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NEUTRINO FAMILIES: THE EARLY UNIVERSE MEETS ELEMENTARY PARTICLE/ACCELERATOR PHYSICS*

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ABSTRACT

The first laboratory test of cosmological theory is now underway. The number of neutrino families in nature, N_ν, plays a key role in elementary particle physics as well as in the synthesis of the light elements during the early evolution of the Universe. We describe the cosmological arguments which limit N_ν as well as the techniques employed in accelerator experiments to count the number of neutrino flavors. We present the current limit on N_ν from the CERN $\bar{p}p$ collider and other experiments and compare it to the cosmological bound. This comparison is one of the best tests for the relevance of cosmological constraints to elementary particle physics and directly tests the Big Bang model at an earlier epoch than is possible by traditional astronomical observations. The special case of a 4th generation of quarks and leptons, which is marginally allowed cosmologically, is outlined and we describe present attempts to search for the corresponding charged lepton.

INTRODUCTION

The interaction between cosmology and particle physics has grown at an explosive rate during the last decade. One of the first predictions to come from physics at the frontier of these fields was that big bang nucleosynthesis constrains[1] the number of light ($\lesssim$ 10 MeV) neutrino flavors, N_ν; this constraint probably limits the number of quark and charged lepton flavors as well. Such a cosmological constraint is extremely important since particle theory in general does not limit N_ν. It is, therefore, of great relevance that this cosmological prediction[1] is finally being tested in the laboratory, by collider experiments. This first test of a cosmological theory at a high energy physics facility will provide a check on the hot big bang model back to an earlier epoch than is feasible with any of the traditional astronomical techniques.

In this comment we review the fundamental significance of neutrino counting and its relationship to "generation" counting. We review the current status of the arguments from primordial nucleosynthesis[2,3] which lead to the present bound $N_\nu \leq 4.0$ (the "standard" $N_\nu = 3$ is completely consistent with big bang nucleosynthesis). Next, we examine the possibilities for neutrino counting at $\bar{p}p$ and e^+e^- colliders, present the new limits[4] from CERN and PEP and discuss the future prospects. We note that cosmological and accelerator experiments do not "measure" exactly the same quantities and we use cosmological limits to neutrino masses to delimit neutrino properties. We conclude with a speculative look at the possibility of a fourth generation which is marginally allowed at present.

NEUTRINO FAMILIES: THE QUARK-LEPTON CONNECTION

At present, three generations of quarks and leptons are known. Only the t-quark and the τ-neutrino remains to be completely confirmed. As is well known, each generation contains six quarks (3 colors of "up" quarks with $Q = +2/3$ and 3 colors of "down" quarks with $Q = -1/3$) and two leptons (a charged lepton and a neutrino). It is of fundamental importance to determine if additional families of quarks and leptons exist.

In the past, the discovery of a new generation has been made by first discovering a charged lepton (see Table 1). This was due largely to the lower mass of the charged lepton and/or the cleaner experimental signature (e.g.: consider the μ -lepton versus the strange or charmed quark). Today, we may be in a similar situation in that either a charged lepton from W or Z decay or, an additional neutrino flavor could provide the first evidence for another generation. In contrast, the quarks of a fourth generation, if it exists, may well be out of reach of the present colliding beam machines. In contrast, a bound to the total number of neutrino flavors may provide an upper limit to the number of quark-lepton generations.

A remarkable aspect of the hot big bang model for the evolution of the Universe is the dependence of primordial nucleosynthesis--in particular, the synthesis of ^{4}He - on N_ν, the number of light neutrino ($m_\nu \lesssim 10$ MeV) flavors.[1,2,3] The present limit on the number of neutrino families derived from Z° decay is completely consistent with the cosmological bound. This represents the first accelerator test of cosmology. The cosmological bound limits the number of "relativistic degrees of freedom" which were present during big bang nucleosynthesis whereas the accelerator data limits the number of particles, which could be very massive ($\lesssim M_Z/2$) but, must couple to the Z°. That the two bounds very nearly coincide helps rule out (or, at least, constrain) the numbers of new "heavy" neutrinos and/or "light" exotic particles.

Laboratory experiments show directly that the ν_e and ν_μ are light[5] (in the context of our discussion). Despite an heroic effort to lower the upper limit to the mass of the τ-neutrino, laboratory data[6] still permits a "heavy" ν_τ. However, by combining astrophysical and accelerator data, it has been argued that the ν_τ must be light. For convenience, we shall write $\delta N_\nu = N_\nu - 3$. Although we expect $\delta N_\nu \geq 0$, if the cosmological bound should eventually turn out to yield $\delta N_\nu < 0$, the question of the ν_τ mass might have to be reopened.

PRIMORDIAL NUCLEOSYNTHESIS AND δN_ν

During the early evolution of the Universe ($t \lesssim 1$ sec.) when the temperature is high ($T \gtrsim 1$ MeV) the charged current weak interactions: $e^-(p,n)\nu_e$, $e^+(n,p)\bar{\nu}_e$ and, occasionally, decay ($n \rightarrow p + e^- + \bar{\nu}_e$), along with the inverse reactions, occur sufficiently rapidly to ensure that the neutron-to-proton ratio is maintained at its equilibrium value,

$$n/p = \exp(-\Delta m/T). \qquad (1)$$

Later, when the Universe cools to $T = T_* \approx 0.7$MeV, this equilibrium can no longer be maintained and the n/p ratio effectively "freezes out". Although n → p conversions still occur (for $T \lesssim T_*$), the rate of such processes is too slow to permit the n/p ratio to follow eq. (1) although n/p does continue to decrease as the universe cools. However, to a first approximation then, for $T < T_*$,

$$n/p \approx (n/p)_* = \exp(-\Delta m/T_*) \quad . \tag{2}$$

The freeze-out temperature, T_*, is determined by the competition between the (charged-current) weak interaction rate Γ_{wk} $(= n_e \langle \sigma_{wk} v \rangle)$ and the universal expansion rate $t^{-1} \sim H$ (H is the Hubble parameter). The higher the universal density (for a fixed temperature), the faster the universe expands and the earlier the freeze-out occurs. For extra, light particles (those which are relativistic during nucleosynthesis), $t_* \rightarrow t'_*$ where[2]

