polarize the electron beams, i.e., ability to produce left- and right-handed electron beams e_L and e_R, will be not only useful but also indispensable for the potentiality in physics of this collider. e_L-p and e_R-p collisions will provide clear-cut information on "right-hand currents", which is one of the very important subjects to go beyond the standard Weinberg-Salam electro-weak theory.

The CM energy $\sqrt{s}$ = 3.35 TeV of our collider is one order of magnitude larger than the Z° threshold. We do not have theories reliably applicable in such high energy regions. Nevertheless, we may guess the total cross-section for all charged-current processes (1.3) to be of the order of

$$\sigma_{tot} = \pi \frac{1}{(M_W)^2}\left(\frac{g^2}{4\pi}\right)^2 \sim 10^{-34}\text{cm}^2 \qquad (1.5)$$

where M_W is the mass of weak charged vector meson, and g is the coupling constant in W-S theory

$$g = e/\sin\theta_W, \tag{1.6}$$

θ_W being the Weinberg angle,

$$g^2/4\pi \simeq 0.031, \ (\sin\theta_W)^2 \simeq 0.23. \tag{1.7}$$

This estimate (1.5) will be valid at

$$s \gtrsim M_W{}^2. \tag{1.8}$$

Under this condition (1.8), single and double W (or Z°) production cross-sections will be of the order of:

$$\begin{aligned} \sigma(e + p \to W + X) &\simeq \frac{g^2}{4\pi}\,\sigma_{tot} \sim 3 \times 10^{-36}\text{cm}^2 \\ \sigma(e + p \to W + W + X) &\simeq \left(\frac{g^2}{4\pi}\right)^2\sigma_{tot} \sim 10^{-37}\text{cm}^2 \end{aligned} \tag{1.9}$$

where σ_{tot} is given in (1.5). It is needless to stress that all possible efforts should be focused to increase the luminosity so as to be able to detect such rare processes.

We can also try to take a more conservative approach. To this end we have computed the inclusive cross-sections for the processes (1.2) and (1.3) based upon

single boson (γ, W, and Z) exchange mechanisms
quark/parton model
and QCD-corrections.

The numerical results of such calculations are summarized in the Appendix.

Discussions and comments on e-p experimental physics will briefly be sketched in below. The experiment, Stage I, is described in §2 and more refined experiments, Stage II, will be discussed in §3 and §4.

2. EXPERIMENT: Stage I

The simplest experiment to be done by the e-p collider at the earliest stage is naturally general scan of deep inelastic scatterings

$$e + p \to e + X \tag{2.1}$$

by observing only the final electron energy E_e' and its angle θ with respect to the incident electron direction. This classical experiment will provide us information on the structure functions of the proton.

It is interesting to see whether the structure functions will be consistent with "smooth extrapolation" (see Fig. A1 in the Appendix) or not. We expect, of course, it will not be the case and hope to find out something new, e.g.,

structures of quarks and/or electron,
new particles (new leptons and new flavours)

and so on.

As was emphasized in §1, the use of the polarized electron beams will allow to extract information on "right-hand currents" and new bosons coupled thereto.

Finally, the inclusive reactions

$$e + p \to \nu + X \qquad (2.2)$$

may be studied if total energy and momentum of X can be estimated in some ways. It is interesting to compare both structure functions of protons derived from (2.1) and (2.2).

3. EXPERIMENTS: Stage II

More refined experimental set-ups than that described in §2 will include wide-angle general detectors among others. Electro-magnetic shower counters, muon-identifiers, hadron-calorimeters (to measure axes and energy flows of hadronic jets) are necessary components of detector systems. Particle identification systems would be desirable to have though technologically difficult. Detectors will be arranged as double-arm or triple-arm (or "all solid angle") systems.

Specific detectors for each particular process must be designed optimally, see below.

3.1 PROTON AND CURRENT FRAGMENTATIONS

We expect that e-p collisions at multi-TeV range consist of dominantly two fragmentations:

$$e + p \to e(\text{or } \nu) + X(\text{current fragmentation}) + Y(\text{proton fragmentation}). \quad (3.1)$$

When any fragment has a large invariant mass, current or proton fragmentation itself would exhibit multi-jet structure as clearly seen in PETRA data.

