Excess of Electron-like Showers in Neutrino Reactions: A Possible Interpretation

I. Mini Boone Anomaly (FNAL)
Too many events looking like $\bar{\nu}_e n \to \bar{e} p$
As if $\phi(\nu_e) \sim 2.4\ \phi(\nu_e)_{beam}$

II. Anomaly in Fine-Grained Calorimeters (CERN, BNL)
Too many "connected showers" (electron-like) compared to "disconnected showers" (photon-like)
As if $\phi(\nu_e)_{obs} / \phi(\nu_e)_{expected} = 2.2 \pm 0.6$

III. Possible Interpretation:
- New Perspective on π^0 Background
- π^0 Interaction versus π^0 Decay
- π^0- Induced Compton electrons: a new source of electron-like showers.

Unexplained Excess of Electronlike Events from a 1-GeV Neutrino Beam

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The MiniBooNE Collaboration observes unexplained electronlike events in the reconstructed neutrino energy range from 200 to 475 MeV. With 6.46×10^{20} protons on target, 544 electronlike events are observed in this energy range, compared to an expectation of 415.2 ± 43.4 events, corresponding to an excess of $128.8 \pm 20.4 \pm 38.3$ events. The shape of the excess in several kinematic variables is consistent with being due to either ν_e and $\bar{\nu}_e$ charged-current scattering or ν_μ neutral-current scattering with a photon in the final state. No significant excess of events is observed in the reconstructed neutrino energy range from 475 to 1250 MeV, where 408 events are observed compared to an expectation of 385.9 ± 35.7 events.

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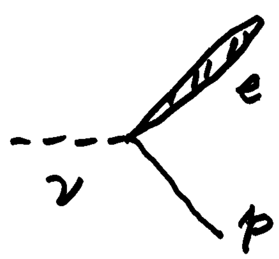
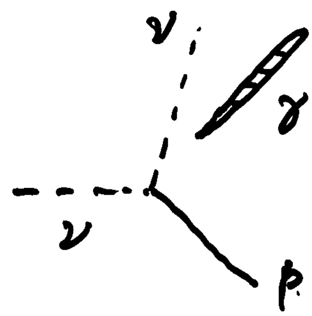
In a previous Letter [1], the MiniBooNE Collaboration reported initial results on a search for $\nu_\mu \to \nu_e$ oscillations. The search was motivated by the LSND observation [2] of an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam that implied larger values of Δm^2 than any of the currently confirmed oscillation measurements. The MiniBooNE result showed no evidence of an excess of electronlike events for neutrino energies above 475 MeV. However, a sizeable excess of electronlike events was observed from 300 to 475 MeV. This Letter reports on a more detailed investigation of the low-energy electronlike events [3]. Published explanations for the low-energy excess range from anomaly mediated neutrino-photon coupling [4] to neutrino oscillations involving sterile neutrinos [5–9] to Lorentz violation [10]. In the course of this investigation, many improvements have been made to the data analysis, and the data sample has increased from 5.58×10^{20} protons on target (POT) to 6.46×10^{20} POT. The excess of electronlike events per-

Summary of MiniBoone Observations

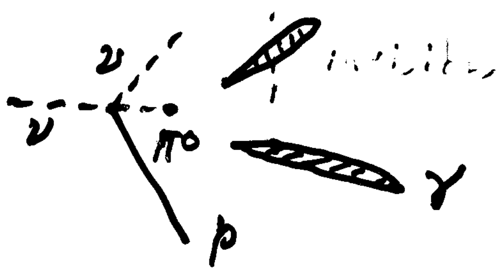
Search for events that look like
$\nu_e + n \to e^- p$ (one track, one shower/ring
and kinematics compatible with CCQE)
Experiment cannot distinguish between
e and γ



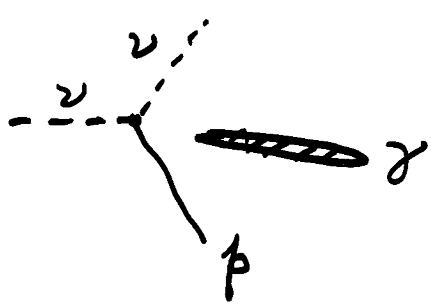


Require careful estimate of BG (Table)
Two items of particular interest:

NC π^0 :
($\nu p \to \nu p \pi^0$)



NC radiative
($\nu p \to \nu p \gamma$)



Final Result : Electronlike excess

Observed 544 } Difference $129 \pm 20 \pm 38$
BG 415 } $200 < E < 475$ MeV

Final Results: Background event breakdown

Process	200 – 300	300 – 475	475 – 1250
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \rightarrow \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
Dirt Events	11.5	12.3	11.5
Other Events	18.4	7.3	16.8
ν_e from μ Decay	13.6	44.5	153.5
ν_e from K^+ Decay	3.6	13.8	81.9
ν_e from K_L^0 Decay	1.6	3.4	13.5
Total Background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

- Above 475 MeV still dominated by intrinsic nue
- At low E transitions to NC π^0 and Δ->Nγ dominated bkgs

CERN

ANOMALOUS ELECTRON PRODUCTION OBSERVED IN THE CERN PS NEUTRINO BEAM

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Neutrino interactions in a fine-grain calorimeter have been analysed with emphasis on events with associated electromagnetic showers. The good granularity of the detector allows to separate photon from electron showers. The number of events with an electron was found to be about three times larger than expected on the basis of the beam composition. This may be interpreted as due to $\nu_\mu \to \nu_e$ oscillations.