$$(t/t')_* = \left(1 + \frac{7}{43}\,\delta N_\nu\right)^{1/2} \quad . \tag{3}$$

Since almost all neutrons that exist when nucleosynthesis takes place as the universe cools to ~ 0.1MeV get incorporated into ^{4}He, the earlier the freeze-out, the more neutrons survive and thus the higher the ^{4}He abundance. The primordial mass fraction of ^{4}He (Y_p) increases with δN_ν as[2]

$$\Delta Y_p \approx 0.014\ \delta N_\nu \quad . \tag{4}$$

In the context of the effect on the helium abundance, δN_ν is the effective number of neutrino species,[2]

$$\delta N_\nu = \sum_F{}' \left(\frac{g_F}{2}\right)\left(\frac{T_F}{T_\nu}\right)^4 + \frac{8}{7}\sum_B{}' \left(\frac{g_B}{2}\right)\left(\frac{T_B}{T_\nu}\right)^4 \quad . \tag{5}$$

In (5) the summations are over all relativistic fermion (F) and boson (B) species of temperature T [relative to the ordinary (e,μ,τ) neutrino temperature T_ν]; the primes indicate that photons, electrons and ordinary neutrinos are omitted from the sum; g is the number of helicity states. For a fourth generation neutrino, $g_F = 2$, $T_F = T_\nu$ and $\delta N_\nu = 1$; this corresponds to a predicted increase in the helium abundance (over the standard result) of $\Delta Y_p \approx 0.014$.

We emphasize that this cosmological constraint applies to all species which are relativistic at nucleosynthesis regardless of the interaction strength. For example, if there were a species of light, right-handed neutrino which coupled to a new gauge boson Z_R° (with $m(Z_R^\circ) > m(Z_L^\circ))$, then $g_F = 2$ but $T_F < T_\nu$ so that $\delta N_\nu = (T_F/T_\nu)^4 < 1$. In contrast, this constraint does not apply to a heavy (>>MeV) neutrino with ordinary weak interactions since such particles would be non-relativistic during big bang nucleosynthesis.

The predicted value of Y_p in the standard model ($\delta N_\nu = 0$) requires knowledge of the neutron half-life ($\tau_{1/2}$): the larger $\tau_{1/2}$ the more neutrons survive to be incorporated in ^{4}He. An uncertainty $\delta\tau_{1/2}$ in the half-life (measured in minutes) corresponds to an uncertainty in Y_p of

$$\delta Y_p \approx 0.014\ \delta\tau_{1/2} \quad . \tag{6}$$

By comparing (4) and (6) we see that the present experimental uncertainty[3] in $\tau_{1/2}$ ($\delta\tau_{1/2} \approx \pm 0.1$ min.) leads to a small uncertainty in the predicted bound on the number of neutrino flavors ($\delta N_\nu \approx \pm 0.1$).

Finally, in the standard model, Y_p depends weakly on the nucleon abundance; more nucleons relative to (black-body) photons means that nucleosynthesis begins slightly earlier when more neutrons are present. The nucleon abundance, however, cannot be determined directly from astrophysical observations. But, the abundances of the other light elements (D, ^{3}He, ^{7}Li) produced in the big bang do depend on the nucleon abundance. Therefore, we may relate the predicted abundance of ^{4}He to the abundances predicted for the other light elements and utilize observational data on abundances to constrain the predicted range of Y_p. As Yang et al[2] emphasized, the primordial abundance of D plus ^{3}He provides just such a constraint. The relation between Y_p and $y_{23p} = (D+{}^3He)/H$ is shown in Figure 1. The recent analysis of Steigman et al[7] suggests that $Y_p \lesssim 0.254$, $\tau_{1/2} \gtrsim 10.4$ min. ($\tau_{1/2} = 10.5\pm0.1$ min) and $y_{23p} \lesssim 10^{-4}$ so that

$$(\delta N_\nu)_{BBN} \lesssim 1.0 \quad . \tag{7}$$

NEUTRINO COUNTING AT COLLIDERS: PRESENT RESULTS AND FUTURE PROSPECTS

The counting of neutrino families at colliders relies on the production and decay of real or virtual Z° bosons. Within the framework of the standard electroweak theory the Z° is universally coupled to leptons and quarks. Thus, in the decay of the Z°, the branching ratio to the standard 3 neutrino species--as well as to new families--is prescribed. Basically, there are two ways to count neutrino families at colliders[4]:

(A) Direct detection of $Z^\circ \to \nu_i\bar{\nu}_i$,

(B) Measurement of the total width of the Z° to determine the neutrino partial width $\Gamma(Z^\circ \to \nu_i\bar{\nu}_i)$.

Technique (A) can be used at a $\bar{p}p$ or an e^+e^- collider by detecting either

$$\bar{p}p \to Z^\circ + \text{gluon} \tag{8}$$

$$e^+e^- \to Z^\circ + \text{photon} \tag{9}$$

Recently both processes (8) and (9) have been observed and lead to limits on δN_ν, with process (9) occurring via virtual Z°'s at present since e^+e^- energies are below M_{Z° until SLC and LEP begin operations.

The measurement of the Z° width can be carried out directly or by a determination of the ratio of Z° to W widths. The direct measurement from the CERN collider experiment gives a very poor limit to δN_ν at present. Technique B gives the best present limit on δN_ν.[7] This technique uses a directly measured ratio of the $W \to e\nu_e$ and $Z^\circ \to e^+e^-$ rates to give

$$R = \frac{R(W \to e\nu_e)}{R(Z^\circ \to e^+e^-)} = \left(\Gamma_Z / \Gamma_W\right) \left(\frac{\Gamma_{W \to e\nu}}{\Gamma_{Z \to e^+e^-}}\right) \left(\frac{\sigma_{W^+} + \sigma_{W^-}}{\sigma_{Z^\circ}}\right) . \tag{10}$$