Relevant kinematics for this process (3.1) has been described in the article by R. Turlay et al[1]) in these proceedings.

A glance at a few values of hadron emission angle θ_h with respect to the incident proton beam direction:

p_T	$p_{\|\|}$	$\theta_h = p_T/p_{\|\|}$
0.5 GeV/c	1 TeV/c	5×10^{-4}
1 GeV/c	10 TeV/c	1×10^{-4}
0.1 TeV	10 TeV	10^{-2}

will immediately tell us: to investigate the proton jet we need to have very fine angular resolution at quite near the incident proton direction. Considering multi-jet structure of proton fragmentation as well as anything unexpected, we may set-up detectors for proton-fragmentation to cover a few degrees.

It may be worth considering the scheme with finite e-p crossing angle to facilitate analyses of proton fragmentation.

On the other hand, current fragmentation will distribute over wider angular range, from forward to side-wise.

It will suffice to determine "axis" and "energy flow" of an individual jet in detecting fragmentations (likely to be multi-jets).

A possible experimental set-up is described by R. Turlay et al$^{1)}$ in these proceedings.

Separation between proton and current fragmentations will be the larger for the larger CM energy. The larger electron beam energy (say 350 GeV rather than 140 GeV) may be preferable for designing detectors.

3.2 LARGE p_T PHENOMENA

By the time of realization of this e-p collider, large p_T events with respect to jet axes will be understandable. Interesting "large" p_T at that time will be of the order of $p_T = 0.1 \sim 1$ TeV/c. Such high p_T will be carried either by single particles or by hadron-clusters (jets).

Such large p_T objects are related to short-distance behaviour of strong interactions or consist of decay products of very massive "particles", in either case very interesting to study.

Importance to detect large p_T leptons rather than hadrons need not be stressed.

3.3 SEARCH OF NEW PARTICLES

Some of relevant discussions to search new massive particles has already been given. Nevertheless, it would be very important to design experiments for new particle search.

For example, detection of

$$\text{massive}\begin{cases} e^-e^+ \text{ pair} \\ \mu^-\mu^+ \\ \gamma\gamma \quad \text{pair} \\ \text{etc.} \\ \text{hadron pairs or jet pairs} \end{cases}$$

will be quite powerful to establish very massive particles and their natures (see the excellent contribution by B. Barish et al.[2]).
Based upon knowledge available, we can design relevant detector systems to detect specific processes such as

$$e + p \rightarrow \begin{cases} W^\pm + X \\ W^\pm + W^\pm + X, \\ Z^\circ + W + X \\ H \ + X \\ H + H' + X \end{cases} \tag{3.2}$$

where H and H' are massive particles, say Higgs' bosons.

3.4 SOMETHING NEW

Any interesting new discoveries by experiments described above should be pursued further with more refined detector systems.

The W-S theory predicts definite pattern of C- and P-violations. Any deviation from such theoretical expectations are worth while to search

Moreover we may try to investigate more fundamental questions, e.g. CP violation, lepton or baryon number non-conservations. Even though we are aware of difficulties in performing such tests, it is very interesting to see (or to set upper bound) how much the rates, e.g.

$$\begin{aligned} &e^- + p \rightarrow \mu^\mp + p \text{ (or } \mu^\mp \text{ hadrons)} \\ &e^\pm + e^\mp \rightarrow \mu^\pm + e^\mp \end{aligned} \tag{3.3}$$

are. Of course the low energy data on

$$\begin{aligned} &\mu^- + (\text{Nucleus}) \rightarrow e^- + (\text{Nucleus}) \\ &\mu^- + (\text{Nucleus}) \rightarrow e^+ + (\text{Nucleus}) \\ &\mu \rightarrow e + \gamma \\ &\mu^\pm \rightarrow e^\pm + e^\pm \pm e^\mp \end{aligned} \tag{3.4}$$

will give us some informations[3] on (3.3). But large "extrapolation" into "entirely unknown" very large energy regions may not be reliable, making experiments of the type (3.3) worth to try (even with negative results !).

