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Isolating the Scattering of Longitudinal W^+'s at the SSC using Like-Sign Dileptons*

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Abstract

We explore the l^+l^+ mass spectrum from W^+W^+ scattering at the SSC. We delineate the cut procedures required to suppress transverse polarization and $t\bar{t}$-induced backgrounds below the level of the crucial signal due to strong scattering of longitudinally polarized W^+'s.

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If a relatively light Higgs boson (*i.e.* with mass below 600 to 700 GeV) does not exist, then the scattering of longitudinally polarized vector bosons (W_L, Z_L) will be strong when the vector boson (VB) pair has a high energy or invariant mass. The ability to detect this enhancement in VB scattering (if present) is an important goal for the next generation of accelerators, in particular the SSC. It was asserted in Ref. [1] that such enhancement would be most apparent in the scattering of like-sign, longitudinally polarized W's: $W_L^{\pm}W_L^{\pm} \to W_L^{\pm}W_L^{\pm}$; the impetus for this is that compared to the other VB scattering channels the like-sign channel has intrinsically the smallest background level. Unfortunately, it was found in Ref. [2] that the Standard Model (SM) yield of like-sign transversely polarized W-pairs ($W_T^{\pm}W_T^{\pm}$) would overwhelm any enhancement in the longitudinal mode scattering. To detect any longitudinal enhancement it seemed necessary to measure the polarizations of the W^+-pairs. Of course, this is not possible since charge determination of the W-pairs limits us to the purely leptonic decay modes. The only viable alternative is to find ways of suppressing the yield of like-sign W_T-pairs while retaining the signal for the like-sign W_L-pairs. This is the objective of the present paper.

While this work was in progress we learned of similar work by Barger et.al.[3]. In Ref. [3], however, a potentially dominant $t\bar{t}$ induced background was not considered. As we will see the necessity to deal with this background requires a somewhat different approach to signal enhancement. We also identify a new set of cuts which turn out to be slightly more efficient than those used in Ref. [3], whether or not the $t\bar{t}$ induced background is important. In this paper, we demonstrate that the transverse polarization background and the crucial $t\bar{t}$-induced background can both be greatly suppressed by appropriate cuts on the observables associated with the l^+l^+ final state, while at the same time sacrificing remarkably little of the signal of interest. Furthermore, we find a rather distinct signal for a $W_L^+W_L^+ \to W_L^+W_L^+ \to l^+l^+\nu\nu$ event: two back to back, like-sign, isolated leptons. In contrast to Ref. [3] we also find that "spectator-quark-tagging" may be efficient and necessary in enhancing the signal to background ratio for the like-sign W_L-scattering process. The difference comes about because we use a different tagging criteria.

W^+W^+ scattering is just one component of the complete set of subprocess diagrams that yield $q_1q_2 \to q_3q_4W^+W^+$. (The 'spectator' quarks q_3 and q_4 will play an important role in suppressing the backgrounds.) For our investigation, we have employed a complete calculation of all tree-level electroweak diagrams contributing to this type of subprocess as computed in the SM for a Higgs boson, ϕ^0, with large mass. In this letter we only consider the case of $m_{\phi^0} = 1$ TeV. This calculational procedure is only one of many possible characterizations of what may occur if longitudinal vector boson scattering becomes strong. Other approaches include different types of unitarization procedures[4]; these will not be explored here. However, the experimental techniques we develop are probably nearly optimal for enhancing the LL signal of interest relative to the backgrounds, regardless of the specific model that nature chooses. Our techniques would allow observation of an LL scattering signal larger than or comparable in magnitude to that predicted in the SM computation in the case of $m_{\phi^0} = 1$ TeV. Detection of an LL scattering signal substantially smaller than predicted by the tree-level SM computation might not be possible.

Of course, not all 'background' subprocesses are purely electroweak in nature. There is a class of gluon-exchange diagrams introduced in Ref. [5], and studied for the like-sign channel in Ref. [6], that must be considered. An example is $uu \to ddW^+W^+$ in which the quarks scatter by gluon exchange, and the W^+'s are emitted from initial or final quark lines. These subprocesses are enormously suppressed by the full set of cuts we consider; explicit results for them will be given but only cursorily discussed.

