Can new heavy gauge bosons be observed in ultra-high energy cosmic neutrino events?

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A wide range of models beyond the Standard Model predict charged and neutral resonances, generically called $W'$- and $Z'$-bosons, respectively. In this paper we study the impact of such resonances on the deep inelastic scattering of ultra-high energy neutrinos as well as on the resonant charged current $\bar{\nu}_e e^- \rightarrow X$ scattering (Glashow resonance). We find that the effects of such resonances cannot be observed with the Pierre Auger Observatory or any foreseeable upgrade of it.

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New charged and neutral resonances are predicted in many well-motivated extensions of the Standard Model (SM) such as theories of grand unification (GUTs) or models with extra spatial dimensions [1]. These extensions generally do not predict the precise energy scale at which the new heavy states should manifest themselves. However, for various theoretical reasons (e.g. the hierarchy problem) new physics is expected to appear at the TeV scale and is searched for at the Large Hadron Collider (LHC) which will soon operate at a center-of-mass energy of $\sqrt{s} = 13$ TeV. At the same time, important restrictions on new physics scenarios are imposed by low-energy precision observables. On the other hand, highly energetic interactions of cosmic rays in the atmosphere involve processes at higher center-of-mass energies than those reached by the LHC. Motivated by this fact, we study the prospects to observe new spin-1 resonances in collisions of ultra-high energy (UHE) neutrinos with nuclei in the atmosphere as analyzed by the Pierre Auger Collaboration or a future neutrino telescope. For example, for neutrinos with an energy of about $10^{19}$ eV, the center-of-mass energy of the neutrino-nucleon interactions is about $\sqrt{s} \approx 140$ TeV, considerably extending the energy range accessible at the LHC. So far, no UHE neutrino events have been observed by the Pierre Auger Observatory which has led to improved limits on the diffuse flux of UHE neutrinos in the energy range $E_\nu \gtrsim 10^{18}$ eV [2,3].

The potential of the Pierre Auger Observatory for testing new physics scenarios like extra dimensions or the formation of micro-black holes has been studied in [4] and [5]. In this report we revisit the predictions for cross sections in the SM, and we explore the impact of new charged ($W'$) and neutral ($Z'$) gauge bosons on these quantities. We address the following questions: (i) Assuming the LHC does observe new charged or neutral spin-1 resonances, how would this affect the predicted neutrino cross sections? (ii) Assuming the LHC does not discover any new spin-1 resonances, what are the prospects to observe heavy $W'$- and $Z'$-bosons with masses larger than 5 TeV using UHE cosmic neutrino events?

For definiteness, we consider $W'$ and $Z'$ bosons due to an extended $G(221) \equiv SU(2)_1 \times SU(2)_2 \times U(1)_X$ gauge group. In this framework, constraints on the parameter space from low-energy precision observables have been derived in [6] and the collider phenomenology has been studied in [7–10]. Several well-known models emerge naturally from different ways of breaking the $G(221)$ symmetry down to the SM gauge group [6], in particular Left-Right (LR) [11–13], Un-Unified (UU) [14,15], Non Universal (NU) [16,17], Lepto-Phobic (LP), Hadro-Phobic (HP) and Fermio-Phobic (FP) [18,19] models. In addition, we present results for the Sequential Standard Model (SSM) [20], where the $W'$- and $Z'$-bosons are just heavy copies of the $W$- and $Z$-bosons in the SM. This is motivated by the fact that the SSM often serves as a benchmark model in the literature [21,22].

In the SM, the following neutrino interactions can take place in the atmosphere [25,26]: (i) Charged current deep-inelastic scattering (CC DIS): $\nu_e N \rightarrow \ell^- X$, $\bar{\nu}_e N \rightarrow \ell^+ X$. Here, $\nu_\ell$ stands for the three neutrino flavors $\nu_e, \nu_\mu, \nu_\tau$. (ii) Neutral current deep-inelastic scattering (NC DIS): $\nu_\ell N \rightarrow \nu_\ell X$, $\bar{\nu}_\ell N \rightarrow \bar{\nu}_\ell X$. (iii) The Glashow resonance (GR) [27,29]: $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e + e^-$, $\nu_\ell e^- \rightarrow \nu_\ell + e^-$, $\bar{\nu}_\ell + e^-$, $\nu_e \tau$ and $\bar{\nu}_e + e^-$ also has a non-resonant neutral current $t$-channel contribution. (iv) Non-resonant neutrino-electron scattering: (a) $\nu_e e^- \rightarrow \nu_e e^-$, which has contributions from $W$ and $Z$ exchange diagrams. (b) Charged current $\nu_\mu e^-$ and $\nu_\tau e^-$ scattering in the atmosphere: $\nu_\ell e^- \rightarrow \ell^- + \nu_\ell (\ell = \mu, \tau)$. Note that the corresponding process with incoming anti-neutrinos is not possible. (c) Neutral current scattering of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, $\bar{\nu}_\tau$, and $\bar{\nu}_e$: $\nu_\ell e^- \rightarrow \nu_\ell e^-$, $\bar{\nu}_\ell + e^- \rightarrow \bar{\nu}_\ell + e^-$. In the following, we mainly focus on the dominant cross sections of neutrino–nucleon DIS and neglect the contributions from non-resonant neutrino–electron scattering which are smaller by several orders of magnitude. The $W'$- and $Z'$- resonances contribute to the $\nu N$ DIS, where the main contribution comes from the interference with the SM amplitudes. We also consider the Glashow reso-
nance, which has attracted a lot of interest in the literature as a way to detect extra-galactic neutrinos and as a discriminator of the neutrino production mechanism of the relative abundance of the pp and p\gamma sources. While the GR is entirely negligible at energies \( E_\nu \geq 10^8 \) GeV there is a new, potentially interesting, resonance due to the W'-boson which we call GR' in the following.