4. TAGGED PHOTON EXPERIMENTS

The electron tagging system will allow the photo-reaction studies

$$\gamma + p \to \text{hadron} + X. \qquad (4.1)$$

Using the 140 GeV e - 20 TeV p collider, one can achieve the CM energies much higher than the photon beam obtained by 20 TeV proton machine bombarded on stationary targets. Also notice that the tagging technique can supply polarized photons from an unpolarized electron beam, thus increasing potential richness in photon physics.

5. IMPORTANCE OF THE VERY HIGH ENERGY e-p COLLIDER

We have discussed in the preceding sections several experiments to be done with the e-p collider. We shall now compare the use of this e-p collider with other facilities demonstrating uniqueness of the e-p collider.

The e-p collider can reach the CM energy of multi-TeV range under the feasible technology. Whereas the e^+-e^- colliders of such high energies would be extremely difficult if not impossible. Experimental studies going beyond the W-S theory would require the CM energies far much larger than several 100 GeV. Hence the e-p colliders of multi-TeV range should be indispensable in this respect.

The 20 TeV proton accelerator, which feeds the proton beam to our e-p collider, will supply electron, muon, neutrino and photon beams of 5 $\sim$ 15 TeV (preparation of purified electron and photon beams may be difficult tasks). Such beams bombarded on stationary targets will have CM energies and q^2 ranges far much smaller than those available by the 140 GeV e - 20 TeV p collider. This provides another argument in favour of the e-p collider.

Thirdly, polarized e-p collider will be the most unique facility which can only be used successfully to check existence of "right-hand currents".

Finally, we repeat that all kind of valuable information are very likely "hidden" in rare processes and improvement of the luminosity must be really rewarding.

* * *

REFERENCES

1) R. Turlay et al., in these proceedings.
2) B. Barish et al., in these proceedings.
3) K. Teshima and Y. Yamaguchi, to be published.

Appendix

This appendix contains definitions of kinematical variables and estimations of various cross-sections due to one boson exchange (photon, Z and $W^{\pm}$) for the proposed e-p collider. Here, we restrict ourselves to the deep inelastic scatterings. This may seem to be meaningless because, as stressed in the text, we expect W- and Z-boson productions in the present energy region. Nevertheless we believe that these estimations play the role of reference to further investigations. The reactions we consider are

$$e_L^- + p \to e^- + X\ ,\quad e_L^- + p \to \nu_e + X\ ,\quad e_R^- + p \to e^- + X \quad \text{and} \quad e_R^- + p \to \nu_e + X$$

(the unpolarized proton beam is assumed).

The design values of beam energies and luminosity are given by

$$E_e = 140\ \text{GeV},\ E_p = 20\ \text{TeV} \quad \text{and} \quad L = 10^{31}\ \text{cm}^{-2}\text{sec}^{-1}\ , \tag{A.1}$$

respectively. The system has the total energy

$$E_{cm} = 3.35\ \text{TeV}, \tag{A.2}$$

$$s = E_{cm}^2 = 1.12 \times 10^7\ \text{GeV}^2\ .$$

In the deep inelastic scattering experiments, we observe the outgoing lepton (electron or neutrino) with the energy E'_ℓ at the angle θ with respect to the incoming electron. As usual we introduce the following kinematical variables:

$$Q^2 = 4E_eE'_\ell \sin^2\frac{\theta}{2} = sxy.$$

$$= \frac{2E_p}{M_p}(E_e - E'_\ell \cos^2\frac{\theta}{2})$$

$$= sy/2M_p \tag{A.3}$$

where M_p is the proton mass and

$$E'_\ell = E_e(1-y) + E_pxy.$$

In Fig. A1 we show the distribution functions of various quarks in the proton by putting $u = u_v + \xi$, $d = d_v + \xi$

