Complementarity of Resonant and Nonresonant Strong
$WW$ Scattering at the LHC

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Abstract

We exhibit a complementary relationship between resonant $WZ$ and nonresonant $W^+W^+$ scattering in a chiral Lagrangian model of the electroweak symmetry breaking sector with a dominant "$\rho$" meson. We use the model to estimate the minimum luminosity for the LHC to ensure a "no-lose" capability to observe the symmetry breaking sector.

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Introduction

Partial wave unitarity implies that new quanta from the electroweak symmetry breaking sector have masses at or below about $4\sqrt{\pi/\sqrt{2G_F}} \simeq 2$ TeV. Since the bound is only a rough estimate, the lightest new quanta could be a few times heavier, in which case they would not be directly observable at the LHC with any imaginable luminosity. The most effective signal of the symmetry breaking sector would then be strong like-charge $WW$ scattering, $W^+W^+ + W^-W^-$. We will consider the complementary relationship between resonant $J = 1$ scattering in the $WZ$ channel and nonresonant scattering in the like-charge $WW$ channel. Unless there is a Higgs boson-like resonance, the $W^+W^+$ and/or $WZ$ channels provide much better prospects for detecting strong scattering signals than the $ZZ$ channel.

To incorporate the chiral symmetric dynamics of the electroweak symmetry breaking sector, we use a chiral Lagrangian model with a TeV scale $I = J = 1$ $\rho$ resonance. Incorporating $SU(2)_L \times U(1)_Y$ gauge symmetry, the model is equivalent to the BESS model (with $b = 0$), though we do not share the interpretation of $\rho$ as a gauge boson, choosing instead to regard the model just as an effective Lagrangian for vector meson dominated, strongly coupled dynamics. Applied to QCD we find (see figure 1) that the model fits both $\pi^+\pi^0$ and $\pi^+\pi^+$ scattering data very well, to surprisingly high energy. (There is no tuning of parameters; the only inputs to figure 1 are the standard values of $F_\pi$, $m_\rho$, and $\Gamma_\rho$.)

Applied to the electroweak sector with $m_\rho \lessapprox 2$ TeV, the model implies a large resonant $WZ$ cross section and a somewhat suppressed $W^+W^+$ cross section. For larger values of $m_\rho$ the resonant $WZ$ signal decreases but nonresonant $W^+W^+$ scattering increases. This complementary relationship occurs because the chiral symmetry preserving contact interaction associated with cross-channel $\rho$ exchange suppresses $W^+W^+$ scattering, with less suppression for larger $m_\rho$.

In this paper we estimate the “no-lose” luminosity needed to provide an observable signal for any value of $m_\rho$ in at least one of the two channels. We define a robust criterion for a significant signal and then compute the minimum luminosity required to meet it. We consider collider energies of 14 and 10 TeV, corresponding to the LHC design energy (with 1.8° K magnets) in the first
case and, in the last case, to the energy achievable in the LEP tunnel using existing \((4.2^\circ \text{K})\) magnet technology. For the benefit of future generations (of archaeologists if not physicists) we also present results for 40 TeV.

We find that the required luminosities are 60 and 190 fb\(^{-1}\) for the LHC with 14 and 10 TeV respectively and 5 fb\(^{-1}\) for 40 TeV. These numbers codify the trade-off between energy and luminosity for this class of physics, reflecting the energy dependence of both signal and background cross sections. They do not reflect real-world complications that could effect the viability of high luminosity running such as event pile-up, instrumental radiation effects, or neutron-induced backgrounds.

A preliminary account of this work was presented previously.\(^{10}\) Similar results have been obtained by Bagger \textit{et al.}\(^{3}\). (One of several important differences, reflected in the quoted signals, is that we have optimized the cuts specifically for the chiral Lagrangian model for each particular value of \(m_\rho\), as will be done \textit{in vivo} experimentally, while the signals quoted in reference \(^{3}\) for all models refer to a single set of cuts chosen to optimize the signal for the standard Higgs boson model with \(m_H = 1\) TeV.) Strong \(WZ\) scattering signals with less complete background studies have been reported previously.\(^{1,11,12}\) A more detailed account of our results will be presented elsewhere.\(^{13}\)