The experiment PS191 at CERN searched for decays of heavy neutrinos using a decay detector followed by a fine-grain electromagnetic calorimeter. The trigger conditions were set by a scintillator hodoscope at a depth of 1.7 radiation lengths inside the calorimeter. The purpose of the hodoscope was to select events where one or more showers traversed the hodoscope plane. The threshold for the acceptance of the scintillator signals was set to twice the minimum-ionization value in the scintillator (as measured in a calibration run). If more than one scintillator slab ($30 \times 300 \times 1$ cm^3) out of the available twenty gave a signal, then the event was accepted even if the amplitudes corresponded to the minimum-ionizing level. These conditions were such that, as a by-product, about a thousand neutrino interactions were recorded in the calorimeter modules preceding the hodoscope. Clearly, shower-associated interactions were favoured in this sample. An analysis of these events shows an abnormal abundance of electrons stemming directly from the vertex of the interaction which cannot be explained on the basis of the neutrino beam composition except as an improbable statistical fluctuation.

Details of the beam and a general description of the apparatus are given elsewhere together with the results on neutrino decays [1]. The beam consisted of ν_μ with an energy spectrum peaking at ~600 MeV and a small admixture, (0.7 ± 0.2)%, of ν_e at somewhat higher energies. Fig. 1 shows the energy spectrum of the neutrino fluxes calculated using two independent and consistent simulation programs [‡1]. Both ν_μ and ν_e fluxes are simulated by these programs currently used by most low-energy neutrino experiments; in particular, the ν_e source from μ decays has been included in the calculation. The part of the apparatus that we are concerned with is the calorimeter, made of flash-tube chambers separated by 3 mm thick iron plates. The granularity of the detector is 17% of a radiation length and the transversal dimensions of the tubes are 5×5 mm^2. The "target" region for the interactions under study consisted of 10 layers of "flash-tube/iron-plate" sandwiches weighing a total of ~5 t. The surface covered by the detector across the beam was 6×3 m^2. The same target structure was repeated beyond the hodoscope for a total of 30 identical sandwiches, i.e., an additional 5.1 radiation lengths. The fine granularity of the detector allows

‡1 See ref. [2] and calculations independently performed by us on μ decays, and ref. [3].

BNL

SEARCH FOR NEUTRINO OSCILLATIONS

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A search for $\nu_\mu \to \nu_e$ (and $\bar{\nu}_\mu \to \bar{\nu}_e$) oscillations has been conducted with the AGS wide-band neutrino beam at the Brookhaven National Laboratory. We find more ν_e ($\bar{\nu}_e$) interactions than were expected on the basis of the number of incident ν_e ($\bar{\nu}_e$) calculated as part of the neutrino beam. The excess is about a factor two over the expectation, the statistical significance being about two and a half standard deviations for ν_e and weaker for $\bar{\nu}_e$.

1. Introduction

The CERN PS191 Experiment [1] had been designed to search for neutrino decays by looking in an appropriate calorimeter for electron showers associated with a decay configuration observed in an upstream helium-filled volume. Intrinsic to the detector performance was the capability of observing electron production in neutrino interactions within the calorimeter itself. No example of neutrino decay was observed in this investigation. Instead we were confronted with an abnormal electron production by neutrino in a ν_μ beam with a small contamination of ν_e [2]. The statistical significance of the effect was marginal and we were motivated to repeat the experiment at BNL [3] with an improved apparatus and a more intense beam.

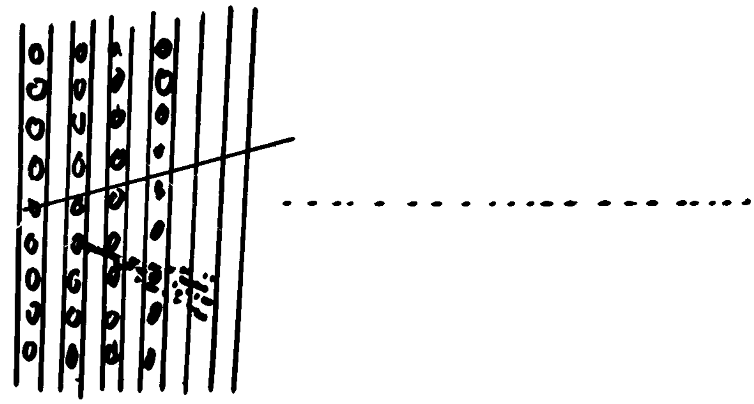
2. Detector

The detector is shown in fig. 1. Its primary component was a fine-grained calorimeter made of sandwiches of 3 mm thick iron plates between flash-tube chambers [4] built by the Fréjus Collaboration for their proton-decay search. The cross section of the tubes was 5×5 mm^2 and their length 6 m; they were assembled to give only the vertical coordinate. The iron thickness between sensitive planes represented ~17% of a radiation length. The front surface of the detector covered an area of 3×6 m^2. The total weight was 30 t of which only 7 t were used in the fiducial volume. Being compact and dense this calorimeter had a large angular acceptance.

A liquid-scintillator veto counter [#1] was the first detection plane of the apparatus. It was followed by ten calorimeter modules which served as target region for the neutrino interactions. Two plastic-scintillator hodoscopes followed them and were used for trigger purposes. Another set of calorimeter modules interleaved with lead plates of increasing thickness were placed downstream of the trigger planes to measure and contain the showers originating in the target. There was a total of ~15 radiation lengths from the central plane of the target region to the end of the detector. The first plane of the apparatus was located 175 m from the neutrino production target.

[#1] We are indebted to the E734 Collaboration for the use of a part of their liquid-scintillator system.

Summary of CERN/BNL (Fine-Grained Cal.)



One (or more) tracks
One (or more) showers

L = disconnection between vertex
and nearest shower

Distribution in L well fitted by an exponential, except for excess in first bin.

