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DEEP INELASTIC DISTRIBUTIONS IN HIGH ENERGY NEUTRINO COLLISIONS*

B. C. Barish, J. F. Bartlett, D. Buchholz, F. Jacquet, F. S. Merritt, F. J. Sciulli, L. Stutte, H. Suter†

California Institute of Technology, Pasadena, California 91109

and

G. Krafczyk

National Accelerator Laboratory, Batavia, Illinois 60510

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Abstract

The results of the analysis of ~1000 ν events of the type $\nu + N \rightarrow \mu^- +$ hadrons from the NAL dichromatic beam are presented. Distributions in terms of the scaling variables $x = \frac{Q^2}{2m\nu}$ and $y = E_h/E_\nu$ are presented. The x distribution is compared with F_2^{ed} (x) from SLAC; the Q^2 distribution is tested for the presence of the propagator term $F_2(x) \rightarrow F_2(x) / (1+Q^2/\Lambda^2)^2$; and the y distributions are fit to the form $\frac{d\sigma^{\nu N}}{dy} = 1 + a(1-y)^2$. A smaller amount of $\bar{\nu}$ data will also be presented.

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THEORETICAL EXPECTATIONS (BEST GUESSES)

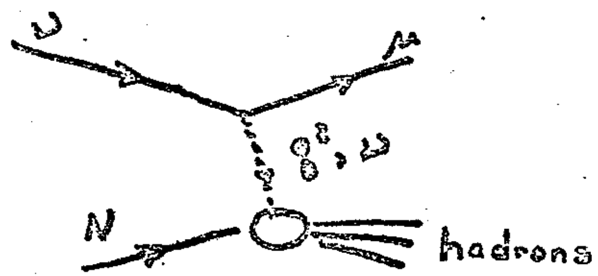
Assumption 1: V-A and Scaling

The Theoretical expectations for the scattering of neutrinos from nucleons revolve around two major assumptions: V-A coupling for the weak interaction, and the scaling hypothesis for hadron coupling. The former assumption is very well tested by the weak decays of meta-stable particles, with energy releases of a few hundred MeV. The scaling hypothesis was originally found to work in the measured electromagnetic cross-sections

$$e^- + N \rightarrow e^- + \text{hadrons}$$

made at SLAC.

In this picture, the incident neutrino of energy E_ν emits a virtual boson propagator and μ^- at the upper lepton vertex. This propagator carries laboratory energy $\nu = E_\nu - E_\mu$, and invariant 4-momentum transfer



$$t = q^2 = -Q^2 = (E_\nu - E_\mu)^2 - (\vec{p}_\nu - \vec{p}_\mu)^2.$$

At momentum transfers where the rest mass (Λ) of this propagator becomes important ($Q^2 \approx \Lambda^2$), an apparent violation of scaling will be observed.

The scaling (dimensionless) variables are defined as $x = \frac{Q^2}{2M\nu}$ and $y = \nu/E_\nu$ with M = nucleon (target) mass. At high energies, the scaling variables have a kinematic range $0 < x < 1$, $0 < y < 1$. In kinematic regions where $Q^2 \rightarrow \infty$, $\nu \rightarrow \infty$, but the ratio remains finite, one expects that the differential cross-section for the process $\nu_\mu + N \rightarrow \mu^- + \text{hadrons}$ will be of the form

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G^2 M E_\nu}{\pi} \left\{ F_2(x)\ (1-y) + 2xF_1(x)\ \frac{y^2}{2} \mp xF_3(x)\ y(1-\frac{y}{2}) \right\}$$

where F_1, F_2, F_3 are 3 structure functions describing the hadronic vertex. The important point is that the (V-A) + scaling hypotheses require the cross-section to depend linearly on neutrino energy times some function of the dimensionless parameters, x and y. Some additional dependence on Q^2, ν, or E_ν would indicate a breakdown of either V-A, or scaling, or both. For example, the finite mass propagator might result in the modification:

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} \rightarrow \frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} \frac{1}{(1+Q^2/\Lambda^2)^2}$$

Assumption 2: Callen-Gross Relation

If we postulate that neutrino scattering from nucleons behaves as if the nucleons consisted of predominantly spin 1/2 constituents, then the Callen-Gross relation would hold: $\boxed{F_2(x) = 2x\, F_1(x)}$. The differential cross-sections take a somewhat simpler form:

$$\frac{d\sigma^{\nu}}{dxdy} = \frac{G^2ME_{\nu}}{\pi} \left\{ q(x) + \bar{q}(x)\ (1-y)^2 \right\} \tag{1}$$

$$\frac{d\sigma^{\bar{\nu}}}{dxdy} = \frac{G^2ME_{\nu}}{\pi} \left\{ q(x)\ (1-y)^2 + \bar{q}(x) \right\} \tag{2}$$

where $\quad q(x) = \dfrac{F_2(x) - x\, F_3(x)}{2} \qquad \bar{q}(x) = \dfrac{F_2(x) + x\, F_3(x)}{2}$

In the parton model, these functions have a very simple physical interpretation. For example, $q(x) = x\, f_q(x)$, where x is the fraction of the total nucleon momentum carried by the nucleon constituent which engages in the scattering and $f_q(x)\,dx$ is the normalized probability for finding quark constituents with fractional momentum between x and $x+dx$. The function $\bar{q}(x)$ is similarly related to the anti-quark component of the nucleon. The different dependences on y are a reflection of the different helicity selections in the V-A theory between particle and anti-particle at velocities approaching c.

Assumption 3: Small Anti-quark Component

If we assume $\bar{q}(x) \ll q(x)$ for $x > 0$, the differential cross-section becomes as follows:

$$\frac{d\sigma^{\nu}}{dxdy} \simeq \frac{G^2ME_{\nu}}{\pi}\, q(x) \simeq \frac{G^2 m_p E_\nu}{\pi}\, F_2(x) \tag{3}$$

$$\frac{d\sigma^{\nu}}{dxdy} \simeq \frac{G^2ME_{\nu}}{\pi}\, q(x)\ (1-y)^2 \tag{4}$$

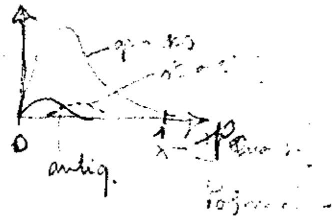
with $q(x) = F_2(x) \propto F_2^{ed}(x)$, neglecting the effect of strange quarks. Since the x-distribution relates to nucleon constituents, we expect the same shape to occur in neutrino scattering off equal admixtures of neutrons and protons as occurs in inelastic electron scattering from deuterium. The normalization of the two functions is different, however, because the electron scattering depends on the charge of the constituents while neutrino scattering is independent of electric charge.

