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SIGNALS FOR TAU NEUTRINO EVENTS IN A BEAM DUMP EXPERIMENT*

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ABSTRACT

Ways of detecting tau neutrinos emerging from a beam dump are studied. Key signatures are elaborated and contrasted with background arising from muon and electron neutrino interactions. Expected event rates are given for various neutrino spectra.

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The existence of a heavy charged lepton, τ^-, with mass 1.785 ± 0.010 GeV has now been well established[1] in $e^+ - e^-$ annihilation experiments carried out at SPEAR and DORIS. On the other hand, the corresponding existence of its own associated neutrino, ν_τ, has mainly been inferred[1] from the charged lepton momentum spectrum best described by the 3-body decay modes $\tau^- \to \nu_\tau e^- \bar{\nu}_e$ and $\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$. Postulating the existence of such a neutrino, upper limits have been placed on its mass, the latest[2] being $m_\nu \leq 250$ MeV (95% c.l.). The charged e^- (or μ^-) momentum spectrum strongly favors a V - A interaction at the $\tau - \nu_\tau$ vertex with a weak interaction coupling strength $G^2 \geq 0.12\ G_F^2$ inferred from an upper experimental limit for the τ lifetime.[2] In short, it appears that the τ lepton and its associated neutrino, ν_τ, couple (probably with full strength) to the ordinary charged W field in precisely the same fashion as do the $e^- - \nu_e$ and $\mu^- - \nu_\mu$ leptons.

Theoretically it is most appealing, given the success[3] of the standard Weinberg - Salam SU(2) x U(1) gauge model,[4] to place the ν_τ and τ leptons simply into a new doublet family.[5] Other possibilities such as assigning the τ to a triplet representation with $\nu_\tau \equiv \nu_e$, either in the $SU(2)_L \times U(1)$ gauge group or in an expanded $SU(3)_L \times U(1)$ gauge group, encounter difficulties connected with mixing angles and universality.[6] In any event, one would like to isolate ν_τ interactions and to confirm that the tau neutrino is a new entity and not, for example, the electron neutrino. In this paper we study ways in which ν_τ interactions in a new class of counter detectors can be identified in beam dump experiments which serve to enhance the ν_τ signal. We show that the ν_τ signal can be separated from the background reactions.

The main source of tau neutrinos[8] is decay of F charmed mesons which are pair produced in the beam dump target by the primary proton reaction

$$p + N \rightarrow F^{+} + F^{-} + X \qquad (1)$$

Both primary and secondary $\overset{(-)}{\nu}_\tau$'s arise in the F decays

$$F^{\pm} \rightarrow \tau^{\pm} + \overset{(-)}{\nu}_\tau \qquad (2a)$$

$$\tau^{\pm} \rightarrow \overset{(-)}{\nu}_\tau + (\ell^{\pm}\overset{(-)}{\nu}_\ell \text{ or hadrons}), \quad \ell = e, \mu \qquad (2b)$$

yielding identical flux spectra for the ν_τ and $\bar{\nu}_\tau$ beams. The beam dump enables one to suppress the copious flux of ordinary ν_μ and ν_e neutrinos from π and K decays in favor of neutrinos arising from the decay of short-lived charmed particles. Neutrino flux spectra calculated by Mori[9] for a 400 GeV primary proton beam incident on a copper target are illustrated in Fig. 1 for a detector subtending an angle of 0 - 2 mrad and placed 250 m downstream of the target dump. By missteering the beam, one can further suppress the $\overset{(-)}{\nu}_\mu(\pi + K)$ and $\overset{(-)}{\nu}_e(K)$ background fluxes, but one can not suppress the $\overset{(-)}{\nu}_\mu(D)$ and $\overset{(-)}{\nu}_e(D)$ fluxes relative to the $\nu_\tau(F)$ flux.