Typical result

No. of showers in lowest bin = 363 ± 18
Expected from simulation 299 ± 21
Excess (interpreted as electrons) = 64 ± 28
Expected from ν_e contam: (compare)

$$\frac{\text{Observed Electrons}}{\text{Electrons expected from beam contam}} = 2.2 \pm 0.6$$

BNL

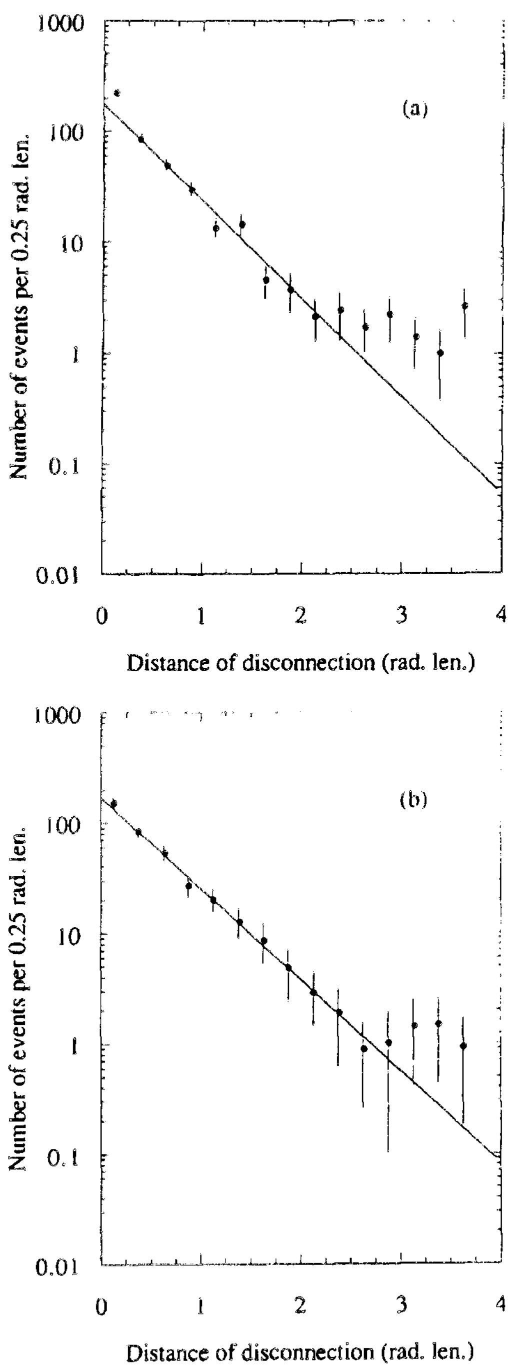


Fig. 4. Distribution of the disconnection distance: Data in (a), simulation in (b).

ated. To take into account this effect a correction was applied on both data (fig. 4a) and simulation (fig. 4b). We found that this correction affected some 6% of the connected showers.

The second bias acted in the opposite direction, namely it caused truly connected showers to appear disconnected because of detector inefficiency. In order to deal with this effect we applied a global correction to the disconnection distribution obtained from the (efficiency-free) Monte Carlo simulation. The inefficiency of the chambers was measured throughout the experiment using minimum ionising tracks from the two-track events. The probability for a genuine electron to appear disconnected by 0, 1 and 2 chambers turned out to be 0.83, 0.13 and 0.04, respectively.

Electron events are of course expected to come from the ν_e component in the neutrino beam. To estimate how many such events should be present in the experiment we relied on another "ad hoc" Monte Carlo sample. This sample was generated with an incident neutrino beam consisting only of ν_e and it was scanned in order to evaluate the capabilities of both detector and scanner to correctly recognise the ν_e interactions. The relative normalisation was obtained via the two-track events. The result of the simulation and its scan was that the expected number of electron events from the ν_e contamination to be found in our sample was 53 ± 6(stat.) ± 11 (syst.). The detector inefficiency will have the effect of spreading out these events over the first three bins of the plot of fig. 4b. From these numbers we conclude that the predicted (integrated) flux ratio after our cuts is

$$\nu_e/\nu_\mu = [0.61 \pm 0.06(\text{stat.}) \pm 0.10(\text{syst.})]\% .$$

The effective number of electrons in our data was obtained from the measured disconnection distribution. Without introducing any hypothesis on the distribution or amount of the π^0 background, we directly subtracted the simulated distribution (including the expected ν_e contamination mentioned above) from the experimental distribution. The simulation included 2.6 ± 1.4 events expected from the hadron background on the basis of the pion calibration runs. Fig. 5a shows the subtracted distribution. There is a clear signal for zero-disconnected showers, viz. electrons.

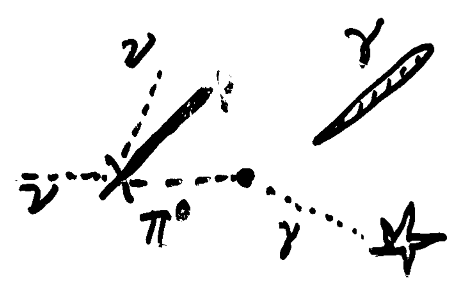
The total number of excess electrons was obtained by summing the first three bins. Over this range there were 363 ± 18 events to be compared with the 299 ± 21 events expected from the simulation (errors include the systematic uncertainty on the beam flux). The net excess is 64 ± 28 events. The total number of

III. Possible Interpretation

(i) Standard Mechanism for Single Shower Event associated with π^0 Decay: Sequential Process

$$\pi^0 \to \gamma\gamma \qquad (1)$$

$$\hookrightarrow \gamma + N \to \underbrace{X}_{\text{low energy nuclear fragments "Star"}}$$



Final State contains a photon-like shower and a star, both displaced from the neutrino vertex.

Cross section for sequential process may be written as

$$\frac{d\sigma}{dy}(\pi^0 + N \to \gamma X)\Big|_{seq} = 2\,\sigma_{\gamma N}(y)$$

$$y = E_\gamma / E_\pi$$

This is the <u>photonuclear absorption</u> cross section included in the MiniBoone background calculations. (Accounts for ~ 40 BG events)

(ii) <u>New Perspective on Photonuclear Absorption</u>:

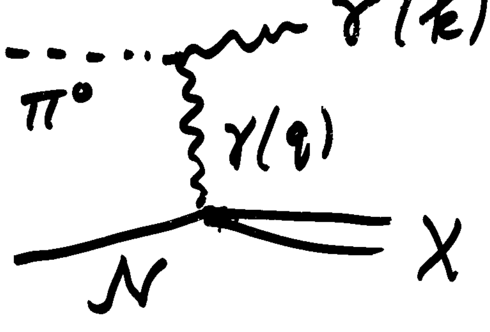
Consider $\pi^0 + \mathcal{N} \to \gamma + X$ as a π^0 interaction (instead of a sequential process $\pi^0 \to \gamma\gamma$, followed by $\gamma + \mathcal{N} \to X$).

