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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 "ρ" 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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Disclaimer

Introduction

Partial wave unitarity implies that new quanta from the electroweak symmetry breaking sector have masses at or below about $4\sqrt{\pi/\sqrt{2}G_F} \simeq 2$ TeV.[1] 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, $W^+W^+ + W^-W^-$.[1, 2, 3] 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.[4]

To incorporate the chiral symmetric dynamics of the electroweak symmetry breaking sector, we use a chiral Lagrangian model[5] with a TeV scale $I = J = 1$ ρ resonance. Incorporating $SU(2)_L \times U(1)_Y$ gauge symmetry, the model is equivalent to the BESS model[6] (with $b = 0$), though we do not share the interpretation of ρ 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[7] we find (see figure 1) that the model fits both $\pi^+\pi^0$ and $\pi^+\pi^+$ scattering data[8, 9] very well, to surprisingly high energy. (There is no tuning of parameters; the only inputs to figure 1 are the standard values of F_π, m_ρ, and Γ_ρ.)

Applied to the electroweak sector with $m_\rho \lesssim 2$ TeV, the model implies a large resonant WZ cross section and a somewhat suppressed W^+W^+ cross section. For larger values of m_ρ 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 ρ exchange suppresses W^+W^+ scattering, with less suppression for larger m_ρ.

In this paper we estimate the "no-lose" luminosity needed to provide an observable signal for *any* value of m_ρ 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° 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 *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_ρ, as will be done *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]

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 ρ exchange contribution at threshold. The partial wave amplitudes a_{IJ} are then

$$\begin{aligned} a_{20} &= \frac{-\beta}{32\pi}\left\{\frac{s-2m_\pi^2}{F_\pi^2} - \frac{f_{\rho\pi\pi}^2}{m_\rho^2}(2m_\rho^2+3s-4m_\pi^2) \right. \\ &\quad \left. + 2\frac{f_{\rho\pi\pi}^2}{\beta^2 s}(m_\rho^2+2s-4m_\pi^2)\ln\left(1+\frac{\beta^2 s}{m_\rho^2}\right)\right\} \end{aligned} \tag{1}$$

$$\begin{aligned} a_{11} &= \frac{\beta^3}{96\pi}\left\{\frac{s}{F_\pi^2} - s\frac{f_{\rho\pi\pi}^2}{m_\rho^2}\left(\frac{m_\rho^2-3s}{m_\rho^2-s}\right) \right. \\ &\quad \left. + 3\frac{f_{\rho\pi\pi}^2}{\beta^2 s}(m_\rho^2+2s-4m_\pi^2)\left[\frac{-4}{\beta^2}+\frac{4m_\rho^2+2\beta^2 s}{\beta^4 s}\ln\left(1+\frac{\beta^2 s}{m_\rho^2}\right)\right]\right\} \end{aligned} \tag{2}$$

where β is the pion velocity in the center of mass, $F_\pi = 93$ MeV, and $f_{\rho\pi\pi}$ is determined from the ρ width,

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

measured to be 151 MeV.

We unitarize these amplitudes by the K-matrix prescription

$$a_{IJ}^K = \frac{\mathrm{Re}(a_{IJ})}{1 - i\mathrm{Re}(a_{IJ})}. \tag{4}$$

For a resonant amplitude $\mathrm{Re}(a)$ is evaluated with $\Gamma = 0$, and a^K is then equivalent to the commonly used broad resonance prescription[14] in which Γ 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 ρ-induced contact interaction cancels the ρ 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 ρ-induced contact term grows faster than the ρ 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_π with $v = 246$ GeV and taking the Goldstone boson limit, $m_\pi = 0$.[1] The model is then completely specified by choosing m_ρ and Γ_ρ.

[1] W boson mass corrections are of the order of the corrections to the equivalence theorem. They are controlled by not applying the model too close to the WW threshold: the cuts used

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 ρ in conventional technicolor, since m_ρ 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 ρ provides the largest $I = 1$ signal and the smallest for $I = 2$, while the 4 TeV ρ provides the smallest $I = 1$ signal and the largest for $I = 2$. As m_ρ 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 ρ 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

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

$$\sigma^\downarrow = S/\sqrt{S+B} \geq 3 \tag{6}$$

$$S \geq B, \tag{7}$$

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.