The key idea of this technique is that $\Gamma_{W \to e\nu} / \Gamma_{Z \to e^+e^-}$ is reliably calculated in the standard model once $\sin^2\theta_W$ is known and, $\left(\sigma_{W^+} + \sigma_{W^-}\right) / \sigma_{Z^\circ}$ is determined from QCD calculations.[7] Actually the calculation of the ratio of cross sections is more reliable than the individual terms due to cancellations in the ratio. Finally, it is possible to determine Γ_W if we know all of the important decay modes of the W. The Z° and W widths are given as [including the possibility of 4th generation charged lepton (L) and the t quark].[4]

$$\Gamma_Z = [2.54 + \Gamma_{Z \to t\bar{t}} + \Gamma_{Z \to L\bar{L}} + 0.17\delta N_\nu]\text{GeV} , \tag{11}$$

and

$$\Gamma_W = [2.2 + \Gamma_{W \to t\bar{b}} + \Gamma_{W \to L\nu_L}]\text{GeV} . \tag{12}$$

As we show later, the present limit on the mass of a possible 4th generation lepton reduces the contribution to the Z° width to a negligible value. This is not true however for the W width. Thus, the intrinsic uncertainty in the ratio of Z to W widths comes from the t and L mass (or existence) and limits the accuracy of this technique in determining δN_ν. In Fig. 2 we show estimates of the uncertainty of the various techniques used to measure δN_ν.[4] While it may be relatively easy to reach an uncertainty in δN_ν of ~2, to achieve greater accuracy will be very difficult with the ratio of widths technique. When adequate statistics are collected for processes (8) and (9) it will be possible to measure δN_ν to $\lesssim \pm 1$.

A variant on direct width measurements is to study the partial width for the process $Z^\circ \to \nu\bar{\nu}$ by

$$\gamma + Z^\circ \to \gamma + \nu\bar{\nu}$$

and look for the scattered γ in coincidence with nothing (the nondetectable neutrinos). This can be done for real Z°'s at SLC or LEP or for virtual Z°'s using heavy $q\bar{q}$ states

$$\gamma + (q\bar{q}) \to \gamma + (\text{virtual } Z^\circ) \to \gamma + \nu\bar{\nu}.$$

We now turn to the present measurements of, or limits to, δN_ν. Fig. 3 shows a comparison of the limits reached with the various techniques. The UA1 and UA2 results on the ratio of widths can be combined to give[4]

$$\delta N_\nu \leq 2. \tag{13}$$

A similar bound - using virtual Z°'s - from $e^+e^- \to \gamma\nu\bar{\nu}$ is obtained from the data of MAC and ASP at PEP and CELLO at PETRA.[14] That δN_ν is small is also suggested by the data which is consistent with $M_W^2 = M_Z^2(1-\sin^2\theta_W)$. Radiative corrections due to extra, low mass neutrino flavors with corresponding new quarks would cause a deviation in this relation.[15] The data suggests $\delta N_\nu \lesssim 2$.

These measurements are all in excellent agreement with the cosmological results (see Fig. 3). From current experimental data we may conclude that, at most, there may be a fourth or possibly, a fifth family of quarks and leptons. Given the present uncertainty (~±2) in the neutrino counting techniques, the direct search for a fourth generation lepton is of great significance. We turn to this search next.

THE 4TH GENERATION: SEARCH FOR THE CHARGED LEPTON

Several years ago it was pointed out that it might be possible to discover a 4th generation lepton (and the corresponding neutrino) through observation of[10] W decaying to monojets of dijets and missing transverse energy,

$$W \to L + \bar{\nu}_L \quad , \; L \to \bar{q} + q + \nu_L \; . \qquad (14)$$

This method has led to a specific technique to search for L and there are now limits on the mass M_L from the UA1 group. We recount the technique and then discuss the mass range that ultimately can be searched in this way.

Consider the decays of the $W^{\pm}$ particles

$$W^{+}\rightarrow L^{+}+\nu_{L} \tag{15}$$

$$W^{-}\rightarrow L^{-}+\bar{\nu}_{L} \tag{16}$$

where L is a new sequential lepton with mass in the range 23 to 70 GeV/c^2 and $\nu_L(\bar{\nu}_L)$ are fourth generation neutrinos (antineutrinos) which are assumed to be light. The hadronic decays of the $L^{\pm}$ are expected to be

$$L^{+}\rightarrow u+\bar{d}+\bar{\nu}_{L}, \tag{17}$$

$$L^{+}\rightarrow c+\bar{s}+\bar{\nu}_{L}, \tag{18}$$

$$L^{-}\rightarrow \bar{u}+d+\nu_{L}, \tag{19}$$

$$L^{-}\rightarrow \bar{c}+s+\nu_{L}. \tag{20}$$

We do not distinguish between decays with heavy flavors and those with (u,d) quarks because there is no realistic possibility of separating these processes in any of the existing or forthcoming detectors at $\bar{p}p$ colliders.

Two techniques have been proposed to search for the heavy lepton:[10,11,12]

(i) Observation of an excess of single lepton events with missing energy in a region where $W\rightarrow \ell+\nu_{\ell}$ is suppressed and reduction of the corresponding background from $W\rightarrow\tau+\nu_{\tau}\rightarrow\ell+\nu_{\ell}+\nu_{\tau}+\nu_{\tau}$ with a microvertex detector.

(ii) Observation of one or two jet events with missing energy from the L decay.

In this comment we describe in detail the second possibility.

The proposed experimental technique makes use of a background suppression by detecting two jets from the heavy lepton production and decay that are on the same side of the $\bar{p}p$ line of interaction (i.e. within 180° of each other). As we will show, this selection and certain requirements on the jets from the decay serve to reduce the expected backgrounds. Fig. 4 illustrates the technique that has been proposed.

