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Weak Boson Effects in Charged Current Neutrino and Antineutrino Interactions at Very High (DUMAND) Energies

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ABSTRACT

We have calculated the charged current neutrino and antineutrino total cross sections and y-distributions at very high energies (1-100 TeV) using the standard quark-parton model. A range of W boson masses was considered which includes the value in the Weinberg-Salam model. The parametrization of the quark structure functions was chosen to fit the highest energy data available (100-200 GeV) so that scaling violations could be neglected. The W boson propagator causes the total cross sections to turn over and enhances the y-distributions at small y for high energies. It was shown that the presence of an admixture of antineutrinos in the flux as large as 25% does not mask the effect of the W boson propagator on the neutrino cross section or on the neutrino y-distribution. The expected flux spectrum of atmospheric neutrinos was folded in and counting rates per bin over a range of intervals in E_ν and y were computed for a 1 km^3 (10^9 ton) DUMAND array. It was also found that a 25% admixture of antineutrinos in the flux did not appreciably affect these counting rates.

I. INTRODUCTION

Weak interactions are presumably mediated by vector bosons which, because of their large mass, have not been observed at present laboratory energies. Several effects, in addition to their actual production, are expected to appear at higher energies. Here we shall consider the effects of the charged intermediate vector boson ($W^{\pm}$) propagator on charged current neutrino and antineutrino interactions above about 1 TeV. Specifically, the effects on the y-distributions and the total cross sections have been calculated in the framework of the quark-parton model. The y-distributions show considerable peaking at small y and the total cross sections turn over with increasing energy as has been shown previously.[1] In physical terms, the interaction is simply becoming more peripheral as the energy increases. If the W mass is not too high ($M_W \lesssim 100$ GeV/c^2) significant effects begin to show up at neutrino energies $E_\nu \gtrsim 1$ TeV and therefore can be studied in the DUMAND array.

In the following we shall show that:

(i) Potential complications in the analysis of the W boson propagator effects arising from scaling violations in the quark-parton structure functions as predicted by QCD can be avoided.

(ii) A 25% admixture of antineutrinos, which give a y-distribution which is already peaked at small y for low energies, will not mask the effect of a W boson propagator.

(iii) The counting rates in a 10^9 ton DUMAND array for the expected flux of atmospheric neutrinos are quite ample for the effects of a W propagator to be statistically significant if $M_W \lesssim 100$ GeV/c^2.

II. WEAK BOSON PROPAGATOR EFFECTS

The inelastic charged current neutrino scattering process $\nu_\mu + N \rightarrow \mu^- + X$ is shown in Figure 1.

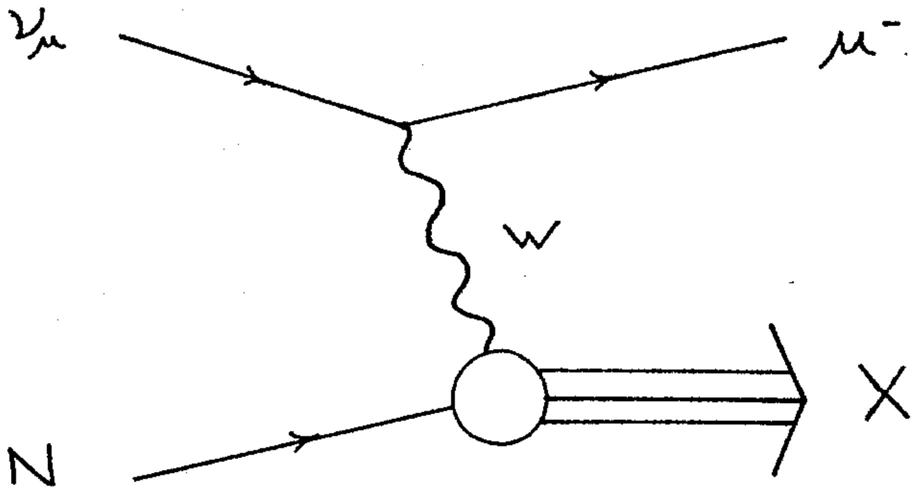

Fig. 1 Neutrino Scattering.

