Fermi National Accelerator Laboratory

FN-434
2060.000

THE INTENSITY AND SPECTRA OF LEPTONS EMERGING FROM A HIGH DENSITY BEAM DUMP

Jorge G. Morfín
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

July 1986

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

The Intensity and Spectra of Leptons Emerging from a High Density Beam Dump

Jorge G. Morfín
Fermilab, Batavia, Il. 60510

There is currently an effort underway to redesign the Direct Neutral Lepton Facility (DNLF) such as to make it considerably less expensive. One of the changes will be a redesign of the sweeping magnets which will necessitate a recalculation of the background muon flux traversing the various detectors in the beam line. The end result will be new constraints on the allowable proton dump-detector distances. Since there has also been several new results concerning charm particle production and decay it is an appropriate time for an update of our earlier calculations[1] of neutrino and anti-neutrino spectra emanating from the dump, and event rates in the Tohoku and 15-Foot bubble chambers. In addition, the same methods will be used to calculate the muon spectra produced in the dump since various attempts to calculate this spectra in the original DNLF calculations[2] differed by several orders of magnitude.

METHOD AND CALIBRATION

As in the earlier calculation, the basic Monte Carlo is a modified version of NUADA[3]. This Monte Carlo has been extensively and successfully used to calculate neutrino fluxes both at CERN and at Fermilab. In particular, experiment E-594 has compared[4] the production of neutrino quasi-elastic scattering with both the shape and absolute magnitude of NUADA predictions, as shown in Fig. 1, and found the agreement to be within 15%. This then is assumed to be the inherent error introduced by NUADA in calculating the various lepton spectra and event rates.

There is now an additional calibration of the NUADA predictions using the results of Fermilab Beam Dump Experiment E-613. The details of the experiment are to be found in reference 5 and in the presentation of M.

Crisler at this Workshop. To briefly summarize, the experiment searched for the interaction of neutrinos in a massive 47 ton calorimeter located 57 m downstream from the primary proton dump. The source of the neutrinos was presumably D-meson production and decay (prompt) and

those pions and kaons (conventional) which decayed before they could interact in the dump. The initial 400 GeV protons were cascaded through the dump assuming that the proton inelasticity (ε) was 0.3 and that $\sigma(D)$ scales as $S^{1.3}$. Both of these assumptions are questionable with measured values of ε varying as high as 0.5 for these energy protons and a slower growth of $\sigma(D)$ at higher S favored by some theoreticians. Whether ε is 0.3 or 0.5 does not have a major effect on the results, but the correct S dependence of the cross section is crucial in scaling up to Tevatron energies. For the part of the experiment which attempted to determine the A-dependence of $\sigma(D)$, dumps of Be(A=9), Cu(A=64) and W(A=184) were used. The total exposure was 2.9×10^{17} protons on target with the majority on the W-dump. The results essential for the calibration of NUADA were;

1. $\sigma(D)$ scales as $\mathbf{A^{0.75}}$.
2. With this A-dependence, $\sigma(D)$ = **(57.2±2.9±8.5) μb/N.**
3. $d\sigma(D)/dx_F \propto x_F(1-x_F)^{3.2 \pm 0.2}$.
4. $d\sigma(D)/dp_T \propto e^{-(1.5 \pm 0.2)p_T}$.
5. In the W-dump exposure **(53 ± 6)** prompt υ plus $\bar{\upsilon}$ events per 10^{16} incident protons were found.

There are two comments concerning the above results that should be kept in mind; this is the first experiment to explicitly measure an $\mathbf{A^{0.75}}$ dependence of $\sigma(D)$ and, contrary to those experiments which directly measure D production, $\sigma(D)$ is determined by **assuming** that all prompt neutrinos come from D production and decay i.e. if there are additional sources, $\sigma(D)$ will be overestimated.

The cross check of NUADA with the above E-613 results was performed by modeling the experimental configuration and the above results 1. - 4. then seeing what NUADA predicts as the sum total $\upsilon + \bar{\upsilon}$ events and their energy distribution. The results were a prediction of **42 ± 8** events for $\varepsilon = 0.3$ (10% less for $\varepsilon = 0.5$) which is just over one

standard deviation away from the E-613 result. The energy distribution is shown in Fig. 2. NUADA predicts a harder υ energy distribution than was found by E-613 and, in particular, 25% fewer events with $E_\upsilon < 40$ GeV. In general, the agreement is good -- within 1.5 s.d. -- but not spectacular. Assuming results 1, 4, 5 above and inelasticity of 0.5, the <u>best fit from NUADA</u> yields:

i) $\sigma(D) = (88 \pm 13)\ \mu b/N$ for $A^{0.75}$

ii) $d\sigma/dx_F \propto x(1-x_F)^{4.0}$

If D production follows a linear A scaling dependence, then:

$$\sigma(D) = (24 \pm 4)\ \mu b/N \text{ for } A^{1.0}.$$

This value is consistent with the hydrogen bubble chamber results of $\sigma(D) \approx 20\ \mu b$ for this energy. However, it should be emphasized that it is impossible to reproduce the E-613 results for Tungsten <u>and</u> Beryllium with an $A^{1.0}$ dependence of σ! <u>Whether the correct A-dependence is $A^{0.75}$ or $A^{1.0}$ is not critical for this exercise.</u> <u>What is significant is that with an effective crosssection on Tungsten of $\boldsymbol{\sigma_W(D) = 103\ \mu b}$ NUADA can reproduce the E-613 results.</u> Let me emphasize again that there is an alternative approach. As can be seen from Fig. 3, even the scaled-up D production of prompt neutrinos does not fit the E-613 results at low energies. It is quite possible that there is another source of relatively lower energy prompt leptons that we are not considering which is causing us to overestimate $\sigma(D)$.

The last step necessary before predicting event rates at the Tevatron Beam Dump is to scale the above results from $E_P = 400$ GeV ($\sqrt{S} = 27.4$ GeV) to $E_P = 1$ TeV ($\sqrt{S} = 43.3$ GeV). As mentioned before, even this is not straightforward. If one assumes the $S^{1.3}$ scaling a la E-613 then

$$\frac{\sigma(\sqrt{S} = 43.3 \text{ GeV})}{\sigma(\sqrt{S} = 27.4 \text{ GeV})} = 3.3$$

However, Bourquin and Gaillard[6] have derived an energy dependence as in

Fig. 4 which predicts that $\sigma(D)$ should only increase a factor of 2.0 between 400 GeV and 1 TeV. A good indication of which energy scaling is closer to the truth should be possible when the 800 GeV results become available and can be compared to the 400 GeV results. Bourquin and Gaillard predict that this ratio should be 1.8 while $S^{1.3}$ scaling predicts that this ratio should be 2.5. So as not to have too many figures confusing the issue, Bourquin-Gaillard scaling will be assumed for all figures. Both results will be shown in the tables. The D crosssection at 1 TeV may be summarized as follows

	Effective σ_W	$A^{0.75}$	$A^{1.0}$
B-G Scale	206 μb	176 μb/N	48 μb/N
$S^{1.3}$ Scale	340 μb	290 μb/N	79 μb/N

NEUTRINO EVENT RATES AT THE TEVATRON BEAM DUMP FACILITY

Event rates will be calculated for the two bubble chambers that will be in the beam line. They are assumed to have the following physical characteristics:

1) **Tohoku Chamber**
   <r> = 0.5 meters,
   m = 0.8 tons,
   L(Dump detector separation) = 60 or 90 meters

2) **15 Foot Chamber**
   Holographic Fiducial Volume;
   m = 3.8 tons,
   1/2 within r = 0.6 meters,
   all within r = 1.75 meters
   L = 160 or 190 meters.