The observable parton-level particles for the purely leptonic decay modes of the W^+W^+ pair are the charged leptons (we consider $l = e, \mu$) and the two spectator jets. One would hope to detect the presence of the heavy Higgs through an excess of like-sign lepton pairs over a large interval of their pair invariant mass M_{ll} in comparison to the number expected were the Higgs light. Our standard of comparison will be the number of events expected if $m_{\phi^0} = 50$ GeV. These events are almost entirely from $W_T^+W_T^+$ final states. We will consider M_{ll} as our final observable and try to optimize cuts designed to maximize the above-mentioned enhancement in the M_{ll} spectrum. There are many subprocesses that are insensitive to the mass of the Higgs, and it is these that we wish to discriminate against while retaining most of the excess attributable to the longitudinal vector boson scattering diagrams that are large when the Higgs is heavy.

With regard to the final leptons, aside from M_{ll} and the transverse momenta magnitudes and rapidities of the individual leptons (p_T^l and y_l respectively), two particularly useful variables can be defined. These are δp_T^{ll} and z_{ll}, obtained from the transverse momenta of the two l^+'s as:

$$\delta p_T^{ll} = |\vec{p}_T^{\,l_1} - \vec{p}_T^{\,l_2}|, \quad z_{ll} = \hat{p}_T^{l_1} \cdot \hat{p}_T^{l_2} \,. \tag{1}$$

In events for which $|y_l| < 3.5$ for both leptons, the scattering of longitudinally polarized vector bosons tends to produce events where the p_T^l's are large, where the two leptons are nearly back to back (z_{ll} near -1), and for which δp_T^{ll} is large. In contrast, $W_T^+W_T^+$ final states tend to yield a significant number of events with z_{ll} not near -1 and with small δp_T^{ll} values. This latter will also be true of the $t\bar{t}$ background to be discussed later. An examination of the distributions shows that the following lepton cuts are a good choice for enhancing the LL/TT ratio:

$$|y_l| < 3.5, \quad p_T^l > 75 \text{ GeV}, \quad z_{ll} < -0.8, \quad \delta p_T^{ll} > 200 \text{ GeV}\,. \tag{2}$$

The sequential impact of these and other cuts to be discussed shortly is displayed in Table 1. Note that the imposition of the z_{ll} and δp_T^{ll} cuts yields a substantial increase in the LL/TT ratio at little cost to the LL signal. Though they also enhance the LL/TT ratio, the y_l and p_T^l cuts are imposed primarily to ensure that the leptons are not only observable but that their charge can be determined. From row 1 and column 1 of Table 1 it follows that best obtainable rate for the signal is about 12 events per SSC year, and that is before we impose any other signal enhancing cuts! In fact lepton charge determination may require a more stringent y_l cut. Thus, in Table 1 we have also displayed (in parenthesis) the results of requiring $y_l < 2$. The bottom line rates are not that much affected by the more stringent lepton rapidity cut. Unless otherwise noted, the rest of the numbers quoted in this paper are with the $|y_l| < 3.5$ cut.

Cut	$\sigma(W_L^+W_L^+)$	$\sigma(W_T^+W_T^+)$	$\sigma(t\bar{t})$	$\sigma(g-\text{exch.})$
$\lvert y_l\rvert < 3.5$ (2.0), $p_T^l > 75$	25 (19)	85 (24)	1720 (890)	27 (9.7)
$z_{ll} \leq -0.8$, $\delta p_T^{ll} \geq 200$	22 (18)	39 (12)	1200 (540)	11 (4.8)
$p_T^{\text{max},5} \leq 125$	16 (12)	6.1 (1.8)	800 (420)	1.4 (.51)
$p_T^{\text{max},2} \leq 70$	20 (15)	21 (5.9)	520 (210)	1.6 (.37)
$p_T^{\text{max},5} \leq 125$, $p_T^{\text{max},2} \leq 70$	14 (11)	4.7 (1.4)	480 (200)	.63 (.26)
$p_T^{\text{max},5} \leq 125$, $M_{jl}^{\text{min}} \geq 200$	12 (9.6)	3.4 (1.2)	.88 (.59)	.14 (.06)

