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$I = 1,\ J = 1$ resonances in the Padé unitarized $W_L^+ W_L^-$ scattering amplitude

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We show that the Padé unitarized $I = 1,\ J = 1$ partial wave amplitude for $W_L^+ W_L^-$ elastic scattering exhibits resonant behavior for relatively low values of the Higgs-boson mass parameter m_H. The p-wave resonance can occur when $\sqrt{s} \gtrsim m_H$. This is in contrast with the $I = 0,\ J = 0$ resonance which occurs in the $W_L^+ W_L^-$-$Z_L^0 Z_L^0$ system for $\sqrt{s} \ll m_H$. The observability of the $I = 1$ resonance in high-energy pp collisions is examined.

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Recently, it has been shown [1–3] that the [1,1] Padé unitarized $I = 0,\ J = 0$ partial wave amplitude for the $W_L^+ W_L^-$-$Z_L^0 Z_L^0$ system exhibits a resonance of mass μ with $\mu \lesssim m_H$. The width of this resonance decreases as m_H increases. For $m_H \gtrsim 10$ TeV, the essential features of the resonant behavior can be obtained from the one-loop-corrected $I = 0$ s-wave amplitude $c_{I=0}$ which is expressible as an expansion in powers of fs as [4, 5]

$$c_{I=0}(s) = fs + \frac{f^2s^2}{2\pi}\left[-\frac{25}{9}\ln\left(\frac{s}{m_H^2}\right) - \frac{3346}{108} + \frac{11\sqrt{3}}{2}\pi + 2\pi i\right], \tag{1}$$

$$= c_{I=0}^{(1)} + c_{I=0}^{(2)}\,. \tag{2}$$

Here f denotes

$$f = \pi\frac{1}{(4\pi v_0)^2}\,, \tag{3}$$

and v_0, the Higgs-field vacuum expectation value, is given by

$$v_0^2 = \frac{4m_W^2}{g^2}\,. \tag{4}$$

The [1,1] Padé approximant for this amplitude is

$$c_{I=0}^{[1,1]} = \frac{c_{I=0}^{(1)\,2}}{c_{I=0}^{(1)} - c_{I=0}^{(2)}}\,. \tag{5}$$

Using the fact that, for eigenamplitudes, perturbative unitarity relates the imaginary part of the one-loop correction to the square of the Born contribution, we can write

$$c_{I=0}^{[1,1]} = \frac{c_{I=0}^{(1)\,2}}{c_{I=0}^{(1)} - \mathrm{Re}c_{I=0}^{(2)} - ic_{I=0}^{(1)\,2}}\,. \tag{6}$$

For resonances which are sufficiently narrow, the resonant mass μ can be determined by the requirement that the real part of the denominator in Eq. (6) vanish at $\sqrt{s} = \mu$. The expressions for the resonance mass μ and its width $\Gamma(\mu)$ given in Refs. [1, 2] can be obtained by expanding $c_{I=0}^{(1)}(s) - \mathrm{Re}c_{I=0}^{(2)}(s)$ about the point $s = \mu^2$.

From earlier investigations of unitarity effects in $\pi\pi$ scattering [6, 7], the existence of an $I = 1$ p-wave resonance in the unitarized $W_L^+ W_L^- \to W_L^+ W_L^-$ amplitude of the standard model is not entirely unexpected. The difference between the $I = 0$ and $I = 1$ cases is that the $s \ll m_H^2$ limit analogous to Eq. (1) cannot be used to analyze the $I = 1$ resonance [8]. For this channel, the corresponding expression is

$$c_{I=1} = \frac{fs}{6} + \frac{f^2s^2}{2\pi}\left[\frac{143}{54} - \frac{\sqrt{3}}{2}\pi + \frac{\pi}{18}i\right], \quad s \ll m_H^2\,. \tag{7}$$

Not only is Eq. (7) independent of m_H, but the real part of the associated Padé denominator,

$$c_{I=1}^{(1)}(s) - \mathrm{Re}c_{I=1}^{(2)}(s) = \frac{fs}{6} - \frac{f^2s^2}{2\pi}\left[\frac{143}{54} - \frac{\sqrt{3}}{2}\pi\right], \tag{8}$$

is positive definite. Consequently, there is no resonance in this limit.