Some of the ν_τ's produced in the dump will interact in the downstream detector. Interactions of interest include

$$\nu_\tau + N \rightarrow \tau^{-} + X$$

$$\hookrightarrow \nu_\tau + \mu^{-} + \bar{\nu}_\mu \qquad (3a)$$

$$\hookrightarrow \nu_\tau + e^{-} + \bar{\nu}_e \qquad (3b)$$

$$\hookrightarrow \nu_\tau + \text{hadrons} \qquad (3c)$$

as well as the neutral current interaction

$$\nu_\tau + N \rightarrow \nu_\tau + X \qquad (4)$$

In order to identify the above reactions as being induced by tau neutrinos, we must find characteristics which distinguish them from ordinary ν_μ- and ν_e-induced charged current (CC) and neutral current (NC) interactions.

The neutral current reaction (4) and the apparent neutral current reaction (3c), as well as their $\bar{\nu}_\tau$ counterparts, will enhance the apparent NC/CC ratio over that prevailing in a pure $\overset{(-)}{\nu}_\mu$ beam. Since the $\overset{(-)}{\nu}_\tau$ flux from Fig. 1 is about thirty times smaller than that of the ν_μ and $\bar{\nu}_\mu$ fluxes, the NC/CC ratio will only be increased at most 3% by the additional $\overset{(-)}{\nu}_\tau$ interactions. Since the uncertainty in the neutrino flux is greater than this, one can not use this test as an accurate indicator of ν_τ interactions.[10]

Reaction (3c) will lead to events with two apparent hadron showers present. One could attempt to identify such events,[11] but our Monte Carlo studies show that the typical opening angle is $8^\circ - 10^\circ$ between the two shower directions whereas the spread in one hadron shower is $20^\circ - 30^\circ$; moreover, typically only 1 - 3 hadrons originate from the tau decay, so this test also will generally not be successful in identifying $\overset{(-)}{\nu}_\tau$ events.

The apparent charged current reaction (3a) with one muon and two neutrinos, however, appears to be a reliable indicator of a $\overset{(-)}{\nu}_\tau$ interaction as will be made clear.[6] The muon serves to tag the interaction as being neutrino- or antineutrino-induced, while the two neutrinos carry off momentum which generally results in a sizable imbalance in the momentum measured transverse to the neutrino beam direction. The azimuthal opening angle between the muon and (missing) neutrino pair in a plane perpendicular to the beam direction is peaked toward 0°, while the corresponding angles between the muon and hadron spray or between the neutrino pair and hadron spray are peaked dramatically toward 180°. These features are shown in Fig. 2 and can be understood by noting that the tau lepton and hadron spray are emitted on opposite sides of the beam direction and that the decay leptons tend to follow roughly the parent τ direction.

By making a cut, for example, of $p_{\perp missing} > 1$ GeV/c on the missing momentum perpendicular to the beam direction, one can eliminate most of the background arising from ordinary mismeasured $\overset{(-)}{\nu}_\mu$ charged current events while reducing the ν_τ signal by only about 50%. Since the missing transverse momentum is strongly correlated with the azimuthal opening angles, by making the $p_{\perp missing} > 1$ GeV/c cut, one finds the $\Delta\phi_{mH}$ angular distribution is even more dramatically peaked toward 180^o as shown in Fig. 3. The x_{vis} distribution determined by the visible energy and momentum transfer is sharply peaked toward zero, while the y_{vis} distributions for the ν_τ and $\bar{\nu}_\tau$ reactions are dramatically shifted toward high y as also shown in Fig. 3. These distributions serve as additional checks[12] that $\overset{(-)}{\nu}_\tau$ interactions are the primary source of the events surviving the $p_{\perp missing}$ cut.

Until the present time no counter experiments were able to perform the $p_{\perp missing}$ test since none could measure with reasonable accuracy the direction of the hadronic spray. New detectors which have the capability to the measure the direction of the hadron spray have been or are being built by the CERN - Hamburg - ITEP - INFN, Michigan - Wisconsin - Ohio State, and FNAL - MIT - MSU - NIU collaborations.[13-15] It is estimated that these detectors may be able to measure the hadronic spray direction sufficiently well to determine $p_{\perp missing}$ to an accuracy of $\simeq \pm 0.5$ GeV/c. Hence the tests we proposed above are feasible.

