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Partially strong *WW* scattering

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What if only a light Higgs boson is discovered at the CERN LHC? Conventional wisdom tells us that the scattering of longitudinal weak gauge bosons would not grow strong at high energies. However, this is generally not true. In some composite models or general two-Higgs-doublet models, the presence of a light Higgs boson does not guarantee complete unitarization of the WW scattering. After partial unitarization by the light Higgs boson, the WW scattering becomes strongly interacting until it hits one or more heavier Higgs bosons or other strong dynamics. We analyze how LHC experiments can reveal this interesting possibility of partially strong WW scattering.

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Introduction.—The CERN Large Hadron Collider has just started running to uncover the mystery of electroweak symmetry breaking (EWSB). The ultimate goal of the LHC is to search for the Higgs boson and hopefully any new physics beyond the standard model (SM). Physicists have been excited about mapping new observations to the parameter spaces in various models, known as the "inverse LHC problem." However, one may anticipate that only one light Higgs boson is found in the first few years of LHC run. This is perhaps one of the most pessimistic scenarios. A light Higgs boson h of mass $m_h \lesssim 130$ GeV can be discovered through the $\gamma\gamma$ or WW^* modes. Since this mass is below the WW or ZZ threshold, it would be hard to probe how much this light Higgs boson is directly linked to EWSB. Several recent works have suggested precision measurements in the branching ratios of the light Higgs boson [1–3] and $W_L W_L$ scattering [1,3,4] to unravel the nature of EWSB.

In this paper, we propose to use the scattering of longitudinal weak gauge bosons to probe whether the light Higgs boson completely or just partially unitarizes the scattering amplitudes. Longitudinal weak gauge boson scattering is an old idea [5] and it has been used to impose a unitarity bound on the mass of the Higgs boson. At high energies, the longitudinal components of the weak gauge bosons recall their identities as the Goldstone bosons of the EWSB sector [6]. The scattering amplitudes of these Goldstone bosons with purely gauge contributions grow with energy as s/m_W^2, where s is the squared center-of-mass (CM) energy of the $W_L W_L$ system. Here we use W to generically denote either W or Z boson, unless otherwise stated. In the SM with a light Higgs boson, the amplitude will be completely unitarized by the Higgs boson. Once $\sqrt{s}$ goes beyond the light Higgs boson mass, the scattering amplitude will no longer grow like s/m_W^2. If the SM with a light Higgs by itself were indeed an ultraviolet (UV) complete theory, that would be our final prediction albeit a boring one. However, many issues such as the fine-tuning problem in the SM Higgs boson mass, massive neutrinos, leptogenesis and/or baryogenesis, dominant dark matter, and dark energy contents in the Universe are not easy to fathom without introducing new physics.

In many extensions of the SM, e.g., two-Higgs-doublet model (2HDM), little Higgs model, etc., there is usually one light Higgs boson surviving at low energy. However, the light Higgs boson by itself may not be fully responsible for the symmetry breaking so that $W_L W_L$ scattering is only partially unitarized by the light Higgs boson. Such an idea was recently mentioned first in Ref. [1] and then in Ref. [3]. Terms growing like s/m_W^2 in the scattering amplitude, usually canceled quite efficiently between the gauge and Higgs diagrams in the SM, creep back and render the scattering amplitude strong after hitting the light Higgs pole. At a sufficiently high energy, there will be the other part of the EWSB sector, e.g., the heavier Higgs boson of the 2HDM or the UV completion of the little Higgs models, to eventually unitarize the $W_L W_L$ scattering. Nonetheless, if the scale of this UV part is far enough from the light Higgs boson, the onset of strong $W_L W_L$ scattering between the light Higgs mass and the UV scale should be discernible at the LHC.

