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ДОКЛАДЫ РАППОРТЕРОВ RAPPORTEURS' REVIEWS

E – 1803

NEUTRINO PHYSICS
(Experimental)

Rapporteur G. Bernardini

Secretaries: V.S. Evseyev
L.A. Mikaelyan

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NEUTRINO PHYSICS
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I. The works which I have to report are those of the un-official Neutrino Session hold a week ago. They could be considered the extension (for momenta order of magnitude higher than those involved in μ -capture and β-decay) and continuation of the celebrated experiment of Reines and Cowans. Everybody knows that this new line of research had its origin in a proposal formulated by Pontecorvo at the Rochester-Conference in Kiev in 1959 and by Schwartz in 1960 in a letter to Physical Review.

In the last Rochester-Conference at CERN Schwartz reported the results of the first experiment done on this line at Brookhaven by a group led by Lederman, Schwartz and Steinberger.

The experiment gave the answer to one of the major problems discussed in the first Pontecorvo's paper. The neutrino associated with μ-capture and inverse reaction, is different from the β -decay neutrino. Actually the existence of two neutrinos was an old story and its implications had been already analysed and thouroghly discussed in several papers by Markov, Nishijima, and Schwinger.[*]

The people who attended the informal session enjoyed a discussion on possible names for these two neutrinos. Pontecorvo proposed mu -neutrino and el-neutrino. One may also use the more conservative names muon-neutrino and electron-neutrino. As much as possible I will avoid names and use the symbols ν_μ and ν_e

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[*] During the Conference I learned that the matter is even older than I thought and it goes back to a work of SAKATA in 1943.

In the Brookhaven experiment statistics was just good enough and Lapidus assuming a possible very large pseudoscalar term ($G_p > 10\ G_A$) casted some doubts about the conclusions. However in a subsequent paper the Columbia group solely on the basis of C.V.C. demonstrated that if the reaction

$$\nu_\mu + n \rightarrow p + e$$

had been allowed the minimum number of expected electrons (with a 30% uncertainty due to the scarce knowledge of the spectrum) had to be 12, while the maximum possible number of observed electrons was 6. The Brookhaven experiment showed also that the number of simple μ-tracks was consistent with the cross-section evaluated by Cabibbo and Gatto, Lee and Yang and Yamaguchi for the elastic-channel.

Since then to my knowledge, on this field beside the report at Siena of the preliminary results of the CERN experiment and a report by Faissner at the Hamburg meeting in 1963 nothing has been published.

2. The largest fraction of the time of the neutrino-session has been spent on the reports by Cundy, Faissner and Gaillard on the CERN experiments, but other interesting papers and proposals have been presented and discussed and I would like first to mention them.

I apologize if in an undeserved manner I will report on them too briefly.

2. Among the papers I found here one by Falomkin et al. refers to a new measurement of the limit of the mu-neutrino mass. It is somewhat a by-product of the beautiful experiment done by the authors on μ-capture by He^3. The range of the triton emitted in the reaction

$$\mu^- + He_2^3 \rightarrow H^3 + \nu_\mu$$

has been carefully measured using the reactions

$$\pi^- + He^3 \rightarrow H^3 + \cancel{2}\,\pi^0,$$
$$\pi^- + He^3 \rightarrow H^3 + \gamma,$$
$$n + He^3 \rightarrow H^3 + p$$

for calibration.

The results is that the mass of the mu-neutrino is

$$m_{\nu_\mu} = 6^{+2}_{-6} \text{ MeV.}$$

In another paper by Mikaelyan and Spivak is discussed the possibility to observe at fairly low energy the $\tilde{\nu}_e$ electron scattering. Everybody knows how important would be to know something about it. The cross-section is

$$\sigma \simeq 10^{-41} \text{x (lab. energy in GeV).}$$

i.e. about a factor 1000 smaller than the lepton-nucleon cross-section at energies of the order of one GeV.

It is proposed to built a special reactor where part of the thermal neutrons are absorbed in Li^7 producing Li^8 with the emission of $\tilde{\nu}_e$ whose maximum energy is ~ 13 MeV. The short period of Li^8 makes it possible to use the reactor in the pulsed operating conditions, according to a suggestion by S.M. Fainberg. Under these circumstances the recoiling electrons will be detectable because the background will be strongly reduced and because of their relatively high energy.

With a reactor of a power of about 10^5 Kw, a flux of the order of 10^{15} $\tilde{\nu}$/cm^2 is expected. This is adequate to compete with the very small cross-section; which is (above 2 MeV) $\sigma \gtrsim 10^{-44}$ cm^2. In 24 hours equivalent to 10 seconds effective operation one expects in a ton of NaJ about 40-80 recoil-electrons in a range 2-5 MeV, with a tolerable background.

During the discussion prof. Reines said that the reaction $\tilde{\nu}_e + p \rightarrow \beta^+ + n$ is now studied in an experiment now in progress at the Savannah River Piant. The experiment should be capable of a precision measurement of the interaction constant and of the β^+ spectrum.

Also the $\tilde{\nu}_e - e$ scattering is being approached. The key idea of the experiment is to make use of the spatial distribution (in a low Z medium) of the compton collisions to eliminate the photon background. In this experiment where the coincidence technique cannot be used, this is the largest part of the background. A NaJ anticoincidence detector surrounding a properly segmented organic scintillator detector will have the virtue to reduce the unwanted spurious counts. The signal rate above 2 MeV is expected to be a few per day with a background below this level.

3. I said before that most of the session was spent talking and discussing about the CERN experiment. While I thank personally the chairman prof. Schwartz for this consideration, I will take advantage of the situation to forward some information of general character upon the experiment.

If something was really good on it this was the beam. The short pulse extraction (designed and put into operation by Kuiper, Plass and collaborators) had practically 100% efficiency and pushed into an external copper target (a rod 25 cm. long and 4 mm in diameter) in the average 5×10^{11} protons per pulse. The particles emitted (mostly pions), were focussed toward the detectors by a device originally designed by V. Der Meer. The energy of the extracted proton beam incident on the target was 24.9 GeV. The decay path is 25 m., the iron shielding is also 25 m. corresponding to the range of a 28 GeV μ -meson. The "magnetic horn" of V. Der Meer is similar to a conical mirror. It allows to enhance for more than an order of magnitude the total fluxes particularly in the energy region above 4 GeV. Furthermore it allows to have at wish (apart from contaminations) beams of mu-neutrinos or mu-antineutrinos. Apart from a short period the "horn" has been used so far for focussing positive particles and hence to produce mu-neutrino beams. The corresponding spectra evaluated by V. Der Meer and coworkers by an elaborate but straight-forward combination of orbit calculations and kinematical rules is plotted in slide I.

Slide I.

The two curves refer respectively to an old and a new improved version of the horn. There are several sources of error in them; the most important of which lies on the uncertainty about the π and k production. Particularly uncertain is the part of the spectrum above 4 GeV. Furthermore the calculated spectrum concerns only the mu-neutrino originated from primary mesons produced in the target and decaying in the tunnel: secondary sources from interaction in the walls of the horn, of the shielding etc... were neglected. They may contribute apprecialy below 0.5 GeV.

4. One of the detectors placed in the CERN mu-neutrino beam had been a large heavy liquid bubble chamber placed in the more favourable conditions, that is immediately after the iron shield, the other was a multitons spark-chamber.

The main characteristics of the bubble chamber are the following:

Liquid CF_3Br density 1,5 grm/cm^3

radiation length X_o = 11.5 cm.

interaction length λ_o = 68 cm.

Fiducial volume 220 I. = 1/3 ton.

Field 27 KG.

The persons who contributed to the paper presented by Cundy are M. Block, H. Burmeister, D. Cundy, B. Einen, C. Franzinetti, J. Keren, R. Mllerud, G. Myatt, Nicolich A. Orkin-Lecourtois M. Paty, D. Perkins, C. Ramm, K. Schultze, H. Sletten, K. Soop, R. Stump, W. Venus, H. Yoshiki.

To them I would like to add Bingham and Innocenti for their relevant contributions in the 1963 program.

The identification of the tracks was made following the standard procedures based on curvature, ionisation, δ -ray counting etc...

In this manner protons can be clearly distinguished from π and μ 's. Of course π and μ 's cannot be separated. The distinction between π 's and μ 's was then made on the basis of the observable interactions. The residual contamination of π 's which have been taken as μ 's cannot exceed 5% of all the events.