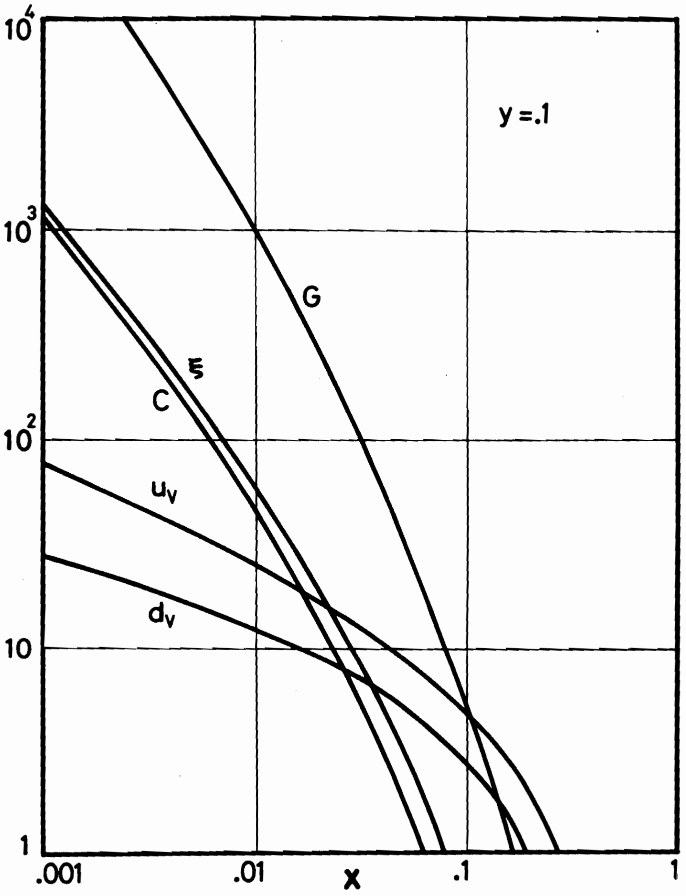

Fig. A1 Distribution function vs. x

where v refers to "valence" and ξ to "sea", $\xi = \bar{u} = \bar{d} = s = \bar{s}$, $c = \bar{c}$, and gluon, G. The distribution functions at $Q^2 = 7.86\ (\mathrm{GeV}/c)^2$, given in Ref. A1, were taken as our standards and the QCD corrections thereof at higher Q^2 were calculated by the method of Ref. A2.

Fig. A2 shows the event rate per day ($L\, d^2\sigma/dxdy$) × (8.64×10^4 sec) for the reaction

$$e^-_L + p \rightarrow e^- + X$$

in the standard $SU(2)_L \times U(1)$ model with $\sin^2\theta_W = 0.23$ (Ref. A3). For future convenience we give the relations between Δx, Δy and $\Delta E'_\ell$, $\Delta\theta$

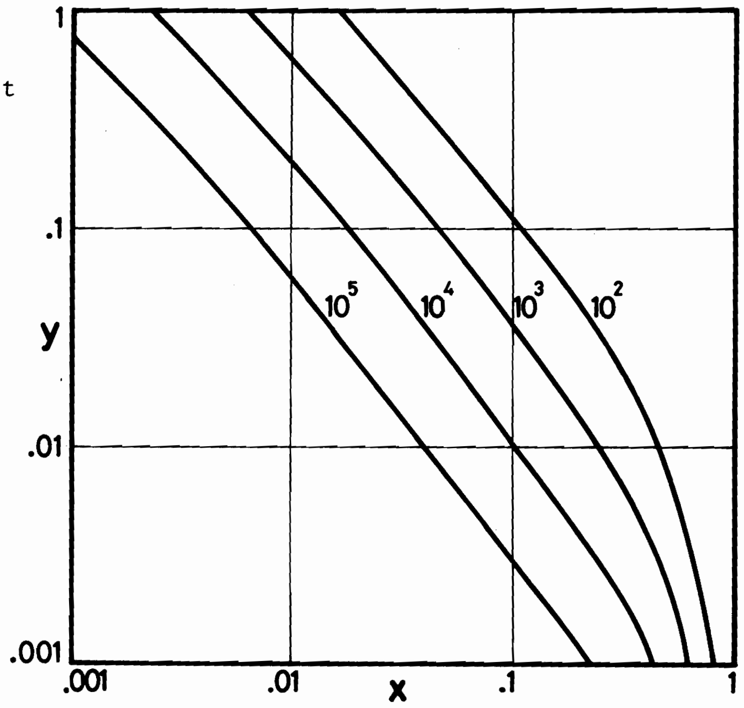

Fig. A2 Yield (ev/day/dxdy) vs. x, y

$$\frac{\Delta x}{x} = \frac{1}{y}\left(\frac{\Delta E'_\ell}{E'_\ell}\right) + \frac{|1 - E_p x/E_e|}{\tan(\theta/2)} \cdot \Delta\theta$$

