

APPENDIX

In this appendix we summarize some of the conventions and notation used in this paper:

Metric and γ matrices — as in S. D. Drell and J. D. Bjorken,

"Relativistic Quantum Mechanics" (McGraw Hill, 1964):

$$a \cdot b = a_\mu b^\mu = a_0 b_0 - \vec{a} \cdot \vec{b}$$

$$\gamma_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \vec{\gamma} = \begin{pmatrix} 0 & \vec{\sigma} \\ -\vec{\sigma} & 0 \end{pmatrix}$$

$$\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_{\mu\nu} = \frac{i}{2} [\gamma_\mu, \gamma_\nu], \quad \not{a} = \gamma \cdot a$$

$\epsilon_{\mu\nu\alpha\beta}$ is the completely antisymmetric unit tensor with

$$\epsilon_{0123} = -\epsilon^{0123} = 1.$$

States are taken to have the covariant normalization:

$$\langle P' | P \rangle = 2E (2\pi)^3 \delta^3(\vec{P} - \vec{P}')$$

and spinors are normalized by: $\bar{u}(p, s) u(p, s) = 2m$.

Symbols

G Fermi's constant

θ_c Cabibbo angle

J^+, j^+ currents which increase the charge of the states on which they act

J^-, j^- currents which decrease the charge of the states on which they act

j lepton current

J^0 $\Delta Y = 0$ hadron current

J^1 $|\Delta Y = 1|$ hadron current

m lepton mass

M target mass

P target four momentum

q four momentum transfer to the target

$Q^2 = -q^2 > 0$ in the physical region

$\nu = q \cdot P$

$\omega = \frac{1}{x} = \frac{2\nu}{Q^2}$

$\theta = \theta_{\nu\ell}$ = laboratory angle between direction of final lepton and the incoming neutrino

f_π = pion decay constant

(= 0.96 m_{π^+} (experiment) = 0.86 m_{π^+} (Goldberger-Treiman))

g_W semiweak coupling constant = $(M_W^2 G/\sqrt{2})$

Form Factors

Quasi-elastic form factors — our form factors (Eq. 3.13)

are related to others commonly used by:

Adler (A2)/Pais (P4)	Marshak <u>et al.</u> (M4)	This paper
g_V	$g_V + 2mf_V$	$F_V^1 + \xi F_V^2$
f_V	f_V	$\xi F_V^2/2M$
h_V	h_V	F_V^3/M
g_A	g_A	$-F_A$
f_A	h_A	F_A^3/M
h_A	$-f_A$	$-F_P/M$

N* production — our form factors (Eq. 3.58) are related to others

commonly used by:

Albright and Liu (A12, A13) ($\Delta \rightarrow M$ in Ref. A11)	Berman and Veltman (B16)	Kim (K8)	This paper (the form factors used by Bijtebier (B20) and Salin (S1) are the same except $1/M^n \rightarrow 1/M_\pi^n$ and the signs in brackets should be used)
F_1^V	a_1	F_V	$\frac{\Delta C_3^V}{M} + \frac{K \cdot q C_4^V}{M^2} + \frac{P \cdot q C_5^V}{M^2} + C_6^V$
$\frac{F_2^V}{\Delta}$	$\frac{a_2}{\Delta} + \frac{(M' - M)a_3}{\Delta}$	$\frac{-G_V}{M} + \frac{(M' - M)H_V}{M^2}$	$\frac{-C_3^V}{M}$
$\frac{F_3^V}{\Delta^2}$	$\frac{-a_3}{\Delta^2}$	$\frac{-H_V}{M^2}$	$\frac{-C_3^V}{2M^2} - \frac{C_4^V}{2M^2}$
$\frac{F_4^V}{\Delta^2}$	$\frac{a_4}{\Delta^2}$	$\frac{F_V}{- q ^2} + \frac{\Delta G_V}{M q ^2}$	$\frac{-C_5^V}{2M^2} + \frac{C_4^V}{2M^2}$
F_A	b_1	F_A	$\frac{-(M' - M)C_3^A}{M} + \frac{K \cdot q C_4^A}{M} + C_5^A$ (+) (-)
$\frac{F_2^A}{\Delta}$	$\frac{b_2}{\Delta}$	$\frac{-G_A}{M}$	$\frac{C_3^A}{M}$ (-)
$\frac{F_3^A}{\Delta^2}$	$\frac{b_3}{\Delta^2}$	$\frac{-H_A}{M^2}$	$\frac{C_4^A}{2M^2}$ (-)
$\frac{F_4^A}{\Delta^2}$	$\frac{b_4}{\Delta^2}$	$\frac{F_p}{M^2}$	$\frac{C_4^A}{2M^2} - \frac{C_6^A}{M^2}$ (+)

$$(\Delta = M_p + M_{N^*})$$

Polarizations — our lepton and baryon polarizations are defined on p 36 and p 67 respectively. We describe a particle's polarization as

<u>longitudinal</u>	if it is parallel to its momentum (\vec{K})
<u>transverse</u>	if it is perpendicular to the plane defined by \vec{K} and the momentum of the incoming neutrino (\vec{k})
<u>perpendicular</u>	if it is in the plane defined by \vec{K} and \vec{k} and perpendicular to \vec{K}

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Table 1

Tests of some hypotheses about weak interactions.

Hypothesis	Best evidence from decay processes	Possible tests in neutrino reactions
$\mathcal{L}_{\text{eff}} \sim J_{\lambda}^{\dagger} J^{\lambda}$	Fits all observed decays	E_{ν} and ϕ dependence of cross sections (2.10)
2 component neutrino theory	Fits all observed decays	Probability of producing right-handed lepton (antilepton) $\sim m^2$ (2.12)
Conservation of lepton numbers L_e and L_{μ}	Fits all observed decays $\left(\frac{\Gamma(\mu^{\pm} \rightarrow e^{\pm})}{\Gamma(\mu^{\pm} \rightarrow \text{all})} < 2 \times 10^{-8} \right)$	$\frac{\sigma(\nu_{\mu} \rightarrow e^{-})}{\sigma(\nu_{\mu} \rightarrow \mu^{-})} < 1\%$ $\frac{\sigma(\nu_{\mu} \rightarrow \mu^{+})}{\sigma(\nu_{\mu} \rightarrow \mu^{-})} < 4.6 \times 10^{-3}$
(The weaker hypothesis that $L_{\mu} + L_e$ and the sign of $(-1)^{L_e}$ are conserved \rightarrow detectable $\bar{\nu}_e$ admixture from μ decay in ν beams (see p. 7)		
Absence of neutral currents	Fits all observed decays $\left(\frac{\Gamma(K_L^0 \rightarrow \mu^+ \mu^-)}{\Gamma(K_L^0 \rightarrow \text{all})} < 1.9 \times 10^{-9} \right)$	$\frac{\sigma(\nu_{\mu} p \rightarrow \nu_{\mu} p)}{\sigma(\nu_{\mu} n \rightarrow \mu^+ p)} < 0.12 \pm 0.06$
Universality of e and μ interactions	Fits all observed decays $\left(\frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_{\mu})} = (1.00 \pm 0.03) \times \text{theory} \right)$	Comparison of $\nu_{\mu} (\bar{\nu}_{\mu})$ with $\nu_e (\bar{\nu}_e)$ initiated reactions

Table 1 (cont'd.) - 2

<p>$\Delta Y \leq 1$</p>	<p>Fits all observed decays</p> $\left(\frac{ A(\Xi^- \rightarrow ne^- \nu) }{ A(\Xi^- \rightarrow \Lambda e^- \nu) } < 0.28 \right)$	<p>$\bar{\nu}_\mu n \rightarrow \mu^+ \Xi^-$ $\nu_\mu p \rightarrow \mu^- \bar{p} K^+ K^0$ $\bar{\nu}_\mu p \rightarrow \mu^+ \Lambda(K^0 + \bar{y} \bar{K}^0)$ ($y=0$ if $\Delta Y \leq 1$), etc. (see Table 2)</p>
<p>$\Delta Y = \Delta Q$ if $\Delta Y = \pm 1$</p>	<p>Fits all observed decays</p> $\left(\frac{\Gamma(K^+ \rightarrow \pi^+ \pi^+ e^- \bar{\nu}_e)}{\Gamma(K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e)} < 0.023 \right)$ $\frac{A(\Delta Y = -\Delta Q)}{A(\Delta Y = \Delta Q)} \lesssim 10\% \text{ in } K_{l3}^0 \text{ decay}$	<p>$\nu_\mu n \rightarrow \mu^- \Sigma^+$ $\nu_\mu p \rightarrow \mu^- \Sigma^+ \pi^+$ $\nu_\mu n \rightarrow \mu^- \bar{p} (K^0 + y \bar{K}^0)$ ($y=0$ if $\Delta Y = \Delta Q$), etc. (see Table 2)</p>
<p>$\Delta I = 1 \ 2$ if $\Delta Y = \pm 1$</p>	<p>Tests in K_{l3}^0 decay work to $\pm 10\%$</p>	<p>$\frac{\sigma(\bar{\nu}_\mu n \rightarrow \Sigma^- \mu^+)}{\sigma(\bar{\nu}_\mu p \rightarrow \Sigma^0 \mu^+)} = 2$ and many other relations (Eqs. 2.14-2.17)</p>
<p>$\Delta I = 1$ if $\Delta Y = 0$</p>	<p>Untested</p>	<p>$\frac{\sigma(\nu_\mu p \rightarrow N^{*++} \mu^-)}{\sigma(\nu_\mu n \rightarrow N^{*+} \mu^-)} = 3$ and other relations (p. 39)</p>
<p>Charge symmetry condition for $\Delta Y = 0$ current</p>	<p>Lack of mirror symmetry in nuclear β decay is evidence against this (unless due to isospin violation)</p>	<p>Structure functions for mirror processes related by $W_i^{\nu p} = W_i^{\bar{\nu} n}$, $W_i^{\bar{p} p} = W_i^{\nu n}$ ($\Delta Y = 0$) \rightarrow obvious relations (e.g.) between $\sigma^{\nu d}$ and $\sigma^{\bar{\nu} d}$.</p>
<p>Absence of second class currents (\equiv charge symmetry condition if T conserved)</p>	<p>Lack of mirror symmetry of ft values requires 2nd class currents if CPT holds (unless due to isospin violation)</p>	<p>Fixes relative phases of quasielastic form factors</p>

Table 1 (cont'd.) - 3

CVC	$\frac{V}{g_\mu} \simeq g_\beta$	Limits number of independent vector form factors. No parity violation when $\theta_{\nu\ell} = 0$
Isotriplet current	Weak magnetism predicted to $\pm 20\%$ $\Gamma(\pi^+ \rightarrow \pi^0 e^+ \nu_e) = (0.95 \pm 0.07) \times \text{theory}$	Vector form factors given by electroproduction
PCAC	Goldberger-Treiman relation works to $\sim 10\%$	$\sigma_\nu(\theta_{\nu\ell} = 0) \propto \sigma_\pi \propto A^2 3''$
Current algebra	Adler-Weissberger relation works to $\sim 5\%$	Adler sum rules (2.24 and 2.25) see Tables 7 and 8
T violation	$\frac{\Gamma(K_L^0 \rightarrow \pi^+ \pi^-)}{\Gamma(K_L^0 \rightarrow \text{all})} \sim 2 \times 10^{-3}$ $\frac{\Gamma(K_L^0 \rightarrow \pi^+ \ell^- \nu)}{\Gamma(K_L^0 \rightarrow \pi^+ \ell^- \bar{\nu})} \neq 1$	Transverse polarization of lepton or baryon in quasi-elastic process. Transverse polarization of lepton when hadrons unobserved.

Table 2

Reactions allowed by charge conservation but forbidden by the $\Delta Y = 0, \pm 1$ rule and the $\Delta Y = \Delta Q$ rule for $\Delta Y = 1$ transitions.

Each box represents a reaction. The boxes representing reactions with the same initial state are grouped into rectangles, the initial state being inscribed in the upper right hand corner. The final state consists of the appropriate lepton and a baryon and a meson chosen from the corresponding position in the left hand column and the top row respectively. (The column headed vac. represents reactions with a single baryon in the final state).

X — indicates that the reaction has $\Delta Y > 2$

0 — indicates that the reaction has $\Delta Y = 1$ and $\Delta Y \neq \Delta Q$

The same results obtain, of course, if the pseudoscalar mesons are everywhere replaced by the corresponding vector mesons.

Table 2

	π^-	K^-	K^0	$\pi^0\eta^0$	Vac	\bar{K}^0	K^+	π^+
Ω^-			x	x	x	$\bar{\nu}n$ x	x	$\bar{\nu}p$ x
Ξ^- Ξ^{*-}				x	x	x		x
Υ^{*-} Σ^-							x	
N^{*-}				o				o
Ξ^0 Ξ^{*-}	x	$\bar{\nu}n$ x		x	x	$\bar{\nu}p$ x	o	$\bar{\nu}n$ x
Σ^0, Λ^0 Υ^{*0}		x				x		o
N^{*0} n			o					
Υ^{*+} Σ^+		$\bar{\nu}p$ x		o	o	$\bar{\nu}n$ x		$\bar{\nu}p$ o
N^{*+} p						o		
N^{*++}		$\bar{\nu}n$ o				$\bar{\nu}p$ o		

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Table 3

Characteristics of Dimuon Events. (H3) $p_{1\pm}$ is the component of the μ^\pm momentum p^\pm perpendicular to the direction of the incident ν_μ . $p_{1\pm} = p_\pm \sin \theta_{\mu^\pm}$ (the $p_{1\pm}$ given for the trilepton process disagrees with that obtained by other authors -- see the text).

Process	p_{1+}	p_{1-}	θ_{μ^+}	θ_{μ^-}	p_{μ^+}	p_{μ^-}	Remarks
Trilepton (coherent)	0-50 MeV	0-50 MeV	Small	Small	Small	$\sim E_\nu$	$p_{1\pm}$, θ_{μ^\pm} are multiple scattering limited
W production (incoherent)	$\approx M_W/2$	0-100 MeV/c	Large	Small	$> \frac{1}{2} M_W$	Moderate	
Background from single π production	300	~ 500		Medium	Small	$> \frac{1}{2} E_\nu$	
Background from multiple π production	~ 300	~ 500	Small	Small to Large	Small	$> \frac{1}{2} E_\nu$	

Table 4

Errors expected from a ν experiment at ANL with 10^{18} incident protons^{D3}.
Dipole formulae were assumed for F_A , F_V^1 and F_V^2 parametrized by M_A ,
 M_V and WM respectively. ξ is the strength of the weak magnetism term F_V^2 ,
as in the text.

Table 4

Unknowns	NEUTRINO			ANTINEUTRINO		
	Flux Unknown	Flux 10%	Flux Exact	Flux Unknown	Flux 10%	Flux Exact
M_A	78	51	35	85	83	82
M_A	293	221	198	97	84	82
M_V	881	553	477	182	117	105
M_A	748	494	416	158	108	100
ξ	5.2	3.3	2.7	1.0	0.6	0.6
M_A	389	302	246	219	184	179
M_V	892	580	487	293	258	248
WM	140	115	100	200	177	172
M_A	922	726	694	237	188	182
M_V	999	583	489	387	300	281
ξ	6.3	4.0	3.5	2.9	2.2	2.1
WM	149	135	130	264	247	245

Table 5

Isobar coupling constants for $\nu n \rightarrow \mu^- N^{*+}$ in various models - adopted from B20. The static model results are essentially the same as Berman and Veltmans'. The multipole content of these form factors may be obtained using the formulae in Adler's ^{A6} Appendix 5.

	Berman and Veltman	Salin	Bijtebier	Adler**
C_3^V	2.0*	2.0	2.0	1.85
C_4^V	0	0	0	-0.89
C_5^V	0	0	0	0
C_A^3	0	0	0	0
C_A^4	0	2.7	2.9 to 3.6	-0.35
C_A^5	-1.2	0***	-1.2	-1.2

* Corrected (see p. 90).

** Approximate equivalent values deduced by Bijtebier.

*** This model violates PCAC which gives $C_A^5 \simeq -1.2$.

Table 6

t channel quantum numbers for weak and electromagnetic structure functions. ^{P1}

Structure Functions	$(-1)^J P$	$(-1)^J C$	I^G	Regge Trajectory
$W_{1,2}^{\gamma p} + W_{1,2}^{\gamma n}$	+	+	0^+	P, f_0, f'
$W_{1,2}^{\gamma p} - W_{1,2}^{\gamma n}$	+	+	1^-	A_2^0
$W_{1,2}^{\nu p} + W_{1,2}^{\bar{\nu} p}$	+	+	0^+	P, f_0, f'
$W_{1,2}^{\nu p} - W_{1,2}^{\bar{\nu} p}$	+	+	1^+	ρ
$W_3^{\nu p} + W_3^{\bar{\nu} p}$	+	+	0^-	ϕ, ω
$W_3^{\nu p} - W_3^{\nu n}$	-	-	1^-	A_1

Table 7

Quark model sum rules for $\Delta Y=0$ reactions in the scaling region (assuming scale invariance).

Sum rules from commutators of currents	Comments
$\int \frac{d\omega}{\omega} (F_2^{\nu n} - F_2^{\nu p}) = 2$	The Adler sum rule. ^{A5} True in all reputable models.
$\int \frac{d\omega}{\omega^2} (F_1^{\nu n} - F_1^{\nu p}) = 1$	Bjorken's "backward" sum rule. ^{B22} True in all models in which the elementary fields have spin 1/2.
$-\int \frac{d\omega}{\omega^2} (F_3^{\nu p} + F_3^{\nu n}) = 6$	Peculiar to the quark model. ^{G18} (R.H.S.=2 in Sakata and Fermi-Yang models.)
Sum rules from commutators of currents and their time derivations in models with renormalizable interactions	
$2 F_1^{\gamma, \nu, \bar{\nu}} = \omega F_2^{\gamma, \nu, \bar{\nu}}$	Callan-Cross relation. ^{C6, G18} Depends on the elementary fields having spin 1/2.
$F_5^{\nu, \bar{\nu}} = 2 F_1^{\nu, \bar{\nu}}$ $F_4^{\nu, \bar{\nu}} = 0$	$\left. \begin{array}{l} \text{-- follows from } 2 F_1 = \omega F_2 \text{ and kinematical inequalities.} \\ \text{asymptotic chiral symmetry.} \end{array} \right\} \text{L20}$
$12(F_1^{\gamma p} - F_1^{\gamma n}) = F_3^{\nu p} - F_3^{\nu n}$	
$F_1^{\nu p} + F_1^{\nu n} \leq \frac{18}{5} (F_1^{\gamma p} + F_1^{\gamma n})$	Peculiar to the quark model. ^{L18, L20} (\rightarrow equality with $\frac{18}{5} \rightarrow 2$ in Sakata or Fermi-Yang model.)

Table 8

Quark model sum rules for $\Delta Y=1$ reactions in the scaling region (assuming scale invariance).

Sum rules from commutators of currents

$$\int \frac{d\omega}{\omega} (f_2^{\bar{\nu}} - f_2^{\nu}) = \langle 3Y + 2I_3 \rangle \quad (\text{A5})$$

$$2 \int \frac{d\omega}{\omega^2} (f_1^{\bar{\nu}} - f_1^{\nu}) = \langle 3Y + 2I_3 \rangle \quad (\text{B22})$$

$$- \int \frac{d\omega}{\omega^2} (f_3^{\bar{\nu}} + f_3^{\nu}) = \langle 4B - Y + 2I_3 \rangle \quad (\text{G18})$$

Sum rules from commutators of currents and their time derivatives in models with renormalizable interactions

$$2f_1^{\nu, \bar{\nu}} = \omega f_2^{\nu, \bar{\nu}} = f_5^{\nu, \bar{\nu}} \quad (\text{G18, L20})$$

$$f_4^{\nu, \bar{\nu}} = 0 \quad (\text{L20})$$

with

$$U_p = \frac{F_1^{\nu n}}{2} - \frac{F_3^{\nu n}}{4}, \quad U_n = \frac{F_1^{\nu p}}{2} - \frac{F_3^{\nu p}}{4}$$

$$U_{\bar{n}} = \frac{F_1^{\nu n}}{2} + \frac{F_3^{\nu n}}{4}, \quad U_{\bar{p}} = \frac{F_1^{\nu p}}{2} + \frac{F_3^{\nu p}}{4}$$

$$U_{\lambda} + U_{\bar{\lambda}} = 9(F_1^{\gamma p} + F_1^{\gamma n}) - \frac{5}{2}(F_1^{\nu n} + F_1^{\nu p})$$

$$U_{\lambda} - U_{\bar{\lambda}} = f_1^{\nu p} - f_1^{\bar{\nu} p} + \frac{F_1^{\nu n} - F_1^{\nu p}}{2} - \frac{F_3^{\nu n} + F_3^{\nu p}}{4}$$

the f_i are given by (L19, L20)

$$f_1^{\nu p} = U_{\lambda} + U_{\bar{p}}, \quad f_3^{\nu p} = 2(U_{\bar{p}} - U_{\lambda}), \quad f_1^{\bar{\nu} p} = U_p + U_{\bar{\lambda}}, \quad f_3^{\bar{\nu} p} = 2(U_{\bar{\lambda}} - U_p)$$

$$f_1^{\nu n} = U_{\lambda} + U_{\bar{n}}, \quad f_3^{\nu n} = 2(U_{\bar{n}} - U_{\lambda}), \quad f_1^{\bar{\nu} n} = U_n + U_{\bar{\lambda}}, \quad f_3^{\bar{\nu} n} = 2(U_{\bar{\lambda}} - U_n)$$

i. e., the f_i are determined by the F_i and (e.g.) $f_i^{\nu p} - f_i^{\bar{\nu} p}$ (in the parton model the U_i are the distribution functions for the quarks).

Table 10

Yield of events in 10^6 picturesAssume: 10^6 pictures at 2×10^{13} protons/pulse

500 BeV protons

Horn focusing

$$\frac{\bar{\nu} \text{ flux}}{\nu \text{ flux}} = \frac{1}{3}$$

<u>Reaction</u>	<u>$15 \text{ m}^3 \text{ H}_2$</u>	<u>$15 \text{ m}^3 \text{ D}_2$</u>	<u>$10 \text{ m}^3 \text{ Ne}$</u>
Total	0.5×10^6	1.0×10^6	6×10^6
$\nu n \rightarrow \mu^- p$	-	1.4×10^4	1×10^5
$\nu p \rightarrow \mu^- p \pi^+$	1.8×10^4	1.8×10^4	1.2×10^5
$\nu n \rightarrow \mu^- n \pi^+$	-	4.8×10^3	3.2×10^5
$\bar{\nu} p \rightarrow \mu^+ \Lambda^0$	200	200	1300
$\bar{\nu} p \rightarrow \mu^+ \Sigma^0$	70	70	400
$\bar{\nu} n \rightarrow \mu^+ \Sigma^-$	-	130	800

Table 11

W and four-fermion search in neon

Assume: 10^6 pictures at 2×10^{13} protons/pulse

500 BeV protons

Horn focusing

<u>Reaction</u>	<u>Events in $10 \text{ m}^3 \text{ Ne}$</u>
$\nu_{\mu} \text{ Ne} \rightarrow \text{Ne} \mu^{-} e^{+} \nu_e$	100
$\nu_{\mu} \text{ Ne} \rightarrow \text{Ne} \mu^{-} \mu^{+} \nu_{\mu}$	50
$\nu \text{ Ne} \rightarrow \mu^{-} W^{+}$	
Mw = 5	2.5×10^5
8	2.5×10^4
10	5.5×10^3
12	1.2×10^3
14	250
16	50

Table 12

Cross sections used in compiling Tables 10 and 11.

<u>Reaction</u>	<u>σ in cm^2</u>	
Total	$0.8 E_\nu \times 10^{-38}$	
$\nu n \rightarrow \mu^- \bar{p}$	0.7×10^{-38}	
$\nu n \rightarrow \mu^- \bar{p} \pi^0$	0.24×10^{-38}	} Adler $\times 2$ because of CERN experiments
$\nu n \rightarrow \mu^- n \pi^+$	0.32×10^{-38}	
$\nu p \rightarrow \mu^- p \pi^+$	0.88×10^{-38}	
$\bar{\nu} p \rightarrow \mu^+ \Lambda^0$	3×10^{-40}	} Cabbibo and Chilton corrected by Cabbibo (depends on M_A)
$\bar{\nu} p \rightarrow \mu^+ \Sigma^0$	1×10^{-40}	
$\bar{\nu} n \rightarrow \mu^+ \Sigma^-$	2×10^{-40}	
$\nu \text{Ne} \rightarrow \text{Ne} \mu^- e^+ \nu$	$10^{-42} - 10^{-40}$	} Coherent on Neon
$\nu \text{Ne} \rightarrow \text{Ne} \mu^- \mu^+ \nu$	$10^{-42} - 10^{-40}$	
$\nu p \rightarrow \mu^- p W^+$	$10^{-42} - 10^{-36}$	depending on M_W and E_ν

Figure Captions

1. Approximate neutrino event rates as a function of time (taken from P15 and updated slightly). In the interests of clarity the expected results of improvements planned for Brookhaven (\rightarrow 100/hour) and Argonne (\rightarrow 20/hour) in 1973 have not been included. Although it will use an iron target (so that the scale of this figure does not really apply) we have included the event rate expected in the first experiments planned for NAL for comparison (in this experiment it is planned to introduce the liquid H_2 store as a target at some stage; this should yield $\sim \frac{1}{2}$ events/hour).
2. Production of neutrino beams at proton accelerators (schematic!).
3. Neutrino fluxes obtainable at various accelerators in 1973. ^{C10} (Perfect focusing assumed. Hagedorn-Ranft^{H1} predictions used for π/K yields for $E_p > 70$ GeV; Sanford-Wang^{S2} used for $E_p < 70$ GeV. Experimental data used for SLAC. The number of interacting protons corresponds to 10^5 incident protons on the target assumed. The flux was averaged over a detector with radius 1.8 m.)
4. Predicted neutrino spectra for a variety of incident energies at NAL. ^{C10} (Assuming 450 m decay length, 1000 m. shielding, 1.35 m radius detector, Hagedorn-Ranft production model^{H1} and perfect focusing.)
5. $\nu/\bar{\nu}$ spectra for a possible NAL beam operating at 200 GeV primary proton energy. ^{K3} (Assuming 600 m. decay length, 300 m. shielding and 2.5 m. target — m. f. p. = 0.9 m.)
6. ν_e flux from K_{l3}^+ and μ^+ decay expected in the NAL ν_μ beam shown in figure 5. ^{K3}

7. Spectra in the NAL "monoenergetic" beam — schematic (θ is the angle the neutrino makes with the primary π/K beam).
8. The coherent cross section to order $G^2 \alpha^2$ with a target nucleus $A = 56$ C28 for

$$\begin{aligned} \text{a) } & \nu_{\mu} Z \rightarrow \mu^{-} e^{+} \nu_e Z \\ \text{b) } & \nu_{\mu} Z \rightarrow \mu^{-} \mu^{+} \nu_{\mu} Z \\ \text{c) } & \nu_e Z \rightarrow e^{-} e^{+} \nu_{\mu} Z \end{aligned}$$

full lines — exact (numerical) calculation

dashed lines — asymptotic formulae (see text)

$$\sigma_0 = G^2 \alpha^2 Z^2 m_{\mu}^2 = 3.03 \times 10^{-44} Z^2 \text{cm}^2.$$

(the dipole form factor given in the text was used).

9. Numerical results to order $G^2 \alpha^2$ for the coherent process $\nu_{\mu} Z \rightarrow \mu^{-} e^{+} \nu_e Z$ for various nuclei. C28

full lines — nuclear form factor in text

dashed lines — $F(q^2) = \exp(q^2 R_0^2/10)$

σ_0 as in figure 8. (Similar curves are given in C28 for $\nu_{\mu} Z \rightarrow \mu^{-} \mu^{+} \nu_{\mu} Z$ — see also figure 8.)

10. Cross sections for the quasielastic process in the conventional theory with $m = 0$ and dipole forms

$$\frac{F(0)}{\left(1 - \frac{q^2}{0.73 \text{ GeV}^2}\right)^2}$$

for the form factors F_A and $F_V^{1,2}$ L12 (the dotted line is the limit for σ_{ν} and $\sigma_{\bar{\nu}}$ as $E \rightarrow \infty$).

