PROSPECTS FOR MULTIPLE WEAK GAUGE BOSON PRODUCTION AT SUPERCOLLIDER ENERGIES

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ABSTRACT

We discuss the prospects for observing multiple weak gauge boson production at the SSC and LHC. We summarize conventional perturbative cross sections for processes involving 1-6 final state weak gauge bosons and compare them with more speculative scenarios including 1) a toy model of a strongly interacting Higgs sector patterned after hadronic multipion production and 2) the nonperturbative production of $\gtrsim O(\alpha_W^{-1}) \simeq 30$ weak gauge bosons in a weakly coupled gauge sector.

1. Introduction

The purpose of the Superconducting Super Collider (SSC) is to explore the nature of the electroweak symmetry breaking sector and, in the process, possibly provide a first glimpse beyond the familiar physics of the minimal standard model (MSM). With the realization of the SSC on the horizon, the phenomenology of a MSM Higgs boson between $80 \text{ GeV} \lesssim M_H \lesssim 800 \text{ GeV}$ has been repeatedly reworked in order to demonstrate the feasibility of a comprehensive search. But aside from the tangible goal of the Higgs boson there could also be new phenomena awaiting us in the domain of multi-TeV weak interactions.

In this paper we discuss the phenomenology of possible surprises in multi-TeV weak interactions at hadron supercolliders. In particular we investigate whether multiple weak gauge boson production can effectively signal the presence of nonperturbative phenomena in either the electroweak symmetry breaking sector or the weak gauge sector. For definiteness, we concentrate on two specific scenarios: 1) a toy model for strong dynamics in the weak symmetry breaking sector where the inelastic scattering of longitudinal weak gauge bosons is patterned after inelastic...
hadronic multipion processes\(^2\) and 2) a model in which nonperturbative effects in the weak gauge sector lead to potentially large cross sections for the production of \(\gtrsim \mathcal{O}(\alpha_W^{-1}) \simeq 30\) weak gauge bosons\(^3\)\(^-\)\(^5\). We focus on these scenarios not because there is convincing theoretical justification for either but rather because both admit a straightforward analysis which suggests the prospects for their observation (if indeed they exist at all). Our analysis will typify the requirements for exposing new phenomena involving multiple gauge boson production in the environment of a hadron supercollider.

The outline of the paper is as follows. In sect. 2 we present the conventional expectations for multiple gauge boson production at hadron colliders. Sect. 3 discusses a strongly interacting Higgs sector modeled after hadronic multipion processes and sect. 4 outlines the spectacular signatures anticipated if nonperturbative phenomena in the weak gauge sector appear above parton-parton center of mass energies in the multi-TeV range. In sect. 5 we summarize our results and conclude.

Fig. 1. Production rates of weak gauge bosons at accelerators assuming:
\[
\begin{align*}
\mathcal{L}_{SppS} &= 6 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1} \text{ with two detectors at } \sqrt{s_{pp}} = 63 \text{ TeV}; \\
\mathcal{L}_{Tevatron} &= 6 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1} \text{ with two detectors at } \sqrt{s_{pp}} = 1.8 \text{ TeV}; \\
\mathcal{L}_{LEP} &= 1.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \text{ with four detectors at } \sqrt{s_{e^+e^-}} = 91.17 \text{ GeV}; \\
\mathcal{L}_{SSC} &= 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \text{ with two detectors at } \sqrt{s_{pp}} = 40 \text{ TeV}; \\
\mathcal{L}_{LHC} &= 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \text{ with two detectors at } \sqrt{s_{pp}} = 14.6 \text{ TeV}. 
\end{align*}
\]

Rates are dominated by processes involving single W and Z production. Hadron collider cross sections are from Ref. 6.

2. Conventional Perturbative Results

Since the 1983 CERN debut of the W and Z bosons, progress in accelerator technology has fostered the notion that current and future facilities effectively act as W and Z factories. The SSC and LHC will take the industrialization of weak gauge boson production well beyond the current prolific success of LEP and lead to the production rates of \(\mathcal{O}(10^2 - 10^3)\) bosons/s (see Fig. 1). Not only will hadron supercolliders make single weak gauge boson production typical, but also they will advance the study of multiple weak gauge boson processes.

