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Searches for unstable neutral leptons in low-multiplicity events from electron-positron annihilation

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Upper limits are given on the production of unstable neutral leptons in electron-positron annihilation at 29 GeV. The searches use selected two- and four-charged-particle events and are most sensitive to neutral-lepton masses of the order of 1 GeV/c^2 and smaller. However, results are given for masses up to 14 GeV/c^2.

I. INTRODUCTION

This paper describes a set of searches for unstable neutral leptons which could be produced in electron-position annihilation at 29 GeV total energy. These searches used selected events with two or four charged particles and are most sensitive in the detection of neutral-lepton masses in the range of 1 GeV/c^2 and smaller. No evidence for unstable neutral leptons was found; some model-dependent upper limits on production cross sections are given. The data was collected using the Mark II detector at the PEP electron-positron collider at SLAC.

The known neutral leptons are the ν_e, ν_μ, and ν_τ neutrinos associated with the e, μ, and τ charged leptons, respectively. The obvious and important experimental question is "Do other neutral leptons exist?" There is no comprehensive answer to this question,[1] the significance of an experimental search depends upon the models used for the production and decay of the neutral lepton as well as on the method and energy.

The philosophy of the searches described in this paper is based on three observations.

(1) In high energy, such as 29 GeV, e^+e^- annihilation there are relatively few events produced with four charged particles, no photons, and total charge zero. The major known sources of such events are purely electromagnetic processes such as $e^+e^-\to e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $e^+e^-\tau^+\tau^-$, $\mu^+\mu^-\mu^+\mu^-$, and $e^+e^-\to\tau^+\tau^-$ where one τ decays to one charged particle and the other τ to three charged particles, no photons being produced in either decay. The physics of these processes is known.

(2) There are relatively few events produced with two charged particles, no photons, and total charge zero if the events from $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, γe^+e^-, $\gamma\mu^+\mu^-$ are removed by a collinearity and coplanarity angular cuts and other criteria (Sec. V).

(3) In many models an unstable massive neutral lepton in the mass range of 1 GeV/c^2 or smaller has a substantial branching fraction into two charged particles, with or without neutrinos. Therefore the process

$$e^+e^-\to L^0\bar{L}^0\,, \tag{1}$$

with both L^0's, decaying, could have the signature of four charged particles, no photons, and total charge zero. The signature of two charged particles, no photons, and total charge zero can occur if the L^0 has an all neutrino decay mode in addition to the two-charged particle decay mode. The two-charged-particle and all neutrino decay modes are most prominent when the L^0 mass is of the order of 1 GeV/c^2 or smaller. Therefore these searches emphasize that mass region, although the region up to 14 GeV/c^2 is examined.

The significance of the searches depends upon the production and decay models used for the L^0. Examples of models and illustrative branching fraction calculations are presented in Sec. II, Appendix A, and Appendix B.

The apparatus and the criteria used for general event selection are presented in Sec. III. As described in Sec. III B, these searches are directed to models in which both L^0's decay within a few centimeters of their production point; hence there is an upper limit on the L^0 lifetime. No attempt is made to look for displaced vertices in the work described in this paper.

Sections IV and V give the results for four-charged-particle and two-charged-particle events, respectively. All combinations of particle types were allowed for the four-particle events; the two-particle events were required to have at least one electron. The results consist of upper limits on the number of events found in the smaller mass range of the L^0. We present a few illustrative examples of how these results can be interpreted. Our main object is to present the results with sufficient generality so that the reader can apply them to other models and hypotheses for unstable neutral leptons.

II. MODELS FOR UNSTABLE NEUTRAL LEPTONS

A large number of hypotheses and models for unstable neutral leptons have been proposed;[1–5] we shall not review them here. Rather we present a limited discussion of some models which illustrate the significance of our searches, models connected to the mass range and experimental signatures available in 29-GeV e^+e^- annihilation processes. We begin with models which conform to our present understanding of the weak interaction. Then we discuss models which do not conform.

A. Fourth generation, conventional weak interactions, no mixing

A simple extension of our present knowledge of the leptons and the weak interactions would consist of a fourth lepton generation

$$\begin{bmatrix} L^0 \\ L^- \end{bmatrix}_L, \quad (L^0)_R, \quad (L^-)_R \tag{2}$$

which obeys the Weinberg-Salam theory with no mixing with other lepton generations. Then the L^0 will be unstable only if

$$m_{L^0} > m_{L^-}, \tag{3}$$

where m is mass. The lower limit on m_{L^-} is about 20 GeV/c^2 from e^+e^- collider searches for sequential charged leptons. Hence in this model m_{L^0} would be above 20 GeV/c^2 and could not be produced in $e^+e^- \to L^0\bar{L}^0$ at 29 GeV. Consequently this model is not applicable to our searches.

B. Fourth generation, conventional weak interactions, mixing

A further extension of our present knowledge of leptons copies the behavior of the quarks in the weak interaction and allows mixing between generations. In the simplest form of this model, the fourth generation

$$\begin{bmatrix} L^0\cos\phi - \nu_l\sin\phi \\ L^- \end{bmatrix}_L, \quad (L^0)_R, \quad (L^-)_R \tag{4a}$$

mixes with one of the known generations

$$\begin{bmatrix} L^0\sin\phi + \nu_l\cos\phi \\ l^- \end{bmatrix}_L, \quad (l^-)_R \tag{4b}$$

where $l = e$, μ, or τ. The L^0 decays through the charged weak current, Fig. 1(a).

Conventional weak-interaction theory and weak universality put upper limits on $\sin\phi$. This leads to a restricted model which is discussed further in Appendix A. As discussed there this model is not useful to these searches for small L^0 masses because of the relatively long lifetime it implies for L^0 masses below 2 GeV/c^2.

C. Charged current and neutral branching fractions

We use conventional weak-interaction theory to calculate[5–7] the branching fractions for some decays via the charged current, Appendix B. The purpose is to illustrate the significance of our searches. Therefore we do a similar calculation, Appendix B, for the neutral current decay process in Fig. 1(b), even though the $L^0-\nu$ vertex violates conventional theory. Figures 2 and 3 give the branching fractions for the charged current and neutral current. In particular, they give B_{C2} and B_{N2}, the branching fractions for decay to two stable charged particles and no photons, with or without neutrinos. Stable means $e^\pm$, $\mu^\pm$, $\pi^\pm$, or $K^\pm$.

