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Search for New Heavy Leptons*

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Abstract

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Invited talk at the XXIVth International Conference on High Energy Physics, Munich, Germany, August 4–10, 1988

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Abstract

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1 Introduction

The Standard Model of the strong- and electroweak interactions has at least three families of quarks and leptons and the first search at a new energy regime naturally includes the search for a fourth generation. If the mass pattern of the three known generations can be taken as a guide, one expects the leptons of the fourth generation to be the lightest. The charged leptons would be observable easily, but the neutral lepton might be either stable or unstable by decaying into the lighter leptons, depending on the mixing between the different generations. If the neutral lepton decays inside the detector, it gives very specific signatures. If it is stable, is is practically invisible, since it is neutral and exhibits only the weak interactions, so one has to use indirect search methods in such a case, like e.g. tagging via the photons from initial state radiation or by studying the properties of the W and Z^0 bosons. We will review both these indirect - and direct search methods for both charged - and neutral leptons with new data from TRISTAN and new analysis of data from PEP and PETRA and the CERN $p\bar{p}$ collider.

2 Search for Charged Heavy Leptons

Charged leptons can be pair produced easily in e^+e^- or show up as decay products of W-decays in $p\bar{p}$ collider experiments. The corresponding Feynman diagrams are shown in Fig. 1. If the neutrino is heavier than the corresponding charged lepton, the latter will be stable. If the neutrino is lighter, the charged lepton will decay into this neutrino by emission of a W (see Fig. 1c). We will consider both cases separately.

2.1 Limits on Stable Charged Leptons.

The cross section for the production of L^+L^--pairs in e^+e^- is given by:

$$\sigma(e^+e^- \rightarrow L^+L^-) = \beta(3-\beta^2)\sigma_{\mu\mu}$$

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Figure 1: **Feynman diagrams for production and decay of charged and neutral heavy leptons.**

The threshold factor proportional to the L^+ velocity β gives a rapid rise to the asymptotic value, which is equal to the μ-pair cross section. The signature of stable new leptons is very similar to the signature of μ-pair production: two minimum ionizing particles back to back in the detector. If the particles are light, this would double the apparent μ-pair cross section. If the new leptons are close to threshold, their velocity is small and they can be identified either by the *larger ionization* or by the *longer time-of-flight*. Since these signals are unmistakable, one can observe new leptons close to the maximum limit of the beam energy and since TRISTAN has the highest energy (56 GeV in the c.m. at TRISTAN versus 46.78 GeV at PETRA and 29 GeV at PEP) the best limits come from the TRISTAN experiments AMY, TOPAZ, and VENUS. **They quote 95% C.L. lower limits on new stable, charged leptons of 27.8, 25, and 27.6 GeV/c^2, respectively[1].**

2.2 Limits on Unstable Charged Leptons.

Charged leptons can decay via the diagram shown in Fig. 1c, which gives rise to a lepton and two neutrinos or a pair of quarks and a neutrino.

Therefore, the signature for pair production of charged, unstable heavy leptons are lepton pairs (preferably unlike leptons, like the classical $e\mu$-pair signature for the discovery of the τ-lepton), quark jets or the mixed signature of an isolated lepton and quark jets.

The decay branching ratios for a sequential heavy lepton are well known in case of a massless neutrino, since a W has identical couplings to leptons and quarks. Assuming the top quark to be too heavy, one finds 9 possible decay modes: $e\nu_e$, $\mu\nu_\mu$, $\tau\nu_\tau$, 3 $u\bar{d}$, and 3 $c\bar{s}$ and each decay modes has approximately the same branching ratio of 1/9=11%, if one neglects small phase space and QCD corrections. This leads to the following signatures for the pair production of charged heavy leptons: 1/9 of the decays show acoplanar lepton pairs, 4/9 show acoplanar jets and 4/9 show the mixed mode of an isolated lepton with jets. In addition all signatures have missing visible energy and momentum carried away by the neutrinos. Missing energy can also originate from initial state radiation. However, since such missing energy is usually directed along the beam direction, one usually cuts on the missing momentum in the plane transverse to the beam direction. Such a cut is made conveniently by requiring a minimum acoplanarity between the planes defined by an incoming and outgoing particle and the plane defined by the remaining incoming and outgpoing particle. **The 95 % C.L. lower limits on new, unstable charged leptons from AMY, TOPAZ, and VENUS are 27.8, 26.8, and 27.6 GeV/c^2, respectively[1].**

These limits are appreciably better than the corresponding limits of about 22.7 GeV/c^2 from the PETRA experiments[2], but the best limit is still the published limit from the UA1 Collaboration[3], who searched for the decays of real W's into a fourth generation of a charged and neutral lepton. The signature is a monojet from the charged lepton decay (Figs. 1b and 1c). They quote at 90 % C.L. a lower limit of $M(L^-)$=41 GeV/c^2. However, this number is rather sensitive to the quoted confidence level: at 95 % this limit is 6 GeV/c^2 lower[4]. The reasons is simple: the decay width of the W is rather sensitive to the mass $M(L^-)$, which makes the expected number of events slowly varying with the mass, as shown in Fig. 3 from the thesis of Mohammadi[4]. Furthermore the large background (QCD, W-decays into $\tau\nu_\tau$, followed by hadronic τ decays and gluon radiation from Z^0 production with the Z^0 decaying into invisible neutrinos) makes it difficult to put very tight limits on the number of monojets from new heavy leptons. The observed number of monojets (17) is comparable to the monojets expected from this background (17.8). The 90 and 95 % C.L. on the number of monojets have been indicated in Fig. 3 as thin horizontal lines. In contrast, there is little difference between a 90 or 95 % C.L.in the results from e^+e^- annihilation, since there the background is small and in addition the expected number of events rises rapidly to the asymptotic value near threshold.

2.3 Searches for Charged Leptons in Case of Massive Neutrinos.

In the previous sections the charged lepton was assumed to decay into a W and a massless neutrino. This prejudice stems from the fact that all known neutrinos have masses consistent with zero, but this does not need to be so. If the neutrino is massive and stable, the signatures stay similar; one only has to take into a account the smaller phasespace, so the limits on the charged heavy lepton mass become dependent on the neutrino mass. The excluded contours in the $M(L^0)$ versus $M(L^-)$ plane are shown in Fig. 2a. The region above the diagonal corresponds to $M(L^0) > M(L^-)$ and we have the stable L^+ scenario described before. The curve from the UA1 Coll. has been estimated via a rough Monte Carlo simulation by Barnett and Haber[5] and should be considered approximate only. The endpoint for $M(L^0)$ is correct, since this has been quoted by the UA1 group themselves[4]. Note that this figure gives the 95% C.L. limits and not the 90% C.L. limits quoted in the literature[3,5].

2.4 Searches for Close Mass Pairs.

As shown in Fig. 2a there is a small region with $M(L^0)$close to $M(L^-)$, which is not excluded. There are several difficulties in this region:

- if $M(L^0)$ becomes close to $M(L^-)$, the latter lifetime becomes long and one has to worry about tracks not coming from the interaction point or no decay at all inside the detector.
- If most of the energy of the decay products is in the neutrino mass, the remaining particles have little energy, which makes lepton identification and triggering more difficult.
- The branching ratios become sensitive to the mass difference $\delta = M(L^-) - M(L^0)$. (see Fig. 4. If δ is below the pion mass, the charged lepton becomes stable and the previous limits apply.