Fig. 2 Perturbative cross sections relevant to weak gauge boson production at the SSC. Processes involving strongly produced \(t\) quarks are indicated by darker shading. \(\sigma(W^+ + W^-)\) and \(\sigma(Z)\) are from Ref. 6. Rates for nonresonant WWWW and ZZZZ production are from Ref. 8; \(\sigma(WWWZ), \sigma(WWZZ)\) and \(\sigma(WZZZ)\) are estimated assuming \(\sigma(4Z) = f^4\sigma(4W)\) so that each additional Z reduces the cross section by \(f \simeq 0.43\). Nonresonant \(6t\) rate is estimated assuming \(\sigma(6t)/\sigma(4t) = \sigma(4t)/\sigma(2t)\). Remaining cross sections are compiled from Ref. 7.

Figure 2 indicates the relative importance of various perturbatively calculable processes relevant to weak gauge boson production at the SSC. One of the most
notable features is the role of $t$ quark contributions: each $t$ quark decay in the standard model produces a $W$ boson. As pointed out by Barger, Stange and Phillips\textsuperscript{7} copious $W$ production from the weak decays of strongly produced $t$ quarks presents a serious background to processes such as nonresonant $WWWW$ production.

By multiplying the processes of Fig. 2 by the appropriate branching fractions to weak gauge bosons, one obtains in Fig. 3 the SSC cross section as a function of the total weak gauge boson multiplicity $n_W + n_Z$. An annual SSC integrated luminosity of $10 \text{ fb}^{-1}$ suggests the production of (but not necessarily detection of!) $\mathcal{O}(1)$ event/year containing five or more weak gauge bosons. This provides us with a useful reference point for our subsequent discussion of more speculative mechanisms for multiple gauge boson production.

Fig. 3 SSC cross section for total weak gauge boson multiplicity $n_W + n_Z$ summed over the processes of Fig. 2. Also shown (dashed) is the cross section omitting contributions from $t$ quarks (dark shaded processes in Fig. 2).

3. A Strongly Interacting Symmetry Breaking Sector?

The MSM has repeatedly defended its position as an accurate and economical description of Nature at all energy scales probed by experiments to date. This is not to say that the MSM is a definitive model; rather, we have not yet achieved laboratory energies sufficient to test all its attendant features — this is the purpose of the SSC. Aside from searching for the Higgs boson, supercolliders can also investigate the nature of the breakdown of $SU(2)_L \times U(1)_Y$. Whereas the Higgs potential of the MSM can accommodate a weakly coupled theory, it might turn out that the breakdown of $SU(2)_L \times U(1)_Y$ is actually due to underlying strong dynamics (e.g., like technicolor\textsuperscript{9}).

The obvious place to look for possible effects of underlying strong dynamics is in the scattering of longitudinal weak gauge bosons $W_L \sim W_{L}^{\pm}, Z_L$ which, through the equivalence theorem of Cornwall, Levin and Tiktopoulous\textsuperscript{10}, are intimately related to the corresponding Goldstone bosons $w \sim w^{\pm}, z$ ensuing from symmetry breakdown. The simplest manifestation of strong dynamics would be the appearance of resonances in assorted $ww \rightarrow pp$ channels\textsuperscript{‡}. Though there is not yet a preferred candidate for a theory of such resonances, a variety of phenomenological models involving resonances has been studied with moderately encouraging results\textsuperscript{11}. In this section we wish to go beyond strong ($2 \rightarrow 2$) scattering in the symmetry breaking sector and discuss the possibility of inelastic ($2 \rightarrow \text{many}$) processes. Though such channels may not be a priority for discovering underlying strong dynamics, they would nevertheless be present and should be investigated.