In order to estimate the relative number of $\overset{(-)}{\nu}_\tau$ events which can be expected in a typical beam dump experiment, we use the flux curves of Fig. 1 and fold in the branching ratios for the leptonic and nonleptonic tau decay modes to get the relative event rates (without cuts) listed in

Table I. With the inclusive $\nu_\mu \to \mu^-$ charged current reaction normalized to 10,000 events,[16] we find approximately 40 $\nu_\tau \to \tau^- \to \mu^-$ events of type (3a) and 15 corresponding antineutrino $\bar{\nu}_\tau \to \tau^+ \to \mu^+$ events. These numbers are conservative estimates based on a 3% branching ratio for $F \to \tau\nu_\tau$ and a 10 μb $F\bar{F}$ production cross section compared to a $D\bar{D}$ production cross section of 100 μb. The $F\bar{F}$ cross section may be closer to one-half of the $D\bar{D}$ cross section, and the $F \to \tau\nu_\tau$ branching ratio based on $f_F = f_K$ is probably also low. In any case, the proposed test should be feasible provided most of the ν_μ-induced background are vetoed by the $p_{\perp missing} > 1$ GeV/c cut.

Mismeasured $\nu_\mu \to \mu^-$ events which survive the $p_{\perp missing}$ cut will yield a flat to slightly forward peaked $\Delta\phi_{mH}$ distribution which is to be contrasted with the sharply peaked backward $\Delta\phi_{mH}$ signal from the ν_τ-induced events. Other sources of background include ordinary neutral current events with a π or K decay into a muon which can be eliminated by a suitable muon energy cut; neutral current induced charmed pair production followed by one semileptonic decay but the cross section times branching ratio is negligibly small; ν_μ-induced single charm production with decay of the charmed particle into the electron mode and the electron shower misidentified as part of the hadron shower; and $\overset{(-)}{\nu}_e$-induced single charm production with decay of the charmed particle into the muon mode, again with the electron shower misidentified as part of the hadron shower. Distributions for the latter two backgrounds are given in Fig. 4a,b and 4c,d, respectively. The ν_μ-induced single charm signals are quite distinct from the ν_τ signals, while the $\bar{\nu}_e$-induced single charm signals are more nearly identical to the ν_τ signals. In general, however, a fair fraction of events involving electron showers can be identified as such and the small fraction of these background events surviving the $p_{missing} > 1$ GeV/c cut renders both single charm production backgrounds harmless.

We have argued that the tests proposed will separate a ν_τ signal from ordinary ν_μ- and ν_e-induced background. If the desired signal is detected, one must still rule out other possible interpretations. Yet another sequential neutrino ν_λ, where λ^- is a new more massive lepton than the tau, can be eliminated since the production rate would be suppressed in the beam dump and the interaction rate suppressed in the detector, thus yielding a negligible signal. Massive electron-type heavy lepton production by the ν_e beam will also yield a negligible signal unless the mass of the heavy electron is close to the present experimental lower limit of 4 GeV. One can expect that this mass limit will be raised in the near future at both the PETRA and PEP storage rings.

Finally, one would like to conclude that ν_τ is not identically equal to ν_e. This requires that we distinguish reaction (3a) from

$$\nu_e + N \rightarrow \tau^- + X$$
$$\quad\quad\quad\quad \hookrightarrow \nu_e + \mu^- + \bar{\nu}_\mu \qquad (5)$$

The latter reaction would occur at the level of ≥ 0.12 (2/3) (0.19) x (event rate for $\nu_e \rightarrow e^-$) $\geq$ 110 events compared to 40 predicted events for (3a); where the factors 0.12, 2/3 and 0.19 correspond to the present lower limit on the $\nu \rightarrow \tau$ coupling, a threshold suppression factor, and the tau branching ratio into the muon mode. In other words, if the tau is ν_e-induced, one would expect that more tau events will be observed in the detector than are predicted for a distinct ν_τ beam. In order to rule out this possibility, one must accurately determine the $F\bar{F}$ production cross section and the $F \rightarrow \tau\nu_\tau$ branching ratio. A distinct, but relatively small τ signal in the counter detector would favor a sequential ν_τ interpretation for the origin of the selected events.

