

**PHENOMENOLOGY OF MULTI-W PROCESSES
IN COSMIC RAYS ***

D.A. Morris[†]

University of California, Los Angeles
405 Hilgard Ave., Los Angeles, CA, U.S.A.

A. Ringwald[‡]

Theory Division, CERN
CH-1211 Geneva 23, Switzerland

Abstract

We report on a study of the potential of various cosmic ray physics experiments to search for Standard Model processes involving the nonperturbative production of $\gtrsim \mathcal{O}(\alpha_W^{-1}) \simeq 30$ weak gauge bosons. Whereas present and near-future experiments are insensitive to proton-induced processes, neutrino-induced processes give rise to promising signatures and rates in AMANDA, DUMAND, MACRO and NESTOR, provided that a cosmic neutrino flux exists at levels suggested by recent models of active galactic nuclei. The Fly's Eye currently constrains the largest region of parameter space characterizing multi-W phenomena.

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[†]email: morris@uclahep.bitnet

[‡]email: ringwald@cernvm.cern.ch

1. Introduction

A few years ago it was realized¹⁻⁴ that, even within the context of a weakly coupled Standard Model, lowest-order perturbative calculations of the inelastic scattering of quarks and leptons involving the production of $\gtrsim \mathcal{O}(\alpha_W^{-1}) \simeq 30$ weak gauge bosons result in an explosive (and unitarity violating) growth of the associated parton-parton cross section above center-of-mass energies $\gtrsim \mathcal{O}(\alpha_W^{-1} M_W) \simeq 2.4$ TeV. Thus, perturbation theory, when applied to large order processes (*e.g.*, like the production of $\mathcal{O}(\alpha_W^{-1})$ weak bosons) breaks down somewhere in the multi-TeV range. It is presently an open theoretical question whether large-order weak interactions become strong at this energy scale (in the sense of having observable cross sections) or whether they remain unobservably small at all energies. The answer almost certainly lies beyond the realms of conventional perturbative techniques (see Ref. 5 for an overview). Given the stakes involved, a quantitative consideration of experimental constraints on multi-W production is clearly desirable. In this talk we report on our recent investigations of this question^{6,7}.

Until the commissioning of the proposed Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC), which would be ideal for observing or constraining multi-W phenomena over a wide range of energies and cross sections^{8,9}, cosmic rays provide the only access to the required energy scales. In order to investigate multi-W processes in a quantitative manner we take a phenomenological approach. We first parametrize multi-W processes in terms of parton-level thresholds and cross sections and then explore the sensitivity of current and near-future cosmic ray experiments to various signatures of multi-W phenomena. We consider both atmospheric and underground phenomena induced by cosmic ray protons and neutrinos.

We demonstrate that even if proton-induced atmospheric multi-W phenomena occur in Nature, the features of the resulting air showers are unlikely to allow one to distinguish them from fluctuations in a much larger background of generic showers. On the other hand, ultrahigh energy neutrinos, for which a sizeable flux has recently been conjectured from sources such as active galactic nuclei¹⁰⁻¹³ offer exciting possibilities for observing or constraining multi-W phenomena^{14,15}. Subsurface detectors such as AMANDA¹⁶, DUMAND¹⁷, MACRO¹⁸, and NESTOR¹⁹ can be sensitive to neutrino-induced multi-W phenomena in certain regions of multi-W parameter space.

The structure of this talk is as follows. In sect. 2 we characterize multi-W phenomena by a two-parameter working hypothesis which frees us from specifying an underlying (most likely nonperturbative) mechanism for multi-W production. We also describe the gross features of multi-W phenomena and present discovery limits for the LHC and SSC. We discuss proton-induced and neutrino-induced multi-W phenomena in sects. 3 and 4, respectively. We consider a variety of detection techniques and present discovery limits which may be contrasted with the superior sensitivity of future hadron colliders. In sect. 5 we conclude.