The absence of a viable theory of strong dynamics for $ww \rightarrow pp$ scattering is exacerbated when one contemplates $ww \rightarrow \text{multi-w}$ processes. To circumvent this problem, consider the following analogy. The symmetry-breaking Lagrangian

\textsuperscript{‡} For the remainder of this section we will exploit the equivalence theorem and express our results in terms of the equivalent Goldstone bosons $w \sim \{w^{\pm}, z\}$.
of the MSM is that of a $SU(2)_L \times SU(2)_R$ chirally symmetric linear $\sigma$ model: the
same type of model that successfully describes low-energy $\pi\pi$ scattering (e.g., for
$\sqrt{s_{\pi\pi}} \lesssim 700$ MeV). The correspondence between the two theories is expressed by
the associations

$$w \leftrightarrow \pi,$$
$$H \leftrightarrow \sigma,$$
$$v \simeq 246 \text{ GeV} \leftrightarrow f_\pi \simeq 93 \text{ MeV},$$

so that, at least formally, linear $\sigma$ model predictions for low-energy $\pi\pi$ scattering
are related to MSM predictions for $ww$ scattering at a cms energy $\sqrt{s_{ww}}$ by equating

$$\sqrt{s_{ww}} = \frac{v}{f_\pi} \sqrt{s_{\pi\pi}} \simeq 2600 \sqrt{s_{\pi\pi}}.$$  \hspace{1cm} (4)

The logical leap we propose is to take the analogy between the low-energy limits of two models (i.e., between the linear $\sigma$ model below $\sqrt{s_{\pi\pi}} \lesssim 700$ MeV and
the MSM symmetry breaking sector below $\sqrt{s_{\pi\pi}} \lesssim 2$ TeV) and, by fiat, to extend
the analogy to higher energies. By doing so, we treat $ww \rightarrow \text{multi}-w$ processes as scaled-up versions of multipion production (with the same scaling factor as in
Eq. 4). Admittedly, there is no compelling physics reason why Nature should use inelastic pion physics as a detailed template for $ww$ scattering — we adopt this
ansatz simply for its definiteness. In general, if the underlying strong dynamics
does not replicate pion physics there will be additional weak Goldstone bosons in
the spectrum\textsuperscript{12} and the scaling in Eq. 4 is modified with the consequence that
inelastic multi-$w$ phenomena generally appear below $\sqrt{s_{ww}} \simeq 2$ TeV.

Once the decision is made to pattern $ww \rightarrow \text{multi}-w$ processes after multipion production, many details follow naturally. As one anticipates a near-constant
$\pi\pi$ cross section of $\sigma_{\pi\pi}^{\text{total}} \simeq \mathcal{O}(15 \text{ mb})$ above $\sqrt{s_{\pi\pi}^{\text{inelastic}}} \simeq \mathcal{O}(1 \text{ GeV})$ due to the
production and decay of many low-lying hadronic resonances, one might similarly
expect

$$\hat{\sigma}(ww \rightarrow \text{multi}-w) = \hat{\sigma}_0^{ww} \Theta(\hat{s}_{ww} - \hat{s}_0^{ww}),$$

where $\hat{\sigma}_0^{ww} = (f_\pi/v)^2 \times \sigma_{\pi\pi}^{\text{total}} \simeq \mathcal{O}(1 \text{ nb})$ and $\sqrt{s_0^{ww}} = (v/f_\pi) \times \sqrt{s_{\pi\pi}^{\text{inelastic}}} \simeq \mathcal{O}(2 \text{ TeV}).$

Just as the total inelastic $\pi\pi$ cross section receives contributions from final states
with variable multiplicity, so too must $\hat{\sigma}_0^{ww}$ be partitioned. In practice one assumes
a Poisson multiplicity distribution with a mean determined by the average pion
multiplicity for the corresponding $\pi\pi$ process\textsuperscript{2}. Limited transverse momentum
in hadronic reactions suggests $\langle p_T \rangle_w \simeq (v/f_\pi) \times \langle p_T \rangle_{QCD} \simeq 1 \text{ TeV}$. The cms energies
of the SSC and LHC are actually too low for such “limited” $\langle p_t \rangle_w$ to be of concern — for all practical purposes multi-$w$ final states would be essentially isotropic.

