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SMALL MULTIPLICITY EVENTS IN $e^+ + e^- \to Z^0$ AND UNCONVENTIONAL PHENOMENA*

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ABSTRACT

Events with two–, four– or six–charged particles and no photons produced through the process $e^+ + e^- \to Z^0$ provide an opportunity to search for unconventional phenomena at the SLC and LEP electron-positron colliders. Examples of unconventional processes are compared with the expected background from electromagnetic processes and from charged lepton pair production.

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A. INTRODUCTION

At the Z^0 , the process

$$e^+ + e^- \rightarrow Z^0 \rightarrow n\text{-charged-particles} + 0\text{-photons} \tag{A1}$$

where $n = 2$, 4 or 6; provides an opportunity to search for unconventional processes. The behavior and rate of background events from conventional processes can be calculated, and the events occupy limited regions in the space of kinematic variables. This paper provides a concise description of this opportunity.

There are several unconventional processes which can yield small multiplicity, 0–photon events. The signatures for some of these processes have been fully discussed, other processes are less known. The discussion here is based on a classification by general production mechanisms and event topology. For example, there are similarities in the signatures for the charged sequential lepton ($L^\pm$) process

$$\begin{aligned} e^+ + e^- &\rightarrow Z^0 \rightarrow L^+ + L^- \\ L^+ &\rightarrow \ell^+ + \nu_\ell + \bar{\nu}_L \\ L^- &\rightarrow \ell^- + \bar{\nu}_\ell + \nu_L \end{aligned} \tag{A2}$$

and the supersymmetric scalar lepton ($\tilde{l}^\pm$) process

$$\begin{aligned} e^+ + e^- &\rightarrow Z^0 \rightarrow \tilde{\ell}^+ + \tilde{\ell}^- \\ \tilde{\ell}^+ &\rightarrow \ell^+ + \tilde{\gamma} \\ \tilde{\ell}^- &\rightarrow \ell^- + \tilde{\gamma} \end{aligned} \tag{A3}$$

if

$$\begin{aligned} m_L \gg m_\ell \quad &, \quad m_L \gg m_{\nu_L} \\ m_{\tilde{\ell}} \gg m_\ell \quad &, \quad m_{\tilde{\ell}} \gg m_{\tilde{\gamma}} \end{aligned} \tag{A4}$$

Here, ℓ means e or μ, ν is a neutrino, $\tilde{\gamma}$ is a photino and m means mass. When m_L and $m_{\tilde{\ell}}$ are greater than about 20 GeV/c^2, these processes yield acollinear two–charged–particle events with substantial energy and missing momentum. There is little background to such events from conventional processes.

On the other hand, suppose $m_L - m_{\nu_L}$ or $m_{\tilde{\ell}} - m_{\tilde{\gamma}}$ is small, of the order of 1 GeV/c^2. Then, depending on m_L or $m_{\tilde{\ell}}$, such events may have small visible energy and two–virtual–photon processes may cause a troublesome background.

I also discuss unconventional processes which might produce four–charged leptons. A well-known example is a neutral lepton L° which mixes with the e or μ:

$$\begin{aligned} e^+e^- &\rightarrow Z^0 \rightarrow L^0 + \bar{L}^0 \\ L^0 &\rightarrow \ell^- + \ell'^+ + \nu_{\ell'} \\ \bar{L}^0 &\rightarrow \ell^+ + \ell'^- + \bar{\nu}_{\ell'} \end{aligned} \tag{A5}$$

An instructive example is to suppose that an unknown, very high energy, interaction has a low energy residual interaction at the Z^0 mass which yields directly

$$e^+ + e^- \rightarrow Z^0 \rightarrow \ell^+ + \ell^- + \ell'^+ + \ell'^- \tag{A6}$$

As I show in sec. E, if the ℓ and ℓ' are required to be μ's, one can search to very small cross sections in the process in eq. A5 or A6.

The comparison of signatures for unconventional processes with the backgrounds from conventional processes depends upon the particle detector. For this paper I use a simplified model of the Mark II detector (sec. B) as it has been upgraded by my colleagues and myself for use at the SLAC Linear Collider (SLC).

Having made many searches for new particles and been successful only once, I know that one cannot precisely set search criteria until the experiment is working and the data is in hand. Usually one does not achieve the expected search sensitivity, unexplained background and imperfect equipment usually intervene first. Therfore, I shall limit myself to indicating general directions for signature selection, and proceed by example.

The plan of the paper is that backgrounds for two–charged–particle events are described in sec. C and compared in sec. D with examples of such events from unconventional processes. In secs. E and F, I discuss the background and unconventional process examples for four–charged– and six–charged–particle events, respectively.

B. SCHEMATIC DETECTOR, ACCEPTANCES AND CROSS SECTIONS

1. Schematic Detector

I discuss and calculate backgrounds and unconventional process systems using a schematic magnetic detector based on the upgraded Mark II detector.[1] In the following list θ is the smallest angle (0°–90°) between the direction of motion of a particle and the e^+e^- beam line, p is the magnitude of a particle momentum and E is its energy.

$$\text{charged particle momentum measured:} \cos\theta < 0.85 \tag{$B1a$}$$

$$e \text{ identified:} \cos\theta < 0.85,\ E > 1.\ \text{GeV} \tag{B1b}$$

$$\mu \text{ identified:} \cos\theta < 0.85,\ E > 1.5\ \text{GeV} \tag{B1c}$$

$$\gamma \text{ detected and energy measured:} \cos\theta < 0.95 \tag{B1d}$$

$$e \text{ detected for veto: } \theta > 15 \text{ mrad}, \ E > 0.2 \text{ GeV} \tag{B1e}$$

$$\gamma \text{ detected for veto: } \theta > 15 \text{ mrad}, \ E > 0.2 \text{ GeV} \tag{B1f}$$