2. Multi-W Parameterization

In the absence of a reliable first-principles calculation of multi-W production, we parametrize the quark-quark or neutrino-quark cross section for multi-W production by

$$\hat{\sigma}_{\text{multi-W}} = \hat{\sigma}_0 \Theta(\sqrt{\hat{s}} - \sqrt{\hat{s}_0}). \quad (1)$$

By convoluting the subprocess cross section of Eq. (1) with the appropriate quark distribution functions, one obtains the multi-W production cross sections of Fig. 1 for protons and neutrinos striking stationary nucleons and electrons. Motivated by suggestions that multi-W production may be an intrinsically nonperturbative phenomenon, the quark distribution functions are evaluated at a momentum transfer scale of $Q^2 = M_W^2$. The curves in Fig. 1 are universal in the sense that they have been scaled by $\hat{\sigma}_0$ and $\sqrt{\hat{s}_0}$.

Fig. 1. Universal curves parametrizing multi-W production cross sections in proton-nucleon (pN), proton-electron (pe^-), neutrino-nucleon (νN) and neutrino-electron (νe^-) collisions. Curves are for protons and neutrinos with laboratory energy E colliding with nucleons and electrons at rest. $E_p^{(pN \text{ thresh})} = \hat{s}_0/(2m_p)$ is the proton threshold energy for pN multi-W processes.

For definiteness, we will assume throughout this talk that $\hat{\sigma}_0$ refers to the production of exactly 30 W bosons; allowing for the production of variable numbers of W's (and Z's and possibly prompt photons) is straightforward but is an unnecessary complication at the level of our investigation. An optimistic range of parameters to consider might encompass

$$\begin{aligned} \frac{m_W}{\alpha_W} \simeq 2.4 \text{ TeV} &\leq \sqrt{\hat{s}_0} \leq 40 \text{ TeV}, \\ \frac{\alpha_W^2}{m_W^2} \simeq 100 \text{ pb} &\leq \hat{\sigma}_0 \leq \sigma_{\text{inel}}^{pp} \times \left(\frac{1 \text{ GeV}}{m_W}\right)^2 \simeq 10 \mu\text{b}. \end{aligned} \quad (2)$$

The lower limit of $\sqrt{\hat{s}_0}$ is suggested by the energy scale at which perturbation theory becomes unreliable^{3,4} whereas the upper range is of the order of the sphaleron mass²⁰. The lower limit of $\hat{\sigma}_0$ is characteristic of a geometrical “weak” cross section and the upper limit range is a geometrical “strong” cross section suggested by analogies between the weak SU(2) gauge sector and the color SU(3) gauge sector²¹.

The simultaneous production of $\mathcal{O}(30)$ W bosons at future hadron colliders like the LHC or SSC would lead to spectacular signatures^{8,9}. Since approximately 20 charged hadrons (mainly π^\pm 's) arise from hadronic W decays one could typically expect 400 π^\pm 's in one multi-W event accompanied by $\simeq 400$ photons from the decay of $\simeq 200$ π^0 's. The charged hadrons would have a minimum average transverse momentum of order $p_T^\pi \geq \mathcal{O}(m_W/30) \simeq (2-3)$ GeV if the W bosons are produced without transverse momentum. Similarly, one could expect $\simeq 5$ prompt muons

($\simeq 3$ from W decays and $\simeq 2$ from c , b , or τ decay) carrying a minimum average transverse momentum of $p_T^\mu \geq \mathcal{O}(m_W/2) \simeq 40$ GeV. Analogous situations hold for other prompt leptons such as e^\pm, ν etc. No conventional reactions in the Standard Model are backgrounds to multi-W processes⁹.

Figure 2 shows the regions in $\sqrt{\hat{s}_0} - \hat{\sigma}_0$ space accessible to the LHC and the SSC. The contours correspond to 1 and 10 events (assuming 100% detection efficiency) for 10^7 s of operation. These contours may be used as a benchmark to evaluate the effectiveness of various cosmic ray physics experiments for constraining multi-W phenomena.