11. Differential cross section for the quasielastic process; as in figure 10 with $0.73 \text{ GeV}^2 \rightarrow 0.71 \text{ GeV}^2$. D3

12. Contributions of the structure functions "A", "B" and "C" to the differential cross section for the quasielastic process (P9 quoted in D3) where

$$\sigma = \left[\text{"A"} + \text{"B"}(s-u) + \text{"C"}(s-u)^2 \right] / E^2.$$

13. Simulated experiment at the AGS (Brookhaven)(P9 quoted in D3). The model input is the same as in figures 11 and 12.
14. Average transverse polarizations in quasielastic neutrino scattering as a function of the neutrino energy. ^{D4}
- a) Bound of $O(\alpha)$ contribution of the elastic intermediate state.
- b) Bound of $O(\alpha)$ contribution of the inelastic intermediate states.
- c) Predictions of Cabibbo's theory of T violation (see text for a discussion of the form factors used).
- labels: p polarization of proton in $\nu n \rightarrow \mu^- p$
n polarization of neutron in $\bar{\nu} p \rightarrow \mu^+ n$
 μ polarization of muon in $\bar{\nu} p \rightarrow \mu^+ n$.
15. Exclusion factors defined in text for C^{12} . ^{B11}
16. Exclusion factors defined in text for Fe^{56} . ^{B11}
17. Ratio of deuteron to neutron cross sections in the quasielastic process for $E_\nu \gg 1$ obtained using a Hulthen wave function in the closure approximation. ^{B33}
18. Results of the Argonne experiment for quasielastic events on an iron target. ^{K15}
The upper and lower solid curves are the experimenters theoretical results for a free neutron and for the Fermi gas model. The three dashed curves were obtained ^{B11} from the free neutron curve using 1) symmetric Fermi gas; 2) asymmetric Fermi gas; 3) shell model ($\bar{\sigma}$ = cross section per neutron).
19. Same experiment and solid curves as figure 18. 3) is as in figure 18. 4) is curve 3) increased by 30% (the experimenters regard their absolute flux as uncertain to this degree).
20. Results of the CERN spark chamber experiment ^{H5} for events with $E_\nu > 1.4$ GeV and $\cos\theta_{\nu\mu} > 0.8$:

- inelastic + elastic ($M_A = 0.84$ GeV)
 - - - - inelastic + elastic ($M_A = 0.5$ GeV)
 - - - - - inelastic contamination.
21. Results of the CERN bubble chamber experiment for the elastic cross section^{B45} as a function of the visible energy (E_{vis}).
22. Q^2 distribution of quasielastic events in the CERN bubble chamber experiment^{B45}
- experimental values.
 - π^0 contribution
- theoretical curve for $M_A = 0.7$ GeV.
23. Total cross section for $\bar{\nu}p \rightarrow \Lambda\mu^+$ as a function of the antineutrino energy in the Cabibbo theory. The same q^2 dependence was taken for all form factors.^{W9}
24. Total cross section for $\bar{\nu}n \rightarrow \Sigma^-\mu^+$ (otherwise as for figure 23).^{W9}
25. Polarizations in $|\Delta Y| = 1$ antineutrino reactions at $E_\nu = 0.5$ GeV (in a double-pole approximation with six form factors) and a comparison $\Delta Y = 0$ curve^{M4}
1. $\bar{\nu}p \rightarrow \mu^+n$
 2. $\bar{\nu}p \rightarrow \mu^+\Lambda$
 3. $\bar{\nu}p \rightarrow \mu^+\Sigma^0$
 4. $\bar{\nu}n \rightarrow \mu^+\Sigma^-$
- (This figure and figure 26 are reproduced by permission of John Wiley and Sons, Inc.)
26. Polarizations as in figure 25 except $E_\nu = 5$ GeV.^{M4}
27. Berman-Veltman angles (defined in the N^* rest frame).
28. Total pion production cross section in Adler's model with $W < 1.39$ BeV, by a neutrino incident on a target consisting of $\frac{1}{2}p + \frac{1}{2}n$. Curve (a) — Born approximation plus resonant multipoles; curve (b) — full model, including

dispersion integral corrections to the small partial waves; curve (c) — full model, multiplied by the electroproduction experiment/theory ratio $R(k^2)$.

The values of M_A^2 are in $(\text{BeV})^2$.^{A6}

29. Total pion production cross section in Adler's model with $W \leq 1.39$ GeV by antineutrinos incident on CF_3Br . The values of M_A^2 are in GeV^2 . Theoretical curves calculated from the Born approximation plus resonant multipole model.^{A6} Experimental points from Y4. The same experiment gave a neutrino cross section compatible with Adler's model with M_A^2 in the range 0.71 to 2 GeV^2 ($\sigma \sim (0.6 \pm 0.2) \times 10^{-38} \text{ cm}^2/\text{nucleon}$ — see reference Y4 or Adler's figure 25. In a later experiment on C_3H_8 ^{B46} the events originating on free protons were selected; this (presumably) more reliable procedure gave a much larger result — see figure 35).
30. $\frac{d\sigma}{dQ^2}$ for single pion production in Adler's model^{A6} using the Born approximation plus resonant multipoles all multiplied by the experiment/theory ratio for electroproduction. The theoretical curves are normalized to the number of events. (The data is from the CERN CF_3Br experiment — see the discussion in the previous figure caption.)
31. Differential cross section for $\nu n \rightarrow N^* \mu^-$ for each form factor taken one at a time as $F_i = \frac{1}{(1-q^2/b^2)^{2n}}$ with $b = 850 \text{ MeV}$.^{A12} Dashed curves — $n = 1$; solid curves — $n = 2$. The form factors are those defined by Albright and Liu^{A12} (see the appendix).
32. Total cross sections corresponding to figure 31.^{A12}
33. q^2 and $M^2(\pi p)$ distributions for $(\mu^- \pi^+ p)$ events with $E_{\text{vis}} > 1 \text{ GeV}$ originating on free protons in the CERN C_3H_8 experiment.^{B46}
34. Distributions in the Berman and Veltman angles (figure 27) for events with

- $1.3 < M^2(\pi p) < 1.9 \text{ GeV}^2$ and $\sin^2 \frac{\alpha}{2} < 0.1$ (same experiment as figure 33).^{B46}
35. Cross section for $\nu p \rightarrow \mu^- \pi^+ p$ (same experiment as figures 33 and 34^{B46}).
The errors shown are purely statistical. Systematic errors are $\pm 20\%$.
36. The $Q^2 - \nu$ plane for neutrino scattering.
I. Elastic scattering: $Q^2 = 2\nu$
II. Threshold for π production: $Q^2 = 2\nu - 2Mm_\pi - M_\pi^2$
III. Line of fixed missing mass M^* : $Q^2 = 2\nu + M^2 - M^{*2}$.
37. Total neutrino-nucleon cross section as a function of neutrino energy E . The freeon cross sections have been multiplied by 1.35 to normalize them to the propane cross sections for $E_\nu > 2 \text{ GeV}$. The errors shown are statistical only.^{B47}
38. Plot of \bar{Q}^2 versus the neutrino energy.^{M10, M11}
39. Form of the distributions in $y = \nu/ME$ for three ranges of neutrino energy.
The dotted lines in the first and last bin indicate the raw data before making small corrections for the exclusion principle in elastic events and for the E dependent coefficient in Eq. (3.67) so that (3.74) applies^{M10, M11}. (The labels $F_1 = F_3 = 0$, etc. really mean that the integrals over these quantities are equal, weighted as in (3.74)).
40. Fits to the ratios A and B (Eq. 3.118) for all the data with $E > 1 \text{ GeV}$.^{M11} The broad hatched area is the physical region allowed by the positivity conditions (3.77). The ellipse is the likelihood contour corresponding to one standard deviation from the best fit. A and B together determine $r = (\sigma^{\nu n} + \sigma^{\nu p}) / (\sigma^{\bar{\nu} p} + \sigma^{\bar{\nu} n})$ and lines of constant r are shown (see the text for a discussion of the significance of these results).
41. Fraction F of "clean" events with an identified proton (momentum

- $\lesssim 0.8 \text{ GeV}/c$ plotted against q^2 .^{M10} "Clean" events have net secondary charge $Q = 0$ or $+1$ and do not contain more than one identified nucleon (indicating that the nucleus did not necessarily break up).
42. Average pion multiplicity in "clean" events (see caption to figure 41) plotted against $\log \nu$.^{M10} The authors of the paper from which this figure is taken^{M10} caution that because of uncertainties due to the fact that the target is a nucleus (so that, e. g., the selection of "clean" events biases against large multiplicity) it is only possible to conclude that \bar{n} increases slowly with ν . In spite of this we give this figure because it shows the only data now available.
43. The forward neutrino cross section averaged over free neutrons and protons.
- (a) The inelastic cross section according to Adler's theorem using $\sigma_\pi = 35 \text{ mb}$ for missing mass $W > 2.13 M_p$ and a resonance formula for $W < 2.13 M_p$.
- (b) The contribution to the inelastic cross section from $W < 2.13 M_p$. (c) The elastic cross section.^{B10}
44. The differential cross section for the forward process in the resonance region for a neutrino energy $4M_p$ (upper curve) and the result (lower curve) of multiplying by the square of the modulus of the shadow factor, the potential V being computed in a modified forward scattering approximation. W is the invariant mass of the final hadron system.^{B10}
45. The inelastic differential cross section $d\sigma/d\cos\theta$ in our model averaged over free neutrons and protons and over the CERN neutrino spectrum. The muon energy was required to be $> 1.2 \text{ GeV}$. The longitudinal contribution (which is liable to shadowing) and the transverse contribution (which is not) are shown separately. The horizontal scale is related to $\cos\theta$ by $\cos\theta = 1.0 - 0.00095 x$.^{B10}

46. Cross sections for $\nu N \rightarrow \mu^- W^+ N$ with $N = \text{proton/neutron}$, $M_W = 7 \text{ GeV}$, $K = 0, \pm 1$ and dipole form factors. B43
47. "Elastic" cross section ($\nu p \rightarrow \mu^- W^+ p$), as in figure 46 with $K = 0$, and "inelastic" cross section ($\nu p \rightarrow \mu^- W^+ + \dots$). B43
48. Incoherent total cross sections for W production off protons and neutrons without allowing for the Pauli principle or the Fermi motion (i. e., the free nucleon cross section $\sigma(p)$ of table 9 is plotted; we refer to the table for an illustration of the influence of nuclear effects which would not change the qualitative features of this figure) and the coherent cross section per nucleon in typical cases. $M_W = 8 \text{ GeV}$, $K = 0$. B43
49. Plot of the fraction of μ^- 's with energy greater than a specific E_{μ^-} in $\nu p \rightarrow \mu^- W^+ p$. Solid curves: $M_W = 5 \text{ GeV}$. Dashed curves: $M_W = 10 \text{ GeV}$ ($K = 0$ in both cases). B44
50. The angular distribution of the μ^- with respect to the neutrino direction in $\nu p \rightarrow \mu^- W^+ p$ ($K = 0$). B44
51. Plot of $\sigma_\nu = \sigma_{\text{inel.}}(x, y) + \sigma_W$ against x and E_ν for $M_W = 7 \text{ GeV}$. The cross sections are for Pb²⁰⁸. C23
52. Scatter plot of $M_{\mu p}$ versus $\cos \theta_{\mu \nu}$: \times freon (1963-1964); propane (1967); the continuous curve is the expected elastic distribution. B45
53. Ideograms, histograms, and least squares fitted means for the $M_{\mu\pi}$ distribution for events giving one possible single muon-pion combination in the 1967 neutrino experiment. a. Total distribution for 217 ν events and 12 $\bar{\nu}$ events, the latter also shown separately (34 ν events are off scale). The inset shows the mass distribution of the seven Λ^0 obtained in the experiment. b. Distribution for 106 ν events and 6 $\bar{\nu}$ events remaining after selecting out

events with $1.125 < M^* < 1.350$ GeV (21 ν events are off scale). c. Ideograms of all ν events and all $\bar{\nu}$ events in the region of $M_{\mu\pi} = 0.425$ GeV. The weighted means and their standard errors are shown for all the largest groups of three or more consecutive values of $M_{\mu\pi}$ with a confidence level $\geq 50\%$. The two groups indicated are: WM(17 ν) = 0.423 ± 0.002 GeV; WM(4 $\bar{\nu}$) = 0.424 ± 0.003 GeV. ^{R1}

54. Anti-neutrino cross section ratios for Y_1^* compared to N^* production. ^{W9} Here

$$R_1 = \frac{\sigma(\bar{\nu}_\mu + N \rightarrow Y_1^{*-} + \mu^+)}{\sigma(\bar{\nu}_\mu + N \rightarrow N^{*-} + \mu^+)} \text{ and } R_2 = \frac{\sigma(\bar{\nu}_\mu + p \rightarrow Y_1^{*0} + \mu^+)}{\sigma(\bar{\nu}_\mu + p \rightarrow N^{*0} + \mu^+)} .$$

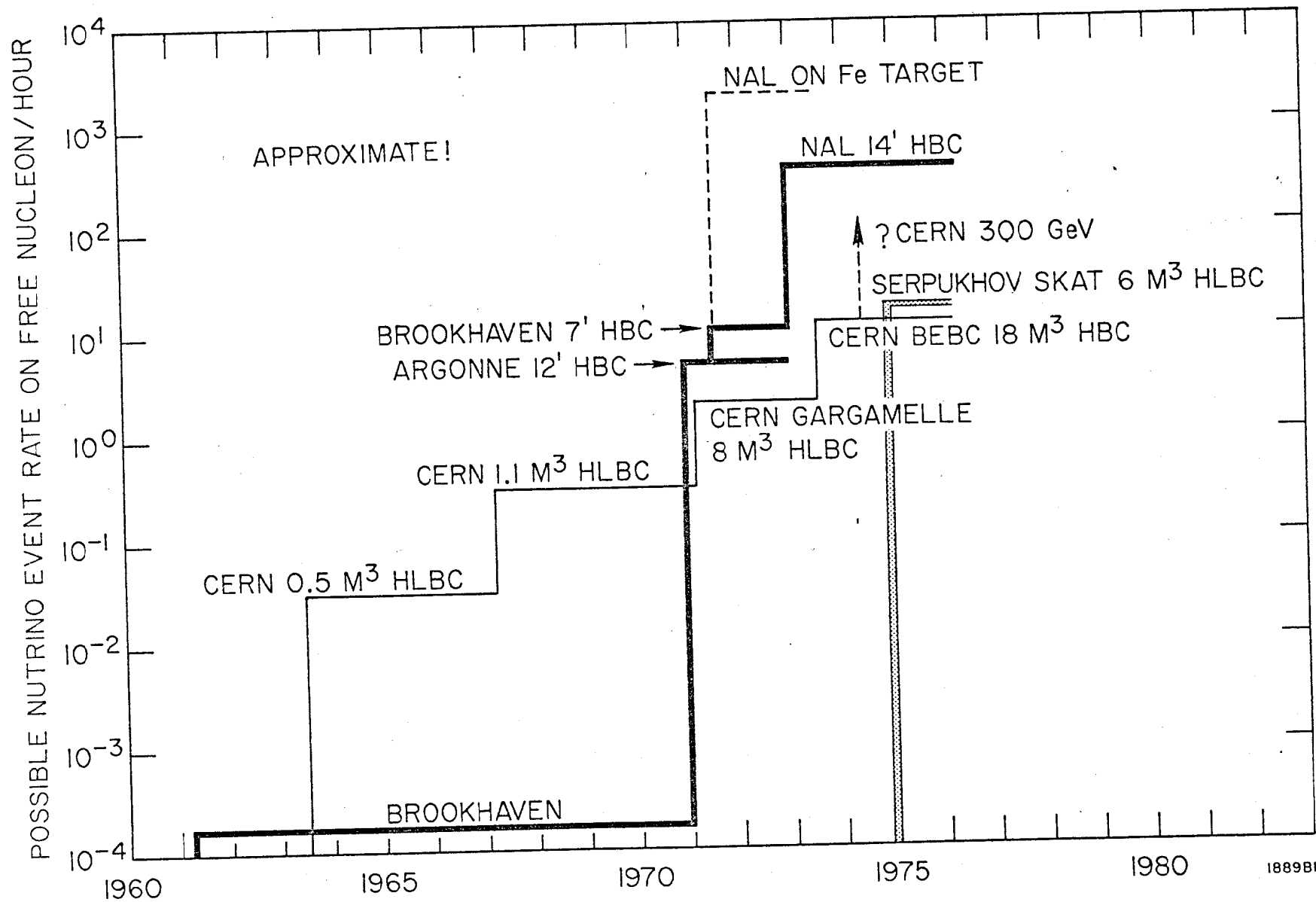
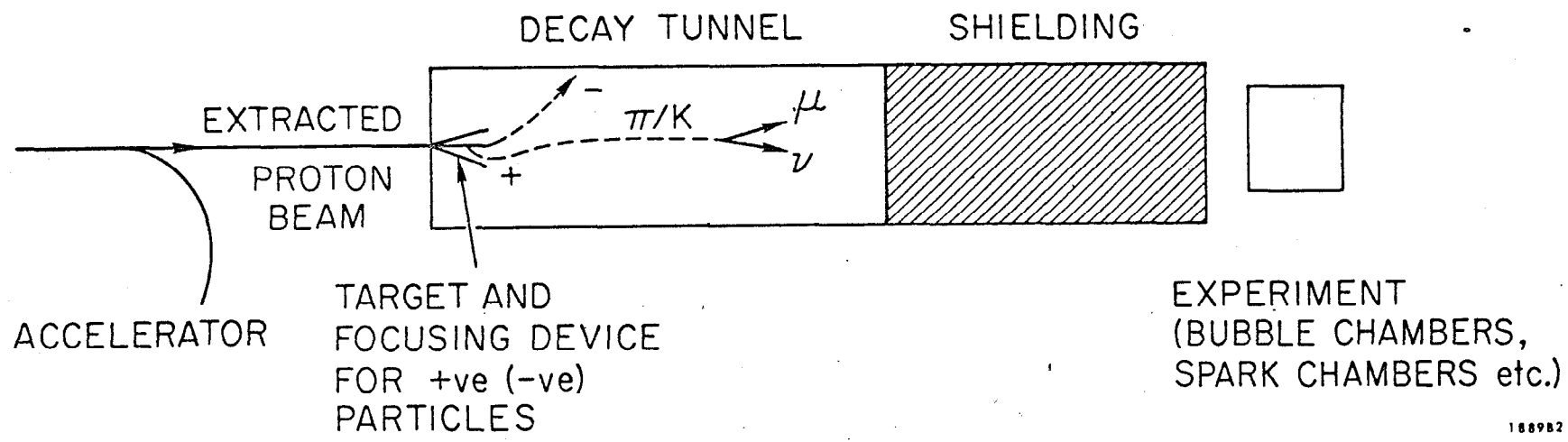


