Multi-W(Z) Production in High-Energy Collisions?

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ABSTRACT
There exists the possibility that the cross-section for the nonperturbative production of many, $\mathcal{O}(\alpha_W^{-1} \approx 30)$, weak gauge bosons may be as large as $\mathcal{O}(100 \text{ pb} - 10 \text{ } \mu\text{b})$ above a parton-parton center-of-mass threshold in the range 2.4 - 30 TeV. We review the theoretical considerations which lead to this suggestion and outline its phenomenological implications, both for present cosmic ray as well as for future collider experiments.

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1. Introduction

Experiments at LEP are vindicating triumphantly the Standard Model, testing it with a precision approaching one part in a thousand. The only missing links are the top quark and the Higgs boson. So far LEP has given us no direct evidence for physics beyond the Standard Model. Indeed, the Standard Model may be valid, as an effective theory, up to very high energies, say the Planck mass, $10^{19}$ GeV, if the Higgs mass is below several hundreds of GeV.

This, however, does not necessarily imply that no new phenomena will be seen in the multi-TeV range, i.e. in the energy range which will be explored by LHC and SSC. There is the intriguing possibility [1-6] that, above a parton-parton center-of-mass (CM) threshold in the range $2.4 - 30$ TeV, the cross-section for the nonperturbative production of many, $\mathcal{O}(\alpha^{-1}_W \simeq 30)$, weak gauge bosons may be as large as $\mathcal{O}(100 \text{ pb} - 10 \mu\text{b})$. Unfortunately, there is only circumstantial evidence for this to happen which is, to a large extent, just based on the observation that lowest-order calculations for the production of $\mathcal{O}(\alpha^{-1}_W)$ weak gauge bosons, both with and without association of baryon and lepton number violation, violate unitarity near the threshold $\mathcal{O}(m_W/\alpha_W)$.

It is the purpose of this lecture to review the theoretical status of the subject and to discuss prospects of cosmic ray and collider experiments to constrain or even observe multi-W(Z) production in high-energy collisions.

2. ‘Theory’ of Multi-W(Z) Production

2.a. Multi-W’s(Z’s) with B & L Violation

That there may be a large cross section for the production of $\mathcal{O}(\alpha^{-1}_W)$ weak gauge bosons was suggested first [1-3] by investigations of electroweak baryon (B) and lepton (L) number violation. For definiteness, we will consider the prototype model of weak interactions, the fundamental SU(2) Higgs model with chiral fermions, defined by the following action:

$$S[W, \phi, \bar{\Psi}_L, \Psi_L] \equiv \int d^4x \left\{ -\frac{1}{2} \text{tr}(F_{\mu\nu}F^{\mu\nu}) + |D_\mu \phi|^2 - \lambda \left(|\phi|^2 - \frac{v^2}{2}\right)^2 + \sum_{j=1}^{12} \bar{\Psi}_L^{(j)} i\gamma_\mu D^\mu \Psi_L^{(j)} \right\}. \quad (1)$$
This model corresponds to the electroweak theory in the limit of \( \sin^2 \theta_W \to 0 \) and of vanishing fermion masses. The superscripts at the fermion fields \( \Psi^{(j)} \), \( j = 1, \ldots, 12 \), label the different fermionic flavours in the Standard Model with three generations.

Due to the chiral anomaly [7], \( B \) and \( L \) are not strictly conserved in the Standard Model [8]. In the presence of non-trivial \( SU(2) \) gauge fields \( W_i \), the fermionic quantum numbers change according to [8]

\[
\Delta L_e = \Delta L_\mu = \Delta L_\tau = \frac{1}{3} \Delta B = - \Delta N_{CS},
\]

where

\[
N_{CS} \equiv \frac{\alpha_W}{4\pi} \int d^3 x \, \epsilon^{ijk} \text{tr} \left( F_{ij} W_k - \frac{2i}{3} W_i W_j W_k \right)
\]
denotes the Chern-Simons number of the gauge field. As is suggested by eqs. (2) and (3), one needs strong, nonperturbative gauge fields, of order \( g^{-1} \), in the intermediate state in order to change the Chern-Simons number, or, equivalently, the fermion numbers by an integer amount. This is reflected by the fact that there exists an energy barrier [9] between gauge fields whose Chern-Simons numbers differ by an integer (Fig. 1). The minimum barrier height is given by the energy of a static saddle-point solution, the so-called “sphaleron” [10], which slightly depends on the Higgs mass and is of order

\[
M_{sp} = B \left( m_H / m_W \right) \frac{m_W}{\alpha_W} \approx (7 - 14) \text{ TeV}.
\]