Total cross-sections:

Integrating equations (1) and (2) over y, we obtain

$$\sigma^{\nu} = \frac{G^2ME_{\nu}}{\pi} \int \left(q(x) + \frac{1}{3}\ \bar{q}(x) \right) dx$$

$$\sigma^{\bar{\nu}} = \frac{G^2ME_{\nu}}{\pi} \int \left(\frac{1}{3}\ q(x) + \bar{q}(x) \right) dx$$



Thus, for $\int \bar{q}\, dx \ll \int q\, dx$

$$\boxed{\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} \simeq \frac{1}{3}\left(1 + 2.7 \frac{\int \bar{q}\, dx}{\int q\, dx} \right)}$$

and the ratio of neutrino to anti-neutrino cross-sections is identically 1/3 in the limit of no anti-quark component in the nucleon. This cannot be exactly true, since we expect that $\bar{q}\,(0) = q\,(0)$ at exactly $x = 0$, to satisfy the sum rule: $\int \frac{\bar{q}(x) - q(x)}{x}\, dx = 3$.

Away from $x = 0$, however, we might expect to be dominated by the three valence quarks. Deviations from a ratio of 1/3 provide a measure of this anti-quark component. The CERN-Gargamelle experiment, for example, finds

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = 0.38 \pm .02,$$ indicating perhaps a small, but finite,

anti-quark component.

Independently of how large the anti-quark component is, the sum of the cross-section is

$$\boxed{\begin{aligned} \sigma^{\nu} + \sigma^{\bar{\nu}} &= \frac{4}{3}\, \frac{G^2 M}{\pi}\, E_{\nu} \int_0^1 \left(q(x) + \bar{q}(x)\right) dx \\ &= \left\{ \frac{4}{3}\, \frac{G^2 M}{\pi} \int F_2(x)\, dx \right\} E_{\nu} \\ &= \left(\alpha^{\nu} + \alpha^{\bar{\nu}}\right) E_{\nu} \end{aligned}}$$

Here $\int F_2(x)\, dx$ is the fraction of the nucleon momentum carried by non-strange quarks. In addition, this integral is related to the similar quantity $\int F_2^{ed}(x)\, dx$ measured in electron-deuteron scattering by the mean-square charge of the constituents (with small corrections for strange quarks and neutron-proton excess).

The best quark-parton model prediction, using the SLAC data, is $\alpha^{\nu} + \alpha^{\bar{\nu}} = 1.10 \times 10^{-38}\ \text{cm}^2/\text{GeV}$, with 54% of the momentum carried by the non-strange quarks. The measured value from CERN is

$$\alpha^{\nu} + \alpha^{\bar{\nu}} = (1.02 \pm .10) \times 10^{-38}\ \text{cm}^2/\text{GeV}$$

EXPERIMENTAL DATA

3. Caltech-NAL

The Caltech-NAL experiment utilizes a narrow band beam to obtain its neutrinos. This involves a momentum-analyzed hadron beam traveling in the forward direction toward the apparatus. The small angle decays then give neutrinos into the apparatus as shown schematically in figure 12 for an idealized case of a monochromatic pion and kaon beam. The two energy bands of neutrinos correspond to the decays of the pion and kaons, respectively.

In the real beam at NAL, the momentum spread of the hadrons is about ± 18%. Events wherein the muon and hadron energies are both detected allows us to reconstruct the incident neutrino energy to about 25%. The experimental spectrum for 1522 observed ν events are shown in figure 13. Even with the overall resolution in detection and beam