In summary, we have argued that a ν_τ flux can be produced in a suitable beam dump exposure, that a small fraction of the neutrino events detected will be of the type (3a) $\nu_\tau \rightarrow \tau^- \rightarrow \mu^-$ if the extended Kobayashi - Maskawa SU(2) x U(1) gauge model[5] is correct, that a cut on $p_{\perp missing} >$ 1 GeV/c can eliminate most of the background and that the azimuthal angle and y_{vis} distributions have characteristic signatures which can be exploited to isolate the ν_τ events. Accurate knowledge of the $F\bar{F}$ strong interaction production cross section and the $F \rightarrow \tau\nu_\tau$ branching ratio will enable one to decide the issue whether ν_τ is a sequential neutrino or whether $\nu_\tau \equiv \nu_e$.

References

1. M. L. Perl et al., Phys. Rev. Lett. 35, 1489 (1976); G. Feldman et al., ibid. 38, 117 (1977); M. L. Perl et al., Phys. Lett. 63B, 466 (1976); ibid. 70B, 487 (1977); J. Burmeister et al., ibid. 68B, 297 (1977); R. Brandelik et al., ibid. 73B, 109 (1978).
2. W. Bacino, et al., Phys. Rev. Lett. 42, 749 (1979).
3. C. Baltay, in Proceedings of the 19th International Conference on High Energy Physics, Tokyo, 1978.
4. S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in Elementary Particle Theory, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.
5. M. Kobayashi and K. Maskawa, Progr. Theor. Phys. 49, 652 (1973).
6. S. L. Glashow and S. Weinberg, Phys. Rev. D15, 1458 (1977); E. A. Paschos, ibid. D15, 1966 (1977).
7. Other accounts of this work can be found in C. H. Albright and R. E. Shrock, Phys. Lett. (to be published), and C. H. Albright, R. E. Shrock and J. Smith, Phys. Rev. D (to be published).
8. See, eg., F. Sciulli, in Proceedings of the 1978 Neutrino Conference, Purdue.
9. S. Mori, Fermilab Internal Reports TM - 774 and TM - 848.
10. **V. Barger and R. J. N. Phillips, Phys. Lett. 74B, 393 (1978).suggested** an analogous test but neglected the decay $F^{\pm} \to \tau^{\pm} + \overset{(-)}{\nu}_{\tau}$ and assumed (contrary to our findings) that the $\overset{(-)}{\nu}_{\tau}$ flux originated from decays of b- and t-flavored mesons.
11. **This test was suggested by F. Sciulli, see ref.** 7.
12. Such effects of heavy lepton production were discussed by C. H. Albright and C. Jarlskog, Nucl. Phys. B84, 467 (1975); C. H. Albright, C. Jarlskog, and L. Wolfenstein, ibid. B84, 493 (1975).

13. CERN - Hamburg - ITEP - INFN collaboration, CERN experiment WA - 18, K. Winter, spokesman.

14. Michigan - Wisconsin - Ohio State collaboration, FNAL experiment E613, B. Roe, spokesman.

15. FNAL - Massachusetts Institute of Technology - Michigan State - Northern Illinois collaboration, FNAL experiment E594, J. K. Walker and F. E. Taylor, spokesmen.

16. For a standard beam dump experiment with a typical massive counter detector, 2,000 to 20,000 inclusive $\nu_\mu \rightarrow \mu^-$ events is a reasonable estimate.

Table I. Relative event rates (with no cuts) applicable to a 400 GeV primary proton beam with a copper dump and a detector downstream subtending an angle of 0 to 2 mrad.