At low energies (\( \ll M_{sp} \)) anomalous \( B \& L \) violating processes are only possible by quantum tunneling, i.e. the corresponding amplitudes are exponentially suppressed by a Gamow factor,

\[
A_{E \ll M_{sp}}^{\Delta N_{CS}=1} \propto e^{-\frac{2\pi}{\alpha_W}} \sim 10^{-78},
\]

which leads to unobservably small cross sections or decay rates [8].

Let us consider now high-energy parton-parton (e.g. quark-quark or neutrino-quark) collisions. As has been suggested in refs. [11,12], one expects that the dominant \( B \& L \) violating processes will involve \( \mathcal{O}(\alpha_W^{-1}) \) W’s (Z’s), simply because sphaleron-like intermediate states will typically decay into many W’s and Z’s [13]. Therefore one should try to calculate anomalous amplitudes involving an arbitrary number of weak gauge bosons,
which are given, up to analytic continuation and LSZ reduction, by the following euclidean path integral:

\[
A_{n_W}^{\Delta N_{CS}=1} \sim \int D\phi D\bar{\Psi}_L D\Psi_L e^{-S_E[W,\phi,\bar{\Psi}_L,\Psi_L]} \prod_{i=1}^{12} \bar{\Psi}_L^{(i)}(x_i) \prod_{j=1}^{n_W} W_{\mu_j}(y_j).
\]  

(6)

The leading contribution in \(\alpha_W\) to the path integral appearing in eq. (6) may be found by semiclassical methods: The integral receives its dominant contribution from that region in field space in which the euclidean action, \(S_E\), attains its minimum; i.e. one has to find a classical solution, with \(\Delta N_{CS} = 1\), and expand the integrand about it. This classical solution* is called ‘instanton’ [14].

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* Actually, some complication arises in the electroweak theory due to its mass scale introduced by symmetry breaking: by scaling arguments one may show that strictly speaking no exact solution exists [15]. A systematic semiclassical expansion can be done nevertheless if the field trajectory about which one expands is a ‘constrained instanton’ [15] or, more generally, a ‘valley trajectory’ [16].

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**Fig. 1:** The static bosonic energy \(E\) versus the Chern-Simons number and the effective radius \(R\) of the energy density distribution. Gauge fields with integer difference in Chern-Simons number are separated by an energy barrier. The minimum barrier height is taken at the sphaleron, a saddle-point solution of the static field equation, with an energy \(M_{sp} \sim m_W/\alpha_W\) and a radius \(\sim m_W^{-1}\).

Schematically, one obtains [1,2], in the leading-order expansion about the instanton,

\[
A_{n_W}^{\Delta N_{CS}=1} \text{ lead.-ord.} \sim n_W! \, \alpha_W^{n_W/2} \, e^{-2\pi/\alpha_W} \, m_W^{-n_W}. 
\]  

(7)
At high energies, these point-like amplitudes violate unitarity, since according to eq. (7) the corresponding cross-sections grow like phase space. Due to the factorial growth of the amplitudes (7) with the number of produced gauge bosons, this violation of unitarity sets in already at multiplicities of order $n_W^0 \sim 1/\alpha_W$ and at parton-parton CM energies of order $\sqrt{s_0} \sim m_W/\alpha_W$.