In the standard quark-parton picture the differential cross section is

$$\frac{d\sigma_\nu}{dxdy} = \frac{\beta^2}{(\beta + xy)^2} \frac{G^2 M_N E_\nu}{\pi} \left[q(x) + \bar{q}(x)(1 - y)^2 \right] \tag{2.1}$$

where

$$\beta = M_W{}^2/2M_N E_\nu \tag{2.2}$$

$$y = (E_\nu - E_\mu)/E_\nu \tag{2.3}$$

and

$$xy = Q^2/2M_N E_\nu \quad . \tag{2.4}$$

The factor $[\beta/(\beta + xy)]^2$ represents the effect of the W propagator and clearly is important at very high neutrino energies. The quark and antiquark structure functions $q(x)$ and $\bar{q}(x)$ do, in fact, depend also on Q^2 due to scale breaking. However, at high energies this Q^2 dependence becomes small[2] (unless x is near zero) and therefore can be neglected in the region of interest to us. We can therefore avoid the complications arising from scale breaking by using the structure functions determined by Wang from the highest energy data available (100-200 GeV):[1]

$$q(x) = \bar{q}(x) + [\, 1.79(1-x)^3(1+2.3x) + 1.07(1-x)^{3.1}\,]\; x^{1/2} \tag{2.5}$$

$$\bar{q}(x) = 0.3\,(1-x)^7 \quad . \tag{2.6}$$

The cross section for antineutrino scattering ($\bar{\nu}_\mu + N \rightarrow \mu^+ + X$) is obtained from Eq. (2.1) by interchanging $q(x)$ and $\bar{q}(x)$.

The total cross sections σ_ν and $\sigma_{\bar{\nu}}$ for neutrino and antineutrino scattering have been computed numerically for $M_W = \infty$, 80 and 50 GeV/c^2 and are shown in Figures 2 and 3, respectively. At low energies σ_ν and $\sigma_{\bar{\nu}}$ rise approximately linearly with energy but turn over and asymptotically increase only as log E (not $\log^2 E$). Clearly the effects of the W propagator begin to be important above 1 TeV unless M_W is much larger than the currently popular expectations of about 80 GeV/c^2. (In the Weinberg-Salam model $M_W = 84$ GeV/c^2 if $\sin^2\theta_W = 0.2$.)

The y-distributions for both neutrino and antineutrino scattering are quite sensitively affected by the W propagator. To illustrate this point we have