Fig. 1



188982

Fig. 2

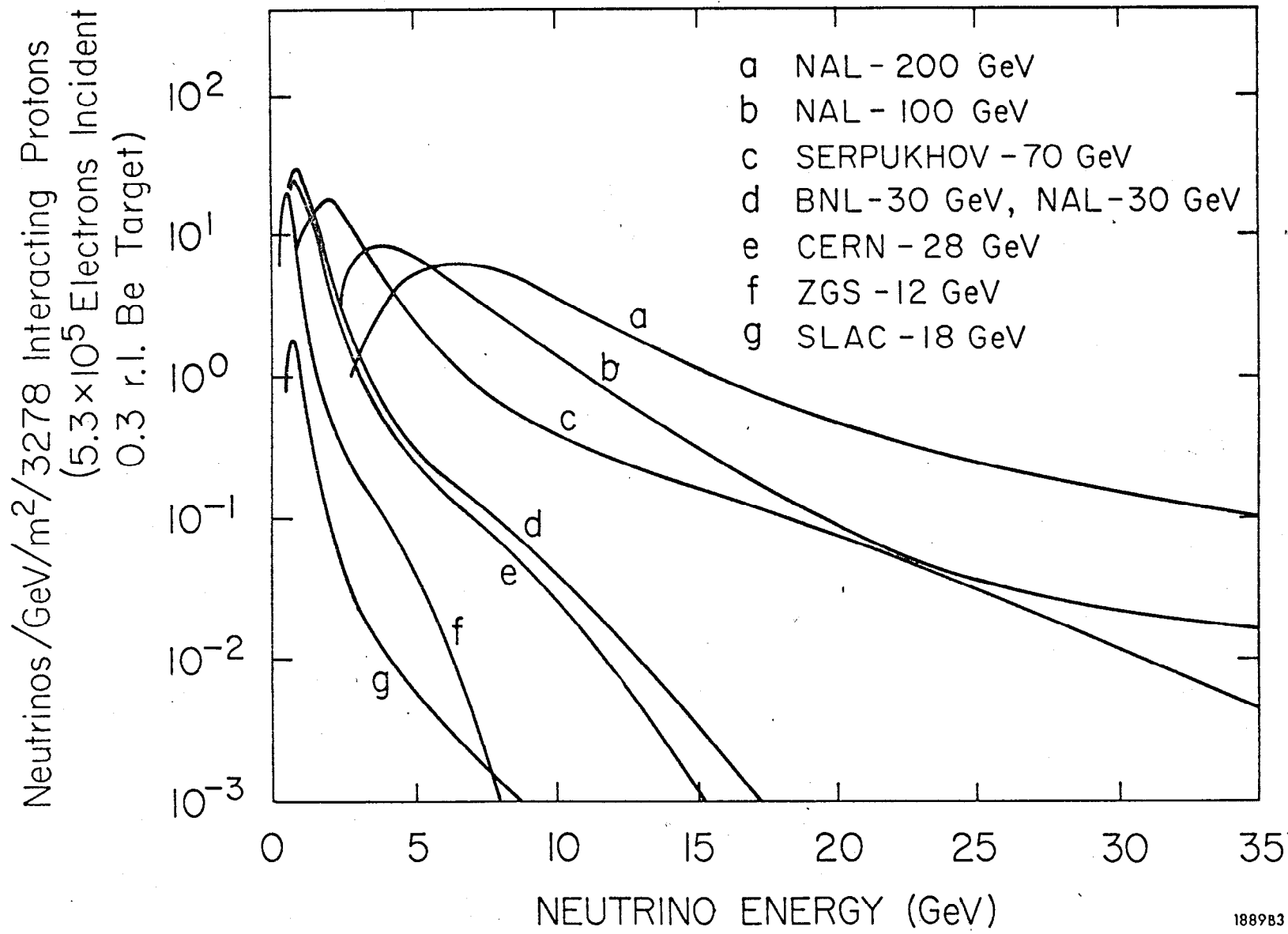


Fig. 3

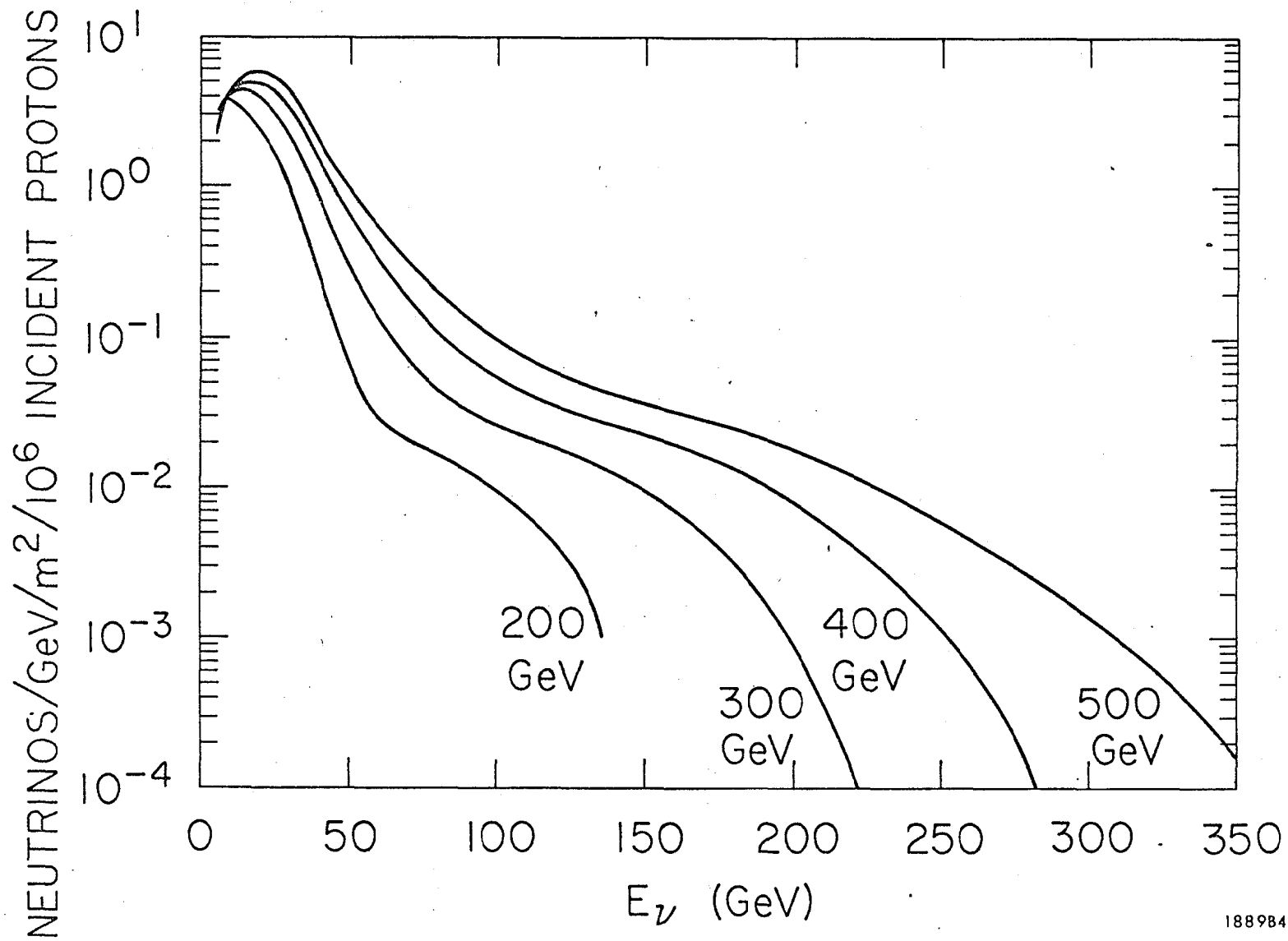


Fig. 4

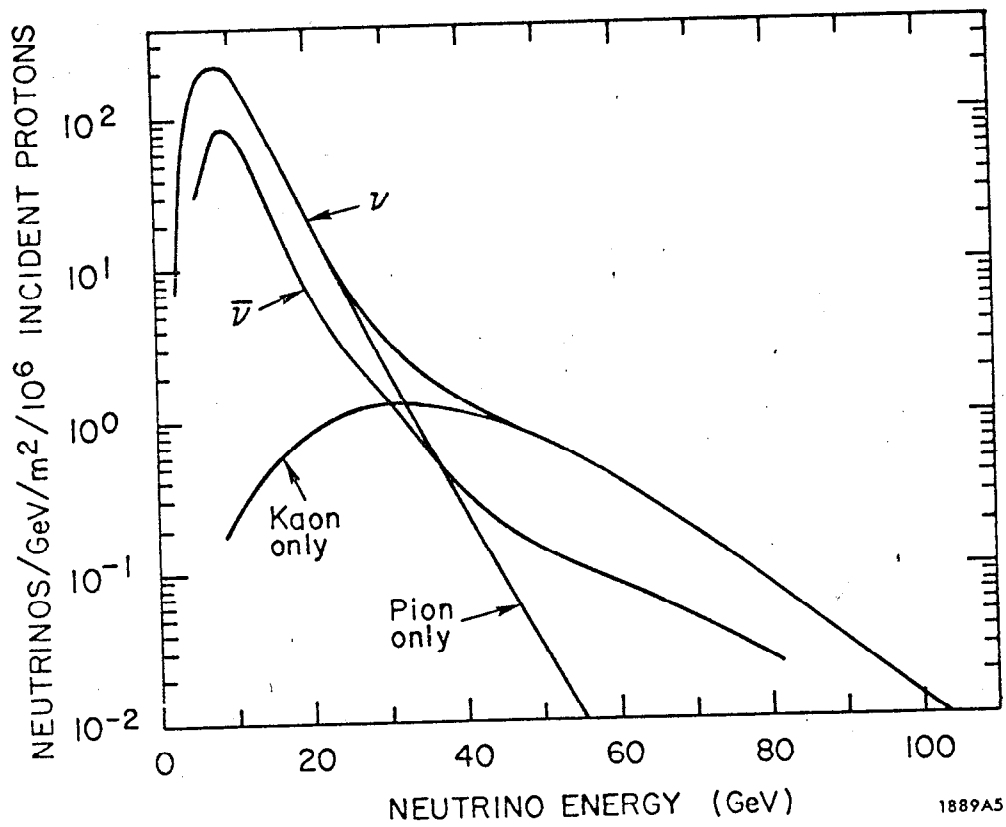


Fig. 5

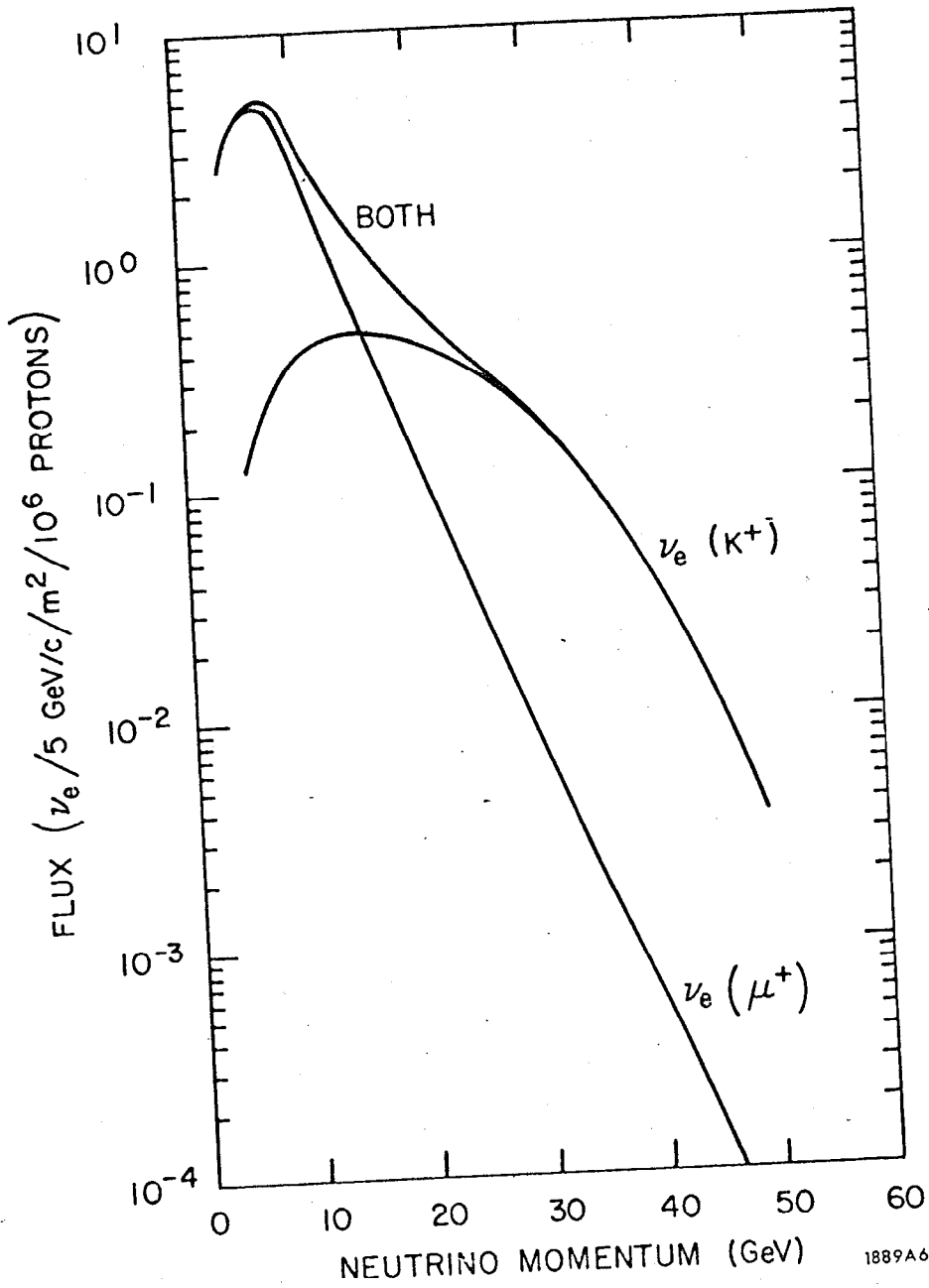
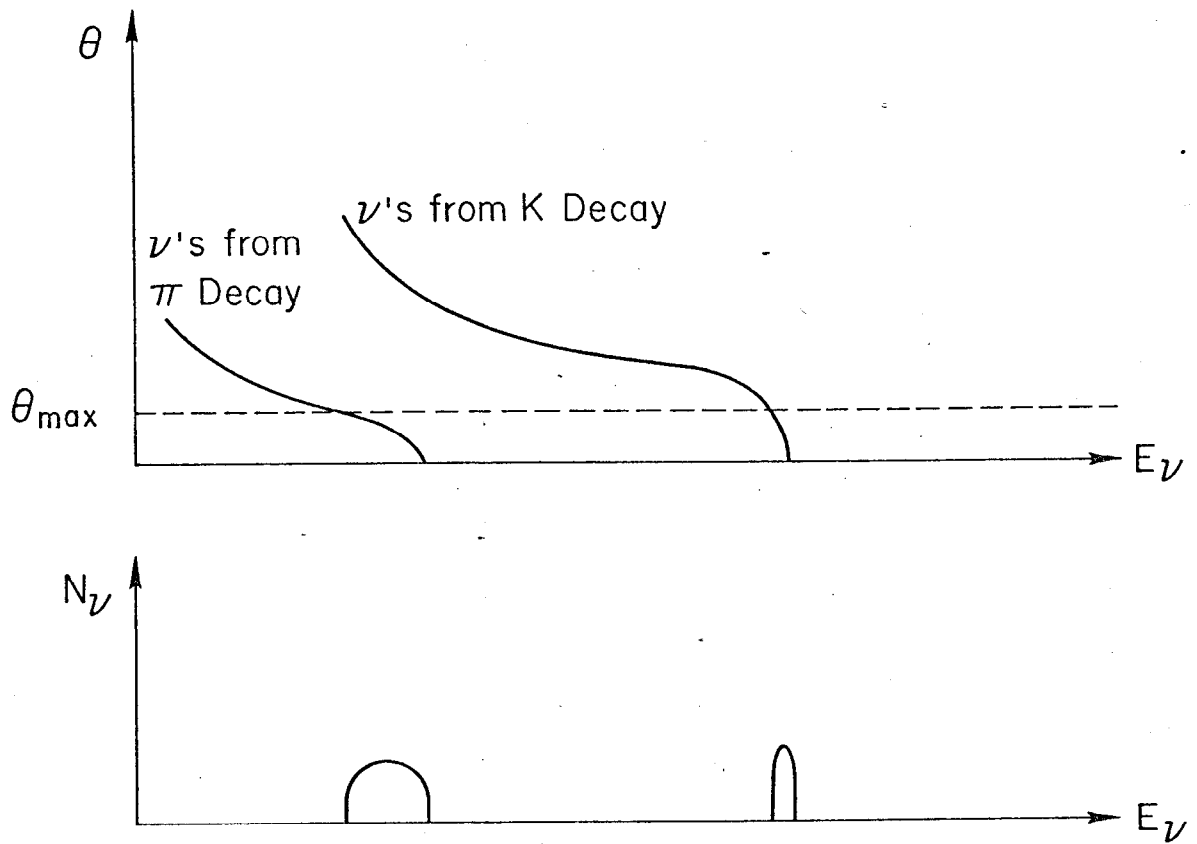
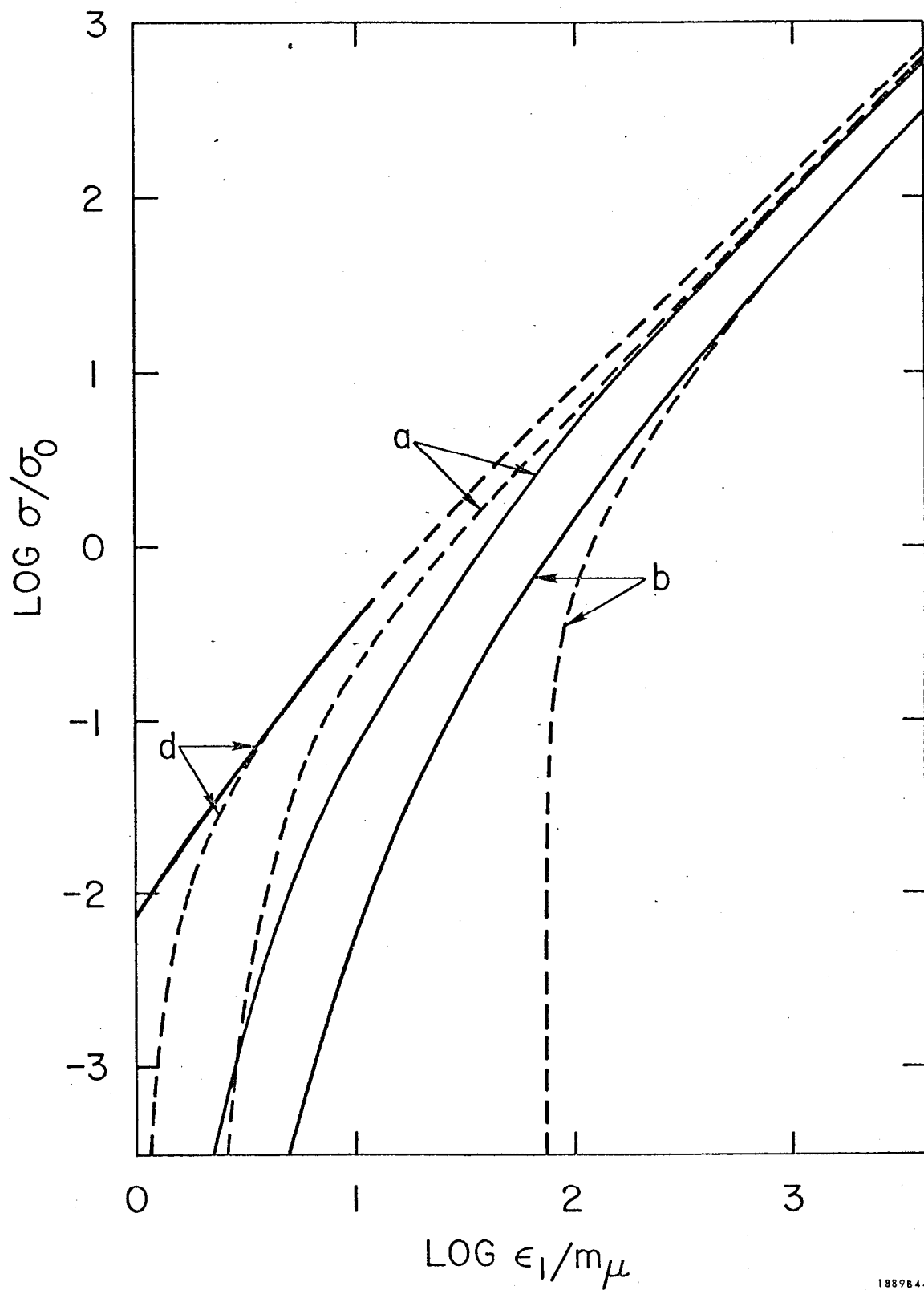


Fig. 6



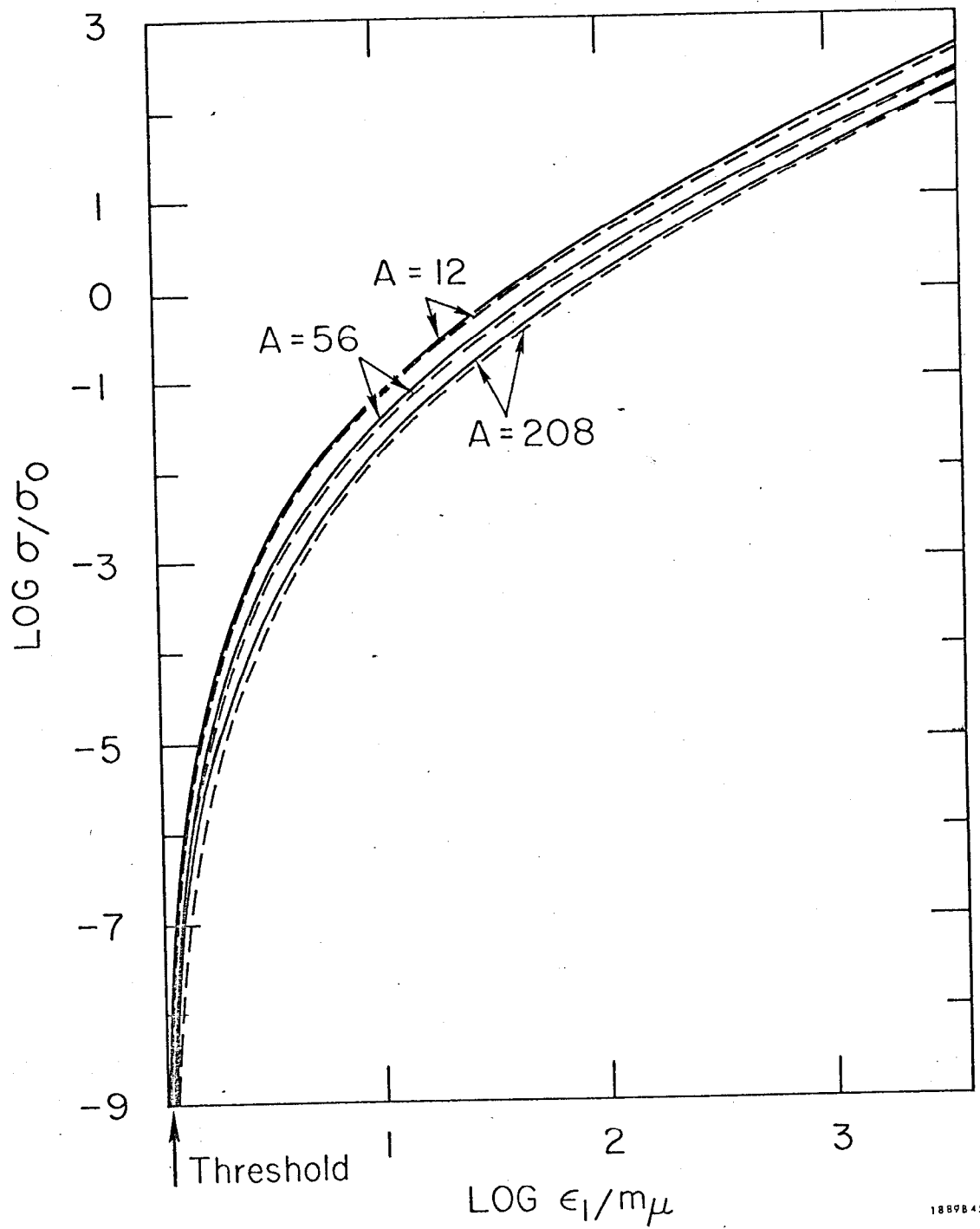
1889A7

Fig. 7



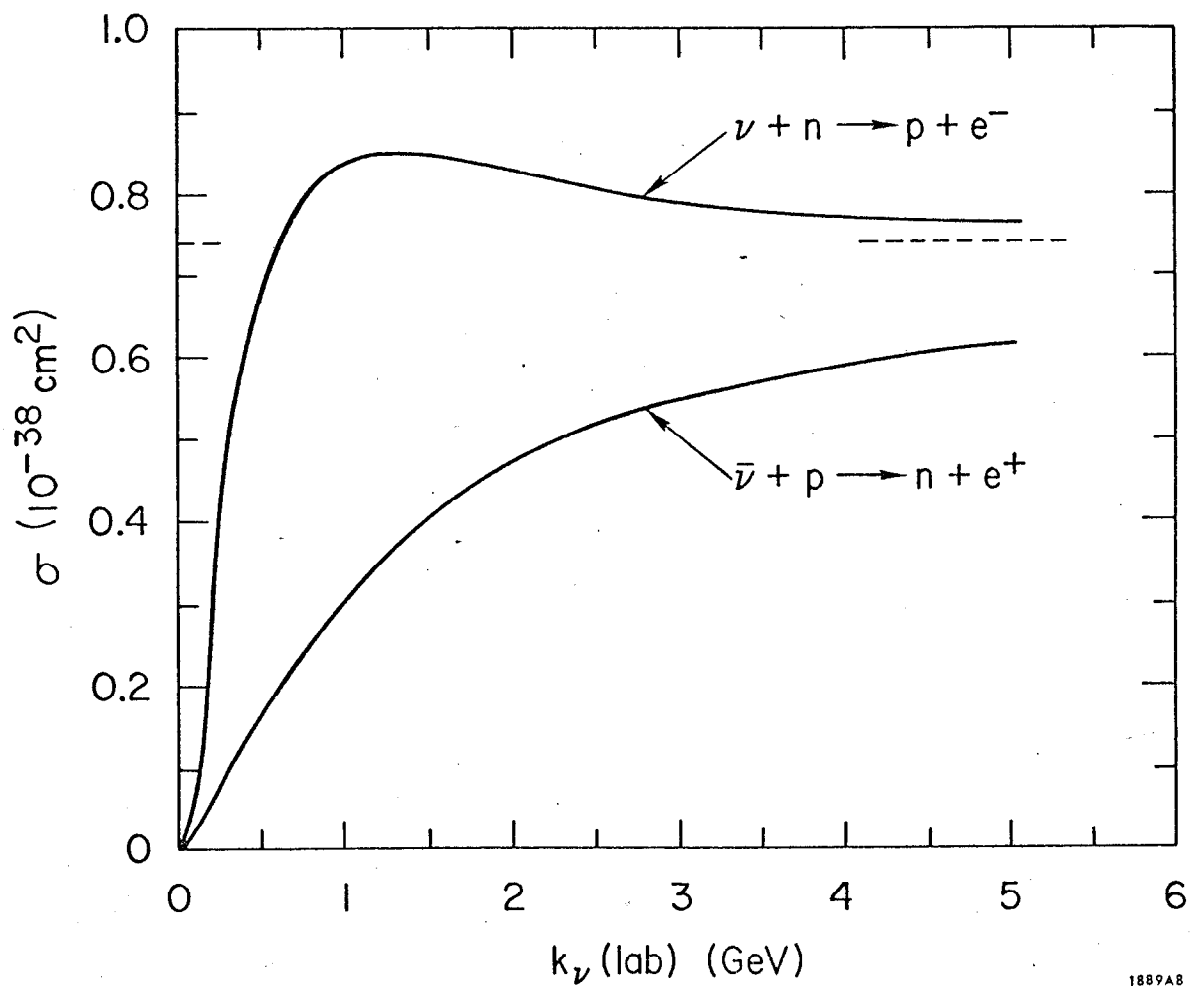
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Fig. 8



1889B45

Fig. 9



1889AB

Fig. 10

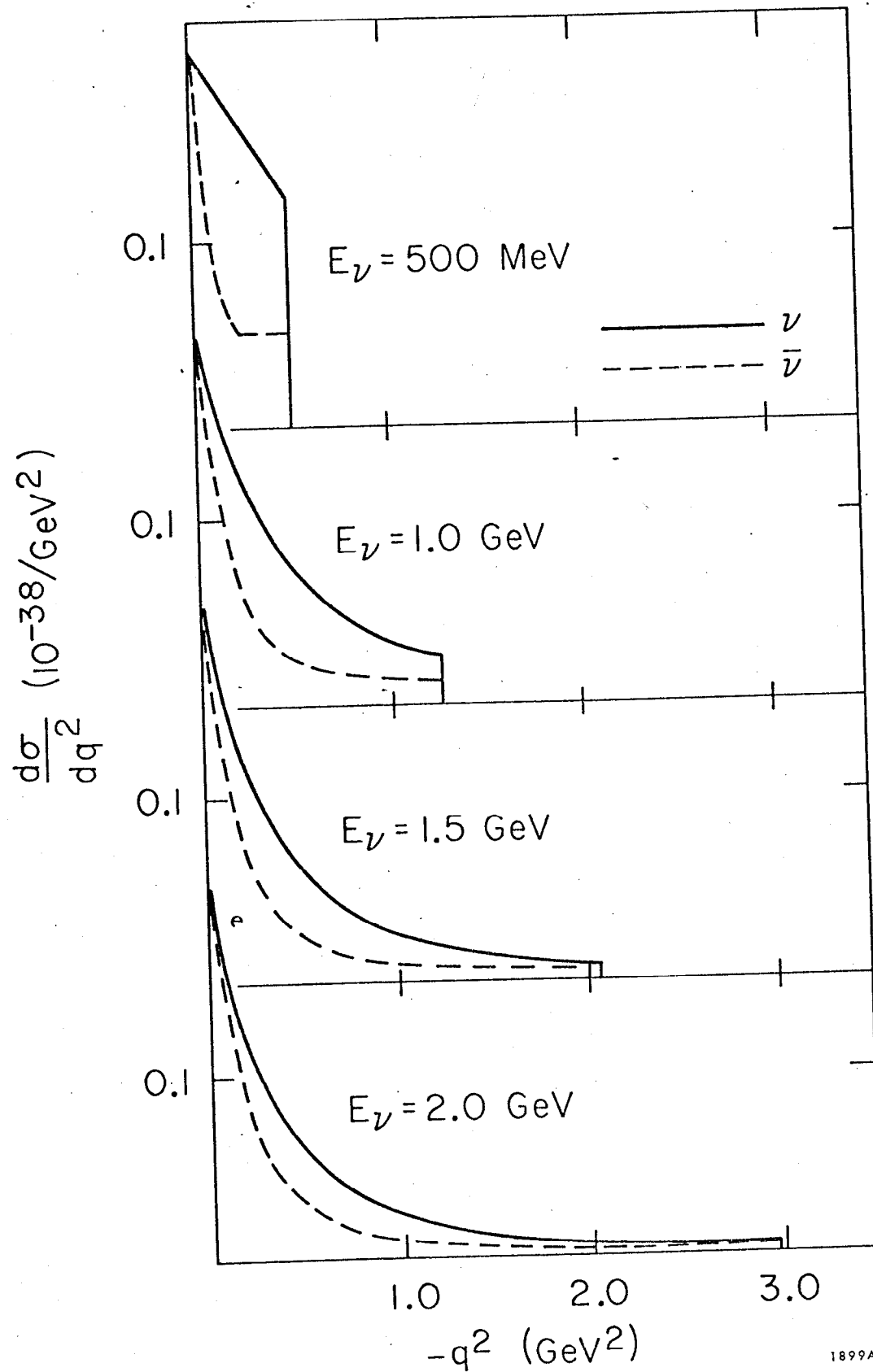
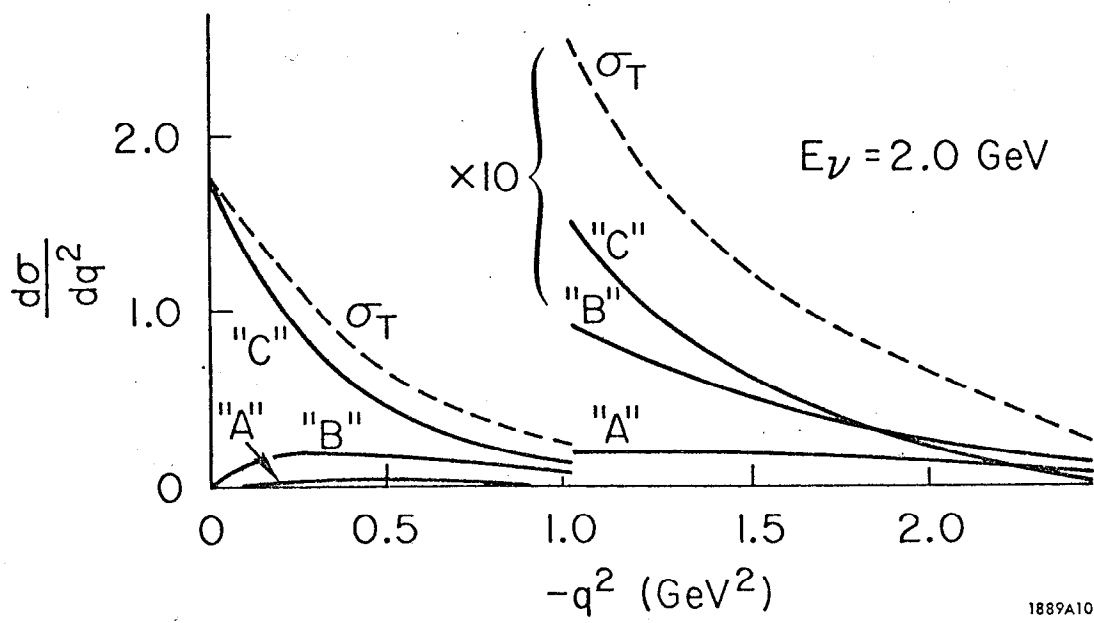
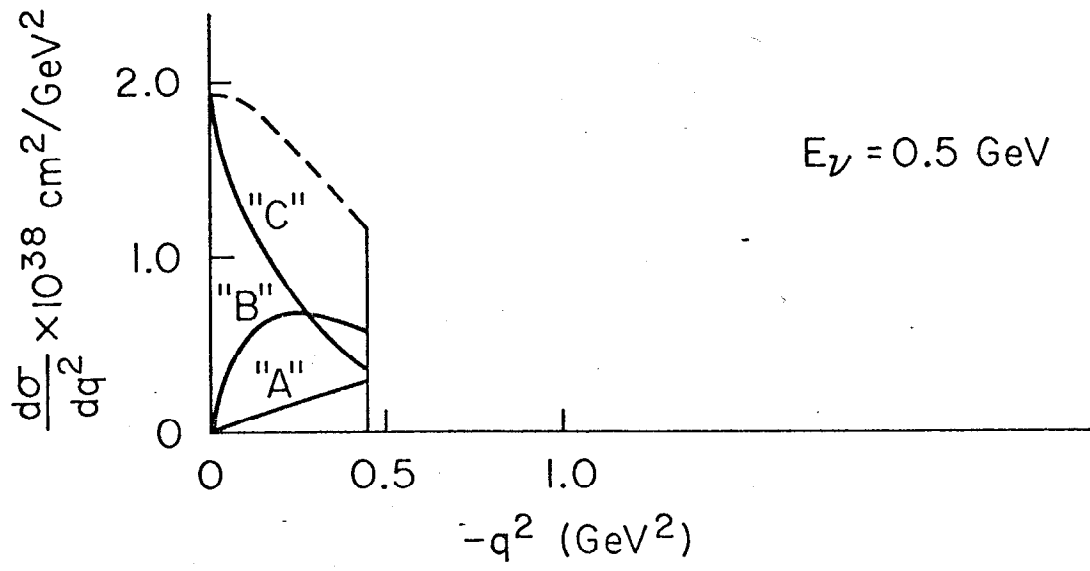