Neutral pions have been identified from kinematics when both γ 's materialised inside the chamber. Few single γ 's found are compatible with the detection efficiency of the chamber. The neutron background for events above 300 MeV is negligible.

Concluding in the Bubble Chamber the errors due to the misinterpretation of the nature of tracks are thought to be not larger than those due to statistics. The other detector was a multitons spark-chamber. The list of the persons who contributed to the spark-chamber experiment is the following. H. Bienlein, A.Bohm, G. von Dardel, H. Faissner, F. Ferrero, J. -M. Gaillard, H.J. Gerber, B. Hahn, V. Kaftanov, F. Krienen, C. Manfredotti, M. Reinharz, R.A. Salmeron, P.G. Seiler, A. Staude, and H.J. Steiner, J. Stein and myself.

The multitons spark chamber has two versions: the 1963 and the 1964, in principle not very different. It consists of three sections. Going down stream with the incident mu-neutrinos the first section is made by relatively thin plates and can be considered a "high resolution production chamber". The second is a magnet with interleaved spark chamber which indicates the sign of the crossing particles; the third is a thick layers "range" chamber. The 1963 edition, shown in slide 2.

Slide 2.

See **Faissner's report**

was a general purposes instrument. The "production region" was made by a front part in aluminium and brass to increase the efficiency in detecting showers. One of the purposes was to confirm the Brookhaven result.

The magnet was an extemporary Helmholtz coil kindly given in loan from Saclay, quite limited in aperture and field strength.

The 1964 edition was mainly designed for the search of the intermediate boson. The high resolution region was made by 5 tons of aluminium plates ~ 7 mm thick, followed by set of thin brass plated equivalent to 8 radiation lengths. But the main difference was the replacement of the Helmholts coil by a set of 25 large magnitized iron plates with 18 interposed spark-chamber units. The overall assembly in shown in slide 3.

Slide 3.

See Gaillard's report

The magnitized iron plates with their field of 17 KG allow to indentify the sign of all particles born inside and having a range $\geqslant$ 200 grm/cm^2 and to estimate with 25% accuracy the momenta of all crossing particles with momenta ranged between 1,5 and 30 GeV/c.

The down-stream part of the apparatus that is the range section was 1500 grm/cm^2 thick. At the end two slabs 15 cm. thick of magnitized iron were able to identify in most of the cases the sign of the escaping particles.

In the spark chambers also in the high resolution sections a good discrimination is possible only between showers and single tracks. The many calibrations show that this discrimination is unambiguous for electrons and photons above 300 MeV.

For "single-line" tracks the distinction between a non-interacting or μ-like particle and all others lies in the possibility of identifying single scattering from "stars" along the track. Then its reliability and accuracy depend on the length of each track and on the goodness and completeness of the calibrations. Other procedures related to multiple scattering, ranges etc... are also applied whenever it is possible.

5. It is probably unnecessary to mention that in the analysis of the events always as a working hypothesis a conservation law was assumed for μ-leptons. A conservation law similar to that valid for the el-neutrino may be considered a normal thing. However if $\nu_\mu \neq \nu_e$ is not al all trivial to show that really this assumption is consistent with the results.

Let consider for instance the reaction chain which starts from a parent π and ends with a μ-neutrino event. It has to be written

$$\left.\begin{array}{l}\pi^+ \to \nu_\mu + \mu^+ \\ \quad \hookrightarrow + N_1 \to \mu_2 + N^*\end{array}\right\} \to N_2 + \mu^+ + \mu_2 +$$

+ hadrons

In total $\pi^+ + N \to \mu^+ + \mu_2 + N +$ hadrons, then μ_2 must be negative. If no hadrons beside N_2 are present in the final state the reaction is elastic and charge conservation imposes that N_1 is a neutron.

Thus with mu-neutrino only the elastic reaction is allowed

(I) $\nu_\mu + n \to p + \mu^-$

On the other hand a great variety of inelastic reactions may be expected. The analysis of the bubble chamber events show that most of them are of the type

(2) $\nu_\mu + N_1 \to N_2 + n\pi + \mu^-$

(Actually in the bubble chamber out of a total of 459 events only 7 cases of strange particle production have been observed) Allowing for undetected K_2^0's or mistaken K's they can be at the most 3% of the total. If one takes into account the detection efficiency the observed events seem to be compatible with a regular associated production. For more details see Doct. Cundy's report .

Hence if we will have a beam of pure π^+ the second μ would be always negative. The "magnetic horn" allows to have an almost clean beam of mu-neutrinos. There is a $\tilde{\nu}_\mu$ contamination because particles emitted at angles $\leq 1.5^\circ$ remain inside the inner cone of the horn and do not suffer deflection; but due to the favourable π^+/π^- ratio and the limited solid angle, this contamination is estimated to be 6% for the 1963 horn and ~ 3% in the 1964 horn versions.

The sign analysis of the μ -tracks crossing the magnet region in the spark-chamber gave the following results.

	N^+ / N^- in per cent	
	Expected	found
1963	6%	$(8 \pm 4)\%$
1964	3%	$2.5 \pm 1.0\%$

The Bubble Chamber complements these results, particularly in the low energy region. In it the frequence of the reaction

$\nu_\mu + N \to \mu^+ + N +$ anything

is $\leq$ 6%; and that of the reaction $\nu_\mu + N \to N +$ anything is less than 2%.

Hence combining all results one finds that the μ -lepton number is conserved at least within 2%.

6. Because the discussion of results having a general character as for instance the two-neutrinos, neutral currents, heavy bosons etc... requires some nomenclature and some information about the procedures followed in classifying the events, it

is then better for sake of clarity to speak first about *elastic* and *inelastic* interactions.

The problem is here to obtain a reasonable discrimination of the events which can be assigned to the reaction: (1) with respect to the inelastic ones:

(2) $\nu_\mu + N \rightarrow \mu^- + N + \pi' S$

The discrimination is of course much harder for the spark-chamber than for the bubble-chamber. Starting from the last a first step in separating reaction (I) from (2) can be made if one considers all events where *only* proton tracks (one or more) are associated with the μ -track as belonging to (I), and all others to (2). In other words considering all "*non pionic*" events as "*elastics*", all others as "inelastic". In doing so, with the present statistics the only serious source of error comes from the inelastic reaction where the pions have been absorbed in the parent nucleus. The non pionic events are 236; the others 218. Various kinematical tests have been made to extract from the 236 those which were hiddening a pion. These tests are all based on the idea that neglecting Fermi motion the visible energy (E_{vis}) is a defective but on the average not too bad measurement of the incident neutrino energy E. Obviously $E_{vis} < E_\nu$ because of the escaping neutrons. On the average the higher are energy and multiplicity the larger is the error; but the undetected energy $E_\nu - E_{vis}$ seems to be a small fraction of E[*]. For instance for the truly elastic-events

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[*] This is to some extent due to the fact that in pion-nucleon collision the pion changes direction but loses only a fraction $\approx \frac{m_\pi}{M}$ of its energy.

E_{vis} must be equal to the energy calculated from the μ-momentum and angle with the two-body kinematics. Most of the non-pionic events fit this requirement within the limits of the spread expected by the neglected Fermi momentum = 270 MeV/c. Similarly one may plot the invariant mass M^* of the visible non leptonic part of each event versus E_{vis}

(3) $$M^* = (E_{vis} + M - E_\mu)^2 - (\vec{V} - \vec{\mu})^2$$

Again the non pionic-events when plotted are at the right place around the line $M^* = M$; as expected if most of them were elastic.

For more details reference is made to the Doct. Cundy's report.

