W SEARCHES WITH HIGH-ENERGY NEUTRINOS AND HIGH-Z DETECTORS

A. K. Mann
University of Pennsylvania

ABSTRACT

The feasibility of W searches with high-energy neutrinos incident on high-Z material and spark-chamber detection of the final-state particles is assessed. It appears from consideration of W production and detection rates, event recognition and possible backgrounds that a realistic W search in an interesting region of W mass can be made at NAL with that experimental technique.

In part as a result of the work of the NAL 1968 Summer Study several detailed calculations have become available which make it possible to consider quantitatively W-search experiments using incident ν's and high-Z spark chambers. In particular, calculations of the cross section σ_W for the reaction $\nu + Z \rightarrow \mu^- + W^+ + Z$ as a function of neutrino energy by A. C. T. Wu,[1] and calculation of the ν flux for various drift spaces and shield options by Nezrick[2] now permit alternative ν-beam designs to be treated quickly.

In this note we use that information as well as other results of the 1968 Summer Study to evaluate the feasibility of W searches with high-energy ν's incident on high-Z material and spark-chamber detection of the final-state particles. This technique has certain recognized disadvantages at the low ν energies of BNL and CERN; the expected counting rate for W's of mass between 1 and 2 GeV/c^2 is very low and the unambiguous recognition of W production and decay against the very large background of ν-induced inelastic events is quite difficult. We assess here the extent to which those disadvantages are also present at higher ν energies and consider the consequences of certain simplistic assumptions concerning experimental cross sections and design parameters.

I. NEUTRINO FLUX

There are two essential features that largely determine the neutrino beam design in W-search experiments: (1) Even though the threshold energy for W production on high-Z material is relatively low, the effect of the nuclear form factor on σ_W (reflecting the large minimum momentum transfer) necessitates high ν energies, typically

$E_\nu \geq 30$ GeV for $M_W \sim 5$ GeV/c^2. (2) In part as a consequence of (1), and in part because of the weak dependence of the integrated ν-flux distributions on the π, K drift space and shield length (see Fig. 3 of Ref. 2), the exact nature of the focusing technique, the drift space and the muon shield are not the determining factors in the design of an experiment to search for $M_W \lesssim 6$ GeV/c^2. The rapid decrease of σ_W with M_W and the rapid falloff of the neutrino spectrum with E_ν will require an optimized ν beam design to search for $M_W \gtrsim 6$ GeV/c^2.

There are several neutrino beam designs that have been thought of in connection with W searches. The two leading designs involve secondary charged particle focusing with either (a) a magnetic horn[2] or (b) standard magnetic quadrupole magnets.[3] It is worth noting, however, that the bulk of the ν spectrum above 30 GeV is apparently the product of kaon decays (see Fig. 24 of Ref. 2) and that completely unfocused kaons will give rise to a neutrino beam of half-angle $\theta_\nu \sim 1/(\beta\gamma)_p \sim 1/200$. For a total length of 10^3 meters between the kaon source and the neutrino detector, the radius of the ν distribution at the detector will be less than 5 m. Hence the requirements placed on the focusing system are not severe unless the last factor of two in neutrino intensity is demanded. From Fig. 19 of Ref. 2 we find that the yield of neutrinos from kaons with E_ν between 30 and 70 GeV and magnetic horn focusing is about 3.5 times the yield with no focusing at all.

In this note we use Nezrick's calculations for a real horn focusing system (Fig. 24) divided by a factor of 2 to approximate the ν yield for any quadrupole focusing arrangement. This yields--for a 600 m drift space and a 300 m shield (independent of the shield constitution)--

$$\frac{1}{2}\int_{25}^{105} \frac{dI_\nu(E_\nu)}{dE_\nu}\, dE_\nu \approx 19\ \nu/\mathrm{m}^2 \text{ per } 10^6 \text{ inc. protons.} \qquad (1)$$

Or for 5×10^{12} incident protons on target per second (the design figure for the accelerator is 1.5×10^{13} per second), one obtains

$$I_\nu = 9.5 \times 10^7\ \nu/\mathrm{m}^2\text{ - sec for } E_\nu > 25 \text{ GeV.}$$

Note from Fig. 3 of Ref. 2 that for a 300 m drift space and a 150 m Fe shield the integral in (1) is increased by a little less than a factor of 2, and for a 300 m drift space and 300 m shield (2/3 earth) one obtains about the same value as in (1); these values illustrate the statement that the ν yield is not acutely sensitive to the exact beam design.