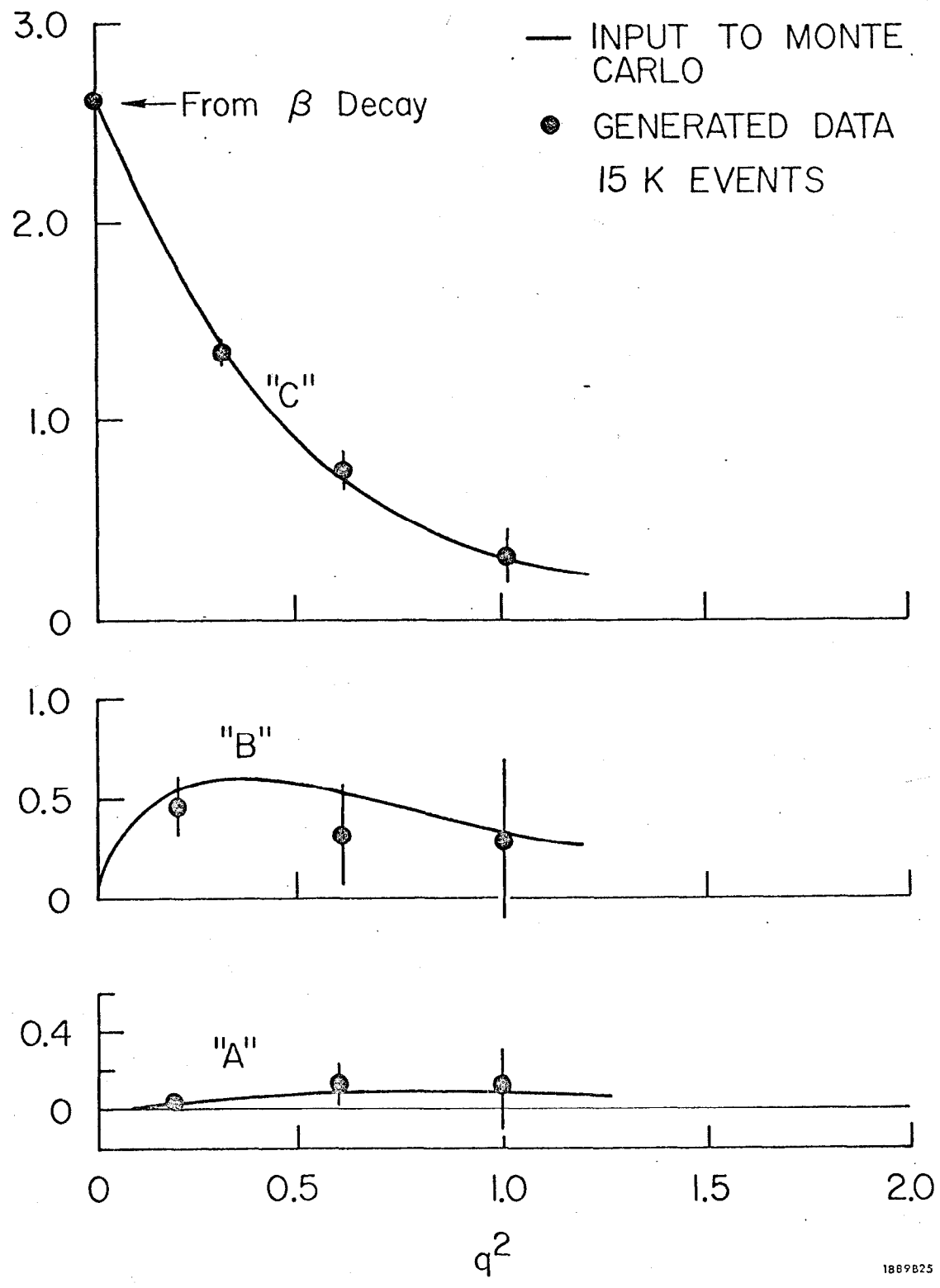
Fig. 11



1889A10

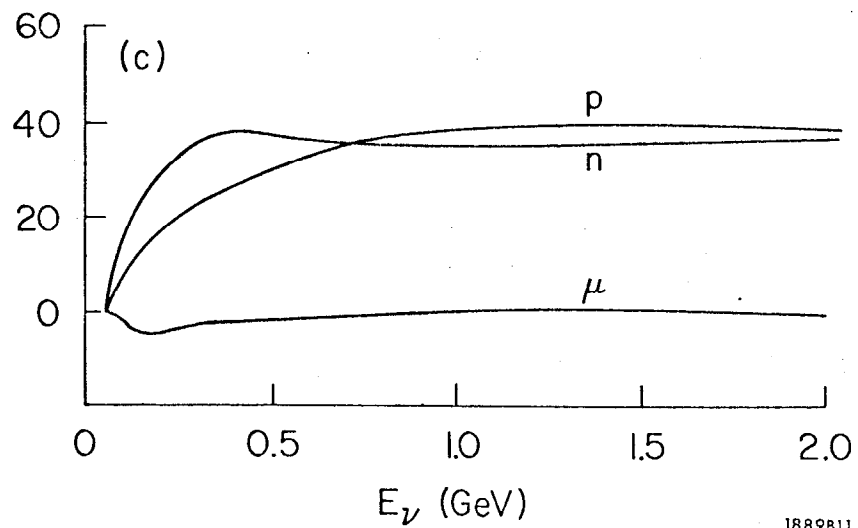
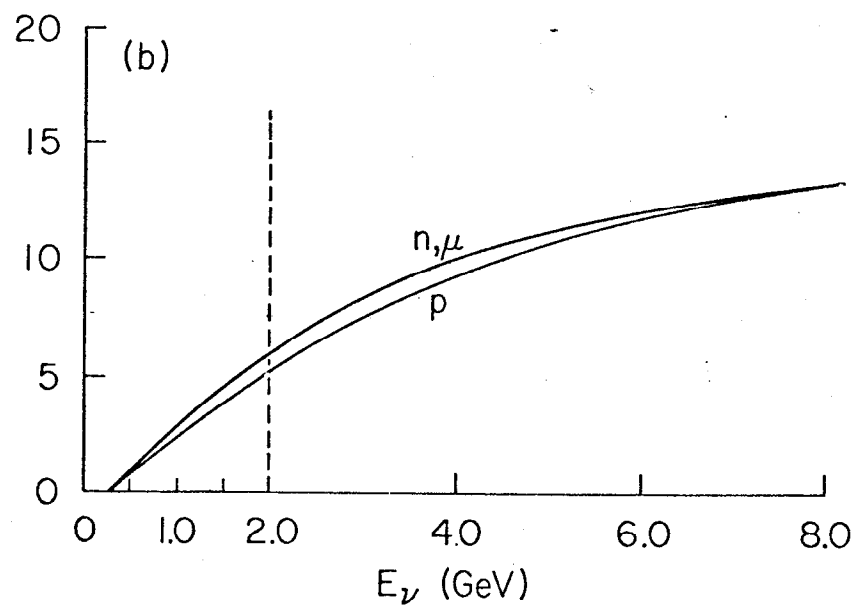
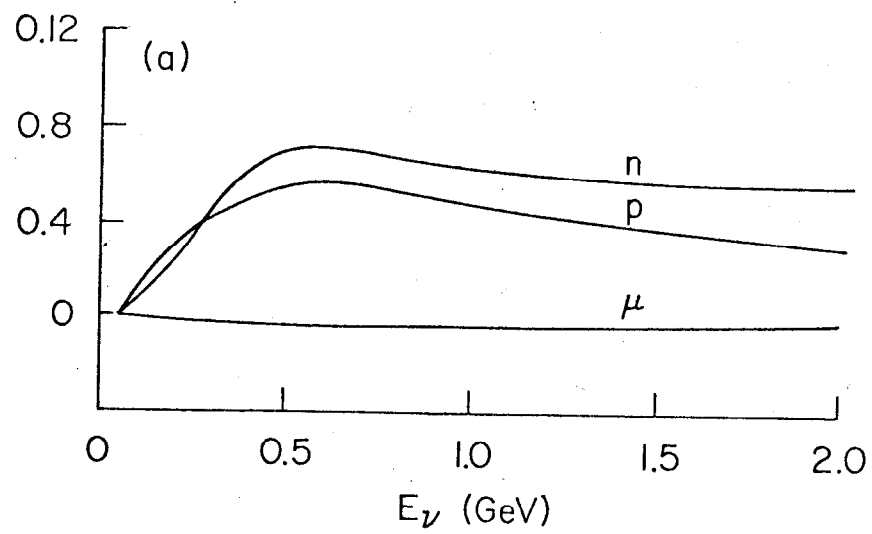
Fig. 12

SEPARATION OF TERMS "A","B","C"



1889B25

Fig. 13



1889B11

Fig. 14

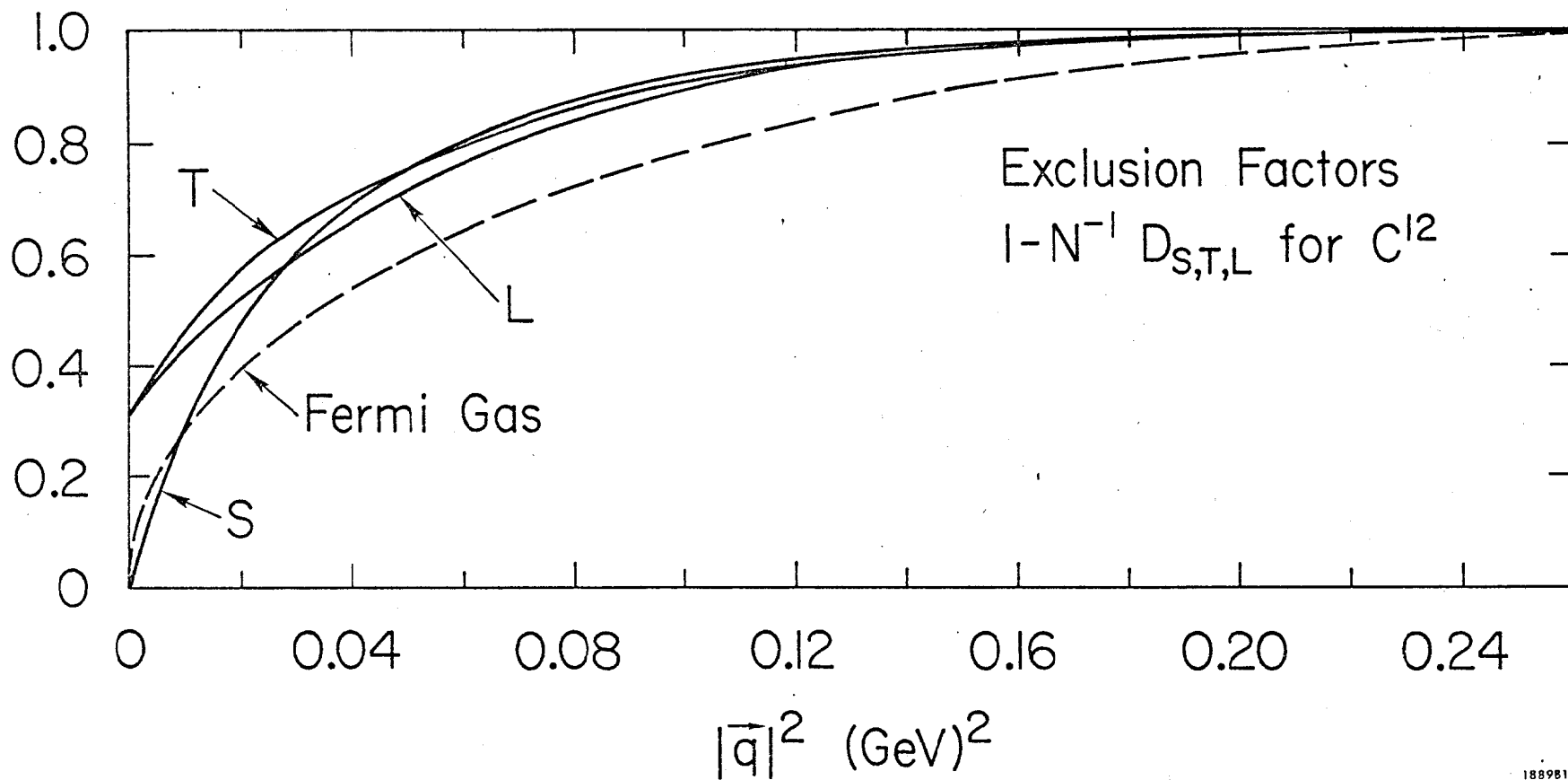


Fig. 15

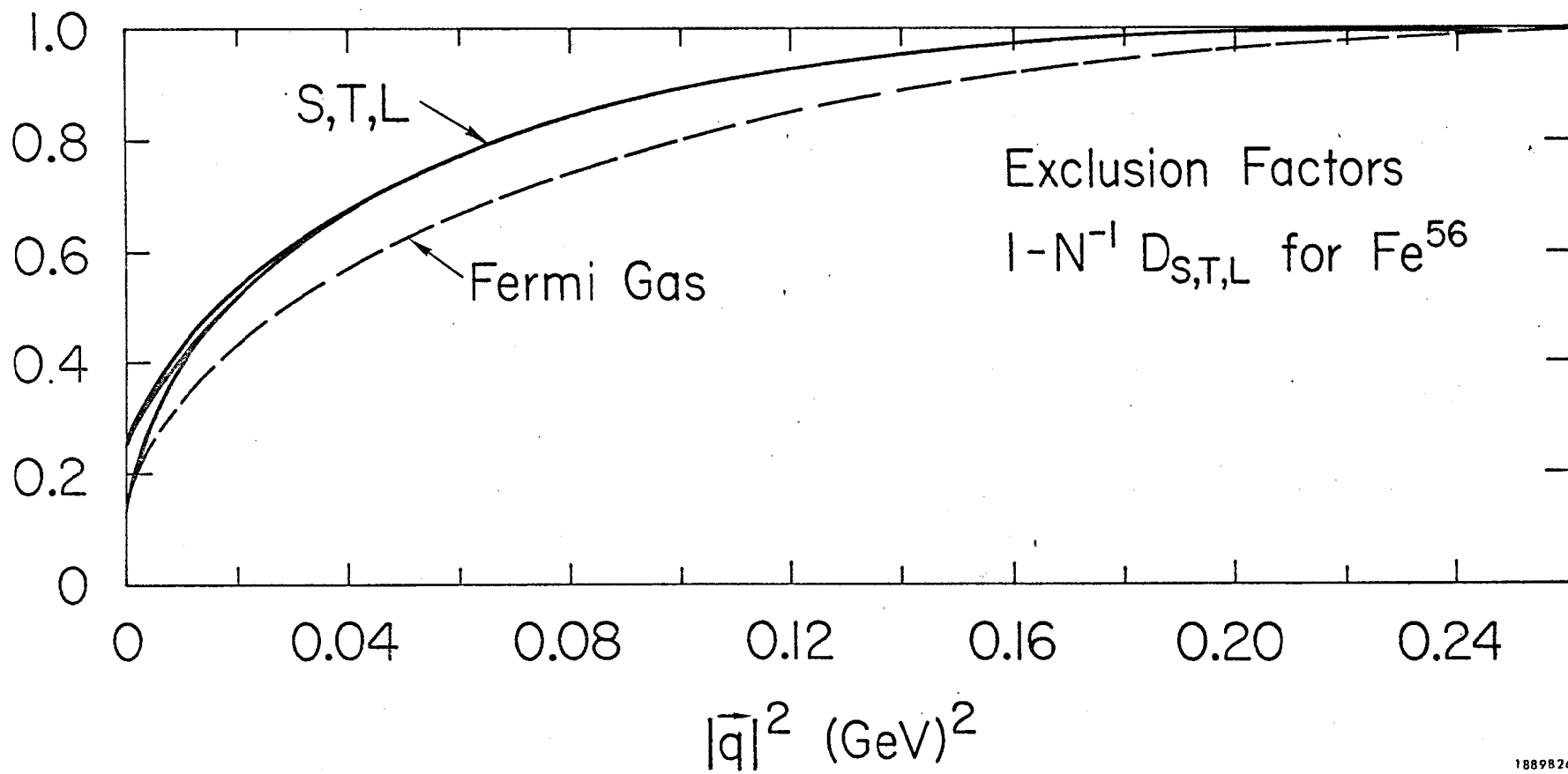
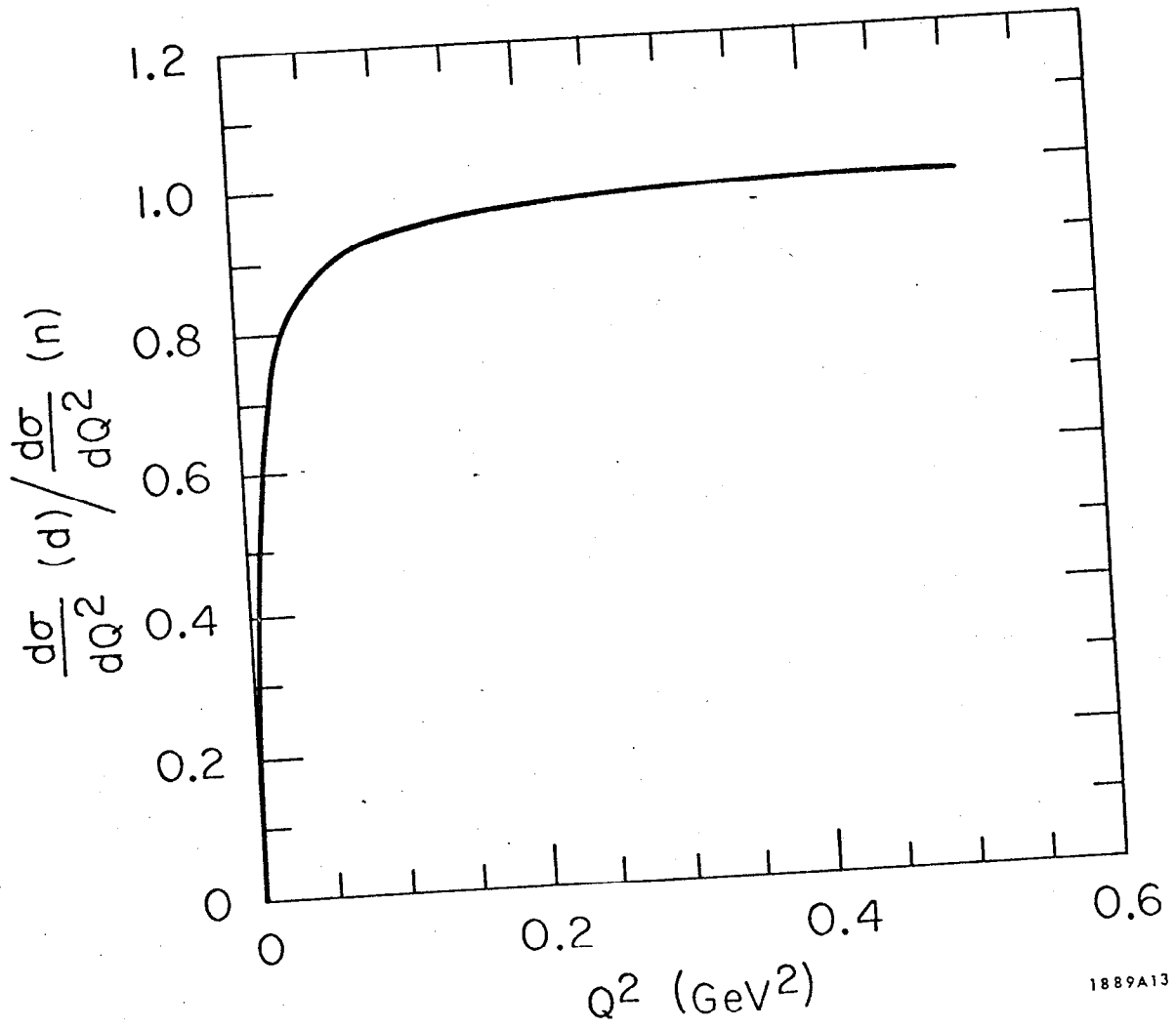


Fig. 16



1889A13

Fig. 17

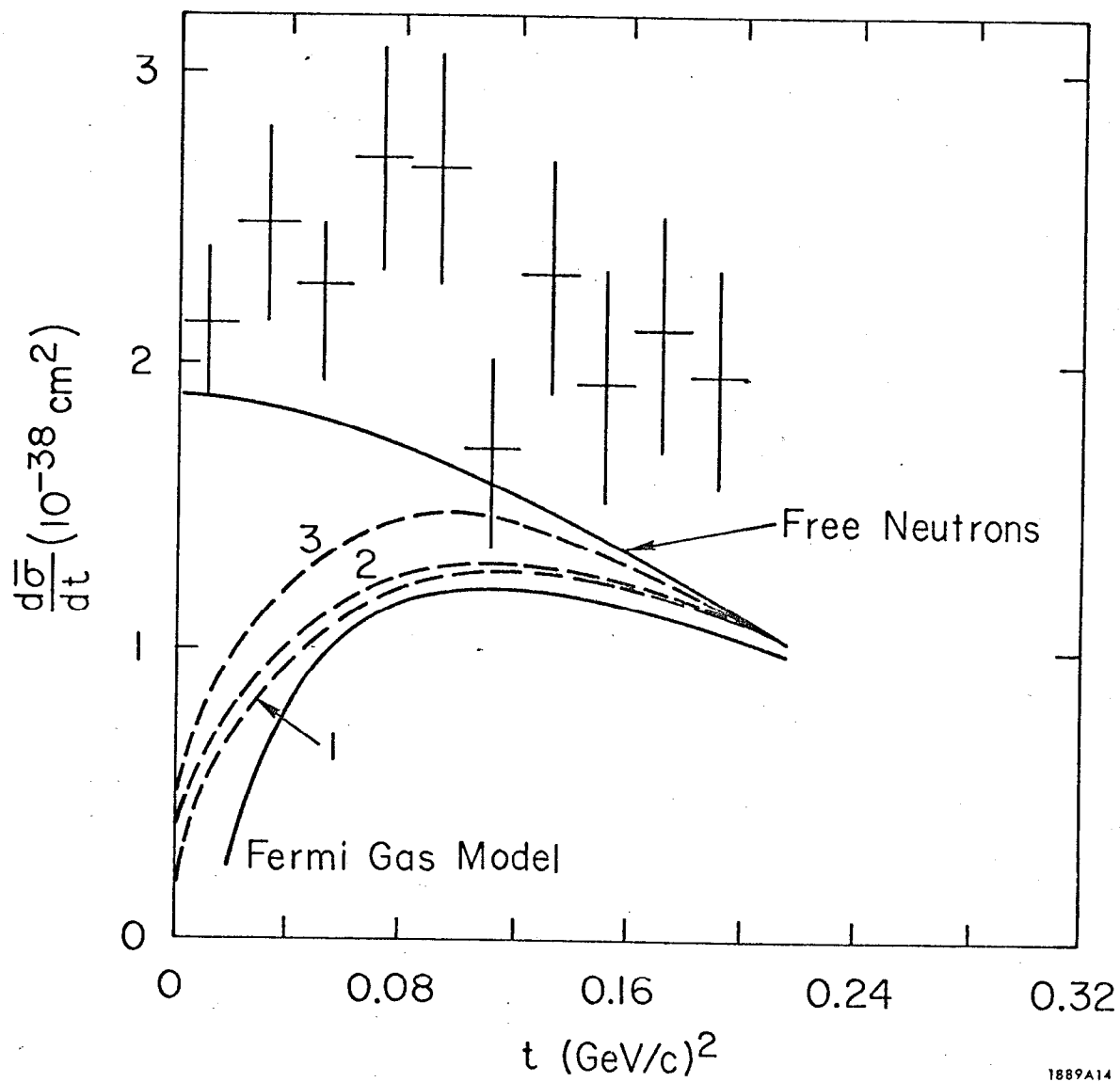
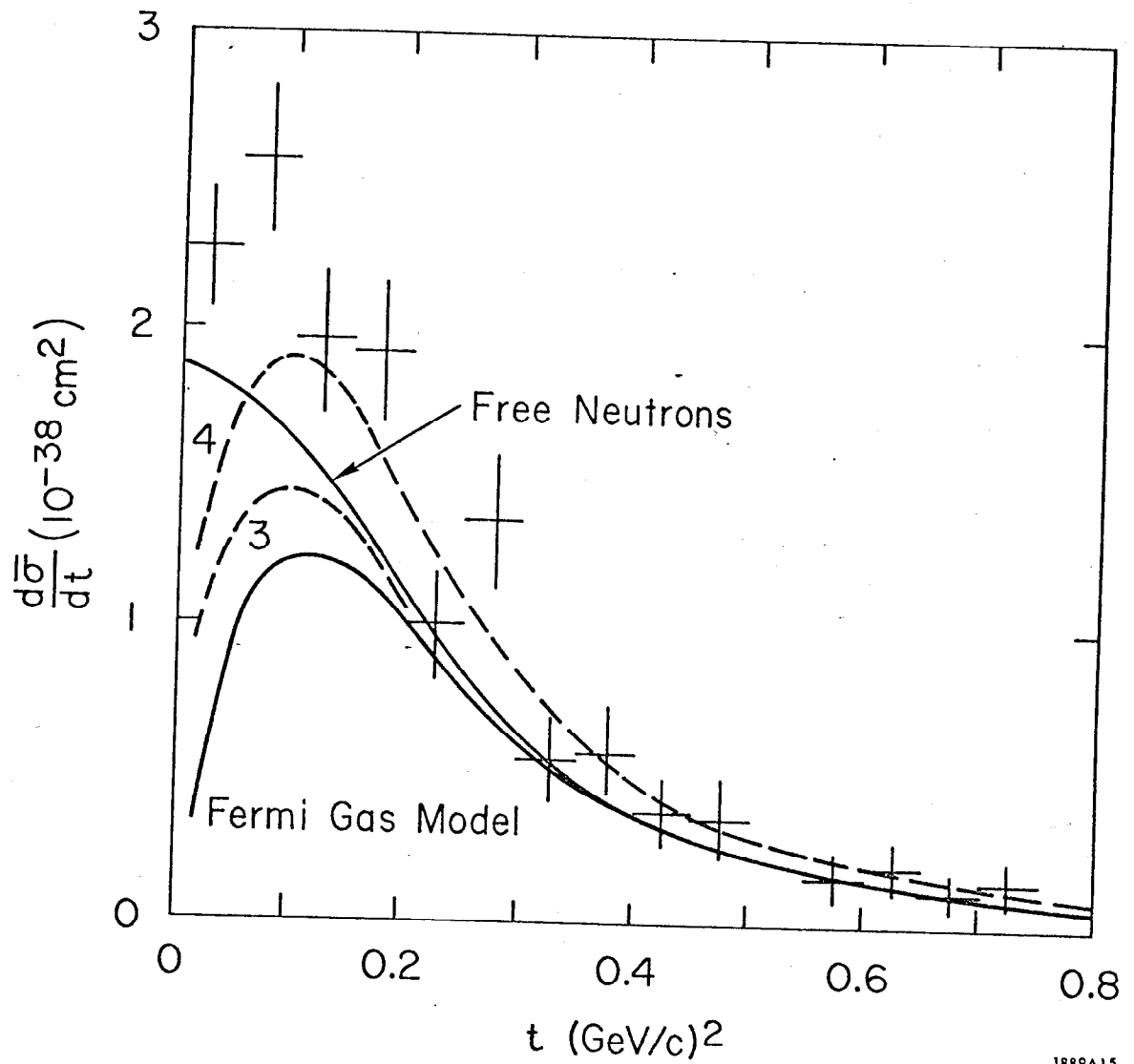
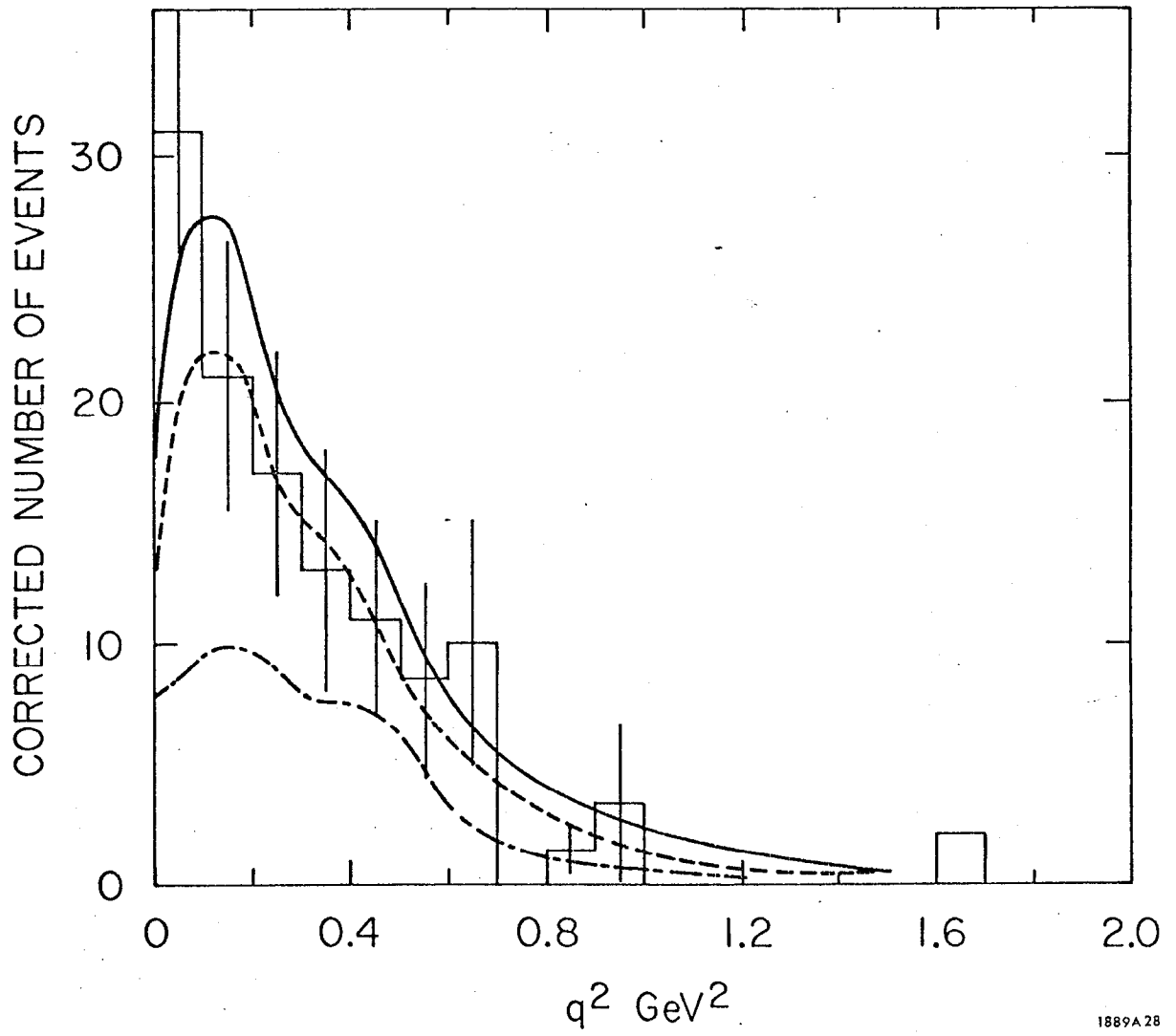