[Note : $\tau_{\pi^0} = 10^{-16}$ sec

For $E_\pi \sim 300$ MeV, $d_\pi \sim 6 \times 10^{-6}$ cm

Thus the π^0 encounters several hundred atoms before it decays. Should be legitimate to treat the process as an interaction.]

Possible Diagram



Two problems :

(i) $\pi^0 \to \gamma\gamma$ vertex has a factor α

[$g_{\pi\gamma\gamma}\, \epsilon_{\mu\nu\rho\sigma}\, k^\mu \epsilon^\nu q^\rho \epsilon'^\sigma$

$$g_{\pi\gamma\gamma} = \frac{\alpha}{\pi f_\pi} \; ; \; \Gamma_{\pi\to\gamma\gamma} = \frac{m_\pi^3}{64\pi} g^2_{\pi\gamma\gamma} \approx 8\,\text{eV}]$$

So σ would appear to be factor α^2 smaller

(ii) The variable q^2 takes values in the range

$$-s(1-y) < q^2 < m_\pi^2 y$$

ranging from negative (space-like) values to positive (time-like) values, and passes through zero. Thus the $1/q^2$ propagator blows up.

Solution:

Recall kinematics of $\pi^0 \to \underbrace{\gamma(k)}_{\substack{\text{real} \\ k^2=0}} + \underbrace{\gamma(q)}_{q^2 \neq 0}$

$$q^2 = -\frac{k_\perp^2}{1-y} + m_\pi^2 y$$

Instability of π^0: $m_\pi \to m_\pi - \frac{i}{2}\Gamma_\pi$

$$\Rightarrow \quad q^2 \to q^2 - i\gamma \quad , \quad \gamma = m_\pi \Gamma_\pi y$$

Suggestion (due to Ginzburg 1995*):

replace propagator $\frac{1}{q^2}$ by $\frac{1}{q^2 - i\gamma}$

Result: finite cross section!

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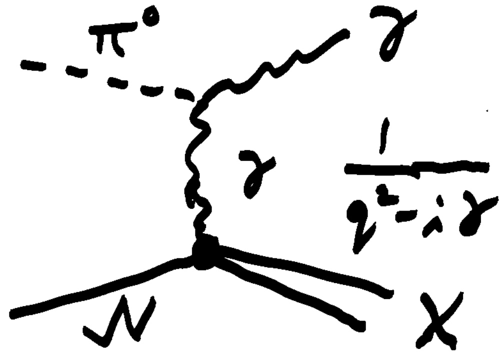
* in the context of $\mu^+\mu^-$ colliders

Calculation

Amp =

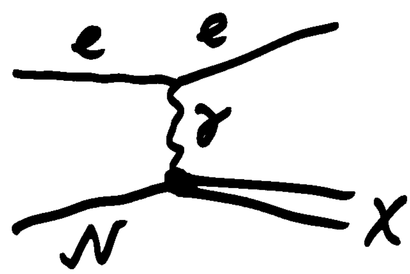


$\frac{1}{q^2 - i\gamma}$

$$|Amp|^2 = \frac{1}{q^4+\gamma^2} P_{\mu\nu} W^{\mu\nu}$$

$$P_{\mu\nu} = -(k\cdot q)^2 g_{\mu\nu} - q^2 k^\mu k^\nu$$

[$W_{\mu\nu}$: same <u>structure function</u> that appears in $ep \to eX$



$\frac{1}{q^2}$

$$\Rightarrow \quad \frac{1}{q^4} L_{\mu\nu} W^{\mu\nu} \Big]$$

Cross section dominated by region $q^2 \simeq 0$

$$\frac{d\sigma}{dy\,dq^2} = \frac{3}{\pi}\gamma \frac{1}{q^4+\gamma^2}\sigma_{\gamma N}(y)$$

Integral over q^2 $[-ve < q^2 < +ve]$

$$\int_{-ve}^{+ve} dq^2 \frac{1}{Q^4+\gamma^2} = \frac{1}{\gamma}\tan^{-1}\frac{q^2}{\gamma}\Big|_-^+ = \frac{\pi}{\gamma}$$

Result $\frac{d\sigma}{dy} = 2\,\sigma_{\gamma N}(y)$

This is <u>identical</u> to cross-section for the case of sequential process $\pi^0 \to \gamma\gamma$, followed by $\gamma + N \to X$!

<u>What is new</u> ?

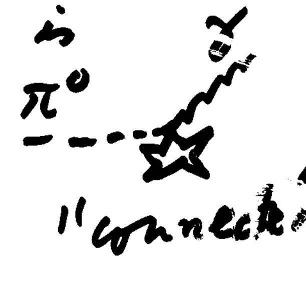
$$\left.\frac{d\sigma}{dy\,dq^2}\right|_{seq} = 2\,\sigma_{\gamma N}(y)\;\delta(q^2)$$