2. Acceptances

In the background and signature calculations, the acceptance for charged particles is set by

$$\cos\theta < 0.85 \tag{B2a}$$

$$p > 1. \text{ GeV/c} \tag{B2b}$$

3. Cross Sections

The approximate, radiatively corrected, cross section for

$$e^+ + e^- \to Z^0 \to f + \bar{f} \tag{B3}$$

is

$$\sigma_{f\bar{f}} \approx 1400 \ T_f(\beta) \text{ pb} \tag{B4}$$

T_f depends upon the f–Z^0–$\bar{f}$ coupling. For conventional charged leptons

$$T_{L^-} \approx \beta(3 - \beta^2)/2 \tag{B5a}$$

For conventional neutral leptons

$$T_{L^0} \approx \beta(3 + \beta^2)/2 \tag{B5b}$$

C. BACKGROUNDS FOR TWO–CHARGED PARTICLE, 0–PHOTON EVENTS

1. $e^+e^- \to \ell^+\ell^-$

The reaction

$$e^+ + e^- \to \ell^+ + \ell^- \tag{C1}$$

where ℓ is an e or μ, gives a pair of collinear particles to the extent allowed by radiative corrections and instrumental errors. When ℓ is a τ, the one–charged–particle, 0–photon decay modes

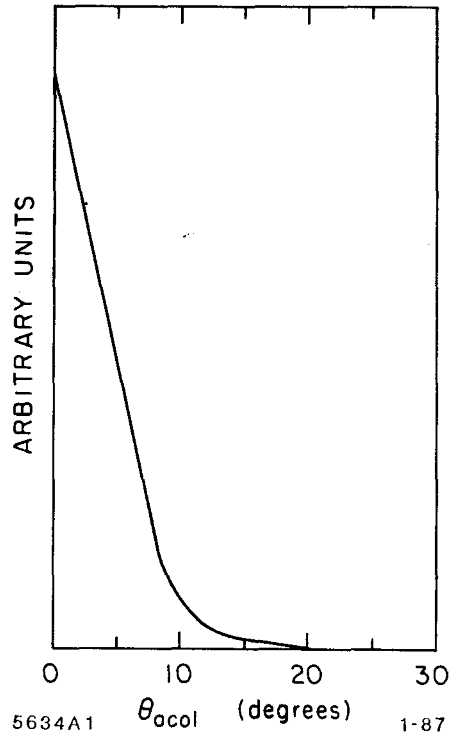

Figure 1

$$\tau^- \to \nu_\tau e^- \bar{\nu}_e \quad , \quad \nu_\tau \mu^- \bar{\nu}_\mu \quad , \quad \nu_\tau \pi^- \quad , \quad \nu_\tau K^- \tag{C2}$$

yield the acollinearity angle distribution of fig. 1. Here, θ_{acol} is defined[2] to be 0 when the particles have exactly oppposite momenta. When

$$\theta_{acol} > 15^\circ \tag{C3}$$

is required, about 0.5% of the decays are accepted under the conditions of eqs. B1 and B2. Hence

$$\sigma(ee \to \tau\tau, \text{2–prong}, \text{0–photon} \approx 1.4 \text{ pb}, \qquad \theta_{acol} > 15^\circ \tag{C4}$$

The efficacy of increasing the lower limit on θ_{acol} to reduce this σ depends upon the level of mistracking in a particular detector.

2. $e^+e^- \to \ell^+\ell^-\gamma, \ell^+\ell^-\gamma\gamma$

The radiative corrections to the reactions in eq. C1 lead to a continuum between lepton pair production and

$$e^+ + e^- \to \ell^+ + \ell^- + \gamma \tag{C5a}$$

$$e^+ + e^- \to \ell^+ - \ell^- + \gamma + \gamma \tag{C5b}$$

The completeness of the photon veto (eq. B1f) for the schematic detector controls the level of background from these reactions. For example, in

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \gamma \tag{C6}$$

the schematic detector does not veto photons with $E_\gamma < 0.2$ GeV or with $\theta\gamma < 15$ mrad. But events with $E_\gamma < 0.2$ GeV are removed by the acollinearity criterion, eq. C3. Events with $\theta_\gamma < 15$ mrad have acoplanarity angles[2] of the order of a degree, hence they can be removed by a nominal acoplanarity angle[2] criterion of

$$\theta_{\text{acop}} > 5^\circ \tag{C7}$$

The practical question is the degree of perfection of the photon veto system. Consider $ee \rightarrow \mu\mu\gamma$ again and suppose no photon veto, only $\theta_{\text{acol}} > 15^\circ$ and $\theta_{\text{acop}} > 5^\circ$, then

$$\sigma(ee \rightarrow \mu\mu\gamma) = 23.\text{ pb}, \qquad \theta_{\text{acop}} > 15^\circ, \theta_{\text{acol}} > 5^\circ \tag{C8}$$

under all other conditions of eqs. B1 and B2. A 1% inefficiency in the photon veto will then leave

$$\sigma(ee \rightarrow \mu\mu\gamma) = 0.2 \text{ pb} \tag{C9}$$

Similar considerations apply to the other reactions in eq. C5.