In order to determine if there is a p-wave resonance for $s \sim m_H^2$, it is necessary to examine the $I = 1$ version of Eq. (6) using

$$c_{I=1}^{(1)}(s) = -\frac{g^2m_H^4}{64\pi m_W^2 s}\left[2 - \left(1 + \frac{2m_H^2}{s}\right)\ln\left(1 + \frac{s}{m_H^2}\right)\right], \tag{9}$$

together with the complete expression for $\mathrm{Re}c_{I=1}^{(2)}(s)$ [4]. In Figs. 1 and 2, we plot the Padé unitarized $I = 1$ amplitude for several values of m_H. The peak in the amplitude represents a true resonance in the sense that the Argand diagram exhibits the expected resonant behavior. For

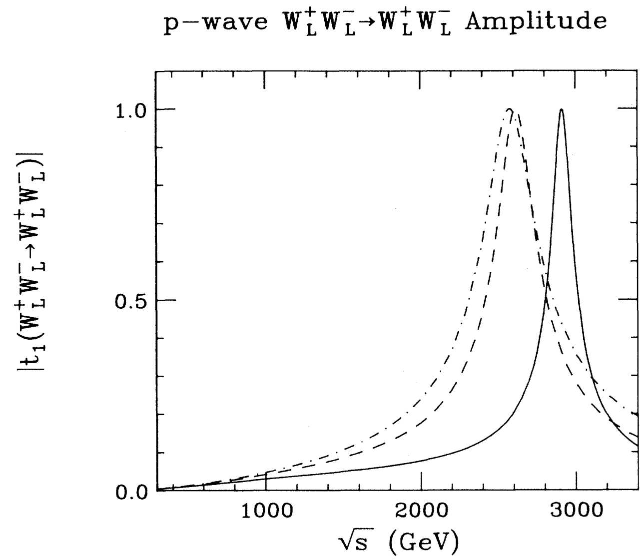

FIG. 1. The Padé unitarized p-wave amplitude $t_1(W_L^+W_L^- \to W_L^+W_L)$ is plotted for $m_H = 1$ TeV (solid), 1.5 TeV (dashed), and 2 TeV (dash-dotted).

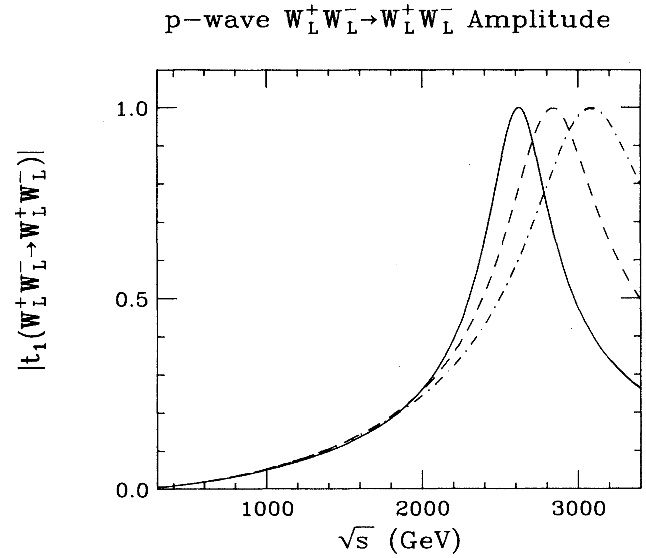

FIG. 2. Same as Fig. 1 with $m_H = 2.5$ TeV (solid), 3.75 TeV (dashed), and 5 TeV (dash-dotted).