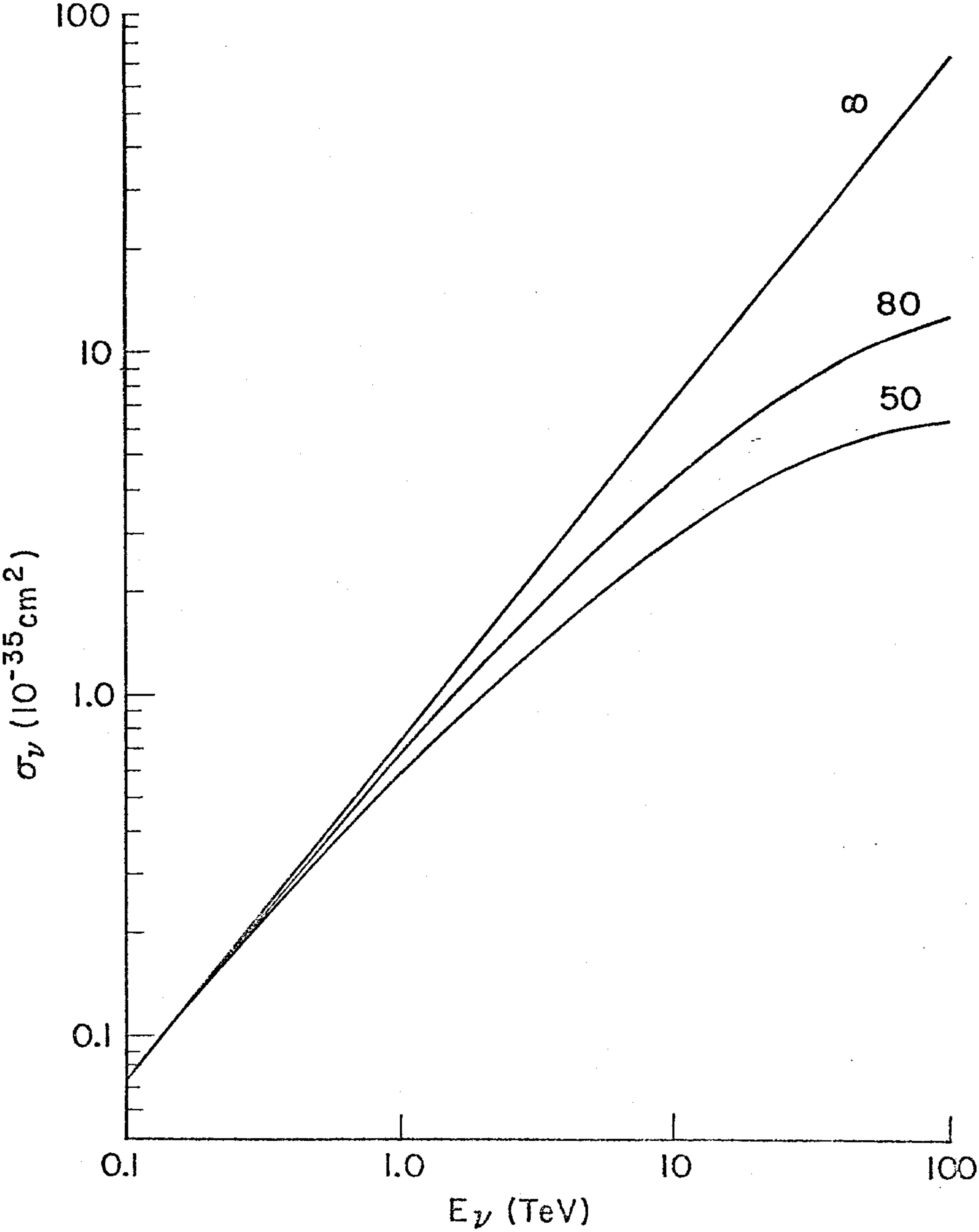

Fig. 2. Neutrino total cross section as a function of energy for $M_W = \infty$, 80 and 50 GeV/c^2.