The differential cross section for DIS mediated by interfering gauge bosons B and B' can be written as

\[
\frac{d^2\sigma}{dxdy} = \sum_{B,B'} \frac{d^2\sigma^{BB'}}{dxdy},
\]

where the Bjorken variable x and the inelasticity y are defined as usual. Furthermore, B, B' \( \in \{W, W'\} \) in the case of CC DIS and B, B' \( \in \{\gamma, Z, Z'\} \) in the case of NC DIS. Each of these terms can be calculated from the general expression

\[
\frac{d^2\sigma^{BB'}}{dxdy} = \frac{2M_BE_\nu G_BG_{B'}}{\pi} \left\{ g_{BB'}^{+i} \left[ xF_1y^2 + F_2(1 - y) \right] \right. \\
\left. \pm g_{BB'}^{-i} \left[ xF_3y \left( 1 - \frac{y}{2} \right) \right] \right\},
\]

where the \( \pm \) refers to \( \nu p \) and \( \bar{\nu} p \) DIS, respectively. Here, \( g_{BB'}^{+i} = C_{jj,L}^{B}C_{jj,L}^{B'} \pm C_{jj,R}^{B}C_{jj,R}^{B'} \) are (anti-)symmetric combinations of the left- and right-handed gauge boson couplings to the fermions \([7]\) and \( G_B = g_B/(Q^2 + M_B^2) \) is taking into account the propagator of the gauge boson B with mass \( M_B \), and \( g_B = \frac{g_\nu}{2\sin\theta_W} \) for charged-current interactions and \( g_B = \frac{g_\nu}{2\cos\theta_W} \) for neutral-current interactions. Furthermore, \( F_{1,2,3}(x, Q^2) \) are the CC or NC DIS structure functions which are generally given as convolutions of parton distribution functions with Wilson coefficients. Here we use the expression in the ACOT scheme \([39,69]\) neglecting all the quark masses with exception of the top quark mass. The latter appears in the bottom quark initiated contribution to the charged current structure functions in form of a slow rescaling prescription where \( F_i(x, Q^2) \sim b(\chi, Q^2) + \tilde{b}(\chi, Q^2) \) with \( \chi = \frac{Q^2 + m_t^2}{2p \cdot q} \equiv x \left( 1 + \frac{m_t^2}{Q^2} \right) \).

We now turn to the Glashow resonance, i.e., the contribution to the cross section from the process \( \nu_e(p_\nu) + e^- (p_\nu) \rightarrow f_i(p_1) + \bar{f}_j(p_2) \) mediated by a resonant \( W \)- or \( W' \)-boson in the s-channel. The differential cross section can be written as

\[
\frac{d\sigma^{BB'}}{dxdy} = d\Omega \times \frac{g_{BB'}^{+i}g_{BB'}^{+j}}{32\pi^2S} \times \left[ (p_a \cdot p_3)(p_b \cdot p_1)(g_{BB'}^+g_{BB'}^+ + g_{BB'}^-g_{BB'}^-) \right. \\
\left. + (p_a \cdot p_1)(p_b \cdot p_2)(g_{BB'}^+g_{BB'}^- - g_{BB'}^-g_{BB'}^+) \right],
\]

where \( d\Omega \) is the solid angle of the final state fermion \( f_i \) which can be either a quark or a lepton, and

\[
D = \frac{(s - M_B^2)(s - M_{B'}^2) + M_BM_{B'}\Gamma_B\Gamma_{B'}}{(s - M_B^2)^2 + M_B^2 \Gamma_B^2} \frac{(s - M_{B'}^2)^2 + M_{B'}^2 \Gamma_{B'}^2}{(s - M_{B'}^2)^2 + M_{B'}^2 \Gamma_{B'}^2}.
\]

