A SEARCH FOR THE W BOSON WITH HIGH-ENERGY MUONS

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ABSTRACT

A search for the W boson using 100-GeV muons is proposed. It is shown that W masses up to about 10 GeV can be seen provided the branching ratio to muon plus neutrino is no worse than 0.1. Background comes in at about 10^{-39} cm^2 and expected rates are one per hour.

I. INTRODUCTION

Muons can be used to produce W bosons by the same coherent process as suggested for neutrinos (Fig. 1). The radiation from the muon line is now in the initial rather than the final state, and the muon polarization is determined by the decay of its parent pion or kaon. Aside from these kinematic factors, one can expect the muon cross sections to be comparable at a given energy to the neutrino cross section.[1] In the absence of detailed calculations for the muon production, we shall assume the neutrino cross sections[2] when estimating rates.

II. METHOD

The method proposed here relies upon a combination of pulse-height analysis, muon track recording, and final-muon energy measurement to exclude all sources of background. The apparatus (Fig. 2) consists of 15 large cylindrical tanks containing liquid scintillator. After each tank is a large optical spark chamber viewed by vidicon tubes as described by A. Roberts.[3] At the end of the array one may eventually place a large magnetized-iron recoil-muon momentum analyzer.

The signature for W production is the emergence of a low-energy muon at a large angle from the detector, accompanied by no recoil particles or showers. We interpret the signature in the following manner:

1. Emergence of a low-energy muon (10-40 GeV) indicates a catastrophic collision in the target.

2. Observance of a transverse momentum for the scattered muon of more than

1 GeV/c indicates a high four-momentum transfer [$q^2 \geq 5\ (\mathrm{GeV/c})^2$] and hence a rare event.

3. Absence of recoil particles of either hadronic or electromagnetic type, even after many interaction lengths, implies energy carried off by neutrinos.

4. Muon-induced weak processes which satisfy all the above criteria can only be explained by production of a W boson which subsequently decays to a muon of low energy plus a neutrino. The final muon energy is low because it decays backward in the W center-of-mass; it has high transverse momentum because the W has a large mass.

Other weak processes are small compared to coherent W production and result in a fair amount of energy transferred to ionizing and showering particles. We see that the W signature is unique and will stand out clearly in an intense background of electromagnetic and nuclear muon interactions. This statement will be reinforced in the section devoted to backgrounds.

III. MUON BEAM

We require a muon beam for this experiment which can satisfy the following requirements:

1. Energy above 70 GeV
2. Intensity greater than 10^6 per second
3. Transverse dimension less than 1 foot
4. Angular divergence less than 1 mrad
5. Halo less than beam intensity.

Such a muon beam has been proposed by T. Yamanouchi[4] and seems entirely reasonable to obtain.

One would probably tag the muons coming in to eliminate freakish background from low-energy beam particles. We anticipate running at 100 GeV/c with a 10% bandwidth and tagging to 1%. Scintillation counter hodoscopes should be adequate for this job.

The muon halo must be held to an integrated flux over an eight foot diameter less than the beam flux. This is never an easy requirement to meet but probably can be done. The restriction on muon halo is a consequence of our severe requirements on counter dead times, which will already be pressed hard by our beam-intensity requirements.

The angular divergence requirement should be relatively easy to meet since 20 nuclear interaction lengths of Be ($2000\ \mathrm{g/cm^2}$) give a projected rms scattering angle of 0.95 mrad. Yamanouchi has shown that 20 nuclear interaction lengths will be sufficient to reduce pion contamination to the equilibrium value of 10^{-6} to 10^{-7}.

IV. APPARATUS

Scintillation Counters

The liquid scintillation counters will be 8 ft in diameter and 10 feet long. Each counter will be filled with 3600 gal of mineral oil with scintillation chemicals added and viewed at each end by three 5 in. photomultiplier tubes. The tank then presents to the muon beam a target of carbon and hydrogen whose thickness is 300 g/cm. This thickness can also be expressed for multiple scattering and electromagnetic shower purposes as 6.5 radiation lengths, and for nuclear attenuation purposes as 3 interaction lengths. Pulse height on minimum ionizing traversals (beam muons) will have a fwhm of about 20% based upon statistics for 1000 photons collected. This corresponds to an energy loss of about 1 GeV. Rise time will be about 20 nsec. The multiple scattering of beam muons will be 0.5 mrad/tank corresponding to an rms displacement from the expected position of 0.05 in. /tank. If one has an array of 15 tanks, the total multiple scattering for beam muons is about 2 mrad and the rms displacement is 3 in. from the expected impact point. The multiple scattering must be small in order to reject straight through beam tracks in the spark chambers.