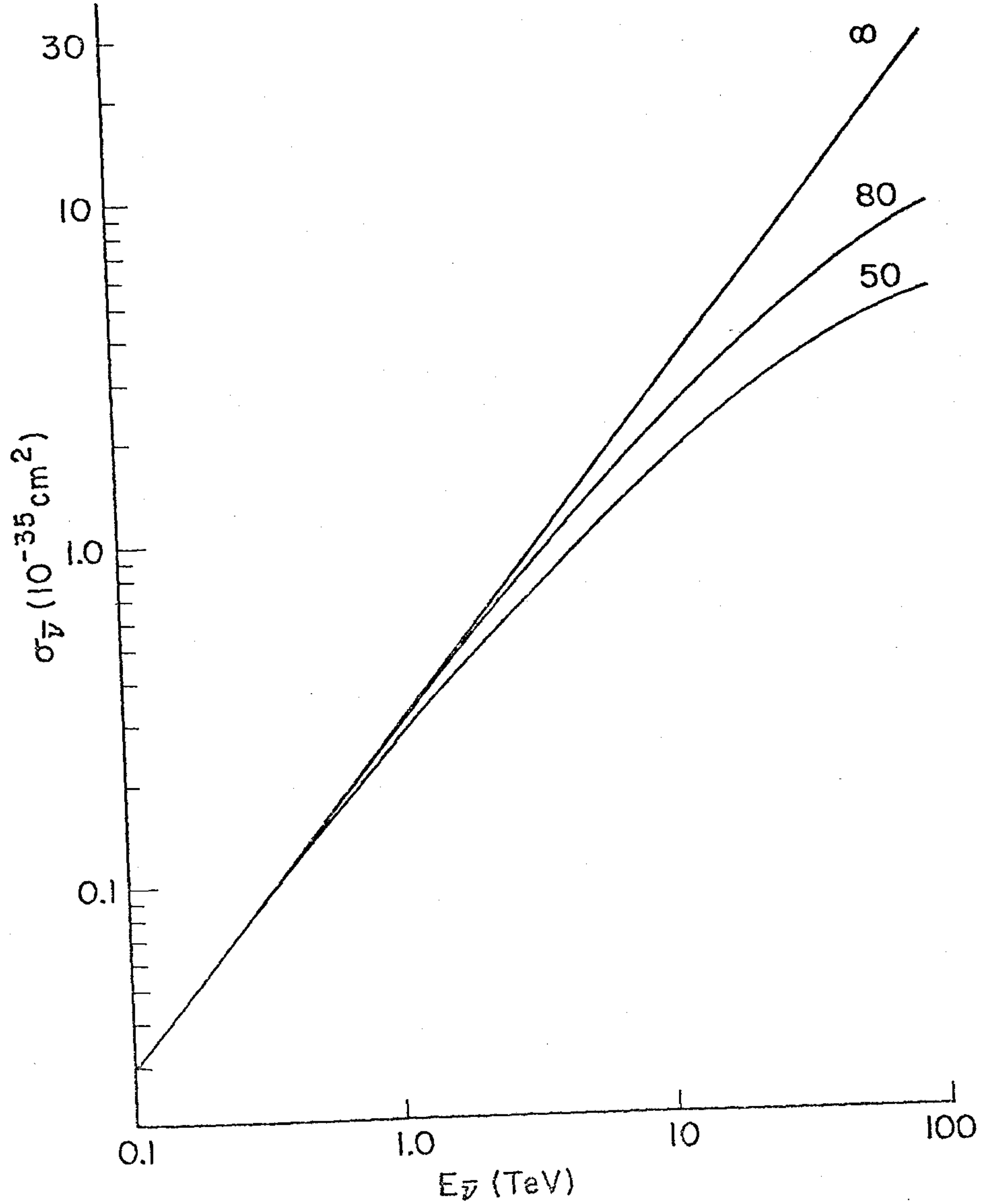

Fig. 3. Antineutrino total cross section as a function of energy for $M_W = \infty$, 80 and 50 GeV/c^2.

numerically computed $d\sigma_\nu/dy$ and $d\sigma_{\bar{\nu}}/dy$ for $E = 10$ TeV and $M_W = 80$ GeV/c^2 and the results are shown in Figure 4. Both y-distributions are markedly peaked at small y relative to their respective shapes at low energies (roughly flat for neutrinos and $(1 - y)^2$ for antineutrinos), particularly the neutrino distribution. This is what one would expect since the interaction is becoming more peripheral at high energies and a smaller fraction of the neutrino energy is being transferred to the hadrons.

Also plotted in Figure 4 is $0.75\ d\sigma_\nu/dy + 0.25\ d\sigma_{\bar{\nu}}/dy$ to illustrate the point that a 25% admixture of antineutrinos, which is a reasonable estimate for DUMAND, in the neutrino flux will not obscure the peaking in the y-distribution due to the W propagator. That is, peaking in the y-distribution caused by the 25% admixture of antineutrinos is quite small ($\sim$ 20%) compared to the peaking arising from the W propagator. Therefore, even though one cannot determine the sign of the muon produced in DUMAND, a rather large admixture of antineutrinos in the neutrino flux will not mask the W propagator effect in the y-distribution. In the next section we shall show rather clearly that this conclusion remains valid when the flux spectrum[3] is folded in and counting rates are calculated.