7. The cross-section for reaction (I) can be written in an invariant form

$$\frac{d\sigma}{dq^2} = \frac{g^2}{32\pi} \frac{1}{E_V^2} \left[A \pm B(S-U) + C(S-U)^2 \right]$$

where

$$q^2 = (V_\wedge - \mu_\wedge)^2 = 2M(E_V - E_\mu)$$

is the four momentum transfer for the elastic interaction; A,B,C are combinations of the form factors, ~~[illegible]~~

If $E_V \gg m_\mu$ for a target nucleon at rest, (*) $S - U = 4ME_V - q^2 = 2M(2E_V - T)$ According to C.V.C. the vector form factors are equal to the e.m. form factors. Then a comparison of the theoretical cross-section with the data is equivalent to a comparison of the axial with the vector interaction. Neglecting the induced pseudoscalar term (which for energies I GeV is very probably smaller than 1%) this comparison is a way to determine the <u>axial form factor</u>. The method eliminates the influence of the poorly known V_μ-spectrum. This can be easily seen considering that the q^2 distribution is given by $\frac{dN}{dq^2} = \int \Phi(E) \frac{d\sigma}{dq^2}(E)\, dE$

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*If motion is taken into account $S - u = 4 E_V(E_f - P_f \cos\alpha) - q^2$ being E_f and p_f the Fermi energy and momentum and α the angle between V_μ and the Fermi-neutron. At high energy and $q^2 \geq 500 \left(\frac{MeV}{c}\right)^2$ the Fermi motion can be neglected.

where Φ (E) is the ν_μ - flux at energy E. But if one divides the events in energy intervals Δ E

$$\Delta N(E_{vis}) \simeq \Phi(E)\,\sigma(E)\,\Delta E$$

Then we can write

$$\frac{dN}{dq^2} \simeq \sum \frac{\Delta N(E_{vis})}{\sigma(E)} \frac{d\sigma(E)}{dq^2}$$

Assuming form factors F_A (q^2) of various types and calculating the corresponding σ(E) and $\frac{d\sigma(E)}{dq^2}$ one finds which F_A fits better the results.

It is worth to remember that this procedure implies the use of E_{vis} for E. As far q^2 is concerned, it could be obtained either in terms of the kinetic energy of the recoiling proton:

$$q^2 = 2\,MT;$$

or better (particularly if more than one proton is emerging) by the visible energy and the μ-angle θ. Precisely $q^2 = -m_\mu + 2E_\nu[E_\mu - p_\mu \cos\theta] \simeq 4EE_\mu \sin^2\theta/2 \simeq 4E_{vis.}E_\mu \sin^2\theta/2$.

This procedure has been applied to the thought elastic events with $E_{vis} \geqslant$ I GeV. The cross-section used was modified for the effects of the Fermi momentum and Pauli principle. It has been calculated by Løvseth.

A maximum likehood procedure was applied to obtain the best fit. The results are given in the following Table where two possible q^2 functions are considered according to the old and the new Stanford fashion.

F_V	F_A	M_A
$\left[I + \left(\frac{q}{0.84}\right)^2\right]^{-2}$	$\left[I + q^2/M_A{}^2\right]^{-2}$	$1.05^{+0.35}_{-0.20}$
$1.19\left[I + \left(\frac{q}{0.6}\right)^2\right]^{-1} - 0.19$	$\left[I + q^2/M_A{}^2\right]^{-1}$	$0.6^{+0.2}_{-0.6}$

In the cross-section a ratio $G_A/G_V = 1.15$ was taken. The interval of q^2 is extended up to ~ I $(GeV/c)^2$. The results say that up to this fairly high limit there is nothing pathological in F_A. A useful check can be done reversing the procedure, that is using the best value of F_A to estimate from the events at various energies, the ν_μ -flux; that is the function ϕ (E). Then this last can be compared with that calculated by V. der Meer et al. Next slide 4 shows the results.

Slide 4.

See Cundy's report

7. It is gratifying to see a different aspect of the "normality" of the axial interaction in the angular distribution of the μ -tracks observed in the spark chamber for the thought elastic events.

The discrimination was done making use of all detectable characteristics able to distinguish a proton from a meson and either one criterium or another was applied according to the circumstances.

Beside a drastic reduction in the fiducial volume, the events which have been considered "elastic" had at most two tracks and nothing else. A track was made by 4 aligned sparks. The longest of the track must not show any interaction, should trigger and if the sign is known, this must be negative, etc... The shorter one must stop, and if the track is long enough it should not have multiple scattering beyond that compatible with a proton; etc... For more details see Doct.Faissner's report.One typical, but not one of the best example is shown in Slide 5.

Slide 5.

See **Faissner's report**

Of this kind 208 events came out from the 1963 run and 143 in 1964. They are very crude data. They must be corrected for triggering efficiency and this is relatively easy. But here more serious than in the Bubble Chamber are the ambiguities due to the uncertainties in the proton track identification and the effect of the pion reabsorption. However a comparison with the bubble chamber shows that the exclusion of those events having more than two prongs reduces the selected ones to a 70% of the possible non-pionic cases. It shows also that in the Bubble Chamber the two prong events are those which fit better the requirement $M^{*} = M$ mentioned above. Finally in the bubble chamber the multi-protons events occur roughly with the same frequency over all the range of E_{vis} and then their subtraction is like a background correction. Probably in the spark-chamber the inclusion of the pion reabsorbtion is partially compensated by the exclusion of the multiprong events.

This conclusion makes a little hard to understand why the rate of the events selected as elastic turns out to be 1.4 higher than the predicted. One may notice that the same conclusion can be derived from the bubble chamber. It is also clear that the rate is unusually high below 0.5 GeV. The simpler explanation is the contribution of secondary sources from the interaction in the walls of the horn and of the tunnel, decays in the shielding etc... as mentioned before.

Leaving out this question of the rates,in slide 6

Slide 6.

See **Faissner's report**

is reported as an example, the angular distributions of the μ -tracks obtained from the 1963 data. The solid curves are those calculated by Løvseth and they are normalized to the number of events. For both samples $F_A = F_V$ gives a good fit, while a value $M_A \geq 2$ GeV in $F_A = (1 + q^2/M_A^2)^{-2}$ seems to be incompatible with the data. The 1964 data **bring** to the same conclusion.

The combination of the bubble chamber and spark chamber data show than that up to (I GeV/c)^2 the behaviour of the so far unknown axial form factor is close to the vector one with 25% accuracy.

8. It may be now appropriate to say something about the elastic ν_e interactions. In CERN beam there is an appreciable number of them due to the K^+_{e3} decay $K^+ \rightarrow \pi^0 + e^+ + \nu_e$. Taking the parent kaons spectra calculated by V. der Meer, one may derive the corresponding flux and spectrum of ν_e.

The expected rate is $\simeq$ 0.7% of the total elastic rate. The spectrum is a smooth well-shaped curve with a flat maximum around 3 GeV. Both flux and shape reflect the large uncertainty on the K spectrum, a point which will be reconsidered later. Now the thin plate section of the spark chamber had a virtue. Electron and photon showers with energy high enough to produce $\gtrsim 20$ sparks are practically unmistakable. The total number of sparks N_s depends of course on the energy of the primary particle and the plate material and thickness. On the average in CERN thin walled spark chambers $N_s \gtrsim 20$ meant $E \gtrsim 300$ MeV. The shower develops in fairly regular conical shape which opening angle depends on the plate material and very little on the initial energy.

In the aluminium and to some extent also in the mixed aluminium + brass - spark chambers it is also possible to reach a fairly clean discrimination between single-electron-showers and π^0 -showers. The discrimination is based on the conversion distance of the photon and on the conical shape mentioned above.

This is particularly true when the event is made by a single shower or by a shower associated with a <u>proton-like</u> track as defined in the previous paragraph because then the robbing effect has little influence on the visible sparks. An example of these showers is shown in slide 7.

Slide 7.

See Faissner's report

We consider these shower events as the ν_e - counterpart of the ν_μ -elastic reactions previously discussed. Actually because the energy of the shower can be determined within a 25% uncertainity and the shower axis within ± 2.5°, the kinematical tests are here more reliable than for the ν_μ -interactions.

The observed elastic ν_e - interactions are 39. The corresponding ratio

$$R = \frac{N\ (\nu_e - \text{elastic})}{N\ (\nu_\mu - \text{elastic})} = (1.2 \pm 0.4)\%$$

If one assumes U.F.I., this ratio proves that <u>at least for the elastic events</u>: a) the fact that ν_μ and ν_e carry two independent quantum numbers has now a limit below 1%; b) the flip hypothesis according to which $K^+ \rightarrow \mu^+ + \nu_e$ is ruled out and a possible mixing of this decay mode with $K^+ \rightarrow \mu^+ + \nu_\mu$ is limited to 20%; c) the $\sigma(\nu_e \rightarrow e)$ "elastic" cross-section has the right order of magnitude required by an extension of U.F.I. up to multi GeV energy. This is not a trivial result and can be emphasized if one compares the q^2 - distribution of these rather few events with that obtained for the ν_μ -reaction in the bubble chamber. The two distributions are quite compatible.

9. To conclude the topic of elastic and inelastic events I would like to say something about the inelastic events and particularly about the production of the nucleon 3/2 3/2 isobar.