There are four reasons for the above choice of ν flux. First, it indicates that quadrupole focusing which permits use of a long beam spill, if desired, is a viable alternative to horn focusing of a ν beam for a W search with spark chambers. Second, the narrow-band ν beam obtained with quadrupole focusing may make possible the tagging of neutrinos in the beam in a manner similar to that used in tagging photons produced by an electron beam.[4] Third, such a neutrino beam is at least compatible with the collection of the associated muons from the kaon decays to form a simultaneous narrow-band muon beam. Finally, if it is recognized that a horn focusing system will occupy only 100 m of the drift space, it is not unrealistic to visualize a quadrupole focusing system in series with the horn system, each utilizing its own converter, which would permit choice of either a broad-band ν spectrum with short spill or a narrow-band ν spectrum with long spill.

II. RATE OF PRODUCTION OF W'S

Table I shows the details of the numerical integration of

$$\frac{1}{2}\int_{25}^{105} \frac{dI_\nu(E_\nu)}{dE_\nu}\,\sigma_W(E_\nu, M_W)\,dE_\nu;$$

$\sigma_W(E_\nu, M_W)$ is taken from Ref. 1 for $M_W = 5\ \mathrm{GeV}/c^2$, and $dI_\nu(E_\nu)/dE_\nu$ is from Fig. 24 of Ref. 2. We find that

$$\frac{1}{2}\int_{25}^{105} \frac{dE_\nu(E_\nu)}{dE_\nu}\,\sigma_W(E_\nu, M_W)\,dE_\nu = 3.9\times 10^{-29}\ \mathrm{cm}^2/\mathrm{Al\ nucleus\text{-}m}^2\text{-sec}, \quad (2)$$

for $M_W = 5\ \mathrm{GeV}/c^2$ and 5×10^{12} incident protons per second.

A neutrino detecting system of 50 metric tons, e.g., a 4.5 m length of aluminim with an area A of 4 m^2, contains approximately $N = 2.7\times 10^{25}$ nuclei/cm^2. Hence

$$\frac{1}{2}\,AN\int_{25}^{105} \frac{dI_\nu(E_\nu)}{dE_\nu}\,\sigma_W(E_\nu, M_W)\,dE_\nu = 4.2\times 10^{-3}\ \mathrm{W/sec}, \quad (3)$$

and for 7×10^4 useful seconds per day we find

$$\text{W production rate} = 294/\text{day},\ M_W = 5\ \mathrm{GeV}/c^2. \quad (4)$$

Detection of W's

It is much more difficult to determine accurately the number of W's that will be observed. This is because the branching ratio of the W into leptons (our interest is particularly into $\mu^+ + \nu_\mu$) is not easily estimated. We focus on the mode $W \to \mu + \nu_\mu$ as an integral part of the event signature (see Section IV). There have been a number of attempts to calculate the lepton branching ratio which are too extensive to describe in detail here. They have been summarized by Yamaguchi[5] from whose paper we take the value

$$(W \to \mu + \nu_\mu)/(W \to \text{all}) \sim 10^{-1}, \text{ for } M_W \sim 5 \text{ GeV}/c^2. \tag{5}$$

We should emphasize the large uncertainty in this value. Although estimates of the probability of decay of W into pions[6] or into multipion resonances[7] have given small values, there is the possibility of some presently unrecognized enhancement that might strongly favor the pionic decay modes. However, the value in (5) appears now to be a reasonable guess at the order of magnitude.

Using (5) and an experimental detection efficiency $\epsilon = 1/3$ we obtain

$$\text{W Detection Rate} \sim 10/\text{day}, \ M_W \sim 5 \text{ GeV}/c^2. \tag{6}$$

Event Signature

The kinematics of the process $\nu_\mu + Z \to Z + \mu^- + W^+$ concentrates most of the incident kinetic energy on the W^+. Indeed, for coherent production which is the dominant process at high E_ν, one finds[8] a peak in the total energy distribution of the μ^- at $E_{\mu^-}^{c.m.} \approx 0.05\ E_{\mu^-}^{max}$, more or less independent of M_W. This implies that a large fraction ($\sim 1/2$) of the μ^- produced by ν's with $E_\nu > 30$ GeV will have total energy in the 1-2 GeV region, while the W^+ energy will extend almost as high as the incident energy.

From the decay of a 5 GeV/c^2 W^+ produced by an incident neutrino with $E_\nu > 30$ GeV we might expect a μ^+ with $p_\perp/p_L > 5 \times 10^{-2}$, i.e., with an exceptionally large transverse component of momentum. Multiple scattering of this muon, even in a thickness of matter sufficient to bring it to rest, will not simulate such a large transverse momentum.