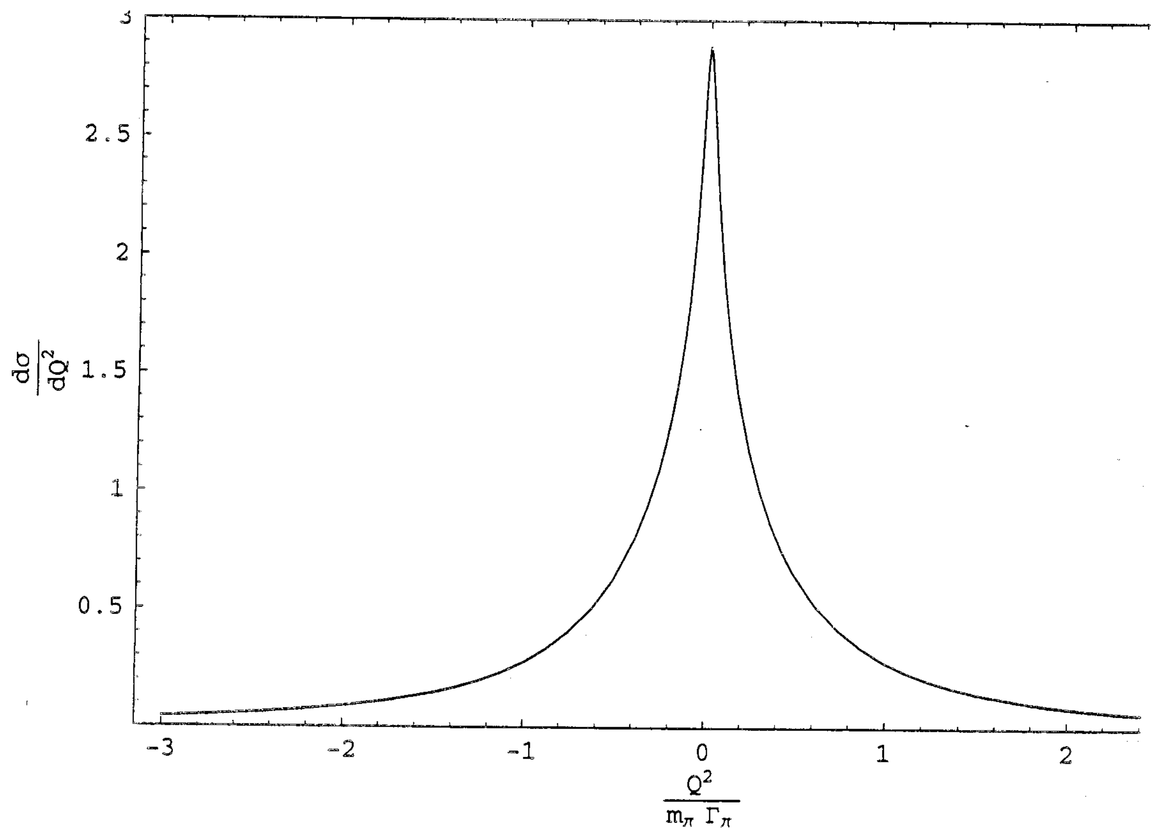
$$\left.\frac{d\sigma}{dy\,dq^2}\right|_{\pi^0\,int} = 2\,\sigma_{\gamma N}(y)\;\frac{\gamma}{\pi}\;\frac{1}{q^4+\gamma^2}$$

<u>Recall</u> : <u>Path length of a virtual photon</u> (q^2) is $L = \frac{2E_\gamma}{q^2}$

Thus $\delta(q^2)$ implies distance from π^0 decay-point to "star" is <u>large</u>

By contrast, π^0-int. scenario has $(\gamma/\pi)\;1/(q^4+\gamma^2)$, so dist is <u>small</u>!





3
2.5
2
1.5
1
0.5
$\frac{d\sigma}{dQ^2}$
-3
-2
-1
0
1
2
$\frac{Q^2}{m_\pi \Gamma_\pi}$

<u>Distribution in "disconnection"</u> $L = \frac{2E_\gamma}{q^2}$ has a simple scaling behaviour:

Define $\lambda \equiv \frac{L}{L_{dec}}$ $\qquad L_{dec} = \gamma_\pi c \tau_\pi$

then

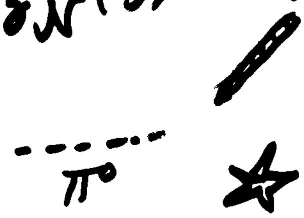
$$\frac{d\sigma}{dy\, d\lambda} = \frac{1}{\pi} \frac{1}{1 + \frac{1}{4}\lambda^2} \sigma_\gamma(y)$$

<u>Conclude</u>:

Process $\pi^0 + N \to \gamma + \text{"Star"}$

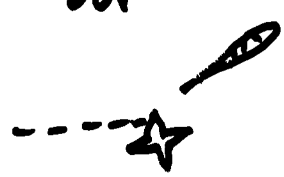
(a) <u>Decay perspective</u> (seq) $(\pi^0 \to \gamma\gamma,\ \gamma N \to X)$

$$\left(\frac{d\sigma}{dq^2 dy}\right|_{seq} = 2\sigma_{\gamma N}(y)\,\delta(q^2)$$



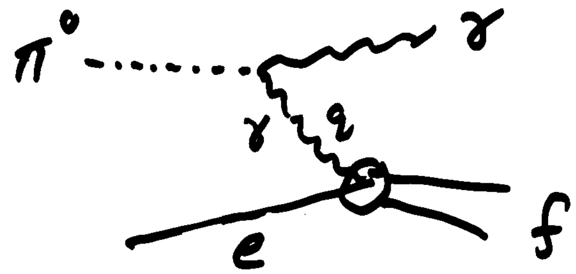
(b) <u>Interaction Perspective</u>

$$\left(\frac{d\sigma}{dq^2 dy}\right|_{int} = 2\sigma_{\gamma N}(y)\,\frac{\gamma}{\pi}\,\frac{1}{q^4 + \gamma^2}$$



However: What we are looking for is a mechanism that produces a connected shower

(iii) <u>New Mechanism for Electronlike Showers : π^0 interaction with electron</u>



$$\frac{1}{q^2 - i\gamma}$$

Treat this in the same way as

$\pi^0 + N \to \gamma + X$

Choose $f = \gamma e$

Result

$$\frac{d\sigma}{dy\, dq^2} = 2\, \underbrace{\sigma_{\gamma e}}_{\text{Compton cross section}}(y)\, \frac{\gamma}{\pi}\, \frac{1}{q^4 + \gamma^2} \qquad \gamma = m_\pi \Gamma_{\pi^0\gamma\gamma}$$