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 $WZ \rightarrow l\nu + \bar{l}l$ where $l = e$ or μ, with net branching ratio $BR = 0.0143$. The production mechanisms are $\bar{q}q \rightarrow \rho$, where the $\rho\bar{q}q$ coupling has its origin in W–ρ mixing[2] computed in the $SU(2)_L \times U(1)_Y$ gauged chiral Lagrangian $\mathcal{L}_{\rm EFF}$[6], and WZ fusion computed using the equivalence theorem[15, 1, 16] and the effective W approximation[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 $O(\alpha_W^2)$ amplitude for $qq \rightarrow qqWZ$. The latter is essentially the $qq \rightarrow qqWZ$ 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, $p_{TZ} > p_{TZ}^{MIN}$, and on the azimuthal angles ϕ_{ll} between the leptons from the Z and the charged lepton from the W, $\cos\phi_{ll} < (\cos\phi_{ll})^{MAX}$, are optimized for each choice of m_ρ and for each collider energy. We also examined the effect of a central jet veto [18] on events with one or more hadronic jets with rapidity $y_j < 3$ and transverse momentum $p_{Tj} > 60$ GeV.[3] 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 with a lepton isolation requirement, against t quark induced backgrounds that

[2]Slightly different results follow from the ρ dominance approximation, to be discussed in detail elsewhere. [13]

[3]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 [1].

are not considered here but are shown to be controllable by Bagger *et al.*[3]

The detector efficiency for $WZ \to l\nu + \bar{l}l$ is estimated[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 $\sigma^{\uparrow} \geq 5.5$ and $\sigma^{\downarrow} \geq 3.3$. Table 1 displays $\mathcal{L}_{MIN}$, 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}^{MIN} and $(\cos\phi_{ll})^{MAX}$. 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 μ'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 $O(\alpha_W^2)$[20] and $O(\alpha_W \alpha_S)$[21] amplitudes for $qq \to qqWW$. 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 $\bar{t}t$ production, require detector simulation. Studies in the SDC TDR[19] show that they can be controlled, at least for $\mathcal{L} = 10^{33}$ cm^{-2} sec^{-1} (see also reference [22]).

A powerful set of cuts that indirectly exploits the longitudinal polarization of the signal has emerged from the efforts of three collaborations.[2, 18, 23]. The most useful cuts are on the lepton transverse momentum p_{Tl}, on the azimuthal angle between the two leptons ϕ_{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,[19] the significance criterion, inequalities (5–6), applied to the uncorrected yields become $\sigma^{\uparrow} > 6$ and $\sigma^{\downarrow} > 3.5$. The minimum luminosities to meet this criterion are summarized in table 2.

Discussion

Table 1 shows that the 1.78 TeV ρ 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 ρ 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 $m_\rho = 1.78$ 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[4]) by the 2.52 TeV ρ 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_ρ 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[3] and experimental[19] 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"[1]) 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.[4][5]

The results presented here for W^+W^+ and WZ scattering are encouraging if luminosities of order $10^{34}cm^{-2}sec^{-1}$ can be achieved and if they can be used. Detector simulations, especially of the W^+W^+ channel, are needed to establish

[4]A rough exploration of m_ρ, Γ_ρ parameter space reveals cases somewhat worse but not dramatically different than the 2.52 TeV ρ considered here.

[5]These results refer to the "silver-plated" channel, $ZZ \to \bar{l}l + \bar{\nu}\nu$.

feasibility at the necessary luminosity.

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Tables

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 $p_{TZ}^{MIN}, \cos(\phi_{ll})^{\mathrm{MAX}}$. 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} 1.4/0.71 475 GeV,1.0	1400 fb^{-1} 0.15/0.11 675 GeV,0.9	No Signal
14 TeV	44 fb^{-1} 3.8/2.0 450 GeV,1.0	300 fb^{-1} 0.58/0.34 675 GeV,1.0	No Signal
40 TeV	4.8 fb^{-1} 33/19 400 GeV,1.0	12 fb^{-1} 13/7.0 500 GeV,−0.4	35 fb^{-1} 5.2/3.1 650 GeV,0.8