In addition to the D crosssection which, when combined with the average D semileptonic branching ratio of 0.101, will give us the rate of υ_μ and υ_e events, we need characteristics of the F meson which will presumably be the source of any tau neutrinos. The main assumption that still must be confirmed experimentally is that,

$$\sigma(F) / \sigma(D) = 0.1 \quad .$$

Presently, the experimental situation indicates that this may be an upper limit! In addition to this ratio of crosssections, the following branching ratios are used as input to calculate the tau neutrino event rates,

$$\mathbf{BR(F \rightarrow \upsilon_\tau + \tau) = 0.02}$$

$$BR(\tau \rightarrow \mu + \upsilon_\mu + \upsilon_\tau) = .185$$

$$e \quad \upsilon_e \quad \upsilon_\tau = .165$$

$$\rho \quad \upsilon_\tau = .221$$

$$\pi \quad \upsilon_\tau = .103$$

The predicted total υ_τ event energy distribution, as well as its various components, is shown in Fig. 5. The event energy distribution of all types of neutrinos is shown in Fig. 6. The following table summarizes the results.

Neutrino Event Rates for 1 TeV protons on a Tungsten Dump. Bourquin-Gaillard σ Scaling. E_υ > 10 GeV. Events /10^{18} protons.

EVENT TYPE	TOHOKU (90m) 15' (190m)	TOHOKU (60m)	15' (160m)
$\sum\upsilon_\tau$CC	**52 events**	**83 events**	**67 events**
$\sum\upsilon_\mu$ CC	2400	3780	3080
$\sum\upsilon_e$ CC	1760	2870	2240
$\sum\upsilon_{\mu+e}$ NC	1280	2050	1640
$\sum(\upsilon_\mu + \upsilon_e)$	**5440**	**8700**	**6960**
	$\sum\upsilon_\tau / \sum(\upsilon_\mu + \upsilon_e) = 0.01$		
	FOR $S^{1.3}$ SCALING		
$\sum\upsilon_\tau$CC	86	137	110
$\sum(\upsilon_\mu + \upsilon_e)$	8560	13760	10940

If we consider the entire 15' fiducial volume, which has a mass of 11.5 tons, then for Bourquin-Gaillard scaling we expect 124 υ_τ events and 14100 conventional neutrino vertices per 10^{18} protons for 190m dump chamber separation. This can be compared directly with the estimates in the E-645 proposal from 1980. At that time, $\sigma(F)/\sigma(D)$ was taken to be 1/3 and the BR($F \rightarrow \tau + \upsilon_\tau$) was assumed to be 3%. The ratio σ(D: 1TeV) / σ(D: 0.4TeV) used was 2.1 and the dump to 15' chamber distance was set at 200m. With this input the proposal stated that 600 υ_τ events per 10^{18} protons should be produced in the total fiducial volume. We can update this with our current knowledge as follows;

$$600 * \frac{0.1}{1/3} * \frac{2\%}{3\%} = 120$$

This compares quite well with the 124 events predicted above for the full fiducial volume of the 15' chamber.

There is one other experimental configuration that has been discussed. It calls for the dump to be very close to the Tohoku chamber ($\approx$ 20m) and then to extract and dump the 150 GeV protons from the main ring every few seconds. Using either method of σ scaling, σ(D; E_p=150 GeV) = 7.5 μb which is consistent with measured values in this region. Following the same procedures as above for this new configuration,

$$\sum \upsilon_\tau = 0.6 \text{ events} / 10^{18} \text{ protons.}$$

The reason that the event rates have dropped much more sharply than the ratio of the crosssections at the two energies is simply a matter of kinematics. In the F decay there is only 0.18 GeV P* to play with. To produce a neutrino with E > 10 GeV in the lab calls for a boost of > 28 F masses. This in turn implies that only those F's with P > 50 GeV (x_F > .3) will have any chance of contributing events within the cuts. Considering now the $(1 - x_F)^4$ F production spectra explains the meager event rates expected with this configuration.

MUON PRODUCTION SPECTRA

The same methods which have been successfully used to model the E-613 results and to predict neutrino spectra can be employed, with relatively minor kinematic modifications, to predict the muon flux coming from the dump. This has become a critical issue since the bubble chambers can only stand so many muons traversing the liquid during expansion before the pictures become to confusing to be usable. On the practical (i.e. monetary) side, it can cost tremendous amounts to design and construct sweeping magnets to limit this muon flux, so it is important to have as accurate a prediction as possible of the **produced** muon flux at the dump. The various attempts to predict this flux have differed by as much as two orders of magnitude depending on the P and P_T considered.

For the present muon spectra predictions D, π, and K decay will be considered, just as in the estimates of the neutrino rates. The rates are for **900 GeV** protons on a 1.2m **copper** dump for ease in comparison with other calculations. The muon momentum distribution is shown in Fig. 7 for $\theta_\mu < 200$ mr and for $E_\mu > 10$ GeV. Below 40 GeV the distribution is dominated by μ's from K and π decay while μ's from D decay increasingly dominate above 50 GeV. The sum from all three processes is ($E_\mu > 10$GeV) 8×10^{-4} μ/proton. The P_T distribution is shown in Fig. 8 for the prompt and non-prompt sources and for three muon momenta, 30 GeV, 70 GeV and 120 GeV. Above 1.5 GeV the distribution is dominated by μ's from D decay.

There are presently three other main muon production models, which were primarily written by colleagues from MIT, Colombia and Fermilab, plus a multitude of variations on these three major themes. For details see reference 2. For the purpose of comparison the model from MIT is particularly important since it is with this model that the detailed background calculations have been made for the new ("Econo") Beam Dump design. The two important kinematic regions which tend to contribute the

majority of background muons are medium energy and low P_T, and low energy high P_T. The predictions for these crucial regions are compared in the following table:

Predicted μ^+ Flux comparison between the MIT and present (J.G.M) calculations. Units: muons / 10^{13} protons.

P_L (GeV)	P_T (GeV)	MIT	J. G. M.
35 - 40	4.8 - 5.3	4.0 E2	1.2 E3
55 - 60	5.3 - 5.8	2.0 E2	4.3 E2
75 - 85	0.0 - 2.0	2.7 E8	1.5 E8
145-155	0.0 - 2.0	8.5 E7	2.6 E7
215-225	0.0 - 2.0	3.2 E7	8.4 E6

The MIT predictions are a factor of 2-3 lower at high P_T, and 2-3 times higher at low P_T, in comparison to the present calculations. A comparison of these results with measured data can be seen in Figs. 9 and 10. In Fig. 9 the ratio $(\mu^+ + \mu^-)/(\pi^+ + \pi^-)$ is plotted vs P_T. Also plotted are the results of experiments[7,8,9,10] which measured the lepton/π ratio as a funtion of P_T for various values of $\sqrt{S}$. The excellent agreement for $P_T > 1$ GeV can be taken as an indication that $\sigma(D)$ does **not** increase significantly compared to the increase in pion multiplicity between $\sqrt{S} = 27$ GeV and $\sqrt{S} = 60$ GeV. The weighted increase[7,10], in the number of pions, over this P_T range is around 1.8. For $P_T < 1$ Gev, the increase as a function of $\sqrt{S}$ is even less. Note that the $S^{1.3}$ scaling of $\sigma(D)$ would predict an increase of σ by a factor of **12.4** over this S range. It is also intriguing that the ratio lepton/π seems to be the same for scattering off protons as well as Copper and Tungsten. This indicates that, at least for $P_T > 1$ GeV, the A dependence of prompt

lepton production and π production is the same. This might be interpreted as supporting, but certainly <u>not</u> verifying, the overall $A^{0.75}$ scaling hypothesis for $\sigma_T(D)$. The results below 1 GeV are interesting in that prompt μ's from D decay cannot explain the peak at 0.4 GeV. There seems to be another source of prompt leptons that is contributing primarily at low P_T and which probably is coming from a single detected arm of prompt lepton pair production[11]. Fig. 10 shows the P_T dependence of the invariant cross section as measured[10] (the data points) and as predicted by the present calculation. The agreement is quite good.