relatively low values of $m_H \lesssim 1$ TeV, the resonance is narrow and occurs at a mass $\mu \gtrsim 3$ TeV. As m_H increases to about 2 TeV, μ decreases to a minimum value of 2.6 TeV. Further increases in m_H yield an increasing value of μ and an increasing width $\Gamma(m_H)$. The behavior of the resonant mass and its width as a function of m_H is summarized in Fig. 3. Also shown as a dashed line is the mass of the $I = 0, J = 0$ resonance for the same range of m_H [1]. The $J = 1$ resonance persists even for low values of m_H whereas the $J = 0$ resonance occurs at $\mu = m_H$ for m_H sufficiently small. For example, when $m_H = 500$ GeV, the $J = 1$ resonance occurs at $\mu = 4$ TeV with an extremely narrow width of about 30 GeV. Any discussion of resonances deduced from a Padé unitarized amplitude must be examined to determine if the resonances are located in a region of s for which the scheme is sensible. This point is treated in some detail in Ref. [9], which obtains results similar to those presented here. Finally, we note that higher partial waves also exhibit resonant behavior. The $J = 3$ partial wave has a resonance at $\mu = 7.4$ TeV for $m_H = 1$ TeV, and when $m_H = 500$ GeV μ exceeds 10 TeV.

We have explored the observability of the p-wave resonance at energies reached at the Superconducting Super Collider (SSC) by computing the W-pair invariant mass distribution for the process $pp \to W_L^+W_L^- X$ using the effective W approximation [10–12]. When the quark and vector boson distribution functions f and $\hat{f}$ are included, the expression for the invariant mass distribution with contributions from the s and p waves is

$$\frac{d\sigma}{dm_{WW}} = \frac{64\pi}{s}\int_{\tau_{\min}}^{1}\frac{d\tau}{\tau}\int_{-y_0}^{y_0} dy\, f(\sqrt{\tau}e^{y})f(\sqrt{\tau}e^{-y})\int_{-\hat{y}_0}^{\hat{y}_1} d\hat{y}\,\hat{f}(\sqrt{\hat{\tau}}e^{\hat{y}})\hat{f}(\sqrt{\hat{\tau}}e^{-\hat{y}})\left(\frac{z_0\mid t_0\mid^2 + 3z_0^3\mid t_1\mid^2}{m_{WW}}\right), \tag{10}$$

where

$$\tau_{\min} = \frac{m_{WW}^2}{s}\,, \quad \hat{\tau} = \frac{\tau_{\min}}{\tau}\,. \tag{11}$$

In Eq. (10), $t_0 = \frac{2}{3}c_{I=0}^{[1,1]} + \frac{1}{3}c_{I=2}^{[1,1]}$, $t_1 = c_{I=1}^{[1,1]}$, and we have included a factor of 2 for the symmetry of the quark distributions in pp collisions. The integration limits y_0, $\hat{y}_0$, and $\hat{y}_1$ are a result of imposing a rapidity cut η_C on both of the final vector bosons. These limits are related to η_C, $\eta = \ln(1/\sqrt{\tau})$, and $\hat{\eta} = \ln(1/\sqrt{\hat{\eta}})$ as

$$y_0 = \min(\eta, \eta_C + \hat{\eta}),\ \hat{y}_0 = \min(\hat{\eta}, \eta_c + y),$$

$$\hat{y}_1 = \min(\hat{\eta}, \eta_C - y)\,. \tag{12}$$

The the value of z_0, which occurs in the range of the $d(\cos\theta)$ integration, is determined by

$$z_0 = \min\left(\frac{1}{\beta}\tanh(\eta_C - \mid y + \hat{y}\mid), 1\right), \tag{13}$$

where $\beta = \sqrt{1 - 4m_W^2/m_{WW}^2}$. The vector boson distribution function $\hat{f}(x)$ used in evaluating Eq. (10) corresponds to the distribution of longitudinal W's,

$$\hat{f}_L(x) = \frac{\alpha_W}{4\pi}\frac{(1-x)}{x}\,, \tag{14}$$

and the quark distribution functions $f(x)$ are the Bologna-CERN-Dubna-Munich-Saclay (BCDMS) fit of Harriman *et al.* [13].