Table 1: We give the electroweak cross sections in femtobarns from LL and TT mode W^+W^+ final states, as well as those from the $t\bar{t}$ ($m_t = 200$ GeV) and gluon-exchange backgrounds, after imposing various cuts. Computations are for the SSC energy of $\sqrt{s} = 40$ TeV. The LL modes are computed in the SM for $m_{\phi^0} = 1$ TeV. For all entries we have integrated over $M_{ll} > 300$ GeV. The lepton cuts of the first row are also imposed in obtaining the second row, and all the lepton cuts of the first two rows are imposed in obtaining all subsequent results. All momenta and mass cuts are in GeV units. Branching ratios for the $W^+ \to l^+\nu$ decays are not included. $\Delta R \geq 0.5$ separation is required between jets and leptons. The numbers in parenthesis are with the requirement $|y_l| < 2.0$.

Having decided on the lepton cuts we must now turn to determining the best means of implementing spectator cuts to further enhance the LL/TT ratio. One can easily demonstrate that the spectator quarks have a transverse momentum distribution of the form dp_T^2/p_T^2 when emitting a transversely polarized vector boson, compared to a spectrum of the form dp_T^2/p_T^4 when emitting a longitudinally polarized vector boson. Therefore, the average p_T of spectator quarks is much smaller for the (latter) interesting subprocesses. The smallness of the p_T of the spectators for scattering of longitudinally polarized vector bosons also implies that the spectator rapidities will tend to be quite large in this case. That these important differences in spectator distributions could be used to enhance the LL/TT ratio has been known for some time, beginning with our work as summarized in Ref.

[7]. However, the direct tagging of both spectator quarks at large rapidity considered there is not very efficient unless spectator jets with rather small p_T can be recognized. Thus, it seems that appropriate first-level spectator cuts can be best implemented by the converse procedure of 'anti-tagging', *i.e.*, by vetoing events with $p_T > p_T^{\rm min}$ in some interval $|y| < y_{\rm max}$. Anti-tagging was also implemented, with success, in Ref. [3]. As we will see our implementation differs substantially from theirs.

In order to optimize our procedures, we considered two possible $y_{\rm max}$ choices, $y_{\rm max} = 2$ and $y_{\rm max} = 5$. In Fig. 1 we compare the cross section for LL compared to TT scattering modes as a function of $p_T^{\rm max,5}$ and $p_T^{\rm max,2}$. Here $p_T^{\rm max,5}$ ($p_T^{\rm max,2}$) is the transverse momentum of the spectator jet with largest p_T that lies in the region $|y| < 5$ (< 2). All events for which neither spectator jet has $|y| < 5$ (< 2) are accumulated in the first bin. From this figure it is clear that a cut on either (and perhaps both) $p_T^{\rm max,5}$ or $p_T^{\rm max,2}$ will be very effective in increasing the relative importance of the LL modes. A $p_T^{\rm max,5}$ cut yields the larger effect. The result of requiring $p_T^{\rm max,5} < 125$ GeV (in addition to the lepton cuts of Eq. (2)) is given in Table 1. There, it is compared to imposing a cut of $p_T^{\rm max,2} < 70$ GeV alone; we see that the latter retains more LL events but that the LL/TT ratio is not as good as for the $p_T^{\rm max,5}$ cut imposed alone. (Imposing the $p_T^{\rm max,2}$ cut alone is quite close to the anti-tagging cut of Ref. [3].) The table also shows that imposing both $p_T^{\rm max,5} < 125$ GeV and $p_T^{\rm max,2} < 70$ GeV yields the best LL/TT ratio.