SCALING THE PRODUCTION RATES

Since two sets of running conditions (1 TeV protons on Tungsten for the neutrino calculations and 0.9 TeV protons on Copper for the muon calculations) were used in this report for ease in comparison with previous calculations, the final table indicates how to scale the reported values from one set of conditions to the other.

1 TeV --> .9 TeV	Bourquin-Gaillard -20%	$S^{1.3}$ -30%
Tungsten --> Copper	$A^{1.0}$ -25%	$A^{.75}$ -3%

Thus, assuming Bourquin-Gaillard S-dependence and an $A^{0.75}$-dependence, in going from 1 TeV protons on a Tungsten dump to 0.9 TeV protons on a Copper dump (or vice versa) there is a change in flux of 23%. The most drastic case involves the $S^{1.3}$ scaling and the $A^{1.0}$-dependence where there is a 55% change in flux. However recall that with the $S^{1.3}$ scaling the predicted flux, based on the E-613 results at 400 GeV, is already significantly higher at 0.9 - 1.0 TeV than with Bourquin - Gaillard scaling. This must be taken into account when predicting the expected absolute flux after an energy change.

ACKNOWLEDGEMENTS

I would like to thank J. "Bj" Bjorken, Sam Childress and Ray Stefanski for useful discussions and suggestions. My thanks also to Anthony Malensek for his thoughtful suggestions and for his assistance with NUADA during the early stages of this work.

REFERENCES

1) J. G. Morfin and A. Malensek, *Prompt Lepton Production from High Energy Beam Dumps,* Fermilab TM-1275.

2) C. Baltay et al., *The Design of the Magnetized Muon Shield for the Prompt Neutrino Facility,* Fermilab TM-1155 and TM-1155R.

3) D. C. Carey and V. A. White, *NUADA,* Fermilab PM0011.

4) A. Cohen (E-594), private communication.

5) R. C. Ball et al., Phys. Rev. Lett., 51, (743) 1983.
M. E. Duffy et al., Phys. Rev. Lett., 52, (1865) 1984.
M. E. Duffy et al., Phys. Rev. Lett., 55, (1816) 1985.
M. E. Duffy et al., *Characteristics of Charm Production by 400 GeV Protons,* Univ. of Wisc. Preprint WISC-EX-86-262, March 20, 1986, Submitted to Phys. Rev. Lett.

6) M. Bourquin and J.-M. Gaillard, Phys. Lett. 59B, (191) 1975.
M. Bourquin and J.-M. Gaillard, Nucl. Phys. B114, (334) 1976.

7) M. Basile et al., Nuovo Cimento 65A, (421) 1981.

8) L. Baum et al., Phys. Lett., 68B, (279) 1977.
M. Barone et al., Nucl. Phys. B132, (29) 1978.

9) F. W. Busser et al., Nucl. Phys. B113, (189) 1976.

10) J. P. Boymond et al., Phys. Rev. Lett., 33, (112) 1974.

11) M. R. Adams et al., Phys. Rev. D27, (1977) 1983.

FIGURE CAPTIONS

Fig. 1 The measured energy distribution of neutrino quasi-elastic scattering from experiment E-594 compared with the predictions of NUADA. The discrepancy at low energy is due to trigger inefficieny.

Fig. 2 The measured E-613 neutrino energy distribution compared to the predictions of NUADA for proton inelasticity $\varepsilon = 0.3$ and 0.5.

Fig. 3 The E-613 neutrino energy distribution compared to the NUADA predictions for $d\sigma/dx \propto (1-x)^{3.2}$ and $(1-x)^{4.0}$. All three curves are normalized to 53 events.

Fig. 4 The predicted energy dependence of $\sigma(D)$ with the Bourquin-Gaillard model.

Fig. 5 The expected υ_τ event energy distribution at the Tohoku (L=90m) and 15'(L=190m) positions. Shown is the sum and the various contributions to the total rate.

Fig. 6 The expected event energy distribution of **all** types of neutrinos at the same two positions as in Fig. 5.

Fig. 7 The momentum distribution of muons produced in the dump with $\theta < 200$mr coming from D, π and K decay.

Fig. 8 The transverse momentum distribution for three values of muon momentum coming from the same three sources as in Fig. 7.

Fig. 9 The ratio of prompt leptons to produced pions as a function of transverse momentum. Data points are from the quoted sources the curve is the prediction of the present calculation.

Fig. 10 The invariant cross section as a function of transverse mometum as measured by Boymond et al. (data points) and as predicted by the present model.

Fig. 1

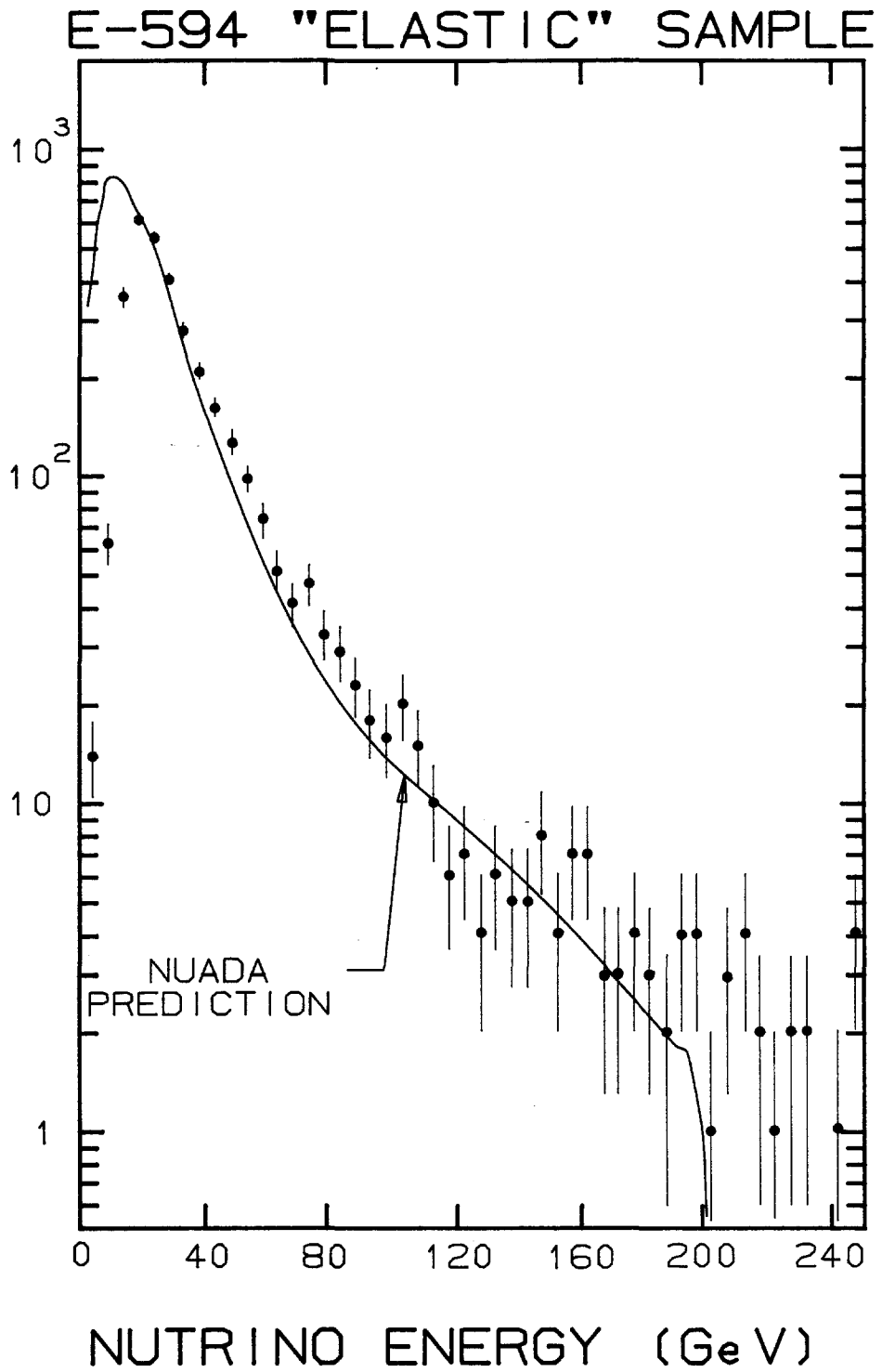

E-594 "ELASTIC" SAMPLE
10^3
10^2
10
1
NUADA
PREDICTION
0
40
80
120
160
200
240
NUTRINO ENERGY (GeV)