3. $e^+e^- \rightarrow e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, e^+e^-\pi^+\pi^-$

The two–virtual–photon processes

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^- \tag{C10a}$$

$$e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^- \tag{C10b}$$

$$e^+ + e^- \rightarrow e^+ + e^- + \pi^+ + \pi^- \tag{C10c}$$

give two–charged–particle, 0–photon events when one e^+ and one e^- are not detected because their angles with the beamline, $\theta_e{}^+$ and $\theta_e{}^-$, are very small. This kinematic situation has been studied in several experiments[3,4] and the results confirm the calculation methods developed by Berands, Daverveldt and Kleiss.[5]

With the acceptance conditions of eq. B2, the cross section in the pion pair process (eq. C10c) is a small fraction of the cross sections for the lepton pair processes (eqs. C10a and C10b), hence the former is ignored here. We use the mnemonic $ee \rightarrow (ee)\ell\ell$ to represent the sum of the processes in eqs. C10a and C10b when one e^+ and one e^-, represented by the symbols (ee), are not detected by tracking or veto devices. The observed cross section,

$\sigma(ee \rightarrow (ee)\ell\ell)$ depends upon the charged particle acceptance criteria and the angular extent of the $e^{\pm}$ veto devices. For example, with $\theta_{\rm acol} > 15^\circ, \theta_{\rm acop} > 5^\circ, p > 1$ GeV/c:

$$\sigma(ee \rightarrow (ee)\ell\ell) \approx 60 \text{ pb} \quad , \quad \theta_{e^{\pm},\rm veto} > 15 \text{ mrad} \tag{C11a}$$

$$\sigma(ee \rightarrow (ee)\ell\ell) \approx 150 \text{ pb} \quad , \quad \theta_{e^{\pm},\rm veto} > 555 \text{ mrad} \tag{C11b}$$

Here, $\theta_{e^{\pm},\rm veto}$ is measured from the beamline. Figures 2 and 3 give the $E_{\rm vis}$ and p_T distributions when the $\theta_{\rm acol} > 15^\circ, \theta_{\rm acop} > 5^\circ, p > 1.$ GeV/c criteria are applied. Here $E_{\rm vis}$ is the total energy of the two observed charged particles and p_T is the vector sum of their momenta transverse to the beamline.

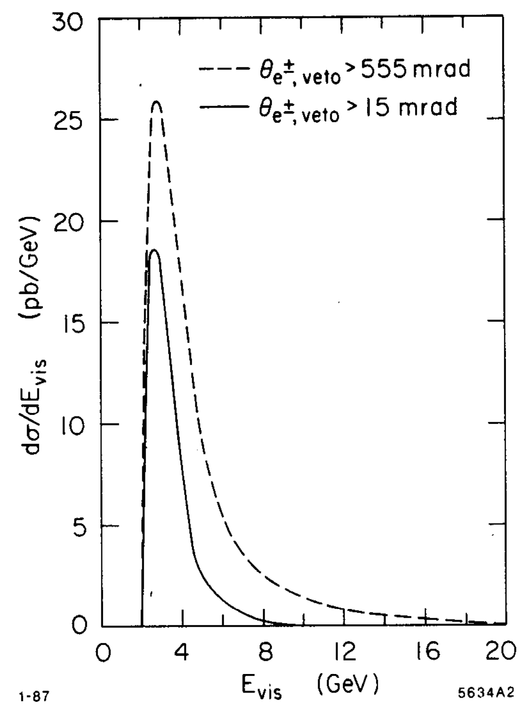

Fig. 2

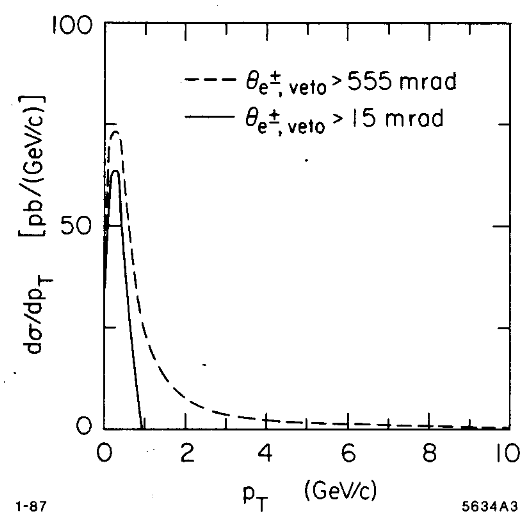

Fig. 3

The $ee \to (ee)\ell\ell$ cross section can be a serious background when one is searching for processes with small E_{vis}, such as the close-mass lepton pair model in sec. D2. This background can also be a problem in searches involving very small cross sections, such as occurred in the search of Perl *et al.*,[6] for neutral leptons in e^+e^- annihilation events produced at 29 GeV total energy.

When an $e^{\pm}$ is detected with $\theta_{e,\text{veto}} > 15$ mrad with perfect efficiency (eq. B1f), the remaining events with $\sigma = 60$ pb (eq. C11a) can be removed with a p_T criterion such as

$$p_T > 0.8 \text{ GeV/c} \tag{C12}$$

However, if the $e^{\pm}$ veto is inefficient there will be a background from a fraction of the dN/dp_T distribution in fig. 3 for $\theta_{e,\text{veto}} > 555$ mrad. For example, 1% inefficiency would give $\theta(ee \to (ee)\ell\ell) \approx 0.7$ pb for events where p_T exceeds the criterion in eq. C12. Such events would have p_T values up to 8 GeV/c and E_{vis} values up to 20 GeV/c. Of course, a larger p_T criterion could be used, but that reduces the efficiency of some searches for unconventional processes.

4. Summary

With criteria

$$\begin{aligned} \theta_{\text{acol}} &> 15^\circ \\ \theta_{\text{acop}} &> 5^\circ \\ p_T &> 0.8 \text{ GeV/c} \end{aligned} \tag{C13}$$

in the schematic detector, the two–charged particle, 0–proton backgrounds have cross sections of the order of a few tenths of a pb to several pb. Inefficiencies in γ and $e^{\pm}$ vetoes can substantially increase these cross sections. Special criteria such as requiring an $e\mu$ pair can substantially decrease some of these cross sections.

