Signals for Neutralino Box Effects at LEP2

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Abstract

We have computed the contribution to the observables of the final two fermion channel at LEP2, at the limiting energy $\sqrt{q^2} = 200 \text{ GeV}$, coming from boxes with two neutralinos of purely gaugino type, of mass $M = 100 \text{ GeV}$. We find a potentially visible effect only for the muon channel, in the cross section and, to a lesser extent, in the forward-backward asymmetry. Analogous effects coming from the chargino box are also briefly discussed.
Among the various proposed theoretical interpretations of the four-jet events excess at LEP2 reported by the ALEPH collaboration, the supersymmetric mechanism with R-parity violation suggested by Carena, Giudice, Lola and Wagner has been recently considered with special attention. This is not only due to the several intrinsic virtues of the proposal, that seems to be able to explain remarkably well the most characteristic features of the ALEPH data, but also to the fact that the same mechanism would provide a satisfactory interpretation of the excess of large $Q^2$ events of neutral current type (positron in the final state) recently observed at HERA. This is made possible by the fact that one restriction on the model coming from LEP2 is that the mass of the neutralino exchanged in the t-channel must lie in a range between $\simeq 80$ and 100 GeV (owing to the kind of diagram involved, only a neutralino of purely gaugino type -bino, wino- would be involved). This restriction is not inconsistent with what is requested in order to explain the HERA neutral current excess.

If the theoretical mechanism proposed in ref. corresponds to physical reality, several possible visible consequences would be effective in a near future at LEP2. In particular, direct production of couples of sleptons and/or of a couple of neutralinos should become detectable. Correspondingly, new excesses in the final 4 jets channel should be seen in the first case. For neutralinos, direct production might be less evident, particularly for values of the mass close to the upper suggested value $M_{\chi^0} \simeq 100$ GeV. In case of future evidence of the proposed slepton production, it would be highly welcome, for a self-consistent test of the overall picture, to identify the presence of the suitable neutralino even if its mass lied in the unfavored region around approximately 100 GeV.

The aim of this paper is precisely that of showing that, should the proposed neutralino mass lie indeed in the 100 GeV region, it would still be possible to predict and detect a sizeable signal in the final muon channel (or, more generally, in the final "lepton" to be suitably defined e.g. by considering muon and $\tau$ production-channel). This would be due to a rather special virtual one-loop effect, exclusively produced by neutralino boxes.

A few words of comments are at this point appropriate. For what concerns LEP1 physics, the one-loop virtual electroweak box contribution is systematically negligible in the theoretical expression of the various observables, to the extent that such contributions are meant to be computed at $q^2 = (p_{e^-} + p_{e^+})^2 = M_Z^2$ (this statement does not apply e.g. to the box contributions to the redefinition of $G_\mu$, where they are computed at $q^2 = 0$). This can be qualitatively understood since, in the various observables, certain gauge-invariant combinations of self-energies, vertices and boxes appear at the one loop level, whose box component carries a multiplicative factor $\simeq (q^2 - M_Z^2)$ that vanishes exactly on Z resonance. When one moves away from the peak, this feature is completely reversed. In particular, the naive expectation is that, when $q^2$ increases, the relative weight of box contributions becomes enhanced until it reaches a "stable" regime at sufficiently large $q^2$ values. One can define this feature as an expected "kinematical" box enhancement. Note that, strictly speaking, these guesses are supposed to be valid for a final two fermion state, for which all variables can be continuously continuated from the Z peak to higher $q^2$ values. In fact, from a glance at the existing rigorous SM calculations at one-loop, one verifies that, indeed, this expectation is verified and in particular that, in the LEP2 energy range $\sqrt{q^2} \lesssim 200$ GeV, a sizeable and evidently "kinematical" increase shows up when one approaches the limiting value $\sqrt{q^2} \simeq 200$ GeV.
The previous qualitative considerations can be made technically more plausible if one adopts for the final two fermion processes in electron-positron annihilation a theoretical description defined as "Z-peak subtracted" representation \cite{7,8}. In such an approach, a kinematical box enhancement \( \simeq (q^2 - M_Z^2) \) appears as the logical consequence of the fact that for the remaining one loop quantities (self-energy, vertices) a systematical subtraction procedure can be performed that makes their contribution, for models of electroweak type, intrinsically depressed with respect to the boxes' one. We do not insist on this point here, since the presentation of refs.\cite{7,8} is sufficiently detailed, and defer to a forthcoming paper for a longer and systematic discussion about boxes' relevance.