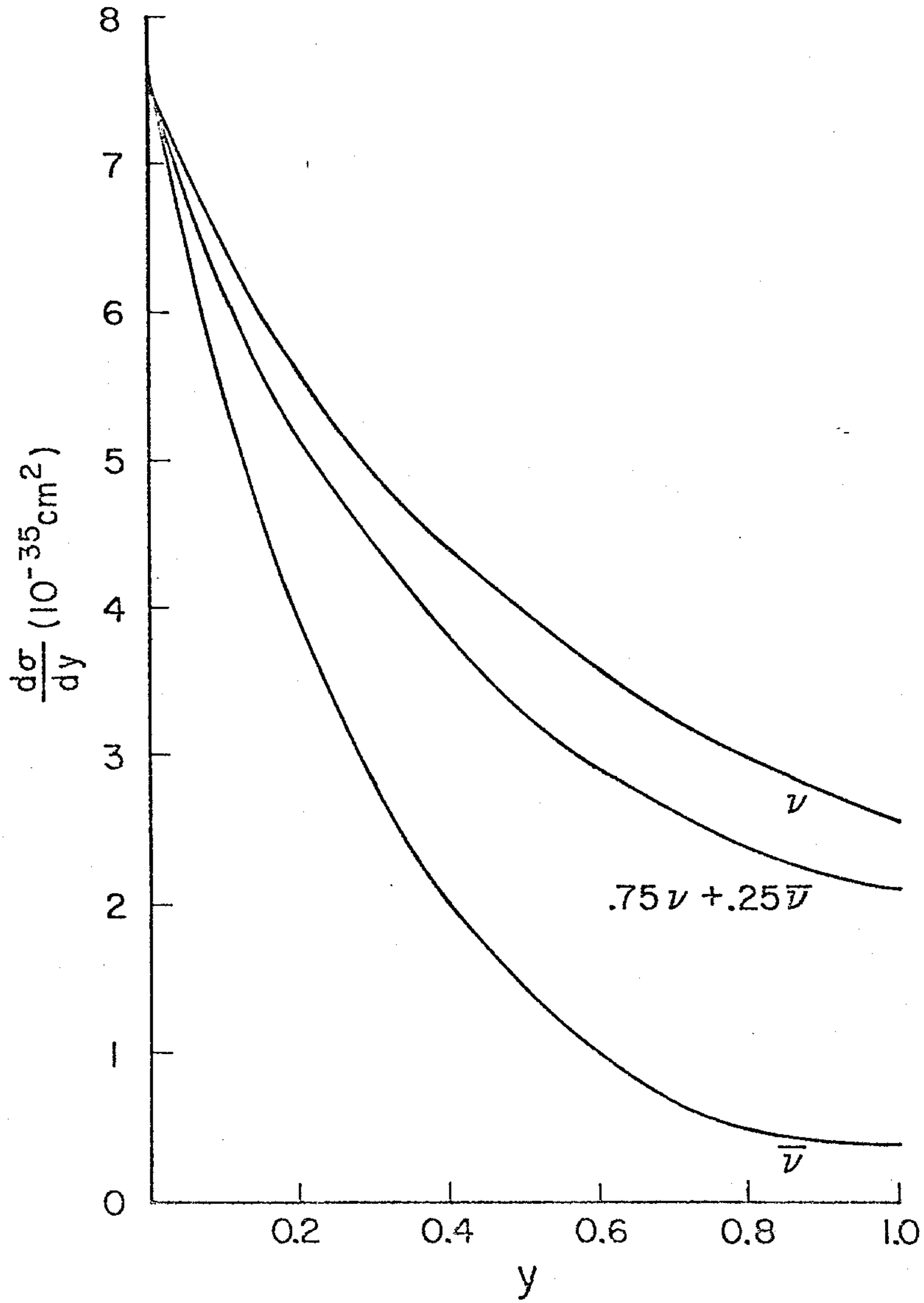

Fig. 4. Effective $d\sigma/dy$ for E = 10 TeV and M_W = 80 GeV/c^2 assuming the incident flux is 100% ν, 75% ν + 25% $\bar{\nu}$ and 100% $\bar{\nu}$.