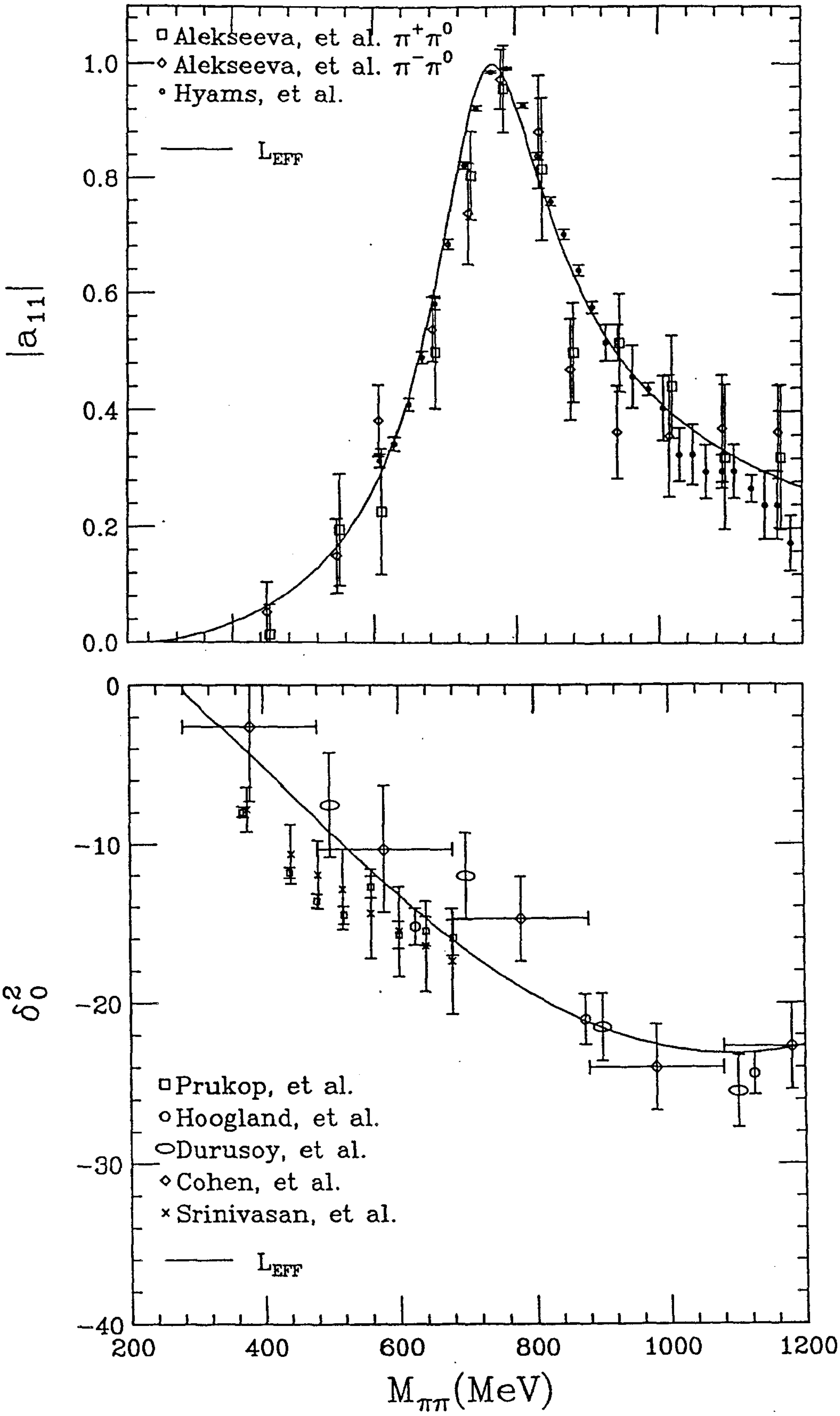
Table 2. Minimum luminosity to satisfy observability criterion for $W^+W^+ + W^-W^-$ scattering for $\sqrt{s} = 10, 14, 40$ TeV and $m_\rho = 1.78$, 2,52, 4.0 TeV. Each entry contains $\mathcal{L}_{MIN}$ in fb^{-1}, the number of signal/background events per 10 fb^{-1}, and the corresponding values of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

	1.78 TeV	2.52 TeV	4.0 TeV
10 TeV	240 fb^{-1} 0.79/0.42 90 GeV,−0.8	190 fb^{-1} 1.0/0.53 80 GeV,−0.85	150 fb^{-1} 1.2/0.59 80 GeV,−0.80
14 TeV	86 fb^{-1} 2.2/1.2 80 GeV,−0.875	63 fb^{-1} 2.9/1.5 70 GeV,−0.875	48 fb^{-1} 3.9/2.0 70 GeV,−0.725
40 TeV	7.4 fb^{-1} 25/12 80 GeV,−0.75	5.2 fb^{-1} 33/12 80 GeV,−0.75	3.6 fb^{-1} 44/12 80 GeV,−0.75