A violation of unitarity is, of course, unacceptable and indicates the importance of higher-order corrections. There are strong arguments that the corrections to the fixed-multiplicity amplitudes exponentiate in the total cross-section of B & L violation, such that, to exponential accuracy, the latter can be written as [17-19]:

$$\hat{\sigma}_{NCS=1}^{\Delta N_{CS}} \propto \exp \left[ \frac{4\pi}{\alpha_W} F \left( \frac{\sqrt{s}}{M_0} \right) \right],$$  \hspace{1cm} (8)

where $M_0 \equiv \pi m_W/\alpha_W$ is of the order of the sphaleron scale (4). From eqs. (5) or (7) we know that $F(0) = -1$. The crucial question is, whether the ‘holy grail function’ $F$ approaches zero at high energies: Only in this case one might hope that the total cross-section of B & L violation becomes of observable size.

**Fig. 2:** Guesses for the high-energy behaviour of the holy grail function $F$. Solid line, ref. [28]. Dashed line, ref. [29].
The perturbative expansion about the instanton yields a low-energy expansion of $F$, whose first few terms are given by [18,20-26]

$$F(\epsilon) = -1 + 0.34 \cdot \epsilon^{4/3} - 0.09 \cdot \epsilon^2 + 0.01 \cdot \left( 4 - 3 \frac{m_H^2}{m_W^2} \right) \cdot \epsilon^{8/3} \cdot \ln \left( \frac{1}{\epsilon} \right) +$$

$$+ \mathcal{O} \left( \epsilon^{8/3} \cdot \text{const.} \right), \quad (9)$$

where $\epsilon \equiv \sqrt{s}/M_0$. From this result the following conclusions can be drawn:

– The total cross-section of B & L violation is exponentially growing, albeit exponentially small, at $(m_W \ll \sqrt{s} \ll M_0)$.

– The different terms in the perturbative expansion of the holy grail function become of comparable size, i.e. the perturbative expansion breaks down, at $\sqrt{s} \sim M_0$.

As a side-remark we note, that, at low energies, the total cross-section (8) is dominated by multi-W(Z) production ($n_W \sim \alpha_W^{-1}$) rather than by multi-Higgs production.

Nothing is known about the behaviour of the holy grail function at energies of the order of the sphaleron scale and above. There are various guesses (see Fig. 2) but a systematic calculation of it is not available at present. Since instanton-based perturbation theory breaks down at the sphaleron scale, new methods have to be developed in order to attack this problem (for reviews see ref. [27]) and to decide ultimately if electroweak B & L violation with the associated production of many W’s and Z’s will be observable at LHC or SSC.

2.b. Multi-W’s(Z’s) without B & L Violation

Soon after the discovery of the high-energy and high-multiplicity breakdown of perturbation theory about the instanton it was suggested that also conventional perturbation theory based on Feynman graphs, as relevant to processes without B & L violation, breaks down at high energies and multiplicities [4,5]. It was argued that perturbative tree-graph amplitudes for multi-Higgs [4,5] and multi-W(Z) [4,30] production have a similar factorial growth with the number of external legs as the leading-order instanton-induced amplitudes (7),

$$\mathcal{A}_{n_W \text{tree-graph}}^{\Delta N_{CS}=0} \sim n_W! \alpha_W^{-n_W/2} m_W^{-n_W}, \quad (10)$$

leading again to a violation of unitarity at large multiplicities of order $\alpha_W^{-1}$ and energies of order $m_W/\alpha_W$. Due to the absence of the Gamow factor (5) in B & L conserving processes,
the tree-level onset of the violation of unitarity for these processes may be at a somewhat smaller energy and multiplicity than for B & L violating processes. There is a lot of ongoing work in this direction, which deals, for technical reasons, mainly with multi-Higgs production [31,32] (for a review see [33]). There are general arguments [34], based on dispersion relations for forward elastic scattering amplitudes and the assumption that perturbation theory is asymptotic, that multi-particle production in weakly-coupled theories is always exponentially suppressed,

\[ \hat{\sigma}_{nW} \geq o(\alpha^{-1}_W) \leq e^{-c/\alpha_W}. \] (11)

This, however, does not exclude the possibility of a small coefficient \( c \ll 1 \), such that numerically an observable cross-section results [35].

