MULTIPLE MUONS FROM NEUTRINO-INITIATED MULTI-W(Z) PRODUCTION

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ABSTRACT

Current underground detectors can search for multiple muons from multi-W(Z) production initiated by ultrahigh energy neutrinos from active galactic nuclei. $O(\mu b)$ cross sections give rise to downward going muon bundles whose features differ from those of atmospheric muon bundles.

1. INTRODUCTION

A variety of recent theoretical results has suggested the intriguing possibility that the cross section for the nonperturbative production of $O(\alpha_{W}^{-1}) \approx 30$ weak gauge bosons (W,Z) may be as large as $O(100 \text{ pb} - 10 \mu b)$ above a parton-parton center-of-mass threshold in the range 2.4–30 TeV [Ri90,Es90, Mc90,Co90,Ri91a]. Unfortunately, the theoretical evidence is largely circumstantial and so it remains an open question as to whether or not large cross sections for multi-W(Z) production are realized in Nature. Though the SSC, LHC and Eloisatron can address this issue conclusively[Fa90,Ri91b], it is natural to ask whether ultrahigh energy cosmic rays can preemptively confront these conjectures.

1.1 Proton and Neutrino Induced Interactions

If nonperturbative multi-W(Z) production exists, it can be induced by energetic collisions between any two weakly interacting partons (e.g., $q, e, \nu$). Characteristic byproducts of multi-W(Z) processes are energetic prompt muons from W(Z) decays. For example, if 30 W bosons are produced then one can expect $O(30 \times Br(W \rightarrow \mu \nu)) \approx 3$ prompt muons which may be observed in deep underground detectors.

Multi-W(Z) production induced by cosmic protons is plagued by small rates and poor signatures due to competing generic processes with $O(40 \text{ mb})$ cross sections[Mo93]. By contrast, multi-W(Z) production induced by ultrahigh energy neutrinos competes only with relatively small $O(\text{nb})$ charged-current reactions. If the multi-W(Z) contribution to the neutrino-nucleon total inelastic cross section $\sigma_{\nu N}^{\text{tot}}$ is also of $O(\text{nb})$, then near-horizontal muon bundles provide a signature of neutrino-induced multi-W(Z) production in the rock surrounding underground detectors[Mo91,Be92]. Large underground detectors like DUMAND and NESTOR would also be...
sensitive to such signals [Mo91, Be92, De92]. In this paper we broaden the prospects for detecting or constraining neutrino-induced multi-W(Z) phenomena in underground detectors by suggesting searches for neutrino-induced muon bundles away from the horizontal direction.

To be quantitative we adopt a working hypothesis [Ri91b] which parameterizes the sudden nonperturbative onset of multi-W(Z) production in parton-parton subprocesses by

\[ \hat{\sigma}_{\text{multi-W}} = \hat{\sigma}_0 \Theta(\sqrt{s} - \sqrt{s_0}). \]  

For purposes of illustration we will consider the production of 30 W bosons by exploring parton-parton center-of-mass thresholds in the range \( \alpha_{W}^{-1} M_W \simeq 2.4 \text{ TeV} < \sqrt{s_0} < 30 \text{ TeV} \) and point cross sections \( 100 \text{ pb} < \hat{\sigma}_0 < 10 \text{ \mu b} \).

2. MULTI-W MUON BUNDLES INDUCED BY NEUTRINOS FROM AGN

2.1 Constraints on Multi-W Phenomena

Apart from the speculative nature of multi-W production, we must also contend with a lack of knowledge of the flux of ultrahigh energy cosmic neutrinos. A quark-neutrino center-of-mass threshold of 2.4 TeV corresponds to a neutrino energy of \( \sim 3 \text{ PeV} \) where recent models have predicted a sizeable neutrino flux from active galactic nuclei [St91, St92]. Regardless of any model, the Fly’s Eye array puts upper limits [Ba85] on the product of the flux times total cross section for weakly interacting particles (which we will assume are neutrinos) in the range \( 10^8 \text{ GeV} < E_\nu < 10^{11} \text{ GeV} \) if such particles initiate extensive air showers deep in the atmosphere. The limit applies only for \( \sigma^{\nu N}_{\text{tot}}(E_\nu) < 10 \text{ \mu b} \) since the possibility of flux attenuation is neglected.