Fig. 2

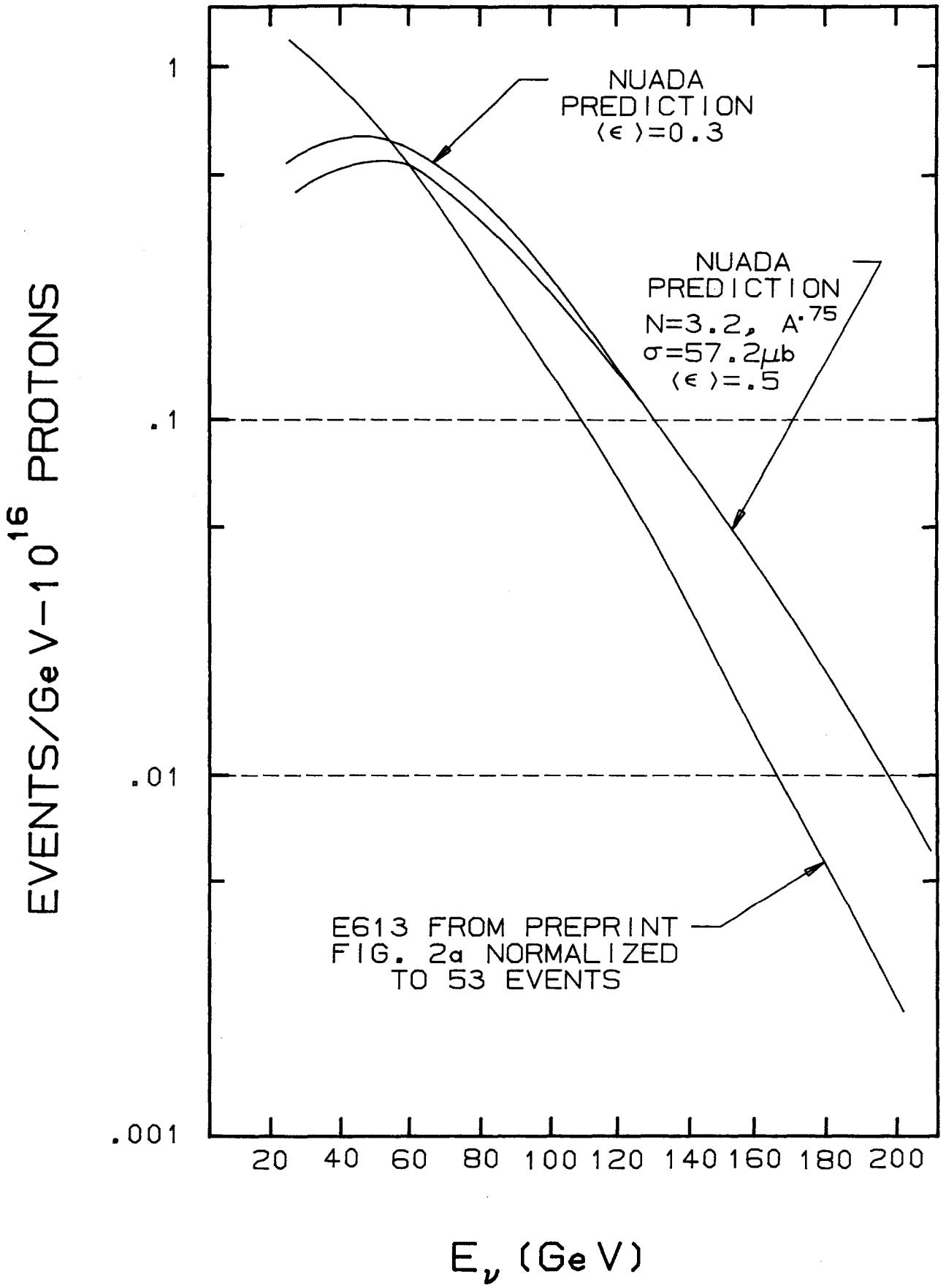

NUADA
PREDICTION
⟨ϵ⟩=0.3
NUADA
PREDICTION
N=3.2, A^.75
σ=57.2μb
⟨ϵ⟩=.5
E613 FROM PREPRINT
FIG. 2a NORMALIZED
TO 53 EVENTS
1
.1
.01
.001
20 40 60 80 100 120 140 160 180 200
EVENTS/GeV-10^16 PROTONS
E_ν (GeV)