$\gamma + e \to \gamma + e$

$$\frac{d\sigma^{\gamma e}}{dz} = \frac{\pi \alpha^2}{m^2} \left\{ \frac{1}{\left[1 + \frac{k}{m}(1-z)\right]^3} + \frac{1}{1 + \frac{k}{m}(1-z)} - \frac{1 - z^2}{1 + \frac{k}{m}(1-z)^2} \right\}$$

$z = \cos\theta_\gamma$ (lab)

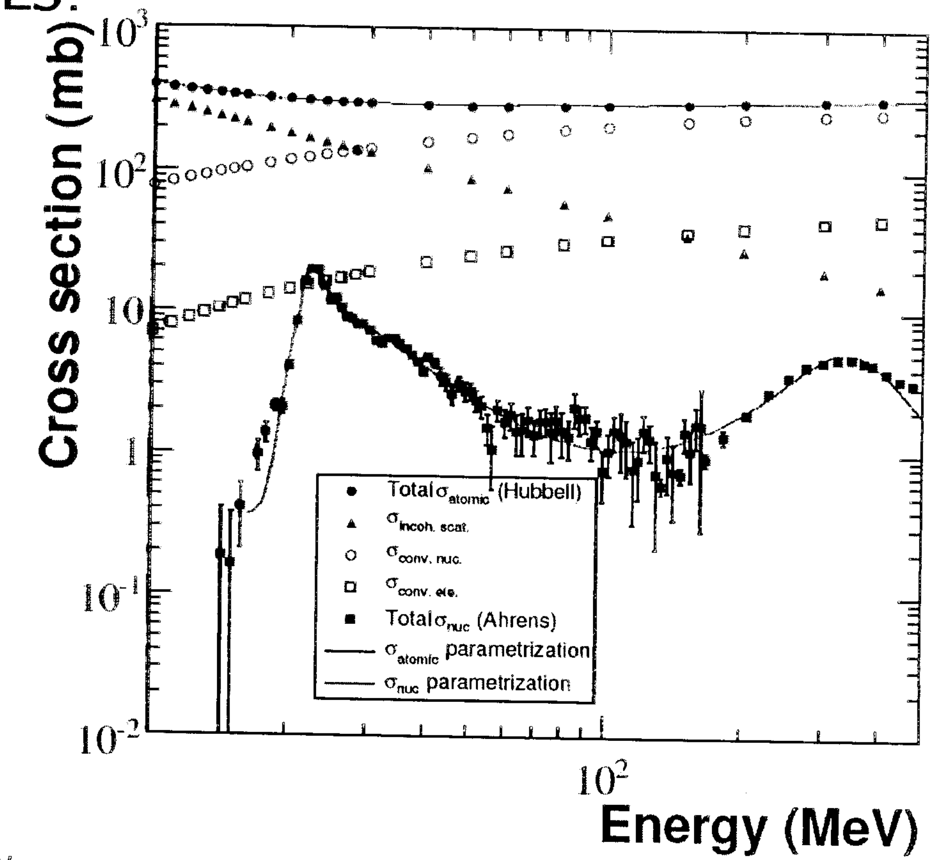
Cross section is large!

For $E_\gamma \sim 300$ MeV, $\sigma(\gamma e \to \gamma e)|_{\text{Carbon}}$ is 7 times larger than $\sigma(\gamma N \to \gamma N)|_{\text{Carbon}}$

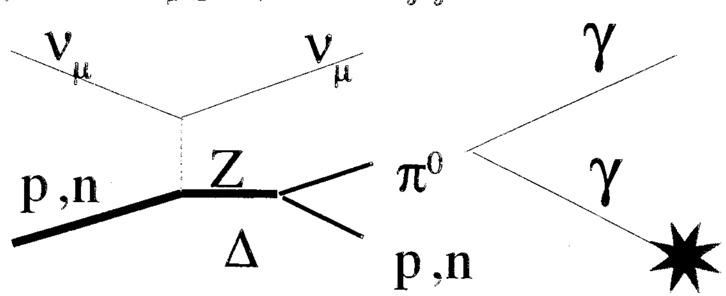
Update #3: Hadronic bkgs/errors in ν interactions

ADDITIONAL HADRONIC PROCESSES:

- Photonuclear interactions
  - Absent in GEANT3
  - Can delete a γ in a NC pi0 interactions, thus creating a single e-like ring
  - 40,000 NC pi0 interactions
  - Well-known cross-section, in fact in GEANT4 which allowed for cross-check
  - Uncertainties enter via final states
- Only hadronic process found to contribute significantly

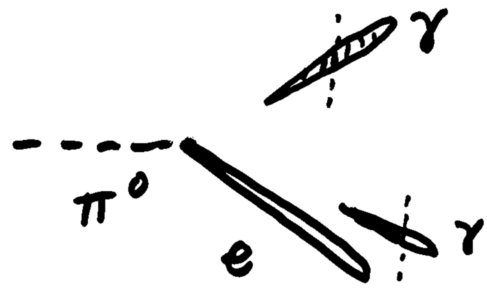


$$\nu_\mu(p,n) \rightarrow \nu_\mu(p,n)\pi^0, \pi^0 \rightarrow \gamma\gamma$$



Consequence : Final State of the form

$\pi^0 e \to \gamma e \gamma$



Connected Electron Shower !
(≡ Compton electron

If the two photons are invisible (low energy, or merging into the electron shower) the above process is a good candidate for

"Excess of Electronlike Events"
(MiniBoone)

or "Excess of Connected Showers"
(CERN/BNL Fine-Grained Calorimeters)

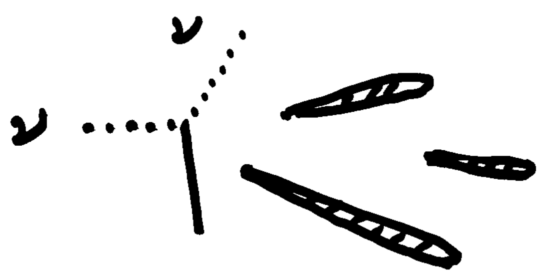
Quantitative Test requires a full simulation of this new mechanism

Comments :

1. Two mechanisms for $\pi^0 + e^- \to \gamma + e^- + \gamma$

(i) Sequential : $\pi^0 \to \gamma\gamma$
followed by $\gamma + e^- \to \gamma + e^-$

Appearance in detector



Three disconnected showers
Dependence on L : $e^{-L/L_{conv}}$
L_{conv} = conversion distance (~ cm.)