Figure 12

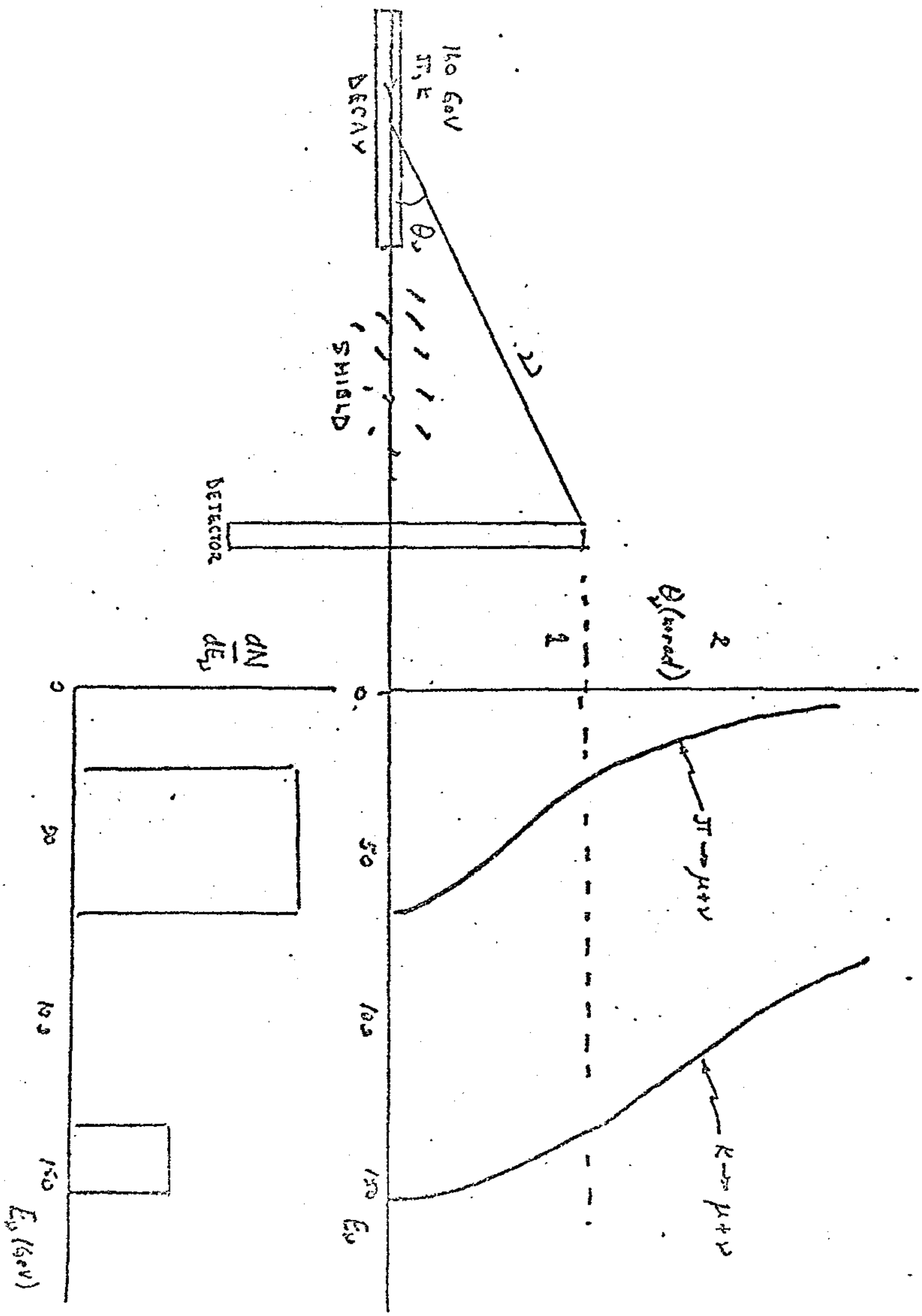
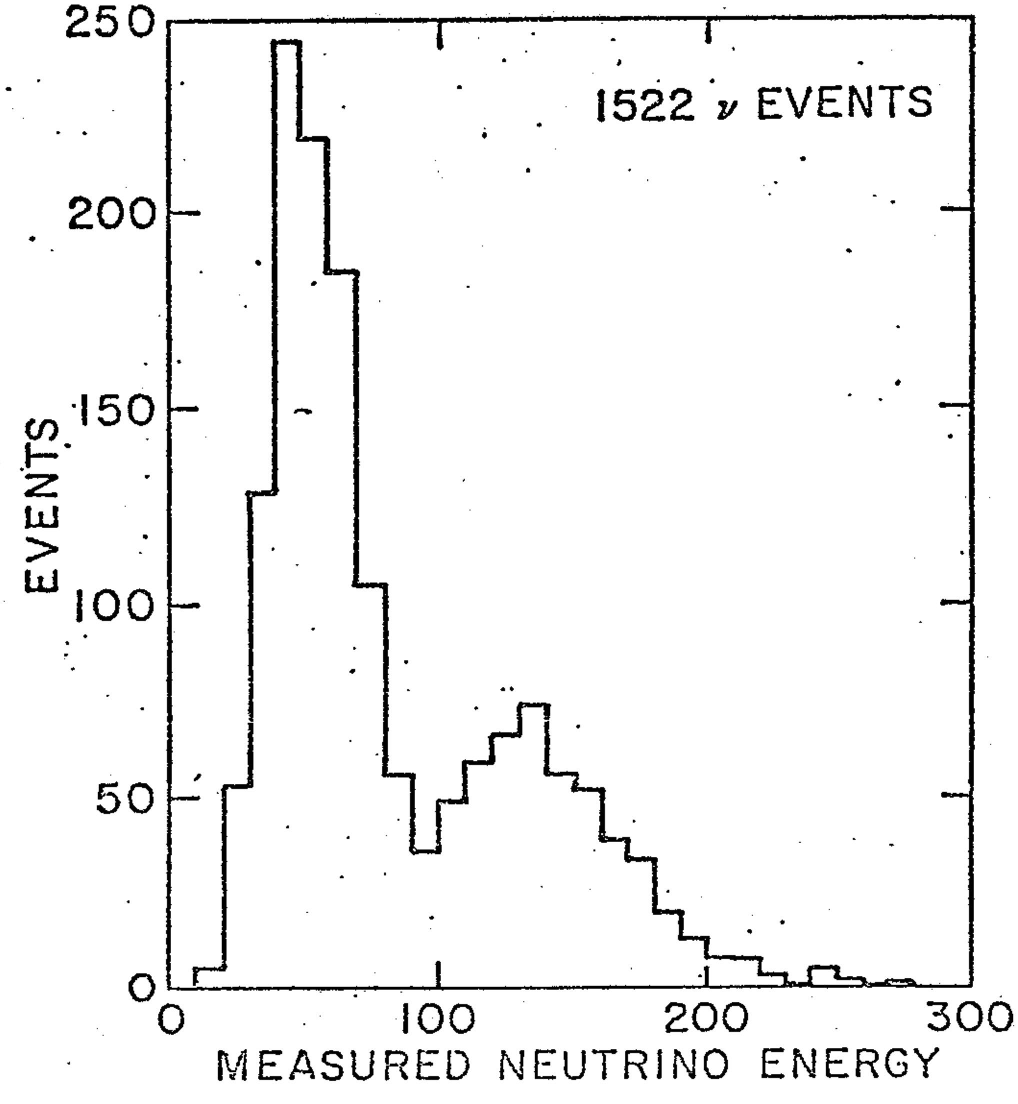


Figure 13



1522 ν EVENTS
EVENTS
250
200
150
100
50
0
0
100
200
300
MEASURED NEUTRINO ENERGY

presently available, the two peak structure expected for this kind of beam is observed.

The detection apparatus is depicted in figure 14. Neutrinos interact in the target calorimeter, consisting of 160 tons of 1.5m x 1.5m steel plate, with scintillation counters and spark chambers distributed throughout. The produced muon is observed in spark chambers, and it its angle is small enough, it enters an iron-core spectrometer magnet. The angle of bend gives the muon momentum.

Measurement of the hadron energy is accomplished with the scintillation counters located throughout the target. The hadronic cascade developing downstream of the interaction point is sampled in the steel. The total pulse height is then proportional to the total energy in the hadron shower.

We estimate our present resolutions as follows:

? E_μ: statistically ~ 21%, systematically ~ 5%

? E_ν E_μ: statistically 15-30%, systematically ~ 10%.

a. Differential Distributions

(1) x-distributions: Precise measurement of x-distributions really require extremely good resolutions. Resolution effects will change the shape of observed x-distributions. Figure 15 shows just such an effect. The curve labelled $F_2(x)$ is the structure function measured by SLAC-MIT with electrons. When we fold in the experimental resolutions for this experiment, we find the expected experimental curve labelled $[F_2(x)]_{smeared}$. If we further fold in the acceptance of the apparatus, we see the lower curve.