So finally, on a purely kinematical basis, one would expect that in a supersymmetric model like the MSSM whose analogies with the MSM are often remarkable, an enhancement of these boxes that correspond to the MSM ones (with WW and ZZ s-channel exchange) appears when moving towards the highest c.m. energy values (in our work, assumed for simplicity to be at \( \sqrt{q^2} \simeq 200 \text{ GeV} \)). This should be valid, in particular, for neutralino boxes on which our attention is now concentrated.

A peculiar feature of the supersymmetric scenario should be now stressed. In the MSM, the relative importance of ZZ boxes is much smaller than that of WW boxes, and one might feel that the same feature should remain in the MSSM. As a matter of fact, the situation here might be rather different, since the genuinely electroweak contributions now arise, not only from a "zino", but also from a "photino" contribution, while photon boxes were not included in the electroweak sector in the SM, but in the QED corrections. Thus, a priori, neutralino boxes might be relevant in the MSSM.

On top of the previously hypothesized kinematical enhancement, boxes can exhibit one extra type of enhancement of "dynamical" type, corresponding to a sort of threshold effect that shows up when \( \sqrt{q^2} \) approaches the value \( M_1 + M_2 \), where \( M_1, M_2 \) are the masses of the two particles that are exchanged in the box (in principle, they might be different). This enhancement is not peculiar of box diagrams, and would appear in self-energies and vertices as well. In the SM specific case, one can actually see such an enhancement e.g. at \( \sqrt{q^2} = 2M_W \), and verify that around the threshold value a "sizeable" (typically, of a relative one-two percent) effect is produced, at least in certain observables. Clearly, this possible enhancement is only fixed by the relevant particle’s masses, and is independent of \( \sqrt{q^2} \).

The simple observation on which our paper is based is that there exist, in principle, situations in which these two boxes’ enhancement effects would sum up. They correspond to the rather privileged case in which the highest energy that is available corresponds, at least approximately, to the sum of the particles’ masses. This would be exactly the case of a box with two neutralinos of the type suggested in ref.\cite{3}, both with a mass of 100 GeV, at an energy \( \sqrt{q^2} \simeq 200 \text{ GeV} \) (that represents a possible goal for LEP2). Note that, for the supposed combination of purely gaugino content, no virtual contribution from self-energies or double neutralino vertices would be allowed. Since direct production in this mass-energy configuration would not be feasible, the box with two neutralinos would represent in this case the only possibly visible effect due to such particles in the final two fermion state. We have consequently computed the related contribution, and
The neutralino effect via boxes corresponds to the two diagrams depicted in Fig.(1). We have computed the contribution to the invariant scattering amplitude for a final fermion-antifermion state. Our analysis, as well as that of ref,[6], will be systematically performed in the ’t Hooft gauge $\xi = 1$. Final results are obviously gauge-independent.

The exchanged sfermions are $\tilde{e}_{L,R}$ and $\tilde{f}_{L,R}$ (for simplicity we will take $L$ and $R$ states with a common mass; in the numerical applications we have taken $m_{\tilde{q}} = 60$ GeV and $m_{\tilde{g}} = 110$ GeV). The intermediate neutralinos ($i$ or $j = 1, .. 4$) in principle consist of four independent Majorana states constructed as mixtures of pure gaugino ($\tilde{W},\tilde{B}$) and pure higgsino ($\tilde{H}_1,\tilde{H}_2$) types. The higgsino components couple to ($f\bar{f}$) proportionally to the fermion mass and we will neglect them. The gaugino couplings to ($f\bar{f}$) are listed in Table 1. The complete amplitude is obtained by summing all 64 combinations ($\tilde{e}_{L,R},\tilde{f}_{L,R},\chi_0^0,\chi_1^0$).