It is supposed to play a dominant role in the one-pion events. It is my opinion that beside many subtilities upon the charge ratio of the observed single pion events, the clear existence of this expected process is shown in the mass distributions. For incident ν_μ energy below 1.5 GeV the maximum of the available phase space is just around the value $M^* \cong 1.3$. It then better to consider only those events with $E_\nu \geqslant E_{vis} \geqslant 1.5$ GeV. Next slide shows the corresponding histogram. It exibits a good evidence for a N^* production.

Slide 8.

See **Cundy's report**

The corresponding rate and relative cross-section has been recently calculated by Berman and Veltman and by Block. It cannot be said, in spite of the plausibility of the introduced assumptions (which stem from a comparison with photo-and electron-production of N^* etc...) that the agreement is good; but it is not clear if it is fault of the theory or of the data. The experimental rate is too low at least for a factor two, but almost certainly an appreciable number of N^*'s in spite of the introduced corrections is hidden by the π reabsorption and the statistics is quite limited.

Finally it has to be said that the total inelastic cross-section looks now more reasonable than in 1963. It is shown in next slide.

Slide 9.

See Cundy's report

The rise with ν_μ -energy is not anymore roughly proportional to $(E_\nu)^2$, but if any, to E_ν ,

10) Having discussed elastic and inelastic events and learned how to recognize electrons and meson tracks we may now consider the answers given by the CERN experiment to the following general questions.

a) To what limits is $\nu_\mu \neq \nu_e$ independently **of** any assumed symmetry between μ-and e-leptons?

b) What is the limit one may place to the presence of neutral currents in the explored high energy region?

c) What is the evidence <u>against</u> **or** <u>for</u> the existence of the intermediate boson $W^\pm$?

a) To the first question a completely unbiased answer is given by the bubble chamber. One may consider the <u>totality</u> of the events simply comparing the number of those having a single electron emerging from the apex, with all others having a μ -track.

Out of 459 events, 5 single electrons have been observed. All these electrons are above 400 MeV. Then **if** one does not assume any **symmetry** between ν_e and ν_μ the conclusion is simply that

$$\frac{\nu_\mu + \mathcal{N} \rightarrow \mathcal{N} + e^- + \cdots}{\nu_\mu + \mathcal{N} \rightarrow \mathcal{N} + \mu^- + \cdots} \cong \frac{1}{100}$$

If instead we assume U.F.I. but $\nu_\mu \neq \nu_e$ **according to the estimat**ed fluxes and the rates of the μ -events one expects the following electron events

1.1 elastic	while	2 are observed
2.2 inelastic	while	3 are observed

This is in excellent agreement with what has found (with a better statistics) considering the elastic events in the spark-chamber. Hence summing up all the results the simpler conclusion is that U.F.I. holds up to momentum transfer of the order of 1 GeV, but ν_μ and ν_e are carrying independent quantum numbers in <u>all</u> their interactions with hadron-currents. The limit of any mixing is less than 1%.

b) For the second question we appeal only to the Bubble Chamber results. The existence of a strangeness conserving coupling $(\bar{\nu}\nu)$ $(\bar{p}p)$ will give rise to the elastic reaction

$$\nu + p \rightarrow \nu + p \qquad (4)$$

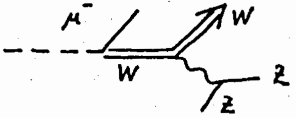
and other inelastic processes. It is then asked how many single recoiling protons have been seen. Below 250 MeV neutron stars and proton recoils are quite copious. They are originated from the abundant fast neutrons emerging from the material around the sensitive liquid and produced by ν_μ-interactions. Considering the events above 250 MeV (this limit for the elastic events corresponds to a momentum transfer $q^2 \geqslant 500$ $(\mathrm{MeV})^2$) one finds that the occurrence of reaction (4) is less than 3%.

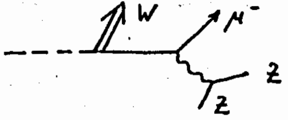
11) We conclude now with the more relevant problems. What about the $W^\pm$?

To my knowledge the existence of the W to mediate current Fermi interaction was proposed years ago by Schwinger.

It was pointed out at Kiev by Pontecorvo and Ryndin that if the mass M_W of W would had been of the order of the proton mass, with the beams of ν_μ-neutrinos available at BNL and at CERN, the production of W would become possible. A complete theory of this process was given in 1960 by Lee and Yang.

The basic diagrams are as follows





of which the last is dominant.

The order of magnitude of the cross-section for this semiweak process is

$$\sigma \sim G\alpha^2 \simeq 10^{-5} M^{-2} \alpha^2 \simeq 10^{-37} cm^2$$

The created boson would then decay with a mean life between 10^{-17} and 10^{-18} **(according to the value of M_W)** either into a lepton pair or into a system of pions and/or kaons. This last mode might be greatly enhanced if M_W is in the neighbourhood of one or more of the several resonant states. In first decay-mode the final state of the over-all reaction

$$\nu_\mu + Z \rightarrow Z (or\ Z^*) + \mu^- + W^+ \rightarrow Z (or\ Z^*) + \begin{cases} \mu^- + e^+ + \nu_e \\ \mu^- + \mu^+ + \nu_\mu \end{cases}$$

contains two opposite charged leptons; the positive leptons being an electron or a muon with equal probability.

The nuclear charge may act "coherently" or "incoherently" **according to the incident** ν_μ energy and the value of M_W. This is determined by the minimum momentum of the exchanged photon, which is:

$$Q_{min} \simeq \frac{M^2}{2E_\nu} \qquad (m_\mu \ll M_W)$$

For $M_W > 1$ GeV the "incoherent" process dominates up to $E \lesssim 8$ GeV. In all cases Q is in the average a small fraction of M_W and similarly to a two-body decay the energy of the μ^--produced first, is picked around

$$E_\mu \cong E_\nu \frac{m_\mu}{M_W} .$$

As shown by Bell and Veltman and Überall the W is strongly longitudinally polarized around the direction of the incident mu-neutrino. The second positively charged lepton is then forced to be polarized in the same direction and it is preferably pushed backward in the C.M. of the W. Consequently in the lab. system the largest fraction of the W energy goes to the second neutrino. At the same time the angular distribution of the positive lepton is broader than of the first μ^-.

Extensive calculations have been made by Lee et al, Solovjev et al, Bell and Veltman, Von Gehlen and more recently by **Wu** et al on the energy dependence of the production cross-section for several nuclei. The shape of the curve $\sigma_W(E_\nu)$ does not change appreciably with M_W, but of course the threshold does. It is around 2 GeV for $M_W \simeq 1$ GeV and $\simeq 5$ GeV for $M_W \simeq 2$ GeV. Then the production rate depends **drastically on** the ν_μ spectrum. Instead the kinematical features of the lepton pairs sketched above are slowly varying with M_W.

A search for these lepton pairs was pushed systematically on the spark-chamber pictures obtained with the 1963 and 1964 set-ups. The search was done looking for possible $(\mu\mu)$ and (μe) events.

As stated before the single electrons can be identified and their number can be corrected for the π^0 background. The problem is then to identify unambigously a μ -track.

For "single line" tracks the **distinction** between a <u>non-interacting</u> or μ -track and all others lies in the possibility of identifying single scatterings or "stars" along the track. Then its **reliability** and accuracy depend on the length of each track and on the goodness and completeness of the calibrations. Apparently only recently the calibrations of the several parts of the equipment reached a satisfactory status.

Once established via calibrations, the mean free path Λ for a <u>visible</u> interaction of pions, protons and kaons a sample of possible $(\mu\mu)$ pairs has been considered. The sample of about 350 events was made selecting events with two tracks each long enough to make sensible a search for interactions*. Obviously the matter was to see if in this sample the total number of interactions <u>was</u>

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*) For further details see Dr. Gaillard's report

less than what should be expected assuming (with all possible configurations) that one of the two tracks was a μ and the other not a μ but a proton, a pion or a kaon in the proportion indicated by the bubble chamber analysis. The results are the following :

		minimum expected	observed
1963	experiment	63	56
1964	"	33	36
		96	92

A similar and somewhat easier analysis was made for the possible (μe) pairs. One of them is shown in slide 10 (see Gaillard report). Out of 1,700 events produced in aluminium, 5 candidates with a shower corresponding to an energy $E > 500$ MeV were found. The other track must belonger than 0.8 nuclear geometrical mean free path Λ_o and non-interacting.

According to kinematics, with this cut-off on E_e, the sample should include 70% of the (μe) decay mode.

However if one takes into account the correction due to the π^o's and the fact that the total non-electronic track length obtained summing up all the events is only about 2Λ one has to conclude that at the most the possible (μe) pairs are 3.