$$\frac{\Delta y}{y} = \frac{1-y}{y}\left(\frac{\Delta E'_\ell}{E'_\ell} + \tan\frac{\theta}{2} \cdot \Delta\theta\right) \quad (A.4)$$

In Fig. A3 we depict the case for $\Delta\theta = 10^{-3}$ rad and $\Delta E'_\ell/E'_\ell = 7 \times 10^{-2}/\sqrt{E'_\ell(\mathrm{GeV})}$. From Figs. A2 and A3 one can easily estimate the relevant event rates.

For small values of y (y=0.1 and 0.25) we show the x-dependence of the cross-sections for $e^-_L + p \rightarrow e^- + X$ and $e^-_L + p \rightarrow \nu_e + X$ in Fig. A4.

The asymmetries between the reactions

$$e^-_L + p \rightarrow e^- + X$$
$$e^-_R + p \rightarrow e^- + X$$

in the standard W-S theory are shown in Fig. A5 (solid line). The asymmetry for the neutral current processes is due to Z-boson exchange, since it vanishes

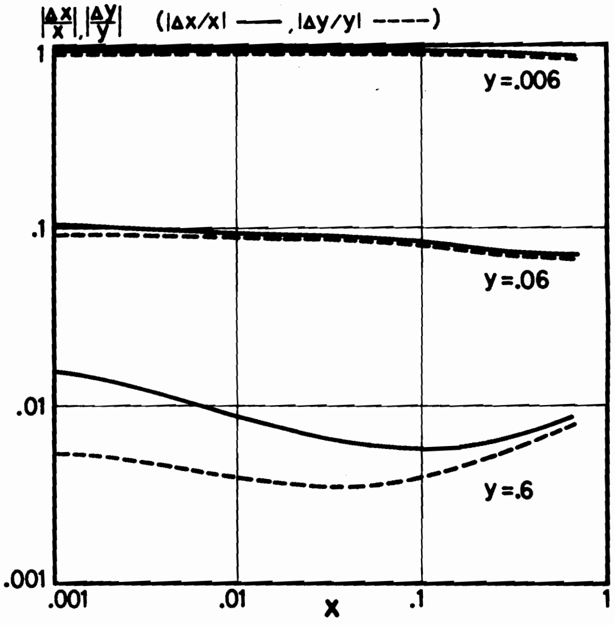

Fig. A3

for single photon exchange only.

Moreover if "right hand currents" exist in nature, the asymmetry for charged currents reactions

$$e^-_L + p \rightarrow \nu_e + X$$

$$e^-_R + p \rightarrow \nu_e + X$$

can be expected. As an example, we choose the model (Ref. A4) of $SU(2)_L \times SU(2)_R \times U(1)$ and the result is shown by the dotted line in Fig. A5. Here, we have adopted the mass value squared

$$M^2_{W_R} = 5 \times 10^4 \text{ GeV}^2$$

of charged boson coupled to the right-hand currents through the relation (θ: mixing angle)

$$M^2_{W_R} \simeq M^2_X \frac{1 - 2\sin^2\theta}{\cos^2\theta}$$

where M_X denotes the mass of the second massive neutral vector boson which is assumed to be $M_X \simeq 3M_Z$ and $\sin\theta$ plays the same role as $\sin\theta_W$ so that the value $\sin^2\theta = 0.23$ is chosen.