Reaction	No. of Events
$\nu_\mu \to \mu^-$	10,000
$\nu_e \to e^-$	7,200
$\nu_\tau \to \tau^- \to \mu^-$	40
$\nu_\tau \to \tau^- \to e^-$	40
$\nu_\tau \to \tau^- \to \nu_\tau$	120
$\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$, $\nu_\tau \to \nu_\tau$	5,100
$\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\bar{\nu}_e \to \bar{\nu}_e$, $\bar{\nu}_\tau \to \bar{\nu}_\tau$	2,300
$\bar{\nu}_\tau \to \tau^+ \to \bar{\nu}_\tau$	45
$\bar{\nu}_\mu \to \mu^+$	3,400
$\bar{\nu}_e \to e^+$	3,000
$\bar{\nu}_\tau \to \tau^+ \to \mu^+$	15
$\bar{\nu}_\tau \to \tau^+ \to e^+$	15

Figure Captions

Fig. 1. Neutrino and antineutrino fluxes for 400 GeV proton interactions in a copper beam dump for a detector 250 m downstream subtending an angular spread of 0 to 2 mrad.

Fig. 2. Distributions in (a) energies, (b) polar angles relative to the beam direction, (c) azimuthal opening angles in a plane perpendicular to the beam, and (d) missing momentum perpendicular to the beam direction and transverse to the apparent production plane shown as solid curves for the chain reaction $\nu_\tau + N \to \tau^- + X$, $\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu$ with cuts $E_\mu > 4$ GeV, $E_H > 5$ GeV. The dashed curves refer to the corresponding $\bar{\nu}_\tau$ reaction.

Fig. 3. Distributions for the $\nu_\tau \to \tau^- \to \mu^-$ (solid curves) and $\bar{\nu}_\tau \to \tau^+ \to \mu^+$ (dashed curves) reactions with cuts $E_\mu > 4$ GeV, $E_H > 5$ GeV and $p_{\perp missing} > 1$ GeV/c.

Fig. 4. Distributions for the background reaction $\nu_\mu + N \to \mu^- + X_c$, $X_c \to x + \nu_e + e^+$ in (a) missing momentum perpendicular to the beam direction with the cuts $E_\mu > 4$ GeV, $E_H > 5$ GeV and (b) the azimuthal opening angles with the additional cut $p_{\perp missing} > 1$ GeV/c. Similar distributions are given for the background reaction $\bar{\nu}_e + N \to e^+ + X_c$, $X_c \to x + \bar{\nu}_\mu + \mu^-$ in (c) and (d). In all cases, the electron is misinterpreted to be part of the hadron shower.