In the bubble chamber $(\mu\mu)$ pairs are not identifiable because the total track length of the possible candidates is too short. There is one possible case of $(\mu^- e^+)$ pair, but the negative non-interacting mesonic track is only 40 cm long and could be also a π^-.

The previous results allow to give a lower limit for M_W. With the assumption that the branching between leptonic decay and pionic decay of the W is 50/50 and with $M_W \leqslant 1.8$ GeV one has for the (μe) pairs:

	Expected	Found
Spark-chamber	$\simeq 11$	$\leqslant 3$
bubble-chamber	$\simeq 3$	$\leqslant 1$

The result of the $(\mu\mu)$ pair analysis is obviously consistent with the conclusion one may derive from that of the (μe) pairs.

However a more precise and significant limit on the W-mass was established making use for the $\mu\mu$ pairs of the sign identification of the tracks; that is with the use of the information provided by the magnetized iron regions. **According to what was said** before the kinematics of the W decay depends very little **on** M_W. Of the two μ's the positive track has **on** the average a higher momentum **than** the μ^-. The average momenta are roughly in the ratio

$$\frac{\langle p^+\rangle}{\langle p^-\rangle} \simeq 1,5$$

Bell and Veltman have calculated in detail angular and momentum distribution of this decay mode. On the basis of these **calculations** one can **choose** a sample of $(\mu\mu)$ candidates and see if they correspond to the range and sign requirements. The sample was made by events with two-μ-like tracks of which one was longer than $7\Lambda_0$ and the other $> 2.4\Lambda_0$. If one again decides about the branching between leptonic and pionic modes, the Bell and Veltman calculation allows then to decide (according **to sign, ranges and** geometrical biases) what are the expected rates. With a branching ratio 50/50 the results are indicated in the following table:

	Expected		Observed
M_W (GeV)	V.D.M.	$q^2 \leqslant 0.2$	
1.3	21	51	none
1.5	11	26	
1.8	4	9	

In the third column the rates have been calculated on the base of the shape of the spectrum found **according to the energy** distribution of ~ 70 events which did not show any visiable track beside the μ and which accordingly show a q^2 value roughly smaller than 0.2. For such small values of q^2 one may consider the relative probabilities for all **processes (elastic or inelastic)** independent **of** the incident energy and also **of** the cut made by the Pauli principle; which estimated influence depends **on** the nuclear models used. Of course in this manner one **gets the** shape of the spectrum and not the absolute flux, but here what is relevant is the proportion of the μ-neutrino above 4GeV **with respect to the total flux**[*]. **The shape of the spectrum obtained by this** method compared with the calculated **V.der Meer's** spectrum seems to show that in the energy region above 4;5 GeV there are about twice mu-neutrinos than expected. A result which, if confirmed,

implies also some modifications concerning the energy dependence of the total inelastic cross-section the rate of the ν_e-elastic events etc...

12) The absence of any evidence in favour of the lepton pairs is not adequate to **prove** that $M_W \geqslant 1.8$. The mesonic decay mode could well be largerly dominant. But in this case some indication of these should be evident in the Bubble Chamber events.

The analysis was limited to the few with $E_{vis} \geqslant 6$ GeV; in total 23. For a $M_W \geq 1.5$ GeV, the calculated production cross-section $\sigma_W(E_\nu)$ when $E_\nu \geq 6$ GeV becomes larger than $\simeq 10^{-38}$ cm^2 and then it is expected to compete successfully with other processes.

Of the 23 events only 14 have a total mesonic charge of +1. The plot of their corresponding effective masses is shown in slide II.

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[*] As shown by M. Block (Letter Submitted to P.R.) the absolute flux can be determined if one would be able to discriminate the true low q^2 elastic events.

Slide II

See **Cundy's report**

If one makes the extreme assumption that the mesonic decay mode is 100% a value $M_W \lesssim 1.3$ is excluded because being absent the leptonic decay, in the region between I and 1.5 GeV one should observe 20 ÷ 50 events. For $M_W \simeq 1.5$ one would expect II events while in total they are 8. Hence this lower limit for the mass cannot be excluded. The numbers above are derived from the ν_μ -spectrum **calculated by V. der Meer.**

In the next months when an increased statistics will be available, if the fact that in the region above 6 GeV there are at least twice as many neutrinos as calculated will be confirmed, probably also for the mesonic decay the lower limit of M_W will shift to at least 1.5. In conclusion as sad it could be, there is no evidence for any heavy boson with a mass $M_W \lesssim 1.3$ and likely the lower limit should be placed around 1.5 ÷ 1.8.

It has been communicated by prof. Schwarts that the preliminary results based on 300 events observed in the new (~ 80 tons) spark-chamber at Brookhaven (and produced by the μ-neutrinos obtained with a 30-GeV extracted proton beam incident on a Be target) are consistent with this conclusion.

Consequently there are little hopes to see any W **through the** leptonic decays with the accelerators now in operation.

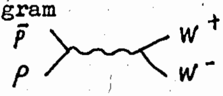
It was then very interesting to know about the progress of an experiment the La Jolla group communicated by prof. Piccioni. Here the W should be produced via proton-proton collisions according to the process:

$$(5)\quad p + p \rightarrow D + W^+$$

It was pointed out by Piccioni that the cross-section for (5) is very likely 10 times larger than that estimated by Bernstein.

The reason is that in this case one should not make the calculations **choosing for simplicity a certain number of Feyman** diagram, but instead to compare the cross-section of reaction (5) with that of a nucleon nucleon collision where a mesonic "fire ball" is produced with a mass of the order of M_W. The "fire balls" are now more fashionable **than** ever and probably **Piccioni's** estimate is right. The experiment is oriented toward the detection of lepton pairs in coincidence with the D. For more details one may see the paper presented in the parallel session.

Finally during the discussion Doct. Zichichi has suggested two methods to detect via the leptonic decays the existence of the W. The first with a p + $\bar{p}$ annihilation, that is according to the diagram



which evidently goes as α^2; the second with all p - N collisions occurring in the internal target of the PS. at CERN, and then looking to the μ's produced at those angles which are not allowed to the μ's coming from π and K decays and (very relevant) to their polarization.

I may then conclude thanking my secretaries Doct. V. Evseev, L. Mikaelyan and V. Vaks for their very valuable support and for quite a few useful discussions; and expressing to Piccioni, Zichichi and all the many others interested in finding the W my warmest wishes for a success.

Received by Publishing Department
on August 19, 1964.

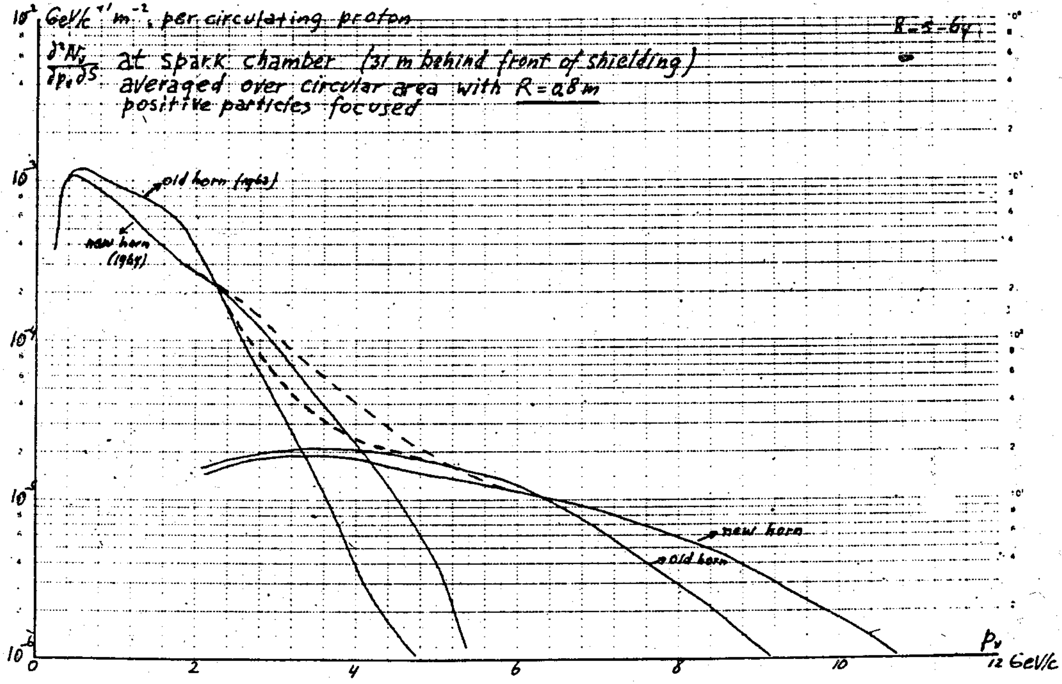

10^{-2} GeV/c^{-1} m^{-2}, per circulating proton
$\frac{\partial^2 N_\nu}{\partial p_\nu \partial S}$ at spark chamber (31 m behind front of shielding)
averaged over circular area with R = 0.8 m
positive particles focused
R-5-64
10^{-3}
10^{-4}
10^{-5}
10^{-6}
old horn (1963)
new horn (1964)
new horn
old horn
0
2
4
6
8
10
12 GeV/c
p_ν

Fig.I.