Our key result is that even if the coupling g_{hWW} deviates by 5% from the SM value, the $W_L W_L$ scattering will indicate a dramatic change in the invariant mass distribution (Fig. 1). If g_{hWW} deviates by 30%, just by counting the event rates one can tell the difference from the SM (Table I). This is of immense interest for LHC experiments. Furthermore, we point out that the $W_L W_L$ scattering probes not only the gauge-Higgs sector but also the pure gauge sector.

Methodology.—In the SM, the hWW coupling is $g_{hWW}^{\rm SM} g^{\mu\nu} \equiv g m_W g^{\mu\nu}$, where g is the $SU(2)$ gauge coupling constant. As a concrete example, consider the scattering of $W_L^+ W_L^- \to W_L^+ W_L^-$, which proceeds through the t

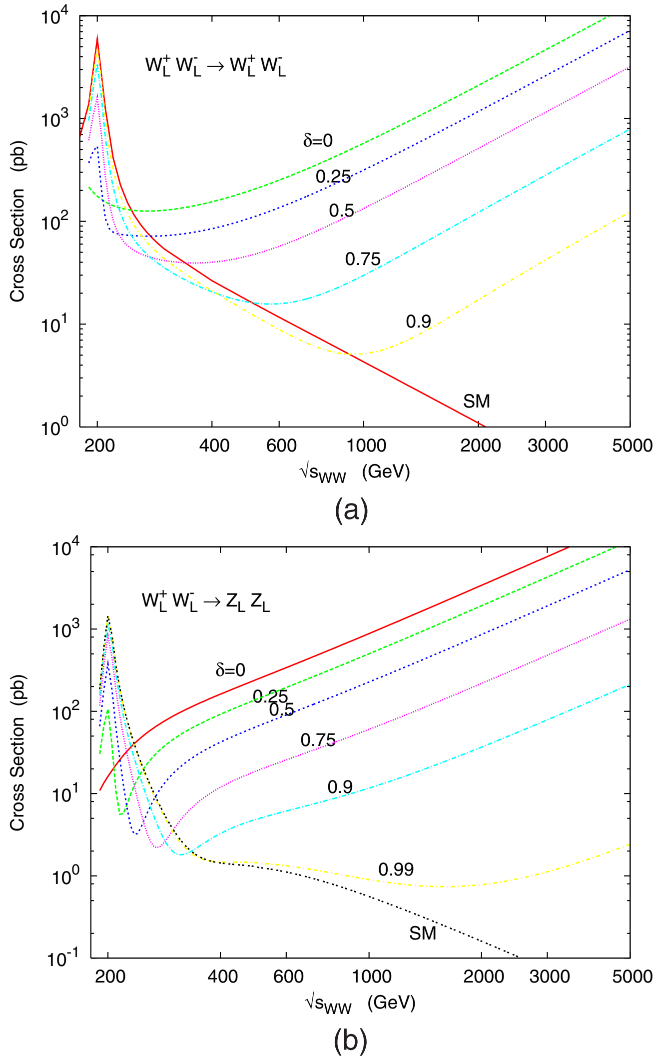

FIG. 1 (color online). Scattering cross sections for (a) $W_L^+ W_L^- \to W_L^+ W_L^-$ and (b) $W_L^+ W_L^- \to Z_L Z_L$ versus $\sqrt{s_{WW}}$. Various values of δ are shown, where $\sqrt{\delta}$ denotes the size of the Higgs-W-W coupling relative to the SM one. A light Higgs boson mass of $m_h = 200$ GeV is assumed together with an angular cut of $|\cos\theta_{WW}| < 0.8$.