D. Models deviating from conventional weak interactions

The models discussed in Secs. II A and II B are in agreement with conventional weak-interaction theory. However, our searches are most useful for putting limits on the existence of neutral leptons which have unconventional weak interactions. We give two examples.

In the first example we consider a pair of neutral lep-

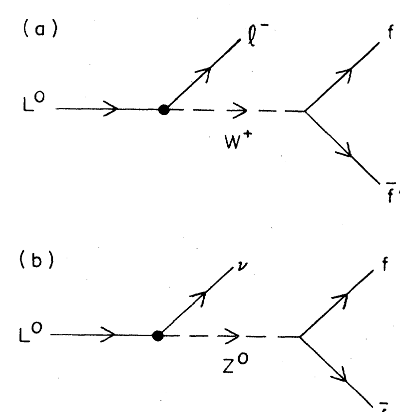

FIG. 1. Diagrams for (a) L^0 decay via the conventional weak-charged current and (b) L^0 decay via a hypothetical, flavor-changing, weak neutral current.

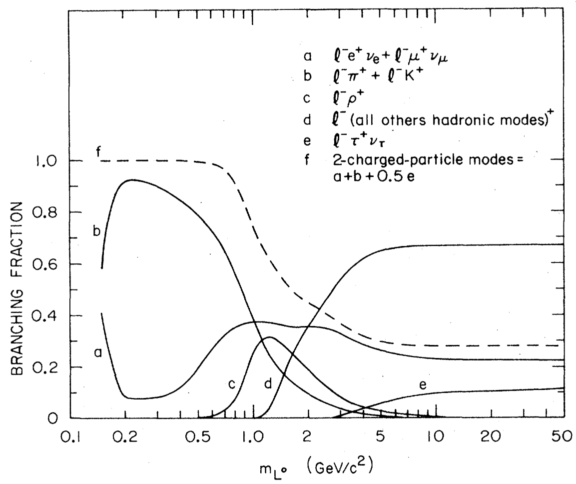

FIG. 2. Branching fractions for the L^0 decay, Fig. 1(a), via the conventional weak-charged current, taking the l^- mass to be zero. Curve f gives B_{C2}, the fraction for decay into two charged particles, no photons, with or without neutrinos.

tons $L^0, L^{0'}$ with the same unique conserved lepton number and

$$m_{L^0} > m_{L^{0'}} .$$

Such a pair does not fit into conventional weak-interaction theory but we can still hypothesize the decay

$$L^0 \to L^{0'} + Z^0_{\text{virtual}} \tag{5}$$

and suppose that the decay models have approximately the branching fractions of Fig. 3.

For the second example consider a singlet heavy neutral lepton L^0 which has the same lepton number as the e^-, μ^-, or τ^-, which decays through a weak charged current, but does not decay through a weak neutral current. This

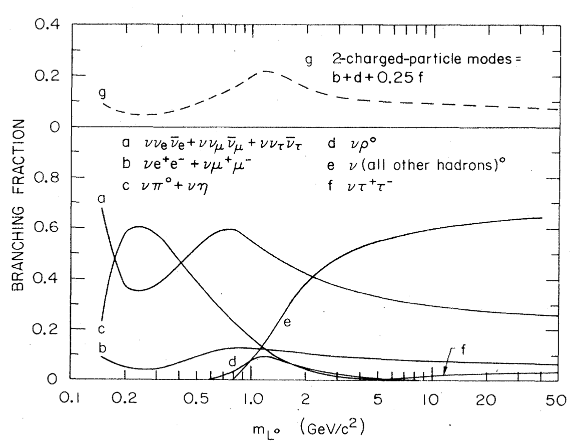

FIG. 3. Branching fractions for the L^0 decay, Fig. 1(b), via a hypothetical, flavor-changing, weak neutral current taking the ν mass to be zero. Curve g gives B_{N2}, the fraction for decay into two charged particles, no photons, with or without neutrinos. Curve a gives B_{N0}, the fraction for decay into all neutrinos.

is a simplistic version of many more profound and intricate heavy neutral lepton models proposed over the last decade. These models may have special properties such as right-handed charged currents. But it is sufficient for our illustrative purposes to use the branching fractions of Fig. 2.

E. $e^+e^- \to L^0 \bar{L}^0$ production cross section

Once we consider neutral leptons with unconventional weak interactions, we cannot calculate the cross section for

$$e^+ + e^- \to L^0 + \bar{L}^0 \tag{6}$$

unless we specify the specific model. The variety of models makes that a tedious task of little utility. Therefore we only calculate[4-6] a cross section based on conventional Weinberg-Salam theory for

$$e^+ + e^- \to Z^0_{\text{virtual}} \to L^0 + \bar{L}^0 . \tag{7}$$

This cross section acts as a standard; hence we call it σ_{stan}:

$$\sigma_{\text{stan}} = \frac{G^2 s (a_e^2 + v_e^2)(a_{L^0}^2 + v_{L^0}^2)}{96\pi(1 - s/m_Z^2)^2} \frac{\beta(3+\beta^2)}{4} , \tag{8a}$$

$$a_e = -1, \quad v_e = -1 + 4\sin^2\theta_W = -0.12 ,$$
$$a_{L^0} = +1, \quad v_{L^0} = +1 . \tag{8b}$$

Here G is the Fermi coupling constant (1.166×10^{-5} GeV^{-2}), s is the square of the total energy, a and v are coupling constants, m_Z is the Z^0 mass, θ_W is the Weinberg angle, and β is the velocity of the L^0 in units of c. We use $\sin^2\theta_W = 0.22$ and $m_Z = 93$ GeV/c^2. Then, including a -5% electromagnetic radiative correction, at 29 GeV

$$\sigma = 0.35[\beta(3+\beta^2)/4] \text{ pb} , \tag{8c}$$

$$N_{\text{stan}} = 77[\beta(3+\beta^2)/4] \text{ events} . \tag{8d}$$

Here N_{stan} is the number of events which would be produced assuming σ_{stan} and based on the 220 pb^{-1} of data used in this analysis (see Sec. III C). N_{stan} does not include the acceptance of the detector. The threshold factor has little effect below $m_L = 10$ GeV/c^2.