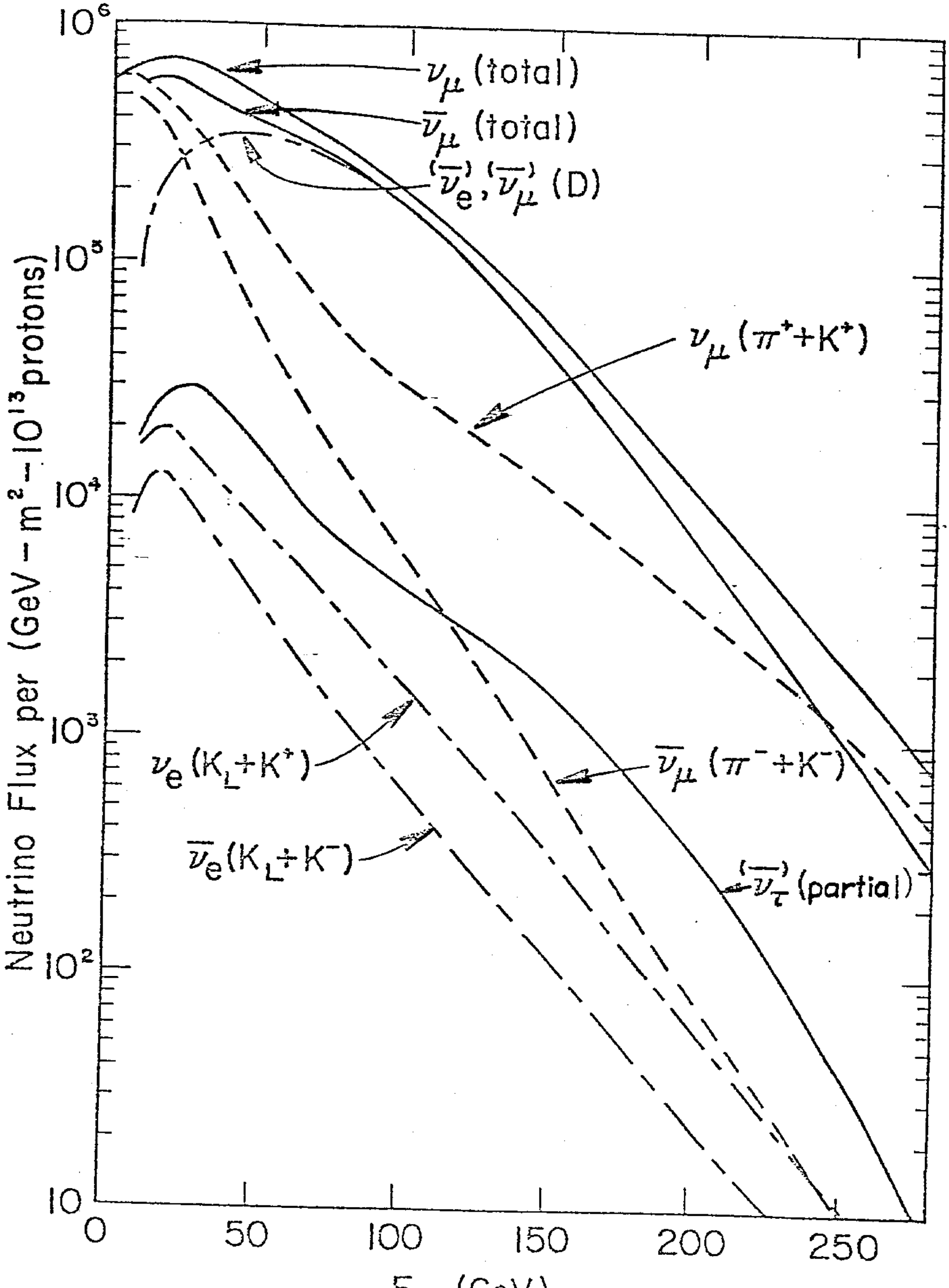
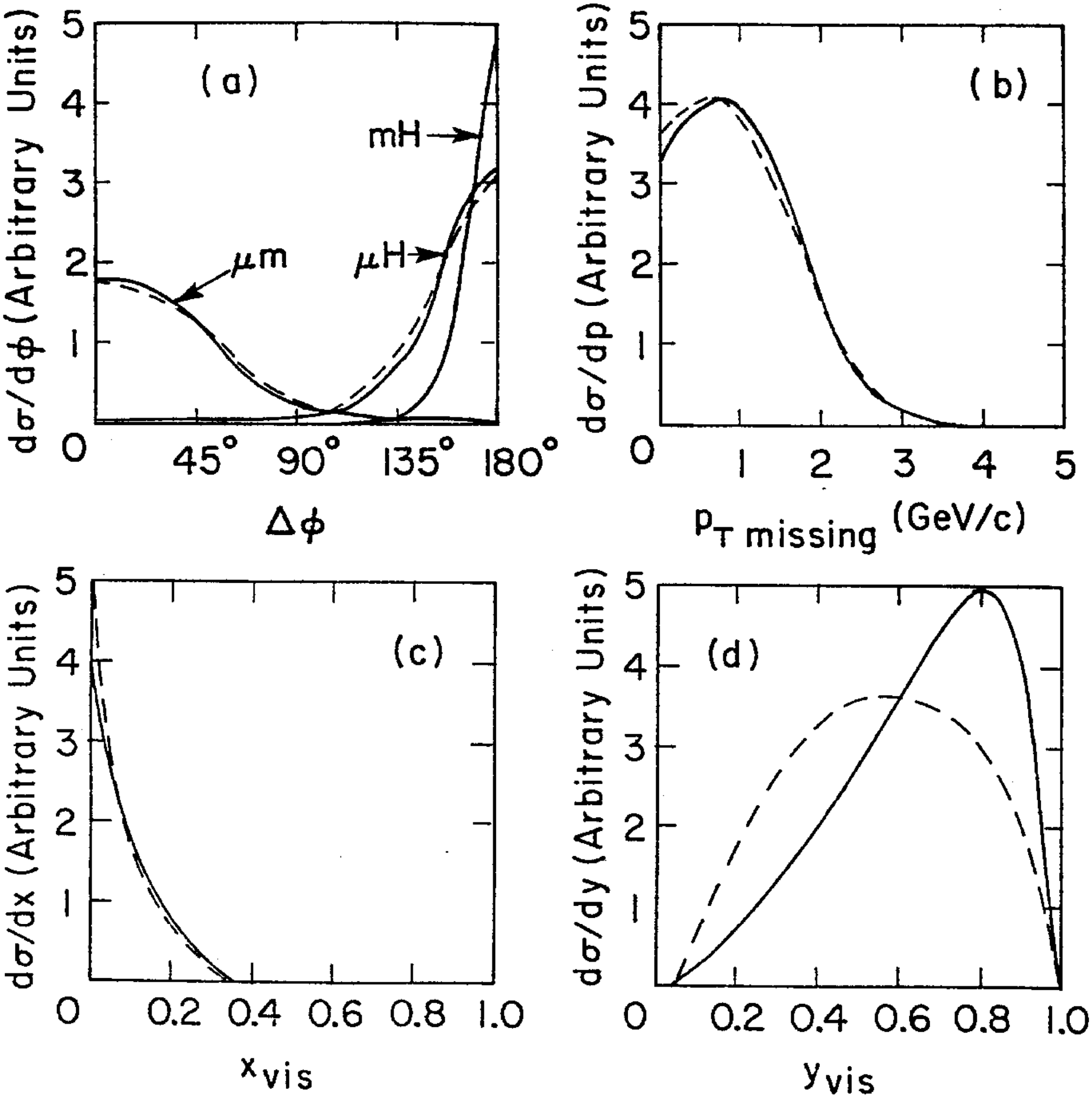