The $pp$ cross section for multi-$w$ production follows from Eq. 5 by using the
effective vector boson approximation\textsuperscript{13} and writing

$$\sigma_{\text{multi}-w}(\sqrt{s}) = \sum_{w_i w_j} \int dx_1 dx_2 \, f_{w_i}(x_1) \, f_{w_j}(x_2) \, \hat{\sigma}_0^{ww} \Theta(x_1 x_2 s - \hat{s}_0^{ww}).$$

(6)
The double sum extends over $w_i \sim \{w^\pm, z\}$ where $f_{w_i}(x)$ is the distribution function of $w_i$ carrying a fraction $x$ of the original proton momentum. Specifically,

$$f_{w_i}(x) = \sum_k \int_x^1 \frac{dy}{y} f_k(y) P_{w_i/k}(\frac{x}{y}),$$

where $f_k(y)$ is the distribution function for quarks or antiquarks of species $k$ inside a proton. The splitting function $P_{w_i/k}(x)$ is the probability that a Goldstone boson $w_i$ carries away a momentum fraction $x$ from a parent quark of species $k$.

Fig. 4 compares the multi-$w$ cross sections at the SSC and LHC (for $\hat{\sigma}_0^{ww} = 1$ nb, $\sqrt{\hat{s}_0^{ww}} = 2$ TeV) to the conventional contributions of Fig. 3. Before any $w$ or $z$ decays are taken into account, $\sigma_{pp}^{\text{multi-}w} \simeq 33$ fb (.85 fb) at the SSC (LHC).

Practical signatures of multiple weak gauge boson production should be phrased in terms of jets and high-$p_T$ leptons. To do this one must impose the relevant $W$ and $Z$ branching fractions on the multi-$w$ signal, the background processes of Fig. 2 as well as on processes related to those of Fig. 2 by additional QCD bremsstrahlung. A simple parton-level analysis based on counting the number of jets plus leptons then gives an idea of the signatures required to see multiple-$w$ production.

Consider multi-$w$ signatures composed of $n_Z$ leptonically reconstructed $Z$'s, $n_l$ prompts leptons (excluding those from $Z$ decay) and $n_{\text{jets}}$ hadronic jets. Assuming $\hat{\sigma}_0^{ww} = 1$ nb and $\sqrt{\hat{s}_0^{ww}} = 2$ TeV the SSC cross section for signatures with $n_Z = 0$, $n_{\text{jets}}/2 + n_l \geq 9$ (with $n_l \geq 2$, $n_{\text{jets}} \geq 6$) is $\simeq .5$ fb with a background of $\simeq .02$ fb. Requiring one leptonically reconstructed $Z$ ($n_Z = 1$) and $n_{\text{jets}}/2 + n_l \geq 6$ (with $n_l \geq 1$, $n_{\text{jets}} \geq 6$) results in a signal (background) of $\simeq .6$ fb ($\simeq .03$) fb. Requiring more than one leptonically reconstructed $Z$ does not enhance the signal. In summary, the $\simeq 33$ fb total yield of multi-$w$ production is reduced to $\mathcal{O}(1 \text{ fb})$ of usable signal which corresponds the production of $\gtrsim 6$ Goldstone bosons. Though such a simple analysis can not be considered conclusive, it nevertheless gives a flavour of the signatures required.

Fig. 4. Contributions to multiple weak gauge boson production the SSC (solid) and LHC (dashed) from conventional processes (see Fig. 2) and a strongly interacting Higgs sector modeled after inelastic $\pi\pi$ physics. The multi-$w$ curves correspond to $\hat{\sigma}_0^{ww} = 1$ nb, $\sqrt{\hat{s}_0^{ww}} = 2$ TeV in Eq. 6.

4. A Nonperturbative Weak Gauge Sector?

Considerable excitement was generated a few years ago when Ringwald\textsuperscript{3} and Espinosa\textsuperscript{4} pointed out a curious problem involving the production of $\mathcal{O}(\alpha_W^{-1}) \simeq 30$ weak gauge bosons in the multi-TeV range. The excitement (and controversy) concerned the results of a classical approximation to a nonperturbative problem involving the violation of baryon plus lepton number in high energy standard model processes. Whereas it was generally believed that the amplitudes for such processes
are exponentially suppressed by a tunneling factor \( e^{-2\pi/\alpha_W} \simeq 10^{-85} \). Ringwald and Espinosa demonstrated that enormous combinatorial factors arising from the large number of final state particles might come to the rescue and compensate for the presumed suppression. Unfortunately, the classical approximation is known to become unreliable in precisely the region where the interesting claims were being made; in this context it is difficult to say whether the suggestions of relatively unsuppressed multiple gauge boson production should be taken seriously or whether they are simply calculational artifacts.