Fig. 18



1889A15

Fig. 19



1889A 28

Fig. 20

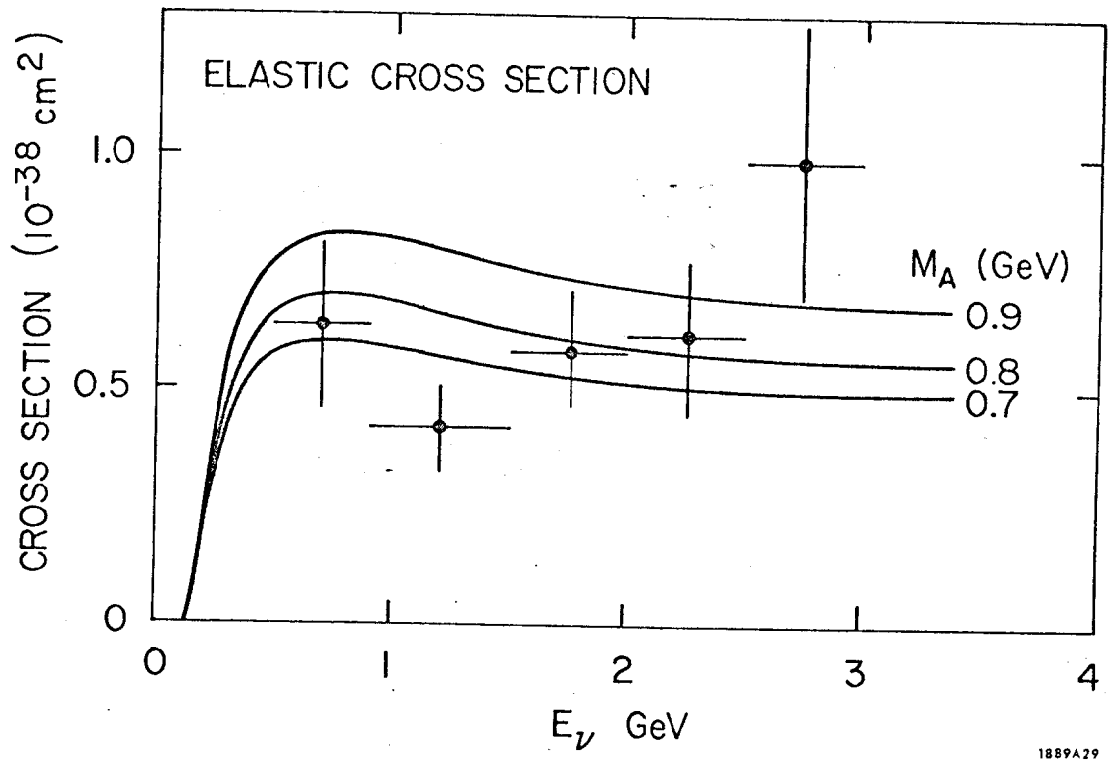


Fig. 21

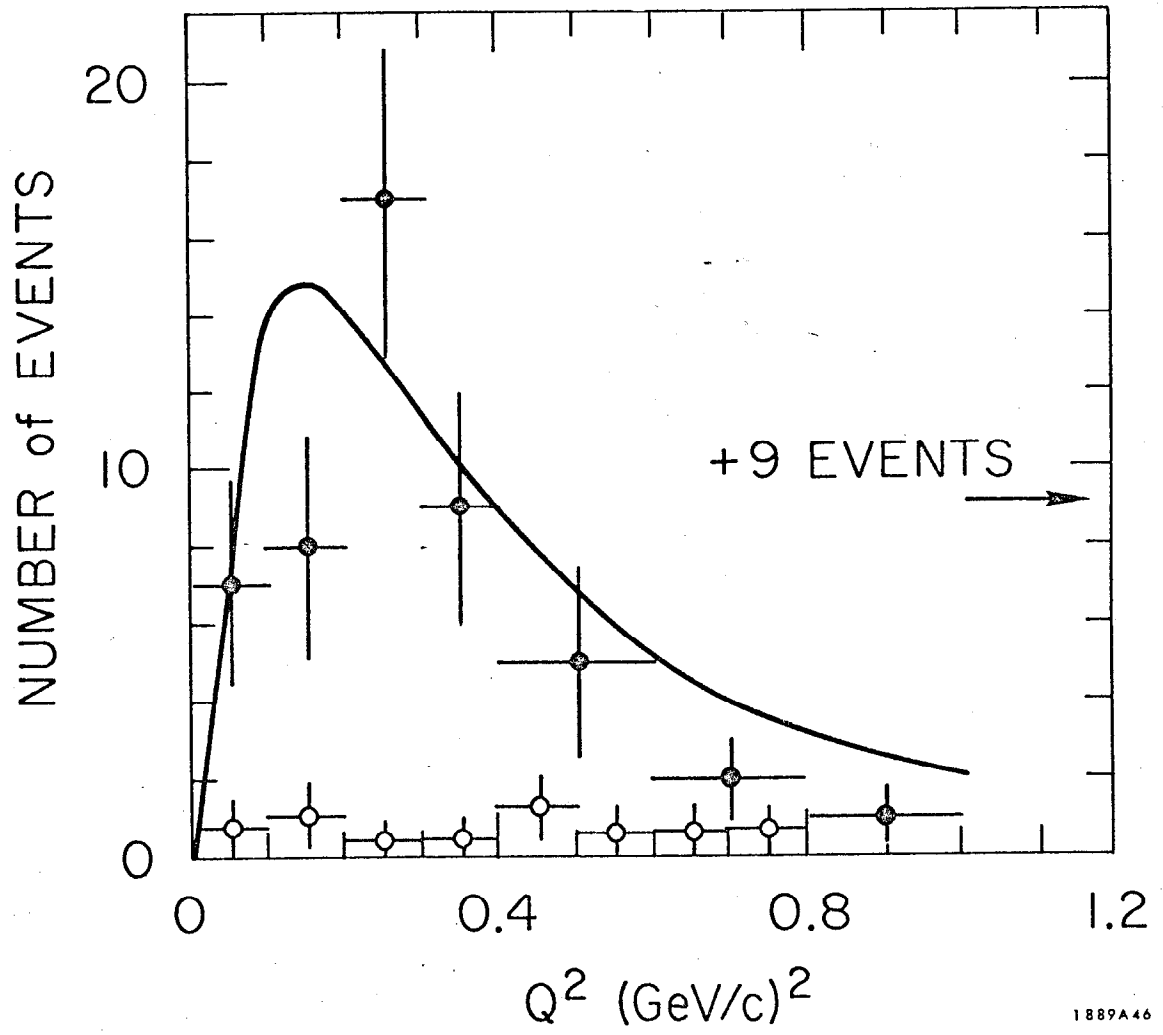


Fig. 22

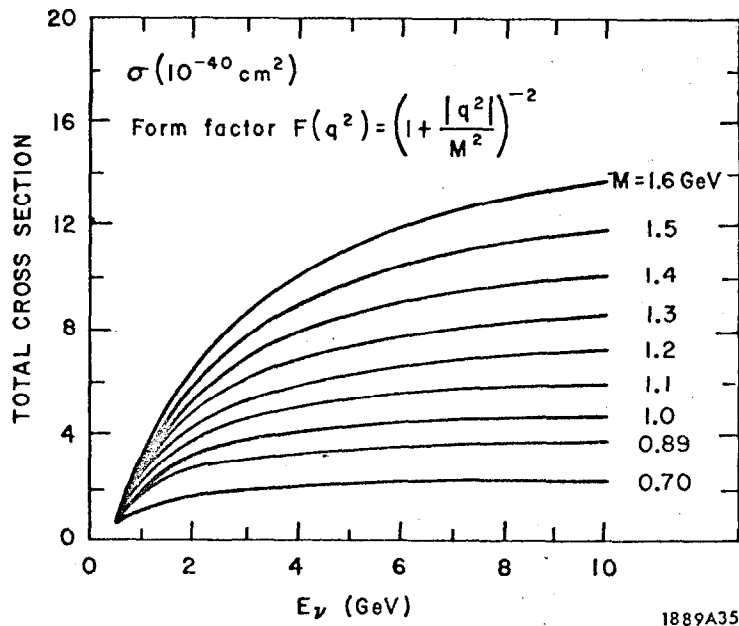


Fig. 23

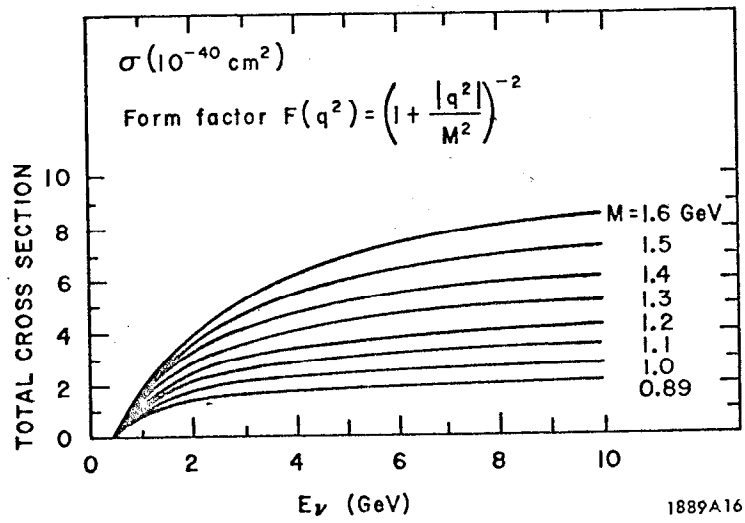


Fig. 24

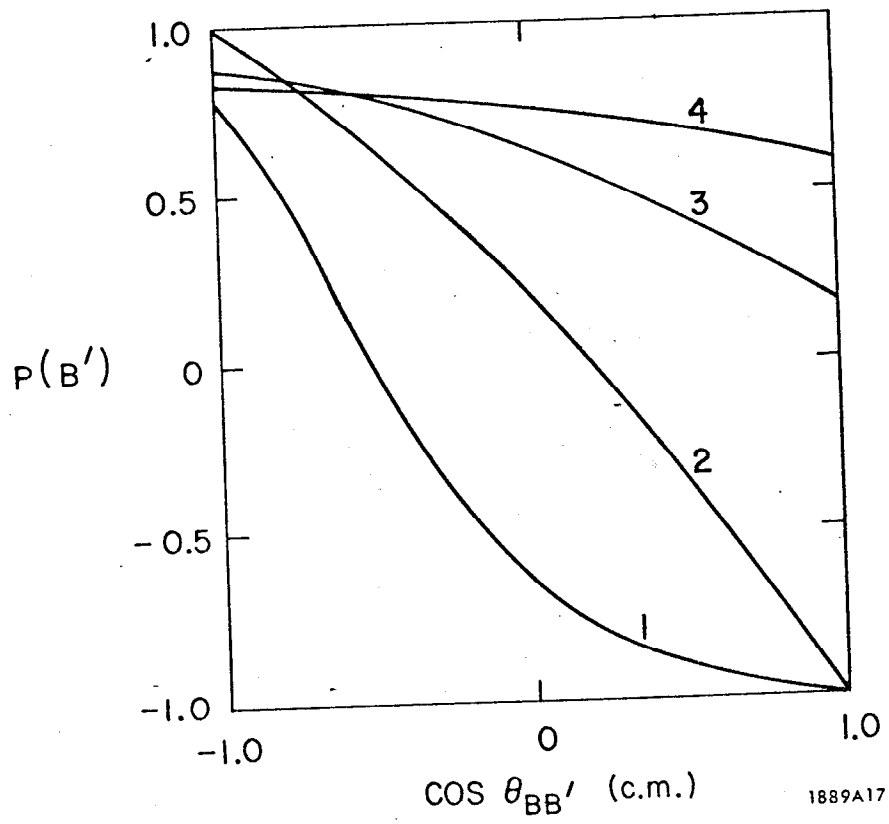


Fig. 25

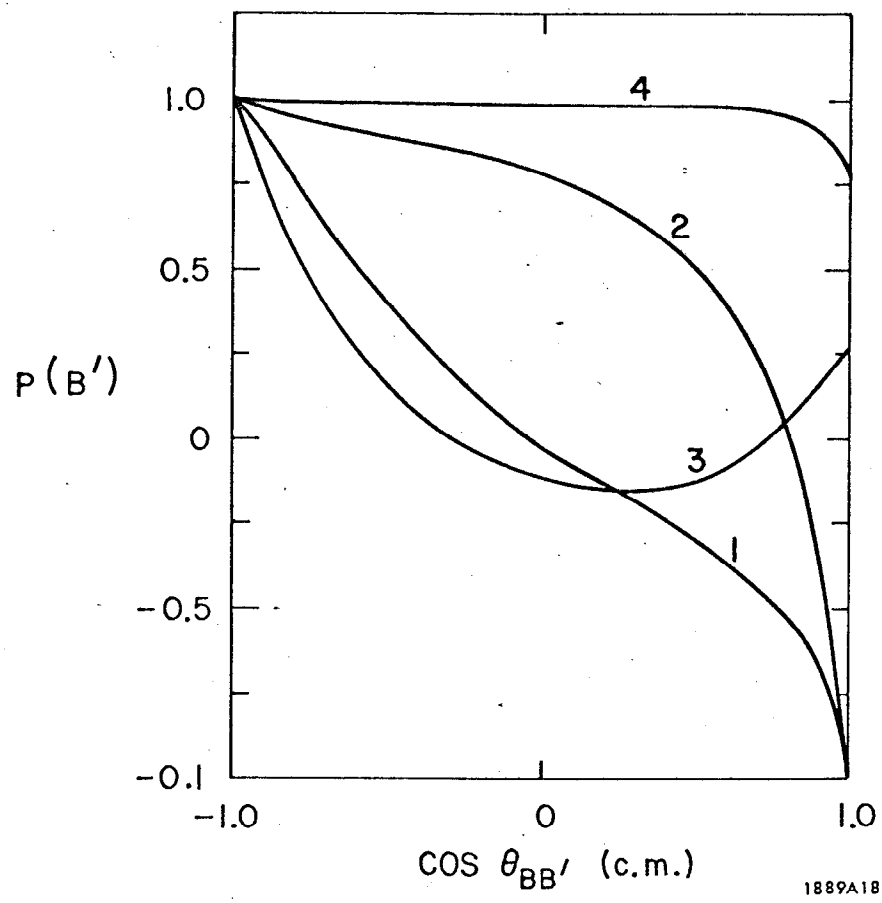
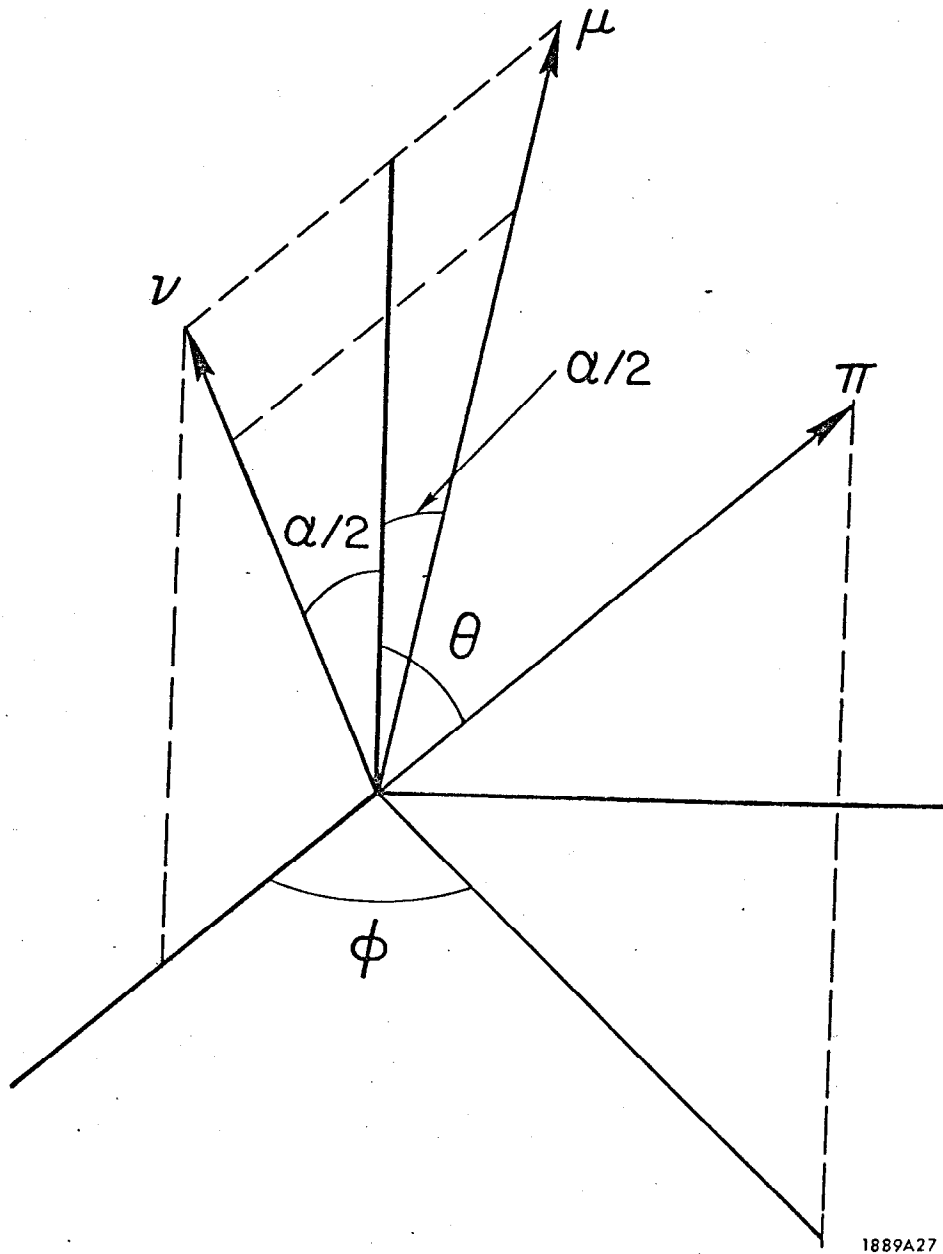


Fig. 26



1889A27

Fig. 27

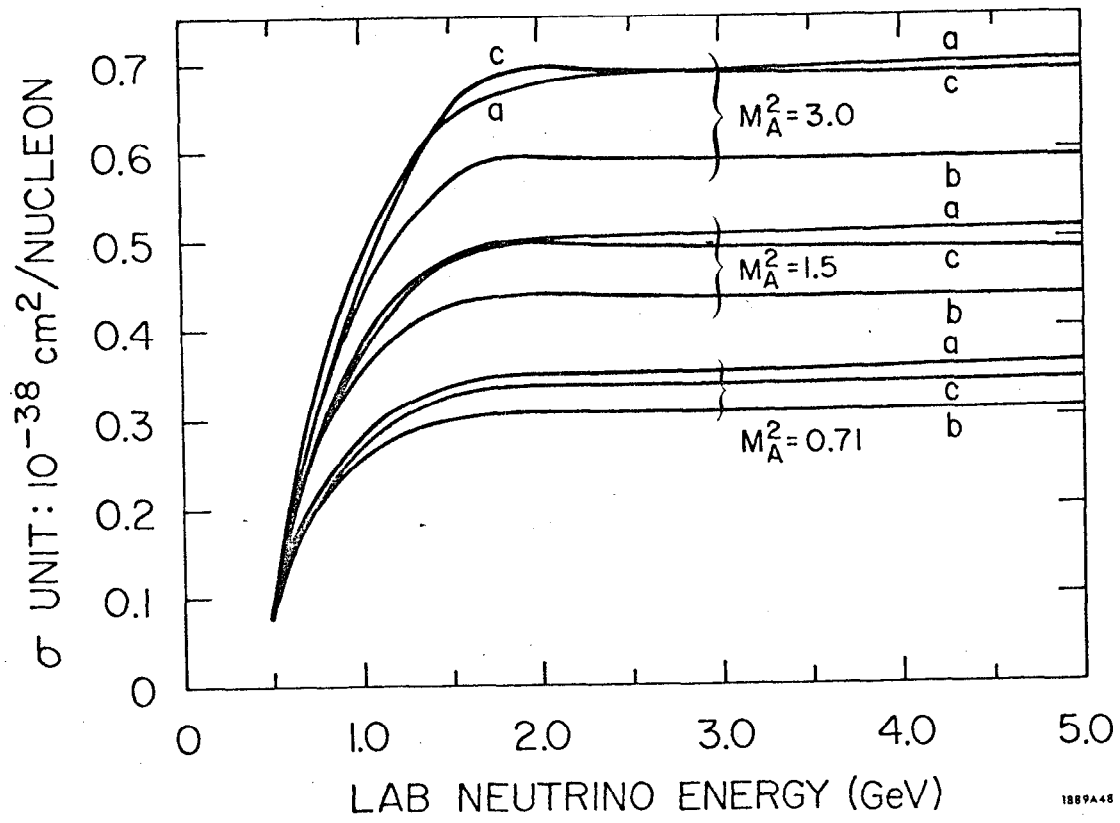


Fig. 28

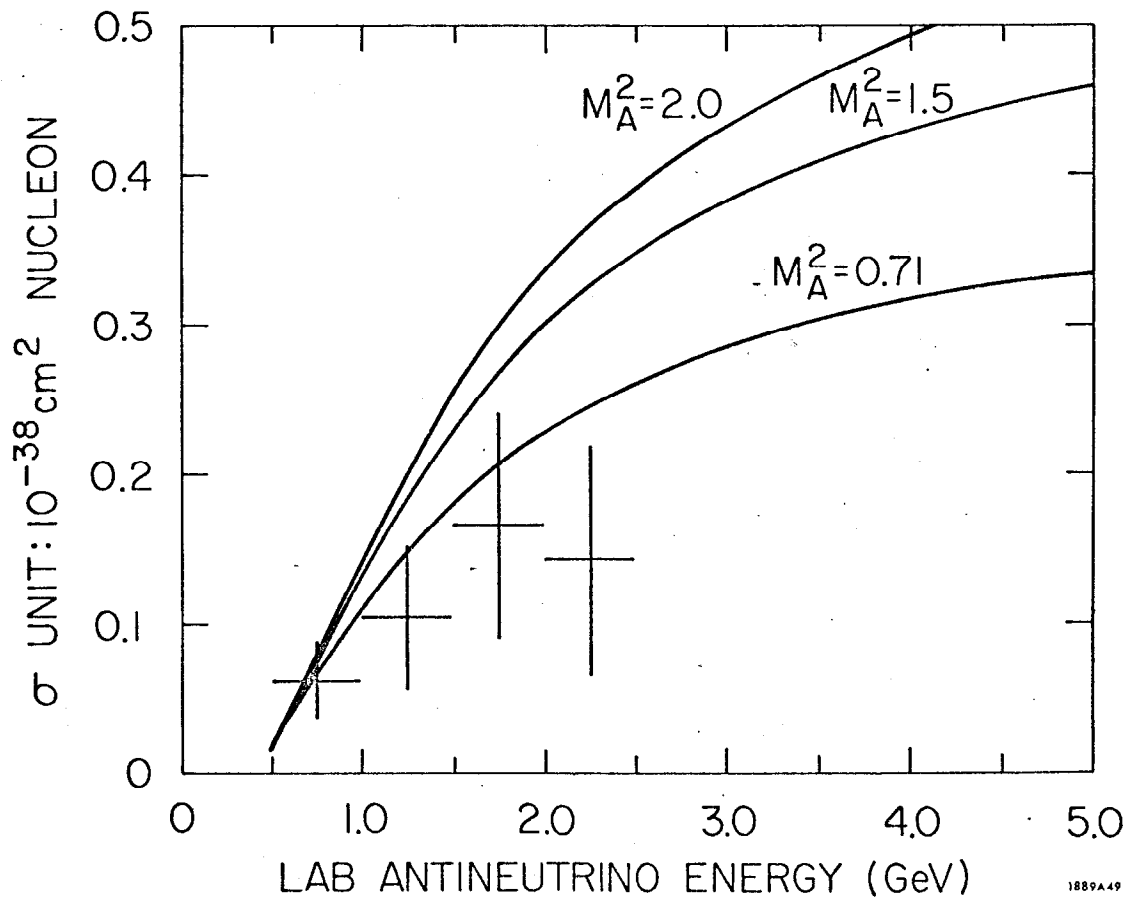
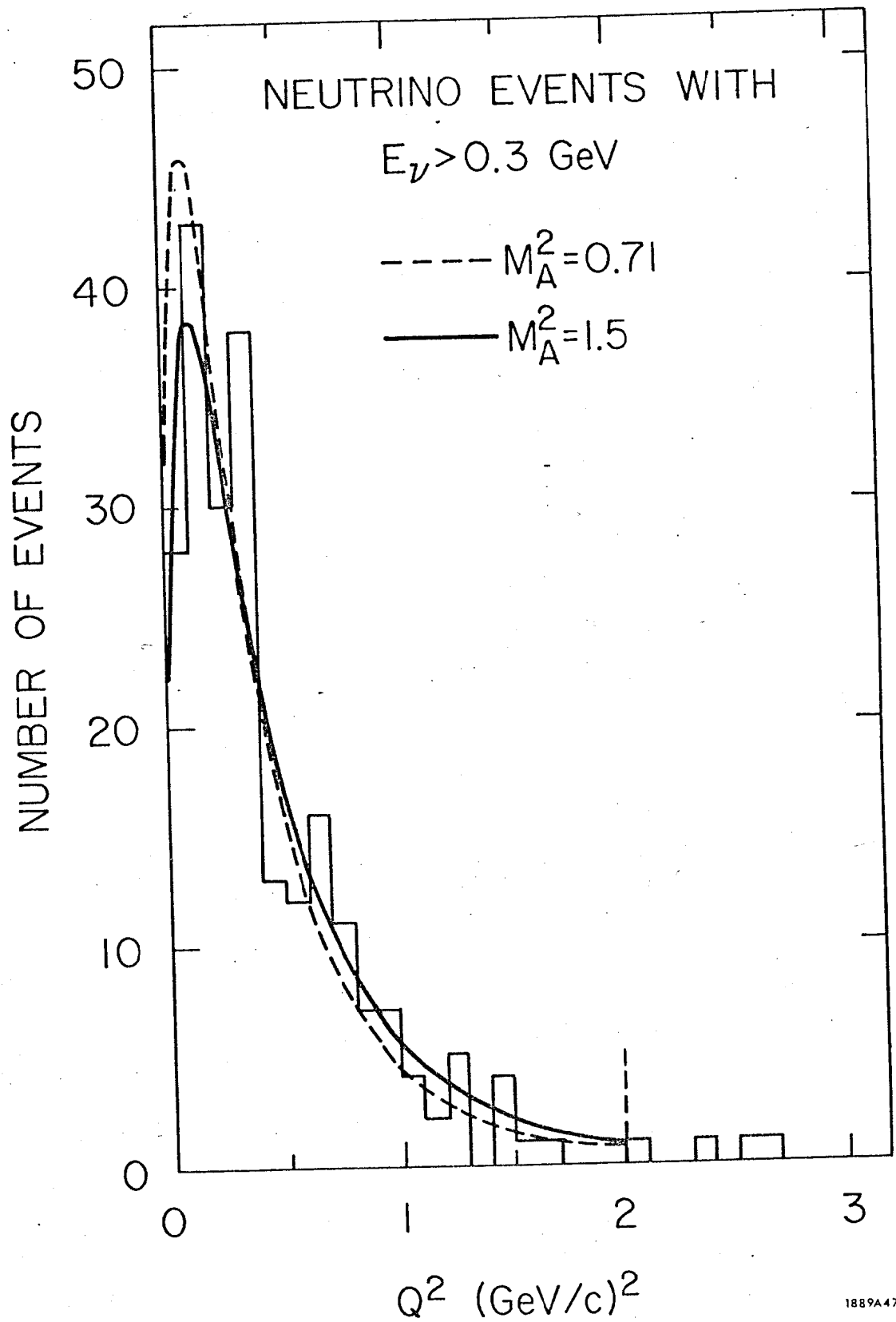