Spark Chambers

The spark chambers will be placed after each scintillation tank and be viewed by two vidicon tubes. Each chamber will be 8 ft square and have perhaps 4 gaps. The gaps will be wide enough to support multiple sparks and appropriate doping of the gas will keep the spark impedance high. All this is well-known technology.

It is important to point out that the chamber will need a 1 μsec memory time to handle the extra long logical delays (the system is about 200 ft long!), and one can expect to see as many as 20 sparks/gap at the expected instantaneous beam rate of 2×10^7/sec. This is the reason for using the vidicon system, as wire chambers of the magnetostrictive type will be far too expensive in scaler requirements, and those of the core type too expensive to build. The vidicon can store an image of the chamber with a 1 mm resolution in real space. This is plenty of resolution for a beam 1 ft in diameter, where the mean separation for 20 tracks one from another is 2.5 in. The resolution is also a perfect match to the multiple scattering displacement per tank.

Before leaving this section let us remark that one will <u>not</u> have the problem of fitting 20! possibilities for each spark gap. The muon tracks will for the most part be arrow straight and few ambiguities will occur. The track of interest will have a kink in it of about 5° and should stand out like the proverbial sore thumb. At 5° it will travel typically through three modules and give an excellent fit. Some final muon energy information can be obtained by the multiple scattering.

Final-Muon Momentum Spectrometer

Once one finds the W by observing the highly kinked muon tracks described above, one will almost certainly want to add a reasonably good momentum analysis on the final-state muon. If the typical decay angles are 5° and the system is 200 ft long, conventional magnets are probably out of the question. One can imagine going to a magnetized-iron spectrometer 40 ft × 40 ft × 1 meter thick with a field of 20 kG. Such a spectrometer would give a transverse momentum kick of 0.6 GeV/c and would permit a 20% type momentum measurement (limited by multiple scattering in the iron). Such a spectrometer would probably cost more than the entire experiment, and it is recommended only after the W has been found and more specific details are being asked for. Multiple scattering of the recoil muon will do nicely for a starter as mentioned before. Here one has about three track segments separated by 6 radiation lengths, and a 50-100%-type momentum determination should be possible. Note that the final muon has only 10-30 GeV/c, so that the error in the overall energy balance is more like 2-10%. This is quite respectable.

Trigger

The system is thought of as having two stages of logic: a fast stage and an intermediate stage. The fast stage will be a beam coincidence pulse from the beam-tagging system placed in anticoincidence with a beam exit counter after all the scintillation tanks. This fast trigger will enable a slower gate with the summed linear pulses of all the scintillation-counter tanks. If this pulse height is consistent with the passing of a noninteracting muon (no big showers present), the spark chambers will be pulsed and an event recorded. All the usual trigger lore will be applied to eliminate systematic biases.

V. RATES

The payoff for any experiment is the rate of data acquisition. For the present system, one is faced with three uncertainties in principle--the W mass, the anomalous magnetic moment, and the branching ratio to muon plus neutrino. The first unknown speaks eloquently for the muon-type search, as the flux of incoming leptons is concentrated at very high energy (100 GeV), and the sensitivity extends (in principle at least) to a W mass of 14 GeV. More to the point, however, is to note that coherent production is possible up to masses of order 5 GeV. This range includes a lot of interesting predictions.

We shall assume the neutrino coherent production cross section for a W mass of 5 GeV and no anomalous magnetic moment, an incoming energy of 100 GeV, and calculate a counting rate. We assume:

$\sigma_W(5,100) = 10^{-36}/\text{cm}^2/\text{nucleon}$

$I_\mu = 5 \times 10^6\ \text{sec}^{-1}$ (100 GeV/c)

$t = 3500\ \text{g/cm}^2$

B = branching ratio to muon plus neutrino

E = efficiency of detection,

then:

$$\text{Rate} = \left(\frac{10^{-36}\text{cm}^2}{\text{nucleon}}\right)\left(6 \times 10^{23}\ \frac{\text{nucleons}}{\text{g}^2}\right)\left(3.5 \times 10^3\ \frac{\text{g}}{\text{cm}^2}\right)\left(5 \times 10^6\ \text{sec}^{-1}\right)\left(3.6 \times 10^3\ \frac{\text{sec}}{\text{hr}}\right)$$

$$\times\ B\ E$$

$$= 36\ B\ E\ \text{hr}^{-1}.$$

Now E is fairly easy to estimate since we want the final muon to be low energy. We therefore let it go backward in the W center-of-mass into say 1/3 of the total solid angle. This makes E = 1/3. The branching ratio to muon plus neutrino cannot be calculated, but an estimate of 0.1 is fairly pessimistic according to most predictions. These estimates give a counting rate of 1 per hour, which is adequate. We have made up for the lack of flux by a very large target.

