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PROPOSAL

SEARCH FOR MASSIVE PARTICLES

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1. INTRODUCTION

The discovery which perhaps could be made at the ISR which would most alter the course of high energy physics would be to identify particles associated with the substructure of the nucleon. While quark searches and less specific hunting for heavy particles has so far yielded no more than hints of the existence of such objects, the ISR will open up a vast new mass range for much more sensitive and less biased searching than has previously been possible.

We propose here a relatively simple experiment which could detect not only quarks of all possible charges, but also other massive particles in the range of roughly 5 to 25 GeV/c^2. The detection system is sufficiently non-specific (employing time-of-flight, ionization loss, and range for several particles simultaneously) so that the limited scope of prior cosmic-ray experiments can be avoided. In addition, during a running time of one day limits on particle production cross sections can be achieved which are at least one (at 5 GeV/c^2) to four (at 25 GeV/c^2) orders of magnitude more sensitive than the best cosmic ray limits. With a perhaps more realistic model of the production process, these figures increase to three to five orders of magnitude greater sensitivity than cosmic ray results.

Thus if any of the present indications for the existence of such particles are correct, these will be seen prolifically. Cross section levels consistent with some models of the production of massive particles can be reached readily. Therefore if such particles exist it seems rather likely that this experiment would detect them. Because an interesting part of this mass range can also be covered with greater sensitivity at NAL, it would be desirable to perform this experiment prior to the NAL work. This is one of the motivations for proposing a simple experiment which can be quickly assembled or disassembled at the ISR and which does not require appreciable running time.

2. MOTIVATION FOR PERFORMING THE EXPERIMENT AT THE ISR

It has long been attractive to consider the simplifying possibility that all particles are made from a few fundamental constituents.[1] This point of view has become more appealing the larger the number of particles found, but it was the success of SU_3 which made this possibility seem likely. One of the principal activities of high energy physics has become the investigation of the consequences if such particles should exist, as well as the actual search for such basic building blocks, whether they be the fractionally-charged quarks[2] or integrally-charged triplets.[3] Much of the future course of high energy physics would be determined by finding such particles.

Because of the strong theoretical motivation, extensive work[4] has been carried out to search for quarks at accelerators within the mass range available. The best limits[5] up to about 5 GeV/c^2 mass are shown for various possible quark charges in Fig. 1. These are sufficiently good, especially for negatively-charged quarks, that it seems quite unlikely that such particles could exist in that mass range.

For particles more massive than 5 GeV/c^2, information comes from very numerous cosmic-ray and geophysical experiments.[6,7] While the evaluation of the latter in terms of cross section limits for particle production is model-dependent, it appears very probable[7] that cosmic-ray particle searches at present set more sensitive limits. Of course it is always possible that some or all of these cosmic-ray experiments have employed triggers or detection techniques which biased against the observation of the desired particles.

If this possibility -- which could only make the limiting cross sections larger -- is ignored, the approximate limits set by cosmic-ray experiments[8] are shown in Fig. 1. These cross sections can be only approximate because they are dependent on the mechanism of producing the particles and the nature of their subsequent interactions. However, several different calculations[9-12] give similar results, so that for the order-of-magnitude estimates desired here the curves of Fig. 1 are probably adequate. Recent unpublished work by Sitte argues for cross sections one to two orders of magnitude larger, so that for our purposes the values in Fig. 1 may be quite conservative.

Unfortunately, not even order-of-magnitude estimates can be given for theoretically-expected cross sections. Results of calculations are highly model dependent. If one believes in a statistical model,[13] a search for heavy quarks is essentially impossible, since the cross section falls off rapidly with mass. Arguments can be given,[9,12] however, as to why a statistical model is not appropriate for the production of very strongly-interacting constituents of a nucleon. It seems reasonable that a model which predicts the production of loosely-coupled assemblages of nucleons, such as H^2 or He^3, would not also be correct for predicting the pair-production of tightly-coupled particles out of which the nucleon is made. Other production models,[9,14] and particularly those[12] giving results consistent with observations of cosmic-ray jets, yield cross sections varying from 10^{-27} to 10^{-30} at 5 GeV/c^2 to 10^{-28} to 10^{-34} at 25 GeV/c^2, and those values are readily obtainable in this experiment.