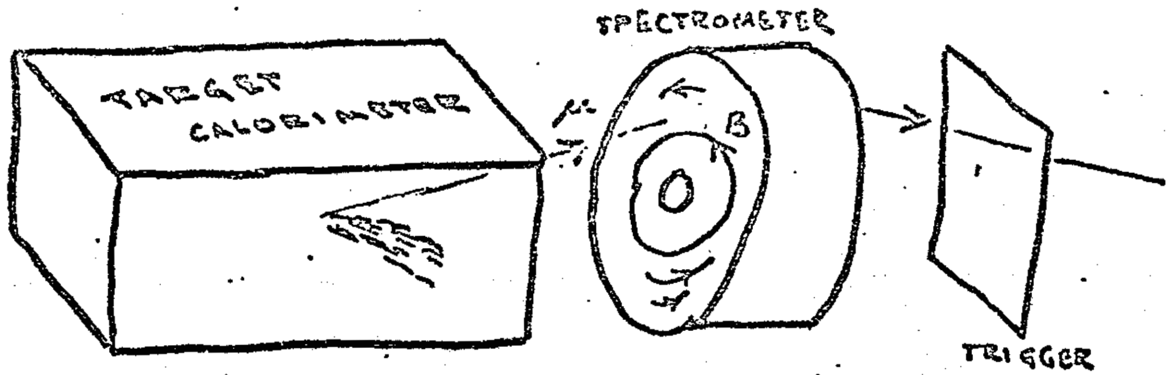
Therefore, it should be emphasized that an $F_2(x)$ structure function of the same form as that obtained at SLAC will result in an experimental distribution that is sharply peaked near $x = 0$, and with a somewhat different falloff, coming from effects of resolution and acceptance.

Figure 16 shows the observed x-distribution for 1027 events inside our fiducial volume where both the muon and the hadron energies are observed. These data were taken with a mean hadron beam setting of 170 GeV, and an observed neutrino energy distribution as shown in figure 13. The solid curve is the expected distribution, assuming the SLAC $F_2^{ed}(x)$ structure function and with resolutions and efficiencies folded in. The agreement with the expected distribution is quite good. There are no statistically significant differences observable between the x-distributions for pion neutrinos and kaon neutrinos.

(2) Q^2-distributions: The distribution in Q^2 corrected for efficiency for all events is shown in the figure 17. The expected distribution in Q^2 assumes the flat y-distribution as well as $F_2^{ed}(x)$ from SLAC. This curve is labelled $\Lambda = \infty$ in the figure. The multiplicative propagator term $[1 + Q^2/\Lambda^2]^{-2}$, gives a much steeper falloff. For $\Lambda = 10$ GeV, for example, the calculated curve, normalized to the data, falls below the data at all points below the first. Figure 18 shows the confidence level for a fit to this propagator term. Above $\Lambda = 15$ GeV/c^2, we have no sensitivity; the fit is equally likely at $\Lambda = 10.3$. Therefore, we place a 90% confidence on a propagator mass for the term we have included: $\boxed{\cancel{\Lambda > 10.3 \text{ GeV}/c^2}}$.

Figure 14

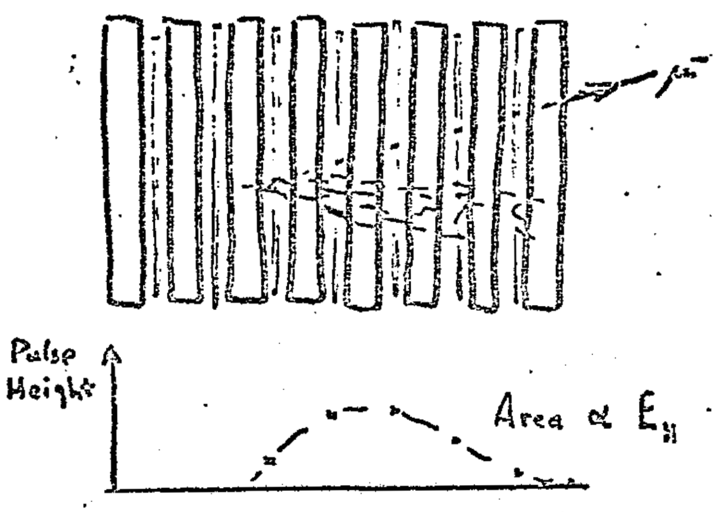
Caltech-NAL Apparatus Schematic [Barish, Bartlett, Brown, Bucholz, Humphrey, Jacquet, Merritt, Stutte, Suter, Shields, Sciulli, Fisk, Krafczyk.]



θ_μ : spark chambers

E_μ: deflection and penetration.