In the UA1 analysis a modified ISAJET Monte Carlo was used in which the decays (15)-(20), and have been included. The full matrix element of the decay, including the polarization of the L, has been included with both right and wrong helicity states generated. In Reference 12 it was shown that the W decay gives a kinematic window up to ~ (65-70) GeV to search for the new lepton. The backgrounds calculated in Reference 12 were also generated initially by the same Monte Carlo but, were modified to take into account the realistic properties of the UA1 detector. This procedure can be applied to the other $\bar{p}p$ collider detectors that are capable of searching for the decay products of the W such as the CDF detector at Fermilab.[4] The possible separation of the heavy lepton signal from the expected background relies on the shape of the jets from decay (17)-(20) as well as the expected missing energy and the unique configuration of the jets as illustrated in Fig. 4. Fig. 5 gives the expected number of one jet and two jet events from the decay of a heavy lepton as a function of the mass from 20 to 75 GeV; these are the expected number after the UA1 monojet and dijet cuts are applied. Note that the monojet rate decreases rapidly with mass but the two jet rate is approximately independent of mass. The detected ratio of the number of monojets and dijets could give a measurement of the mass of the heavy lepton. The backgrounds for the search for $W \to L+\nu_L$ were calculated along with the expected number of monojet and dijet events for 700 nb^{-1} integrated luminosity. The resulting comparison of signal and background in the UA1 experiment gave a lower limit on the 4th generation lepton mass of

$$M_L \geq 41 \text{ GeV} \quad 90\% \quad \text{C.L.} \quad . \tag{21}$$

including all estimates of systematic errors.[13] The resulting limit is sufficient to reduce the branching ratio of $Z \to L + \bar{L}$ to a small value and thus this decay would give a negligible contribution to the Z° total width. There is good reason to believe that the technique described here and used by the UA1 group can be extended to the mass range of $M_L \sim (65-70)$.[40] In Fig. 6 we show the different techniques and machines that may be used to continue the search for L up to 100 GeV. Beyond this mass one must wait for a new generation of hundreds of GeV e^+e^- linear colliders.

If future collider experiments should establish the existence of a fourth family (either directly or from data on the Z° width), there would be two possibilities, each with consequences for particle physics or cosmology. The fourth generation neutrino (<u>if</u> it exists!) could be heavy (>>~10 MeV; but, $\leq M_{Z^\circ}/2$). In that case the neutrino counting from big bang nucleosynthesis is unaffected. Alternately, the fourth generation neutrino could be light. Since, at present, this possibility is just barely allowed, the discovery of a light, new neutrino would lead to a significant cosmological constraint. With $\delta N_\nu = 1$, consistency between the predicted and observed abundances of helium can only be maintained in a low (nucleon) density universe.[2] $\delta N_\nu = 1$ and $Y_p \leq 0.25$ would require that the nucleon to photon ratio be no larger than $\sim 3 \times 10^{-10}$. Then, the nucleon mass density could be no larger than ~ 4% of the critical density. Since current data suggests a total mass density in excess of ~10% of the critical density, we would be led to conclude that non-baryonic dark mass must exist and dominate the current evolution of the Universe.

The mass of a stable fourth generation - indeed, any - neutrino is constrained by cosmology to be either "light" ($\lesssim$40eV) or "heavy" ($\gtrsim$fewGev). Stable neutrinos with masses in the intermediate regime would contribute more to the universal mass density than is allowed by observations. Unstable neutrinos which decay radiatively have their masses and lifetimes constrained by astrophysical data. There are weaker constraints on the masses and lifetimes of neutrinos whose decays are to invisible daughters.

The remarkable interplay between elementary particle/accelerator physics and astrophysics/cosmology provides strong reasons for believing the results of either enterprise. This symbiosis helps to constrain the evolution of the universe during the first ~100 seconds and, provides valuable information about the number of neutrino families in nature.

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TABLE I

Charged Leptons Lead the Way to Discovery of the Families of Quarks and Leptons

electron	~ 1900	1st Generation or family
neutron (d quark)	~ 1932	
electron neutrino	~ 1957	
Muon	~ 1938 - 1948	2nd Generation or family
Strange particles (s quark)	~ 1948 - 1950	
Charm (c quark)	1974	
Muon neutrino (ν_μ)	~ 1962	
τ lepton	1976	3rd Generation or family
b quark	~ 1977	
t quark	$\geq$ 1984	
ν_τ	?	
L lepton	(M_L > 41 Gev/90% C.L.)	4th Generation or family
b'	$M_{b'}$ > 23 Gev	
t'	$M_{t'}$ > 23 Gev	
ν_L	?	

Figure Captions

1. Variation of the primordial mass fraction of ^{4}He (Y_p) with the primordial ratio of D plus ^{3}He to H (y_{23P}). The curves labelled 2, 3, 4 are for N_ν = 2, 3, 4. The thickness of the curves corresponds to a neutron half-life of $\tau_{1/2}$ = 10.5 ± 0.1 min. The allowed region (below and to the left of the hatched lines) is for $Y_p \leq 0.254$ and $y_{23P} \leq 10^{-4}$ (see refs. 2 & 3).

2. Comparison of methods to search for additional neutrino families in nature.

3. Present limits to N_ν from cosmology, $\bar{p}p$ and e^+e^- experiments.

4. Technique to search for the 4th generation heavy lepton at $\bar{p}p$ colliders.

5. Expected number of events with one jet (monojet) or two jets (dijets) and missing energy for the UA1 experiment as a function of the lepton mass.