3. ‘Phenomenology’ of Multi-W(Z) Production

In this section we want to discuss the prospects to observe or constrain possible multi-W(Z) phenomena in experiments dedicated to investigate ultrahigh-energy cosmic rays or in experiments at future hadron colliders such as LHC or SSC.

3.a. Working Picture

In order to confront the idea of possible multi-W(Z) production with experiments some working hypothesis is needed. We will assume [36], as suggested by the results reported above, a sudden onset of multi-W(Z) phenomena on the parton (quark, lepton) level above a certain threshold energy \( \sqrt{s_0} \):

\[ \hat{\sigma}_{nW}^0 = \hat{\sigma}_0 \cdot \theta(\sqrt{s} - \sqrt{s_0}), \] (12)

where the parton cross-section \( \hat{\sigma}_0 \) and the threshold \( \sqrt{s_0} \) lie in between

\[ 0.1 \text{ nb} \sim \frac{\alpha^2_W}{m^2_W} \leq \hat{\sigma}_0 \leq \sigma_{pp}^{\text{inelastic}} \cdot \left( \frac{1 \text{ GeV}}{m_W} \right)^2 \sim 10 \mu \text{b}, \] (13)

\[ 2.4 \text{ TeV} \sim \frac{m_W}{\alpha_W} \leq \sqrt{s_0} \leq 30 \text{ TeV}. \] (14)

For definiteness, we will take

\[ n_W^0 = 30 \] (15)
for the number of produced weak vector bosons*.

The cross-section for multi-W(Z) production in proton-proton and neutrino-nucleon collisions (Fig. 3) is obtained by folding eq. (12) with the corresponding valence- and sea-quark distributions inside the nucleons:

\[
\sigma_{pp}^{0W}(\sqrt{s}) = \sum_{ij, (no \text{ gluons})} \frac{1}{1+\delta_{ij}} \int dx_1 dx_2 \ f_i(x_1)f_j(x_2) \ \hat{\sigma}_{n_0}^{0W}(\sqrt{x_1x_2s}),
\]

(16a)

\[
\sigma_{\nu N}^{0W}(\sqrt{s}) = \sum_{i, (no \text{ gluons})} \int dx \ f_i(x) \ \hat{\sigma}_{n_0}^{0W}(\sqrt{x s}).
\]

(16b)

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**Fig. 3:** Universal curves parametrizing the production cross-sections of \(n_0^W\) weak vector bosons in proton-proton (pp) and neutrino-nucleon (\(\nu N\)) collisions, where \(\sqrt{s}\) is the total CM energy (from ref. [38]).

With the help of (16a) it is possible to calculate the expected event rate of multi-W(Z) processes at LHC (\(\sqrt{s} = 16\) TeV; \(L=10^{34} \text{ cm}^{-2}\text{s}^{-1}\)) and SSC (\(\sqrt{s} = 40\) TeV; \(L=10^{33} \text{ cm}^{-2}\text{s}^{-1}\)), as a function of the parton cross-section \(\hat{\sigma}_0\) and the threshold energy \(\sqrt{s_0}\).

From Fig. 4 it is apparent that LHC can cover only a part of the parameter space, eqs. (13) and (14), which we are contemplating, whereas SSC will be much better in this respect.

Let us have a closer look on the hard parton-parton subprocess in which, say, 30 W’s are produced. These W’s decay immediately into about 400 charged hadrons (mainly \(\pi^{\pm}\)’s), with average transverse momenta of order

\[p_T^\pi \sim \mathcal{O}(m_W/30) \sim (2 - 3) \text{ GeV},\]

(17)

* Results for other values of \(n_0^W\) may be obtained essentially by scaling [36].
and 400 photons (mainly from $\pi^0$'s). In addition one has about 5 prompt muons (3 from $W$ decay and 2 from c, b, or $\tau$ decay), with transverse momenta of order

$$p_T^\mu \sim \mathcal{O}(m_W/2) \sim 40 \text{ GeV}. \quad (18)$$

Similar numbers of other prompt leptons, like electrons, positrons and neutrinos are expected. It is hard to imagine that any other process in the Standard Model can mimick such a final state [36]. However, it is not clear if it will be possible to see any signal of B & L violation in this multi-particle environment [36,37].