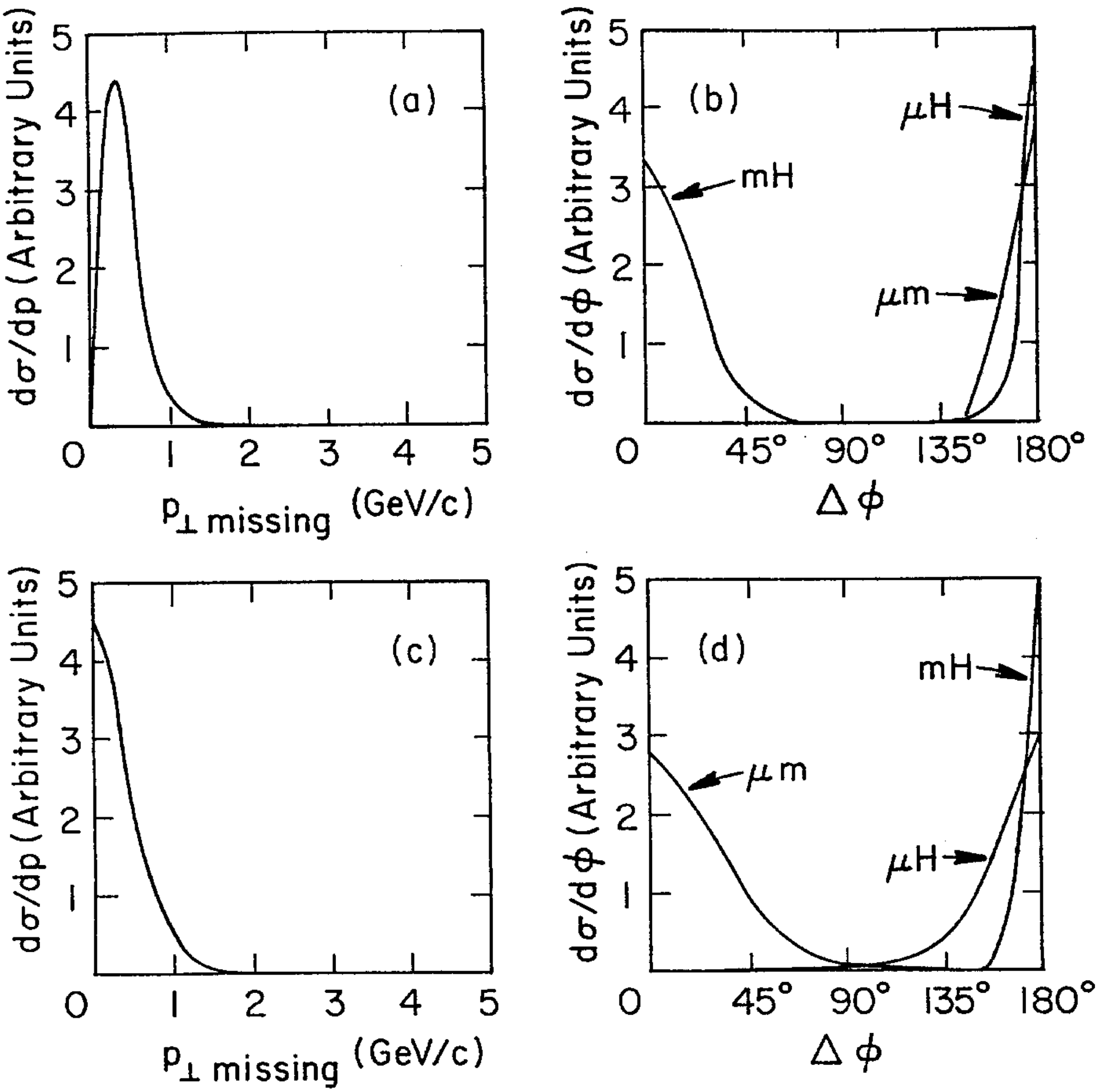