3. Proton-Induced Multi-W Processes

Cosmic ray protons and heavy nuclei constitute a guaranteed flux of high-energy primaries potentially capable of initiating multi-W phenomena. In this section we briefly review⁷ the possibility of exploiting this cosmic flux and isolating multi-W phenomena from generic hadronic reactions at conventional surface arrays which reconstruct the features of an extensive air shower by interpolating or extrapolating measurements of a shower's particle content. We restrict our attention to cosmic ray protons since they provide the dominant flux in terms of energy per nucleon.

Multi-W phenomena initiated by cosmic ray *protons* are plagued by *small rates* and *poor signatures* due to competing purely hadronic processes with $\mathcal{O}(100 \text{ mb})$ cross sections. The small rates are demonstrated in Figure 3 which shows contours

Fig. 2. Contours corresponding to 1 and 10 multi-W events in one year (10^7 s) of operation for the LHC ($\sqrt{s} = 14.6$ TeV; $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) and the SSC ($\sqrt{s} = 40$ TeV; $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$).

Fig. 3. Event number contours in 10^7 s for proton-induced multi-W air showers assuming the Constant Mass Composition model for proton flux. Solid: 100 km^2 conventional surface array sensitive to $E_{\text{shower}} \geq 1$ PeV at zenith angles $\theta \leq 60^\circ$. Dashed: Fly's Eye array sensitive to $E_{\text{shower}} \geq 100$ PeV using aperture of Ref. 30.

for the number of proton-induced multi-W air showers at zenith angles $\theta \leq 60^\circ$ striking a 100 km^2 conventional surface array in 10^7 s. For our calculations we use the cosmic proton flux of the Constant Mass Composition (CMC) model²² (see Fig. 4). For purposes of illustration we optimistically assume an array threshold energy of $E_{\text{thresh}} = 1$ PeV which accommodates all multi-W thresholds above $\sqrt{\hat{s}_0} \geq 2.4$ TeV. In 100 km^2 arrays like AGASA²³ and EAS-100²⁴ inter-detector spacing on the order of .5–1 km makes $E_{\text{thresh}} = 100 - 1000$ PeV more realistic but does not change our conclusions.

Fig. 4. Differential flux of protons and neutrinos used in text. The Constant Mass Composition proton flux is from Ref. 22. The diffuse neutrino flux from active galactic nuclei (AGN) and the 2.7 K photoproduced neutrino flux are taken from Ref. 10. Neutrino fluxes shown are summed over species in the proportion $\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e = 2 : 2 : 1 : 1$.

Though the region of the $(\sqrt{\hat{s}_0}, \hat{\sigma}_0)$ plane accessible to proton-induced multi-W phenomena is small, let us now investigate whether it is possible to convincingly distinguish an air shower of multi-W origin from a generic hadronic air shower. For the remainder of this section, we restrict our attention to the optimistic scenario of a parton-parton multi-W threshold of $\sqrt{\hat{s}_0} = 2.4$ TeV with $\hat{\sigma}_0 = 10$ μb . For this choice of parameters the most probable shower energy is $\simeq 30$ PeV whereas the average shower energy is $\simeq 250$ PeV due to a long tail on the corresponding distribution.

Consider the characteristics of the most probable ($\simeq 30$ PeV) multi-W air showers. To phrase our results in experimentally relevant terms we use the computer program SHOWERSIM²⁵ to simulate multi-W air showers and generate samples of generic proton-induced and iron-induced showers. Figure 5 compares 30 PeV multi-W, proton and iron showers in terms of radial particle densities (with respect to a vertical shower axis) of electrons ($E_e \geq 1$ MeV), muons ($E_\mu \geq 1$ GeV) and hadrons ($E_{\text{had}} \geq 1$ GeV). Each curve is averaged over 25–100 showers taking into account the distribution of the depth of first interaction in the upper atmosphere. The densities in Fig. 5 correspond to an observation depth of 800 g/cm² (roughly the CYGNUS array depth²⁶).

Fig. 5. Lateral distributions of electrons, muons and hadrons in 30 PeV vertical air showers at atmospheric depth of 800 g/cm². Solid curves correspond to proton-induced multi-W showers assuming $\sqrt{\hat{s}_0} = 2.4$ TeV and any value of $\hat{\sigma}_0$. Dashed (dot-dashed) curves correspond to generic showers initiated by proton (iron) primaries. Each curve is an average over 25–100 showers including variations in the depth of first interaction.