Fig. 3

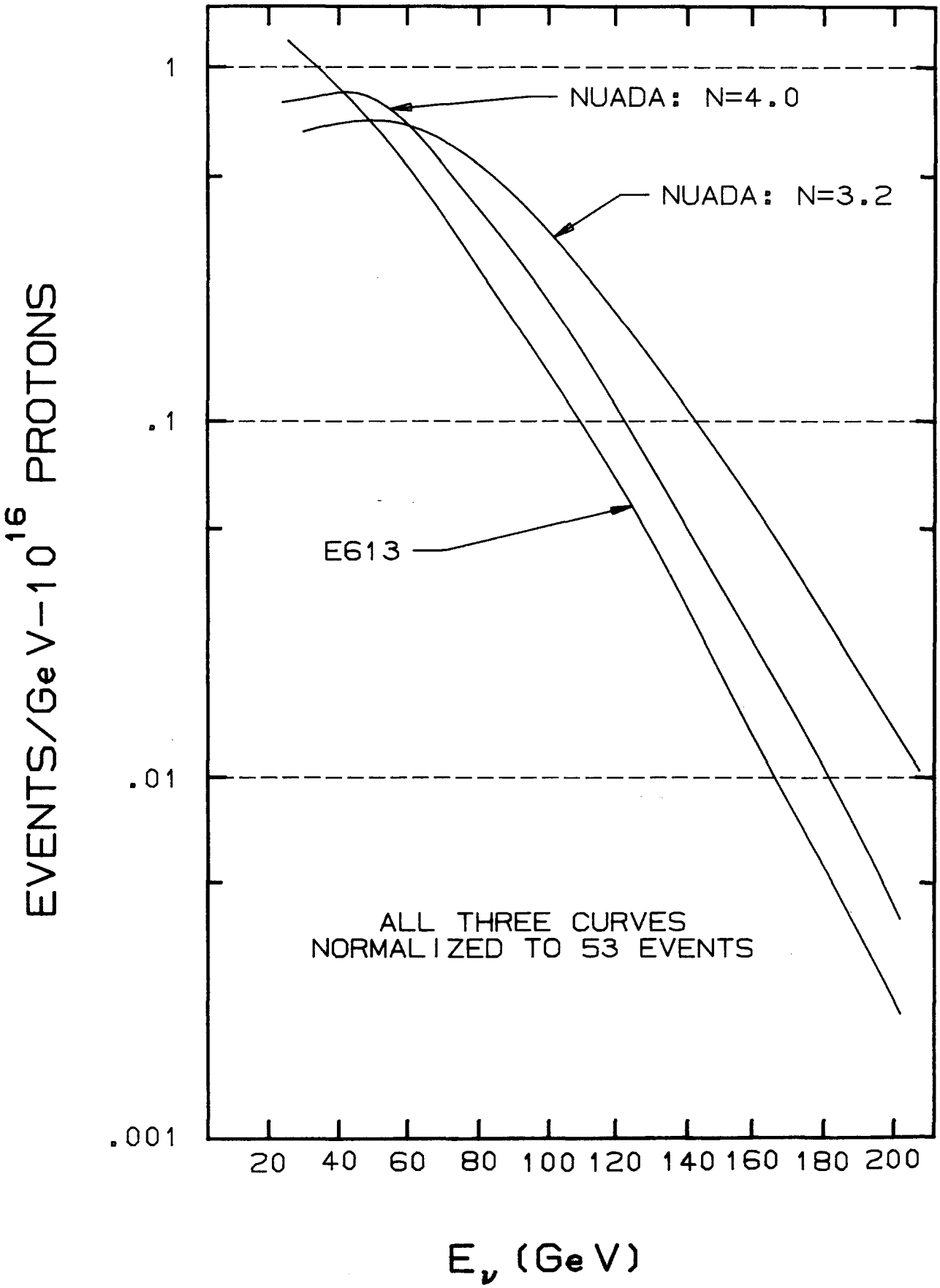

NUADA: N=4.0
NUADA: N=3.2
E613
ALL THREE CURVES
NORMALIZED TO 53 EVENTS
EVENTS/GeV-10^16 PROTONS
1
.1
.01
.001
20 40 60 80 100 120 140 160 180 200
E_ν (GeV)

Fig. 4

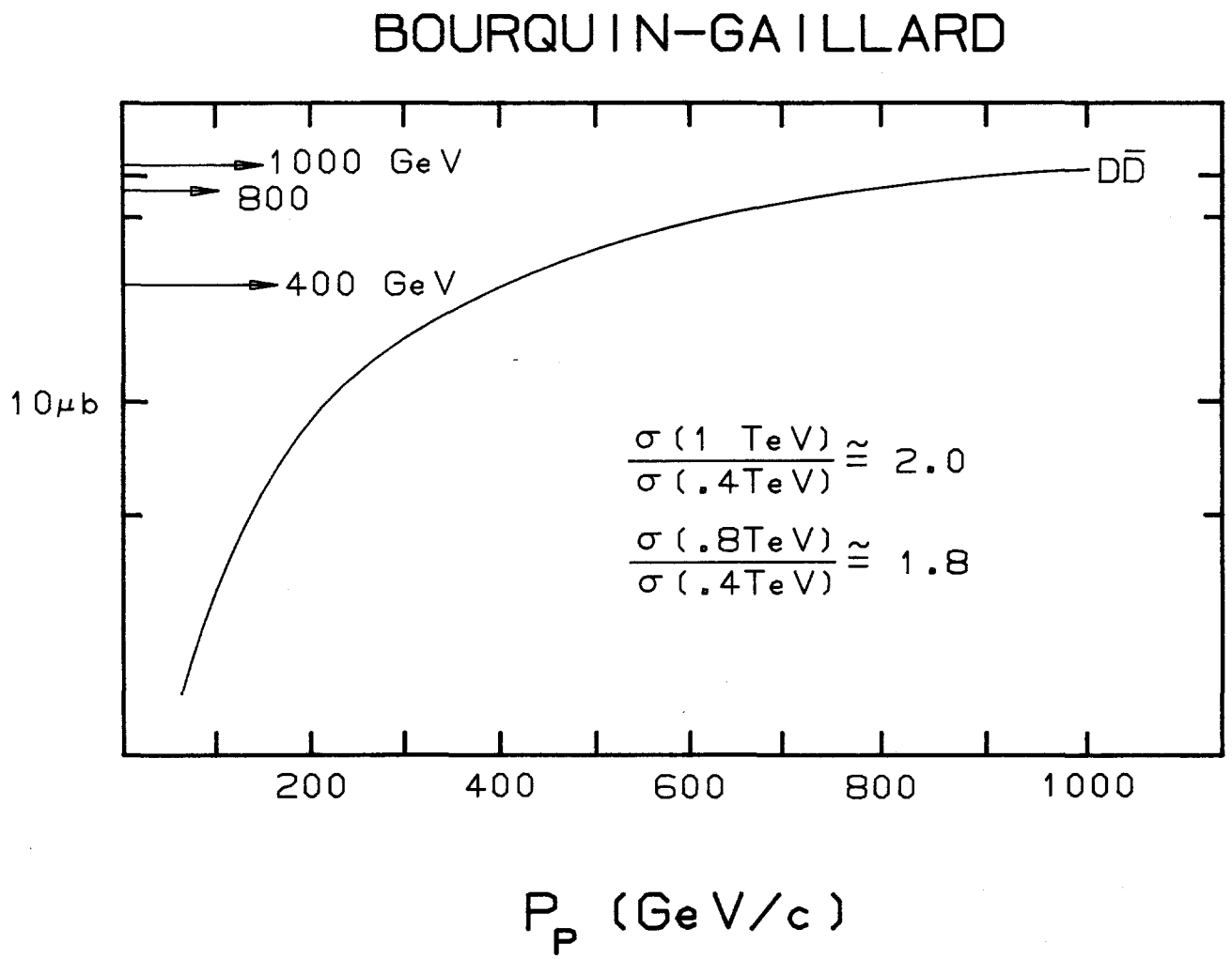

BOURQUIN-GAILLARD
1000 GeV
800
400 GeV
DD̄
10μb
σ(1 TeV)/σ(.4TeV) ≅ 2.0
σ(.8TeV)/σ(.4TeV) ≅ 1.8
200
400
600
800
1000
P_P (GeV/c)