Here, \( \Gamma_B \) is the total decay width of a B-boson, which we approximate by the sum of its partial decay widths into two fermions \([1]\)

\[
\Gamma_B = \sum_{\{f_i,f_j\}} \Gamma_{B \rightarrow f_i,f_j} = \frac{g_{BB'}^{+i}g_{BB'}^{+j}}{6\pi}. \quad (5)
\]

Integrating over the solid angle \( d\Omega \) and summing over the gauge bosons \( B, B' \in \{W, W'\} \) one obtains the total GR cross section

\[
\sigma(s) = \sum_{B,B'} \frac{8g_{BB'}^{+i}g_{BB'}^{+j}}{12\pi} D. \quad (6)
\]

We are now in a position to discuss numerical results for the cross sections of UHE neutrino interactions in the atmosphere. For the CC and NC DIS, we consider an isoscalar target and neglect nuclear effects so that the structure functions are given by the average of the proton and the neutron structure functions, \( F_i = (F_i^p + F_i^n)/2 \). As is well-known, the UHE neutrino cross sections in DIS are sensitive to the PDFs at very small momentum fractions \( x \) down to \( x \approx 10^{-12} \), which results in large uncertainties as shown in Sarkar et al. \([40]\). On the other hand, the UHE neutrino cross sections are quite insensitive to the lower bound for the \( Q^2 \) integration for which we take \( Q^2_{\text{min}} = 1 \) GeV\(^2\). In our calculations we use the next-to-leading order (NLO) ZEUS2002_TR proton PDFs and QCDNUM 16.12 \([41]\) for the scale evolution of the PDFs. Furthermore, for simplicity, we neglect the contributions from the NLO Wilson coefficients which are known to be small. Note that the uncertainties due to the extrapolation of the PDFs into the small-x region and the scale uncertainties are much larger.

Our total cross sections for CC and NC DIS are displayed in Fig. 2 as a function of the incoming neutrino energy \( E_\nu \). We have verified that our cross section for CC DIS (red line) agrees with the results by Cooper-Sarkar et al. \([40]\) within a few percent in the entire energy range shown. It exceeds the CC cross section of Gandhi et al. \([20]\) by about 25% at the highest energies \( E_\nu = 10^{12} \) GeV. Conversely, our result for the NC cross section (green line) is 15% - 20% below the one in \([20]\). In addition to the SM results, we present predictions for the total cross sections in the SSM (red and green crosses) assuming

\[1\] We estimated using Pythia that the W' decay into a pair of gauge bosons is at the level of 1-2%. Note that there are regions of parameter space where the decay of the new gauge boson into additional scalars may be significant. However, even in that case this would not affect our conclusions.
presented. The areas have been obtained by fixing, de-
sections in the new physics scenario and in the SM is
can be seen in Fig. 2, where the ratio of the DIS cross
hold for the other $G^\nu$ and the SSM differ at the 1% level and the correspond-
$M_{W'} = 4$ TeV. We note that the ratio of the total cross
sections could be enhanced by about ten percent by im-
posing a suitable minimal $x_{\text{min}}$-cut on the $x$-integration
at the price of reducing the cross sections. Indeed, the
dominant contribution to the cross section comes from a
region with ultra-small $x$-values (see Fig. 3 in [22]) and
this region is shifted to larger $x$ due to the heavy reso-
nance mass so that a cut on $x$ can considerably reduce
the SM DIS cross section while affecting less the result in
the SSM. For a similar reason, any suppression of the nu-
clear PDFs in the small $x$ region due to saturation effects
would also lead to an enhanced signal to background ra-
tio. However, an increase of the SM DIS cross section by
1 or 2% is clearly not measurable with the Auger Obser-
vation or any foreseeable UHE neutrino experiment.

In Fig. 1 we also show numerical results for the pro-
duction of hadrons in resonant $\bar{\nu}_e\nu e^-$ scattering in the SM
(solid, black line) and in the SSM (dashed, black line). More specifically, we include the contributions with first
and second generation quarks in the final state. As can be
seen, the GR cross section is more than one order of mag-
nitude larger than the total CC neutrino DIS cross sec-
tion at the resonance energy $E_{\nu} = 6.2 \times 10^6$ GeV. However,
it decreases sharply away from the resonance, and the GR
cross section is smaller than the CC DIS cross section by
several orders of magnitude for energies greater than the
Auger Observatory threshold, i.e. $E_{\nu} > 10^8$ GeV. On the
other hand, the contribution from the $W'$ resonance in-
terferes destructively with the SM amplitude at energies
below $10^{10}$ GeV but leads to a clear enhancement of the
cross section in a bin around the $W'$-resonance energy
$E_{\nu}^{\text{res}} = M_{W'}^2/(2m_\nu) \simeq 1.56 \times 10^{10}$ GeV. Still it remains
more than two orders of magnitude smaller than the DIS
cross sections as can be inferred from Tab. 1 where we list
the values of the different cross sections at the peak of
the resonance with mass $M_{W'} = 4$ TeV. For this reason,
the effect of the GR’ resonance is irrelevant for events
with hadronic showers.