The differences between the particle density profiles of 30 PeV showers in Fig. 5 are hardly dramatic. While there are identifiable systematic differences between average showers of different origin, the differences do not appear to be sufficient to discriminate between multi-W showers and fluctuations in generic proton or iron showers. We emphasize this point by noting that in the CMC flux model, the differential fluxes of 30 PeV generic proton-induced, iron-induced and multi-W showers (with $\sqrt{\hat{s}_0} = 2.4$ TeV, $\hat{\sigma}_0 = 10$ μb) stand in the proportion p : Fe : multi-W $\simeq 1.2 \times 10^5 : 1.1 \times 10^5 : 1$. Therefore, the prospects for detecting proton-induced multi-W phenomena using conventional surface arrays are poor (see Ref. 7 for further details).

4. Neutrino-Induced Multi-W Processes

Ultrahigh energy neutrinos could provide particularly striking signatures for multi-W processes. In contrast to proton-induced multi-W processes which must

compete with $\mathcal{O}(100 \text{ mb})$ generic hadronic processes, neutrino-induced phenomena must contend only with $\mathcal{O}(\text{nb})$ weak interaction processes. Even if the total neutrino-nucleon multi-W cross section is as large as $\mathcal{O}(\mu\text{b})$, the majority of all interactions occur deep in the atmosphere or inside the Earth.

A precondition for observing or constraining neutrino-induced multi-W phenomena is, of course, the existence of a flux of ultrahigh energy neutrinos. Though atmospheric neutrinos, *i.e.*, neutrinos produced in hadronic showers in the atmosphere, provide a guaranteed diffuse flux of ultrahigh energy neutrinos, their overall rate in the PeV region is anticipated to be negligible (see, *e.g.*, Ref. 13). Much more promising are the recent predictions of a sizeable flux of PeV neutrinos from active galactic nuclei (AGN)^{10–13}. In this section we discuss the implications of a large AGN neutrino flux for multi-W processes. For definiteness, we use the (revised) Stecker *et al.*¹⁰ AGN neutrino flux. AGN neutrino fluxes calculated under different assumptions in Refs. 11,12 generally agree with Ref. 10 above .1 PeV, which is the energy range we are interested in. In this sense our use of the Stecker *et al.* flux is intended to be representative of a large class of AGN flux models. In Ref. 7 we have checked that, within the parameter ranges of Eq. (2), large neutrino cross sections for multi-W production are consistent with proposed AGN flux models.

In addition to proposed AGN neutrino fluxes, we also consider the possibility of detecting neutrinos which are photoproduced by protons scattering inelastically off the 2.7 K cosmic background radiation (CBR)²⁷, producing charged pions which subsequently decay to neutrinos^{28,29}. As shown in Fig. 4, such processes may provide the dominant component of the neutrino flux at energies beyond $\simeq 1 \text{ EeV}$. The photoproduced neutrino flux, $j_\nu^{2.7 \text{ K}}$, shown in Fig. 4 is taken from Ref. 10.

We divide our discussion of neutrino-induced multi-W phenomena into two sections. In sect. 4.1 we discuss constraints on neutrino-induced multi-W production from the Fly’s Eye. In sect. 4.2 we evaluate the potential of subsurface detectors to observe the showers associated with multi-W phenomena and discuss the detection of distant multi-W phenomena through searches for energetic muon bundles.

4.1 The Fly’s Eye Limits

The Fly’s Eye³⁰ is an optical array sensitive to nitrogen fluorescence light from air showers whose trajectories do not necessarily intersect the array³¹. By detecting fluorescence light emitted as air showers streak across the sky, the Fly’s Eye is capable of reconstructing the longitudinal development of air showers with energy greater than $E_{\text{thresh}} = 100 \text{ PeV}$.