Fig. 5

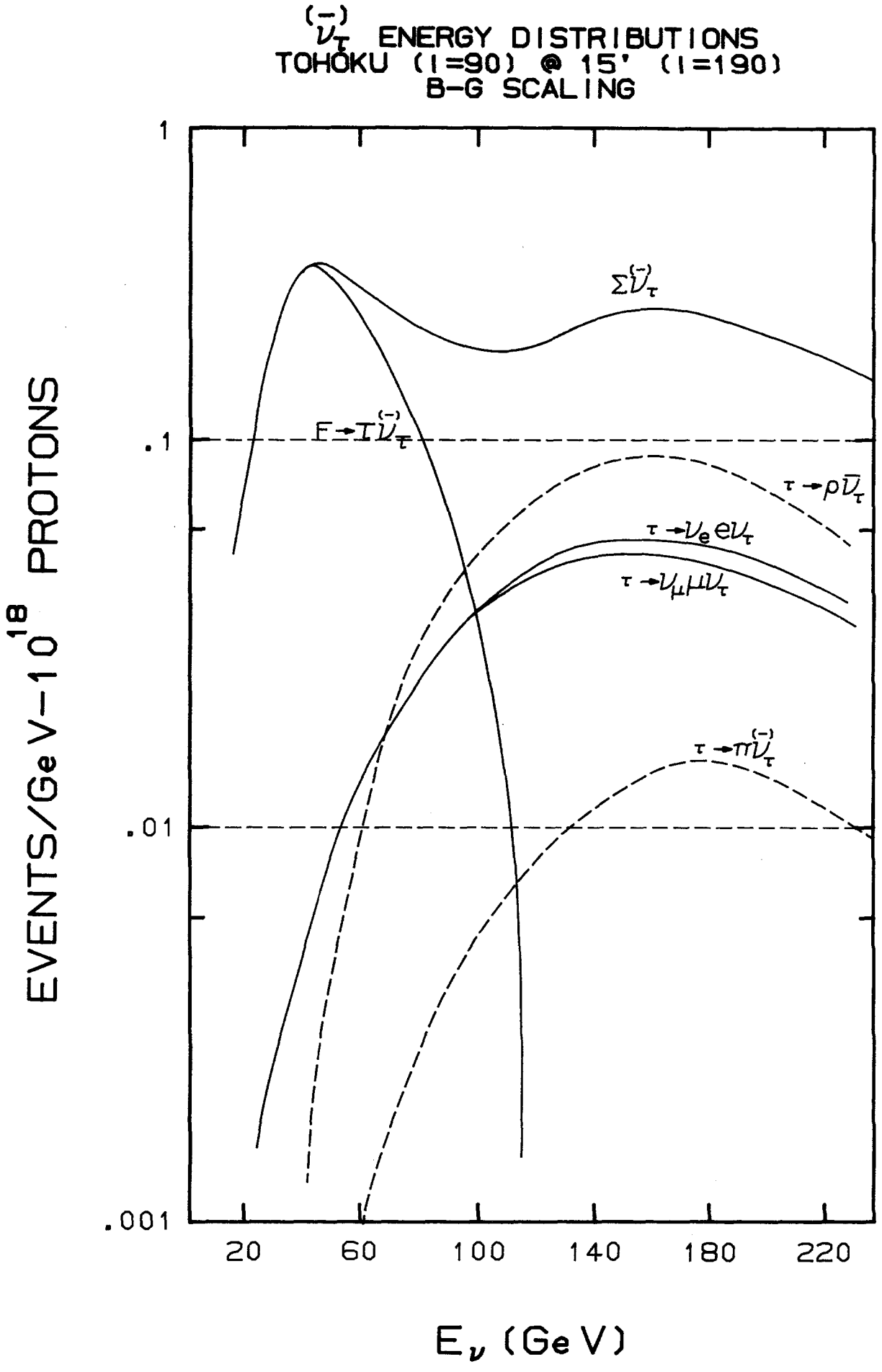

$\overset{(-)}{\nu}_\tau$ ENERGY DISTRIBUTIONS
TOHOKU (l=90) @ 15' (l=190)
B-G SCALING
$\Sigma\overset{(-)}{\nu}_\tau$
$F\to I\overset{(-)}{\nu}_\tau$
$\tau\to\rho\bar{\nu}_\tau$
$\tau\to\nu_e e\nu_\tau$
$\tau\to\nu_\mu\mu\nu_\tau$
$\tau\to\pi\overset{(-)}{\nu}_\tau$
EVENTS/GeV-10^{18} PROTONS
1
.1
.01
.001
20
60
100
140
180
220
E_ν (GeV)

Fig. 6

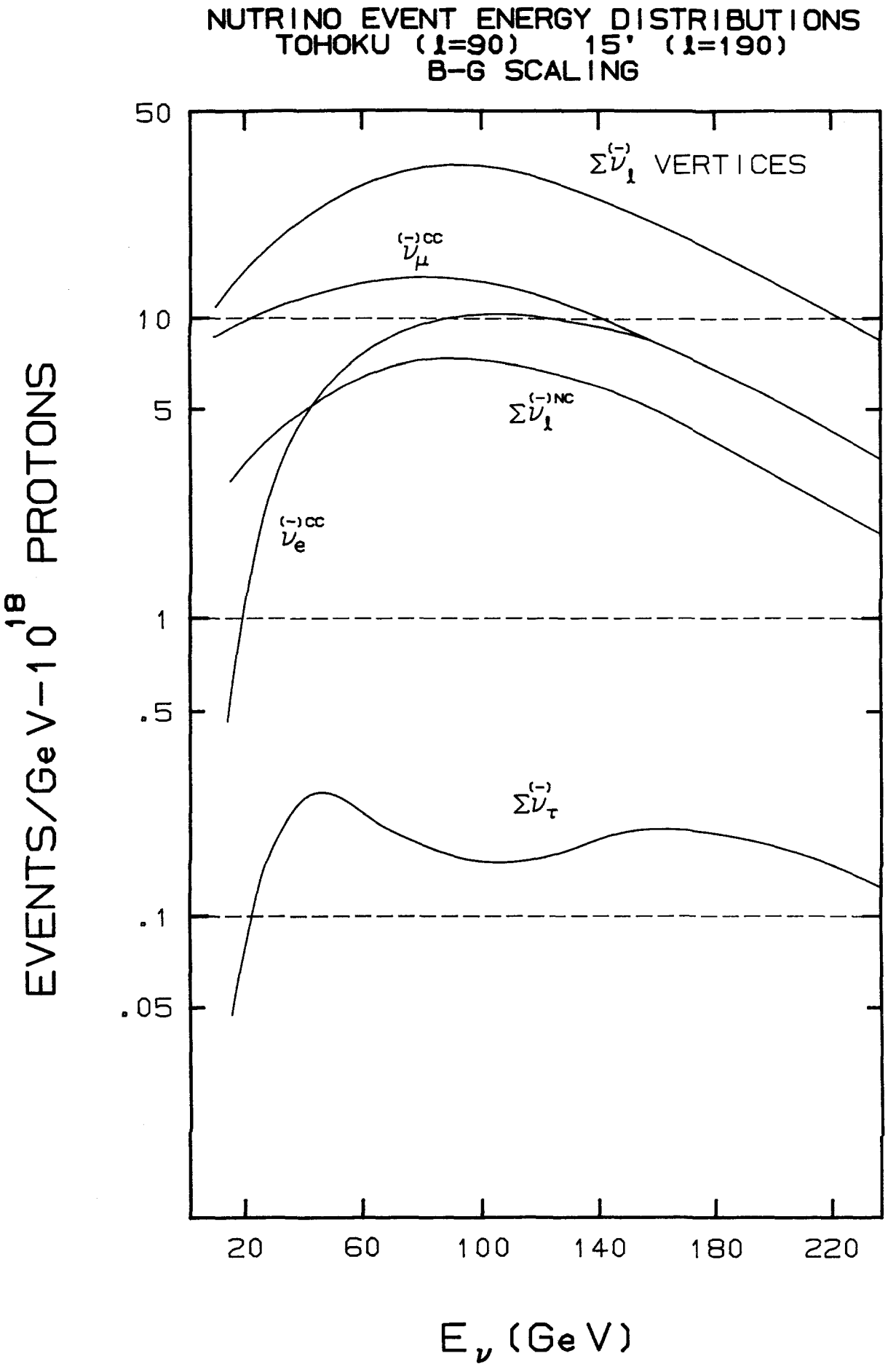

NUTRINO EVENT ENERGY DISTRIBUTIONS
TOHOKU (l=90) 15' (l=190)
B-G SCALING
$\Sigma\overset{(-)}{\nu}_l$ VERTICES
$\overset{(-)}{\nu}_\mu^{CC}$
$\Sigma\overset{(-)}{\nu}_l^{NC}$
$\overset{(-)}{\nu}_e^{CC}$
$\Sigma\overset{(-)}{\nu}_\tau$
50
10
5
1
.5
.1
.05
20
60
100
140
180
220
EVENTS/GeV-10^{18} PROTONS
E_ν (GeV)