Figures 4–6 show the results for $d\sigma/dm_{WW}$ when $m_H = 1$, 2, and 5 TeV, respectively. Even for the low-

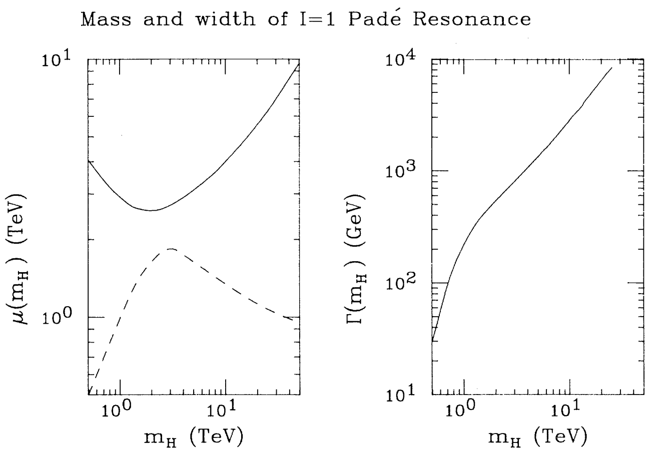

FIG. 3. The mass and width of the p-wave resonance are plotted as a function of m_H. The dashed line in the left-hand graph is a plot of the mass of the $I = 0, J = 0$ resonance.

est resonance mass, corresponding to $m_H \sim 2$, the cross sections are not large. However, for an SSC luminosity of 10^4 pb^{-1}/year, the area between m_{WW} of 2400 and 2800 GeV contains an excess of about 75 events/year above a $q\,\bar{q}$ background of 140 events/year. The same area for an integrated luminosity of 10^5 pb^{-1}/year attained at the CERN Large Hadron Collider (LHC) has approximately 23 extra events above a 220 event/year background. For $m_H = 1$ TeV, the resonance is very narrow and occurs at a relatively large value of m_{WW} where the magnitude of the cross section is smaller. There are about 16 extra SSC events/year between m_{WW} equal 2800 and 3000 GeV out of a total number of events, including background, of 58. Thus, it seems unlikely that the $J = 1$ resonance can be seen for m_H values much smaller than 1 TeV.

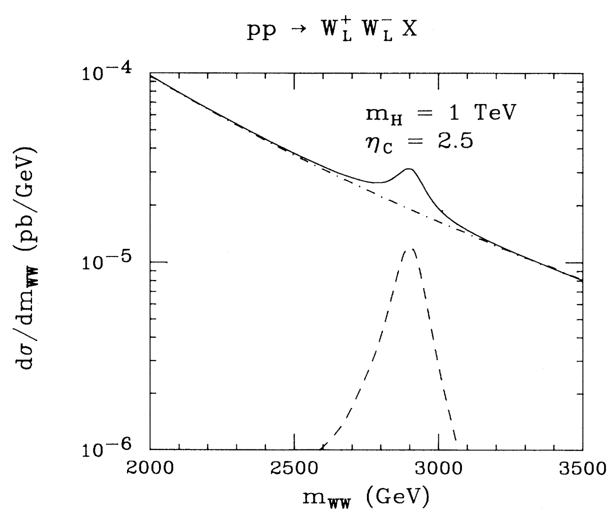

FIG. 4. The invariant mass distribution for the production of $W_L^+ W_L^-$ pairs at an SSC energy of 40 TeV is plotted for $m_H = 1$ TeV. The dashed line is the contribution from $W_L^+ W_L^-$ scattering, the dash-dotted line the contribution from $q\,\bar{q} \to W_L^+ W_L^-$, and the total is given by the solid line. A rapidity cut $\eta_C = 2.5$ is imposed on both W's.