\textbf{The Model}

The naive \(\rho\pi\pi\) interaction breaks chiral symmetry and violates the \(\pi\pi\) low energy theorems. The minimal chiral invariant \(\rho\pi\pi\) interaction\(^{5}\) contains an additional four pion contact interaction that preserves the low energy theorems by cancelling the \(\rho\) exchange contribution at threshold. The partial wave amplitudes \(a_{IJ}\) are then

\[
a_{20} = \frac{-\beta}{32\pi} \left\{ \frac{s - 2m_\rho^2}{F_\pi^2} - \frac{f_{\rho\pi\pi}^2}{m_\rho^2} (2m_\rho^2 + 3s - 4m_\pi^2) \right. \\
+ \left. 2\frac{f_{\rho\pi\pi}^2}{\beta^2 s}(m_\rho^2 + 2s - 4m_\pi^2) \ln \left( 1 + \frac{\beta^2 s}{m_\rho^2} \right) \right\}
\]

\[
a_{11} = \frac{\beta^3}{96\pi} \left\{ \frac{s}{F_\pi^2} - \frac{f_{\rho\pi\pi}^2}{m_\rho^2} \left( \frac{m_\rho^2 - 3s}{m_\rho^2 - s} \right) \\
+ 3\frac{f_{\rho\pi\pi}^2}{\beta^2 s}(m_\rho^2 + 2s - 4m_\pi^2) \left[ \frac{-4}{\beta^2} + \frac{4m_\rho^2 + 2\beta^2 s}{\beta^4 s} \ln \left( 1 + \frac{\beta^2 s}{m_\rho^2} \right) \right] \right\}
\]
where $\beta$ is the pion velocity in the center of mass, $F_\pi = 93$ MeV, and $f_{\rho\pi\pi}$ is determined from the $\rho$ width,

$$\Gamma_\rho = \frac{f_{\rho\pi\pi}^2}{48\pi} 3\beta^3 m_\rho,$$

measured to be 151 MeV.

We unitarize these amplitudes by the K-matrix prescription

$$a^K_{IJ} = \frac{\text{Re}(a_{IJ})}{1 - i\text{Re}(a_{IJ})}.$$ (4)

For a resonant amplitude Re($a$) is evaluated with $\Gamma = 0$, and $a^K$ is then equivalent to the commonly used broad resonance prescription\cite{14} in which $\Gamma$ appears in the Breit-Wigner denominator evaluated at the center of mass energy, $\Gamma = \Gamma(s)$, rather than at the peak of the resonance. The resulting phase shifts, $a = e^{i\delta}\sin\delta$, are compared with $\pi\pi$ data in figure 1. The agreement is very good, though it should not be taken seriously above the resonance because of the ad hoc unitarization prescription and because the two contact interactions are really only known near threshold. The model also lacks an important element of $\pi\pi$ dynamics since it does not reproduce the broad enhancement in the $a_{00}$ data (not shown) below 1 GeV.

An important qualitative success of the model is its ability to reproduce the way in which the $I = 2$ amplitude levels off above threshold. At threshold the $\rho$-induced contact interaction cancels the $\rho$ exchange contribution, leaving just the leading chiral Lagrangian contact interaction that gives the low energy theorem. Away from threshold in the $I = 2$ channel the $\rho$-induced contact term grows faster than the $\rho$ exchange term; it interferes destructively with the low energy theorem amplitude, causing the $I = 2$ amplitude to level off above threshold as observed in the data.

We are interested in the model not as a fully realistic representation of pion interactions, which despite figure 1 it surely is not, but as a tool to explore the relationship between resonant and nonresonant strong $WW$ scattering. We apply the model to the electroweak sector by replacing $F_\pi$ with $v = 246$ GeV and taking the Goldstone boson limit, $m_\pi = 0$.\footnote{W boson mass corrections are of the order of the corrections to the equivalence theorem.} The model is then completely specified by choosing $m_\rho$ and $\Gamma_\rho$.\footnote{W boson mass corrections are of the order of the corrections to the equivalence theorem.}
The range of possibilities is suggested by three cases. We consider minimal (one doublet) $SU(4)$ and $SU(2)$ technicolor; using large $N_{TC}$ lore they imply respectively $m_{\rho}, \Gamma_{\rho} = 1.78, 0.33$ and $2.52, 0.92$ in TeV. The latter is the heaviest $\rho$ in conventional technicolor, since $m_{\rho}$ decreases as $N_{TC}$ and/or the number of techni-doublets are increased. To present an even more difficult target we consider for our third case $m_{\rho}, \Gamma_{\rho} = 4.0, 0.98$ TeV. The mass is set arbitrarily beyond the range of direct observability, and the width is fixed by taking $f_{\rho\pi\pi}$ from the $\rho(770)$ of hadron physics.