Fig. 7

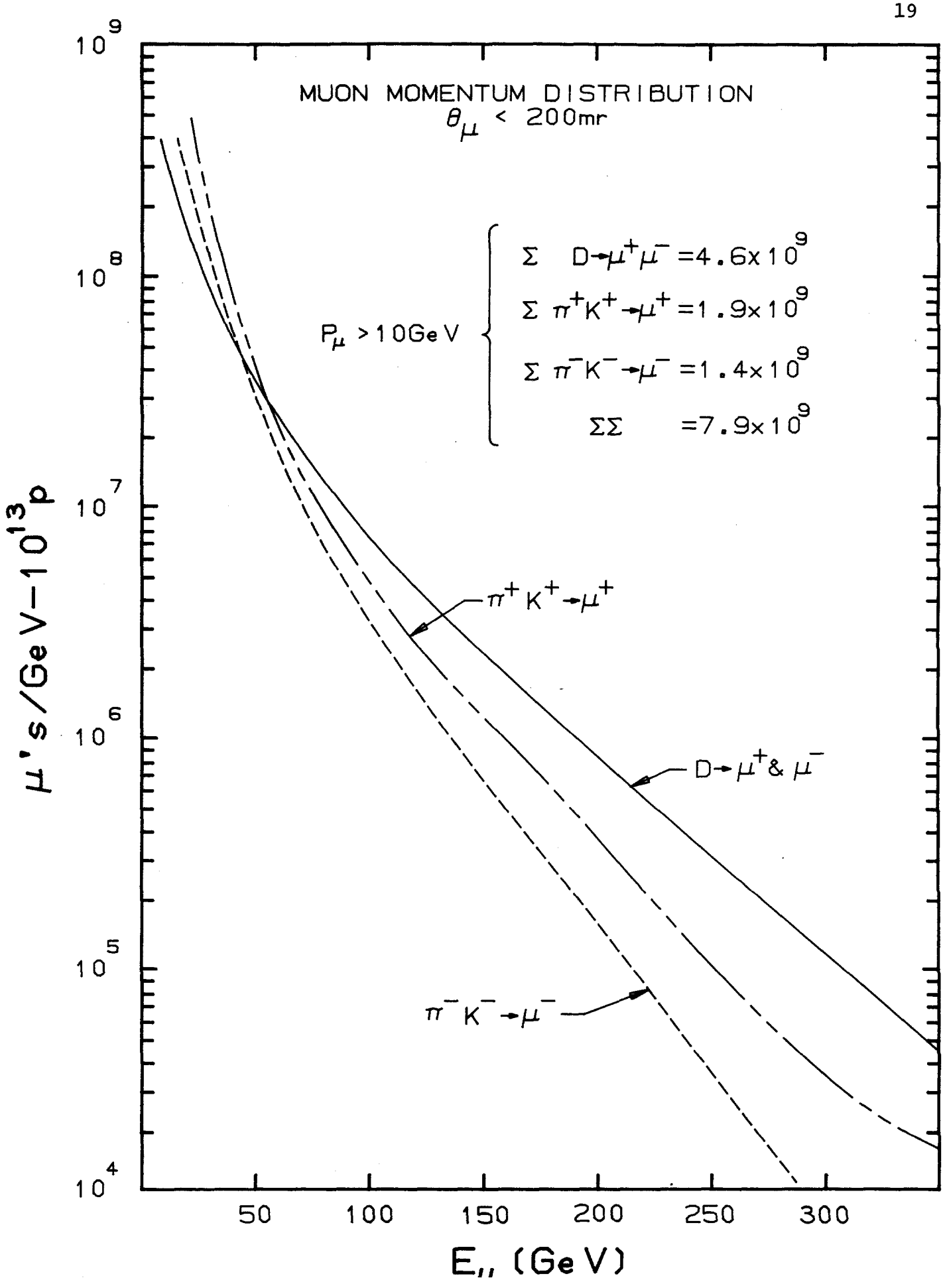

MUON MOMENTUM DISTRIBUTION
θ_μ < 200mr
P_μ > 10GeV
Σ D→μ⁺μ⁻ = 4.6x10⁹
Σ π⁺K⁺→μ⁺ = 1.9x10⁹
Σ π⁻K⁻→μ⁻ = 1.4x10⁹
ΣΣ = 7.9x10⁹
π⁺K⁺→μ⁺
D→μ⁺& μ⁻
π⁻K⁻→μ⁻
μ's/GeV−10¹³p
E,, (GeV)
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
50
100
150
200
250
300

Fig. 8

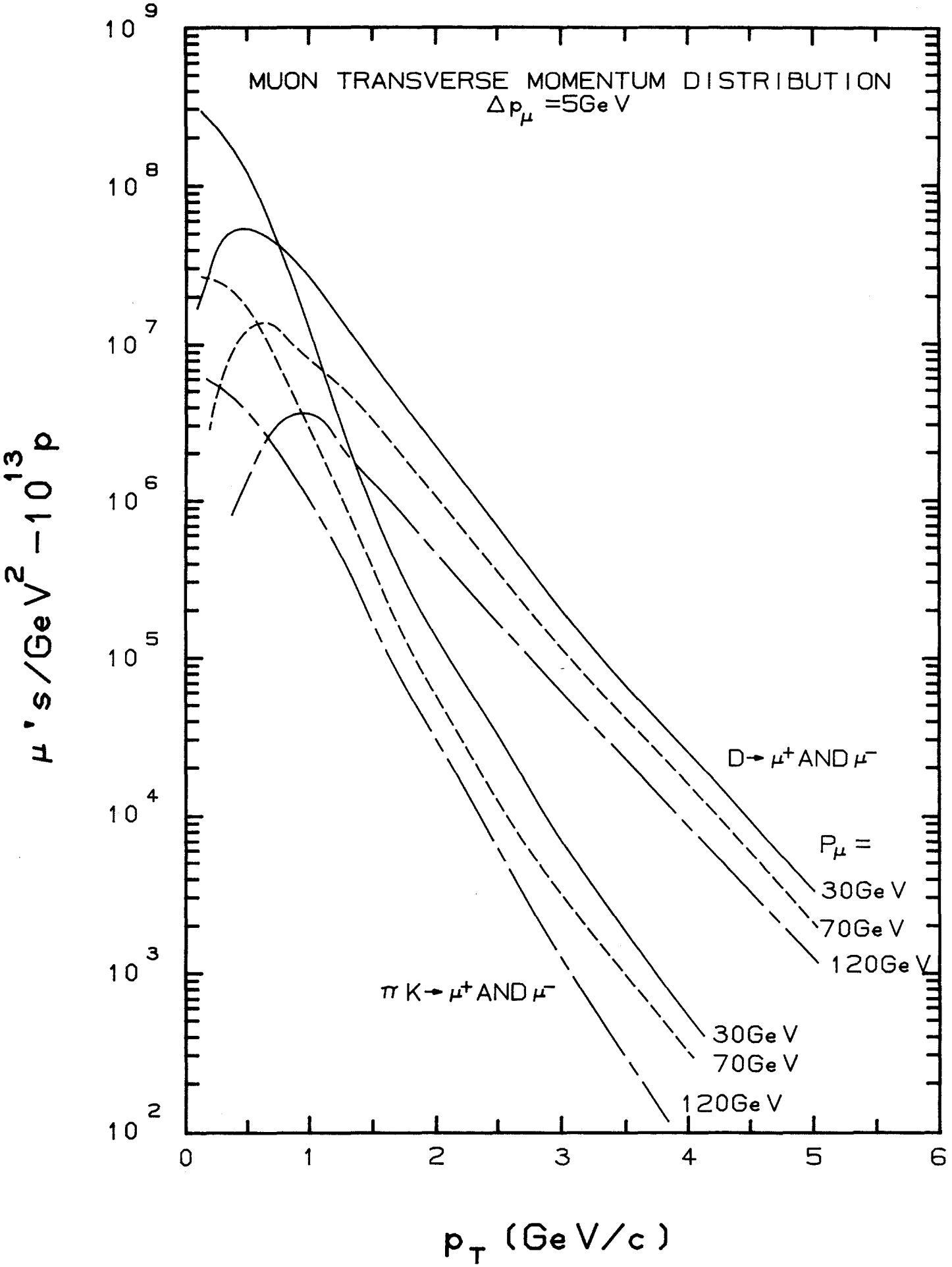

MUON TRANSVERSE MOMENTUM DISTRIBUTION
Δp_μ =5GeV
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
μ's/GeV^2 -10^{13} p
0
1
2
3
4
5
6
p_T (GeV/c)
D→ μ^+ AND μ^-
P_μ =
30GeV
70GeV
120GeV
π K→ μ^+ AND μ^-
30GeV
70GeV
120GeV