Explicit parameterizations of the Fly’s Eye limits, which we denote by \( (j_\nu \sigma^{\nu N}_{\text{tot}} )_{\text{FE}}(E_\nu) \), may be found in Refs. [Ma90, Mo91]. If one considers a particular flux model \( j^{\text{model}}_\nu(E_\nu) \) then in the \( (E_\nu, \sigma^{\nu N}_{\text{tot}}) \) plane the Fly’s Eye excludes regions bounded by

\[ 10^8 \text{ GeV} < E_\nu < 10^{11} \text{ GeV}, \quad \frac{(j_\nu \sigma^{\nu N}_{\text{tot}})_{\text{FE}}(E_\nu)}{j^{\text{model}}_\nu(E_\nu)} < \sigma^{\nu N}_{\text{tot}}(E_\nu) < 10 \text{ \mu b}. \]  

These inequalities may be translated into a corresponding excluded region in \( (\sqrt{s_0}, \hat{\sigma}_0) \) space which parameterizes multi-W phenomena. Fig. 1 shows the excluded region of multi-W parameter space for the (revised) flux of Stecker et al. [St91]; also indicated are the contours of constant detection rates of multi-W muon bundles containing two or more muons. These rates are integrated over all zenith angles assuming standard muon energy-range relations with a detector depth of 3700 hg/cm\(^2\) and an idealized spherical Earth [Mo93].

For a 72 m \( \times \) 12 m \( \times \) 4.8 m detector (MACRO) a vertical flux of \( 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \) corresponds to 26 events per year. Consider two scenarios within reach of such a detector: \( \hat{\sigma}_0 = 10 \text{ nb}, 10 \text{ \mu b} \) for a common threshold of \( \sqrt{s_0} = 2.4 \text{ TeV} \). These cases correspond to total bundle detection rates of \( 1.6 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \) and \( 3.2 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \) respectively. As may be inferred from Fig. 2a, as \( \hat{\sigma}_0 \) increases, the zenith angle distribution of muon bundles becomes less pronounced in the near-horizontal direction and becomes more like the distribution of background atmospheric bundles. However, as seen in Fig. 2b, the relatively small pairwise separation between multi-W muons may distinguish them from atmospheric muons which have much larger separation [Be89, Ah92].
Another feature of prompt muons from multi-W(Z) processes is their large energy. The average muon energy at the detector (depth 3700 hg/cm$^2$) is 50 TeV (150 TeV) for $\tilde{\sigma}_0 = 10 \mu$b (10 nb). Muons of this energy have a large probability of undergoing catastrophic energy loss as they pass through underground detectors[Al92, Me92]. In view of these characteristics, current underground experiments should not constrain their searches for AGN neutrinos to looking only in the near-horizontal direction: they can also search for multi-W interactions by looking for energetic, spatially compact muon bundles closer to the zenith.

An additional technique for discriminating multi-W muon bundles from generic muon bundles exploits the presence/absence of associated extensive air showers. Surface arrays like those at EAS-TOP and Soudan-II can furnish valuable information in this context. Even for the largest $O(10 \mu$b) cross sections we contemplate, over 99% of the corresponding vertical muon bundles originate from multi-W interactions in the Earth. Hence energetic muon bundles without an associated air shower provides an especially convincing signature. The limiting factor in such searches is the solid angle subtended by a surface array.

Fig. 2: Multi-W muon bundles detected at a depth of 3700 hg/cm$^2$ assuming the flux of Stecker et al. [St91]. Shown are curves for $\tilde{\sigma}_0 = 10$ nb (solid) and 10 $\mu$b (dashed) for a common threshold of $\sqrt{\tilde{s}_0} = 2.4$ TeV. a) Zenith angle distribution of bundles integrated with respect to $\cos \theta$. b) Distribution of pairwise muon separation. The solid histogram corresponds to normalized MACRO data (from two supermodules) from Fig. 4 of Ref. [Ah92]. Roughly 10% of the bundles are dimuons and 90% are trimuons.

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