and s channels of γ and Z exchanges, the 4-point vertex, and the s and t channels of Higgs exchanges. The longitudinal polarization of the W boson can be expressed as $\epsilon_L^\mu(p) = p^\mu/m_W + v^\mu(p)$ with $v^\mu(p) \simeq -m_W/(2p^{02}) \times (p^0, -\vec{p}) \sim O(m_W/E_W)$. In the CM system of $W_L^+(p_1)W_L^-(p_2) \to W_L^+(k_1)W_L^-(k_2)$, one can choose $v^\mu(p_1) = -2(m_W/s)p_2^\mu$, and so on. The sum of the amplitudes of all gauge diagrams is, in the high-energy limit,

$$i\mathcal{M}^{\rm gauge} = -i\frac{g^2}{4m_W^2}u + O((E/m_W)^0), \qquad (1)$$

where E denotes the scattering energy. Note that the quartic term proportional to E^4/m_W^4 naively expected from the 4-point vertex is canceled by the γ- and Z-exchange diagrams. On the other hand, the sum of the two Higgs diagrams is

$$i\mathcal{M}^{\rm Higgs} = -i\frac{g^2}{4m_W^2}\left[\frac{(s-2m_W^2)^2}{s-m_h^2} + \frac{(t-2m_W^2)^2}{t-m_h^2}\right] \simeq i\frac{g^2}{4m_W^2}u, \qquad (2)$$

in the limit of $s \gg m_h^2, m_W^2$. Thus, the bad energy-growing term is delicately canceled between the gauge diagrams and the Higgs diagrams. This is a well-known fact in the SM. However, in some extended models that the light Higgs boson has only a fraction of the SM coupling strength with the gauge bosons, one expects the scattering amplitude to keep growing with s after hitting the light Higgs pole.

Given our ignorance of what may lie beyond the SM, we follow the approach adopted by recent studies [1–3] to parametrize the coupling g_{hWW} as a fraction $\sqrt{\delta}$ of its SM value. As a result, the Higgs amplitude in Eq. (2) becomes δ times the SM value. For small enough δ, the total scattering amplitude will grow after the light Higgs pole due to incomplete cancellation of the bad high-energy behavior terms. This is true even for a rather large $\delta = 0.9$. We show in Fig. 1(a) the exact scattering cross sections for

TABLE I. Event rates for longitudinal weak gauge boson scattering at the LHC with a yearly luminosity of 100 fb^{-1} using the EWA for $\delta = 1$ (SM), 0.9, 0.5, and 0 (no Higgs). Branching ratios for the leptonic final states are summed for $\ell = e$ and μ. We set $m_h = 200$ GeV and $M_{WW}^{\rm min} = 300$ GeV.

Subprocess	Number of events			
	$\delta = 1$ (SM)	0.9	0.5	0 (no Higgs)
$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm \to \ell^\pm \nu \ell^\pm \nu$	21	26	57	118
$W_L^\pm W_L^\mp \to W_L^\pm W_L^\mp \to \ell^\pm \nu \ell^\mp \nu$	8	7	17	67
$W_L^\pm Z_L \to W_L^\pm Z_L \to \ell^\pm \nu \ell^+ \ell^-$	4	5	13	33
$W_L^+ W_L^- \to Z_L Z_L \to \ell^+\ell^-\ell^+\ell^-$	0.04	0.12	2	9
$W_L^+ W_L^- \to Z_L Z_L \to \ell^+\ell^- \nu\bar{\nu}$	0.25	0.74	12	50
$Z_L Z_L \to Z_L Z_L \to \ell^+\ell^-\ell^+\ell^-$	0.4	0.32	0.08	0
$Z_L Z_L \to Z_L Z_L \to \ell^+\ell^- \nu\bar{\nu}$	2.4	2	0.5	0

$W_L^+ W_L^- \to W_L^+ W_L^-$ versus $\sqrt{s_{WW}}$, where we have assumed $m_h = 200$ GeV. For the SM case the sum of amplitudes converges to $O((E/m_W)^0)$ terms, and the cross section thus drops like $1/s_{WW}$. When the size of the Higgs amplitude deviates from the SM value, even with a small amount (say $\delta = 0.9$), the cross section will cease falling but start climbing instead around $\sqrt{s_{WW}} \lesssim 1$ TeV. It turns around at lower $\sqrt{s_{WW}}$ for smaller δ's. A similar behavior happens in the $W_L^+ W_L^- \to Z_L Z_L$ channel, as shown in Fig. 1(b), where the turnaround occurs at even lower energies. Not so dramatic feature can also be shown for the nonresonant channels, such as $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$ and $W_L^\pm Z_L \to W_L^\pm Z_L$, where the cross sections only climb up gradually. We will give some realistic event numbers later to support our claim.