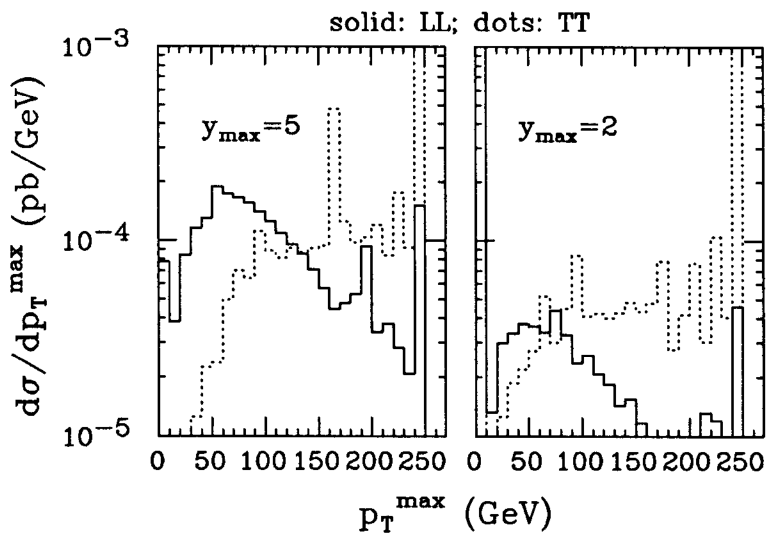

Figure 1: $p_T^{\rm max,5}$ and $p_T^{\rm max,2}$ distributions for TT final W^+W^+ modes compared to $m_{\phi^0} = 1$ TeV LL modes. We take $\sqrt{s} = 40$ TeV. The cuts of Eq. (2) are imposed. Branching fractions for $W^+ \to l^+\nu$ are not included.

A glance at Table 1 shows that the $p_T^{\rm max,2} < 70$ GeV cut is much more effective against the $t\bar{t}$ background (which we shall describe in detail below) than is the $p_T^{\max,5} < 125$ GeV cut. Nonetheless, neither the $p_T^{\max,2}$ cut alone nor a combined $p_T^{\max,2}$-$p_T^{\max,5}$ cut is sufficient to make the LL mode dominant over the $t\bar{t}$ background. The most effective way that we have found to deal with the $t\bar{t}$ background requires tagging at least one of the spectator jets. The reason for this will be discussed shortly. For now, let us define our jet tagging procedure and consider its consequences for the LL and TT modes. Having imposed the lepton cuts of Eq. (2) and imposed $p_T^{\max,5} < 125$ GeV, we require that at least one spectator jet has $|y| < 5$ and $30 < p_T < 125$ GeV. If both spectator jets satisfy this criterion we include both in the analysis. We compute $M_{jl}^{\min} \equiv \mathrm{Min}_{j,l} M_{jl}$, where M_{jl} is the invariant mass of a given spectator jet-lepton combination, and the minimization is to be performed over both leptons and over any spectator jet satisfying the trigger criterion.

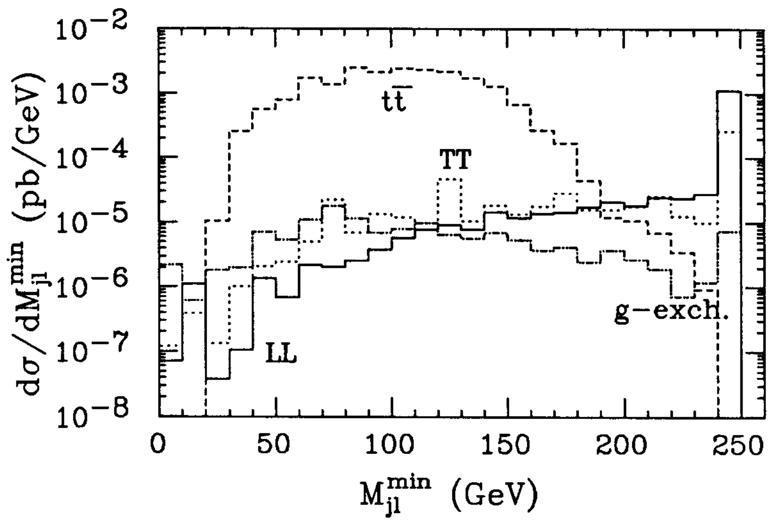

Figure 2: $M_{jl}^{\min}$ distributions for the W^+W^+ final state. Results for the TT mode and the LL mode at $m_{\phi^0} = 1$ TeV are compared. Also illustrated are the distributions from gluon exchange diagrams and from the primary $t\bar{t}$ background (computed for $m_t = 200$ GeV). We take $\sqrt{s} = 40$ TeV and employ the cuts of Eq. (2) with the added requirement of $p_T^{\max,5} < 125$ GeV. Branching fractions for $W^+ \to l^+\nu$ are not included.