Independent of any neutrino flux model, the Fly’s Eye array puts upper limits³² on the product of the flux times total cross section for weakly interacting particles in the range $10^8 \text{ GeV} \leq E_\nu \leq 10^{11} \text{ GeV}$ assuming that such particles initiate extensive air showers deep in the atmosphere. The limits are deduced from the non-observation of downward-moving air showers within the Fly’s Eye fiducial volume such that the shower axis is inclined 80° to 90° from the zenith at the point of impact on the Earth. Showers meeting these criteria could only have been initiated by particles typically penetrating more than 3000 g/cm^2 of atmosphere

before interacting, which excludes showers initiated by ultrahigh energy photons and hadrons.

Assuming that the weakly interacting particles referred to by the Fly’s Eye are neutrinos, we denote the relevant cross section by $\sigma_{\text{tot}}^{\nu N}(E_\nu)$ which receives contributions from both multi-W and familiar charged current weak interactions. The Fly’s Eye limits may be summarized^{14,33} by $(j_\nu \sigma_{\text{tot}}^{\nu N})_{\text{Fly's Eye}} \leq 3.74 \times 10^{-42} \times (E_\nu/1 \text{ GeV})^{-1.48} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$. Since these limits neglect the possibility of flux attenuation in the upper atmosphere due to large inelastic cross sections, they nominally apply only if $\sigma_{\text{tot}}^{\nu N}(E_\nu) \leq 10 \text{ } \mu\text{b}$. If one considers a particular neutrino flux model $j_\nu^{\text{model}}(E_\nu)$ the Fly’s Eye limit excludes regions in the $(E_\nu, \sigma_{\text{tot}}^{\nu N})$ plane bounded by

$$\frac{(j_\nu \sigma_{\text{tot}}^{\nu N})_{\text{Fly's Eye}}}{j_\nu^{\text{model}}} < \sigma_{\text{tot}}^{\nu N}(E_\nu) < 10 \text{ } \mu\text{b}, \quad (3)$$

$$10^8 \text{ GeV} < E_\nu < 10^{11} \text{ GeV}.$$

These inequalities exclude a corresponding region in $(\sqrt{\hat{s}_0}, \hat{\sigma}_0)$ space which parametrizes multi-W phenomena. Figure 6 shows the excluded (hatched) region of multi-W parameter space for the AGN neutrino flux of Stecker *et al.* (*i.e.*, $j_\nu^{\text{model}} = j_\nu^{\text{Stecker et al.}}$ from Fig. 4). If one takes $j_\nu^{\text{model}} = j_\nu^{\text{Stecker et al.}} + j_\nu^{2.7 \text{ K}}$ in Eq. (3), the Fly’s Eye limit enlarges the excluded region in $(\sqrt{\hat{s}_0}, \hat{\sigma}_0)$ space by the area labelled “2.7 K Photoproduced ν ” in Fig. 6 (double hatched).

Though the appearance of an enlarged excluded region is welcome, it is sensitive to details of the assumed CBR flux. Had we assumed a CBR flux component $j_\nu^{2.7 \text{ K}}$ which was a factor of ten smaller than that shown in Fig. 4. (corresponding to a lower redshift), the Fly’s Eye limit would not have introduced an additional constraint⁷. We should keep such uncertainties in mind to avoid attaching undue significance to the excluded regions in Fig. 6. Nevertheless it is intriguing to speculate about detecting CBR neutrinos via multi-W processes since the prospects

Fig. 6. Regions of multi-W parameter space excluded by the Fly’s Eye. The region labelled “AGN ν ” is excluded if one assumes only the AGN neutrino flux of Stecker *et al.*¹⁰. The region labelled “2.7 Photoproduced ν ” is excluded in addition if one includes the neutrino flux contributions due to the inelastic scattering of protons off the cosmic background radiation shown in Fig. 4.

for detecting such neutrinos through generic weak interactions is poor unless the CBR neutrino flux is associated with a very large redshift.

4.2 Subsurface experiments

Detectors deep below the surface of the Earth, be they shielded by rock (*e.g.* MACRO¹⁸), water (*e.g.* DUMAND¹⁷, NESTOR¹⁹, Baikal NT-200³⁴) or ice (AMANDA¹⁶) offer a unique perspective on neutrino-induced phenomena, as has been nicely reviewed by Francis Halzen and Leo Resvanis during this workshop.