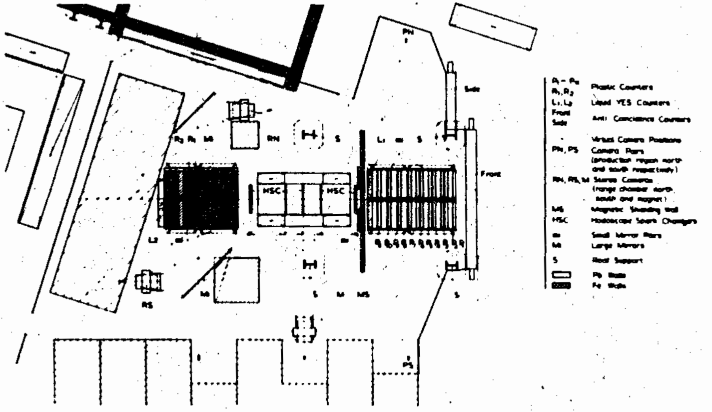
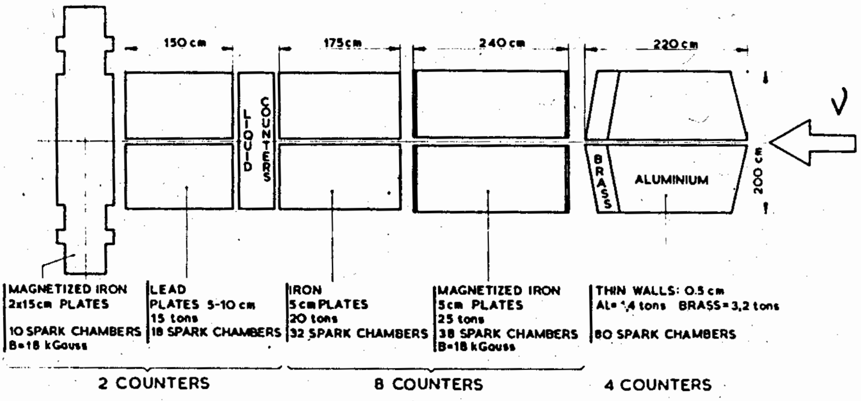


Fig.2.

NEUTRINO EXPERIMENT
SPARK CHAMBERS
FEBRUARY – MAY 1964



SPARK CHAMBER DIMENSIONS

HEIGHT: 1.60 m
DEPTH: 1.00 m
THICKNESS: 3.5 cm

PHOTOGRAPHY . 18° STEREO

Fig.3.

24/7/64

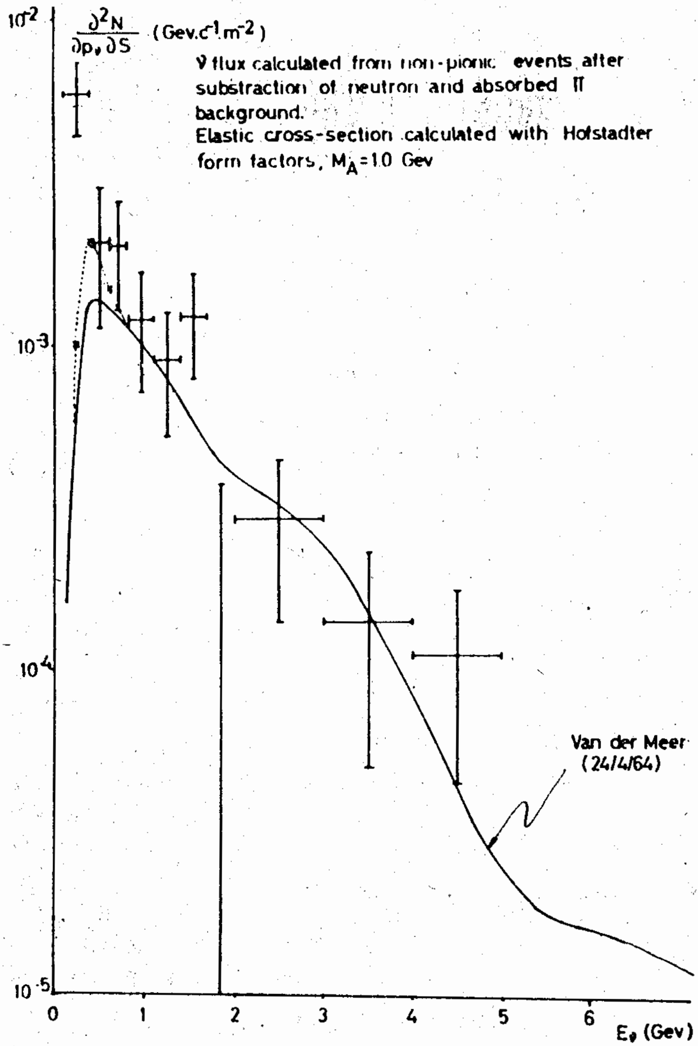

$\frac{\partial^2 N}{\partial p_\nu \partial S}$ (Gev.c^{-1}.m^{-2})
ν flux calculated from non-pionic events after substraction of neutron and absorbed π background.
Elastic cross-section calculated with Hofstadter form factors, M_A=1.0 Gev
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1
2
3
4
5
6
E_ν (Gev)
Van der Meer
(24/4/64)

Fig.4.