Calorimeter



$$E_\nu = E_{tot} = E_\mu + E_H$$

Figure 15

Effect of resolution on $F_2(x)$

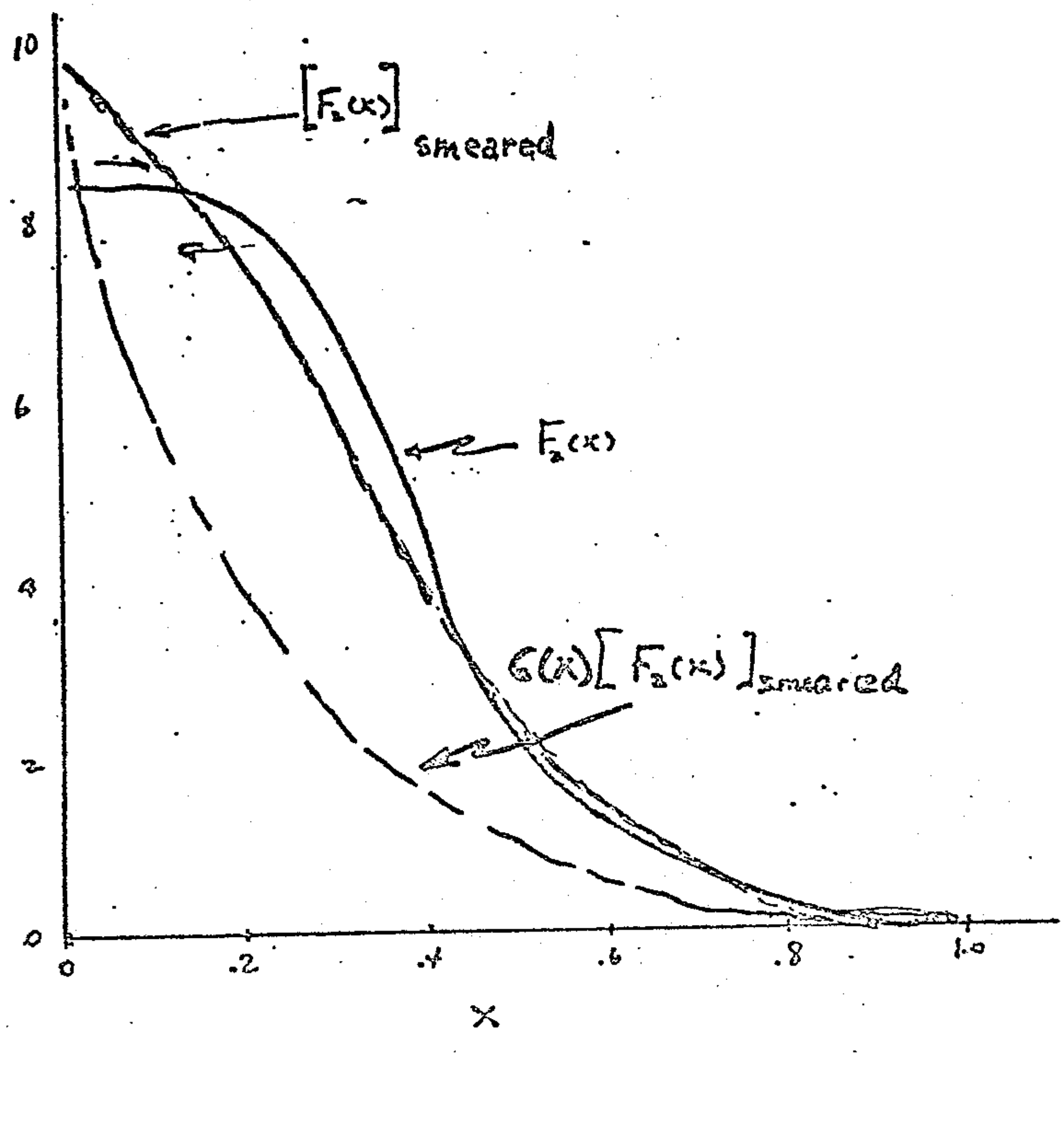
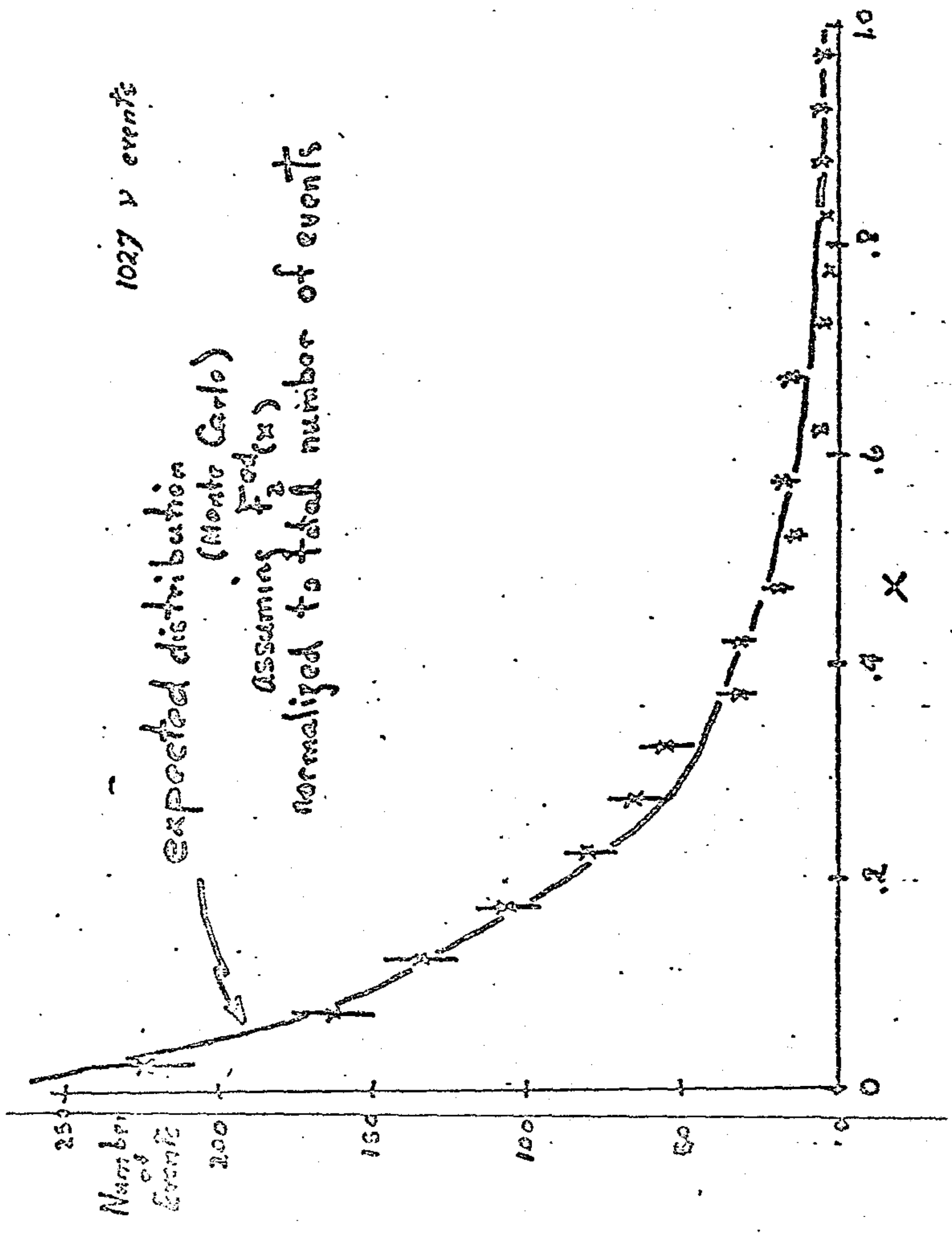
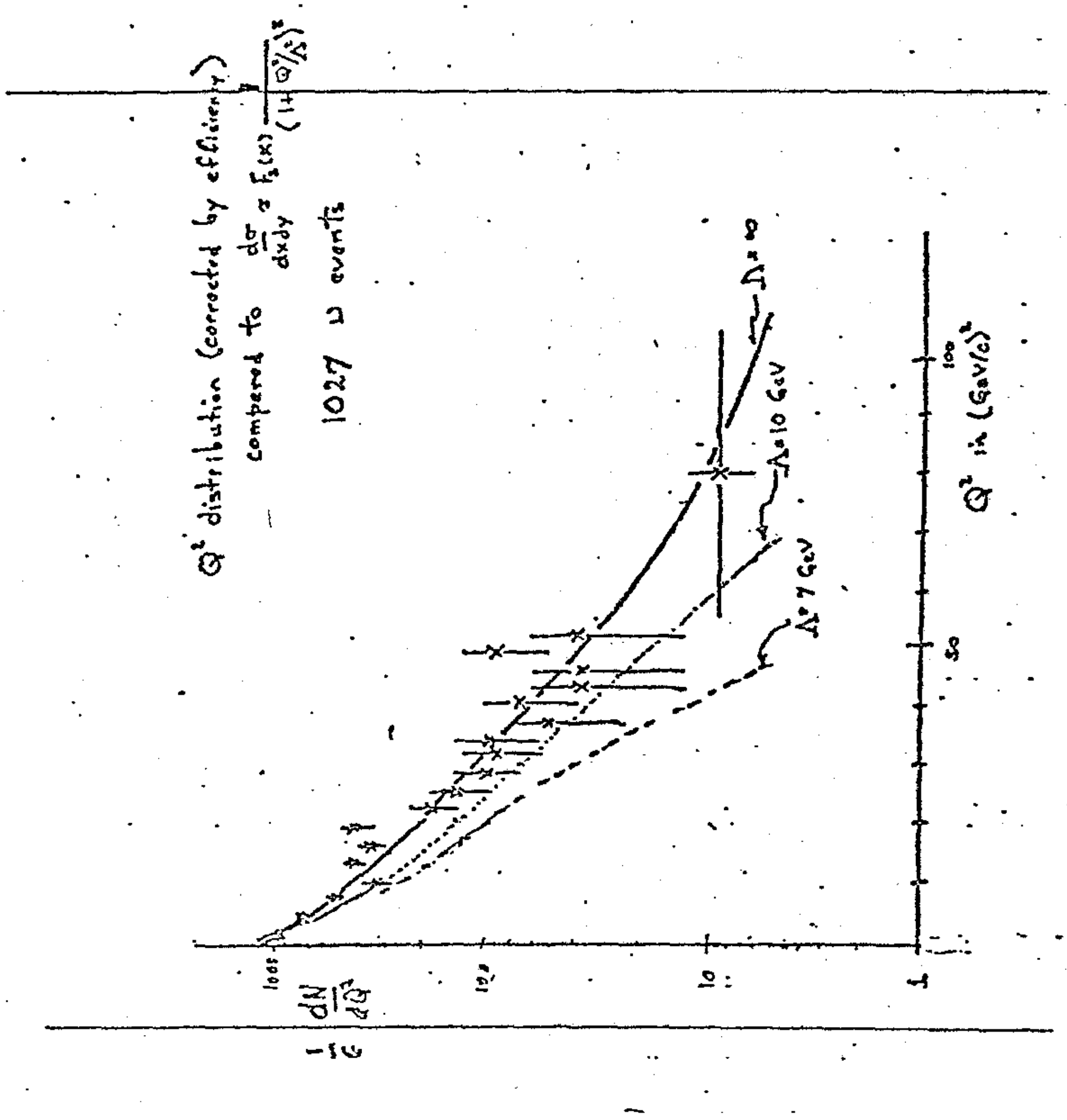