6. Summary of the different methods to continue the search for heavy leptons at various colliders in the world.

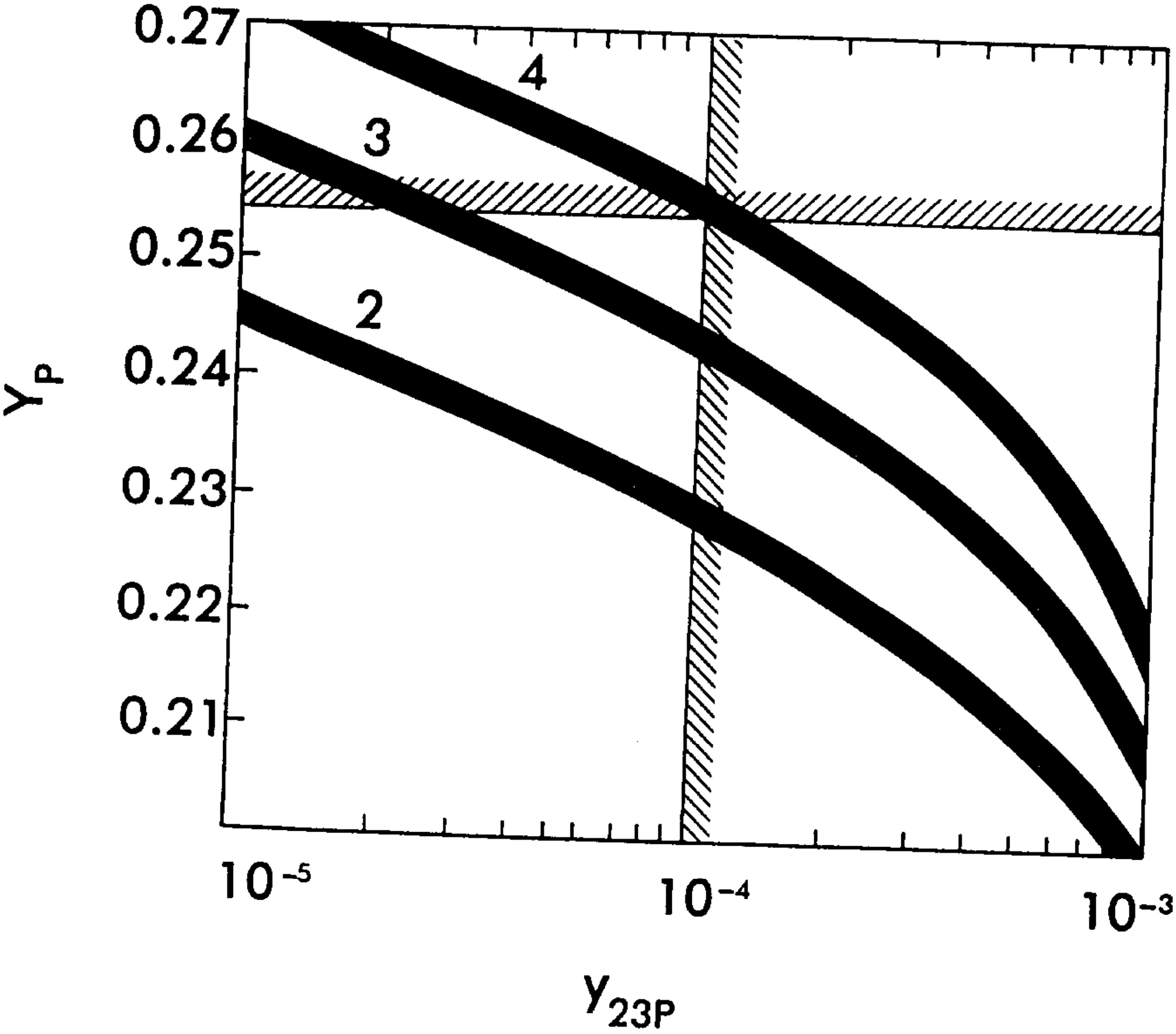

Figure 1

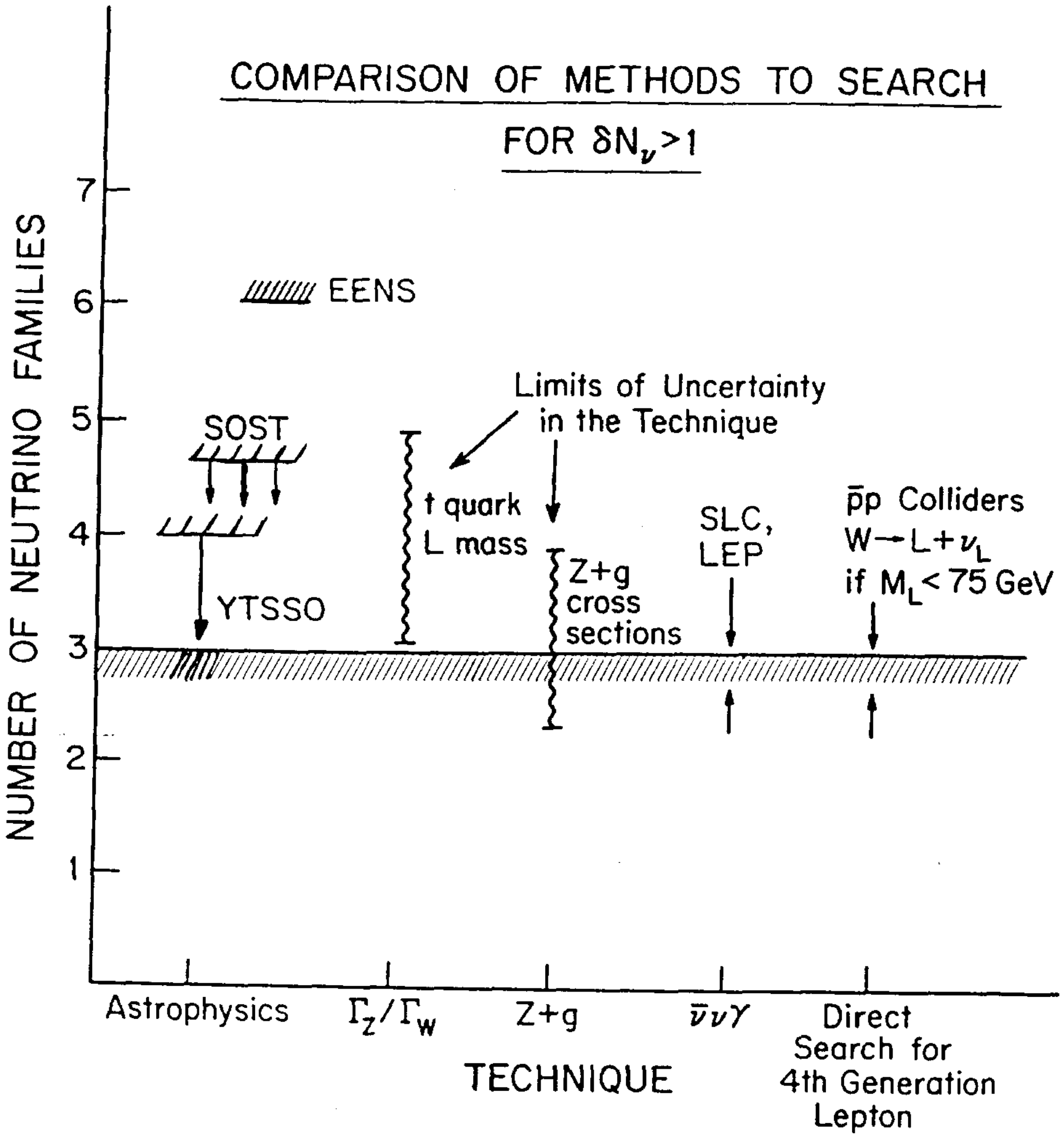
COMPARISON OF METHODS TO SEARCH FOR $\delta N_\nu > 1$
NUMBER OF NEUTRINO FAMILIES
1
2
3
4
5
6
7
EENS
SOST
YTSSO
Limits of Uncertainty in the Technique
t quark
L mass
Z+g cross sections
SLC, LEP
$\bar{p}p$ Colliders
$W \to L + \nu_L$
if $M_L < 75$ GeV
Astrophysics
Γ_Z/Γ_W
Z+g
$\bar{\nu}\nu\gamma$
Direct Search for 4th Generation Lepton
TECHNIQUE