We also analyze the partial-wave coefficients of the scattering amplitudes to determine when unitarity is violated and check the unitarity limit as a function of δ. The partial-wave coefficients for the dominant S-wave WW scatterings are denoted by a_0^I for various channels with definite isospin $I = 0$, 1, and 2 formed by the scattering amplitudes involving $W_L^\pm$ and Z_L. Unitarity demands $|\Re e a_0^I| \leq 1/2$. We show in Fig. 2 the partial-wave coefficients a_0^I ($I = 0$, 1, 2) versus $\sqrt{s_{WW}}$ for various $\delta =$ 0–0.9. Full expressions of the amplitudes are used in our computation. At high energies, a_0^0's are positive while a_0^2's stay negative. The unitarity limit can be read off when each curve reaches $\Re e(a_0^I) = \pm 1/2$. Note that the matrix element of the $I = 1$ channel at high energy is an odd function of $\cos\theta$ such that the partial wave a_0^1 does not show any growing behavior for various δ. The unitarity limits that would be obtained from a_1^1 are significantly weaker than those from $a_0^{0,2}$ due to P-wave suppression. The most severe violation of unitarity is in the a_0^0 channel. For example, unitarity is violated at $\sqrt{s_{WW}} \simeq 1.7(2.7)$ TeV for $\delta = 0.5(0.8)$. The LHC may not be able to directly probe such high CM energies. But the growing behavior of the scattering amplitudes should be palpable at much lower energies.

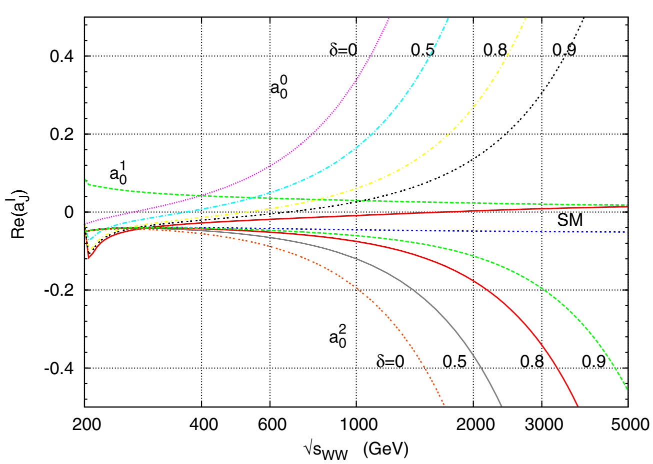

FIG. 2 (color online). The partial-wave coefficients $a_0^{0,1,2}$ versus the CM energy $\sqrt{s_{WW}}$ for various $\delta = $ 0-0.9.

Various models.—The simplest example of partially strong weak gauge boson scattering is the 2HDM [3], in which the light Higgs boson couples to the vector boson with a strength $g_{hWW} = \sin(\beta - \alpha) g_{hWW}^{SM}$, where $\tan\beta$ is the ratio of the VEVs of the two doublets and α is the mixing angle of the two CP even neutral Higgs bosons. If the other neutral Higgs boson H is much heavier, the weak gauge boson scattering amplitudes will enjoy their growths as s/m_W^2 for the energy between the two Higgs boson masses. This heavier neutral Higgs boson couples to the weak gauge boson with a strength $g_{HWW} = \cos(\beta - \alpha) g_{HWW}^{SM}$ such that it can unitarize the rest of the growing amplitudes when $s_{WW} > m_H^2$. A general 2HDM has enough room in the parameter space to allow $\sin(\beta - \alpha)$ to be small while keeping the other Higgs boson H heavy. However, as shown in Ref. [7], it is possible to achieve a light Higgs boson with a small $\sin(\beta - \alpha)$ only when keeping the other neutral one relatively light as well in the minimal supersymmetric standard model (MSSM). The heavier the heavy Higgs boson H is, the closer to 1 the factor $\sin(\beta - \alpha)$ will be. Thus, no appreciable strong weak gauge boson scattering can be observed in the MSSM.