**Fig. 4:** ‘Discovery limits’ for multi-$W(Z)$ phenomena at pp colliders and in underground cosmic ray experiments (taken from refs. [39,41]).

To the left of the solid lines labeled ‘LHC’ and ‘SSC’: more than 100 multi-$W(Z)$ events per year at the corresponding collider.

To the left of the dashed line labeled ‘MACRO’: more than one neutrino-initiated multi-$W(Z)$ muon bundle passing through MACRO during 10 years of running, assuming the (revised) neutrino flux from Stecker et al. [43].

Shaded region: Excluded region from Fly’s Eye limits [45], assuming the (revised) neutrino flux from Stecker et al. [43].
3. b. Multi-W(Z) Phenomena in Cosmic Rays

Since LHC and SSC will be operational only in about a decade, it is worthwhile [38] to consider also the prospects of observing or constraining multi-W(Z) phenomena initiated by the interaction of ultrahigh-energy cosmic ray particles with nucleons in the atmosphere or inside the Earth. The energies (in the Earth’s rest frame) of the primaries should exceed

\[ E \geq \frac{\hat{s}_0}{2m_p} \geq 3.3 \cdot 10^6 \text{ GeV}. \]  \hspace{1cm} (19)

One may consider multi-W(Z) processes initiated by cosmic ray protons and neutrinos: The corresponding (model-dependent) fluxes of protons and neutrinos are shown in Fig. 5.

**Fig. 5:** *Differential fluxes of diffuse cosmic ray protons and neutrinos.*

*Full line:* differential flux of neutrinos from active galactic nuclei as predicted by Stecker et al. (revised) [43].

*Dashed line:* differential flux of protons according to the constant-mass-composition model of ref. [44].

Multi-W phenomena initiated by cosmic ray *protons* are plagued [39] by small rates and poor signatures due to competing purely hadronic processes with $\mathcal{O}(40)$ mb cross-sections. The primary multi-W(Z) process takes place inevitably at the top of the atmosphere and generates an extensive air shower, whose observable characteristics at a ground-level air-shower array, like the MeV-electron component and the GeV-muon component, resembles closely the characteristics of a generic extensive air shower, initiated by a cosmic ray hadron via strong interactions. Moreover, the overall rate of air showers initiated by protons via
multi-W(Z) production is a factor of at least $(10 \mu b / 40 \text{ mb}) \sim 10^{-4}$ smaller than the rate of generic air showers. A characteristic difference between proton-initiated multi-W(Z) air showers and generic air showers is seen in the lateral distribution of the muons with energies above 1 TeV, which may be observed in underground or underwater detectors: The most energetic muons, which originate from W-decay and have a high transverse momentum (see eq. (18)), lead to an excess of muons at distances larger than about 20 m from the shower core. However, underground (underwater) detectors of a size of about $10^5 \text{ m}^2$ are needed in order to expect an appreciable rate of proton-initiated multi-W(Z) muon bundles [38,39]. That means that only the biggest underwater detectors such as DUMAND or NESTOR can expect sizeable rates.

By contrast, multi-W(Z) processes initiated by ultrahigh-energy neutrinos compete only with relatively small $\mathcal{O}(\text{nb})$ charged-current reactions. Moreover, even for the largest, $\mathcal{O}(10 \mu b)$, cross-section we contemplate, over 99% of the primary-neutrino interactions (for vertically incident neutrinos) take place within the Earth rather than in the atmosphere. Due to the large density of rock (or water), all the hadrons and photons from W-(Z-)decay are quickly absorbed. Only the few (three, for $n_W^0 = 30$ W-bosons) prompt muons from W-(Z-)decay, with energies of order 100 TeV and transverse momenta of order 40 GeV, penetrate further, giving rise eventually to a multiple muon event in an underground (underwater) detector [38,40]. The most promising characteristic features [38,39,41] of neutrino-initiated multi-W(Z) muon bundles, distinguishing them from generic atmospheric muon bundles, are the large muon energies, $\mathcal{O}(100 \text{ TeV})$, leading to visible non-ionization energy losses within underground or underwater detectors [42], and the small pairwise muon separation, $\mathcal{O}(20 \text{ cm})$.