In this section we investigate two possible modes for detecting neutrino-induced multi-W phenomena using subsurface experiments. We first consider the prospects for observing contained neutrino-induced multi-W phenomena and later turn to the detection of muon bundles arising from neutrino interactions in the surrounding medium.

Aside from the energy involved, contained neutrino-induced multi-W production would reveal its origins by its enormous multiplicity ($\mathcal{O}(400)$ charged hadrons, $\mathcal{O}(400)$ photons, and a few prompt muons and electrons). Generic deep inelastic νN scattering and the resonant process $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons can also give contained hadron production, but only with significantly lower multiplicity. Figure 7 shows contours for contained multi-W events in 10^7 s in a $.2 \text{ km}^3$ volume of water at an ocean depth of 4.5 km (approximately the characteristics of DUMAND for PeV contained showers³⁵).

Fig. 7. Contours for neutrino-induced contained multi-W events in $.2 \text{ km}^3$ volume of water at an ocean depth of 4.5 km in 10^7 s (appropriate for contained PeV showers in DUMAND). The neutrino flux of Stecker *et al.*¹⁰ is assumed (see Fig. 4).

Of particular interest is the ability for subsurface detectors to detect muons which arise from energetic neutrino interactions up to a few kilometers away. For distant multi-W production the effects of producing hundreds of hadrons and photons will have died off well before reaching the detector but the anticipated 2–3 muons from prompt W decays produced with $E_\mu \simeq \mathcal{O}(100 \text{ TeV})$ and $p_T^\mu \simeq \mathcal{O}(40 \text{ GeV})$ propagate great distances. The signature of multi-W production in this case would be energetic muon bundles.

The ability to detect muons from distant neutrino reactions increases a subsurface detector’s effective neutrino target volume dramatically and is the premise upon which such detectors can act as neutrino telescopes. Considerable effort has recently been directed towards the prospects of detecting ultrahigh energy neutrinos (most likely from AGN) using subsurface detectors¹³. Despite their limited sensitivity to such phenomena, Fréjus³⁶ and Soudan–2³⁷ have already placed useful observational constraints on AGN flux models.

As discussed in Ref. 14, near-horizontal muon bundles in DUMAND and MACRO would be characteristic of neutrino-induced multi-W phenomena. By concentrating on large zenith angles, one can avoid the complications from a large background of muon bundles from generic hadronic interactions in the atmosphere. We present in Fig. 8 contours for muon bundles beyond zenith angles of 80° for MACRO and DUMAND for the AGN neutrino flux of Stecker *et al.*¹⁰; the contours expected for AMANDA and NESTOR (stage 1) are similar to those of the DUMAND contours. Due to our assumed production of 30 W bosons, each muon bundle consists of approximately 3 muons. The average muon energy $\langle E_\mu \rangle$ entering the detector and the average inter-muon separation $\langle r_\mu \rangle$ depend on $\sqrt{\hat{s}_0}$ and $\hat{\sigma}_0$. For example, for $(\sqrt{\hat{s}_0} = 4 \text{ TeV}, \hat{\sigma}_0 = 10 \text{ nb})$ one expects $\simeq 1.5$ bundles per 10^7 s

in DUMAND with $\langle E_\mu \rangle \simeq \mathcal{O}(180 \text{ TeV})$ and $\langle r_\mu \rangle = \mathcal{O}(2.5 \text{ m})$; for $(\sqrt{\hat{s}_0} = 4 \text{ TeV}, \hat{\sigma}_0 = 1 \mu\text{b})$ one expects $\simeq 30$ bundles per 10^7 s in DUMAND with $\langle E_\mu \rangle \simeq \mathcal{O}(70 \text{ TeV})$ and $\langle r_\mu \rangle = \mathcal{O}(3.6 \text{ m})$. Assuming an additional 2.7 K photoproduced neutrino flux component at the level shown in Fig. 4 changes the contours of Fig. 8 by a negligible amount.