* * *

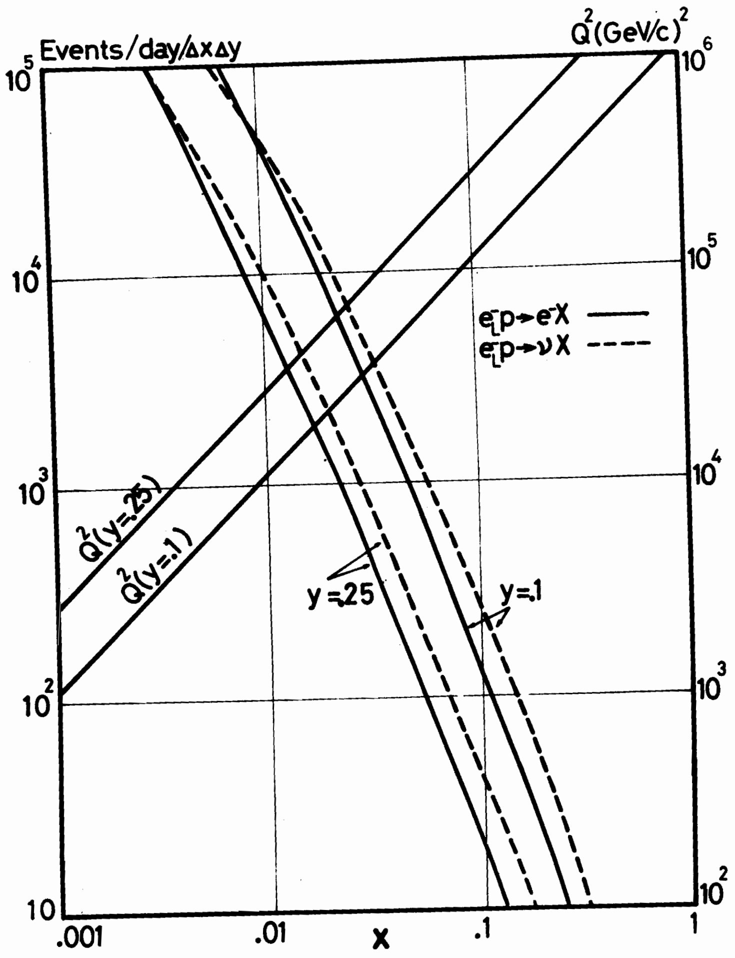

Fig. A4

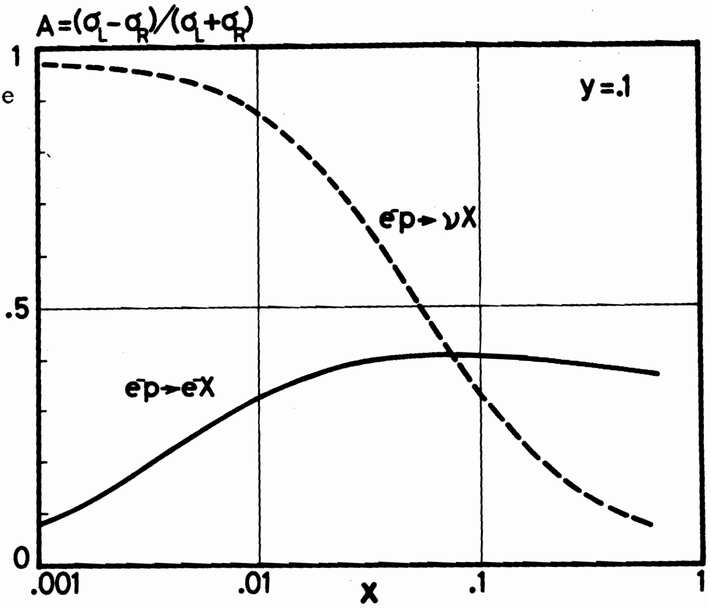

Fig. A5

REFERENCES

A1 A.J.Buras and K.J.N.Gaemers, Nucl. Phys. B132, 1249 (1978).

A2 K. Kato et al., University of Tokyo preprint UT-327 (1979) and K. Kato, Thesis, University of Tokyo.

A3 S. Weinberg, Phys. Rev. Letters 19, 1264 (1967).
A. Salam, in Elementary Particle Theory edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

A4 S. Weinberg, Phys. Rev. Letters 29, 388 (1972).
H. Fritzsch and P. Minkowski, Nucl. Phys. B103, 61 (1976).