In order to calculate the expected rate of neutrino-initiated multi-W(Z) muon bundles in an underground detector one needs to know the incident flux of neutrinos at ultrahigh energies, eq. (19). Recent models have predicted a sizeable ultrahigh-energy neutrino flux from active galactic nuclei [43], see Fig. 5. As can be inferred from Fig. 4, MACRO, a big $(72 \text{ m} \times 12 \text{ m} \times 4.8 \text{ m})$ underground detector situated in Italy at a depth of 1.4 km under the Gran Sasso, can cover already a (small) region of multi-W(Z) parameter space [39,41] until LHC or SSC become operational, under the assumption that the predictions of the ultrahigh-energy neutrino flux in ref. [43] are correct.
It is interesting to note that, under the same assumption, already a part of multi-W(Z) parameter space is excluded [38-41], see Fig. 4. The point is that some of the ultrahigh-energy neutrinos may initiate, via multi-W(Z) production, extensive air showers, starting deep in the atmosphere. The Fly’s Eye air-shower array searched exactly for such a signature [45], namely for air showers initiated by weakly interacting particles (which we will assume are neutrinos) which had penetrated more than 3000 g/cm² of atmosphere before interacting, thus excluding photons or hadrons as primaries. From the nonobservation of such showers they deduce upper limits on the flux times cross-section for primary energies in the range \(10^8 \text{ GeV} \leq E_\nu \leq 10^{11} \text{ GeV}\); explicit parametrizations of the Fly’s Eye limits may be found in refs. [38,46]. The limit applies only for \(\sigma_{\nu N}^{\text{tot}} \leq 10 \mu \text{b}\), since the possibility of flux attenuation is neglected. Using a particular flux model, like the (revised) Stecker et al. [43] flux of ultrahigh-energy neutrinos from active galactic nuclei, the Fly’s Eye limit translates into an upper bound on the neutrino-nucleon cross-section and, finally [39,41], into an excluded region in multi-W(Z) parameter space, see Fig. 4.

4. Summary

Lowest-order perturbative calculations of the cross-section for the production of \(n_W\) weak gauge bosons in parton-parton (e.g. quark-quark or neutrino-quark) scattering violate unitarity at parametrically large multiplicities, \(n_W^0 \sim \alpha_W^{-1}\), and energies, \(\sqrt{s_0} \sim m_W/\alpha_W\). This happens both for processes with and without associated B & L violation. At present, it is an open question whether the actual (– beyond perturbation theory –) multi-W(Z) cross-sections become observably large at such multiplicities and energies. New theoretical methods are needed to answer this important question.

Multi-W(Z) processes at LHC or SSC would be clearly distinguishable from any other Standard Model process, due to the hadronic and leptonic decays of the W’s and Z’s, which lead to hundreds of charged hadrons and photons with transverse momenta in the GeV range, and to tens of prompt leptons with transverse momenta of order 40 GeV. The question whether B & L violation can directly be seen in such a multi-particle environment requires further investigations. Due to its higher proton-proton CM energy, SSC can cover a much larger range of parton-parton multi-W(Z) threshold energies and cross-sections than LHC, see Fig. 4.
Ultrahigh-energy cosmic ray physics is another area where one could look for possible multi-W(Z) production. Current underground detectors such as MACRO are already sensitive to neutrino-initiated multi-W(Z) muon bundles, which are clearly distinguishable from atmospheric muon bundles, for sufficiently low parton-parton threshold energies and large cross-sections, see Fig. 4. Thus, we have not to wait until LHC or SSC are operating in order to constrain or even observe multi-W(Z) production in high-energy collisions.

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