D. SIGNATURES FOR TWO–CHARGED PARTICLE, 0–PHOTON EVENTS FROM UNCONVENTIONAL PROCESSES

In this discussion the unconventional processes are classified according to the effect of the production mechanism on the kinetic variable distributions.

1. Pair Production of Charged Particles with Large Decay Energies

The general process is production of an x^+x^- pair followed by the decays of x^+ and x^- through the weak interaction:

$$e^+ + e^- \to x^+ + x^- \tag{D1}$$

$$x^{\pm} \to y^{\pm} + n_1 + n_2 + \ldots \tag{D2}$$

with the energy released in the decay of the x, large compared to the masses of the y and the $n_1, n_2 \ldots$. Here, $n_1, n_2 \ldots$ are neutral, weakly interacting particles; there may be one or more in the decay. And y^- means e^-, μ^-, π^- or K^-. It can also indicate τ^- when the τ decays into a one–charged–particle, 0–photon mode. The general kinematics are determined by two parameters: (i) the mass of x, called m_x and (ii) the difference, called δ, between m_x and the sum of all the masses of the particles on the right side of the reaction in eq. D2. Explicitly

$$\delta = m_x - \left(m_y + \sum m_n\right) \tag{D3}$$

The case usually discussed is

$$m_x \approx \delta \tag{D4}$$

The best known example[7] is a heavy sequential lepton, L^-, with a near-zero-mass neutrino partner ν_L. Then the decay process in eq. D2 is

$$L^- \to \ell^- + \bar{\nu}_\ell + \nu_L \quad ; \quad \ell = e, \mu \tag{D5}$$

A similar example is the chargino, χ^-, proposed in supersymmetric models, when the χ^- decays to a near-zero-mass photino, $\tilde{\gamma}$:

$$\chi^- \to \ell^- + \nu_\ell + \tilde{\gamma} \quad , \quad \ell = e, \mu \tag{D6}$$

A two–body example, also from supersymmetric models, is the pair production of scalar leptons

$$\begin{aligned} e^+ + e^- \to Z^0 \to \tilde{\ell}^+ + \tilde{\ell}^- \\ \tilde{\ell}^- \to \ell^- + \tilde{\gamma} \end{aligned} \tag{D7}$$

To illustrate the case of a three–body decay

$$x^- \to \ell^- + n_1 + n_2 \tag{D8}$$

I use the following simplified model: (i) the production process in eq. D1 is isotropic, the decay process in eq. D8 is calculated using relativistic phase space, and the masses of the final particles are set to zero. The θ_{acol} distribution is given in fig. 4 for $m_x = 20$, 30 and 40 GeV/c^2. Replacing the phase space calculation by one using some combination of V and A couplings changes these distributions slightly. A feeling for the observed cross section can be obtained by using eq. B4 with $\beta = 1$, using the branching fractions

$$B(x^- \to e^- n_1 n_2) = B(x^- \to \mu^- n_1 n_2) = 0.1 \quad , \tag{D9}$$

and using an acceptance of 0.7 for the criteria of eqs. B2 and C11:

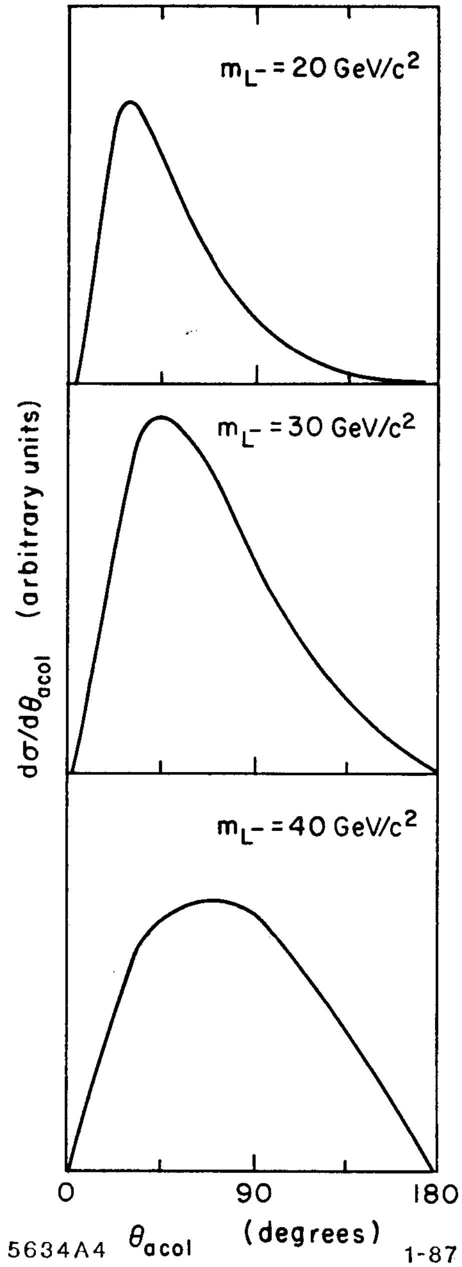

Figure 4

$$\begin{aligned} |\cos\theta| &< .85 \\ p &> 1.\ \mathrm{GeV/c} \\ \theta_{acol} &> 15^\circ \\ \theta_{acop} &> 5^\circ \end{aligned} \tag{D10}$$

Then

$$\sigma = (ee \to L^+L^- \to \ell^+\ell^-, \text{observed}) = 39 \text{ pb} \tag{D11}$$

As is well known this is much larger than the background examples given in eqs. C4 and C9, hence such searches are straightforward. Incidently, the lower limit from the UA1 collaboration[8] of

$$m_{L^-} > 41 \text{ GeV/c}^2 \qquad (90\% \text{ CL})$$

on a charged heavy lepton with a near-zero-mass neutrino partner limits this search using Z° decay to a small mass range.