For simplicity we will take all neutralinos with a common mass $M = 100$ GeV. In this case the sum over all intermediate combinations can be expressed in terms of the pure gaugino contributions ($\tilde{W}\tilde{W}$), ($\tilde{B}\tilde{B}$), ($\tilde{W}\tilde{B}$), ($\tilde{B}\tilde{W}$). After standard but lengthy Dirac algebra the total box amplitude of the $e^+e^-\rightarrow f\bar{f}$ process can be written as

$$A^{NB}(e^+e^-\rightarrow f\bar{f}) = \frac{g^4}{16c_w^4}I_N\{H_{LL}L_{ee}^\mu L_{\mu,ff} + 16s_w^4H_{RR}R_{ee}^\mu R_{\mu,ff} + 4s_w^2H_{LRL_{ee}^\mu R_{\mu,ff} + 4s_w^2H_{RL}R_{ee}^\mu L_{\mu,ff}}\}$$

$$H_{XY} = (\bar{h}_{Xe}^W)^2(\bar{h}_{Ye}^W)^2 + (\bar{h}_{Xe}^B)^2(\bar{h}_{Ye}^B)^2 + 2(\bar{h}_{Xe}^W)(\bar{h}_{Ye}^W)(\bar{h}_{Xe}^B)(\bar{h}_{Ye}^B)$$

with $X$ or $Y = L, R$ and $h_{L,R,\tilde{B}}^W$ given in Table 1; also

$$R_{ee}^\mu, L_{ee}^\mu = \bar{v}(e^+)\gamma^\mu(1 + \gamma^5)u(e^-) \quad R_{ff}^\mu, L_{ff}^\mu = \bar{u}(f)\gamma^\mu(1 + \gamma^5)v(\bar{f})$$

and $I_N$ is a combination of Feynman box integrals computed numerically through the Passarino-Veltman method, ref.[3].

To compute the interference effect with the SM $e^+e^-\rightarrow \gamma, Z\rightarrow f\bar{f}$ amplitude within the Z-peak subtracted method, it is convenient to decompose the expression in eq.(1) on photon and Z Lorentz structures as given in ref.[4,5]:

$$A^{NB}(e^+e^-\rightarrow f\bar{f}) = v_{\mu}(\gamma)\gamma^\mu A_{\gamma\gamma,ff}^{NB}(q^2,\cos\theta) + v_{\mu}(Z)\gamma^\mu A_{ZZ,ff}^{NB}(q^2,\cos\theta)$$

$$+ v_{\mu}(\gamma)\gamma^\mu A_{\gamma Z,ff}^{NB}(q^2,\cos\theta) + v_{\mu}(Z)\gamma^\mu A_{Z Z,ff}^{NB}(q^2,\cos\theta)$$

$$+ v_{\mu}(\gamma)\gamma^\mu A_{\gamma Z,ff}^{NB}(q^2,\cos\theta) + v_{\mu}(Z)\gamma^\mu A_{Z Z,ff}^{NB}(q^2,\cos\theta)$$

with

$$v_{\mu}(\gamma) = eQ_f\bar{u}(f)\gamma^\mu v(\bar{f}) \quad v_{\mu}(Z) = \frac{g}{c_w}(\bar{u}(f)\gamma^\mu(\bar{v}_f - 2\gamma^5I_{3f})v(\bar{f})$$