F. Weakly decaying neutral bosons

The previous decay scheme examples assumed leptons. However our searches are also applicable to neutral bosons, N^0, with two-charged particle decay modes such as

$$N^0 \to l^+ + l^-, \quad l = e, \mu, \tau . \tag{9}$$

This category includes the proposed neutral Higgs particles and the sensitivity of our searches depends upon the model used for the Higgs sector. Another example of this category is a small mass neutral intermediate boson which by unconventional couplings evades present limits on the existence of additional Z^0 particles.

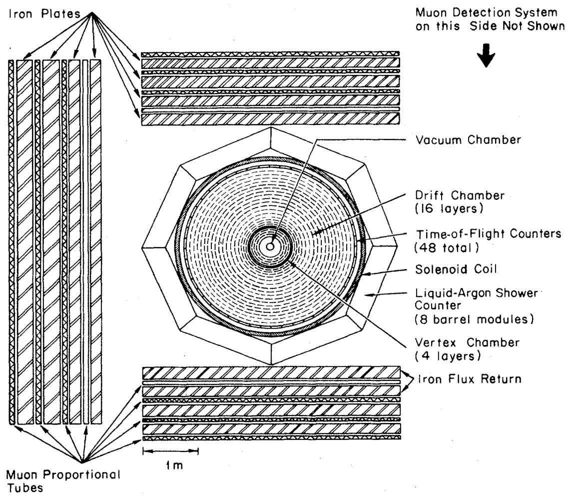

FIG. 4. Cross-section view of Mark II detector.

III. APPARATUS AND GENERAL EVENT SELECTION

A. Apparatus

The Mark II detector, Fig. 4, was used at the PEP electron-positron collider at the Stanford Linear Accelerator Center. The detector is described in Ref. 8. Here we emphasize a few properties of the detector pertinent to the searches described in this paper.

(1) The main drift chamber tracks particles well over about 80% of the 4π solid angle. The charged particles of the events used were required to be within a slightly smaller solid angle, namely, 70% of 4π.

(2) The liquid-argon electromagnetic calorimeter, used to detect electrons and photons, covers about 70% of the 4π solid angle.

(3) The lead-sheet and proportional-chamber detectors (two layers each) at each end of the detector, called end-cap chambers, cover the polar region from about 15° to 40°. These end-cap chambers detect photons and charged particles.

(4) The photon detection system is incomplete since there is a gap about 5° in polar angle between the liquid-argon calorimeter and the end-cap calorimeter, since the liquid-argon calorimeter has eight separate modules with longitudinal walls separating the modules, and since the end-cap chambers themselves have gaps in their angular coverage.

(5) Electrons scattered out of the beam line by polar angles of 21—82 mrad are detected by a small angle tagging system. This is relevant to two-virtual-photon processes $e^+e^- \to e^+e^-\gamma V \gamma V$, where the final e^+ or e^- are scattered close to the beam line.

(6) The muon detection system covers about 45% of the 4π solid angle.

(7) The vertices of the events used in this analysis all lie within a fiducial radius of $r_{\rm fid}=4$ cm of the beam line.

B. Lifetime criterion

Events of interest in these searches must have their decay vertices inside $r_{\rm fid}$. Then the approximate upper limit on the measurable lepton lifetime is

$$T_{\max} \approx r_{\rm fid}/c\gamma \approx 10^{-11} m_L \text{ sec} , \tag{10}$$

where m_L is in GeV, and $e^+e^- \to L^0\bar{L}^0$ production is assumed. One effect of this upper limit is discussed in Appendix A.

C. Data acquisition and general event selection

The data were acquired at 29 GeV over several years with an integrated luminosity of 220 pb^{-1}. The triggering efficiency for the events used here was close to 100%.

Events were selected by the following criteria.

(1) The event's vertex is inside a cylinder of 4-cm radius centered on the interaction point.

(2) There are exactly two or exactly four charged particles with total charge zero in the main drift chamber.

(3) Each particle has $|\cos\theta| < 0.7$, where θ is the angle between the particle's initial vector momentum, p, and the beam axis. This ensures that all the particles are well tracked in the drift chamber, and reduces the background from purely electromagnetic process such as $e^+e^- \to e^+e^-\mu^+\mu^-$.

(4) Each particle has $2.0 < p < 14.5$ GeV/c in the two-particle events and $1.0 < p < 14.5$ GeV/c in the four-particle events. Here p is the magnitude of $\mathbf{p}$.

(5) There are no isolated photons in the liquid-argon calorimeter. An isolated photon lies sufficiently far from all charged tracks such that $\cos\theta_{\gamma j} < 0.99$, $\theta_{\gamma j}$ being the angle between the photon's momentum $\mathbf{p}_\gamma$ and $\mathbf{p}_j$ of the track j. In addition, an isolated photon has $E_\gamma > 300$ MeV.

(6) There are no photon or charged-particle signals in the end-cap chambers.

(7) There are no electron signals in the small-angle tagging system.

(8) The two-charged-particle events have a criterion imposed by the computer program used to process the raw events from the detector. The processing time of the data was reduced by not completing the processing of some types of two-prong and one-prong events. To make sure that we understand the two-charged-particle event efficiency, we require in this work that at least one of the particles be an electron. Such events were completely processed.

(9) The two-charged-particle events have two additional criteria which remove most $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, and two-prong $e^+e^- \to \tau^+\tau^-$ events. These criteria are $\theta_{\rm coll} \le 160°$ and $\theta_{\rm copl} \le 160°$. Here $\theta_{\rm coll}$ is the collinearity angle between the momenta of the two particles and $\theta_{\rm copl}$ is the coplanarity angle using the beam axis. Both angles are 180° when the momenta are exactly opposite in direction.

After the application of these criterion there were

$$\begin{aligned} &\text{Number of four-charged-particle events} = 443 , \\ &\text{Number of two-charged-particle events} = 249 . \end{aligned} \tag{11}$$

D. Kinematics and acceptance calculations

In all kinematics calculations the masses of the observed charged particles were set to 0. This is a negligible error because all particles have $p \geq 1.0$ GeV/c and there are few K's.

The acceptance calculations used phase space for the three-body decay modes which is sufficient for our present analysis.