Summarizing, the events produced by processes defined by eqs. D1, D2 and D4 have the following properties:

1. As m_x approaches $m_Z/2$, the acollinearity increases. Acollinearity and acoplanary criteria such as $\theta_{\rm acol} > 15^\circ, \theta_{\rm acop} > 5^\circ$ separate most of the events from the $ee \to \ell\ell$ and $ee \to \ell\ell\gamma$ backgrounds.
2. For all m_x values the events have large $E_{\rm vis}$ values, hence they separate from $ee \to (ee)\ell\ell$ events.
3. For all m_x values the events have large p_T values.

There have been several detailed discussions[9,10] of how to search for new particles produced by the processes defined by eqs. D1, D2 and D4. I turn to a less known case.

2. Pair Production of Charged Particles with Small Decay Energies

We have recently begun to study models[11] where the production and decay processes are given by eqs. D1 and D2 but

$$m_x \gg \delta \tag{D12}$$

I will concentrate on what I call the close-mass lepton pair model[11,12] The reader can easily extend the discussion to other hypothetical particles, for example, charginos and photinos.

Consider the lepton pair L^-, L° with masses m_- and m_0, respectively. Suppose $m_- > m_0$ but

$$m_- - m_0 = \delta \ll m_- \tag{D13}$$

The charged particle in the decay modes

$$L^- \to \ell^- + \bar\nu_\ell + L^\circ \quad ; \quad \ell = e, \mu \tag{D14a}$$

$$L^- \to \pi^- + L^\circ \tag{D14b}$$

has maximum laboratory momentum

$$P_{\rm max} = E_b \left[1 - \left(\frac{m_0}{m_-}\right)^2\right] \left[1 + \left(1 - \left(\frac{m_-}{E_b}\right)^2\right)^{1/2}\right] \Big/ 2 \tag{D15}$$

Here E_b is the beam energy $m_Z/2$. The ℓ, ν_ℓ and π masses have been set to zero. Using eq. D12

$$E_{\rm vis} < (\delta/m_-)m_Z \tag{D16}$$

Here $E_{\rm vis}$ is the total useable energy.

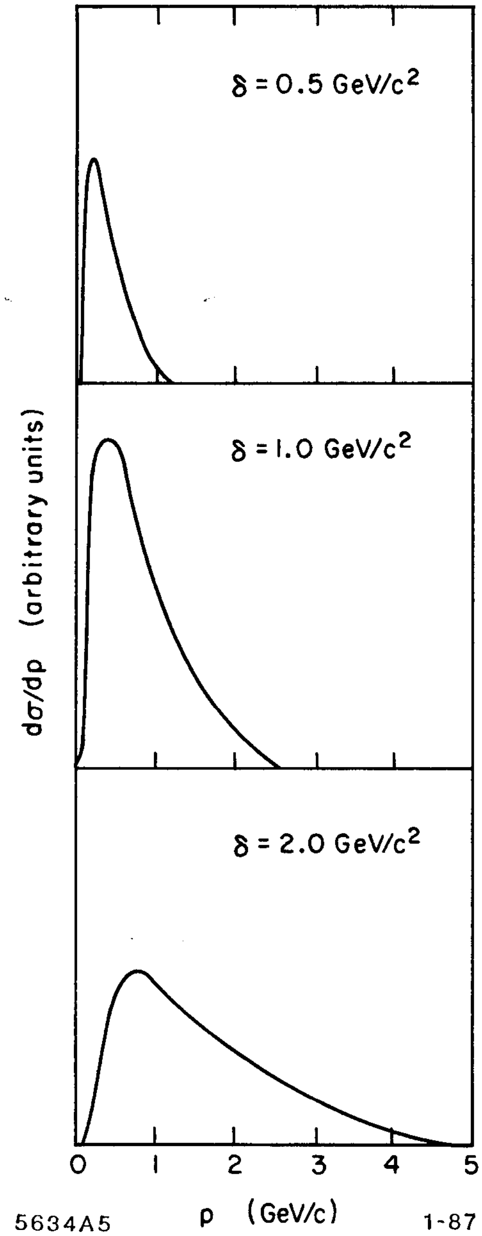

Figure 5

If δ is of the order of a few GeV/c^2 or less, and m_- is of the order of tens of GeV/c^2, $E_{\rm vis}$ is small. Then the $ee \rightarrow (ee)\ell\ell$ background (sec. C3) becomes important. A general discussion is unwieldly because there are now two parameters, m_- and δ; I proceed by example.

Suppose $m_- = 30$ GeV/c^2; consider the decay modes of eq. D14a; set $m_\ell = 0, m_{\nu_\ell} = 0$, and let $\delta = m_- - m_0$ have the values 0.5, 1.0 and 2.0 GeV/c^2. Using the pair production cross section in eqs. B4 and B5a and conventional weak interaction theory with V–A coupling, we calculate kinematic distributions, branching fractions and the observed cross sections for the classic signature

$$e^+ + e^- \rightarrow L^+ + L^- \rightarrow e^\pm + \mu^\mp + \text{ missing energy} \tag{D17}$$

The e and μ momentum distributions are given in fig. 5. Table 1 gives the observed cross sections under the usual criteria

Table 1. Branching fractions and observed cross sections for $e^+e^- \to L^+L^- \to e^\pm\mu^\mp +$ missing energy via $L^- \to L^0 e^- \bar{\nu}^e, L^+ \to \bar{L}^0 \mu^+ \nu_\mu$, with $m_- = 30$ GeV/c^2.