and

$$A_{\gamma\gamma,ff}^{NB}(q^2,\cos\theta) = \frac{g^4}{16c_w^4Q_f Q_f}I_N\{H_{LL}(1 - \bar{u}_e)(1 - \bar{v}_e) + 16s_w^4H_{RR}(1 + \bar{u}_e)(1 + \bar{v}_f) + 4s_w^2[H_{LR}(1 + \bar{u}_e)(1 - \bar{v}_f) + H_{RL}(1 - \bar{u}_e)(1 + \bar{v}_f)]\}$$
\[ A_{Z\gamma,lf}^{NB}(q^2, \cos \theta) = \frac{g^4 s_W^2}{4e^2 c_W^2 I_3 I_f} I_N \{ H_{LL} - 16s_W^4 H_{RR} - 4s_W^2 [H_{LR} + H_{RL}] \} \] (7)

\[ A_{\gamma Z,lf}^{NB}(q^2, \cos \theta) = \frac{g^4 s_W}{8e^2 c_W Q_e I_3 I_f} I_N \{ H_{LL}(1 - \bar{v}_e) - 16s_W^4 H_{RR}(1 + \bar{v}_e) + 4s_W^2 [H_{LR}(1 + \bar{v}_e) - H_{RL}(1 - \bar{v}_e)] \} \] (8)

\[ A_{Z\gamma,lf}^{NB}(q^2, \cos \theta) = \frac{g^4 s_W}{8e^2 c_W Q_e I_3 I_f} I_N \{ H_{LL}(1 - \bar{v}_f) - 16s_W^4 H_{RR}(1 + \bar{v}_f) - 4s_W^2 [H_{LR}(1 - \bar{v}_f) - H_{RL}(1 + \bar{v}_f)] \} \] (9)

with \( \bar{v}_f \equiv 1 - 4|Q_f| s_f^2 \) defined with \( s_f^2 \), the effective Weinberg angle for the \( f \)-fermion. [8]

The contribution to the various observables is then immediately obtained (see the explicit derivation in ref. [8]) in terms of the four quantities

\[ \Delta_{\alpha}^{(NB,lf)}(q^2, \cos \theta) = q^2 A_{\gamma\gamma,lf}^{(NB,lf)}(q^2, \cos \theta) \] (10)

\[ R^{(NB,lf)}(q^2, \cos \theta) = -(q^2 - M_Z^2) A_{Z\gamma,lf}^{NB}(q^2, \cos \theta) \] (11)

\[ V_{\gamma Z}^{(NB,lf)}(q^2, \cos \theta) = -(q^2 - M_Z^2) A_{\gamma Z,lf}^{NB}(q^2, \cos \theta) \] (12)

\[ V_{Z\gamma}^{(NB,lf)}(q^2, \cos \theta) = -(q^2 - M_Z^2) A_{Z\gamma,lf}^{NB}(q^2, \cos \theta) \] (13)

Starting from the two parts \( \sigma_{1,2}^{lf}(q^2, \cos \theta) \) of the angular distribution (expressed in terms of \( Z \)-peak inputs [7, 8])

\[ \sigma_1^{lf}(q^2, \cos \theta) = N_f \frac{4\pi q^2}{3} \left\{ \alpha(0) q_f^2 [1 + 2\Delta_{\alpha}^{(lf)}(q^2, \cos \theta)] \right\} \]

\[ + 2[\alpha(0) Q_f]
\frac{q^2 - M_Z^2}{q^2((q^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)^1/2} \frac{3\Gamma_{1i}^{1/2}[3\Gamma_b^{1/2}]}{N_f M_Z^2 (1 + \bar{v}_f^2)^{1/2}(1 + \bar{v}_f^2)^{1/2}} \]

\[ \times [1 + \Delta_{\alpha}^{(lf)}(q^2, \cos \theta) - R^{(lf)}(q^2, \cos \theta)] - 4s_c c_l \left\{ \frac{1}{\bar{v}_f} V_{\gamma Z}^{(lf)}(q^2, \cos \theta) \right\} \]