Even though $M_{jl}^{\min}$ is primarily defined to deal with the $t\bar{t}$ background, one also finds a significant difference in the $M_{jl}^{\min}$ distributions for LL compared to TT modes. The LL mode has substantially larger $M_{jl}^{\min}$ values on average than does the TT mode. (This is, of course, due to the fact the LL spectator jets tend to have smaller p_T and especially larger $|y|$ than TT spectators, and therefore tend to yield larger jl invariant masses when combined with the high-p_T, small

$|y|$ l^+'s.) This is illustrated in Fig. 2. A cut of $M_{jl}^{\min} > 200$ is fairly optimum, yielding the result given in Table 1. Including $[BR(W^+ \to l^+\nu)]^2 = 4/81$ and multiplying by the expected SSC luminosity, $L = 10\ fb$, yields an event ratio of $LL/TT = 5.93/1.58 = 3.75$. Had we also imposed $p_T^{\max,2} < 70$ GeV, the corresponding result would be $LL/TT = 5.43/1.33 = 4.07$. To illustrate the final result, we compare in Fig. 3 the M_{ll} distributions for the $m_{\phi^0} = 50$ GeV case and for the LL mode of the $m_{\phi^0} = 1$ TeV case, obtained after imposing the lepton cuts of Eq. (2) and the spectator cuts:

$$p_T^{\max,5} < 125 \text{ GeV}, \quad M_{jl}^{\min} > 200 \text{ GeV}, \tag{3}$$

with no $p_T^{\max,2}$ cut. Obviously, the cuts have greatly enhanced the signal with respect to the background, but at nominal SSC luminosity we are left with only a handful of events (roughly 6 for the specific cuts of Eqs. (2) and (3)).

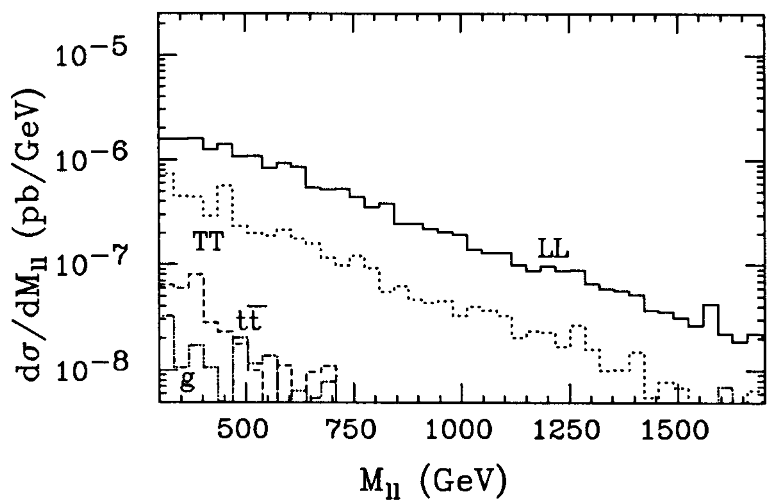

Figure 3: M_{ll} distributions for the W^+W^+ final state TT and LL modes. Also illustrated are the contributions from gluon exchange diagrams and from the primary $t\bar{t}$ background (with $m_t = 200$ GeV). We take $\sqrt{s} = 40$ TeV, and employ the cuts of Eqs. (2) and (3). Branching fractions for $W^+ \to l^+\nu$ *are* included.

In obtaining all the above cross section and event number results, we have imposed the lepton isolation requirement that the ΔR_{lj} separation (where $\Delta R_{lj} = \sqrt{(\Delta\phi_{lj})^2 + (\Delta y_{lj})^2}$ and $\phi_{l(j)}$ is the azimuthal angle for the lepton(jet)) between a spectator jet and either of the l^+'s in the final state be larger than 0.5. This guarantees that for the events which we keep, any experimental lack of isolation of one of the l^+'s will be due to initial/final state radiation or minimum bias effects. This ΔR cut is also incorporated in the following $t\bar{t}$ background analysis.