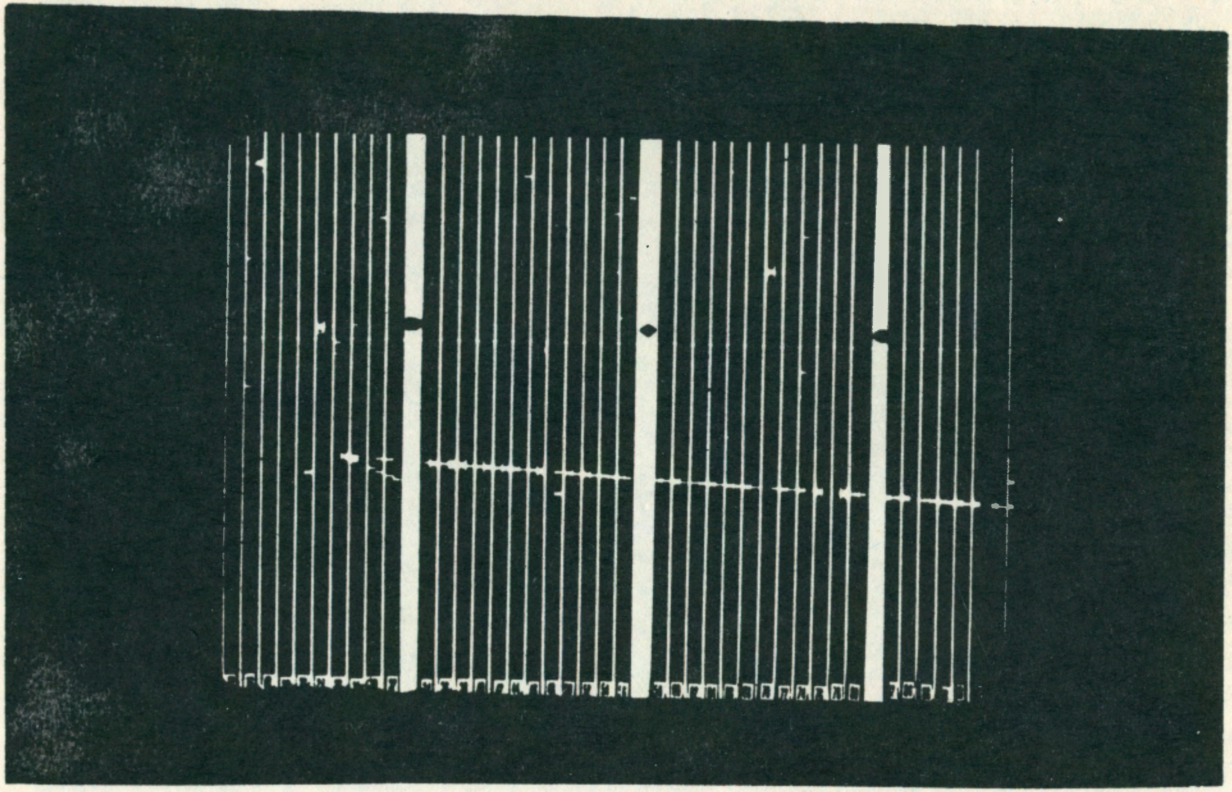
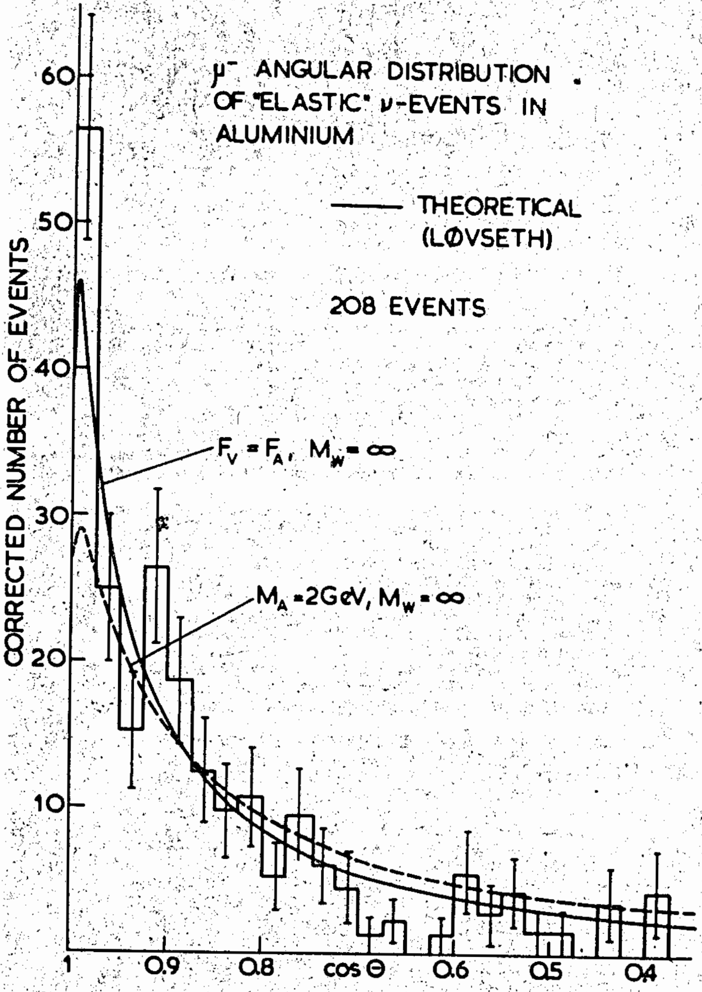


Fig.5.


μ⁻ ANGULAR DISTRIBUTION
OF "ELASTIC" ν-EVENTS IN
ALUMINIUM
THEORETICAL
(LØVSETH)
208 EVENTS
F_V = F_A, M_W = ∞
M_A = 2GeV, M_W = ∞
CORRECTED NUMBER OF EVENTS
60
50
40
30
20
10
1
0.9
0.8
cos Θ
0.6
0.5
0.4

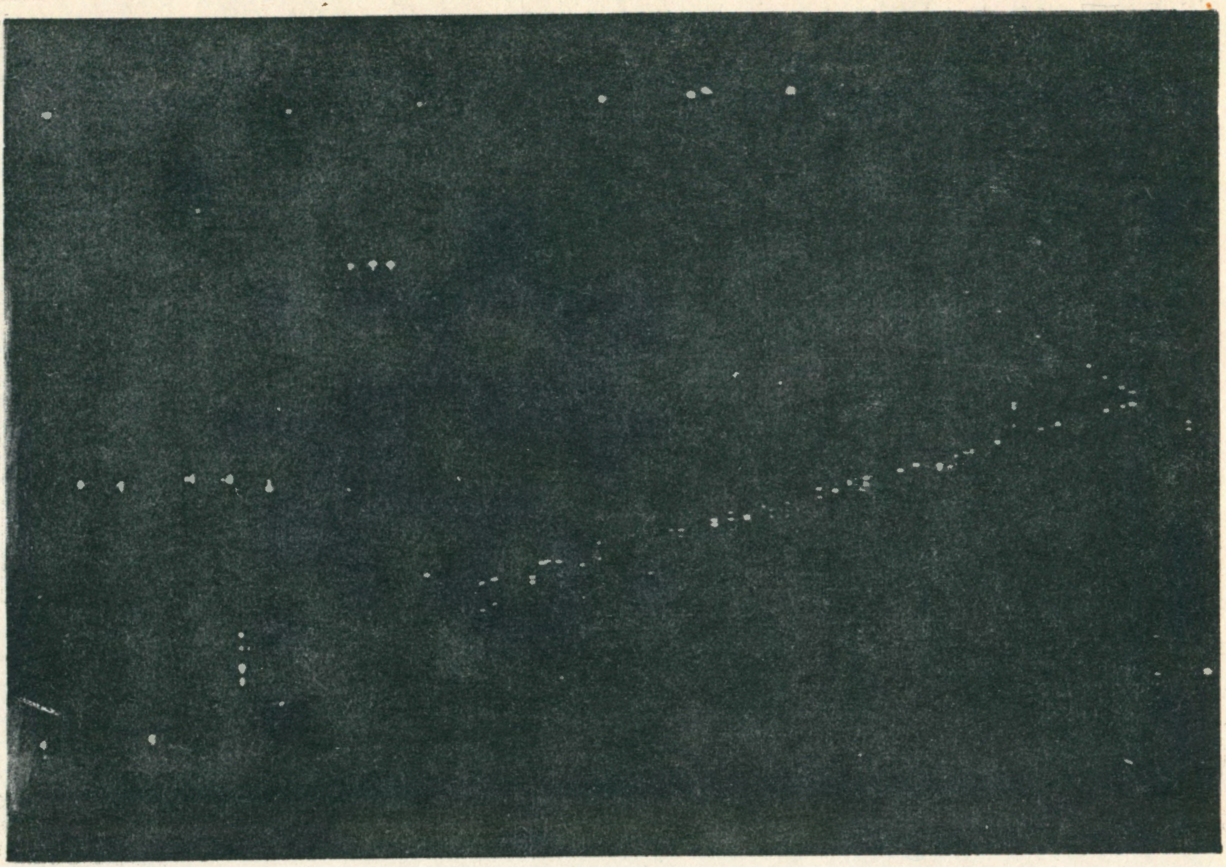


Fig.7.

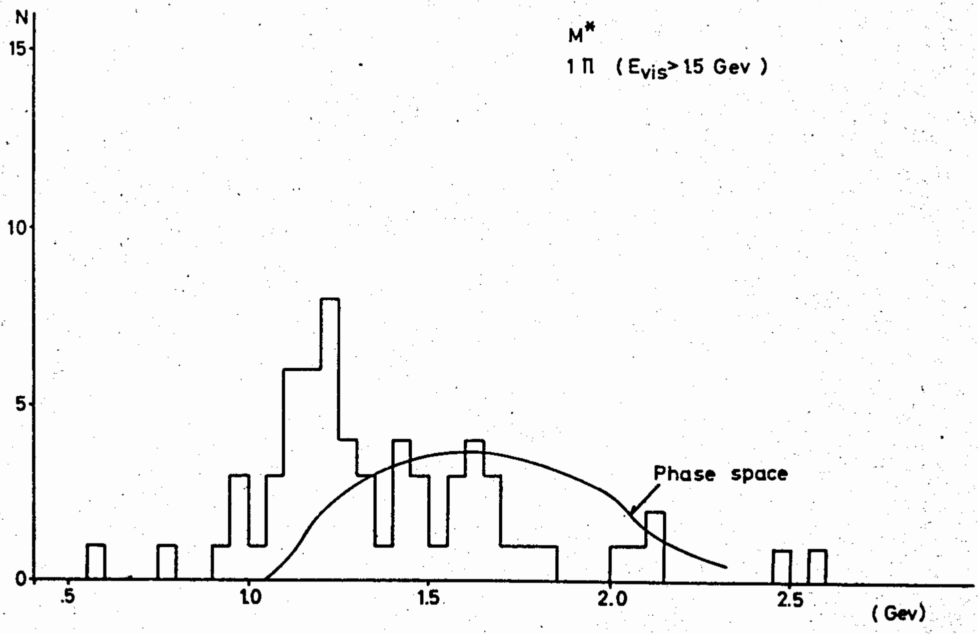


Fig.8.