Fig. 29



1889A47

Fig. 30

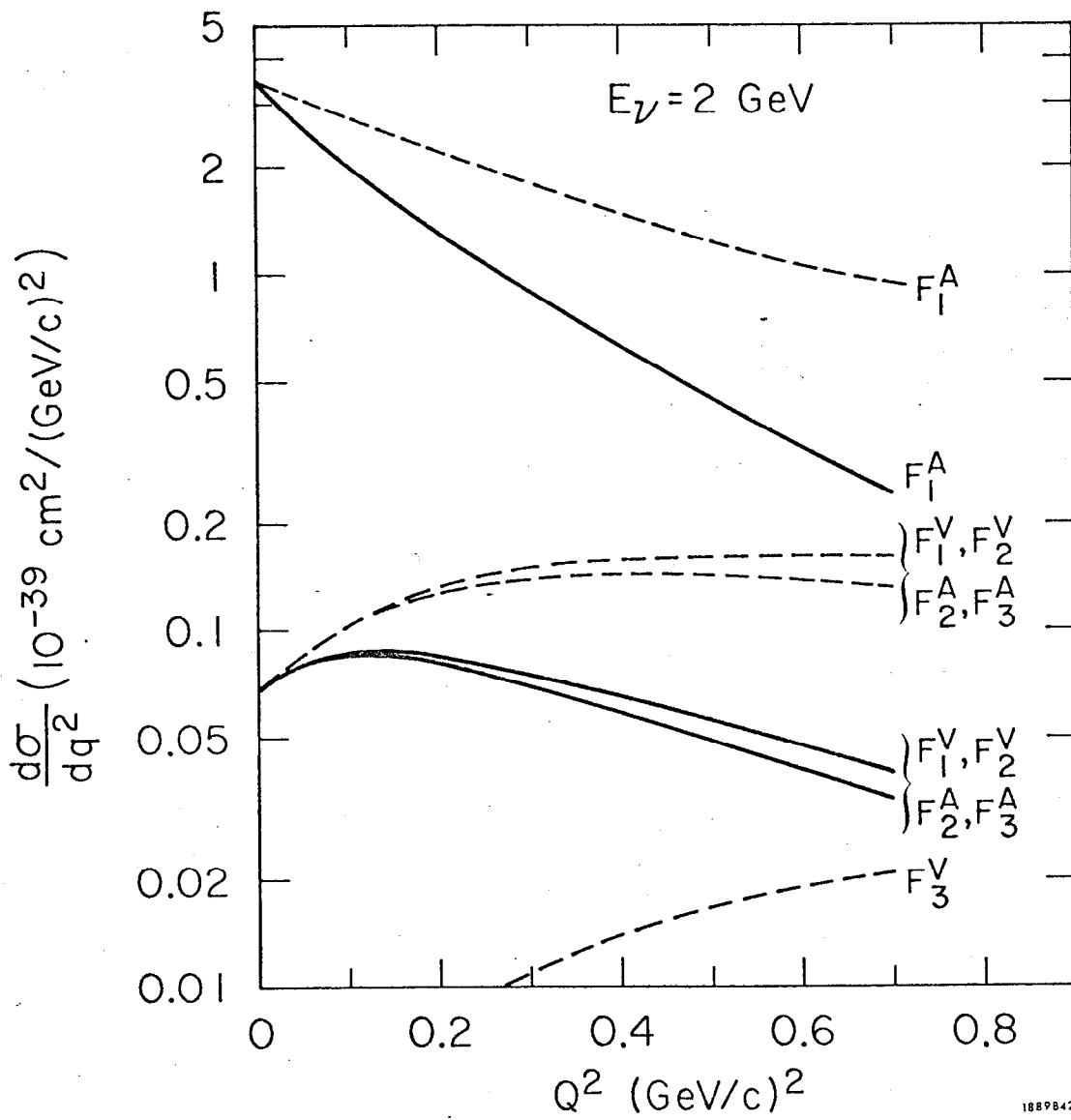


Fig. 31

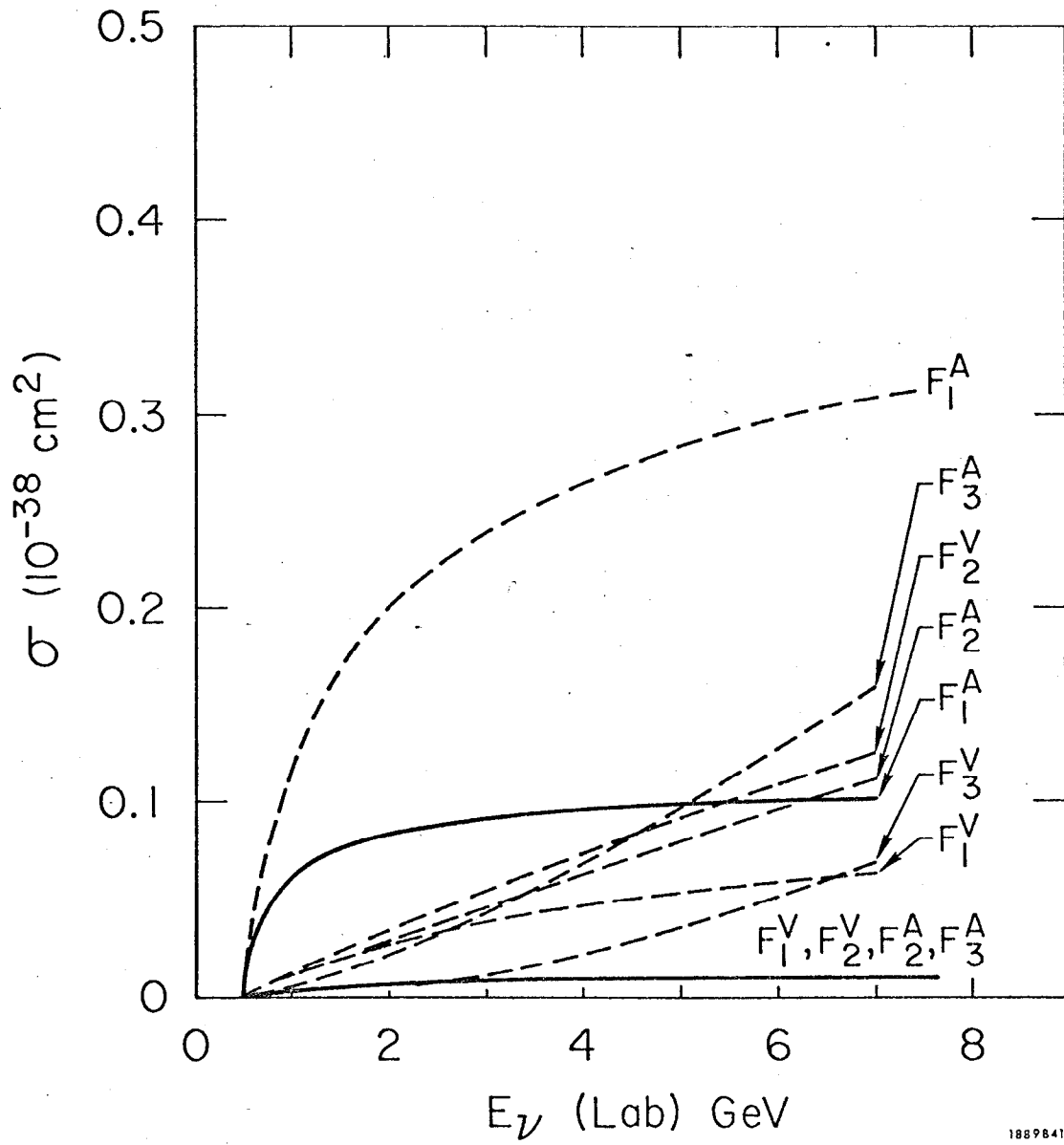
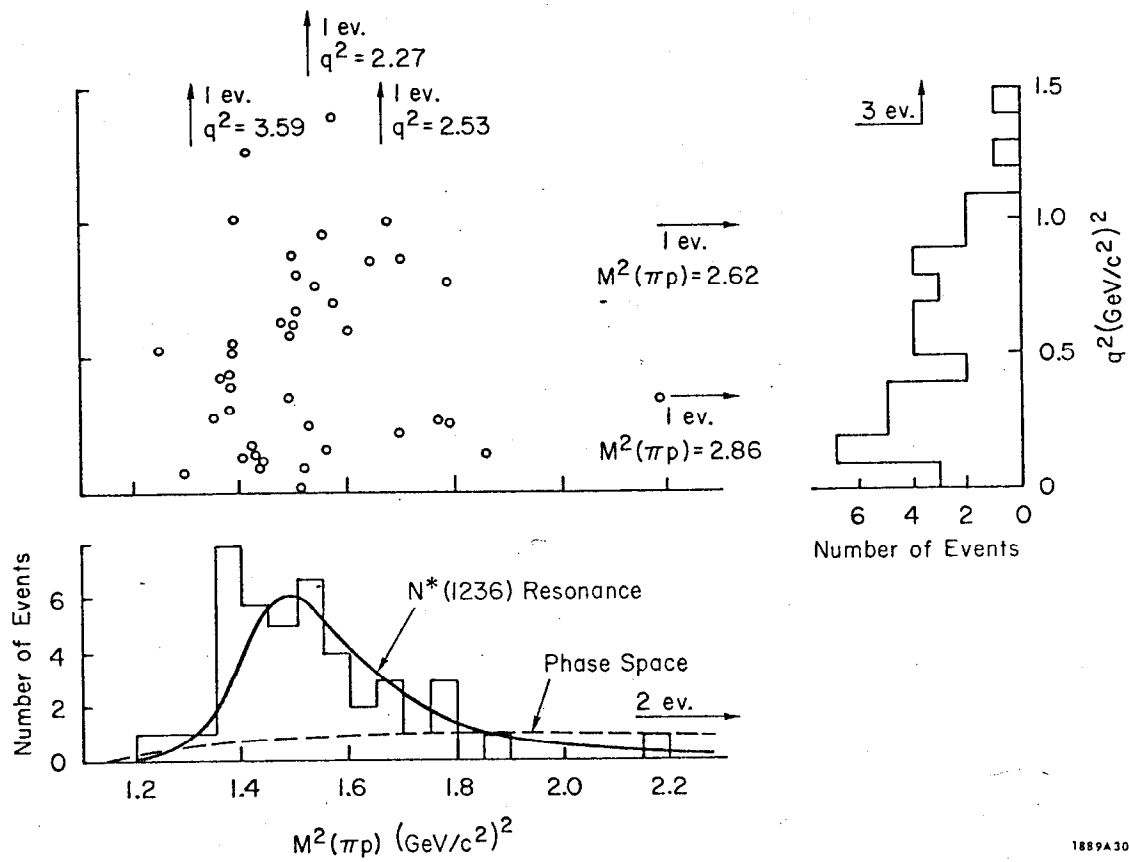


Fig. 32



1889A30

Fig. 33

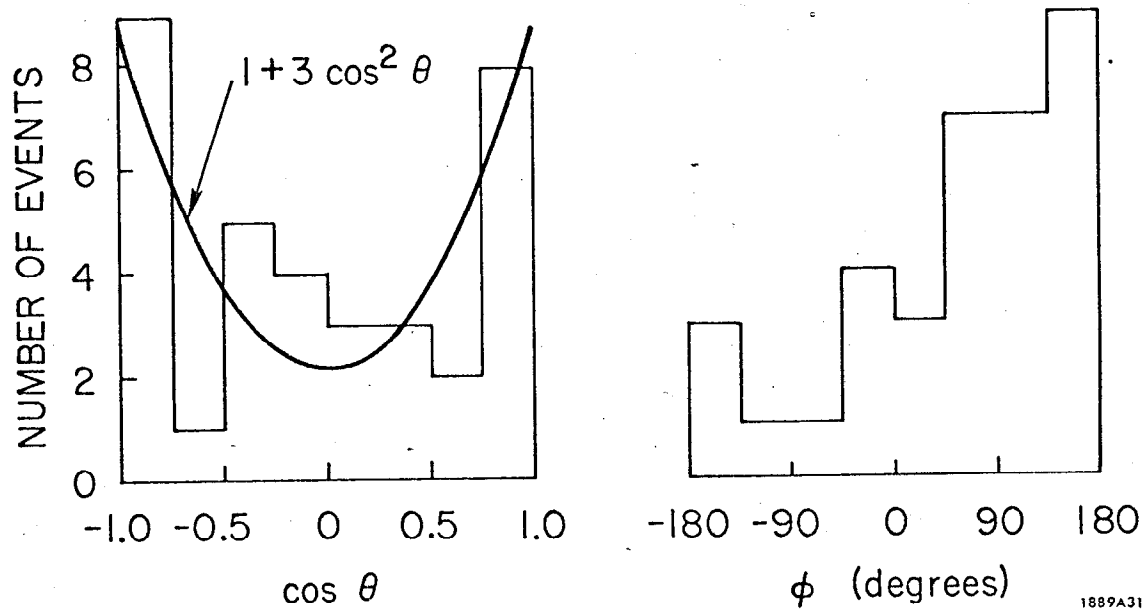


Fig. 34

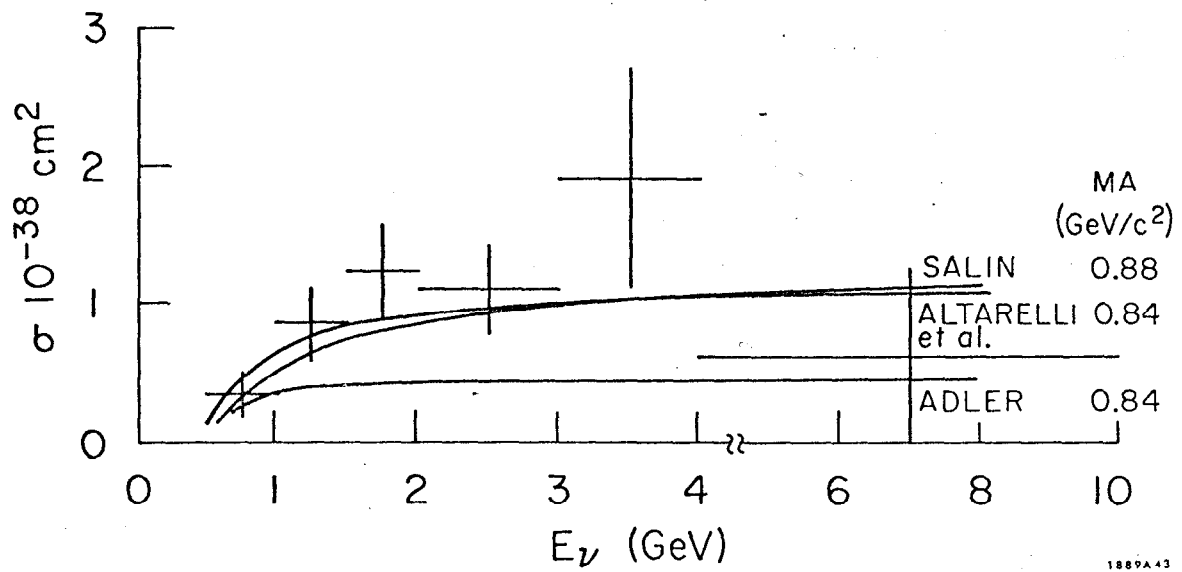
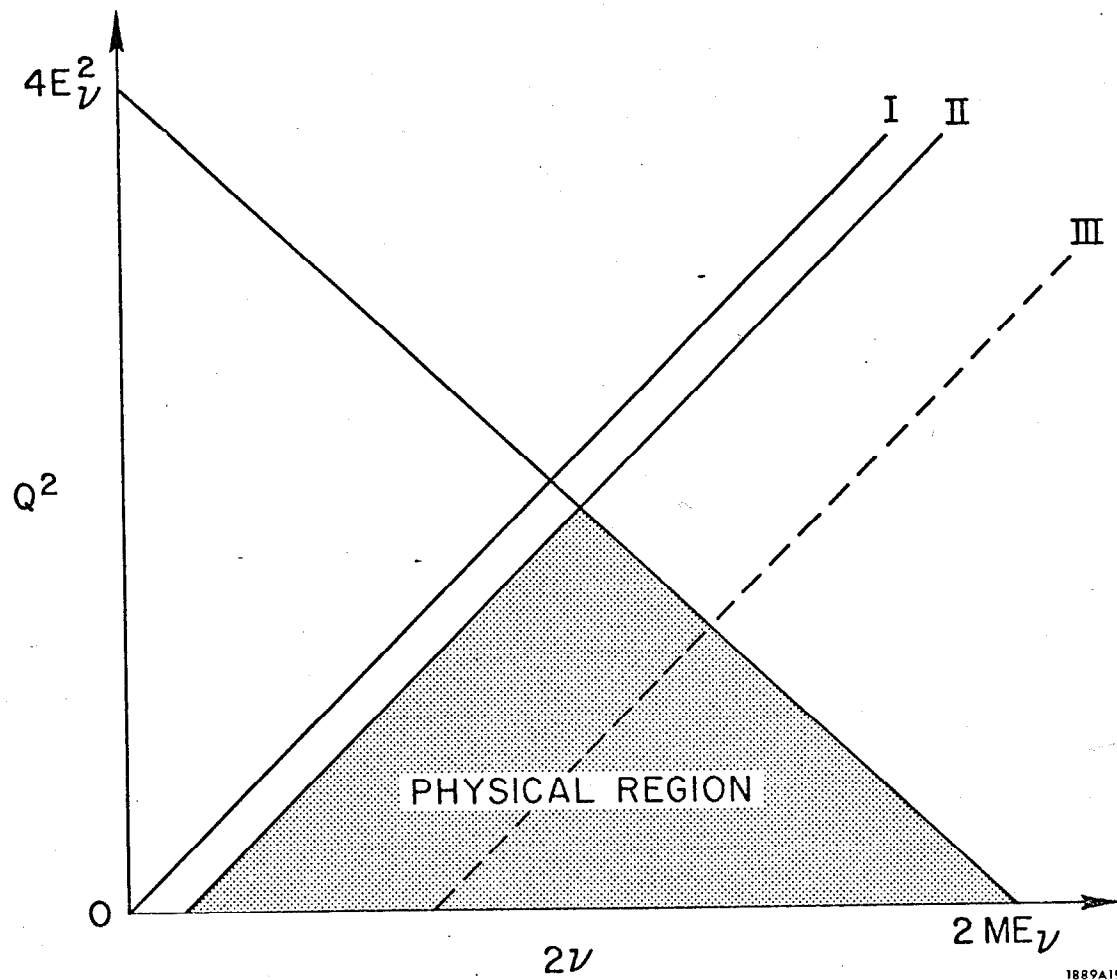
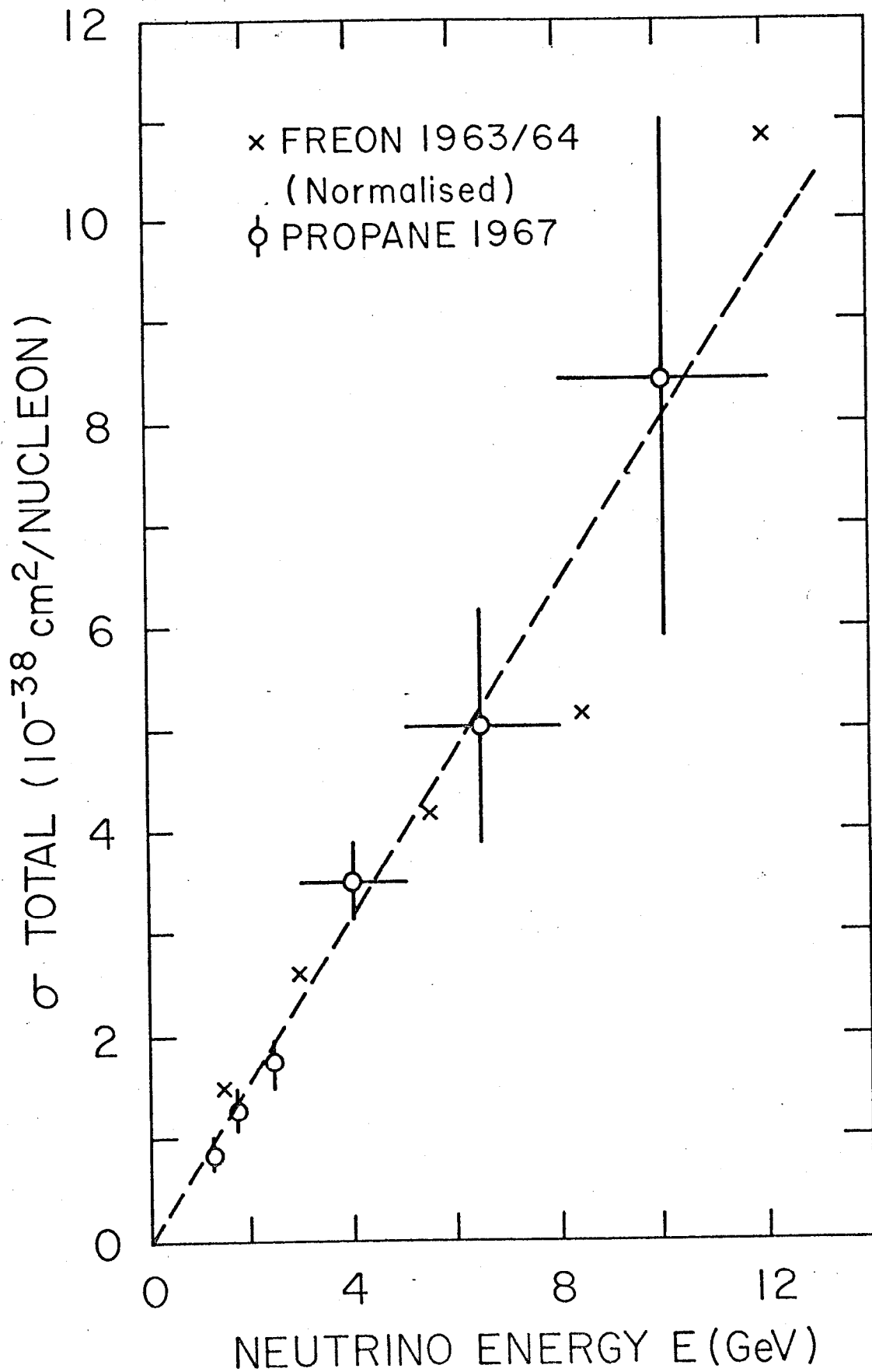


Fig. 35



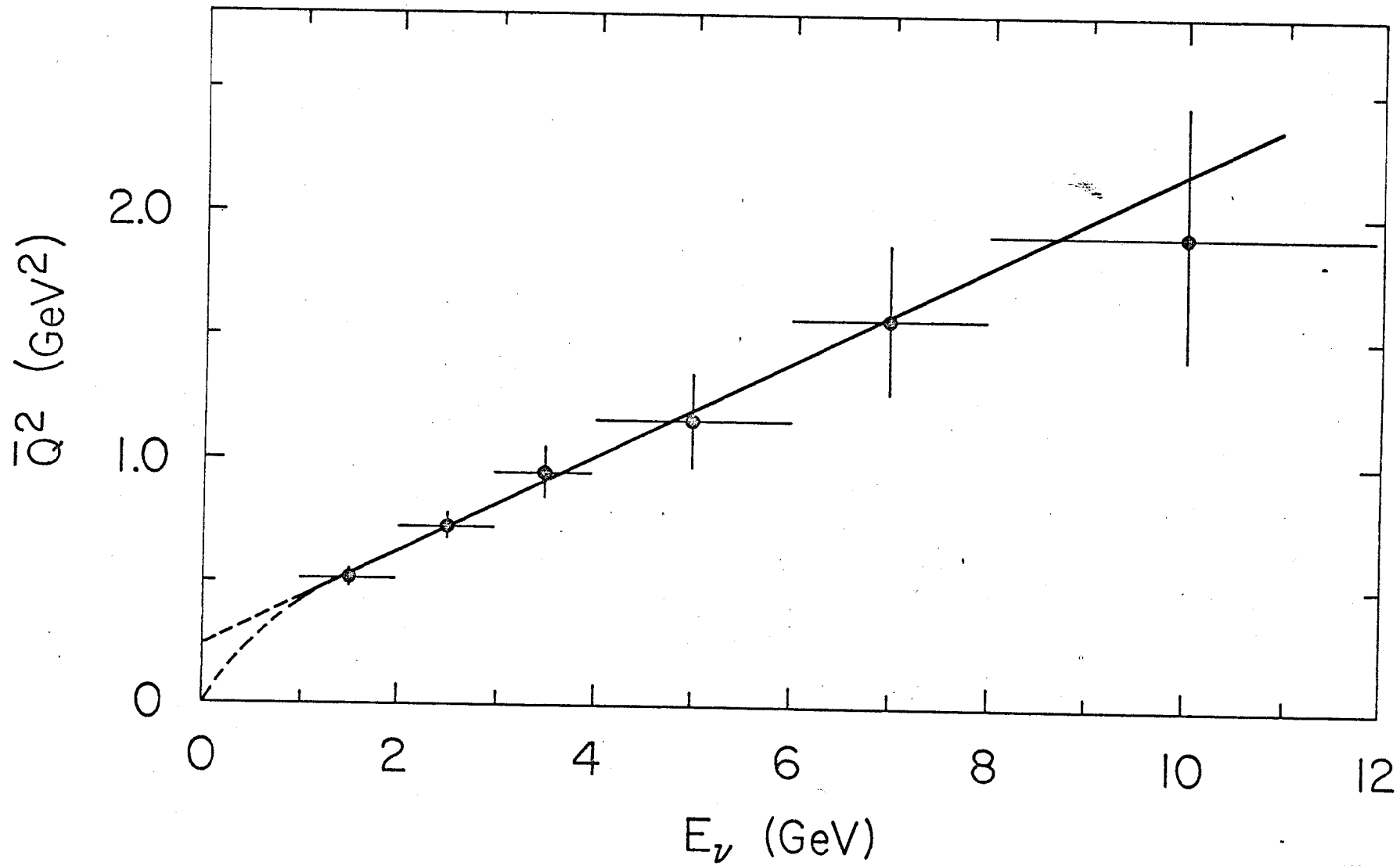
1889A19

Fig. 36



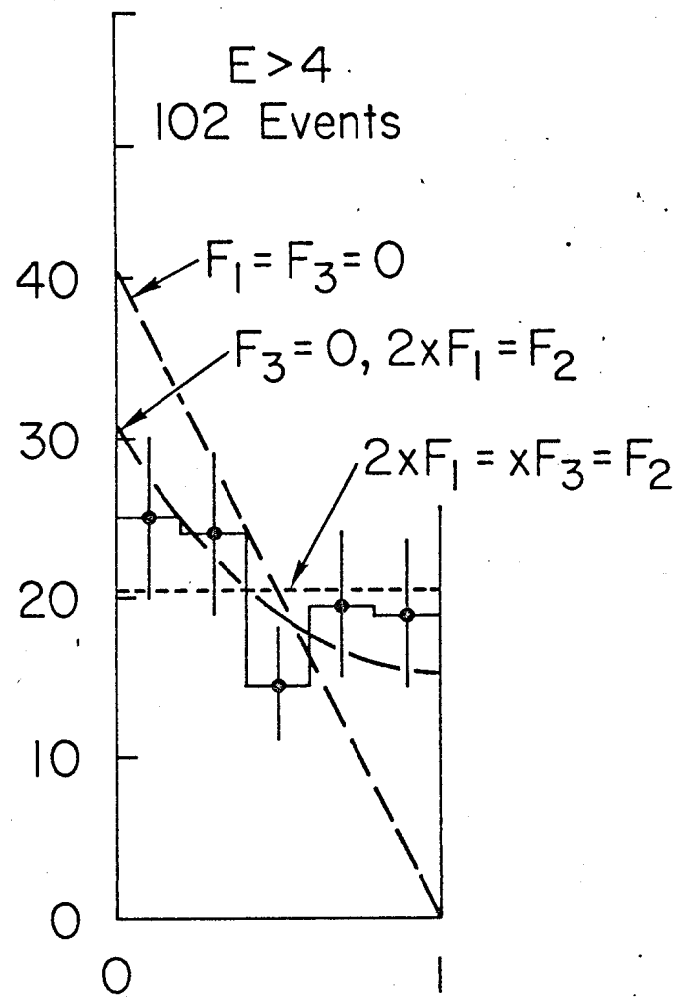
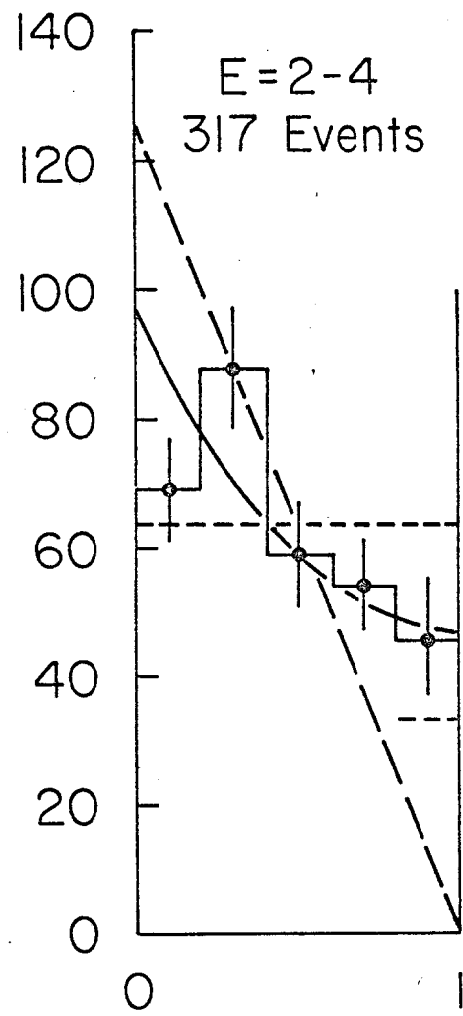
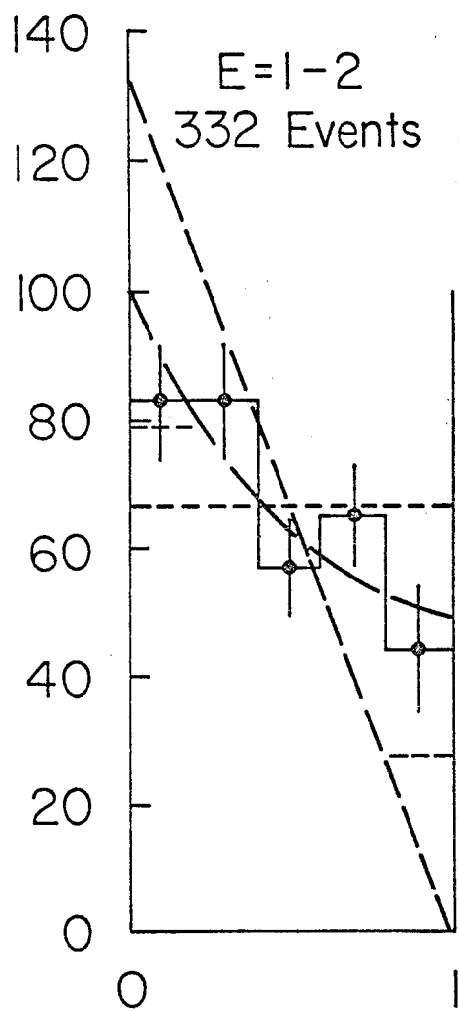
18089A53