\[ + \frac{3\Gamma_{1i}^{1/2}[3\Gamma_b^{1/2}]}{N_f M_Z^2 \Gamma_Z^2} \left\{ [1 - 2R^{(lf)}(q^2, \cos \theta)] - 8s_c c_l \left\{ \frac{\bar{v}_f}{1 + \bar{v}_f^2} V_{\gamma Z}^{(lf)}(q^2, \cos \theta) \right\} \right\} \]

\[ + \frac{\bar{v}_f}{3(1 + \bar{v}_f^2)} V_{Z\gamma}^{(lf)}(q^2, \cos \theta) \right\} \right\} \] (14)

\[ \sigma_2^{lf}(q^2, \cos \theta) = \frac{3}{4} N_f \frac{4\pi q^2}{3} \left\{ 2[\alpha(0) Q_f]
\frac{q^2 - M_Z^2}{q^2((q^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)^1/2} \frac{3\Gamma_{1i}^{1/2}[3\Gamma_b^{1/2}]}{N_f M_Z^2} \right\} \]

5
\[
\frac{1}{(1 + \hat{v}_l^2)^{1/2}(1 + \hat{v}_f^2)^{1/2}}[1 + \tilde{\Delta}_\alpha^{(lf)}(q^2, \cos \theta) - R^{(lf)}(q^2, \cos \theta)]
\]
\[
+ \frac{[3\Gamma_f]}{M_Z^2}[\frac{3\Gamma_f}{N_f M_Z^2}][4\hat{v}_l \hat{v}_f]
\]
\[
(\frac{q^2 - M_Z^2}{M_Z^2} + \frac{M_Z^2 \Gamma_Z^2}{\Gamma_f^2}(1 + \hat{v}_l^2)(1 + \hat{v}_f^2))[1 - 2 R^{(lf)}(q^2, \cos \theta)]
\]
\[
- 4 s_l c_l \{\frac{1}{\hat{v}_l} V^{(lf)}_\gamma(q^2, \cos \theta) + \frac{1}{3 \hat{v}_f} V^{(lf)}_\gamma(q^2, \cos \theta)\},
\]
(15)

one obtains the integrated cross section and the forward-backward asymmetry as:

\[
\sigma^{lf} = \int_1^{+1} d\cos \theta \left[\frac{3}{8} (1 + \cos^2 \theta) \sigma^{lf}_1 + \cos \theta \sigma^{lf}_2\right]
\]
(16)

\[
\sigma^{lf}_{FB} = \left[\int_0^{+1} - \int_{-1}^{0} \right] d\cos \theta \left[\frac{3}{8} (1 + \cos^2 \theta) \sigma^{lf}_1 + \cos \theta \sigma^{lf}_2\right]
\]
(17)

\[
A_{FB,lf} = \frac{\sigma^{lf}_{FB}}{\sigma^{lf}}
\]
(18)

We now consider the observables which are measurable with the highest accuracy at LEP2, namely \(\sigma^\mu\), the total cross section for muon pair production, \(A_{FB,\mu}\), its forward-backward asymmetry and \(\sigma^5\), the total hadron production. For each of them we compute the relative neutralino box effect by inserting in eq.(14, 15) the contributions of eq.(10-13). For each observable this gives the relative effect

\[
\frac{\delta O}{O} = \frac{O^{(SM+NB)} - O^{(SM)}}{O^{(SM)}}
\]
(19)

We first discuss muon pair production. As expected the box effect peaks at \(\sqrt{s} = 2M = 200\ GeV\) as one can see in Fig.2. At this energy \(\tilde{W}\) and \(\tilde{B}\) contributions are of comparable magnitude and cumulative to a total effect of about 1.4 percent on \(\sigma^\mu\). This is at an observable level at LEP2 [10] at the optimal expected experimental accuracy of about relative 0.7 percent [10] for \(\sigma^\mu\) (and \(A_{FB,\mu}\)). The forward-backward asymmetry gets also an effect which peaks at 200 GeV but it is relatively weaker (relative 0.7 percent which means 0.4 percent absolute on \(A_{FB,\mu}\)) at the limiting observability.