ν_μ (total)
$\bar{\nu}_\mu$ (total)
$\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu$ (D)
$\nu_\mu(\pi^+ + K^+)$
$\nu_e(K_L + K^+)$
$\bar{\nu}_\mu(\pi^- + K^-)$
$\bar{\nu}_e(K_L + K^-)$
$\overset{(-)}{\nu}_\tau$ (partial)
Neutrino Flux per (GeV − m^2 − 10^{13} protons)
E_ν (GeV)
10^6
10^5
10^4
10^3
10^2
10
0
50
100
150
200
250

Fig. 1



(a)
mH
μm
μH
dσ/dφ (Arbitrary Units)
Δφ
(b)
dσ/dp (Arbitrary Units)
p_T missing (GeV/c)
(c)
dσ/dx (Arbitrary Units)
x_{vis}
(d)
dσ/dy (Arbitrary Units)
y_{vis}

Fig. 3



(a)
dσ/dp (Arbitrary Units)
p⊥ missing (GeV/c)
(b)
dσ/dφ (Arbitrary Units)
μH
mH
μm
Δφ
(c)
dσ/dp (Arbitrary Units)
p⊥ missing (GeV/c)
(d)
dσ/dφ (Arbitrary Units)
mH
μm
μH
Δφ

Fig. 4