Fig. 37



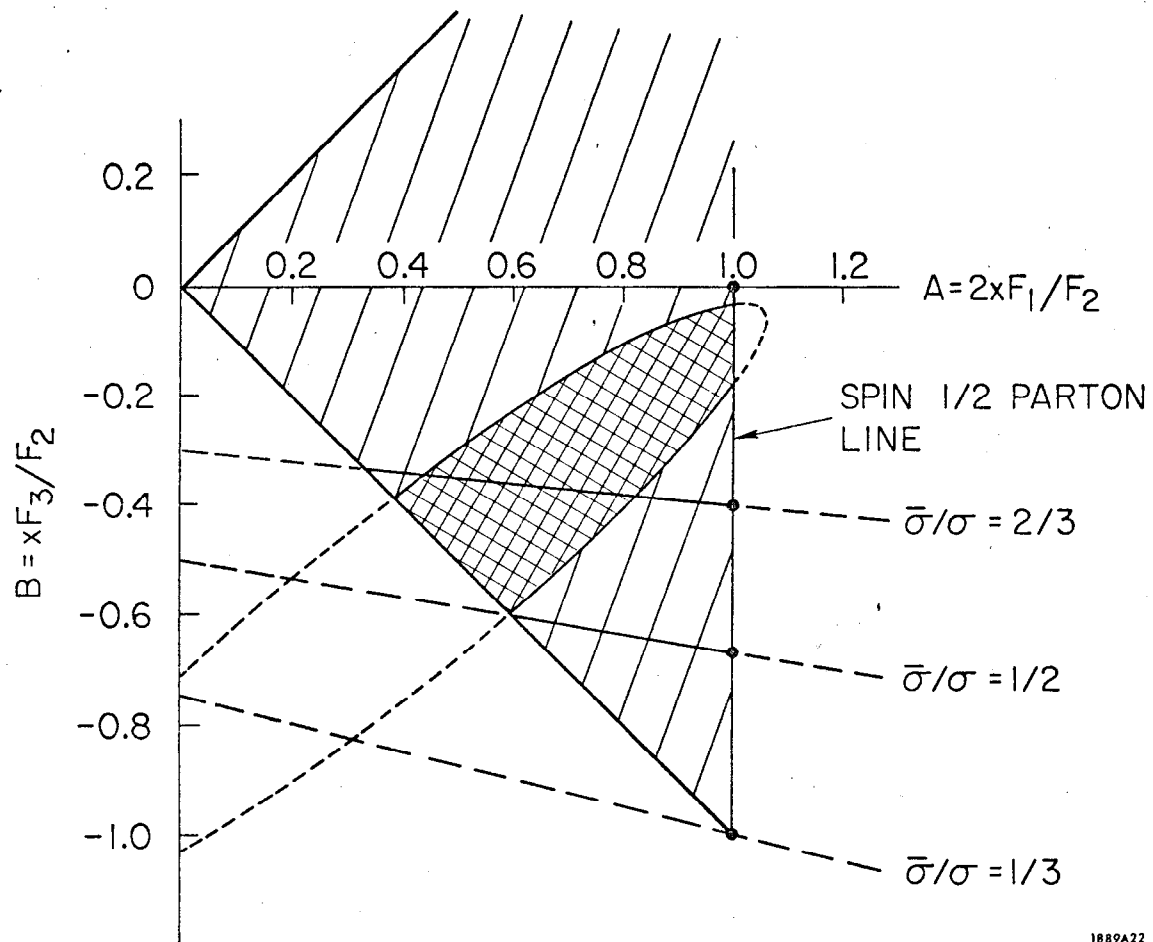
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Fig. 38



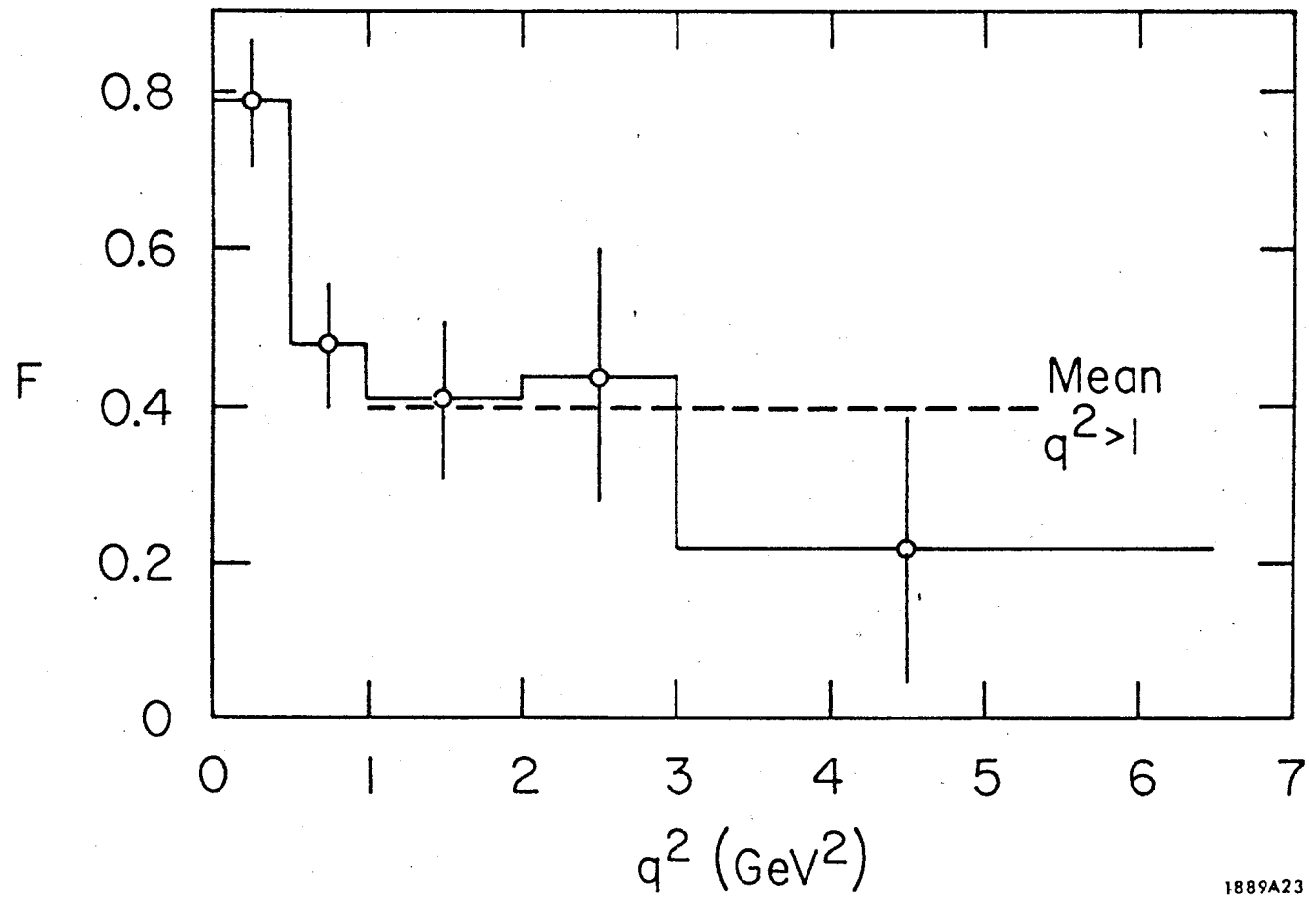
ν/ME

Fig. 39



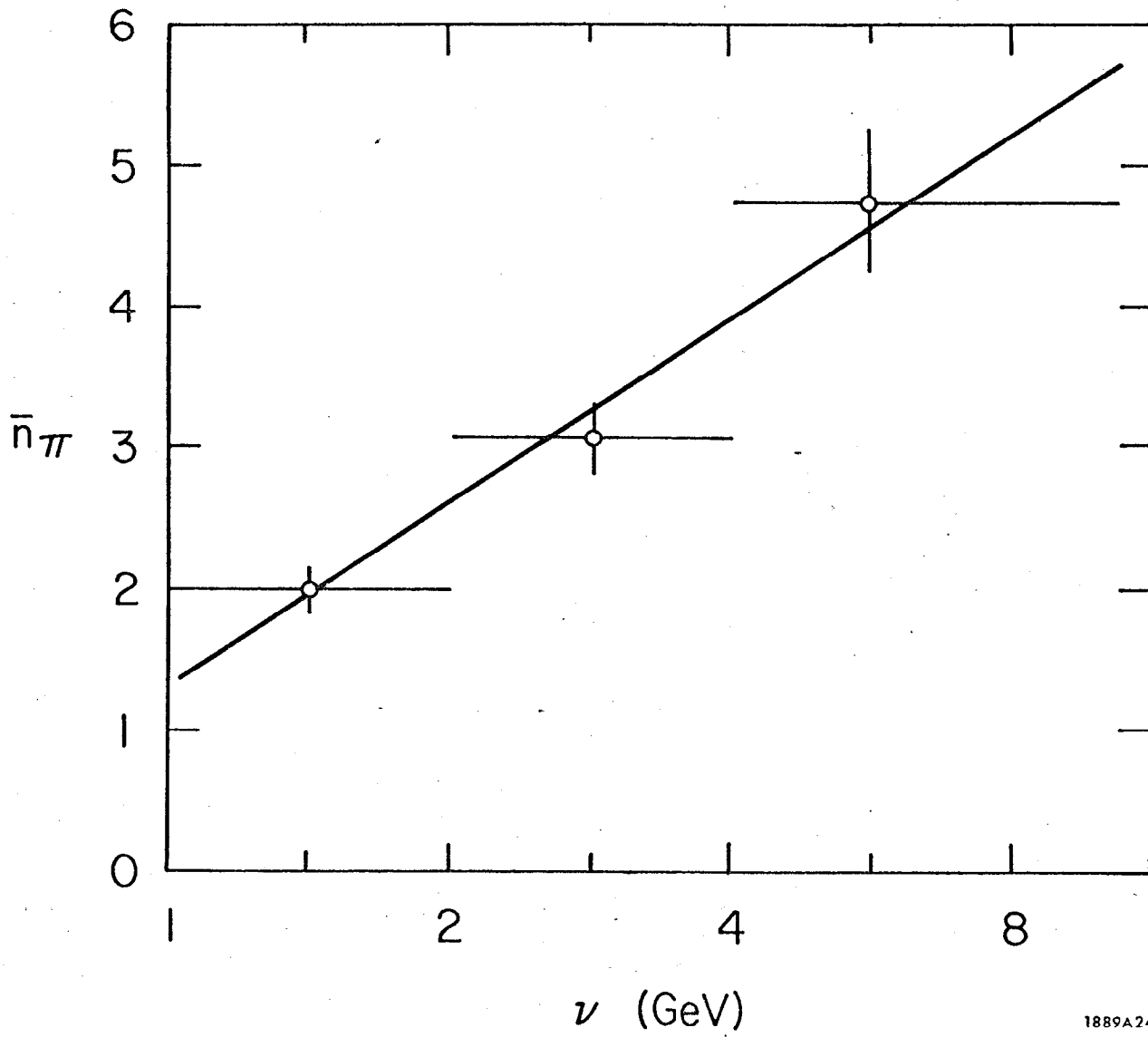
1889A22

Fig. 40



1889A23

Fig. 41



1889A24

Fig. 42

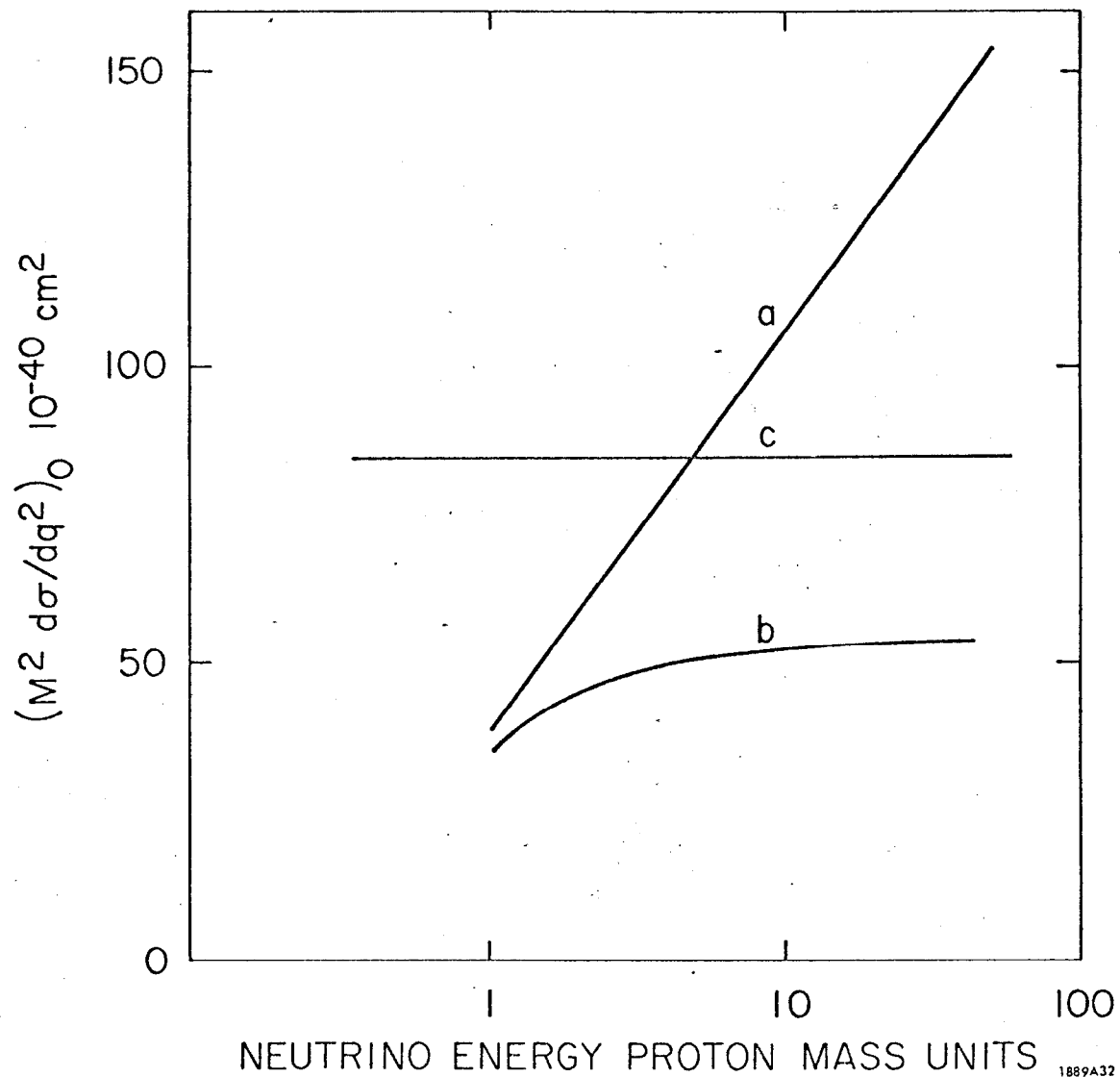


Fig. 43

1889A32

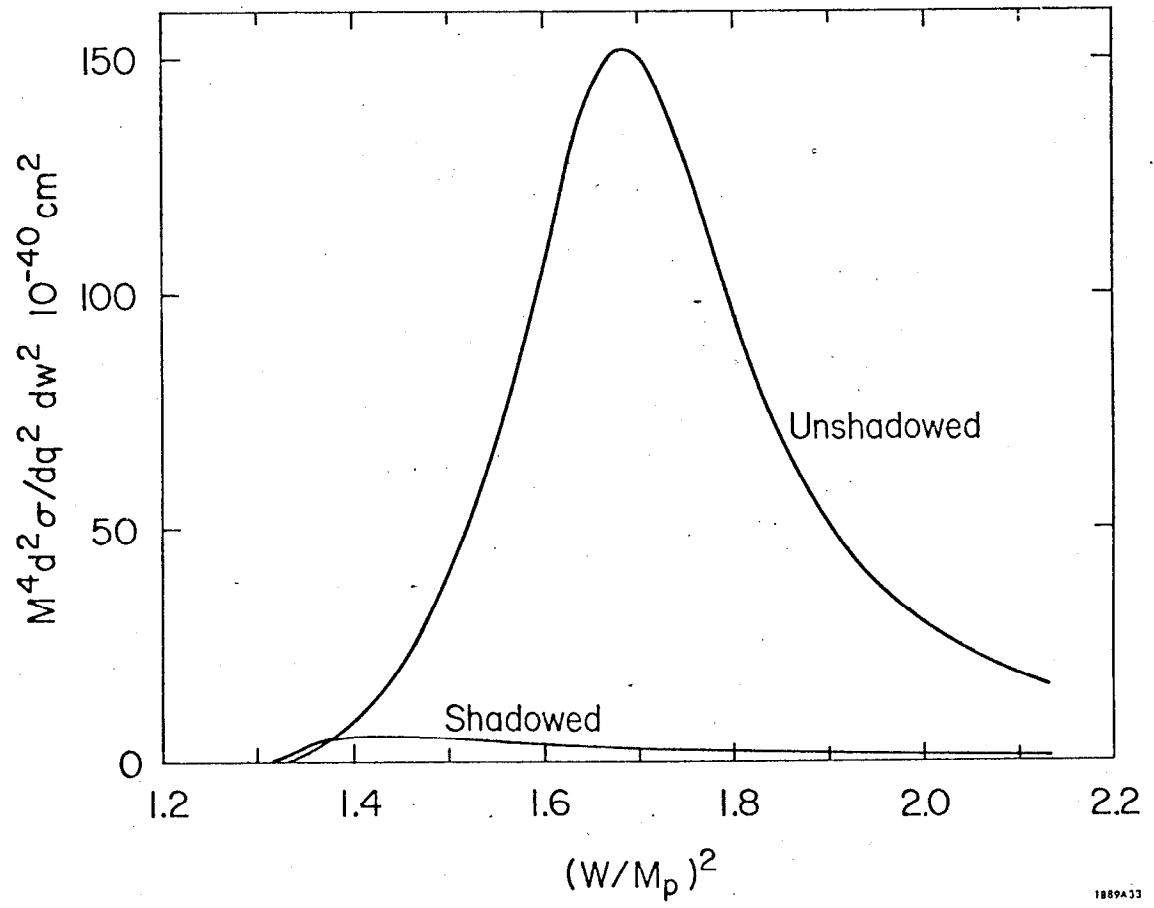


Fig. 44

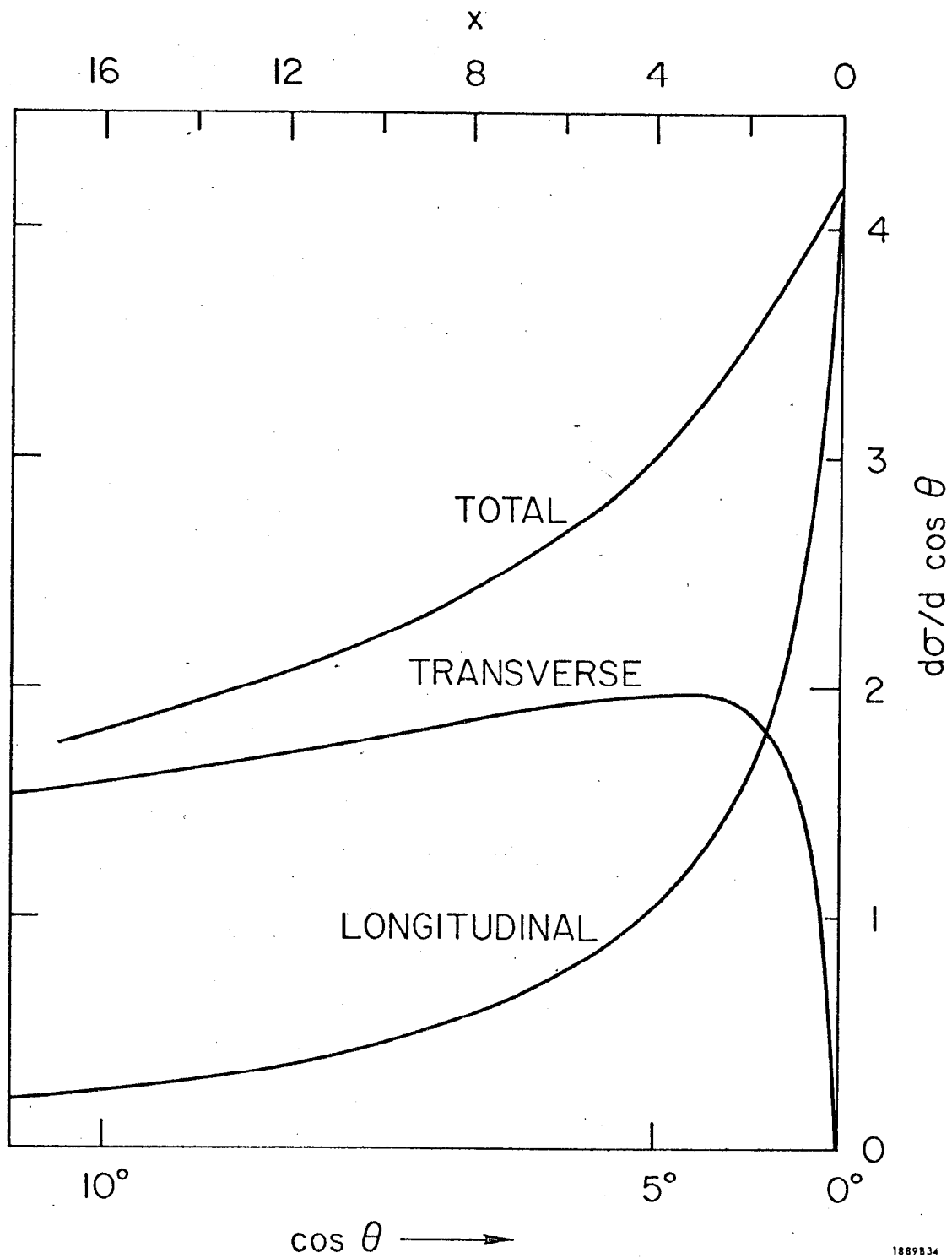
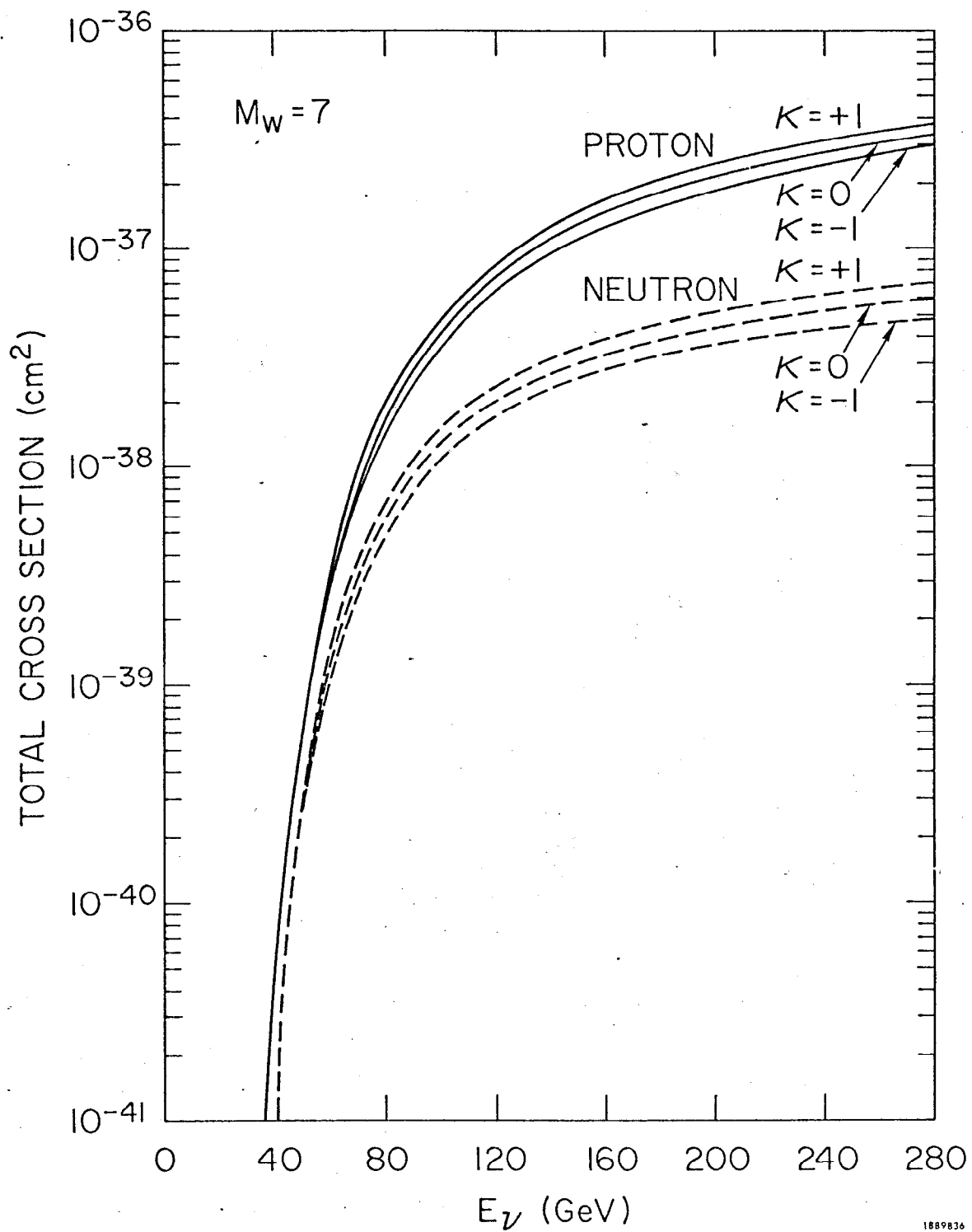