Fig. 9

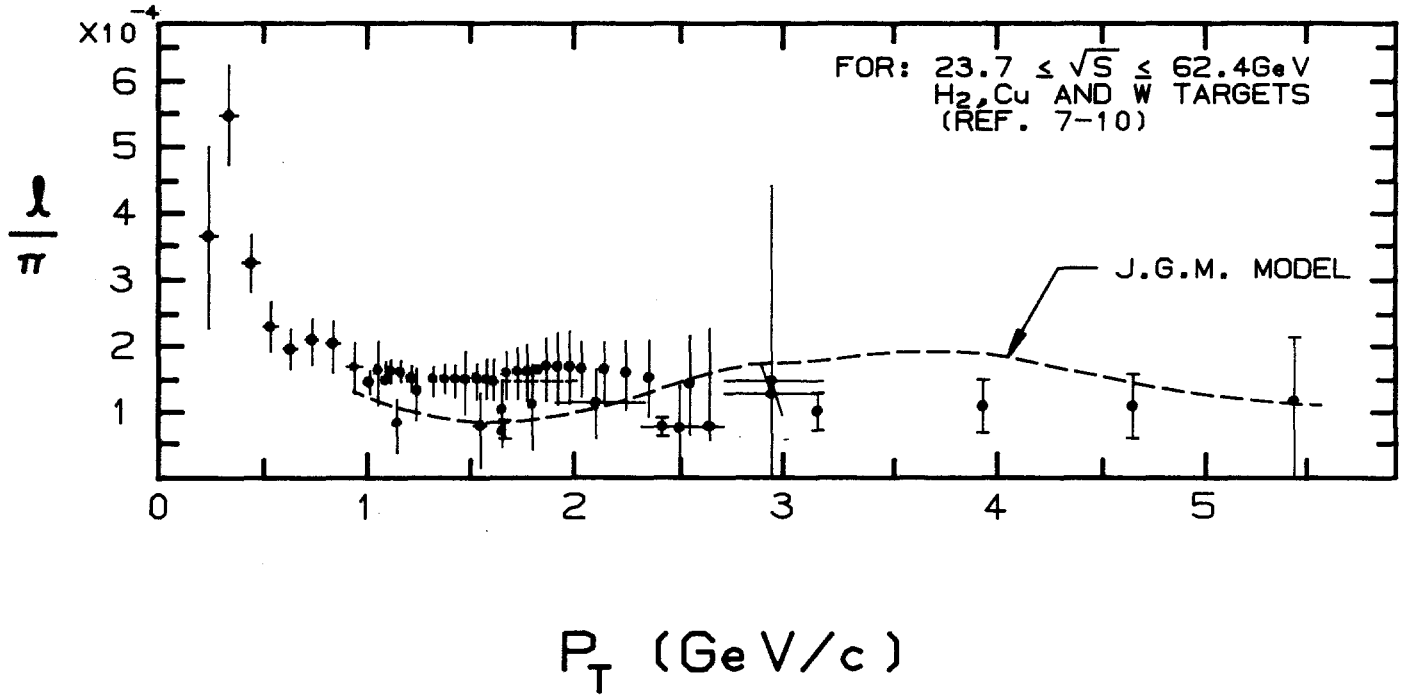
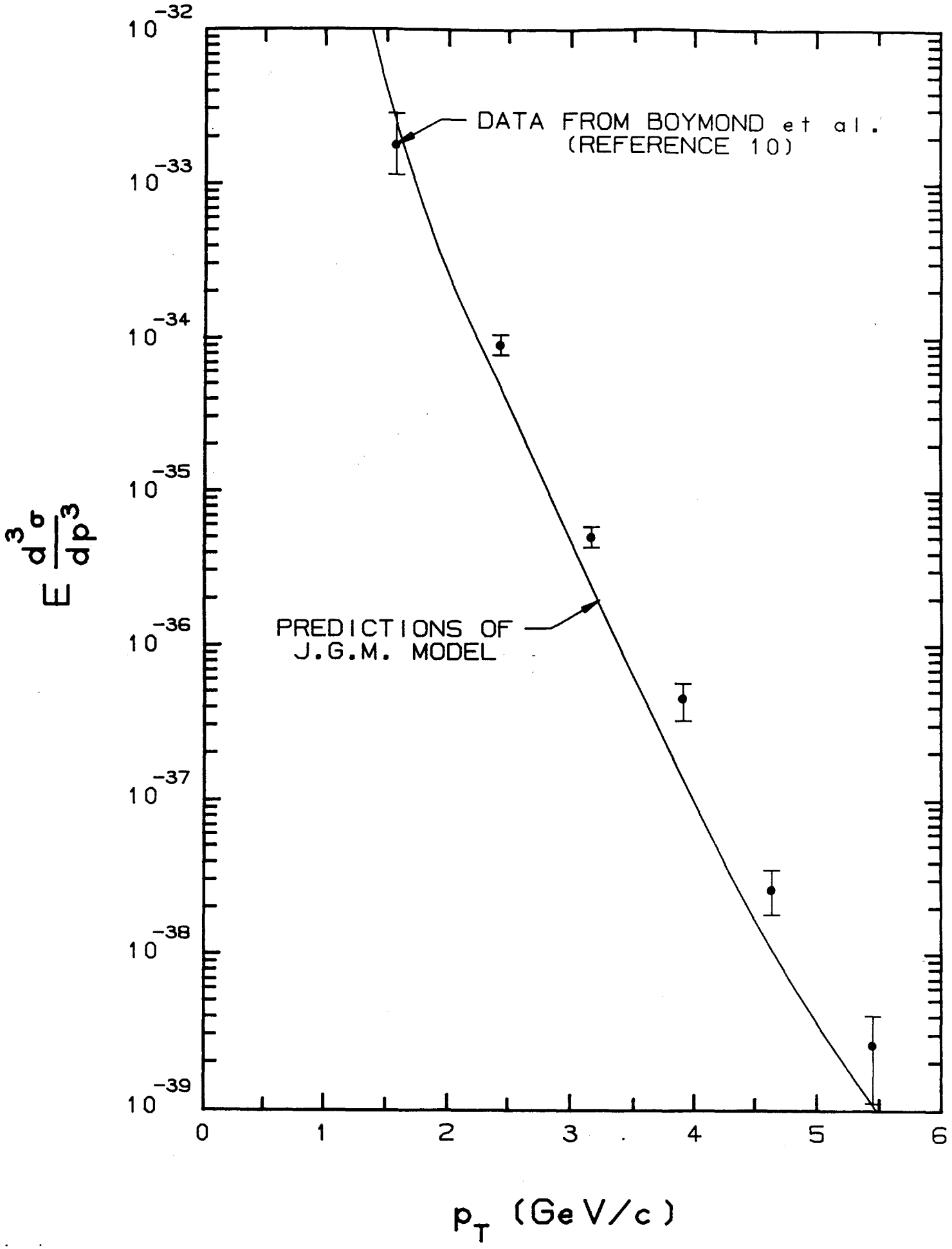

X10^{-4}
6
5
4
3
2
1
$\frac{\ell}{\pi}$
FOR: 23.7 ≤ √S ≤ 62.4GeV
H2,Cu AND W TARGETS
(REF. 7-10)
J.G.M. MODEL
0
1
2
3
4
5
P_T (GeV/c)

Fig. 10


DATA FROM BOYMOND et al.
(REFERENCE 10)
PREDICTIONS OF
J.G.M. MODEL
$E\frac{d^3\sigma}{dp^3}$
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
0
1
2
3
4
5
6
p_T (GeV/c)