Figure 2

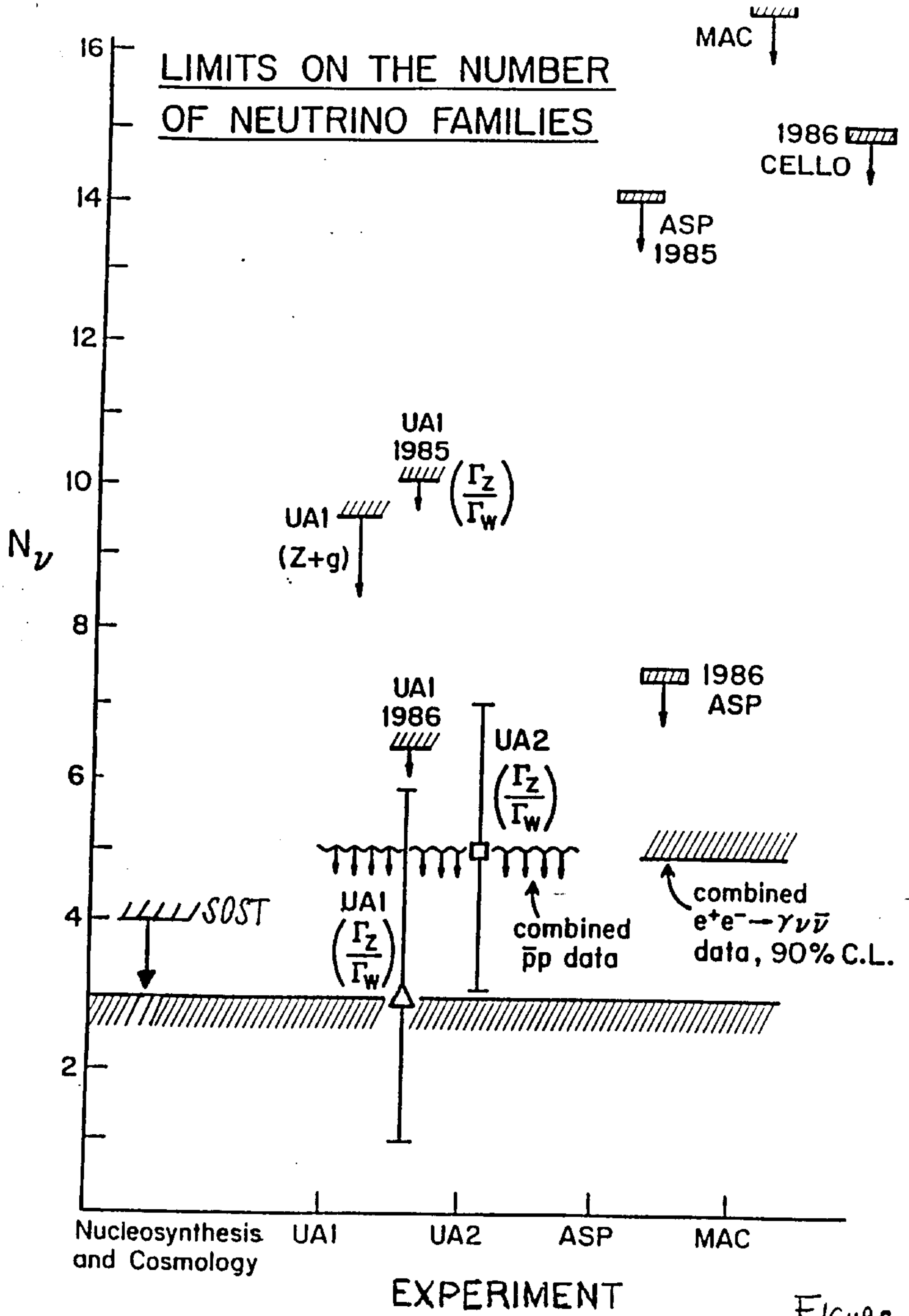
LIMITS ON THE NUMBER OF NEUTRINO FAMILIES
N_ν
16
14
12
10
8
6
4
2
MAC
1986 CELLO
ASP 1985
UA1 1985 $\left(\frac{\Gamma_Z}{\Gamma_W}\right)$
UA1 (Z+g)
1986 ASP
UA1 1986
UA2 $\left(\frac{\Gamma_Z}{\Gamma_W}\right)$
SOST
UA1 $\left(\frac{\Gamma_Z}{\Gamma_W}\right)$
combined $\bar{p}p$ data
combined $e^+e^- \to \gamma\nu\bar{\nu}$ data, 90% C.L.
Nucleosynthesis and Cosmology
UA1
UA2
ASP
MAC
EXPERIMENT

FIGURE 3

$W^+ \to L^+ + \nu_L$ Search
$\hookrightarrow q + \bar{q} + \bar{\nu}_L$
at a $\bar{p}p$ Collider