Figure 16



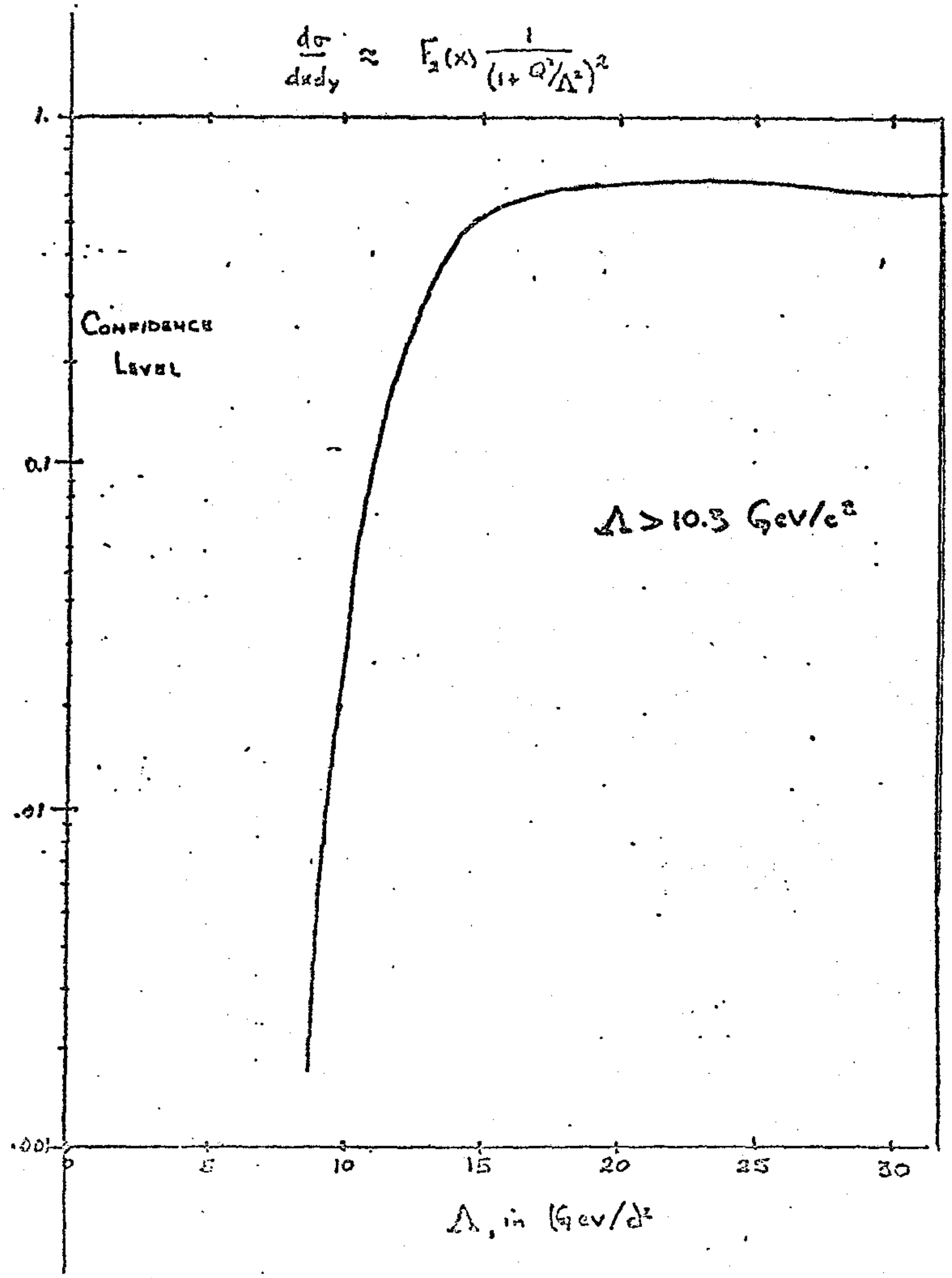
1027 ν events
expected distribution
(Monte Carlo)
assuming $F_2^{\alpha d}(x)$
normalized to total number of events
Number of Events
250
200
150
100
50
0
0
.2
.4
.6
.8
1.0
X