$m_- - m_0$ (GeV/c^2)	$B(L^- \to L^0 e^- \bar{\nu}_e)$	$B(L^+ \to \bar{L}^0 \mu^+ \nu_\mu)$	Observed σ (pb) p > 0. GeV/c	p > 1. GeV/c
2.0	.19	.19	71.	.29
1.0	.17	.16	50.	4.
0.5	.18	.15	51.	0.

$$\begin{aligned} |\cos\theta| &< 0.85 \\ \theta_{\text{acol}} &> 15^\circ \\ \theta_{\text{acop}} &> 5^\circ \end{aligned} \tag{D18}$$

but with

$$\begin{gathered} p > 0.\ \text{GeV/c} \\ \text{or} \\ p > 1.\ \text{GeV/c} \end{gathered} \tag{D19}$$

Figure 5 and Table 1 lead to several comments:

1. As $\delta = m_- - m_0$ decreases below 2. GeV/c^2, the $p > 1.$ GeV/c criterion must be abandoned. But then, according to eqs. B1b and B1c, the e and μ can no longer be identified.
2. Without e and μ identification the observed cross sections are the same size as the $ee \to (ee)\ell\ell$ background cross sections in eq. C11.
3. Comparing fig. 6, the p_T distributions for this model, with fig. 3, one sees that for small values of δ this signature will be submerged by the $ee \to (ee)\ell\ell$ background.

There are, of course, other signatures for the process under discussion: $\ell^\pm\pi^\mp, \ell^\pm\rho^\mp$ and four–charged particles, depending upon δ. And the Z^0 width, when carefully measured, would reflect the existence of an additional L^- and L^0. But when $\delta \lesssim 1.5$ GeV/c^2, it could be very difficult to elucidate the type of process discussed in this section. Incidently, when $\delta \lesssim m_\pi$, the charged particle lifetime becomes sufficiently long for the L^- to appear stable.

3. Production of Two Neutral Particles

Various types of hypothetical leptons[11,13,14] illustrate how two–charged–particle, 0–photon events could come from the decay of the Z^0. If there is a heavy neutral lepton, L^0, which mixes with the e, μ or τ generation then the following could occur

$$\begin{aligned} e^+ + e^- &\to L^0 + \bar{\nu}_1 \\ L^0 &\to \ell_1^- + \ell_2^+ + \nu_2 \end{aligned} \tag{D20}$$

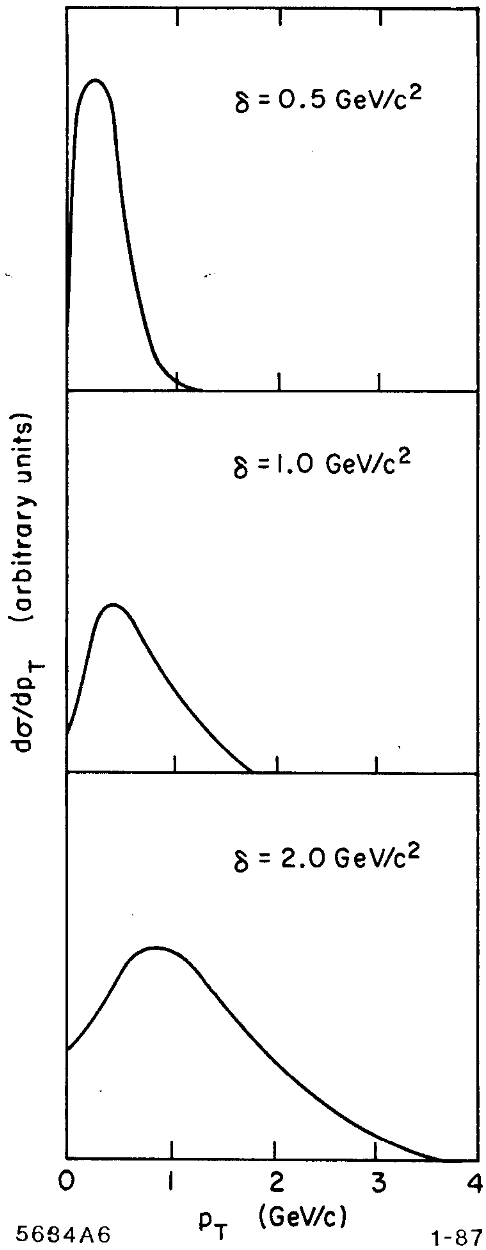

Figure 6

Here ℓ means e, μ or τ and ν is the corresponding neutrino. In a more exotic scheme, consider a pair of neutral leptons L^0, ν_L with the unconventional decay $L^0 \rightarrow \nu_L + \ldots$, then

$$\begin{aligned} e^+ + e^- &\rightarrow L^0 + \bar{\nu}_L \\ L^0 &\rightarrow \nu_L + \ell^+ + \ell^- \end{aligned} \tag{D21}$$

or

$$\begin{aligned} e^+ + e^- &\rightarrow L^0 + \bar{L}^0 \\ L^0 &\rightarrow \nu_L + \ell^+ + \ell^- \\ \bar{L}^0 &\rightarrow \bar{\nu}_L + \nu + \bar{\nu} \end{aligned} \tag{D22}$$

will give two–charged–particle, 0–photon events.

Another possibility is a weakly decaying neutral boson[6], N^0, with

$$\begin{aligned} e^+ + e^- &\to N^0 + \bar{N}^0 \\ N^0 &\to \ell^+ + \ell^- \\ \bar{N}^0 &\to \nu + \bar{\nu} \end{aligned} \tag{D23}$$

In all these processes, as in the process in sec. D1, the events will have

1. large values of θ_{acol}
2. large values of E_{vis}
3. large values of p_T

Although here the large values of θ_{acol} occur for a different reason than the processes in sec. D1. Indeed in contrast to the latter processes, these processes give events which become more collinear as m_0 approaches m_Z or $m_Z/2$. Figure 7 illustrates this for the reactions in eq. D22. Here the masses of ν_L, ℓ and ν are set to zero, and once again relativistic phase space is used for the decay process. The L^0 mass is given for each curve.