(ii) π^0 Interaction $\pi^0 \to \gamma\gamma^*$
$\gamma^* + e^- \to \gamma + e^-$
γ^* is quasi-real, $|q^2| \lesssim \Gamma_\pi m_\pi$

Appearance of event

One shower connected (electron-like)
Dependence on L:
$1/(1 + \frac{1}{4}(\frac{L}{L_{dec}})^2)$ (microns

2. If the two mechanisms occur with probabilities f_{seq} and f_{int}, the process $\pi^0 + e^- \to \gamma + e + \gamma$ has the differential cross section

$$\frac{d\sigma}{dy\,dq^2} = \left[f_{seq}\, \delta(q^2) + f_{int} \frac{\gamma}{\pi} \frac{1}{q^4 + \gamma^2} \right] \cdot 2\,\sigma_{\gamma e}(y)$$

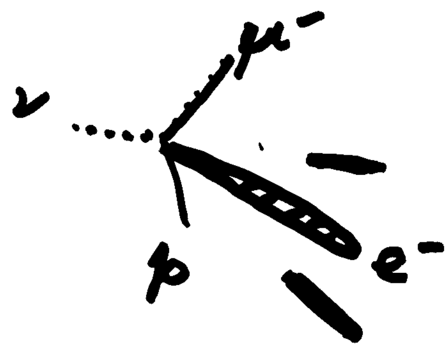
$$f_{seq} + f_{int} = 1$$

Presumably, a complete theory of $\pi^0 + e^- \to \gamma + e^- + \gamma$, incorporating both the decay and interaction features, will determine f_{seq}/f_{int} in terms of the two length scales:

$$L_{decay} = \gamma_\pi c \tau$$

L ~~disconnection~~ conversion ~~[illegible]~~

3. The mechanism for π^0 associated electron-like (connected) showers should be equally valid for <u>charged current</u> interactions, and should give rise to events with <u>$\mu^- e^-$</u> :



$$\nu n \to \mu^- p \pi^0$$
$$\pi^0 \to \gamma + \gamma^*$$
$$\gamma^* + e^- \to \gamma + e^-$$
γ^* : quasi-real
$$|q^2| \lesssim \Gamma_\pi m_\pi$$

<u>Unexplained $\mu^- e^-$ events</u> have been reported in the past*, and perhaps should be looked for once more.

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* See, for example, Faissner et al (1981)

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Observation of Anomalous Muon-Electron Pairs in a Neutrino Exposure

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Abstract. Muon electron pairs were detected in an Al multiplate spark chamber, exposed to a neutrino beam from the CERN PS. The leptons were not accompanied by other particles, except occasionally by protons. The background came mainly from muon associated π^0 production, with one decay gamma lost. It was determined empirically, together with the small contribution from ν_e reactions. For electron energies above 2 GeV the background is 5.7 ± 1.5 events, whereas 18 (μe)-candidates have been observed. Hence the effect is established, with a rate of about 10^{-4} as compared to the muonic reactions above 3 GeV. Charm creation as the origin of this (μe)-production process is excluded; heavy neutral lepton production does not fit the kinematics observed. Instead the events are compatible with the two-body decay of an object with variable invariant mass of order 1 GeV, possibly resulting from axion interactions.

We have observed [1] 18 *muon electron candidates* of the form

$$\nu_\mu + \mathcal{N} \rightarrow e + \mu (+\mathcal{N}')$$

with no other hadron or photon in the same picture, except for occasional short tracks ($\mathcal{N}'$) at the vertex. All of them occurred at a visible total energy above 3 GeV. They were detected in a multiplate spark chamber, exposed to the CERN PS wide band neutrino beam, with an average energy of 2.2 GeV.

The *detector* [2] consisted of 258 Al plates, 2 m × 2 m in size, 1 cm thick and spaced 1 cm apart. The spark chambers were filled with Ne-He, and they were fired every PS pulse. At the end of the set-up there were 12 iron plates, 4 cm thick, interleaved with 3-plate spark chambers, which formed an Internal Muon Identifier (IMI). Two views were photographed, at a stereo angle of 90°, thus providing a clear separation of several structures in one photograph. No magnetic field was applied, and therefore a distinction between e^-, e^+, and γ is not possible. However, single shower and multi shower events (like π^0's) can be separated down to an opening angle of 1°. Also hadron tracks inside showers are readily recognized.

The apparatus was well suited for the *detection of electromagnetic showers* [3], since the radiation length X_0 was only 22 cm in space. Because of its large angular acceptance, and its sizeable length ($22 X_0$), the efficiency for detecting both decay-gammas from a neutrino produced π^0 was typically 60%. The shower-energy was measured by spark counting, and an absolute calibration was achieved by means of a momentum selected electron beam. In the range $0.1 < E_e < 2$ GeV, the energy error was determined $\Delta E_e / E_e = 22\%$. This error does not depend too much on energy, up to 10 GeV.

The *muons* were identified from the absence of nuclear interactions over a certain pathlength l. The discrimination between muons and hadrons was easy, since the Al part of the chamber was already 10 nuclear interaction lengths Λ_0 deep. Another $6 \Lambda_0$ were concentrated in the IMI, at the end of the detector.

"Naked" (μe)-*pairs* have been analysed in 540,000 pictures from neutrino exposures. They have been defined as follows:

1) There must be one track with a length $l > 4 \Lambda_0$, showing neither interaction nor scattering in the chamber ("μ").