Figure 17



Q² distribution (corrected by efficiency)
compared to dσ/dxdy ∝ F₂(x) 1/(1+Q²/Λ²)²
1027 ν events
Λ=∞
Λ=10 GeV
Λ=7 GeV
dN/dQ²
1000
100
10
1
50
100
Q² in (GeV/c)²

Figure 18



$\frac{d\sigma}{dx\,dy} \approx F_2(x)\frac{1}{(1+Q^2/\Lambda^2)^2}$
1.
Confidence Level
0.1
.01
.001
$\Lambda > 10.3$ Gev/c²
0
5
10
15
20
25
30
Λ, in (Gev/c)²

(3) y-distributions: The y-distributions are more effected by the acceptance function than by resolution. The smooth curve shown in figure 19 a is the expected y-distribution observed in our apparatus for ν interactions: effectively, it corresponds to the efficiency of the apparatus in y. The data are also shown with the appropriate statistical error. Figure 19 b shows the same distribution in a log plot. The systematically high points for $y > 0.6$ occur in a region where the efficiency has fallen below 10%. Below this value, there are no systematic departures from the expected flat distribution for neutrinos.

Figure 20 a shows all the neutrino events, with $y < 0.6$, corrected for efficiency and plotted vs. y. The data are consistent with the expected flat distribution. To obtain a numerical estimate of this consistency, we have fit to a function of the form

$$\frac{dN}{dy} = C\left[1 + a(1-y)^2\right]$$

where C is constrained by the overall normalization, and a is a free parameter. It could be thought of as representing an average anti-quark component in the nucleon. Figure 20 b shows the result:

$$\boxed{a = + .05 \begin{smallmatrix} + .25 \\ - .17 \end{smallmatrix}}$$

consistent with zero, and consistent with the 5% average anti-quark component found in the low energy CERN data.

Summarizing these preliminary results of the Caltech-NAL group on the unnormalized distributions:

(1) The data with muon traversing the magnet are consistent with the $F_2^{ed}(x)$ shape observed by the SLAC-MIT group.

(2) The same data fit the expected distribution in Q^2 without an additional propagator term. The data are inconsistent with propagators of masses less than 10.3 GeV/c^2. That is, $\Lambda > 10.3$ GeV/c^2 (90% confidence).

(3) From 1027 ν events with measured muon momentum, a fit to

$$\frac{dN}{dy} = C\left[1 + a(1-y)^2\right],$$ it is found

$$a = + .05 \begin{smallmatrix} + .25 \\ - .17 \end{smallmatrix}$$

consistent with the expected flat y-distribution for ν events.

(4) There appears no obvious dependence on E_ν in either x or y distributions for neutrinos.