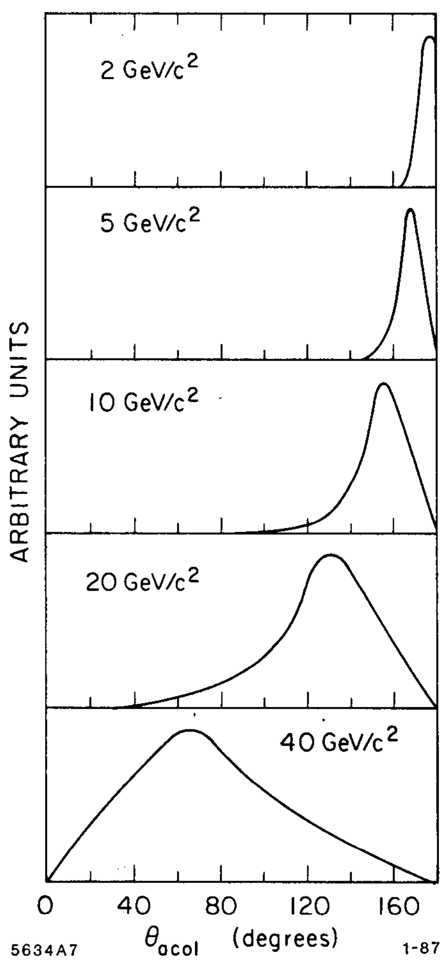

Figure 7

To illustrate what an observed cross section might be, I use eqs. B4 and B5b with $\beta = 1$, and I take the branching fractions from fig. 3 in ref. 6.

$$\begin{aligned} B(L^0 \to \nu_L \nu_i \nu_i) &= 0.25 \\ B(L^0 \to \nu_L \ell\ell) &= 0.07 \end{aligned} \tag{D24}$$

Before any θ_{acol} or θ_{acop} cuts, the acceptance is 0.7 for

$$\begin{aligned} |\cos| &< .85 \\ p &> 1.\ \text{GeV/c} \end{aligned} \tag{D25}$$

Then

$$\sigma(ee \to L^0 \bar{L}^0 \to \ell^+ \ell^-, \text{ observed}) = 69 \text{ pb} \tag{D26}$$

Like the result in eq. D11, this σ allows a straightforward search with respect to the background discussed in sec. C, providing the production cross section and branching fractions are as assumed here.

4. Production through a Central Process

As a final example I consider a central process, perhaps the low energy residual of some much higher energy interaction, where the Z^0 decays to four fermions

$$Z^0 \to f_1 + \bar{f}_1 + f_2 + \bar{f}_2 \tag{D27}$$

If f_1 is a neutrino, and f_2 is a lepton

$$Z^0 \to \nu + \bar{\nu} + \ell^+ + \ell^- \tag{D28}$$

yields two–charged particle, 0–photon events.

The question is how small a cross section could be found in view of the background described in sec. C: e^+e^- and $\mu^+\mu^-$ pairs from $ee \to \tau\tau, ee \to \ell\ell\gamma$ and $e^+e^- \to (ee)\ell\ell$. Important separation criteria are: (i) the lower limit on θ_{acol}, called $\theta_{\text{acol,min}}$ and (ii) the lower limit on E_{vis}, called $E_{\text{vis,min}}$. The former discriminates against all backgrounds, the latter against $ee \to (ee)\ell\ell$. Figure 8 gives the acceptance as a function of these criteria. Relativistic phase space is used and all lepton masses are zero. Useable acceptances can be obtained with large values of $\theta_{\text{acol,min}}$ and $E_{\text{vis,min}}$ and such large values discriminate against the background discussed in sec. C. The lower limit on the detectable cross section from the reaction in eq. D28 will probably be set by detector inefficiencies and malfunctions.

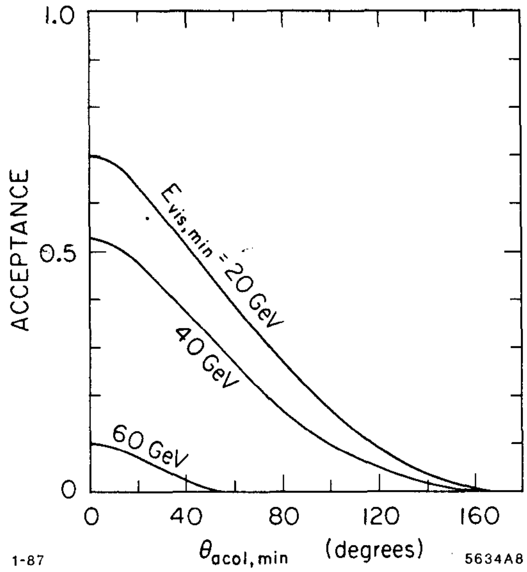

Figure 8

E. BACKGROUND FOR FOUR–CHARGED AND SIX–CHARGED PARTICLE, 0–PHOTON EVENTS

1. $e^+e^- \to \tau^+\tau^-$

The process

$$e^+ + e^- \to \tau^+ + \tau^- \tag{E1}$$

gives four–charged or six–charged particles and 0–photons when one or both τ's decay

$$\tau^- \to \pi^- + \pi^+ + \pi^- \tag{E2}$$

But these events will be obvious and easily separated out.

2. $e^+e^- \to e^+e^-\ell^+\ell^-$

The two–virtual–photon process

$$e^+ + e^- \to e^+ + e^- + \ell^+ + \ell^- \tag{E3}$$

with all particles detected is the main known background from conventional processes for four–charged particle, 0–photon events. The process in eq. E3 has been studied at PETRA[15,16] and compared with calculations using the Monte Carlo methods of ref. 5. Measurement and calculations agreed in the use of ref. 15, but not in that of ref. 16. The latter discrepancy has not been confirmed.