One way to enhance the relative importance of the new
physics signal is to consider pure ‘muon events’ discussed
in Ref. [25] as a rather background free signal of the GR
(in the SM). The corresponding cross section for the reso-
nant production of an electron or a muon is a factor
1/6 smaller than the one shown in Fig. 1 (see rows 3, 4,
and 5 in Tab. 1). As can be seen, at the resonance, the
GR’ cross section in the SSM (row 5, column 4) is about
600 times larger than the one from the SM GR (row 5,
column 3). However, it is necessary to take into account
the non-resonant production of pure muon events which,
Table I. Cross sections at $E_\nu = 1.56 \cdot 10^{10}$ GeV in the SM and the SSM assuming $M_W = M_Z = 4$ TeV. The numbers in the 6th and 7th lines have been taken from figure 8 in [20]. The elastic neutrino scattering off electrons into an electron (line 6) receives contributions from the following processes: $\nu_e e^- \rightarrow \nu_e e^-$, $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$, $\nu_\mu e^- \rightarrow \nu_\mu e^-$, and $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$. The non-resonant production of a muon (line 7) is due to the process $\nu_\mu e^- \rightarrow \mu^- \nu_e$.

| Process | $\sigma$ [pb] (SM) | $\sigma$ [pb] (SSM) |
|---------|------------------|------------------|
| 1. CC DIS $\nu_\nu N \rightarrow \mu^- + X$ | $2.84 \cdot 10^4$ | $2.84 \cdot 10^4$ |
| 2. NC DIS $\nu_\nu N \rightarrow \nu_\nu + X$ | $1.20 \cdot 10^4$ | $1.20 \cdot 10^4$ |
| 3. GR($^0$) to had. $\bar{\nu}_e e^- \rightarrow$ hadrons | $6.6 \cdot 10^{-2}$ | $41.16$ |
| 4. GR($^0$) to e $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ | $1.1 \cdot 10^{-2}$ | $6.86$ |
| 5. GR($^0$) to $\mu$ $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu \mu^-$ | $1.1 \cdot 10^{-2}$ | $6.86$ |
| 6. ES into $e^-$ $\nu_e e^- \rightarrow \nu_e e^-$, ... | $154.50$ | — |
| 7. ES into $\mu^-$ $\nu_\mu e^- \rightarrow \mu^- \nu_e$ | $102.17$ | — |

Contrary to the SM case, is more important than the resonant mechanism. The corresponding cross section in the SM, due to the process $\nu_\mu e^- \rightarrow \mu^- \nu_e$, can be inferred from Fig. 8 in [20]. It depends only very mildly on the neutrino energy for $E_\nu > 10^8$ GeV and we provide its value at the energy of the $W'$-resonance in row 7 of Tab. I. For completeness, we also list the cross section for the elastic neutrino scattering in row 6. We have not calculated the non-resonant elastic neutrino–electron scattering cross sections including additional $W'$ and $Z'$ bosons but it is reasonable to assume that such contributions will modify the SM result at the low percent level in the SSM and the G(221) models when scanning over the allowed parameter range, similar to the DIS case in Fig. 2. Therefore, we estimate that the contribution from the GR' resonance enhances the cross section for muon production in the SM by about 7% at the resonance peak. Needless to say, that this enhancement gets reduced when calculating event numbers in appropriate energy bins. In addition, we have estimated the background to the pure muon events due to CC DIS events where the hadronic shower energy is below the detection threshold which turns out to be much smaller than the signal so that it can be neglected. However, the flux of UHE neutrinos will not be known with a better precision than the uncertainty of the DIS cross sections at very small $x$. Therefore, it seems impossible for general reasons that the very precisely known leptonic cross sections can be used to discover new spin-1 $W'$ and $Z'$ resonances. In addition to these general considerations, the Auger Observatory has not yet detected UHE neutrino events. A detector with a much larger acceptance would be required to measure the much smaller UHE neutrino-electron cross sections.

In conclusion, we have computed UHE neutrino cross sections in the SSM and G(221) models including additional charged and neutral spin-1 resonances. We find that the effects of such resonances are too small to be observed with the Auger Observatory or any foreseeable upgrade of it. Conversely, should such resonances be observed at the LHC or a future hadron collider they will have no measurable impact on the UHE neutrino events. Any deviation from the SM seen in UHE cosmic neutrino events would require another explanation.

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