These difficulties require special selection criteria, which have been investigated first by Perl and Stoker[6]. New results from the Mark-II - and TPC Collaborations have been presented at this Conference and the limits on $M(L^-)$ are shown in Fig. 2b as function of δ, which indicates that most of the gap near the diagonal in Fig. 2a has been excluded. The shaded areas have been excluded from previous searches[7].

Since these more ingeneous searches have been done only with PEP data, the limits only apply for the case $M(L^-)$ <14 GeV/c^2. This causes the kink in the dotted line in Fig. 2a for PEP and PETRA limits.

3 Search for Unstable Neutral Leptons

Stable neutrinos are usually observed as missing energy after the production and decay of its charged lepton partner Therefore the search for charged heavy leptons automatically includes the search for the

Figure 2: **a) Limits on charged heavy leptons. b) as a) in case of close mass pairs.**

Figure 3: **Number of monojets from a new heavy lepton expected in the UA1 detector as function of the heavy lepton mass[4].**

corresponding neutrino and the results shown in Fig. 2 can be interpreted as limits on both charged and neutral heavy leptons.

However, if the neutrino is heavy, there exists the distinct possibility that it will be unstable by mixing with the light neutrinos. For massive particles a left-handed particle can be transformed into a right-handed particle by a boost into a Lorentz frame moving faster than the particle. For massless particles this is impossible, since they move with the speed of light. Therefore, massless neutrinos are states of definite helicity and therefore the real particles coincide with the weak eigenstates. For massive neutrinos this need not to be so and the weak - and mass eigenstates are related by unitary transformations. In this case the charged weak current can be written as:

$$J_W = (\overline{\nu_e}\ \overline{\nu_\mu}\ \overline{\nu_\tau})\ U^\dagger\ \gamma^\mu\ (1+\gamma^5) \begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix} + (\overline{u}\ \overline{c}\ \overline{t})\ \gamma^\mu\ (1+\gamma^5)\ V \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Here V is the well known Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix for the quark sector and U is the corresponding one for the lepton sector. It is conventional to rotate only the vector with the lightest particles. The elements of the matrices U and V describe the relative strength of the weak transitions between the mass eigenstates, i.e. the observable quarks and leptons. The weak quark eigenstates can be written as:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \sim \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

. For the neutrino eigenstates a similar equation can be written, but the matrix is a diagonal matrix as far as we know.

For the quark sector we know that $\sin^2\theta_C$=0.22, where θ_C is the Cabibbo angle and we know also that there is practically no mixing between the heavy quarks of the third generation and the lighter quarks. For the neutrinos the mixing has to be small, since the neutrinos have all similar masses. In case of equal masses there cannot be mixing. It is not understood why neutrinos have such small masses, but several interesting models exist[8] For example the 'seesaw' mechanism in left-right symmetrical models has very light and heavy neutrinos simultaneously[9].

If there is a fourth family of leptons with a massive neutrino, the neutrino may not be stable, but decay into the lighter neutrinos via the charged current, provided the mixing is strong enough.

In case of unstable neutrinos one can search for their production directly, since they will be visible in the detector, provided their lifetime is short enough. Two possible diagrams have been considered: $L^0\overline{L^0}$ production through Z^0 exchange and single production together with a light neutrino through W-exchange. The latter process is restricted to new leptons, which mix with the first generation.

If a heavy neutrino decays, its lifetime is proportional to the inverse of the fifth power of its mass, just like for muon decay.

$$\tau_{L^0} = \frac{m_\mu^5}{m_{L^0}^5}\ \tau_\mu\ \frac{BR(L^0 \to l e \nu)}{f(m,l)\sum_l |U_{lL^0}|^2}$$

Here f(m,l) is a phase space correction factor, which is only significant for mixing with the τ lepton and U_{lL^0} is the corresponding mixing parameter. Clearly small mixing and/or small masses lead to long lifetimes. Depending on the lifetime one has to search for different signatures:

- a) *short lifetime*: search for direct decays into hadrons or leptons (see Fig. 1d).
- b) *long lifetime*: secondary vertex searches.
- c) *very long lifetime*: like stable neutrinos, so one can do neutrino counting by single photon tags or study Z^0-decays.

We will first discuss pair production of unstable neutrinos, then single production, assuming the neutrinos decay inside the detector. Neutrino counting will be discussed in the next section.

Figure 4: **Branching fractions of a sequential charged heavy lepton as function of the mass difference between its mass and the mass of its associated neutrino for a) $\delta = 2$ GeV/c^2 and b) $\delta = 10$ GeV/c^2[6]. The decay modes are** $(1)L^+ \rightarrow l0e^-\overline{\nu_e}, (2)L^+ \rightarrow l0\mu^-\overline{\nu_\mu}, (3)L^+ \rightarrow l0\pi^-, (4)L^+ \rightarrow l0\rho^-, (5)L^+ \rightarrow l0K^-, (6)L^+ \rightarrow l0K^{*-}, (7)L^+ \rightarrow l0a^1_-, (8)L^+$ - **and** $(10)L^+ \rightarrow l0\tau^-\overline{\nu_\tau}$.

Figure 5: **Cross section for production of various heavy leptons as function of center of mass energy.**

Figure 6: **Excluded charged lepton masses as function of mixing parameter.**

Figure 7: **Excluded charged lepton masses as function of mixing parameter combining the results from the previous figure with previous results[14].**

3.1 Search for Pair Production of Unstable Neutral Leptons.

The total cross section for the pair production of heavy leptons through Z^0 exchange is given by:

$$\sigma = \frac{G_F^2\, s}{96\pi}\frac{(M_Z^2}{(s - M_z^2))^2}\beta(3+\beta^2)(1-4\sin^2\theta_W+8\sin^4\theta_W)$$

where G_F is the Fermi constant, θ_W is the electroweak mixing anlge and $\beta = (1-4M(L^0)^2/s)^0.5$ is the velocity of the heavy lepton. This cross section is of the order of a picobarn (see Fig. 5. for comparison the μ-pair cross section at $\sqrt{s}$=44 GeV is 45 pb. The decay diagram of a neutral lepton is shown in Fig. 1d. Pair production leads to final states containing at least 2 oppositely charged leptons plus 2 other charged leptons or quark jets. In case of hadronic decays of the virtual W there is no missing momentum or energy. Fig. 6 shows new limits on the mass of an unstable neutral lepton as function of the mixing parameter. Large mixing parameters correspond to short lifetimes. In this region the AMY Coll.[1] excludes the mass range 17-24.3 GeV/c^2 at the 95 % C.L. in case of dominant mixing with the muon neutrino; the CELLO Coll.[10] excludes the mass range 3.2-17.4 GeV/c^2 in case of dominant mixing with the muon neutrino and excludes the mass range 3.1-18.0 GeV/c^2 in case of dominant mixing with the electron neutrino. The AMY result excludes the interpretation of a spectacular event with two isolated muons and two jets observed by the CELLO Coll.[11] as the production of a pair of neutral leptons. After taking more data the CELLO Coll.[12] concludes that the most likely interpretation of such an event is the production of two virtual photons, one decaying into a μ-pair, the other into a quark pair. Fig. 6 shows also the earlier results from the MARK-II – and the HRS Collaborations [13]. The region at very low masses is not accessible with these searches, since the lifetime becomes too long and the neutrinos escape the detector. In this case the searches of Sect. 4 apply. If the mass of a fourth generation neutrino is very small, it may show up in the weak decays of hadrons as monochromatic peaks in the lepton spectra. These searches and others have been reviewed in detail before[14,15]. An update of the nice summary by Eichler[14] is shown in Fig. 7.