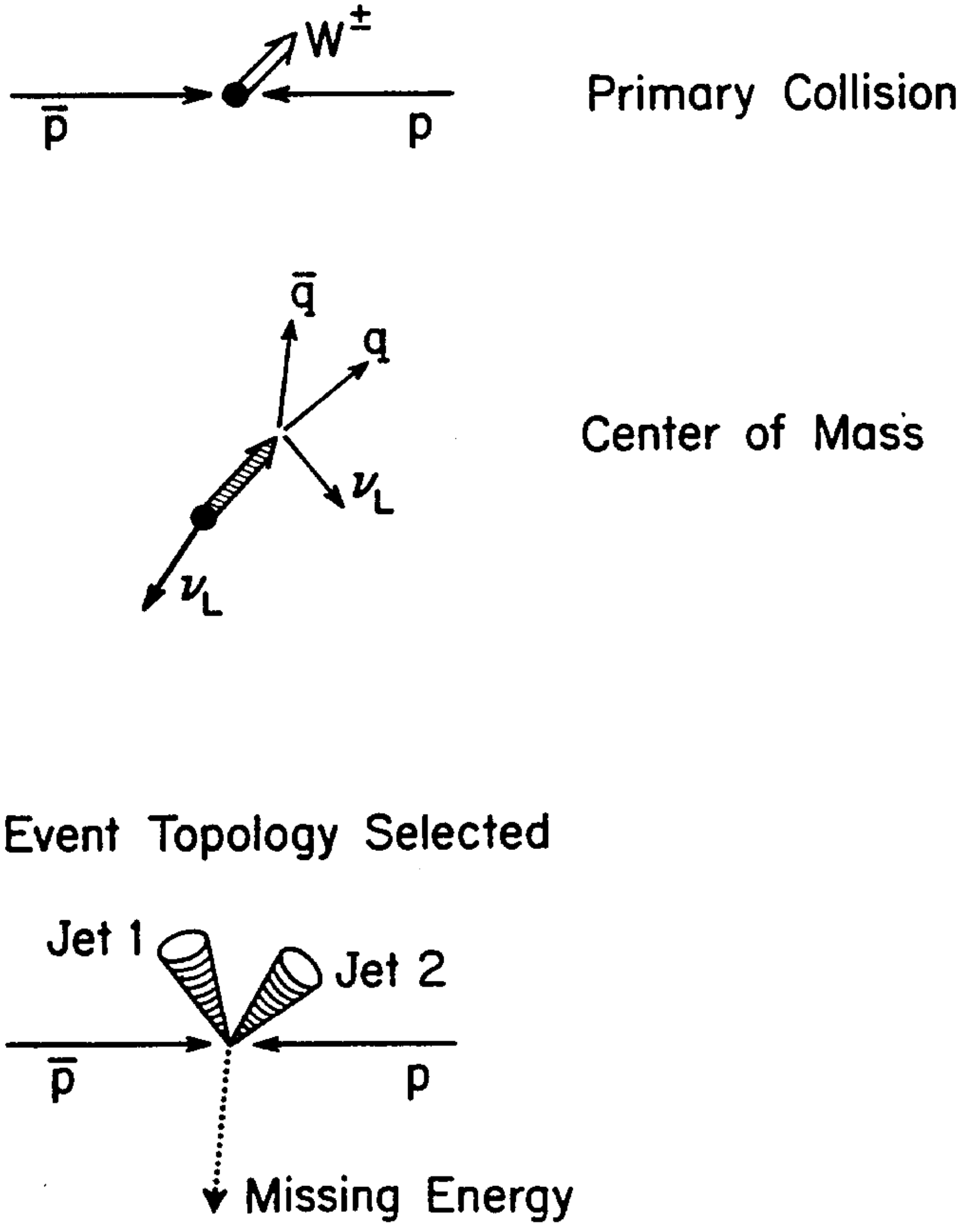

Figure 4

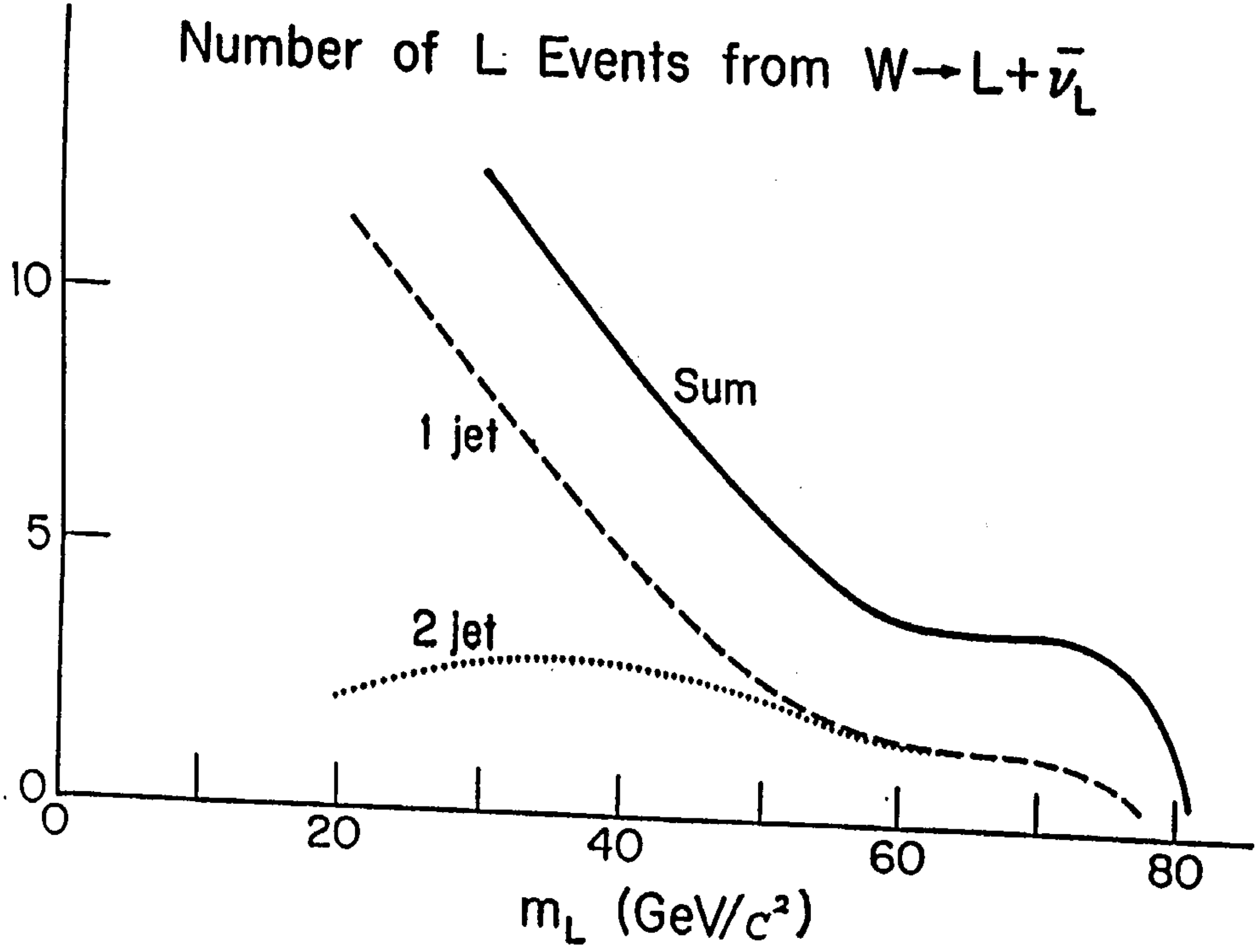
Number of L Events from $W \to L + \bar{\nu}_L$
10
5
0
0
20
40
60
80
m_L (GeV/c^2)
Sum
1 jet
2 jet