In the strongly interacting light Higgs model [1], a compositelike model for the light Higgs boson is assumed with the size of the ratio g_{hWW}/g_{hWW}^{SM} smaller than 1. All other heavier degrees of freedom are integrated out and the effects are parameterized in an effective Lagrangian with an explicit UV cutoff. The partial widths of the light Higgs boson will be affected. Also, the weak gauge boson scattering amplitudes described by some higher dimensional effective operators will also grow with s until the cutoff is reached. Similarly, in a model of multiscalar doublets [2] all the heavy Higgs bosons can be integrated out to give corrections to the partial decay widths of a light Higgs boson, which will affect significantly its discovery modes at the LHC.

Using the conventional $\gamma\gamma$ and $b\bar{b}$ decay modes of the light Higgs boson to hunt for new physics becomes difficult. The $\gamma\gamma$ mode will be suppressed when the strength of g_{hWW} is smaller than its SM value. Similarly, the $b\bar{b}$ mode also suffers because the reduced g_{hWW} coupling would render the associated production of $W^\pm h$ smaller. While these modes become less useful, the $W_L W_L$ scattering would enjoy its partial growth. Thus, using the $W_L W_L$ scattering to probe possible new physics at a higher scale is complementary to the light Higgs branching ratios studied in [1–3]. We also note that in models with an extra Z' boson, the ZWW, $ZZWW$, and hZZ couplings are necessarily modified due to $Z - Z'$ mixing while the hWW coupling remains intact. Partial growth of the longitudinal weak gauge boson scattering in such models is also possible due to incomplete cancellation not only of the quadratic terms (E^2) in the gauge-Higgs sector but also of the *quartic* (E^4) terms in the pure gauge sector [8].

LHC signals.—We show the invariant mass spectrum in Fig. 3 for $pp \to W_L^+ W_L^- \to Z_L Z_L$ and $pp \to W_L^\pm W_L^\pm \to W_L^\mp W_L^\pm$. In Fig. 3(a), the mere $\delta = 0.9$ curve is above the SM one for $M_{WW} > 300$ GeV, in accord with Fig. 1(b), while the $\delta = 0.5$ case is way above the SM prediction. The nonresonant channel $W_L^\pm W_L^\pm$ shown in Fig. 3(b) requires a smaller δ in order to see a large deviation from the SM. We mainly focus on leptonic final states, $WW \to \ell\nu\ell\nu$, $ZZ \to \ell^+\ell^-\ell^+\ell^-$, and $ZZ \to \ell^+\ell^-\nu\bar{\nu}$. The latter mode is used because the four charged-lepton mode of ZZ is too small for realistic event rates. We show the event rates at the LHC for various scattering channels in Table I, with an angular cut of $|\cos\theta_{WW}| < 0.8$ and $M_{WW} > 300$ GeV. Note that all channels, except for $Z_L Z_L \to Z_L Z_L$, have larger cross sections as δ increases, in accord with the figures. The $Z_L Z_L \to Z_L Z_L$ cross section decreases with δ because it goes through only the Higgs diagram, the amplitude of which is proportional to δ. We use the naive effective W-boson approximation (EWA) [9] to estimate the event rates, which is good enough to demonstrate the main idea here. The $W_L W_L$ scattering amplitudes are the same as what we have used above. The Higgs amplitudes are parameterized by δ and then nothing beyond that. The studies of strongly interacting weak gauge boson scattering and various backgrounds were summarized in Refs. [10], based on the techniques of central-jet vetoing and forward-jet tagging. The jet tagging and central-jet vetoing efficiencies under optimized cuts were listed there too. The event rates given in Table I are to be multiplied by those efficiencies. One can readily check that with $\delta = 0.5$ a significant enhancement to the event rates relative to the SM results can be achieved.