3.2 Single Production of an Unstable Neutral Lepton.

The production mechanism of Fig. 1f leads to events with large missing momentum since a light neutrino is produced back to back with the heavy neutral lepton. CELLO excludes these singly produced electron-like neutral leptons in the mass range 0.6-34.6 GeV/c^2 for a V-A current at the eWN vertex and 0.4-37.4 GeV/c^2 for V+A, thus improving considerably the previous JADE limit[13]. Note that this mechanism is sensitive to masses above the beam energy, but is restricted to neutrinos, which mix with the electon neutrino. The limits quoted above assume full mixing.

4 Neutrino Counting.

Long-lived neutrinos may not decay inside a detector and escape invisibly. Nevertheless, one can still detect such neutrinos by more indirect, but very powerful methods: : a) Z^0 decays into 'invisible' neutrino final states, made visible by a single photon from the initial state radiation. b) The ratio of production cross section of W and Z^0 in $p\bar{p}$ collisions. c) Cosmological arguments. d) Measurement of the total width of the Z^0 boson. Results from the first three methods have been summarized in Fig. 8 and will be discussed hereafter.

4.1 Single Photon Searches

Invisible final states in e^+e^- annihilation can be tagged by a photon from initial state radiation The final states can be either a pair of the known neutrinos, neutrinos from a fourth generation, or invisible supersymmetric particles like photinos, sneutrinos, goldstinos, etc. Fortunately, the yield from the known processes can be calculated accurately, since all couplings are known. The bremsstrahlung spectrum is peaked forward and very soft: $d\sigma/dkdcos\theta \propto 1/ksin^2(\theta)$. Here k is the photon energy and θ is the polar angle. Triggering and detecting such soft photons is difficult. Furthermore, one has to make sure that no other particles escape the detector unseen, which implies full efficiency over the whole acceptance (no holes or cracks !). Events in which particles escape into the beampipe (mainly from $ee\gamma$ events) can be vetoed by requiring that the minimum transverse momentum of the photon is so large that kinematically at least one of the leptons in an $ll\gamma$ final state appears inside the acceptance. The main background comes from $e^+e^- \rightarrow Z^0 \rightarrow \gamma\nu\bar{\nu}$. Up to now four experiments have presented such an analysis[16,17]: ASP, which was specifically designed to detect this reaction, and CELLO, MAC, and MARK-J. The limit on the number of neutrino species from MARK-J is 18 and has been omitted from Fig. 8 in order not to make the scale too large.

In all experiments the number of observed events is somewhat below the expected number of events. Combining all the experiments[17] one finds 3.86 observed events compared with 6.11 events expected. The non-integer number of observed events stems from a maximum likelihood fit, which separates the expectation for signal and background. The low number of observed events corresponds to $1.0^{+2.9}_{-1.0}$ neutrino species, which is still consistent with the known number of neutrino species and one can derive a lower limit on the additional number of neutrino species:

$$\Delta N_\nu \leq 3.7\ (4.7) \text{ at } 90\ (95)\ \%C.L.$$

To calculate a limit is somewhat tricky in case the observed number of events is below the expected background. In this case one should take into account that the expected background is not a normal Poisson distribution with mean of 6.11, but after performing the experiment one *knows* that the background cannot exceed the observed number of events. Therefore one should use a truncated Poisson distribution; this was done in the previous numbers. Details can be found in the paper by J.-F. Grivaz and the thesis of H. Jung[18]. The dashed lines in Fig. 8 indicate the less conservative limits if this restriction $N_\nu > 3$ would not have been applied. Note that this figure gives the limits on the total number of neutrino species, defined as $3 + \Delta N_\nu$ and these values have been given as integers.

4.2 Limits from $p\bar{p}$ Collider Experiments.

Another indirect measurement of the number of neutrino species can be obtained from the ratio of the W and Z^0 production cross sections:

$$R = \frac{\sigma(p\bar{p} \rightarrow W \rightarrow X)}{\sigma(p\bar{p} \rightarrow Z \rightarrow X)} \cdot \frac{BR(W \rightarrow e\nu)}{BR(Z \rightarrow ee)} = \frac{\sigma(p\bar{p} \rightarrow W \rightarrow X)}{\sigma(p\bar{p} \rightarrow Z \rightarrow X)} \cdot \frac{\Gamma(W \rightarrow e\nu)}{\Gamma(Z \rightarrow ee)} \cdot \frac{\Gamma_Z}{\Gamma_W}$$

The measurement of R provides a measurement of Γ_Z, the total width of the Z^0 boson. This width increases 170 MeV (~6%) for each additional neutrino species. Of course, one has to assume that all other quantities are known, which is not true. For example, the total width Γ_W of the W depends on the unknown top mass and it would also change if a fourth generation of leptons existed with $M(L^-) + M(L^0)$ below the W mass. Furthermore, the theoretical cross sections are poorly known, because of uncertainties in the structure functions and higher order QCD corrections, although the ratio should be much better known. The measured value of R from the combined UA1[19] and UA2[20] data corresponds to $N_\nu = 1.8^{+2.0}_{-1.5} \pm 0.6$ for a light top and to $N_\nu = -0.1^{+1.7}_{-1.3} \pm 0.6$ for a heavy top. Here we have the same situation as in the previous section, namely the calculated number of neutrino species from the data is less than three, but not inconsistent with three. Therefore, extracting limits is tricky again. The UA1 Coll.[19] finds from the combined UA1- and UA2 data, taking into account the constraint $N_\nu > 3$:

$$\Delta N_\nu \leq 2.9\ (3.2) \text{ at } 90\ \%C.L.$$

for a top mass of 44 (23) GeV/c^2. If the top mass is higher, this limit becomes more stringent. If a new charged lepton with a mass of 41 GeV/c^2 exists (present limit is 35 GeV/c^2 at the 95 % C.L., see previous Section), Γ_W increases and the limit on ΔN_ν increases by 1 unit .

4.3 Limits from Cosmology.

Bounds on the number of different neutrino species can be derived from the helium-4 abundance[21] in our universe and from last years supernovae[22]. The helium-4 abundance depends strongly on the cooling rate of the universe after the inital big bang and this cooling rate depends on the number of relativistic particles, i.e. the number of neutrino species with small masses (less than 1 MeV/c^2). The estimated upper limit on the total number of neutrino species is 4[21] as shown in Fig. 8.

From the observed neutrino burst one has estimated the total energy release; it corresponds roughly to the binding energy of a neutron star, so there is not too much room for energy release in other particles. The estimated upper limit on the total number of neutrino species is 6[22], as shown in Fig. 8. It should be noted that it is difficult to give a realistic error on the limits from cosmology, since they depend on the assumptions of the big bang model and the 'energetics' of supernovae formation. Therefore, these limits should not be considered 90% confidence levels, but rather an indication that cosmological arguments and laboratory experiments do not disagree with each other.