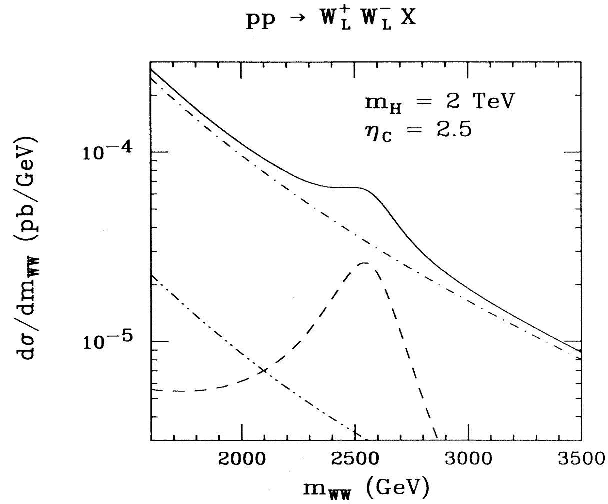

FIG. 5. Same as Fig. 4 except that $m_H = 2$ TeV. The dashed–double-dotted line is the contribution of the s-wave resonance in this region of $W_L^+ W_L^-$ invariant mass.

For m_H larger than 2 TeV the width of the resonance increases, which helps compensate for the somewhat smaller cross section. Thus Fig. 6 shows an excess of 38 events/year for m_{WW} from 2800 to 3200 GeV compared to 108 background events. Thus if data can be collected over a broad range of invariant mass it may be possible to detect the $J = 1$ resonance even if m_H is larger than 5 TeV.

Our results for the signals one might expect in the $I = 1, J = 1$ $W_L^+ W_L^- \to W_L^+ W_L^-$ channel are indicative of the observability of a p-wave resonance. The other $I = 1$ channels, $W_L^{\pm} Z_L^0 \to W_L^{\pm} Z_L^0$, are potentially better candidates from the experimental point of view since they can be more completely reconstructed. Although their p-wave amplitudes are the same as those in the neutral channel, differences in the $W_L^{\pm} Z_L^0$ luminosity and the $q\,\bar{q}$ background require a complete calculation to determine the magnitude of the expected signals in these channels.

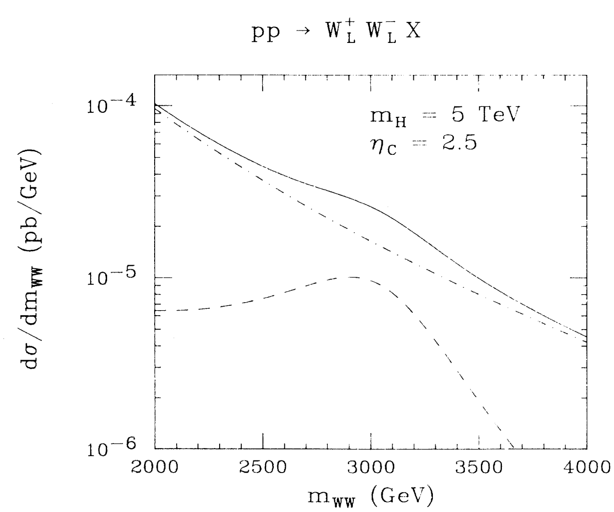

FIG. 6. Same as Fig. 4 except that $m_H = 5$ TeV.

In summary the Padé amplitude for $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$ has resonances for J larger than zero as one might anticipate [6, 7]. We have studied the p-wave resonance determining its position and width for a broad range of possible values of the Higgs-boson mass parameter m_H. We have also calculated the production cross section in pp collisions and find that the resonance should be observable if m_H is larger than 1 TeV up to an m_H value somewhere above 5 TeV. This region of m_H corresponds to a resonance position between 2.6 and 3.2 TeV.

Note added. After the circulation of the unpublished version of this paper [University of Texas, Center for Particle Physics DOE-ER40200-267 (1991)] we became aware of a paper by Atkinson, Harada, and Sanda [9], which reaches similar conclusions.

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