Figure 5

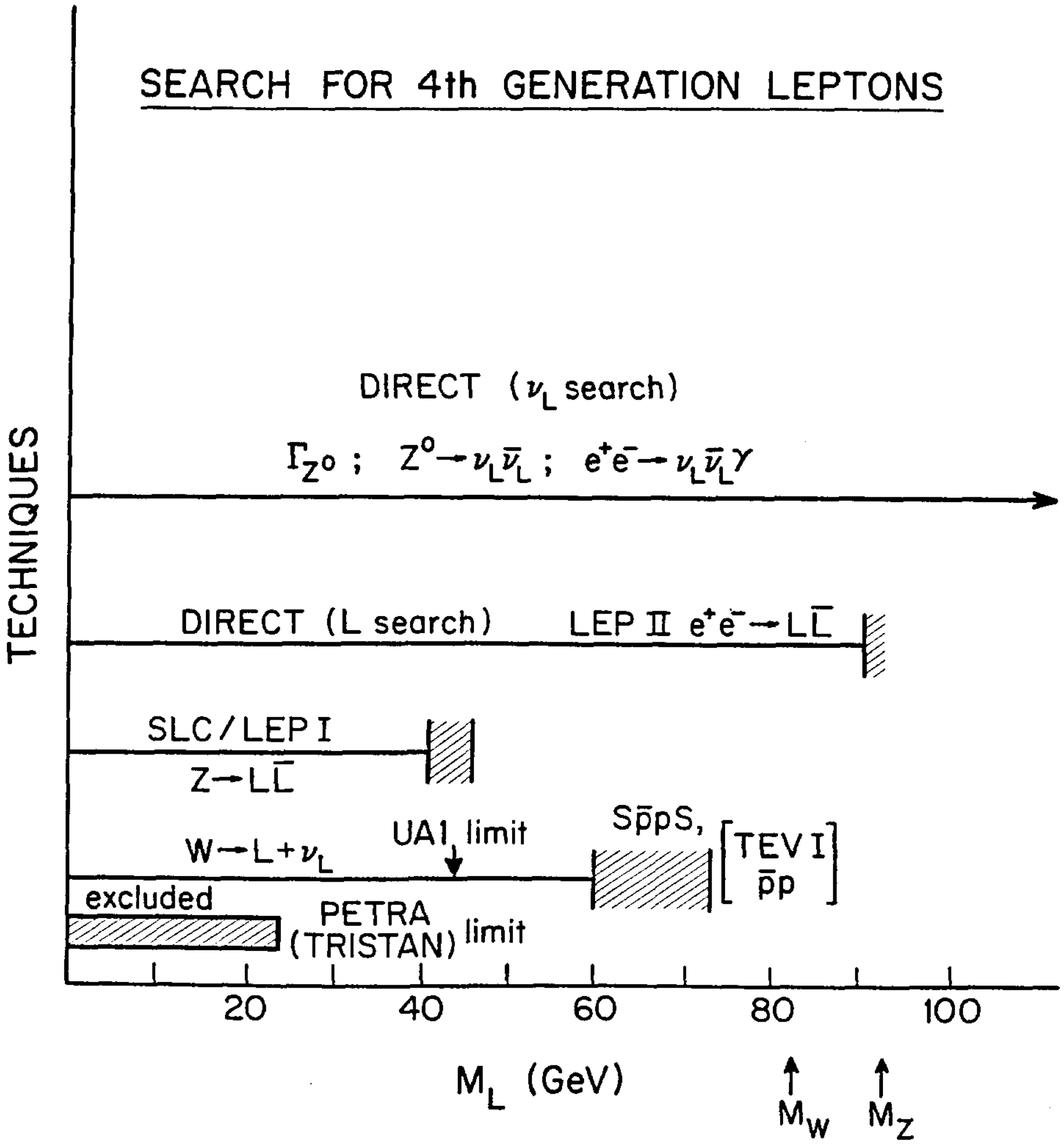
SEARCH FOR 4th GENERATION LEPTONS
TECHNIQUES
DIRECT (ν_L search)
Γ_{Z^0} ; $Z^0 \rightarrow \nu_L \bar{\nu}_L$; $e^+e^- \rightarrow \nu_L \bar{\nu}_L \gamma$
DIRECT (L search)
LEP II $e^+e^- \rightarrow L\bar{L}$
SLC / LEP I
$Z \rightarrow L\bar{L}$
$W \rightarrow L + \nu_L$
UA1 limit
S$\bar{p}$pS,
TEV I
$\bar{p}p$
excluded
PETRA
(TRISTAN) limit
20
40
60
80
100
M_L (GeV)
M_W
M_Z

Figure 6