VI. BACKGROUND

In an experiment of this type where the signal lies a factor 10^6 below the noise (the total μN cross section is about 10^{-30} cm^2), one must be prepared with a powerful gimmick, since arguments against improbable event scenarios usually founder at about 10^{-3} to 10^{-4}. There are two gimmicks at work here--one is the large angle of the recoil muon and the other is the pulse height measurement. The muon angle implies a $q^2 \gtrsim 5\ (\text{GeV/c})^2$, and the low recoil energy a virtual radiator bandwidth of 30% at the high end. These two combine to give a factor of 100 to 1000 background suppression, even if the q^2 behavior falls off only as $1/q^2$ in the deeply inelastic region. Such a rejection factor is helpful but far from sufficient.

Our main force de frappe is the pulse height analysis of the scintillation counters Here we can measure the energy loss in each tank with a resolution of ±100 MeV. The event of interest is coherent on carbon, and the recoil nucleus kinetic energy is limited to less than 100 MeV by form factors. All the energy not given to the muon in the W decay escapes with the two neutrinos. This energy loss will be greater than 60 GeV! We now argue that, starting from a muon of 100 GeV at the center of one of the 8-ft diameter scintillation tanks, no known particles save neutrinos can escape the spectrometer without depositing a fair fraction of the 60 or more GeV. This is because the angle at which any system can recoil is given by $P_{\mu}/E_{lost} \lesssim 3/60 = 0.05$ radians. A system recoiling at this angle must pass through 20 nuclear interaction lengths or 45 radiation lengths of scintillator without interacting. The probabilities for these occurrences are $\sim 10^{-10}$ and 10^{-22} respectively. We combine these numbers with the rejection mentioned before, and find our background at less than 10^{-42} cm^2. Our signal-to-noise ratio is now about 10^6 to 1. Since we want to use as much of the target as possible, we shall actually require the event to occur at least five tanks before the end of the array. This means the true rejection will be more like 10^{-7} for nuclear interaction, corresponding to a background of 10^{-39} cm^2 (still quite comfortable).

If one is unable to refute this background argument, we should be able to limit the W mass in a very clean fashion to less than 8 BeV in a running time of a few weeks. If the experiment were to run a few months, one could limit the mass to less than 10 GeV. Needless to say, these limits are at least competitive, and very likely superior to other proposed W searches.

VII. OTHER CONSIDERATIONS

Cost

The experiment is large and sounds terribly expensive. It is really quite reasonable (by NAL standards) and very modular. We list the items:

Quantity	Item	Cost
15	Scintillation tanks and Instrumentation	$150 K
15	Large spark-chamber modules with vidicons	$150 K
1	Electronics system	$100 K
1	Tape drive and computer interface	$100 K
		$500 K

Addenda

It is traditional when peddling muon experiments to offer extra goodies, special features, and added attractions which come along for free with the main event. We shall stand by tradition.

The first thing which comes to mind is the total inelastic μp cross section which requires that we bury a hydrogen target in the first tank and measure recoil muons and nuclear showers downstream. After we tire of this, we can do wide angle bremsstrahlung from the same target to test QED.

Then, if the running time is sufficiently long, we can look for muon charge exchange ($\mu^+ + e^- \rightarrow \mu^- + e^+$) with a magnet behind the apparatus, and μ^e weak scattering to two neutrinos (one event/year!).

Also, installation of a piece of uranium near the back, plus a magnet behind the whole apparatus puts you into the muon trident business in a nice way. This experiment can test both muon statistics and QED at these energies.

These experiments are all parasitic and should keep lots of people busy while the muon beam is on. It is of further importance to note, however, that the tanks are far from junk when the experiments in the muon beam are over. They should be useful for neutrino physics, absorption counters in the hadron areas, cosmic rays, or liquid scintillation fluid storage.

We have attempted to show that a W search with high-energy muons is feasible and attractive. The cost is not high relative to other proposed searches, the equipment is reuseable, and a number of interesting parasite experiments come along for free. We believe this proposal should receive serious consideration when muon beams and experiments are reviewed.

REFERENCES

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[2] A. C. T. Wu et al., Phys. Rev. Letters 12, 57 (1964).

[3] A. Roberts, Wire Arrays vs Vidicons: A Comparison of Large Wire Arrays with Optical Spark Chambers Using Vidicon Readout, National Accelerator Laboratory 1969 Summer Study Report SS-56, Vol. III.

[4] T. Yamanouchi, A Muon Beam at NAL, National Accelerator Laboratory 1968 Summer Study Report B.2-68-38, Vol. II, p. 1.