To conclude, detailed studies of longitudinal weak gauge boson scattering at the LHC can provide useful hints of new physics at a higher scale, despite the fact that only a light Higgs boson may be discovered during the first few years at the LHC. If unitarity is only partially fulfilled by the light Higgs, the scattering cross sections must be growing as energy increases before it reaches the other heavier Higgs bosons or other UV completions to achieve the full unitarization. These partial growths of the cross sections can be palpable at the LHC provided that the UV part is at a sufficiently high scale. This can be realized in two- or multi-Higgs-doublet models with large $\tan\beta$ as were studied recently in Refs. [2,3], which proposed using the precision measurements of light Higgs boson decays to explore effects from new physics. Our approach of using longitudinal weak gauge boson scattering is complementary to those works but more direct and perhaps more efficient. Partial growth in the WW scattering cross sections can be a generic feature in many extensions of the SM. Detection of such a behavior at the LHC will be fascinating. More realistic studies of WW scattering in the scenario that a lone light Higgs boson is unearthed at the LHC should be a worthwhile pursuit.

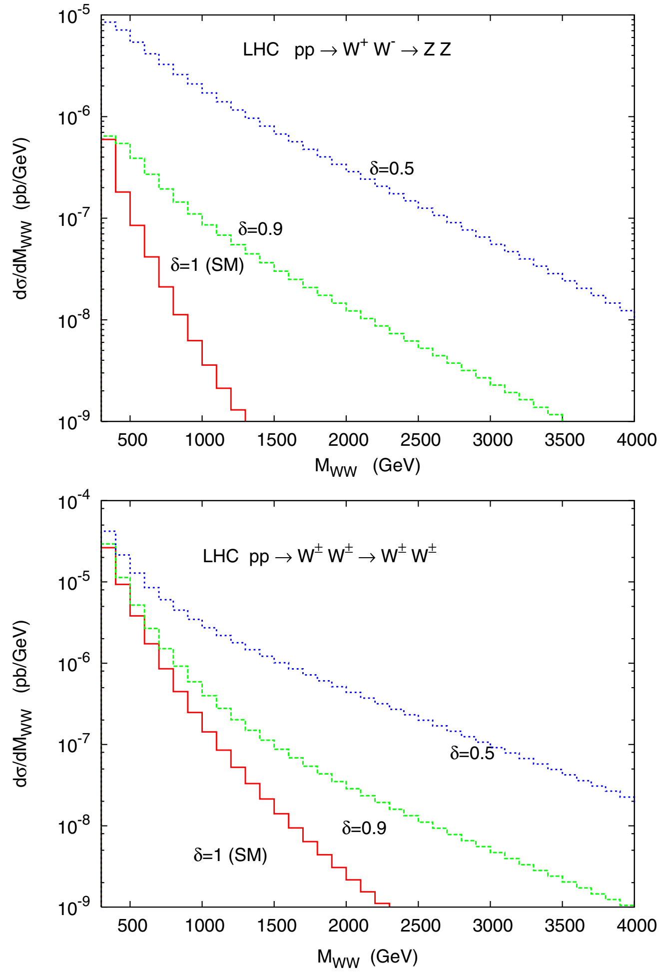

FIG. 3 (color online). Invariant mass distribution for (a) $pp \to W_L^+ W_L^- X \to Z_L Z_L$, (b) $pp \to W_L^\pm W_L^\pm X \to W_L^\pm W_L^\pm$ for $\delta = 1$, 0.9. and 0.5 at the LHC using EWA and $m_h = 200$ GeV.

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