IV. RESULTS: FOUR-CHARGED-PARTICLE EVENTS

A. Events of all energies

1. Further event selection and results

We study the 443 events with four charged particles to look for events from the process

$$e^+ + e^- \to L^0 + \bar{L}^0 \tag{12a}$$

where L^0 has the two-charged-particle decay modes

$$L^0 \to w^+ + x^- , \tag{12b}$$

$$L^0 \to y^+ + z^- + \nu , \tag{12c}$$

and

$$L^0 \to y^+ + z^- + \nu + \nu' + \bar{\nu}'' . \tag{12d}$$

Here the roman letters stand for $e^\pm$, $\mu^\pm$, $\pi^\pm$, or $K^\pm$. The decay in Eq. (12d) allows for decay through the τ mode. To find such events we impose further event selection criteria. The criteria used here are designed to emphasize search sensitivity for small L^0 mass, of the order of 1 GeV/c^2 and smaller. This is done because above this mass range the branching fractions of two-charged-particle decay modes are expected to be small, Figs. 2 and 3. (The other event-selection processes used in this section and the next have the same emphasis.)

We use the following criteria for further event selection.

(a) Most of these events are from τ-pair decays in which one τ decays to one charged particle, the other decays to three charged particles, and there are no photons. The three-charged-particle decay mode of the τ will give three tracks close together in the drift chamber, and the invariant mass of this triplet, m_t, will obey $m_t \leq m_\tau$. This is used to remove τ-pair events by calculating m_t for the four possible sets of triplet tracks, and defining a τ pair as having at least one m_t with $m_t \leq 4.0$ GeV/c^2. This loose upper limit allows for measurement errors, effectively removes τ-pair events, but reduces very little the search efficiency. 400 events are removed as being τ pair events.

(b) Next, events with a possible e^+e^- pair are removed. A possible pair is defined as two oppositely charged particles (each of which is identified as a possible electron) with an invariant mass $m \leq 0.11$ GeV/c^2. Of the remaining 43 events, 24 are removed as having an e^+e^- pair.

(c) The next criterion uses a missing mass

$$m_m{}^2 = \left[2E_{\text{beam}} - \sum_{i=1}^{4} p_i \right]^2 - \left[\sum_{i=1}^{4} \mathbf{p}_i \right]^2 . \tag{13}$$

Here p_i is the magnitude of $\mathbf{p}_i$. If there were no measurement errors, $m_m{}^2 \geq 0$. Allowing for measurement errors, we require $m_m{}^2 > -36.0$ GeV^2/c^4 for a well-measured event. One event fails this requirement and is removed. There are 18 events left.

(d) In an event

$$e^+e^- \to \omega^+ + x^- + y^+ + z^- + (\geq 0\ \nu\text{'s}) \tag{14}$$

which comes from the processes in Eq. (12), there must be at least one way to pair the charged particles, say $(\omega^+ x^-)$ and $(y^+ z^-)$, such that

$$p_\omega + p_x \leq E_{\text{beam}}, \quad p_y + p_z \leq E_{\text{beam}} . \tag{15a}$$

Allowing for measurement errors, the criteria is that there must be at least one way of pairing the charged particles so that

$$p_\omega + p_x \leq 15.6 \text{ GeV}, \quad p_y + p_z \leq 15.6 \text{ GeV} . \tag{15b}$$

This criterion was not met by seven events and these were removed.

There are 11 events left which are consistent with processes such as $e^+e^- \to e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$. Those who have worked with non-τ, four-charged-particle events from e^+e^- annihilation in this energy range may be surprised at the small number of events. Criterion (3) in Sec. III C ($|\cos\theta| < 0.7$) removed many of the four-charged-particle events expected from $e^+e^- \to e^+e^-e^+e^-, e^+e^-\mu^+\mu^-$.

Figure 5 gives the invariant masses of the neutral pairs of particles. When two sets of pairs satisfy Eq. (15b), both sets are shown. Calling the pair masses in a set m_{pr1} and m_{pr2}, the processes in Eq. (12) require

$$m_{\text{pr1}} \leq m_{L^0}, \quad m_{\text{pr2}} \leq m_{L^0} \tag{16a}$$

or

$$m_{L^0} \geq \max(m_{\text{pr1}}, m_{\text{pr2}}) . \tag{16b}$$

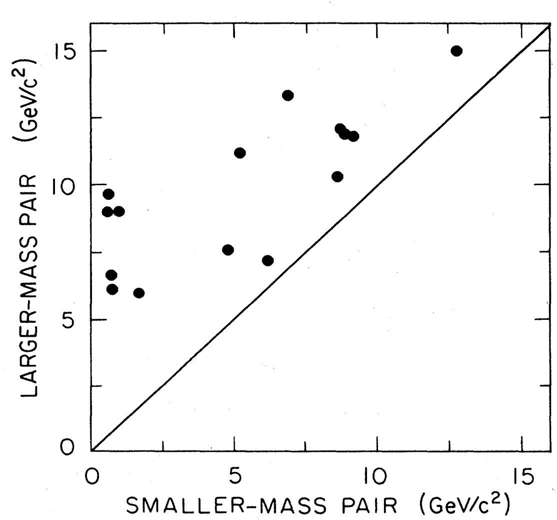

FIG. 5. Invariant masses of two neutral pairs of particles in the 11 events remaining in Sec. IV A after the application of selection criteria. If two sets of pairs satisfy Eq. (15b), both sets are plotted.

The smallest $\max(m_{pr1}, m_{pr2})$ is 6.0 GeV/c^2. Considering the e^+e^- pair criterion, Sec. IV A, and taking into account the mass resolution for the decay mode of Eq. (12b) there are no events with

$$0.11 \le m_{L^0} \le 5.4 \text{ GeV}/c^2 \quad (17)$$

which come from the process in Eq. (12). Pending further analyses, there are 11 events which could come from the process in Eq. (12) with $m_{L^0} > 6.0$ GeV/c^2.

2. Interpretative example

Interpretation depends upon particular decay and production models, such as those discussed in Sec. II. We give one example. Suppose the L^0 decays only through the charged current. Then the relevant decay modes comprise the B_{C2} branching fraction of Fig. 2, namely, $l^-e^+\nu_e$, $l^-\mu^+\nu_\mu$, $l^-\pi^+$, l^-K^+, and $l^-\tau^+\nu_\tau$ with the single charged particle, zero photon modes of the τ. Then for the m_{L^0} mass range in Eq (17) we find the 90%-confidence-level upper limit

$$B_{C2}{}^2\sigma/\sigma_{\text{stan}} \le 2.3/N_{\text{stan}}A_4 \ . \quad (18)$$

Here A_4 is the acceptance in Fig. 6 and N_{stan} is given in Eq. (8d). Figure 7(a) gives the limit. Using the values of B_{C2} in Fig. 2 we also find the 90%-confidence-level upper limit on $\sigma/\sigma_{\text{stan}}$ Fig. 7(b) and 13.