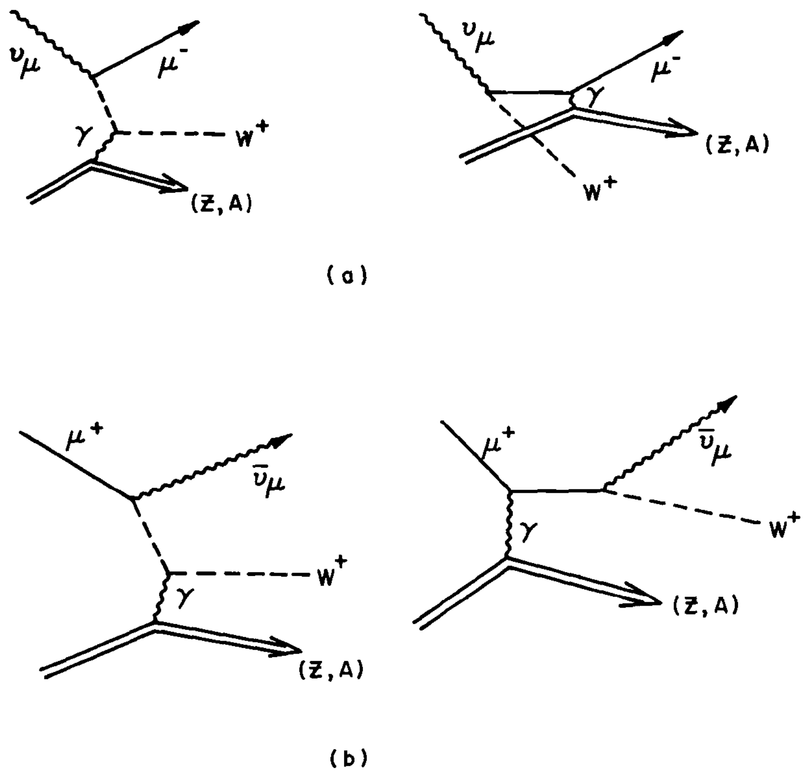

Fig. 1. Coherent production of W bosons by a) neutrinos and b) muons.

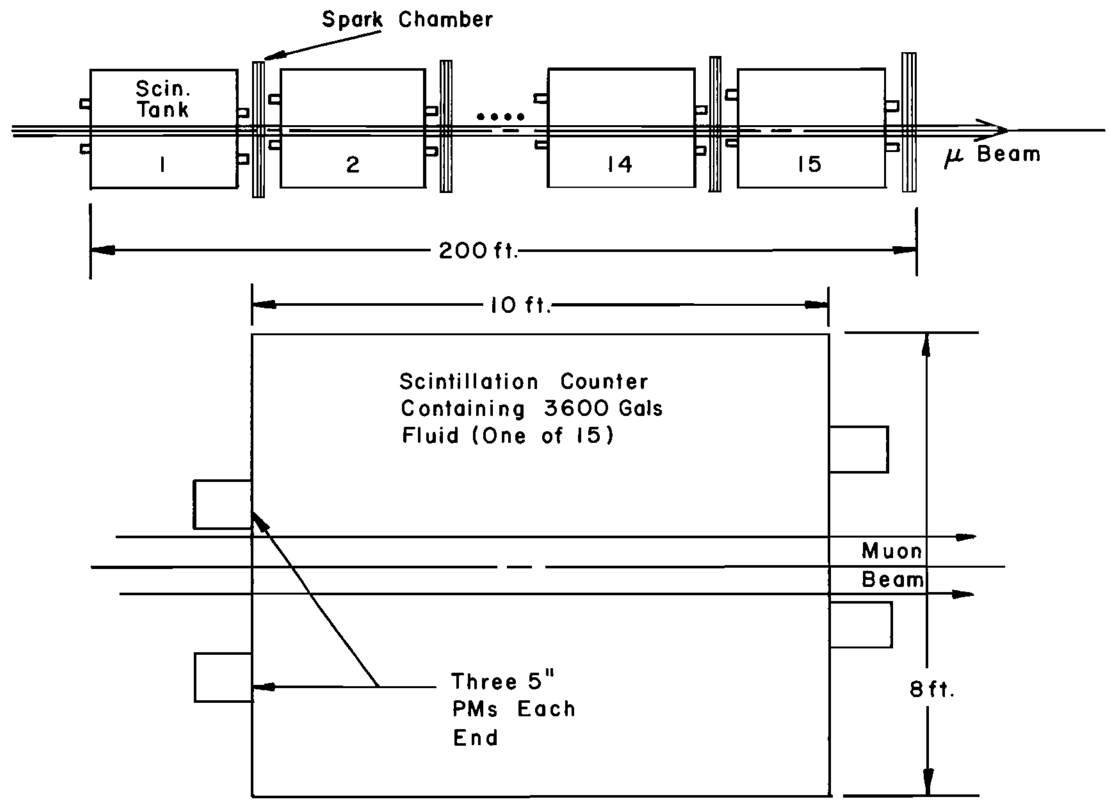

Fig. 2. Layout and details of scintillation spectrometer.