The $I, J = 1, 1$ and $2, 0$ partial waves are shown in figure 2. The 1.78 TeV $\rho$ provides the largest $I = 1$ signal and the smallest for $I = 2$, while the 4 TeV $\rho$ provides the smallest $I = 1$ signal and the largest for $I = 2$. As $m_{\rho}$ increases, both amplitudes approach the K-matrix unitarization of the low energy theorem amplitude (solid lines), from above for $I = 1$ and from below for $I = 2$. If unobservable in one channel the signal may be observable in the other.

This complementarity follows from the suppression of the $I = 2$ amplitude by the contact interaction associated with $\rho$ exchange as discussed above. If $t$ and $u$ channel dynamics enhanced rather than suppressed the $I = 2$ amplitude, the nonresonant limit would be approached from above rather than from below as occurs here. The $W^+W^+$ signals would then be larger than they are in the model considered here, which in this sense is a conservative model of the $I = 2$ amplitude. In either case the amplitudes approach strong nonresonant $WW$ scattering as $m_{\rho} \to \infty$, which becomes the signal of last resort if all quanta from the symmetry breaking sector are too heavy to produce directly.

**Signals:**

Our criterion for a significant signal is

$$\sigma^\uparrow = S/\sqrt{B} \geq 5$$

$$\sigma^\downarrow = S/(S+B) \geq 3$$

They are controlled by not applying the model too close to the $WW$ threshold: the cuts used below ensure that most of the signal is at $\sqrt{s_{WW}} > 500$ GeV. On the other hand, the rapid decrease of the $WW$ effective luminosity as $s_{WW}$ increases ensures that the signals at the LHC are not dominated by $s_{WW}$ much larger than the domain of validity of the effective Lagrangian.
\[ S \geq B, \]  

where \( S \) and \( B \) are the number of signal and background events, and \( \sigma^\uparrow \) and \( \sigma^\downarrow \) are respectively the number of standard deviations for the background to fluctuate up to give a false signal or for the signal plus background to fluctuate down to the level of the background alone. We apply these criteria below after the experimental acceptance is applied. In addition we require \( S \geq B \) so that the signal is unambiguous despite the systematic uncertainty in the size of the backgrounds, expected to be known to within \( \leq \pm 30\% \) after “calibration” studies at the LHC.

For \( WZ \) scattering we detect \( WZ \rightarrow l\nu + \bar{\nu}l \) where \( l = e \) or \( \mu \), with net branching ratio \( BR = 0.0143 \). The production mechanisms are \( \bar{q}q \rightarrow \rho \), where the \( \rho \) coupling has its origin in \( W-\rho \) mixing\(^3\) computed in the \( SU(2)_L \times U(1)_Y \) gauged chiral Lagrangian \( \mathcal{L}_{\text{EFF}} \), and \( WZ \) fusion computed using the equivalence theorem\(\text{[13,1,16]}\) and the effective \( W \) approximation\(\text{[17]}\) with \( a_{11} \) and \( a_{20} \) unitarized as described above. (\( WZ \) scattering has a resonant contribution from \( a_{11} \) and a nonresonant contribution from \( a_{20} \).) The backgrounds are \( \bar{q}q \rightarrow WZ \) and the complete \( O(\alpha^2W) \) amplitude for \( \bar{q}q \rightarrow q\bar{q}WZ \). The latter is essentially the \( \bar{q}q \rightarrow q\bar{q}WZ \) cross section from \( SU(2) \times U(1) \) gauge interactions, computed in the standard model with a light Higgs boson, say \( m_H \leq 0.1 \) TeV.

Requiring central lepton rapidity is both convenient experimentally and helps to enhance the signal relative to the background: we require lepton rapidity \( y_l < 2 \). Cuts on the \( Z \) transverse momentum, \( p_{TZ} > p_{TZ}^{\text{MIN}} \), and on the azimuthal angles \( \phi_{ll} \) between the leptons from the \( Z \) and the charged lepton from the \( W \), \( \cos \phi_{ll} < (\cos \phi_{ll})^{\text{MAX}} \), are optimized for each choice of \( m_\rho \) and for each collider energy. We also examined the effect of a central jet veto\(\text{[18]}\) on events with one or more hadronic jets with rapidity \( y_j < 3 \) and transverse momentum \( p_{Tj} > 60 \) GeV\(\text{[18]}\). Though it is included in the results quoted below, the CJV is not very effective against the \( WZ \) backgrounds considered here since it does not reduce the \( \bar{q}q \) annihilation component of the background. It is likely to be useful, along

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\( ^3 \)Slightly different results follow from the \( \rho \) dominance approximation, to be discussed in detail elsewhere.\(\text{[13]}\)