B. Events with missing energy

1. Further event selection and results

We consider a restriction on the process of Eq. (12) in which the only two-charged-particle decay modes are

$$L^0 \to y^+ + z^- + \nu \quad (19a)$$

and

$$L^0 \to y^+ + z^- + \nu + \nu' + \nu'' \ . \quad (19b)$$

Then there must be missing energy in an event, and a Monte Carlo study indicates that a good criterion is $E_{\text{missing}} \ge 5.0$ GeV. Applying this criterion to the 11 events remaining in Sec. IV A 1, leaves one event with one set of pair masses, 5.1 and 11.2 GeV/c^2.

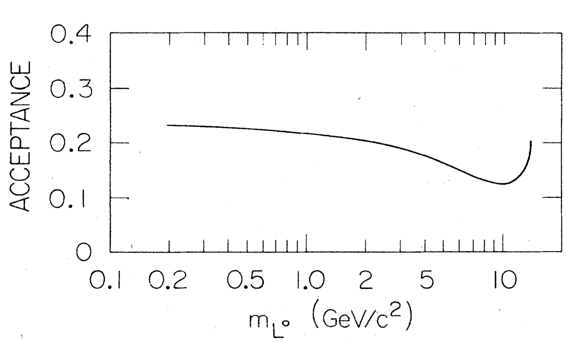

FIG. 6. The acceptance A_4 for hypothetical four charged-particle events from the model of Sec. IV A 2.

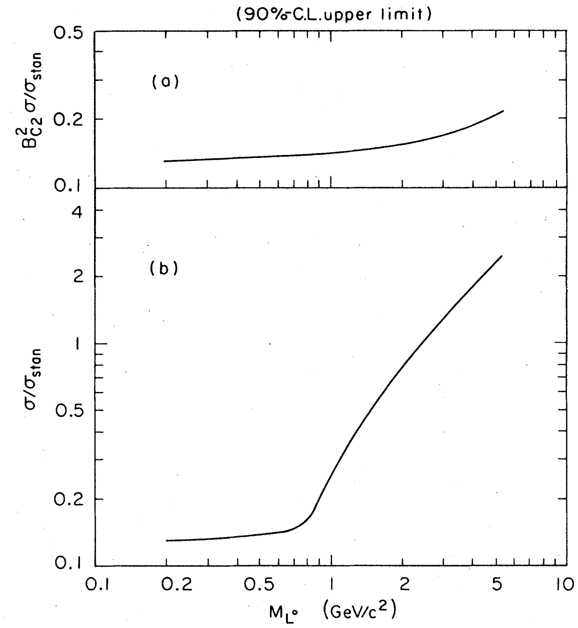

FIG. 7. The 90%-C.L. upper limit on (a) $B_{C2}{}^2\sigma/\sigma_{\text{stan}}$, and (b) $\sigma/\sigma_{\text{stan}}$ for the model of Sec. IV A2 applied to the four-charged-particle-event data.

The argument associated with Eq. (16b) can be applied here; this event must have $m_{L^0} \ge 11.2$ GeV/c^2 if it comes from the process in Eq. (19). There are no events with

$$0.11 \le M_{L^0} \le 11.2 \text{ GeV}/c^2 \ . \quad (20)$$

(There is a negligible effect of the mass resolution on the upper limit because all decay modes include neutrinos.)

2. Interpretative example

An example of how one might interpret this result is to assume that the L^0 only decays through a neutral current, Fig. 1(b). Then the two-charged-particle decay modes are limited to those in Eq. (19) with branching fraction B_{N2}. Figure 8 gives the 90%-confidence-level upper limit on

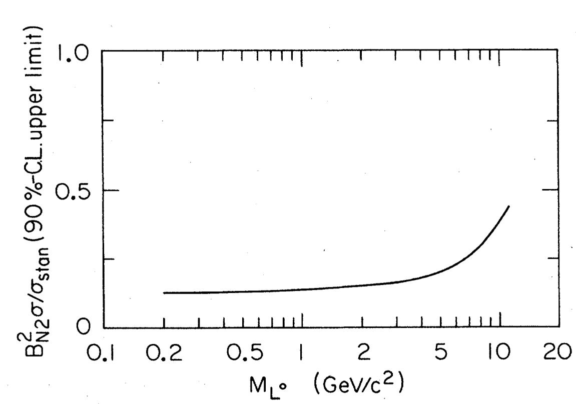

FIG. 8. The 90%-C.L. upper limit on $B_{N2}{}^2\sigma/\sigma_{\text{stan}}$ for the model of Sec. IV B 2 applied to the four-charged-particle event data.

${B_{N2}}^2\sigma/\sigma_{\text{stan}}$. Since ${B_{N2}}^2 \leq 0.048$ when given by Fig. 3, the 90%-confidence-level upper limits on $\sigma/\sigma_{\text{stan}}$ are large (see Fig. 13).

V. RESULTS: TWO-CHARGED PARTICLE EVENTS

Turning to the two-charged-particle events we remind the reader that at least one of the particles had to be identified as an electron. It is necessary to use models for the origin of the two-charged-particle events to further reduce the number of events, namely, 249. We consider two different models.

A. Events with total energy $< E_{\text{beam}}$

1. Further events selection and results

The first model assumes neutral-lepton pair production

$$e^+ + e^- \to L^0 + \bar{L}^0 \; , \tag{21a}$$

with

$$L^0 \to \nu + \nu + \nu \; , \tag{21b}$$

$$\bar{L}^0 \to e^+ + x^- + \nu \; , \tag{21c}$$

or with the L^0 and $\bar{L}^0$ decay modes interchanged. Here ν means neutrino or antineutrino and the same symbol may represent different types of neutrinos. The x may or may not be an e. In this process the total charged particle energy must be less than E_{beam}, excluding measurement errors. To isolate such events we use the following criteria.

(a) The total energy of the two charged particles is

$$E_{\text{tot}} < 13.0 \text{ GeV} \; .$$

(b) The pair mass must be larger than 0.11 GeV/c^2 to eliminate e^+e^- pairs. After application of these two criteria there are 115 events left.

(c) Much of the remaining contribution of two-virtual-photon processes is removed by requiring

$$p_t \geq 3.0 \text{ GeV}/c \; ,$$

where p_t is the component of the total momentum transverse to the beam line. This leaves 41 events in the sample.