We have also computed the effects on quark pair production. As one can expect from the weaker neutralino couplings given in Table 1, the separate effects on \(u \bar{u}\) and \(d \bar{d}\) are somewhat weaker than on muon pair. But they have also an opposite sign for \(u \bar{u}\) and for \(d \bar{d}\) so that they largely cancel in \(\sigma^5\), leaving only a peak of -1 permille. So finally this neutralino box effect consists in a positive effect on the muon pair cross section, correlated to a negative effect on the forward-backward asymmetry and no effect on total hadron production. It peaks at \(\sqrt{s} = 2M\), with a kinematical half-width of about 15 GeV (\(2M \pm 15\ GeV\)).

For comparison and check we have also looked at the chargino case. Assuming that two degenerate couples \(\chi^\pm_i\) exist with a mass \(M = 100\ GeV\), we have computed the corresponding box effect around \(\sqrt{s} = 200\ GeV\) (in fact, for values \(\sqrt{s} < 200\ GeV\) where
direct production is not possible). In this case there is only one box diagram with $(\nu_e, \tilde{f}')$ exchange and intermediate $\chi_i^+\chi_j^-$. Summing over all degenerate $\chi_i$ states or just taking one couple of pure gaugino $\tilde{W}^\pm$, with pure left coupling to $f\tilde{f}'$, one gets a box effect which peaks at $\sqrt{s} = 2M$ with a magnitude of 2 percent on $\sigma^\mu$, 5 permille on $A_{FB}^\mu$ and 1 percent on $\sigma^5$. This effect is very similar but opposite in sign to the standard one due to the WW box. In fact we have checked that apart from mass differences the projection on photon and Z Lorentz structures of the WW and pure gaugino $\chi\chi$ boxes have the same leading expressions. This chargino peak is therefore comparable to the neutralino one (apart from a different sign on $A_{FB}^\mu$ and a larger effect on $\sigma^5$). Remember also that there are now additional chargino contributions (self-energy, vertices) which decrease with the energy relatively to the box contributions as explained in the introduction.

In fact, we have also computed the overall, gauge invariant combination of chargino self-energy, vertices and boxes and found that, within the combination, the box contribution remains the dominant one, in agreement with our general and previously discussed expectations based on the theoretical subtracted approach that we have used.

In conclusion, motivated by an interesting theoretical suggestion whose experimental confirmation is still debated, we have verified that, in a conventional minimal supersymmetric extension of the Standard Model, certain virtual one-loop contributions of box type might have visible effects in the simple and clean final (two) lepton channel at LEP2. The origins of this fact are partially due to a special kinematical enhancement property of box effects, that might make them specially relevant in general at increasing c.m. energy in an electron-positron collision. This should remain valid even in cases where the extra ”dynamical” enhancement produced by a “quasi” resonant configuration were absent. In this case, we would have at $\sqrt{s} > M_Z$ a situation in which for virtual effects there might be a kind of ”box dominance”, quite orthogonal to the situation met on top of $Z$ resonance, that would be more effective when the c.m. energy increases (typically this might be quite relevant for a future 500 GeV LC collider). A systematic investigation along this line is by now in progress.

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Table 1: Gaugino couplings to fermion-sfermion pairs.

|       | $h_{Le}$ | $h_{Re}$ | $h_{Lq}$ | $h_{Rq}$ |
|-------|----------|----------|----------|----------|
| $\tilde{B}$ | $s_W$ | $-1$ | $-\frac{1}{3}s_W$ | $Q_q$ |
| $\tilde{W}$ | $c_W$ | $0$ | $-2I_{3q}c_W$ | $0$ |
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Figure captions

**Fig.1** Box diagrams with sfermion exchanges and intermediate neutralinos for the $e^+e^- \rightarrow f\bar{f}$ amplitude.

**Fig.2** Neutralino box effect on muon pair production in the LEP2 energy range. Relative effect on the cross section (solid); on the forward-backward asymmetry(dashed).
Fig. 1

Fig. 2