We now turn to the $t\bar{t}$ background. One obtains like-sign leptons from the chain $t \to bW^+$, $W^+ \to l^+\nu$, and $\bar{t} \to \bar{b}\ jets$, $\bar{b} \to \bar{c}\, l^+\nu$. Our cuts, especially the $M_{jl}^{\rm min}$ cut, have been designed to eliminate this background as well as the TT mode background. The $M_{jl}^{\rm min}$ cut is very effective for the $t\bar{t}$ background since at the parton level the tagged jet (or jets) and one or the other of the leptons will have actually both come from the decay of the same t quark, and thus will yield a jl invariant mass below m_t. Only as a result of including jet coalescence (combining quarks q_i and q_j with $\Delta_{ij} < 0.5$) does a tail for $M_{jl}^{\rm min} > m_t$ develop. In fact, Fig. 2 shows that the $M_{jl}^{\rm min}$ spectrum of the $t\bar{t}$ background falls very rapidly above the $m_t = 200$ GeV partonic-level limit. Consequently, this background can be removed by combining our $M_{jl}^{\rm min}$ cut included in Eq. (3) with the earlier-delineated lepton cuts of Eq. (2), and cuts on the number of energetic jets. Indeed, we see that the combination of the $M_{jl}^{\rm min}$ and other cuts reduces this $t\bar{t}$ background to about 0.4 event per year. We were unable to accomplish this without the $M_{jl}^{\rm min}$ procedure based on tagging at least one spectator jet.

There are other related backgrounds (see Ref. [3]) but the dominant ones are the like-sign W_T-scattering and the $t\bar{t}$ induced background discussed here. We are confident that our set of cuts will be effective in dealing with the other less important backgrounds[8].

Finally, we note that the results given in the table and the figures show that our procedures are extremely effective in eliminating the g-exchange background. After all cuts, we find less than 0.1 event for $M_{ll} \geq 300$ GeV.

In a longer paper[8] we shall explore the sensitivity of these results to the various parameters. For now we only give a few summary remarks. First, we find that the LL signal rate decreases significantly as we raise the minimum p_T required for the tagged jet. Thus, our procedures will suffer if p_T's greater than, say, 60 GeV are required to recognize a jet at the SSC. For such a $p_T^{\rm min}$, and keeping all other cuts constant, the yearly LL event rate drops to about 4 events. Second, we find that the $t\bar{t}$ background is markedly less severe for smaller m_t values. For instance, for $m_t << 150$ GeV the combined $p_T^{\rm max,5}$-$p_T^{\rm max,2}$ cut is sufficient to reduce it to the level of one event, without a $M_{jl}^{\rm min}$ cut. To be fair, the most efficient cut procedure will depend on m_t; if $m_t << 150$ GeV one jet tagging may not be necessary.

Let us summarize by first noting that our bottom line event rates are similar to those found in Ref. [3]. For the $m_{\phi^0} = 1$ TeV case, following different procedures Ref. [3] finds 4 LL events with a background of 1.9 TT events when integrating over $M_{ll} \geq 400$ GeV, compared to our yields for $M_{ll} \geq 300$ GeV of 6 LL events with background of 1.6 TT events obtained after all cuts (Table 1). The numbers presented so far are for the positive like-charge W-scattering, when the negative charge states are accounted for, we obtain close to 10 events. (Of course, some reduction in these numbers will result from the fact that the efficiency for detecting leptons will not be 100%.) Both studies are optimistic about controlling top quark backgrounds. However, full removal of the $t\bar{t}$ background we have considered appears to require explicitly tagging one jet in order to compute (and impose a lower limit on) the minimum jet-lepton mass variable defined earlier. Such tagging was implemented and included in our final LL event number quoted above. Clearly, the most important conclusion is that, having performed all the necessary cuts, the event rates found imply that high luminosity must be employed in order to use the like-sign lepton channels. Nonetheless, these channels appear to be sufficiently clean (especially for the cuts employed) that the multiple interactions associated with a high luminosity interaction region should not create difficulties. For an integrated luminosity of 100 fb^{-1} a highly significant signal for strong $W_L^+ W_L^+$ scattering should be attainable.

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