(d) There are no photons in these events, but there is the possibility that a photon was not detected because it escaped through one of the small spaces between the walls of the liquid-argon calorimeter (see Sec. III A 4). Therefore we required that the missing momentum not point within 3.6° in azimuthal angle to the spaces between the walls. This left 30 events. Note that the event could still have a photon which passed outside the angular acceptance of the liquid argon calorimeter and the end-cap chambers (see Secs. III A 3 and III A 4).

The invariant mass of the particle pairs in the 30 events is shown in Fig. 9(a). There is just one event with $m < 3.6$ GeV/c^2. Above 3.6 GeV/c^2 there are many events and interesting limits cannot be obtained.

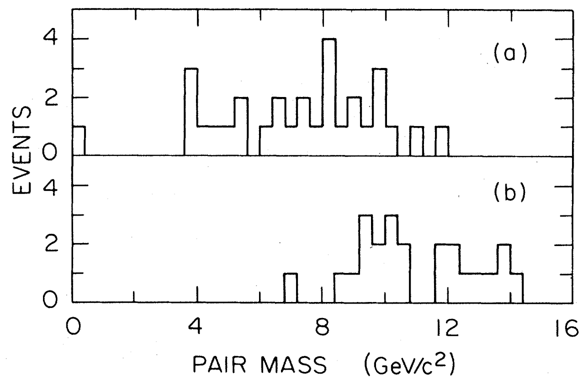

FIG. 9. Pair-invariant-mass distribution of two-charged-particle events fitting (a) criteria of Sec. V A and (b) criteria of Sec. V B.

2. Interpretative example

Consider a neutral lepton which decays through the neutral-current decay modes of Eqs. (21). Then for $m_{L^0} < 3.2$ GeV/c^2 we calculate the 90%-confidence-level upper limits

$$B_{N^0} B_{Nex}\sigma/\sigma_{\text{stan}} \leq 3.9/2N_{\text{stan}}A_2' \; . \tag{22}$$

Here B_{N0} and B_{Nex} are the branching fractions for the decay modes in Eqs. (21b) and (21c), respectively, and A_2' is the acceptance given in Fig. 10. The upper limits on $B_{N0}B_{Nex}\sigma/\sigma_{\text{stan}}$ are given in Fig. 11. The model used for Fig. 3 has the decay mode $L^0 \to e^+ + e^- + \nu$ as a special case of Eq. (21c). Calculation gives $0.017 < B_{N0}B_{Nee} < 0.046$ for $m_{L^0} < 3.2$ GeV/c^2. Hence the 90%-confidence-level upper limits on $\sigma/\sigma_{\text{stan}}$ using this model are high (see Fig. 13).

B. Events with total energy $= E_{\text{beam}}$

1. Further event selection and results

We now follow a different event-selection sequence which selects events in which the total energy of the pair of particles equals E_{beam}, excluding measurement errors. A suitable model is neutral-boson production

$$e^+ + e^- \to N^0 + \bar{N}^0 \; , \tag{23a}$$

with

$$N^0 \to \nu + \bar{\nu} \; , \tag{23b}$$

$$\bar{N}^0 \to e^+ + e^- \; , \tag{23c}$$

or with the N^0 and $\bar{N}^0$ decays interchanged. We use the following event-selection criteria.

We require

$$12.8 \leq E_{\text{tot}} \leq 16.0 \text{ GeV} \; . \tag{24}$$

Then we impose criteria b, c, and d of Sec. V A, the previous section. This leaves a sample of 23 events with the pair-mass spectrum of Fig. 9(b). There are no events with $m_{N^0} < 6.8$ GeV. The acceptance, A_2'' in Fig. 10 can be approximated by a constant value of 0.23. Then for

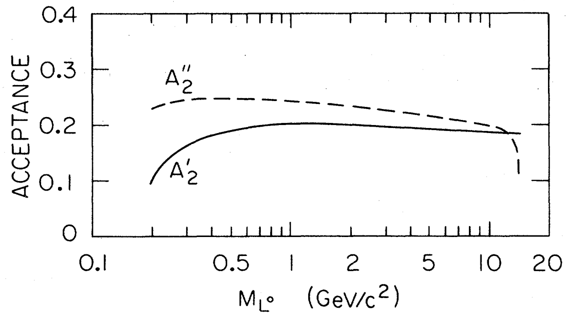

FIG. 10. Acceptances for hypothetical two-charged-particle events. A_2' is for the model of Sec. V A 2, A_2'' is for the model of Sec. V B 1.

$m_{N^0} < 6.3$ GeV (taking account of mass resolution)

$$B_0 B_{ee} \sigma \leq 0.023 \text{ pb}, \quad 90\% \text{ C.L.}\ , \tag{25}$$

where B_0 and B_2 are the branching fractions for the decay modes in Eqs. (23b) and (23c), respectively. We do not give an interpretative example here because we do not have a general model for the N^0 decay modes.

VI. SUMMARY

We have used two- and four-charged-particle events produced in e^+e^- annihilation at 29 GeV to search for unstable neutral leptons produced via $e^+e^- \to L^0\bar{L}^0$. The search is most sensitive to lepton masses of the order of 1 GeV/c^2 or smaller, because L^0 decay modes with zero or two charged particles are expected to be prominent in this small-mass region. However the search was extended up to masses of 14 GeV/c^2. No evidence was found for the existence of unstable neutral leptons.

This search required that the decays occur close to the e^+e^- interaction point, setting an approximate upper limit on the lepton lifetime of

$$T_{\max} \approx 10^{-11} m_L \text{ sec}\ ,$$

where m_L is in GeV. This relatively short lifetime requirement means that this search does not extend the presently known constraints on the usual model of lepton generation mixing outlined in Sec. II B and illustrated in Appendix A and Fig. 12.

In this paper upper limits were established for $BB'\sigma/\sigma_{\text{stan}}$ where the B's are branching fractions, σ is the cross section for $e^+e^- \to L^0\bar{L}^0$, and σ_{stan} is the standard-model cross section for

$$e^+ + e^- \to Z^0_{\text{virtual}} \to L^0 + \bar{L}^0 .$$

The 90%-confidence upper limits are given in Figs. 7(a), 8, and 11; in the smaller-mass range the limits are about 0.1—0.2. Upper limits were also established for neutral-boson production in $e^+e^- \to N^0\bar{N}^0$.