5 Conclusion

There are no signs for a fourth generation of leptons and from the upper limits on the number of neutrino species one expects that at most two or three other generations could exist. The measurement of the total width of the Z^0 in e^+e^- annihilation in the near future will determine the total number of neutrinos with masses below half the Z^0 mass to $\sim$ 0.2 units. In case there are more than three generations, the event topologies of Z^0 decays will tell if they are stable or unstable: if unstable they will show up with very specific decay signatures; if stable they will show up as an anomalous amount of events with nothing else than a single photon from initial state radiation. Therefore the speaker at the next Conference of this kind is likely to present a much clearer picture without having to worry about close mass pairs etc. Let's wait and see.

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Figure 8: **90% C.L. limits on number of neutrino species.**

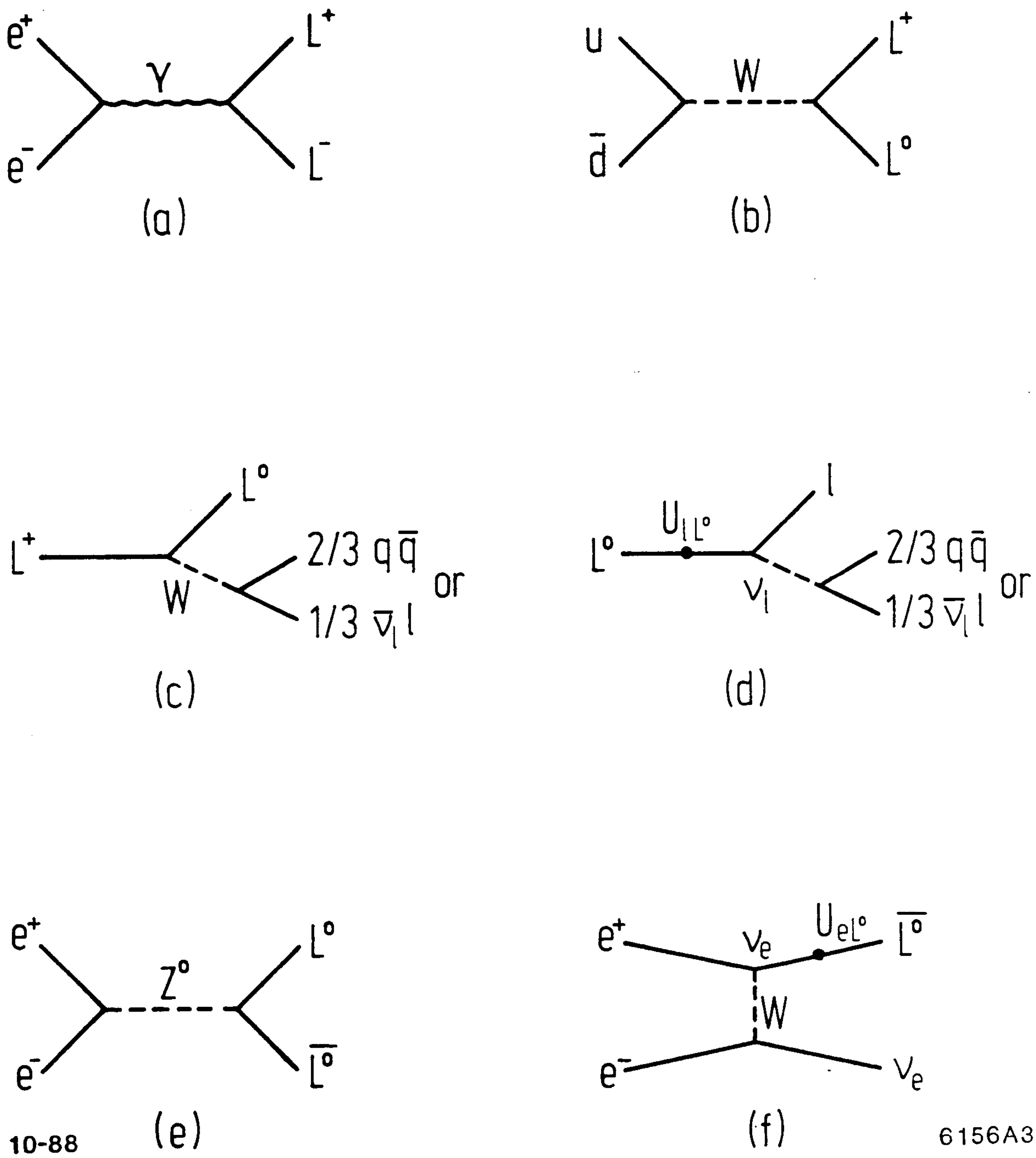

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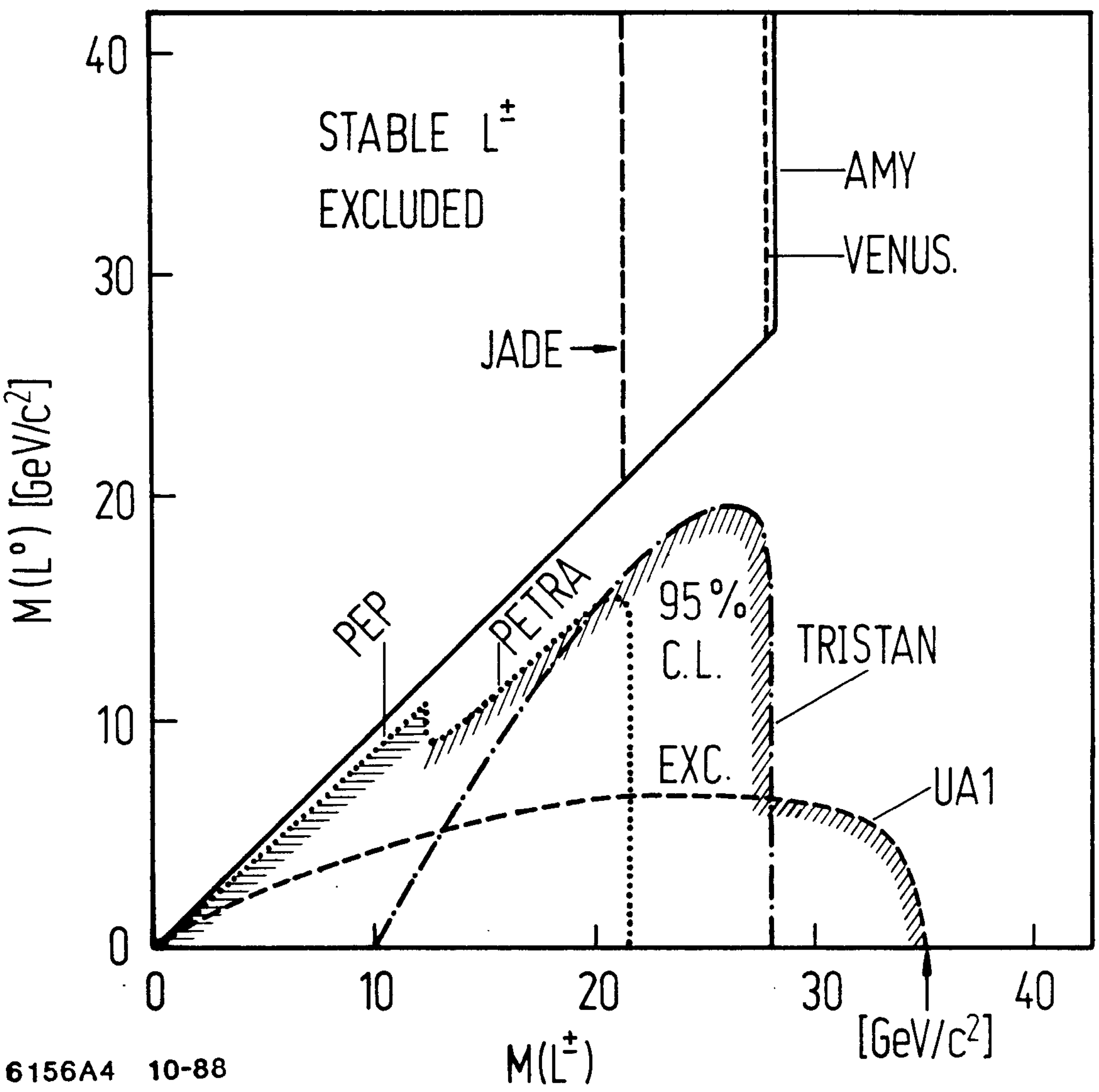
FIGURE 1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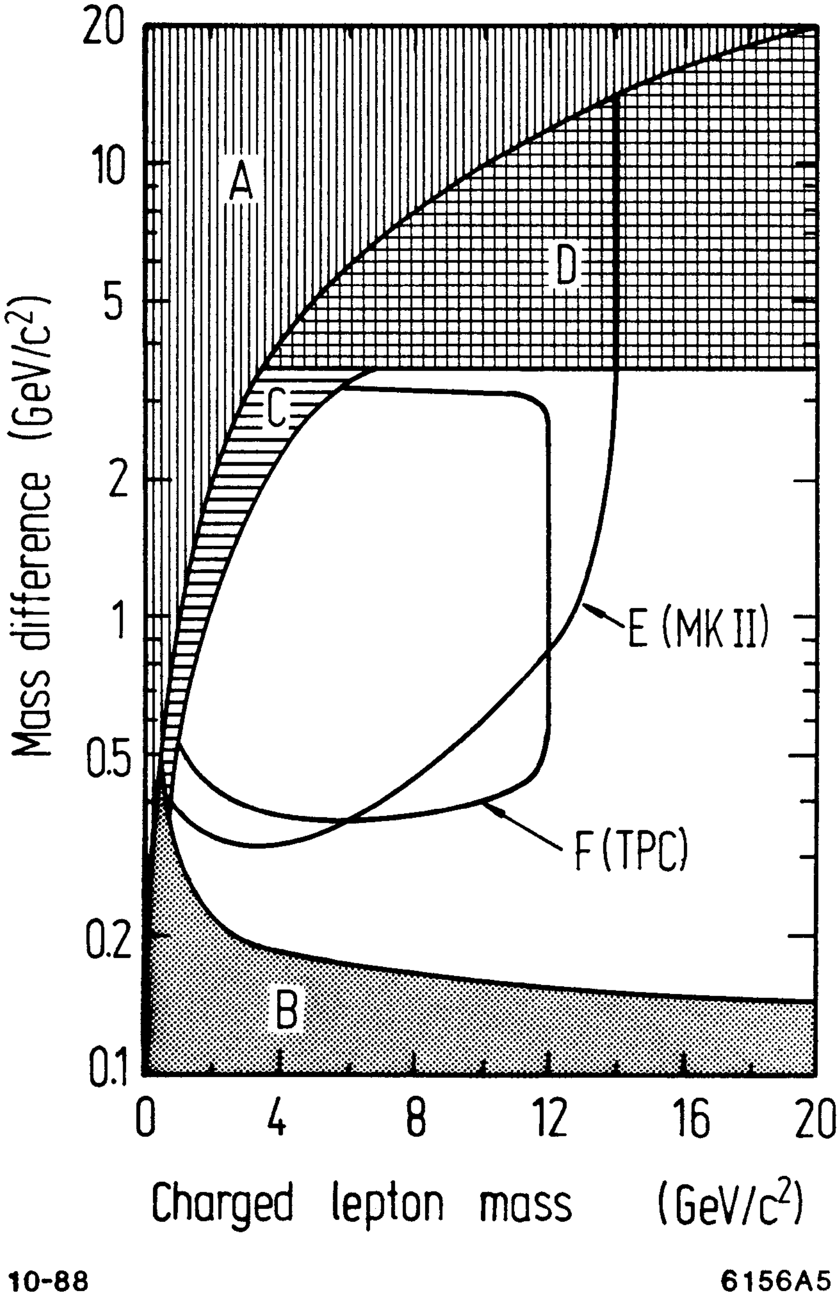
EXC.
TRISTAN
UA1
M(L°) [GeV/c²]
0
10
20
30
40
[GeV/c²]
M(L±)
6156A4 10-88

FIGURE 2A



20
10
5
2
1
0.5
0.2
0.1
Mass difference (GeV/c²)
A
D
C
E (MK II)
F (TPC)
B
0
4
8
12
16
20
Charged lepton mass (GeV/c²)
10-88
6156A5