The findings of Ringwald and Espinosa inspired considerable activity intent on sorting fact from fiction concerning multiple gauge boson production. Cornwall and Goldberg pointed out that dreams of unsuppressed multiple gauge boson production need not be restricted to baryon plus lepton number violating processes: the failure of weak perturbation theory for the production of \( \mathcal{O}(\alpha_W^{-1}) \) weak bosons is a generic feature of large-order processes. The situation today remains unresolved. While no one has demonstrated the theoretical necessity for observably large cross sections for nonperturbative processes involving multiple gauge boson production, likewise no one has produced irrefutable opposing arguments. The only consensus is that 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; the SSC can test whether or not the corresponding physical cross sections are large or small.

Whereas the nonperturbative multi-\( w \) processes discussed in Sect. 3 were due to a strongly coupled theory and produced only a handful of Goldstone bosons, the nonperturbative phenomena we wish to discuss in this section are due to the failure of perturbation theory for the production of \( \mathcal{O}(30) \) weak gauge bosons in a weakly coupled theory. To distinguish between these two cases, let us refer to the former as multi-\( w \) processes (emphasizing the role of strong dynamics between Goldstone bosons \( w^\pm, z \) in the Higgs sector) and to the latter as multi-W processes (which in principle can act in gauge sector).

In the absence of firm theoretical guidance, we parameterize nonperturbative parton-parton multi-W processes by

\[
\hat{\sigma}(qq \to \text{multi} - W) = \hat{\sigma}_0^{WW} \Theta(s_0^{WW} - \hat{s}_0^{WW}),
\]

where the scale \( s_0^{WW} \) is set by the breakdown of perturbation theory for processes involving the production of \( \mathcal{O}(\alpha_W^{-1}) \simeq 30 \) weak gauge bosons (i.e., \( \sqrt{s_0^{WW}} \gtrsim 30M_W \simeq 2.4 \text{ TeV} \)). While there is no strong motivation for the range of \( \hat{\sigma}_0^{WW} \), an optimistic range to consider might encompass

\[
\frac{\alpha_W^2}{M_W^2} \simeq 100 \text{ pb} \lesssim \hat{\sigma}_0^{WW} \lesssim \sigma_{\text{inelastic}}^{pp} \times \left( \frac{1 \text{ GeV}}{M_W} \right)^2 \simeq 10 \mu\text{b},
\]

where the lower limit is characteristic of a geometrical weak cross section and the upper limit follows from an analogy between the weak SU(2) gauge sector and the color SU(3) gauge sector.\(^5\)
Fig. 5. Contributions to multiple weak gauge boson processes at the SSC (solid) and LHC (dashed) from conventional perturbatively calculable processes (see Fig. 2) and hypothetical nonperturbative processes involving the production of $O(\alpha_W^{-1}) \simeq 30$ weak gauge bosons. The multi-W curves correspond to $\hat{\sigma}_0^{WW} = 1 \text{ pb}$, $\sqrt{\hat{s}_0^{WW}} = 10 \text{ TeV}$ in Eq. 10.

Folding the $qq$ cross section with quark distribution functions yields

$$\sigma_{pp}^{\text{multi-W}}(\sqrt{s}) = \sum_{ij} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_0^{WW} \Theta(x_1 x_2 s - \hat{s}_0^{WW}). \tag{10}$$

Figure 5 shows the expected cross sections at the SSC and LHC for $\hat{\sigma}_0^{WW} = 1 \text{ pb}$, $\sqrt{\hat{s}_0^{WW}} = 10 \text{ TeV}$. For this set of parameters $\sigma_{pp}^{\text{multi-W}} \simeq 300 \text{ fb} (0.02 \text{ fb})$ at the SSC (LHC). We interpret $\hat{\sigma}_0^{WW}$ as the parton-parton cross section summed over all gauge boson multiplicities; for purposes of illustration, Fig. 5 partitions the cross section according to a Poisson distribution with a mean of 30. The enormous multiplicity of central hadrons, photons and prompt leptons from the simultaneous decays of 30 gauge bosons has no conceivable background in the MSM. The striking nature of such events at colliding beam facilities, especially their central nature and large traverse energy would make even one or two events sufficient to demonstrate the presence of phenomena beyond that expected from perturbation theory$^5,16$.