Using the Monte Carlo program from ref. 5, with the criteria

$$|\cos\theta| < 0.85 \tag{E4a}$$

$$p > 1. \tag{E4b}$$

$$m_{\ell\ell} > 1.\ \mathrm{GeV/c^2} \tag{E4c}$$

the observed cross section is

$$\sigma(ee \to eeee, ee\mu\mu; \text{observed}) = 0.084 \pm 0.019\ \text{pb} \tag{E5}$$

Here, $m_{\ell\ell}$ represents the invariant masses of $e^+e^-, \mu^+\mu^-$ and $e^\pm\mu^\mp$ pairs; the lower limit eliminates uninteresting events. The uncertainty in σ is from the statistics of the Monte Carlo calculation.

All the $ee \to ee\mu\mu$ events contributing to σ in eq. E5 have one $m_{\ell\ell}$ close to the lower limit in eq. E4c, the other $m_{\ell\ell}$ is usually close to m_Z^0, an expected distribution. For example, if

$$m_{\ell\ell} > 5.\ \mathrm{GeV/c^2} \tag{E6}$$

is required, the observed cross section is reduced to

$$\sigma(ee \to eeee, ee\mu\mu, \text{observed}) = 0.022 \pm 0.008\ \text{pb} \tag{E7}$$

Thus, the criteria in eqs. E4a, E4b and E6 limit $\sigma(ee \to ee\ell\ell$, observed) to very small values.

3. $e^+e^- \to$ hadrons

A possible, albeit very small, background is four–charged or six–charged particle, 0–photon hadronic events from quark-antiquark pair production. I do not know how to calculate this. The cross section for such events in the PETRA–PEP region is not measured to my knowledge. And one cannot depend upon the empirical quantum chromodynamic calculational methods used in the several Monte Carlo programs currently applied to $e^+e^- \to$ hadrons. Such programs are designed and adjusted to fit the behavior of the bulk of hadronic events; not the rare events of interest here.

F. FOUR–CHARGED OR SIX–CHARGED PARTICLE, 0–PHOTON EVENTS FROM UNCONVENTIONAL PROCESSES

Here, as in sec. D, the unconventional processes are classified according to the affect of the production mechanism on the kinematic variable distribution. The background has been discussed in sec. E. Excepting the easily recognized $\tau\tau$ background, the known background is 0.1 to 0.01 pb, eqs. E5 and E7. The limitations on search sensitivity will probably come from a combination of the unknown hadronic background (sec. E) and detector malfunctions and inefficiencies.

1. Four–Charged Particle, 0–Photon Events from Two Neutral Particles

Using the L^0, ν_L model of eq. D22

$$\begin{aligned} e^+e^- &\to Z^0 \to L^0 + \bar{L}^0 \\ L^0 &\to \nu_L + \ell^+ + \ell^- \\ \bar{L}^0 &\to \bar{\nu}_L + \ell^+ + \ell^- \end{aligned} \tag{F1}$$

or the neutral boson model of eq. D23

$$\begin{aligned} e^+ + e^- &\to Z^0 \to N^0 + N^0 \\ N^0 &\to \ell^+ + \ell^- \quad \text{(both } N^0) \end{aligned} \tag{F2}$$

four–charged particle, 0–photon events can be produced. Here ℓ means e, μ or the one–charged–particle, 0–photon decay modes of the τ. Of course the ℓ's could be replaced by π or K mesons, but such decay modes would probably have very small branching fractions for the L^0 or N^0 masses of interest—above several GeV/c^2.

The L^0, ν_L model with the $\nu_L \ell^+ \ell^-$ branching fraction of eq. D24, with the production cross section of eqs. B4 and B5b with $\beta = 1$, and with an acceptance of 0.4 for

$$\begin{aligned} |\cos\theta| &< .85 \\ p &> 1.\ \mathrm{GeV/c} \end{aligned} \tag{F3}$$

gives

$$\sigma(ee \to L^0 \bar{L}^0 \to \ell^+\ell^-\ell^+\ell^-, \text{ observed}) = 5 \text{ pb} \tag{F4}$$

This is a relatively small cross section, but still much larger than the known background cross sections.

The N^0 model would give obvious events with $E_{\rm vis} = m_Z$ within detector precision and radiative corrections. The distributions of pair masses would indicate m_{N^0}, and be very different from the $ee \to ee\ell\ell$ distributions (Sec. E2).

A generalization of the L^0 and N^0 models would add additional neutral, weakly-interacting, particles to the decay modes in eqs. F1 or F2.

2. Production through a Central Process

The central process model in sec. D4 would also give

$$e^+ + e^- \to \ell_1^+ + \ell_1^- + \ell_2^+ + \ell_2^- \tag{F5}$$

Using relativistic phase space, the acceptance under the criteria of eq. F3 is 0.5, again $E_{\rm vis} = m_Z$.

3. Four–Charged or Six–Charged Particle, 0–Photon Events from Charged Particle Production

Here I follow the scheme of the $\tau\tau$ production and decay process. Consider

$$e^+ + e^- \to Z^0 \to f^+ + f^- \tag{F6}$$

with the decay modes

$$f^- \to \ell^- + \nu + \bar{\nu} \tag{F7a}$$

$$f^- \to \ell^- + \ell^+ + \ell^- \tag{F7b}$$

Here, as before, ℓ means e, μ or the one–charged–particle, 0–photon τ decay modes; ν means ν_e, ν_μ or ν_τ.

Such events will be distinctive, particularly the six–charged–particle events with $E_{\rm vis} = m_Z$.

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