FIGURE 2B

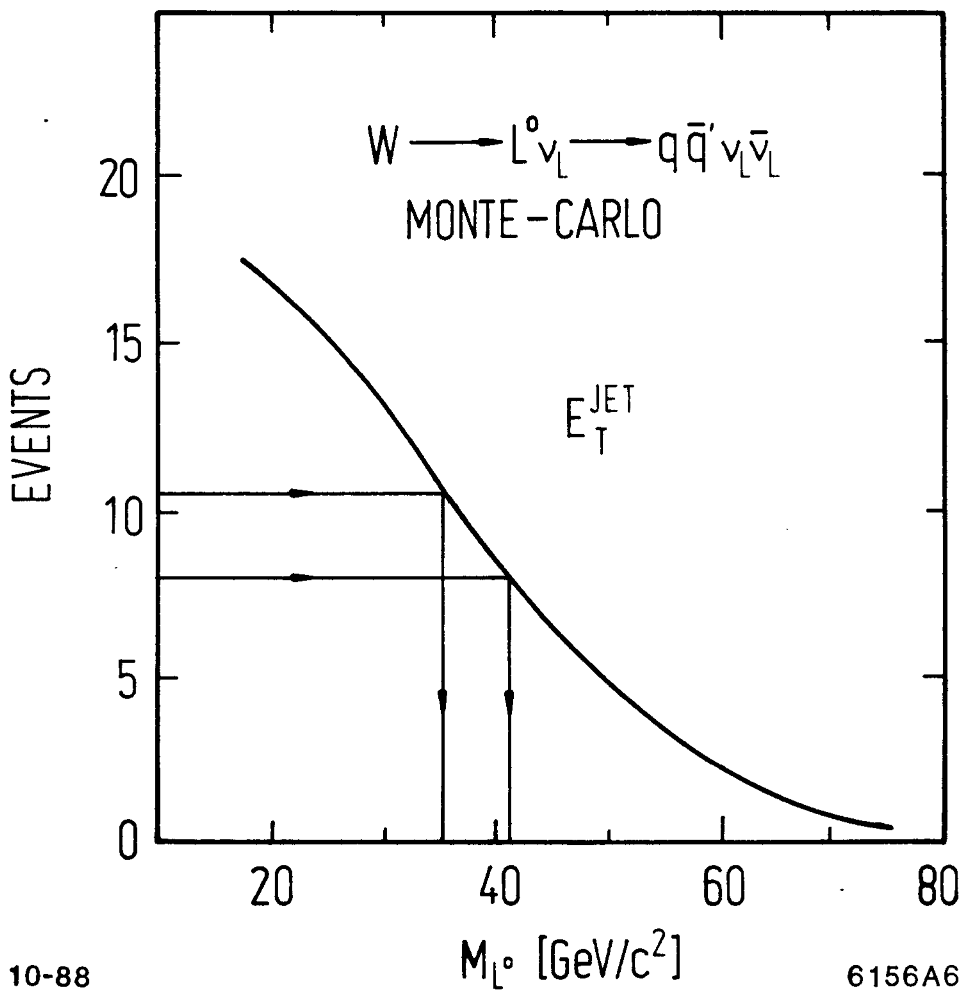

W → L°ν_L → q q̄′ ν_L ν̄_L
MONTE-CARLO
E_T^JET
EVENTS
20
15
10
5
0
20
40
60
80
M_L° [GeV/c²]
10-88
6156A6

FIGURE 3

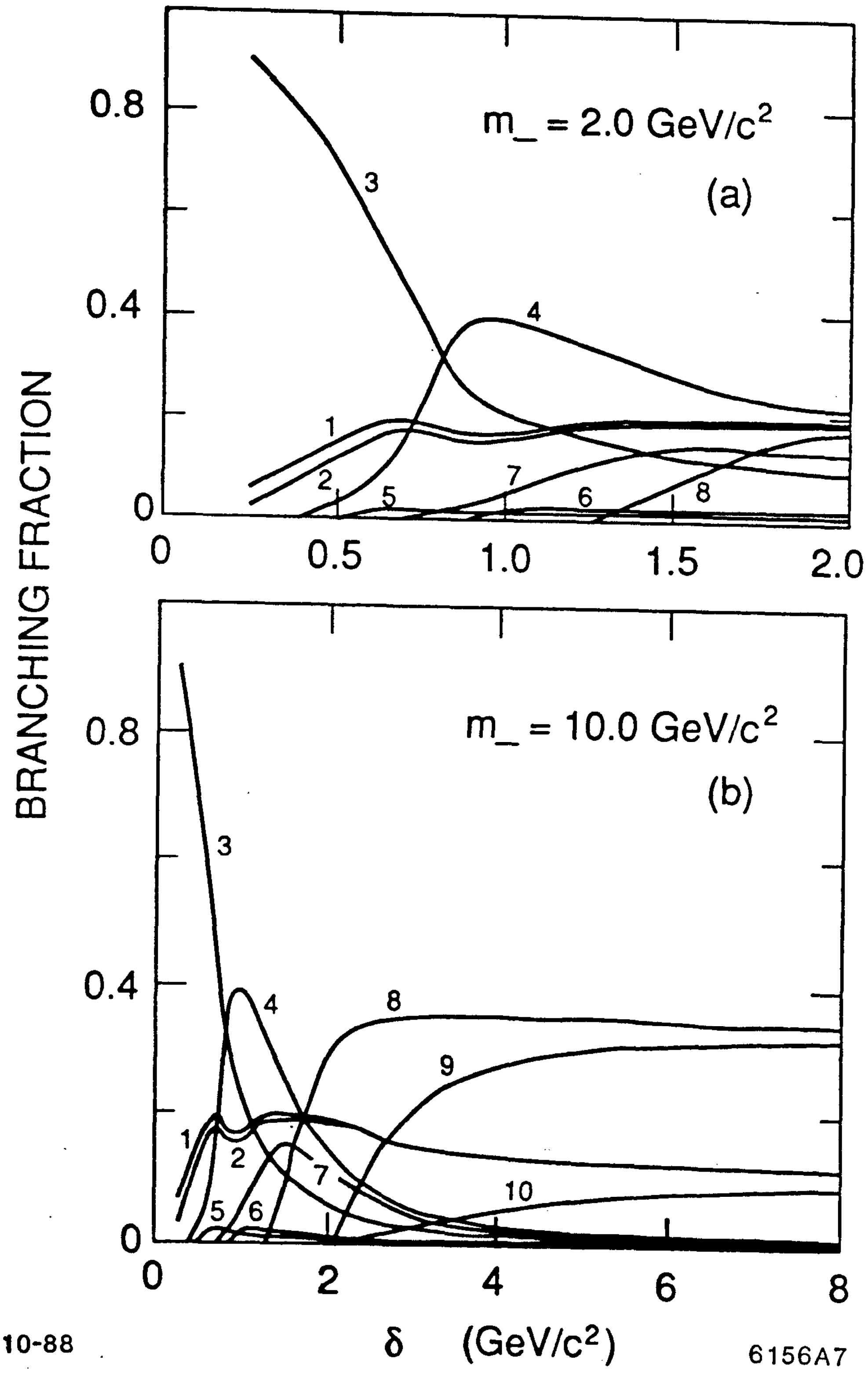

BRANCHING FRACTION
m_ = 2.0 GeV/c²
(a)
m_ = 10.0 GeV/c²
(b)
0.8
0.4
0
0.5
1.0
1.5
2.0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
δ (GeV/c²)
10-88
6156A7