Figure 19

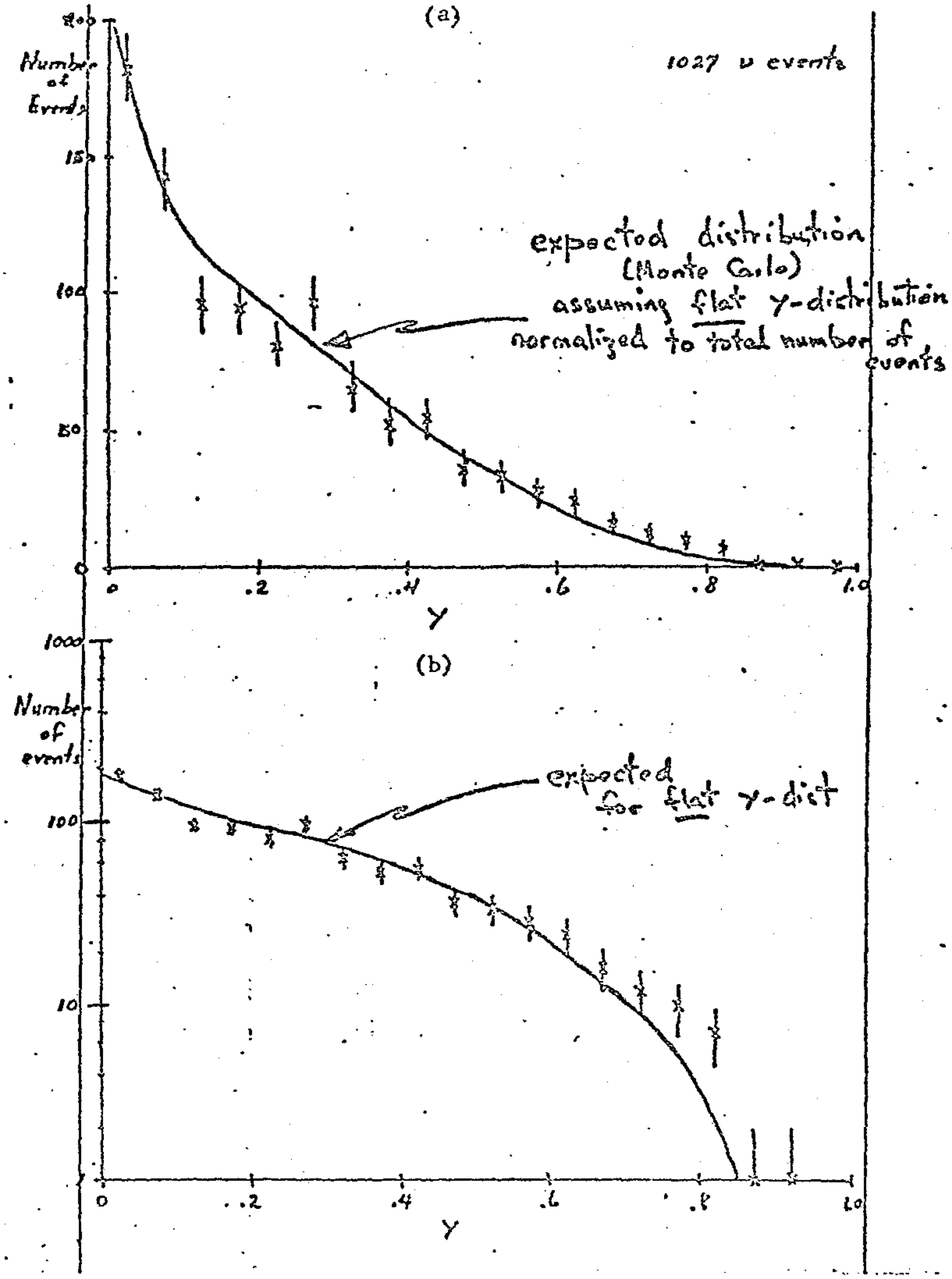
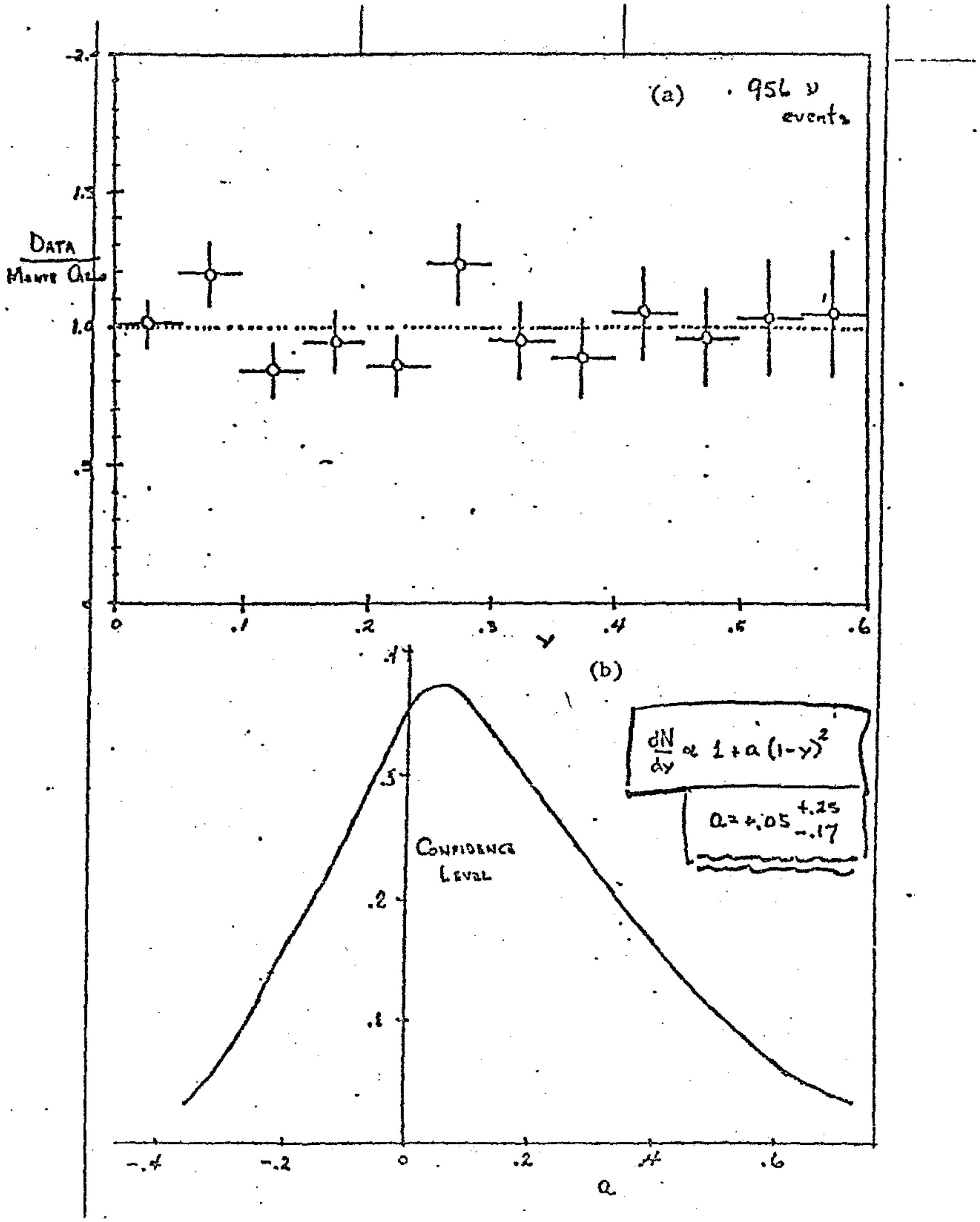

(a)
1027 ν events
Number of Events
200
150
100
50
0
0
.2
.4
.6
.8
1.0
Y
expected distribution (Monte Carlo) assuming flat y-distribution normalized to total number of events
(b)
1000
Number of events
100
10
1
0
.2
.4
.6
.8
1.0
Y
expected for flat y-dist

Figure 20



(a)
956 ν events
Data / Monte Carlo
y
(b)
$\frac{dN}{dy} \propto 1 + a(1-y)^2$
$a = +.05^{+.25}_{-.17}$
Confidence Level
a