\( ^4 \)For \( WZ \) and \( W^+W^+ \) scattering the signal efficiency for the CJV was computed by taking the \( m_H \rightarrow \infty \) limit of the standard model and imposing unitarity as in the linear model of reference\(\text{[1]}\).
with a lepton isolation requirement, against $t$ quark induced backgrounds that are not considered here but are shown to be controllable by Bagger et al.\textsuperscript{3}

The detector efficiency for $WZ \rightarrow l\nu + 7l$ is estimated\textsuperscript{19} to be $0.85 \times 0.95 \simeq 0.8$. Instead of correcting the theoretical cross sections, we take the acceptance into account by rescaling the significance criterion, replacing equations (5) and (6) by $\sigma^+ \geq 5.5$ and $\sigma^- \geq 3.3$. Table 1 displays $\mathcal{L}_{\text{MIN}}$, the minimum luminosity needed to satisfy the criterion, for each model and collider energy. Also displayed are the signal and background cross sections and the optimal values of $p_{TZ}^{\text{MIN}}$ and $(\cos \phi_{ll})^{\text{MAX}}$. For $m_{\rho} = 4$ TeV no signal is indicated for the LHC with either 14 or 10 TeV, because there are no cuts that satisfy $S \geq B$.

The $W^+W^+$ channel has the largest leptonic branching ratio, $\simeq 0.05$ to $e$’s and/or $\mu$’s, and no $\bar{q}q$ annihilation background. The signature is striking: two isolated, high $p_T$, like-sign leptons in an event with no other significant activity (jet or lepton) in the central region. The dominant backgrounds are the $O(\alpha_W^2)$ and $O(\alpha_W \alpha_S)$ amplitudes for $qq \rightarrow qqWW$. The former, like the analogous $WZ$ background discussed above, is computed in the standard model with a light Higgs boson. Other backgrounds, from $W^+W^-$ with lepton charge mismeasured and from $t\bar{t}$ production, require detector simulation. Studies in the SDC TDR\textsuperscript{19} show that they can be controlled, at least for $\mathcal{L} = 10^{33}$ cm$^{-2}$ sec$^{-1}$ (see also reference \textsuperscript{22}).

A powerful set of cuts that indirectly exploits the longitudinal polarization of the signal has emerged from the efforts of three collaborations.\textsuperscript{2, 18, 23}. The most useful cuts are on the lepton transverse momentum $p_Tl$, on the azimuthal angle between the two leptons $\phi_{ll}$, and a veto on events with central jets as defined above. With just the lepton rapidity cut $y_l < 2$ the background is an order of magnitude bigger than the largest of the signals; the additional cuts typically reduce the background by factors of order 200 or 300 while decreasing the signal by factors of only 2 or 3.

Assuming 85% detection efficiency for a single isolated lepton,\textsuperscript{19} the significance criterion, inequalities (5–6), applied to the uncorrected yields become $\sigma^+ > 6$ and $\sigma^- > 3.5$. The minimum luminosities to meet this criterion are summarized in table 2.

\textbf{Discussion}
Table 1 shows that the 1.78 TeV $\rho$ would be observable in $WZ$ scattering at the LHC with 44 fb$^{-1}$ and could even be observed at a 10 TeV collider with 120 fb$^{-1}$. The 4 TeV $\rho$ cannot be distinguished from nonresonant strong scattering, and it offers no signal at the LHC in the $WZ$ channel satisfying inequality (7).

Nonresonant scattering is more readily observed in the $W^+W^- + W^-W^-$ channel; at the LHC the like-charge $W$ pair signal for $m_\rho = 4$ TeV meets the criterion with 48 fb$^{-1}$. The smaller cross section for $m_\rho = 4$ TeV would be observable with 86 fb$^{-1}$. A 10 TeV collider would require 150 and 240 fb$^{-1}$ respectively.

The worst case scenario is represented (roughly speaking) by the 2.52 TeV $\rho$ meson: it is heavy enough to present a small resonant signal in the $WZ$ channel but light enough to effectively suppress nonresonant scattering in the $W^+W^-$ channel. The best signal is in the $W^+W^- + W^-W^-$ channel, where 63 fb$^{-1}$ provide a signal meeting our criterion. This defines the “no-lose luminosity”, since it ensures a significant signal for any value of $m_\rho$ in at least one of the two channels. For 10 and 40 TeV colliders the corresponding “no-lose” luminosities are 190 and 5 fb$^{-1}$ respectively.