FIGURE 4

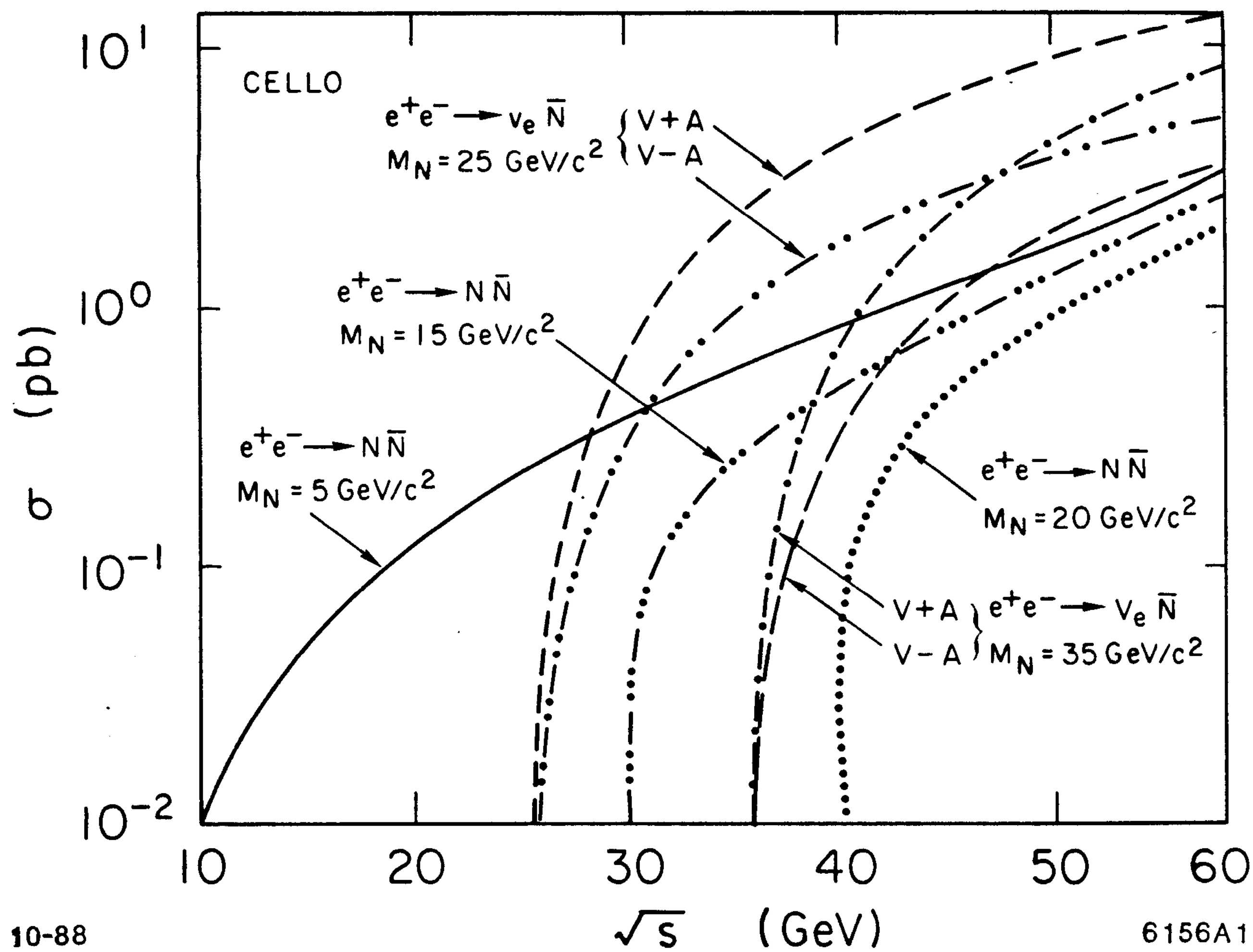
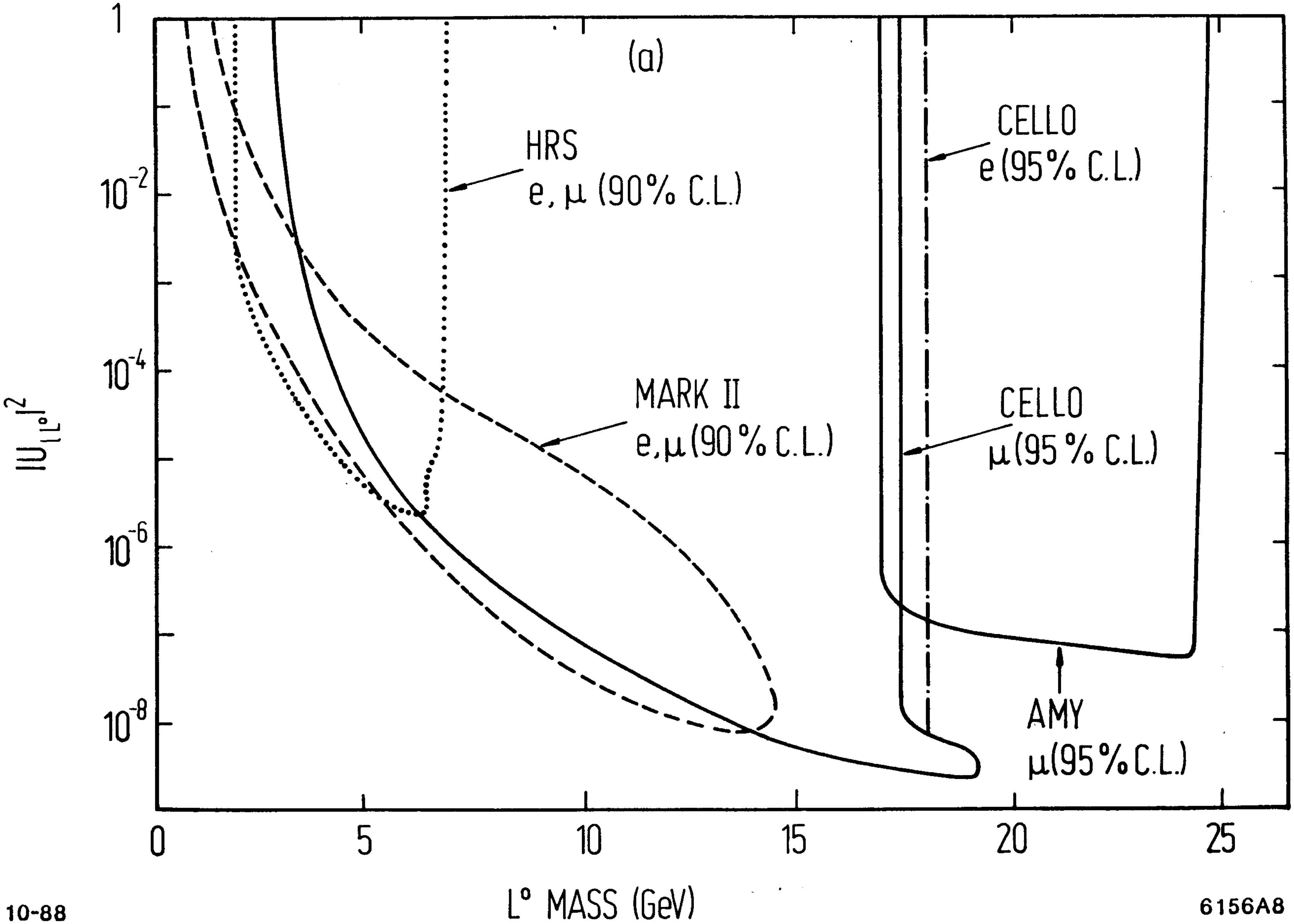
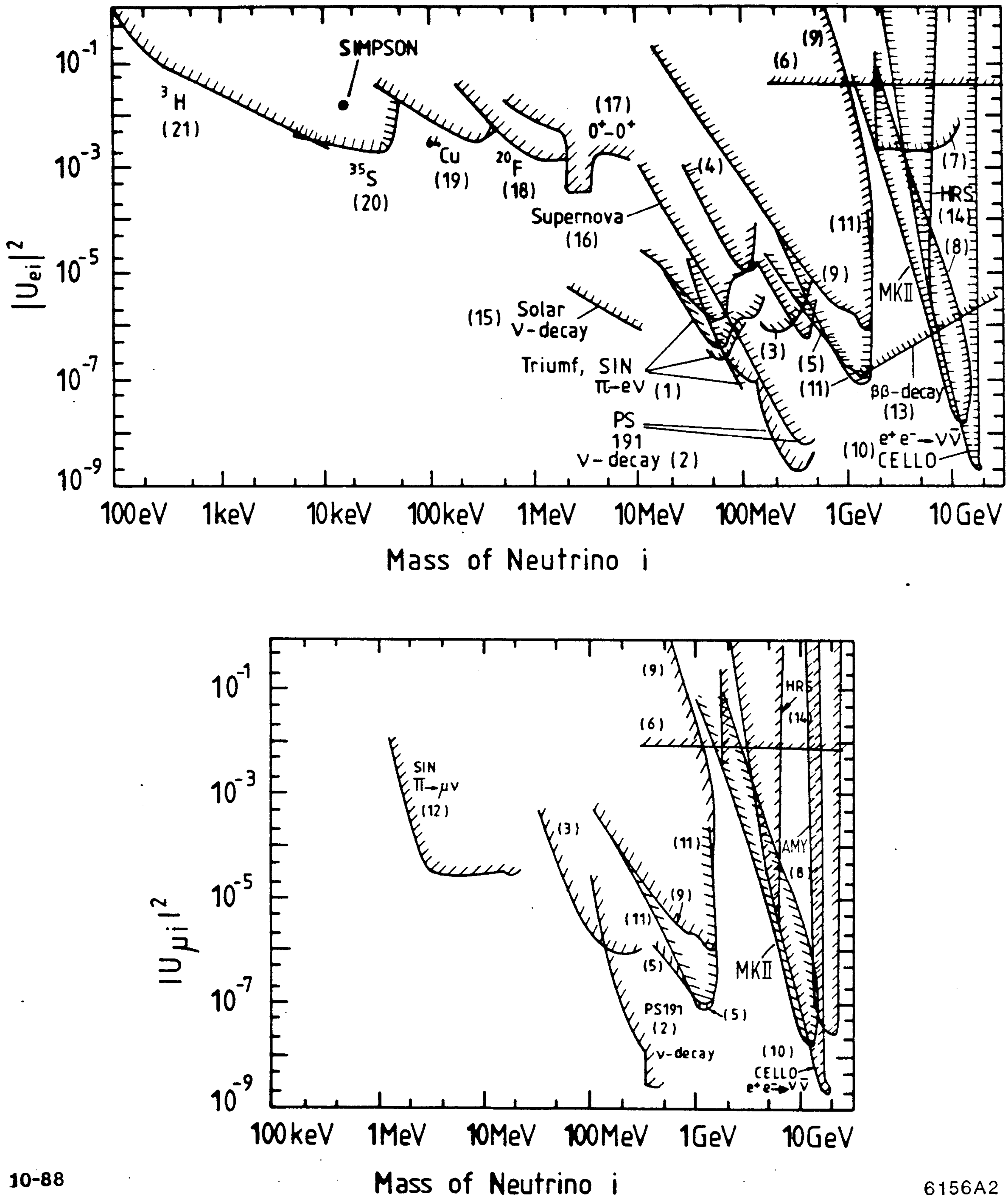