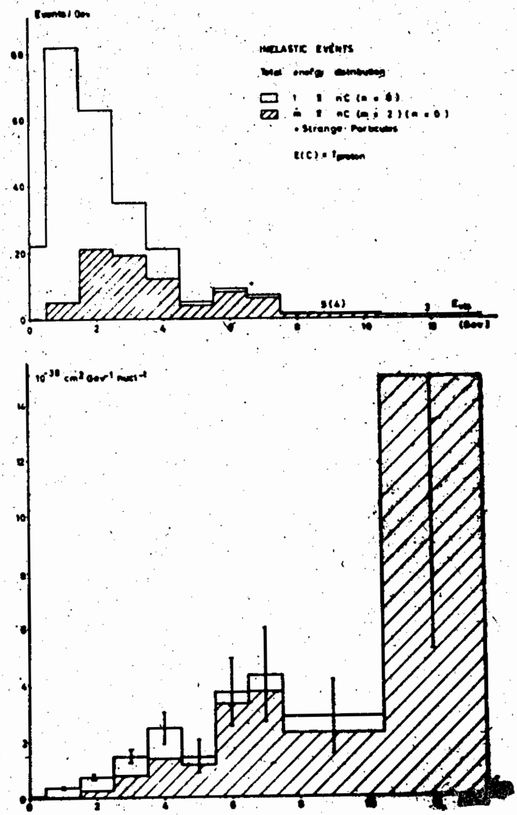

Events / Gev
INELASTIC EVENTS
Total energy distribution
1 π nC (n = 0)
m π nC (m ≥ 2) (n = 0)
+ Strange Particules
E(C) = T_proton
0
20
40
60
80
0
2
4
6
8
10
12
5(4)
3
E_vis
(Gev)
10^-38 cm² Gev^-1 nucl^-1
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12

Fig.9.

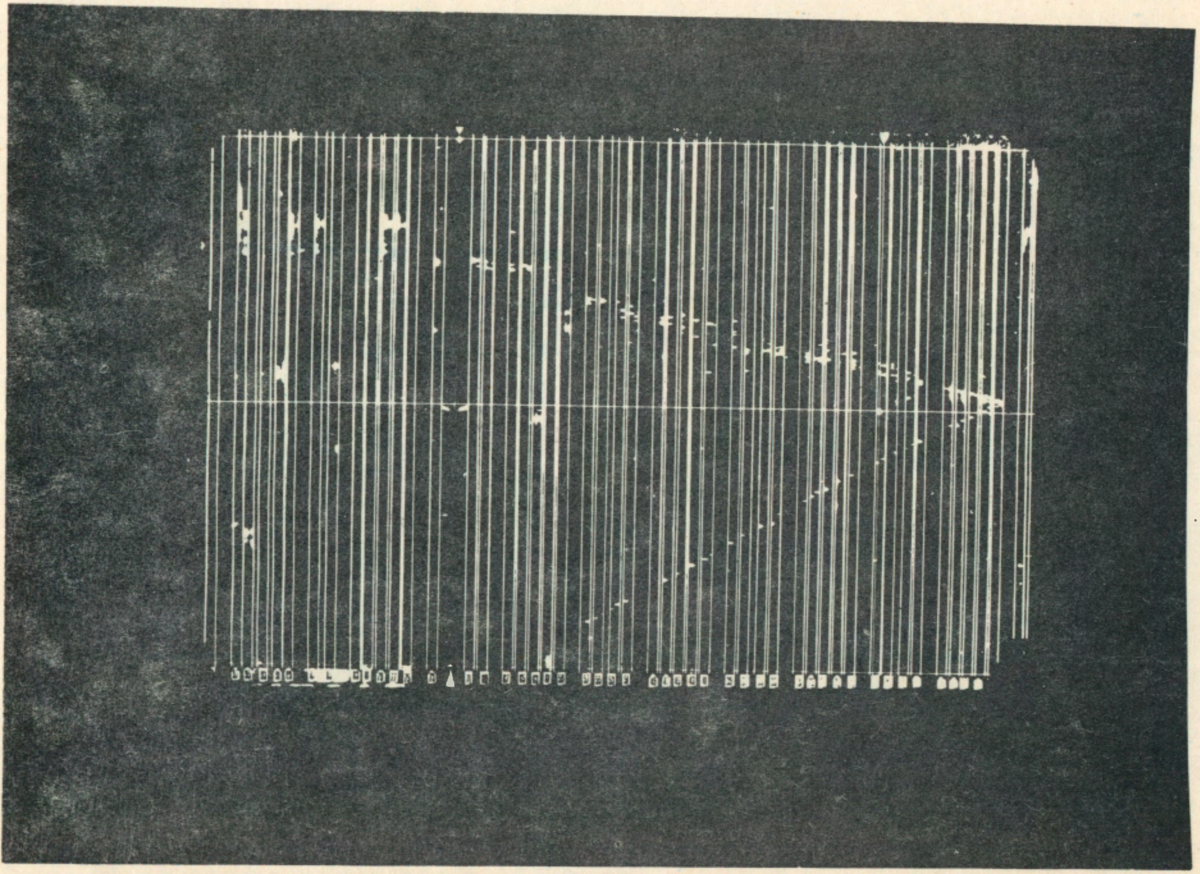


Fig.10.

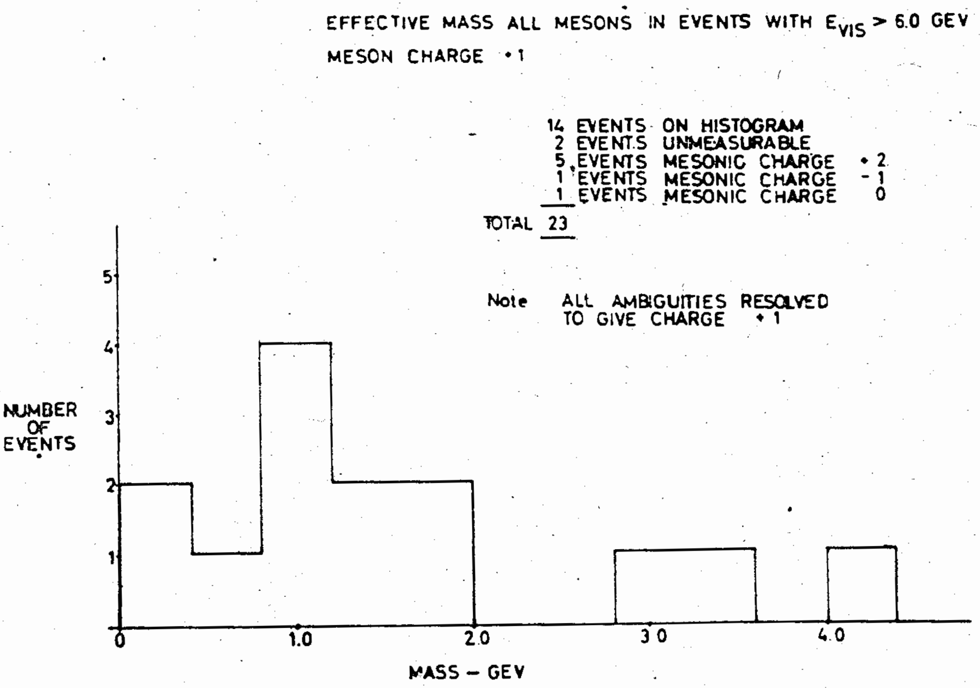

EFFECTIVE MASS ALL MESONS IN EVENTS WITH E_{VIS} > 6.0 GEV
MESON CHARGE + 1
14 EVENTS ON HISTOGRAM
2 EVENTS UNMEASURABLE
5 EVENTS MESONIC CHARGE + 2
1 EVENTS MESONIC CHARGE - 1
1 EVENTS MESONIC CHARGE 0
TOTAL 23
Note ALL AMBIGUITIES RESOLVED TO GIVE CHARGE + 1
NUMBER OF EVENTS
5
4
3
2
1
0
1.0
2.0
3.0
4.0
MASS – GEV

Fig.11.