Fig. 45



1889836

Fig. 46

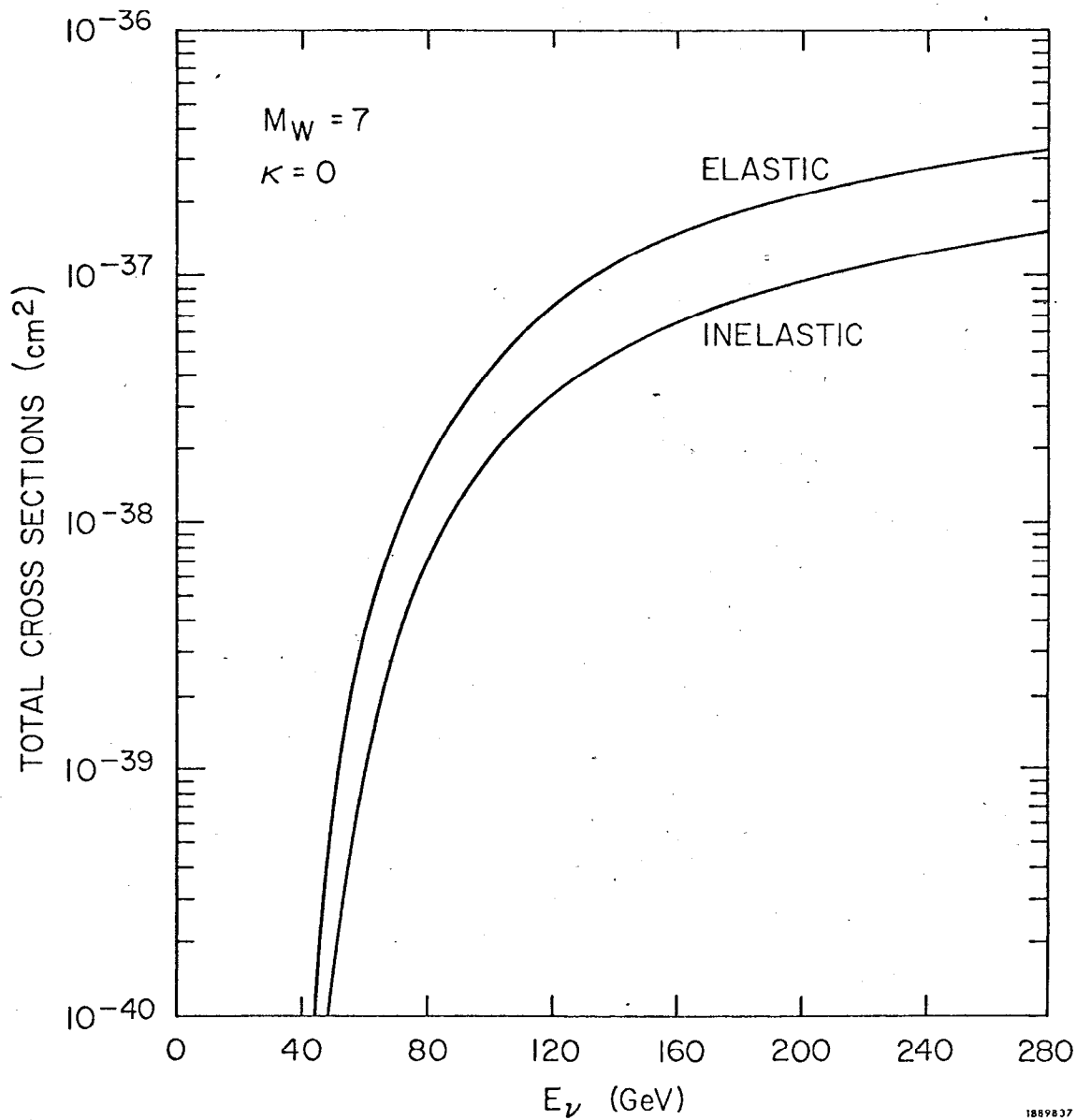


Fig. 47

1889837

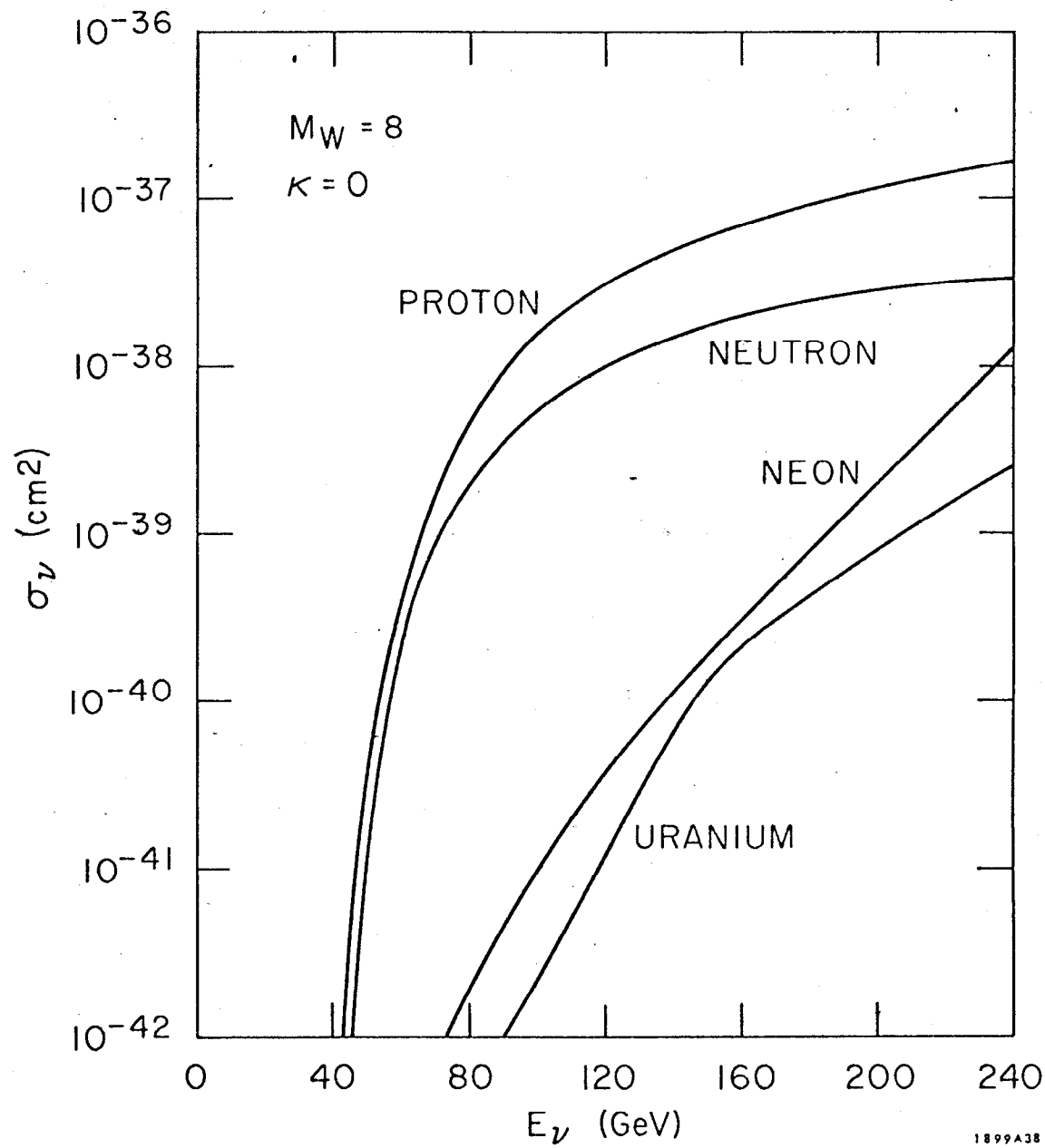
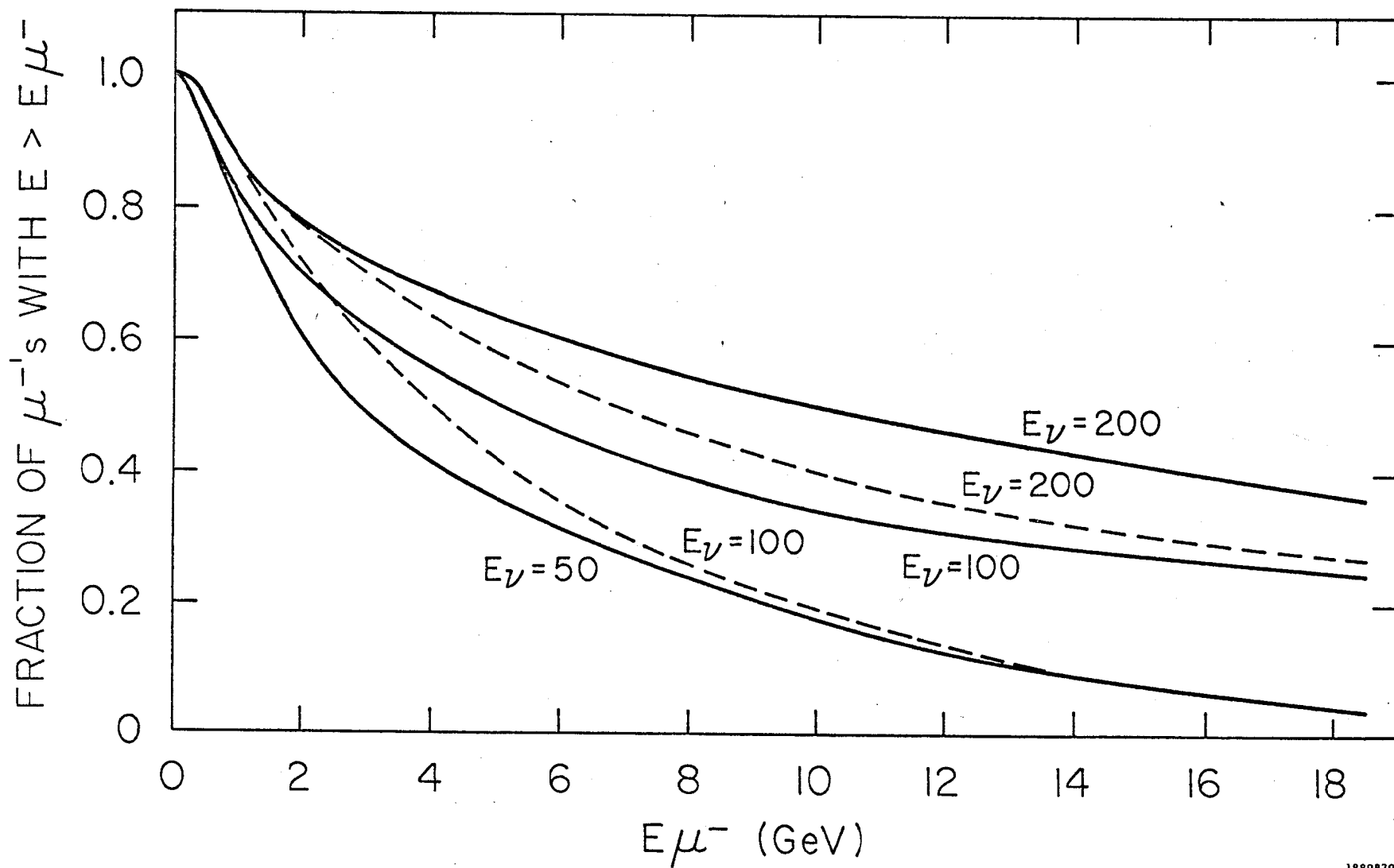
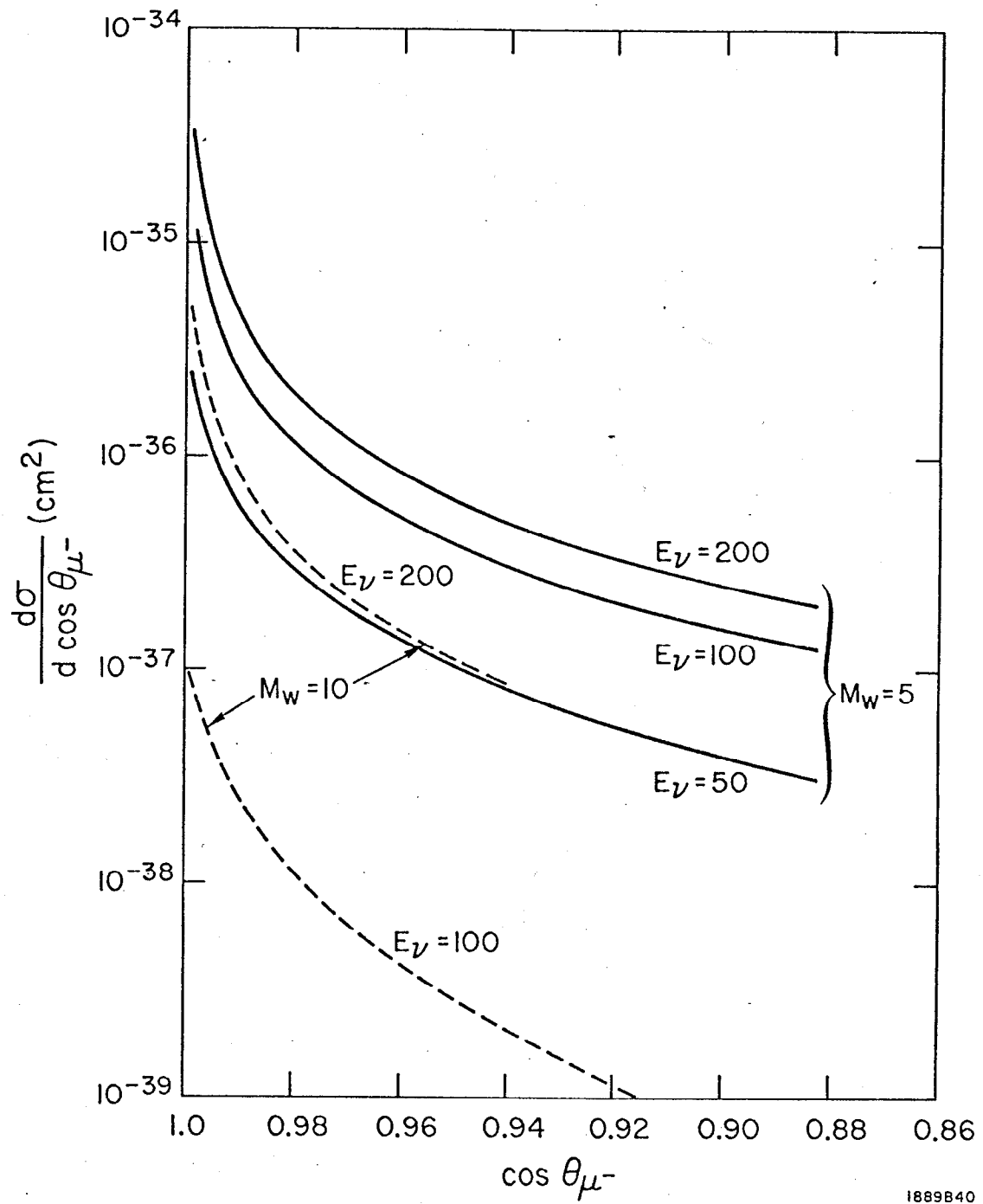


Fig. 48



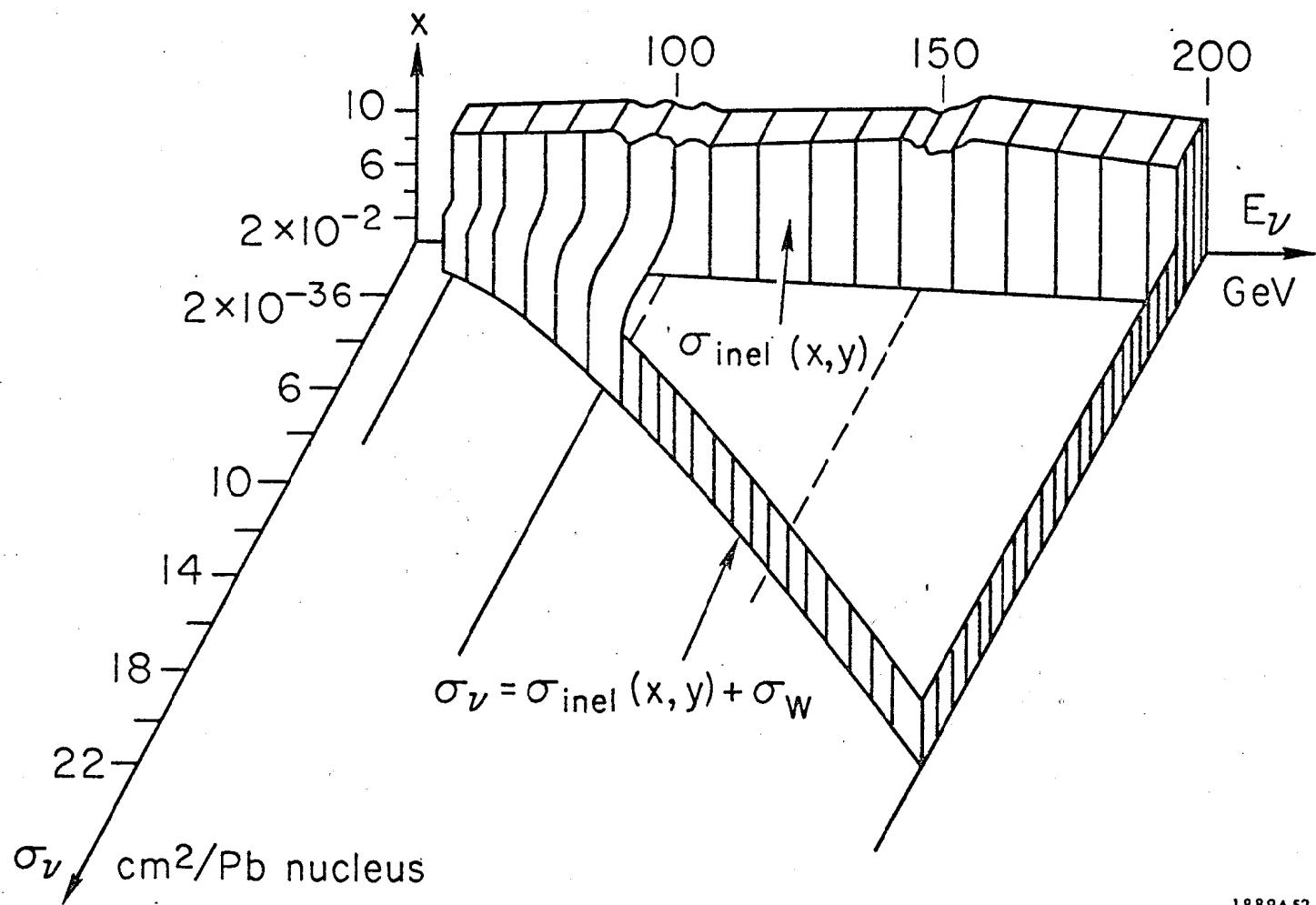
1889839

Fig. 49



1889B40

Fig. 50



1889A52

Fig. 51

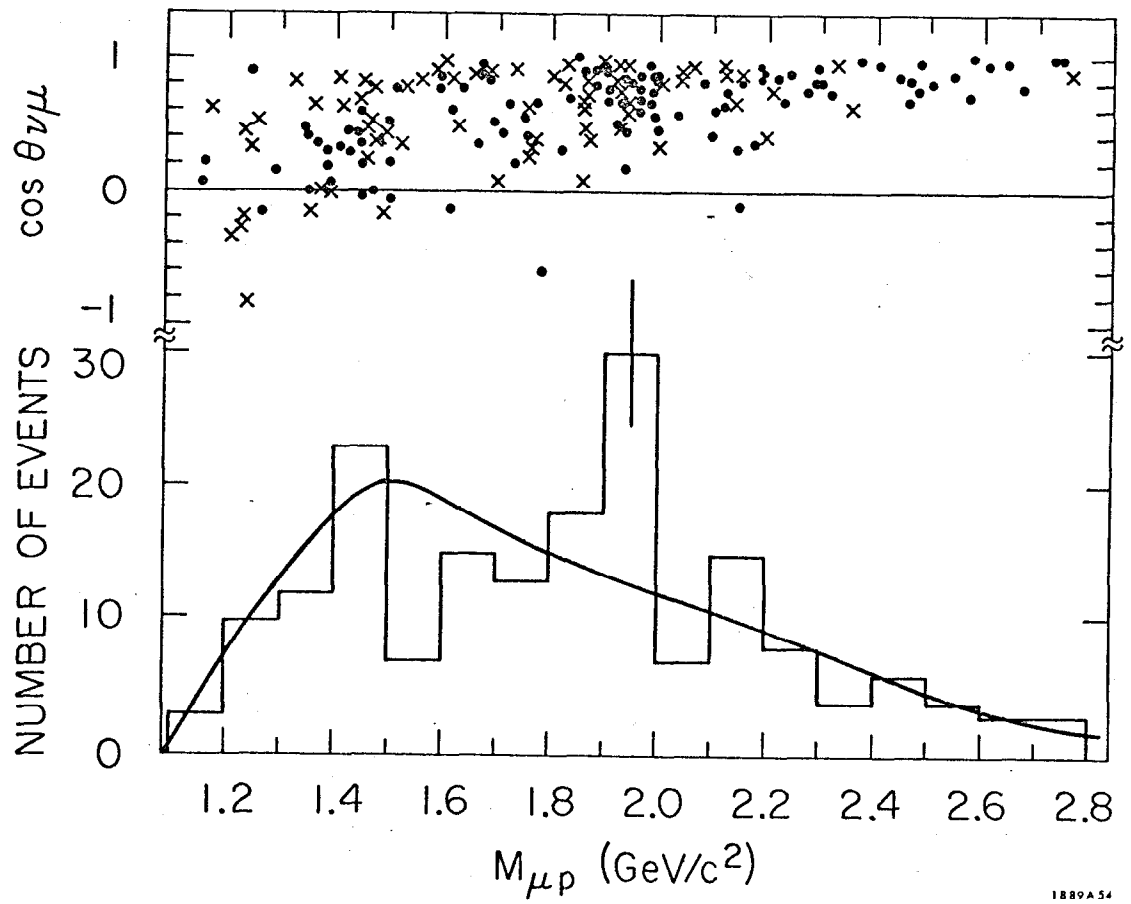
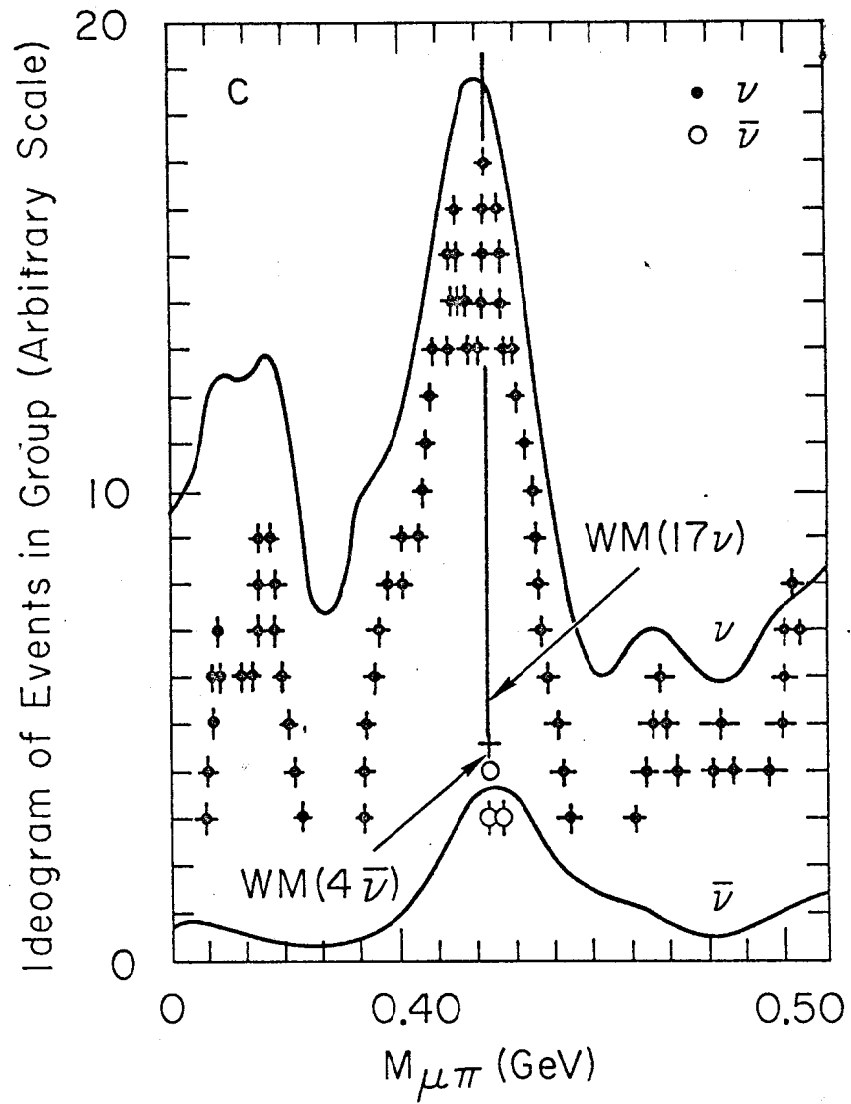
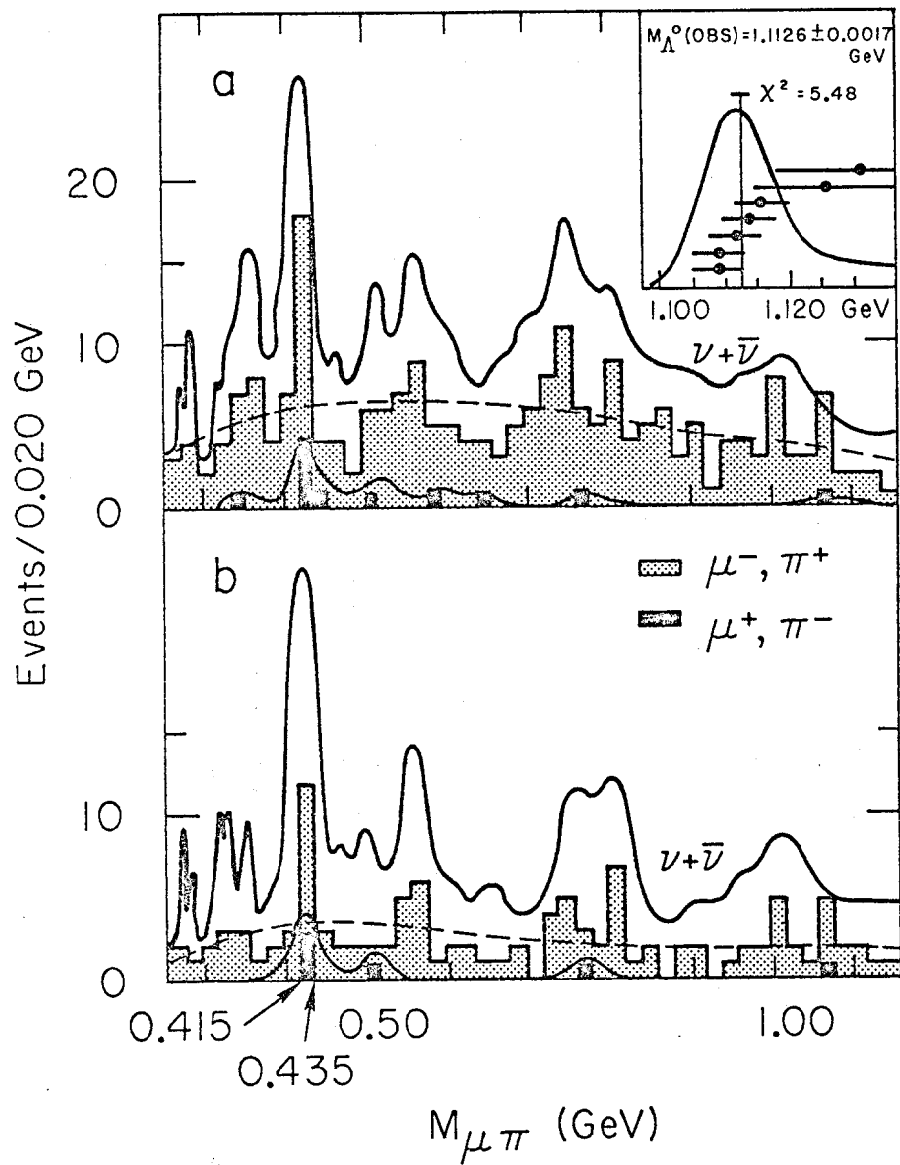
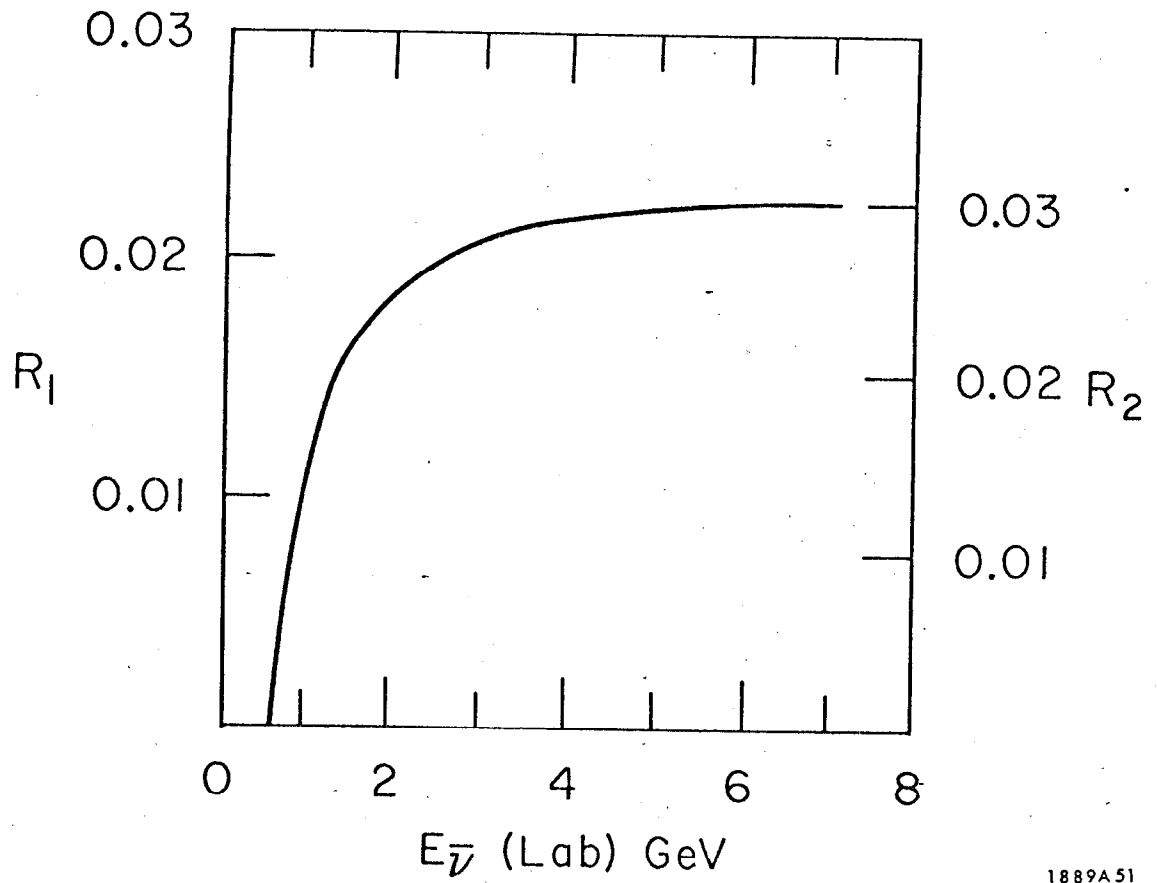


Fig. 52



1889850

Fig. 53



1889A51

Fig. 54