CELLO
e+e− → νe N̄
MN = 25 GeV/c2
V+A
V−A
e+e− → N N̄
MN = 15 GeV/c2
e+e− → N N̄
MN = 5 GeV/c2
e+e− → N N̄
MN = 20 GeV/c2
V+A
V−A
e+e− → Ve N̄
MN = 35 GeV/c2
σ (pb)
10¹
10⁰
10⁻¹
10⁻²
10
20
30
40
50
60
√s (GeV)
10-88
6156A1

FIGURE 5



(a)
HRS
e, μ (90% C.L.)
CELLO
e (95% C.L.)
MARK II
e,μ (90 % C.L.)
CELLO
μ (95 % C.L.)
AMY
μ (95% C.L.)
1
10-2
10-4
10-6
10-8
$|U_{lL^0}|^2$
0
5
10
15
20
25
L° MASS (GeV)
10-88
6156A8

FIGURE 6



10-88

6156A2

FIGURE 7

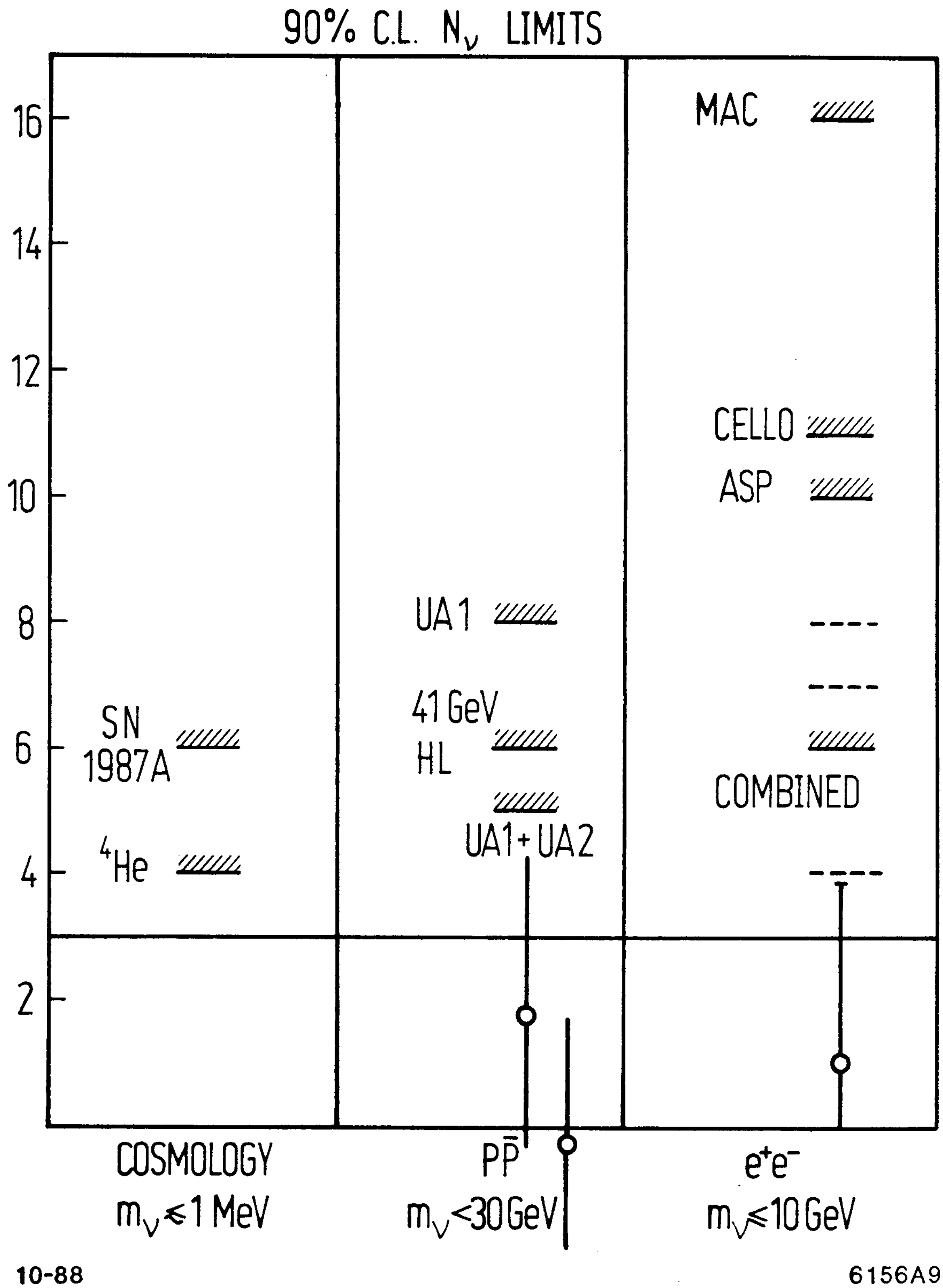

90% C.L. N_ν LIMITS
16
14
12
10
8
6
4
2
SN 1987A
^{4}He
UA1
41 GeV HL
UA1+UA2
MAC
CELLO
ASP
COMBINED
COSMOLOGY
$m_\nu \leq 1$ MeV
$P\bar{P}$
$m_\nu < 30$ GeV
e^+e^-
$m_\nu \leq 10$ GeV
10-88
6156A9

FIGURE 8