Given the spectacular nature of multi-W processes, one might wonder if their existence might not already be constrained by cosmic ray physics experiments. Surprisingly, non-accelerator experiments impose few firm constraints on such phenomena$^17$. If $\sqrt{\hat{s}_0^{WW}} \lesssim 10 \text{ TeV}$ and $\hat{\sigma}_0^{WW} \gtrsim 100 \text{ nb}$ only $O(1 - 1000)$ extensive air showers of multi-W origin induced by cosmic protons would be expected in an 100 km$^2$ surface array in one year. Unfortunately, the characteristics of such air showers would be exceedingly difficult to distinguish from fluctuations in a background which is $O(10^4 - 10^5)$ times larger.

A more promising scenario, but one which involves an additional degree of speculation, involves the possibility of observing multi-W processes induced by cosmic neutrinos. Unlike proton-induced multi-W processes which must compete with $O(100 \text{ mb})$ generic hadronic processes, neutrino-induced multi-W processes compete only with $O(\text{nb})$ generic charged current cross sections — but one has to first assume that a sizeable flux of ultrahigh energy neutrinos exists!

Among the signatures of neutrino-induced phenomena is the underground detection of energetic, spatially compact bundles of muons: typical reactions occur underground so that only 2-3 prompt muons from W decays reach the detector. Fig. 6 shows contours in $(\sqrt{\hat{s}_0^{WW}}, \hat{\sigma}_0^{WW})$ parameter space for the expected number of horizontal muon bundles per year in the underwater detector DUMAND$^{18}$ assuming a cosmic neutrino flux at the level proposed by Stecker et al.$^{19}$ Assuming the same cosmic neutrino flux, the Fly’s Eye$^{20}$, an array which is sensitive to extensive air
showers, excludes the shaded region of Fig. 6. Of course if the required flux of ultrahigh energy neutrinos is absent then absolutely no constraints can be put on multi-W processes in this manner: one must then wait for the SSC and LHC. For comparison, Fig. 6 also shows contours for 1 and 10 multi-W events in one year of operation of the SSC and LHC.

5. Summary

It is an open question whether or not the behavior of the electroweak symmetry breaking sector at the SSC and LHC will be described in detail by a weakly coupled MSM. If the Higgs sector is strongly coupled, new dynamics may be present with the possibility of multiple weak gauge boson production. We have examined a scenario in which underlying strong dynamics in the Higgs sector is patterned after hadronic multipion production and found \( \mathcal{O}(\text{fb}) \) signals for the production of \( \gtrsim 6 \) Goldstone bosons. Though such a model is not intended to be taken literally, it typifies the obstacles encountered if one wishes to exploit the features of nonperturbative phenomena in the Higgs sector.

We have also reviewed the implications of possible large cross sections for the production of \( \mathcal{O}(30) \) weak gauge bosons due to nonperturbative phenomena in the standard model. The SSC and LHC will be the definitive tools for deciding whether or not the cross sections for such processes are large.

Fig. 6. Regions of multi-W parameter space accessed by accelerator and non-accelerator experiments. DUMAND contours correspond to the number of muon bundles (2-3 muons/bundle) in \( 10^7 \) s at zenith angles greater than 80° assuming the cosmic neutrino flux of Stecker et al.\(^{19}\). Shaded region is excluded by the Fly’s Eye array if the Stecker et al. neutrino flux is assumed. SSC and LHC contours correspond to the number of multi-W events expected in \( 10^7 \) s of operation.

6. Acknowledgements

Many of the topics discussed in this paper are derived from enjoyable collaborations with R.D. Peccei, A. Ringwald and R. Rosenfeld. The local organizers of the Madison SSC Symposium in March 1993 and the Argonne Workshop in June 1993 are to be commended for providing a stimulating atmosphere in which to work. D.A.M. is supported by the Eloisatron project.

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