Fig. 8. Contours for neutrino-induced multi-W muon bundles at zenith angles $\theta > 80^\circ$ in 10^7 s at MACRO and DUMAND assuming the AGN neutrino flux of Stecker *et al.*¹⁰.

It may also be possible to constrain multi-W phenomena by searching for non-horizontal muon bundles and thereby enlarge the accessible region in $\sqrt{\hat{s}_0}-\hat{\sigma}_0$ space. Fig. 9 shows contours for muon bundles for zenith angles between 0° and 180° for MACRO for the Stecker *et al.* AGN neutrino flux. An additional 2.7 K photoproduced neutrino flux component at the level of fig. 4 has a negligible effect on the MACRO contours.

Fig. 9. Contours for neutrino-induced multi-W muon bundles for all zenith angles in 10^7 s at MACRO assuming the AGN neutrino flux of Stecker *et al.*¹⁰. Preliminary rates for muon bundles in MACRO presented in Ref. 6 included only AGN ν_μ -induced multi-W processes and hence are smaller than those shown above by a factor of 3.

Whereas the inter-muon separation expected from generic hadronic interactions high in the atmosphere is typically of $\mathcal{O}(5-10 \text{ m})$, neutrino-induced multi-W phenomena occur primarily inside the Earth and result in much more spatially compact muon bundles. Figure 10 compares MACRO data for pair-wise muon separation to the contribution expected from neutrino-induced multi-W phenomena for $(\sqrt{\hat{s}_0} = 2.4 \text{ TeV}, \hat{\sigma}_0 = 10 \mu\text{b})$. The MACRO data is taken from Fig. 4 of Ref. 38 and corresponds to muon bundles at zenith angles $\theta < 60^\circ$ detected by two supermodules operating for 2334.3 hours. The MACRO data contains contributions from muon bundles of all multiplicities; approximately half of the reconstructed pairs come from $n_\mu = 2$ muon bundles. We suggest that by separately examining the pair-wise muon separation in bundles with fixed numbers of muons (*e.g.*, $n_\mu=3$)

Fig. 10. MACRO pairwise muon separation data³⁸ compared with expectations for neutrino-induced multi-W phenomena for $(\sqrt{\hat{s}_0} = 2.4 \text{ TeV}, \hat{\sigma}_0 = 10 \mu\text{b})$ assuming the AGN neutrino flux of Stecker *et al.*¹⁰. MACRO data corresponds to two supermodules operating for 2334.3 hours sensitive to bundles with zenith angle $\theta < 60^\circ$.

as has been done by the Fréjus collaboration³⁹, MACRO may be able to put constraints on the existence of multi-W phenomena. A particularly useful signature of multi-W processes in this respect is the energy carried by each muon. Muons arising from multi-W processes in Fig. 10 would have energies of approximately 80 TeV as they enter the detector and may be distinguished by mechanisms such as

catastrophic energy loss^{36,37}. Though some of the region in $(\sqrt{\hat{s}_0}, \hat{\sigma}_0)$ space to which MACRO is sensitive is already excluded by the Fly's Eye (assuming the same AGN neutrino flux), valuable independent constraints may already be possible from existing MACRO data.

5. Conclusions

The short term outlook for constraining or detecting multi-W phenomena in cosmic ray physics is mixed. Without making additional assumptions (such as assuming the existence of a large cosmic neutrino flux) one must focus on proton-induced processes and conclude that current and future experiments are effectively insensitive to multi-W phenomena over the entire range of parameter space where they might plausibly exist. From this viewpoint one must wait for terrestrial supercolliders before conclusive constraints on multi-W processes are established.

An intermediate scenario is one in which a flux of ultrahigh energy neutrinos is detected in the future but is found to have interactions consistent with generic charged current processes. This may place valuable constraints on the existence of multi-W phenomena, notably from the Fly's Eye limits.

The most optimistic scenario requires a sizeable diffuse flux of ultrahigh energy neutrinos. In this case dedicated subsurface detectors such as AMANDA, DUMAND, MACRO and NESTOR may even indicate whether multi-W processes are real or an artifact of our imperfect understanding of multi-TeV weak interactions.

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