III. DUMAND COUNTING RATES

To estimate the charged current event rates in a 1 km^3 (10^9 ton) DUMAND array we shall use the atmospheric neutrino flux spectrum [3]

$$\phi_\nu(E_\nu) = 13 \times 10^3 (E_\nu)^{-2.8} \sec^{-2} km^{-2} TeV^{-1} \tag{3.1}$$

We shall further assume that any antineutrino admixture in flux has the same energy dependence.

For this neutrino flux and the neutrino cross section given above (Eq. 2.1) we have numerically computed the expected number of events/year in a 10^9 ton array over a range of bins in the energy E and the scaling variable y. The results are given in Tables 1, 2 and 3 for W boson masses $M_W = \infty$, 80 and 50 GeV/c^2, respectively. In each case we have also indicated in the Tables the corresponding event rates if the flux, Eq. (3.1), is composed of 75% neutrinos and 25% antineutrinos. It is clear that, as noted above, the effects of this admixture are rather small ($\sim$20%) in any given bin independent of M_W.

Table 1 shows the event rates if there is no W ($M_W = \infty$). Comparing Table 2 (M_W = 80 GeV/c^2) and Table 3 (M_W = 50 GeV/c^2) with Table 1 the peaking in the y-distribution of events as the energy increases is quite evident. And it is not obscured by a 25% admixture of antineutrinos in the flux.

Finally, the Tables show that the event rates are high enough for the W boson effects to be statistically significant if the W mass is not too large ($M_W \lesssim 100$ GeV/c^2).

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E (TeV) \ y	0.0-0.25	0.25-0.50	0.50-0.75	0.75-1.00
2 - 4	5074 (4825)	4923 (4265)	4822 (3891)	4771 (3704)
4 - 8	1457 (1386)	1414 (1225)	1385 (1117)	1370 (1064)
8 - 16	419 (398)	406 (352)	398 (321)	394 (306)
16 - 32	120 (114)	117 (101)	114 (92)	113 (88)
32 - 64	35 (33)	34 (29)	33 (27)	33 (25)

Table 1: Charged current events/year assuming $M_W = \infty$ GeV/c^2 and a pure neutrino flux. Numbers in parentheses assume an antineutrino admixture of 25% in the flux.

E (TeV) \ y	0.0-0.25	0.25-0.50	0.50-0.75	0.75-1.00
2 - 4	4820 (4588)	4235 (3678)	3787 (3069)	3448 (2693)
4 - 8	1321 (1259)	1071 (932)	900 (732)	780 (612)
8 - 16	349 (333)	250 (218)	193 (158)	157 (124)
16 - 32	88 (84)	52 (46)	37 (30)	28 (23)
32 - 64	20 (20)	10 (9)	6 (5)	5 (4)

Table 2: Charged current events/year assuming $M_W = 80\ GeV/c^2$ and a pure neutrino flux. Numbers in parentheses assume an antineutrino admixture of 25% in the flux.

E (TeV) \ y	0.0-0.25	0.25-0.50	0.50-0.75	0.75-1.00
2 - 4	4488 (4279)	3500 (3049)	2861 (2330)	2427 (1908)
4 - 8	1166 (1114)	787 (689)	588 (482)	469 (372)
8 - 16	286 (274)	159 (139)	107 (89)	81 (65)
16 - 32	65 (63)	28 (25)	18 (15)	13 (10)
32 - 64	14 (13)	5 (4)	3 (2)	2 (2)

Table 3: Charged current events/year assuming $M_W = 50\ \mathrm{GeV}/c^2$ and a pure neutrino flux. Numbers in parentheses assume an antineutrino admixture of 25% in the flux.

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