Thus a possible signature of the production of a W^+ and its subsequent decay to $\mu^+ + \nu_\mu$ is (1) the appearance of two muons with opposite charge, the negative muon with energy less than about 3 GeV, the positive muon with energy greater than 10 - 15 GeV; (2) the positive muon to exhibit an appreciable transverse component of momentum ($p_\perp/p_L \gtrsim 5 \times 10^{-2}$); (3) the observed energy and angular distributions of the μ^+ and μ^-, assuming they occur in sufficient quantities, to compare favorably with calculated distributions.

Apart from the transverse momentum criterion, these criteria are precisely the same as were used in the interpretation of neutrino-induced events in earlier experiments.[9] We can expect that their application will be easier and less ambiguous at the higher neutrino energies at NAL. The distinction between pions and muons is considerably more direct at high energies; for example, 1 meter of iron is about 8 collision lengths for a pion but will be penetrated by a 1.2-GeV muon. It is particularly desirable that the signs of the muon charges be determined unambiguously and that their energies be roughly measured. Both of these aims can be accomplished with a suitable arrangement of magnetized iron to provide magnetic deflection and also range measurement as used in Ref. 9 and discussed by Frisch in an earlier report.[10]

III. BACKGROUND

The principal background that can be easily foreseen will arise from inelastic events such as $\nu_\mu + Z \rightarrow \mu^- + \pi^+ + Z$ with $\pi^+ \rightarrow \mu^+ + \nu_\mu$. We do not know the inelastic cross section $\sigma_{inel.}$ at neutrino energies above a few GeV but if we assume that $\sigma_{inel.}$ continues to increase linearly with E_ν up to the highest NAL energy, we find for example that $\sigma_{inel.}$ (70 GeV) $\approx 5.5 \times 10^{-36}$ cm ^{2}/Al nucleus, i.e. about 4 times $\sigma_W(E = 70,\ M_W = 5)$. To simulate W production and decay the π^+ from the inelastic reaction must have an energy greater than about 10 GeV which implies a mean decay length of 525 m. In 3 m along its path the π^+ will traverse about 1.5 m of Al(Fe) or about 5(12) collision lengths. Hence we can expect to discriminate against π^+ decays by a factor $\sim 10^2$, which in turn indicates a W signal to inelastic background ratio of order unity under the somewhat severe assumption of a linear dependence of $\sigma_{inel.}$ on E_ν.

Another direct source of background is direct pair production of muons through $\nu_\mu + Z \rightarrow \mu^+ + \mu^- + \nu_\mu + Z$ which has been calculated[11] exactly to order $G^2\alpha^2$. However, $\sigma_{\mu\mu}(E_\nu = 50\text{ GeV, Fe}) \approx 3 \times 10^{-40}$ cm^2/Fe nucleus which is probably too small to provide a serious background.

IV. CONCLUSIONS

It appears that neutrinos with $E_\nu \geq 25$ GeV incident on high-Z spark chambers can provide a realistic W search in an interesting region of W mass. For a W mass less than about 6 GeV/c^2 there should be a sufficient detection rate with 50 tons of detector and with a modest ν-beam design if present production cross-section calculations are correct. Questions relating to the branching ratio W $\rightarrow$ leptons, recognition of events, and background will probably not be resolved completely until after a search is actually done but reasonable estimates concerning these problems are not discouraging. For $M_W < 2$ GeV/c^2, recognition of events may be somewhat more difficult than at higher W masses where the large transverse component of momentum of the μ^+ from W^+ decay is expected to be a useful part of the event signature. The rapid decrease of σ_W with increasing M_W will require the most efficient use of NAL neutrinos to allow the observation of W's with mass greater than about 6 GeV/c^2. For instance, the ratio of 8 GeV/c^2 W production to 5 GeV/c^2 W production is 1.8×10^{-2}, i.e., about 5 W's of 8 GeV/c^2 produced per day, assuming the same neutrino flux and detector tonnage for both masses. Even with optimized beam and detector design it is hard to anticipate searching above M_W = 10 GeV/c^2 with neutrinos until the NAL accelerator energy is raised to 400 GeV.

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Table I. Details of the Numerical Integration of

$$\frac{1}{2}\int_{25}^{105} \frac{dI_\nu(E_\nu)}{dE_\nu}\ \sigma_W(E_\nu,\ M_W)dE_\nu .$$

E_ν GeV	$\sigma_W(E_\nu, M_W = 5)$ $\times 10^{38}$ cm^2/Al nucleus	$\frac{1}{2}\ dI_\nu(E_\nu)/dE_\nu$ ν/m^2-GeV-10^6 protons	Product
30	3.8	0.60	2.3
40	23	0.60	13.8
50	52	0.35	17.2
60	92	0.20	18.4
70	130	0.10	13
80	169	0.04	6.8
90	220	0.015	3.3
100	246	0.006	1.5