The determination of upper limits on $\sigma/\sigma_{\text{stan}}$ depends upon the model used to calculate BB'. Three examples, given in the paper, are summarized in Fig. 13. Two of the examples given large upper limits on $\sigma/\sigma_{\text{stan}}$ because in those examples the lepton has a dominant all neutrino decay mode. Upper limits on $\sigma/\sigma_{\text{stan}}$ greater than 1 may be of interest in evaluating models which have e-L^0-W coupling with a large coupling constant.

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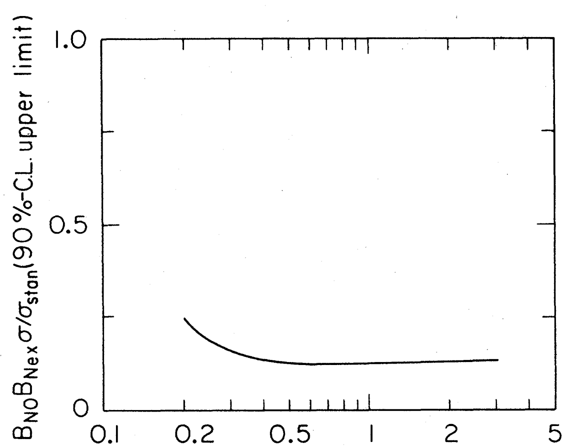

FIG. 11. The 90%-C.L. upper limit on $B_{N0}B_{Nee}\sigma/\sigma_{\text{stan}}$ for the model of Sec. V A 2 applied to the two-charged-particle data.

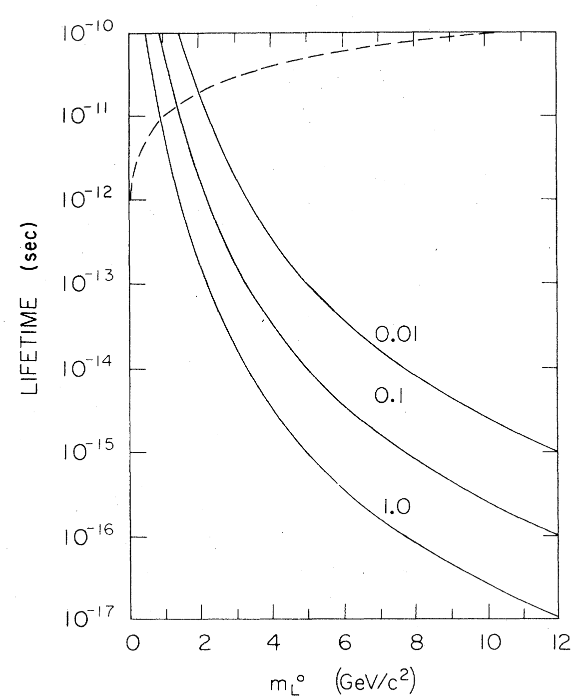

FIG. 12. The solid curves give the lifetime for $L^0 \to e^- +$anything assuming the conventional weak-charged current and the values of the mixing parameter, $\sin^2\phi$, shown on the curves. The dashed curve gives the approximate upper limit on the lifetimes accessible to the search methods in this experiment.

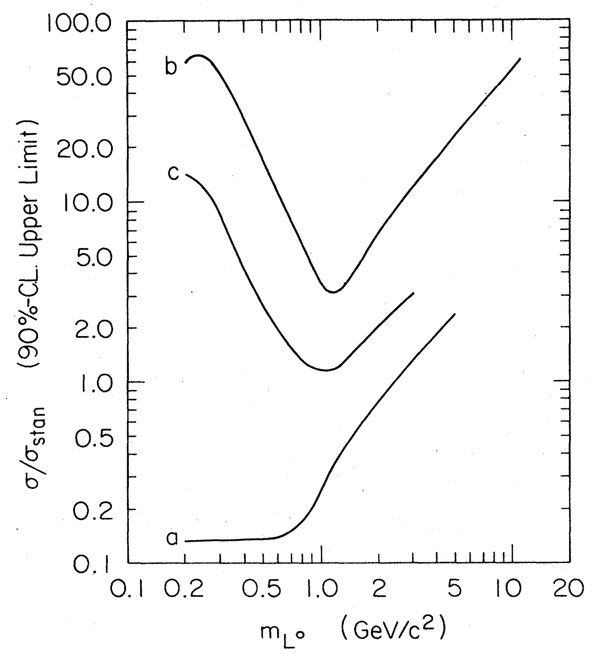

FIG. 13. The 90%-C.L. upper limit on $\sigma/\sigma_{\rm stan}$ for (a) the model of Sec. IV A 2 applied to the four-charged-particle data, (b) the model of Sec. IV B 2 applied to the four-charged-particle data, and (c) the model of Sec. V A 2 applied to the two-charged-particle data.

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APPENDIX A: EFFECT OF WEAK UNIVERSALITY

The effect of weak universality restrictions on the lifetime is illustrated by a model in which ν_e mixes with L^0 as in Eq. (4). From a measurement of the $\pi \rightarrow e\nu_e$ branching ratio, Bryman *et al.*[9] find $\sin^2\phi < 0.027$ with 90% confidence. The solid curves in Fig. 12 give the lifetime, T, for $L^0 \rightarrow e^- +$anything, using the decay process in Fig. 1(a) and the calculations in Appendix B Sec. I, for various values of $\sin^2\phi$. The dashed curve gives the upper limit $T_{\rm max}$, Eq. (10), for the search method used here. When $\sin^2\phi$ is of the order of 0.01 or smaller, our search method requires $m_{L^0} \gtrsim 2.0$ GeV/c^2. But as shown in Fig. 7(b), the search sensitivity decreases rapidly as m_{L^0} increases above 2.0 GeV/c^2.