We have not included top quark related backgrounds. They are distinguished from the signals by higher jet multiplicities and by lepton isolation criteria. Theoretical\footnote{A rough exploration of $m_\rho,\Gamma_\rho$ parameter space reveals cases somewhat worse but not dramatically different than the 2.52 TeV $\rho$ considered here.} and experimental\footnote{These results refer to the “silver-plated” channel, $ZZ \rightarrow \ell\ell + \nu\nu$.} simulations suggest they will not dramatically alter the conclusions reported here, though the experimental simulations were for $10^{33}$cm$^{-2}$sec$^{-1}$ luminosity and should be reconsidered for higher luminosity.

The $ZZ$ channel provides the best signal for scalar resonances such as a heavy Higgs boson, but is less useful for vector resonances or nonresonant scattering. Including the gluon-gluon fusion component with $m_t = 150$ GeV, the nonresonant strong scattering signal (for the “linear model”) is only just observable with 10 fb$^{-1}$ at a 40 TeV collider and would require $\simeq 350$ fb$^{-1}$ at a 16 TeV collider.\footnote{6} The results presented here for $W^+W^+$ and $WZ$ scattering are encouraging.
if luminosities of order $10^{34}\text{cm}^{-2}\text{sec}^{-1}$ can be achieved and if they can be used. Detector simulations, especially of the $W^+W^+$ channel, are needed to establish feasibility at the necessary luminosity.

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Table 1. Minimum luminosity to satisfy observability criterion for \( W^\pm Z \) scattering for \( \sqrt{s} = 10, 14, 40 \) TeV and \( m_\rho = 1.78, 2, 52, 4.0 \) TeV. Each entry contains \( \mathcal{L}_{MIN} \) in \( fb^{-1} \), the number of signal/background events per 10 \( fb^{-1} \), and the corresponding values of the cut parameters \( p_{T_Z}^{MIN}, \cos(\phi_{ll})^{MAX} \). A central jet veto is applied as discussed in the text.

|        | 1.78 TeV | 2.52 TeV | 4.0 TeV |
|--------|----------|----------|---------|
| 10 TeV |           |          |         |
| 120 fb\(^{-1}\) | 1400 fb\(^{-1}\) | No |
| 1.4/0.71 | 0.15/0.11 |          |
| 475 GeV,1.0 | 675 GeV,0.9 | Signal |
| 14 TeV |           |          |         |
| 44 fb\(^{-1}\) | 300 fb\(^{-1}\) | No |
| 3.8/2.0 | 0.58/0.34 |          |
| 450 GeV,1.0 | 675 GeV,1.0 | Signal |
| 40 TeV |           |          |         |
| 4.8 fb\(^{-1}\) | 12 fb\(^{-1}\) | 35 fb\(^{-1}\) |
| 33/19 | 13/7.0 | 5.2/3.1 |
| 400 GeV,1.0 | 500 GeV,−0.4 | 650 GeV,0.8 |
Table 2. Minimum luminosity to satisfy observability criterion for $W^+W^+ + W^-W^-$ scattering for $\sqrt{s} = 10, 14, 40$ TeV and $m_\rho = 1.78, 2.52, 4.0$ TeV. Each entry contains $\mathcal{L}_{MIN}$ in fb$^{-1}$, the number of signal/background events per 10 fb$^{-1}$, and the corresponding values of the cut parameters $p_{Tl}^{MIN}, \cos(\phi_{ll})^{MAX}$. A central jet veto is applied as discussed in the text.

| Energy (TeV) | $\mathcal{L}_{MIN}$ (fb$^{-1}$) | $L$ (fb$^{-1}$) | $Tl$ (GeV) | $\cos(\phi_{ll})$ |
|-------------|--------------------------------|----------------|------------|-----------------|
| 10 TeV      | 240 fb$^{-1}$                  | 190 fb$^{-1}$  | 90 GeV, -0.8 | 0.79/0.42       |
| 14 TeV      | 86 fb$^{-1}$                   | 63 fb$^{-1}$   | 80 GeV, -0.875 | 2.2/1.2         |
| 40 TeV      | 7.4 fb$^{-1}$                  | 5.2 fb$^{-1}$  | 80 GeV, -0.75 | 25/12           |
Figure Captions

Figure 1. The effective Lagrangian model, $\mathcal{L}_{\text{EFF}}$, compared with $\pi \pi$ scattering data\cite{8,9} for $|a_{11}|$ and $\delta_{20}$.

Figure 2. $|a_{11}|$ and $|a_{20}|$ for the effective Lagrangian applied to the electroweak symmetry breaking sector with $m_{\rho} = 1.78$ (dashes), $m_{\rho} = 2.52$ (long dashes) and $m_{\rho} = 4.0$ TeV (dot-dash). The nonresonant $K$-LET model is indicated by the solid lines.
Figure 1a
Figure 2a