2) There must be an electromagnetic shower with an energy $E_e > 300$ MeV, starting immediately at the vertex, i.e. at the origin of the track ("e").

1 Now at CERN, Geneva, Switzerland
2 Now with Bundeswehr-Hochschule, Munich
3 Now at Gesellschaft für elektronische Datenverarbeitung, Aachen

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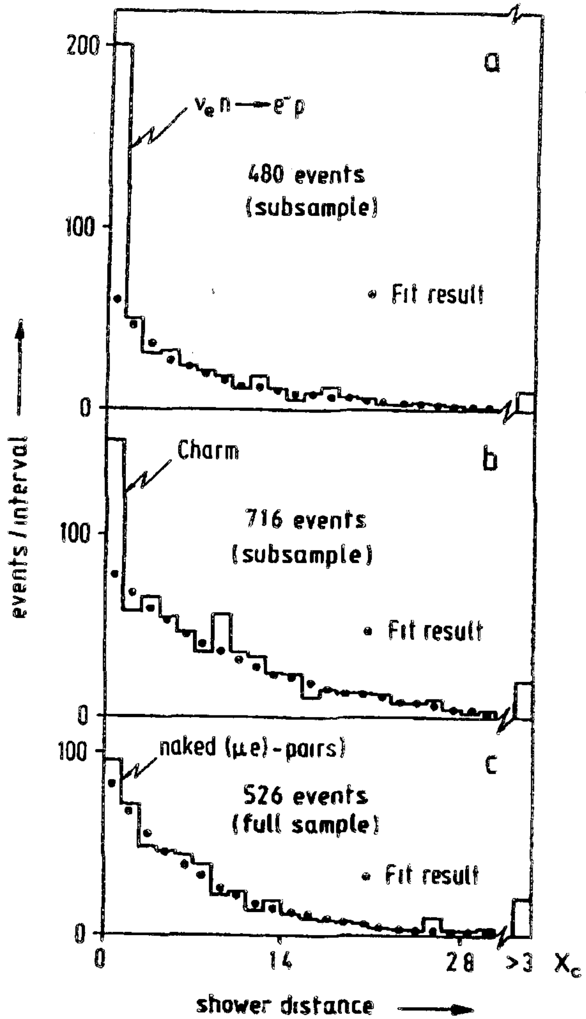

Fig. 2a–c. Distribution of conversion distance for several one-shower samples. The bin width was chosen somewhat larger than the granularity of the aluminium plates. Thus, electrons are concentrated in the first bin, whereas photons contribute to all bins. The points represent the result of an exponential fit to the distribution, excluding the first bin. **a** Shows the large signal of inverse beta decay; **b** shows the clear signal of (μe)-pairs from semileptonic decay of charmed hadrons; **c** represents the result of the search for "naked" (μe)-pairs for all electron energies

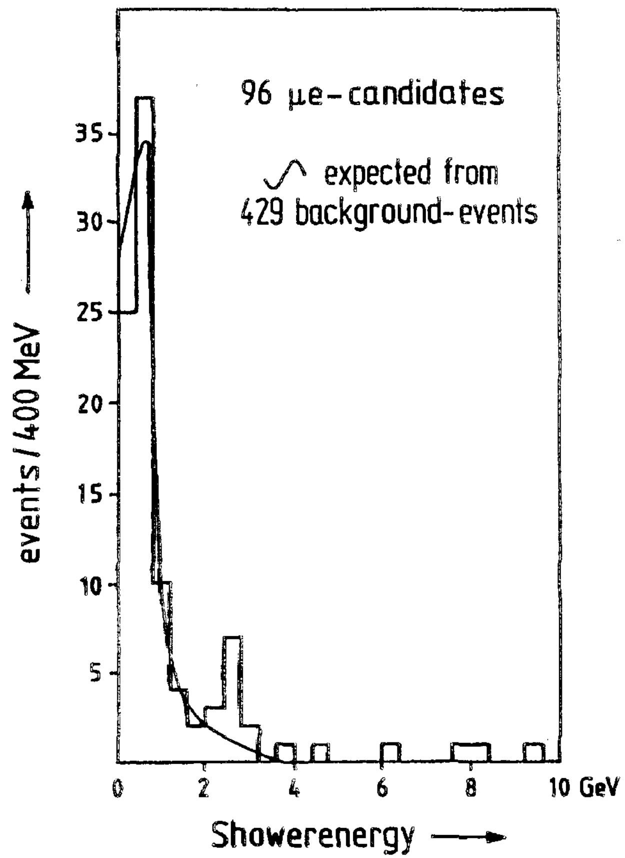

Fig. 3. Energy distribution of the 96 electron candidates of Fig. 2c. The smooth curve represents the distribution expected from photon background. A clear excess of events at larger shower energies is visible

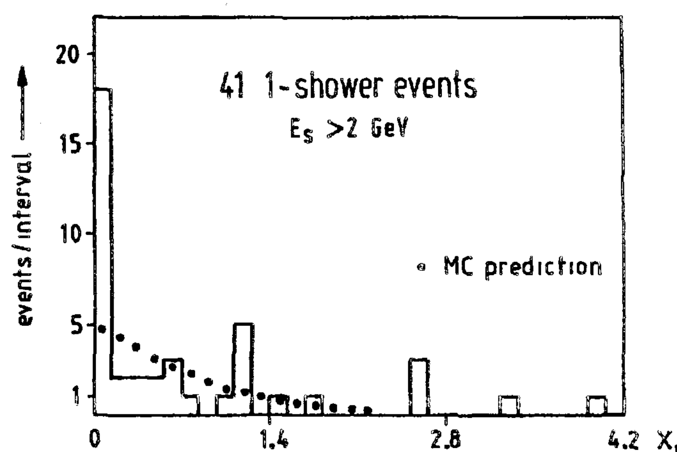

Fig. 1. Typical (μe)-candidate. On the muon track several faint sparks near the vertex were lost in reproduction. Instead, the sparks beyond the electron shower are overexposed