APPENDIX B: BRANCHING FRACTION CALCULATIONS

A. Charged current decay

The branching-fraction and lifetime calculations use Fig. 1(a) and conventional weak-interaction theory.[5–7] The L^0 has mass m in GeV, the l^- is given zero mass and all neutrinos are given zero mass. The decay width for $L^- \rightarrow l^- e^+ \nu_e$ is[7]

$$\Gamma_c = \Gamma(l^- e^+ \nu_e) = G^2 m^5 / 192\pi^3 \, . \quad \text{(B1)}$$

All other decay modes are calculated as ratios to Γ_c. For the lepton l_i with $i = u$ or τ and $y = m_i^2/m^2$ (Ref. 7)

$$\Gamma(l^- l_i^+ \nu_i)/\Gamma_c = 1 - 8y + 8y^3 - y^4 - 12y^2 \ln y \, . \quad \text{(B2)}$$

Turning to the single-hadronic decay modes, we use the formulas of Tsai[10] for $L^- \rightarrow \nu_L + X$ by making the change $L^- \rightarrow L^0, \nu_L \rightarrow l^-$, which can be done since the l^- is massless. For example, from Ref. 10

$$\Gamma(L^0 \rightarrow l^- \pi^+) = 6.71 \times 10^{10} m^3 (1 - m_\pi^2/m^2)^2$$

and from Eq. (B1)

$$\Gamma_c(L^0 \rightarrow l^- e^+ \nu_e) = 3.43 \times 10^{10} m^5 \, .$$

Hence

$$\Gamma(L^0 \rightarrow l^- \pi^+)/\Gamma(L^0 \rightarrow l^- e^+ \nu_e) = 1.95(1 - m_\pi^2/m^2)^2/m_2 \, .$$

In this equation and all equations in this appendix, masses are in GeV/c^2. Using Ref. 10 and proceeding in this manner we find the following.

For the scalar S_i with $i = \pi$ or K

$$\Gamma(l^- S_i^+)/\Gamma_c = C_i (1-y)^2/m^2 \, . \quad \text{(B3)}$$

Here $C_\pi = 1.95$ GeV^2, $C_K = 0.14$ GeV^2.

For the vector V_i with $i = \rho$, K^*, or A, and $y = m_i^2/m^2$

$$\Gamma(l^- V_i^+)/\Gamma_c = C_i (1-y)^2 (1+2y)/m^2 \, . \quad \text{(B4)}$$

Here $C_\rho = 4.27$ GeV^2, $C_{K^*} = 0.31$ GeV^2, $C_{A_1} = 2.21$ GeV^2.

For the multihadron decay modes[7,10]

$$\Gamma(l^- + (\text{hadrons})^+)/\Gamma_c = 3[(1 - 2b_1 + 2b_1^3 - b_1^4) + (1 - 2b_2 + 2b_2^3 - b_2^4)] \, . \quad \text{(B5)}$$

Here the first polynomial is for the production of $u\bar{d}$ quark pairs and $b_1 = (1.0/m)^2$. The second polynomial is for the production of $c\bar{s}$ pairs and $b_2 = (2.0/m)^2$. The b's are dimensionless.

B. Neutral-current decay

We cannot use conventional weak-interaction theory here since the decay in Fig. 1(b) violates that theory. But we need an illustrative calculation for the branching ratios. Therefore we calculate *as if* the flavor-changing neutral current vertex L^0-Z^0-ν behaved exactly the same as the ν-Z^0-ν vertex. We define a basic, fictitious decay width

$$\Gamma_n = (\tfrac{1}{8}\cos^4\theta_W) G^2 m^5 / 192\pi^3 \, . \quad \text{(B6)}$$

All other decay modes are calculated as ratios to Γ_n. We take all neutrino masses to be zero.

The decay $L^0 \rightarrow \nu\nu_i\bar{\nu}_i$ ($i = e$, ν, or τ) in this model has the width[5,6]

$$\Gamma(\nu\nu_i\bar{\nu}_i) = \Gamma_n (a_\nu^2 + v_\nu^2) \, , \quad \text{(B7)}$$

where $a_\nu{}^2+v_\nu{}^2=2.00$. For the sum over all neutrino-pair decay modes

$$\Gamma_\nu(\nu\nu_e\bar{\nu}_e+\nu\nu_\mu\bar{\nu}_\mu+\nu\nu_\tau\bar{\nu}_\tau)/\Gamma_n=8.00 \ . \quad \text{(B8)}$$

Here the constructive interference between the ν and one of the $\nu_i\bar{\nu}_i$ pairs is included.

The decay width for $L^0\to\nu l_i^+ l_i^-$ ($i=e,\mu,\tau$) has a formula[5,6] similar to Eq. (B7) with $a_l{}^2+v_l{}^2=1.01$ and a threshold factor T. Hence

$$\Gamma(\nu l_i^+ l_i^-)/\Gamma_n=1.01T(r) \ , \quad \text{(B9a)}$$

$$T(r)=\int_0^{1-r^2}dx\left[1-\frac{r^2}{1-x}\right]^{1/2}\left[2x^2(3-2x)+r^2x^2\left[\frac{x}{1-x}-6\right]\right] \quad \text{(B9b)}$$

with $r=2m_i/m$.

The decay widths for single-hadron decay modes, such as $L^0\to\nu+\pi^0$, are calculated from the corresponding decay mode in Sec. I of this appendix, such as $L^0\to l^-+\pi^+$, using the ratio Γ_n/Γ_c and a ratio of Clebsch-Gordan coefficients. For the scalar S_i with $i=\pi^0$ or η

$$\Gamma(\nu S_i^0)/\Gamma_n=1.71(1-y)^2/m^2 \ . \quad \text{(B10)}$$

For the vector V_i with $i=\rho^0$ or w

$$\Gamma(\nu V_i^0)/\Gamma_n=3.75(1-y)^2(1+2y)/m^2 \ . \quad \text{(B11)}$$

The multihadron decay modes are calculated using the width[5,6] for decay into a $q\bar{q}$ pair

$$\Gamma(\nu q\bar{q})=\Gamma_n(a_q{}^2+v_q{}^2)(3) \ .$$

The quantity $a_q{}^2+v_q{}^2$ is 1.17 for a u-type quark and 1.50 for a d-type quark. We find

$$\Gamma(\nu+(\text{hadrons})^0)/\Gamma_n =\sum_{j=1}^{3}C_j(1-2b_j+2b_j{}^3-b_j{}^4) \ . \quad \text{(B12)}$$

Here $j=1$ stands for $\mu\bar{\mu}+d\bar{d}+s\bar{s}$ pair production, $j=2$ stands for $c\bar{c}$ pair production, and $j=3$ stands for $b\bar{b}$ production. We use $C_1=12.51$, $b_1=(1.0/m)^2$, $C_2=3.51$, $b_2=(3.1/m)^2$, $C_3=4.50$, $b_3=(10.0/m)^2$. The C's and b's are dimensionless.

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