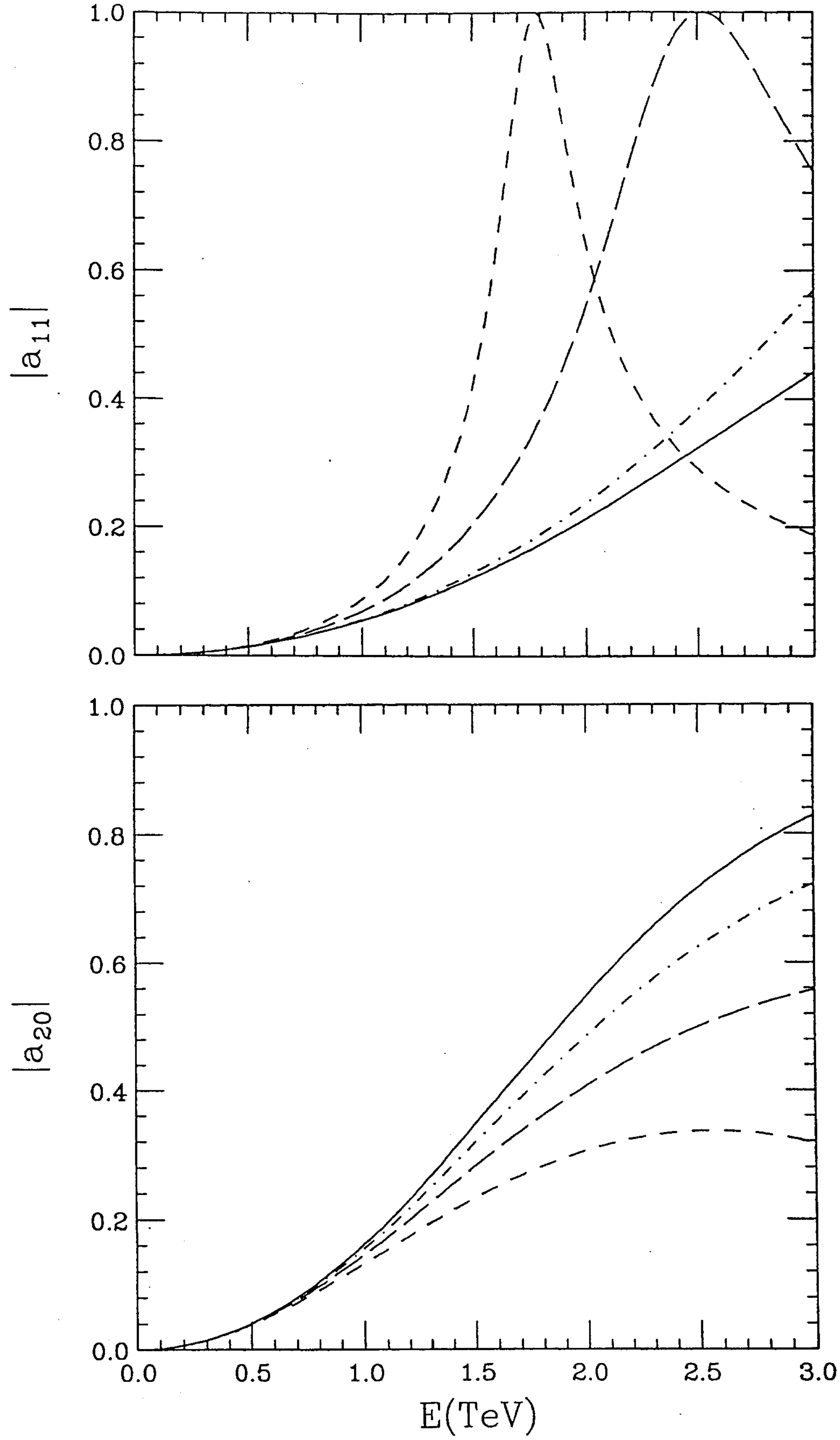
Figure Captions

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



Alekseeva, et al. $\pi^+\pi^0$
Alekseeva, et al. $\pi^-\pi^0$
Hyams, et al.
L_{EFF}
$|a_{11}|$
1.0
0.8
0.6
0.4
0.2
0.0
Prukop, et al.
Hoogland, et al.
Durusoy, et al.
Cohen, et al.
Srinivasan, et al.
L_{EFF}
δ_0^2
0
−10
−20
−30
−40
200
400
600
800
1000
1200
$M_{\pi\pi}$(MeV)



$|a_{11}|$
1.0
0.8
0.6
0.4
0.2
0.0
$|a_{20}|$
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
E(TeV)