Some evidence has been reported for the existence of quarks[15] which would require cross sections one or two orders of magnitude higher than the limits of Fig. 1. This cloud chamber evidence is disputed,[16] but one further event has been observed[17] in a bubble chamber which requires a mass of <6.5 GeV/c^2 if it is charge 2/3, or 8±3 GeV/c^2 if it is charge 1/3. The interpretation of this event has also been disputed,[18] but if such observations were correct this experiment should see the quarks quite readily. They could also be seen at NAL, however.

One of the potential strengths of this experiment is that massive particles which are not fractionally charged can also be observed. Only a few experiments[11,12,19] have been sensitive to such particles, one of which reports[12] evidence for their existence. The observations are consistent with the existence of heavy particles, most likely $\sim$10-15 GeV/c^2, which have long interactions lengths ($\gtrsim$ 375 g/cm^2) and are produced with large cross sections ($\sim 10^{-28}$ cm^2). It is claimed[12] that other experiments, which report limits of $\sim 10^{-28}$-10^{-31} cm^2, would not have observed them, either because too few such particles would slow down sufficiently to be measurable by time of flight, or because the particles probably are not produced in the extensive air showers used as a trigger in the other experiments. Rather it is suggested that these particles are produced in a catastrophic dissociation of the primary particles, with a subsequent slow decay of the heavy particles into muons, leaving little or no energy for an air shower. Such a particle decaying into muons could also explain the anomalous muon flux observed in the Utah experiments.[20] If indeed these heavy particles have been seen, they would be observed prolifically in this experiment, and if they do not exist, limits can be set on their production many orders of magnitude better than those from the cosmic-ray experiments.

Mention should be made also of the interesting idea of Schwinger's[21] which is essentially the union of the quark and magnetic monopole hypotheses wherein dually-charged particles, called dyons, are supposed to be the fundamental constituents of all hadrons. In this scheme, which provides a natural explanation of electric and magnetic charge quantization, it is necessary for the dyon mass to be about 6 GeV/c^2 in order that particle electric dipole moments not be observable.[22] Thus this particle, too, is in our mass range. In Schwinger's version the dyon electric and magnetic charges are both fractional, but the latter would cause the particle to be heavily ionizing. In another version, the dyon is isomorphic with the triplet model[3] and can be made integrally charged electrically and magnetically neutral. In either case our experimental set-up is capable of detecting the dyon.

Whatever the particular characteristics of the particle to be sought, the ISR can provide a unique opportunity for searching for very massive particles, whether fractionally or integrally charged, and -- for a short time at least -- it will provide the only way to detect particles heavier than 5 GeV/c^2.

3. EXPERIMENTAL ARRANGEMENT

The experimental set-up proposed is conceptually a very simple one, a series of hodoscopes covering a large solid angle which permit the measurement of the particle trajectory, time of flight, ionization, and in many cases also range. A minimum range is in any case determined which excludes electrons, muons, pions, kaons, and protons (or antiprotons). Many particles can be handled simultaneously, which not only increases the effective solid angle, but more importantly avoids biasing the observation in a way which makes many of the cosmic-ray observations of dubious value.

While the counters would cover an appreciable range of angles, they are to be set up so as to favor forward-backward production, since all other high-energy processes occur most readily at small momentum transfer. The arrangement is presented schematically in Fig. 2. Shown there are four planes of counters on each end of the interaction region, each plane consisting of ten counters with a small overlap. The overlap, plus a frame of guard counters prevents accepting events in which particles could pass through a counter edge, giving an erroneous measure of ionization loss.

Particle flight time is to be measured between planes of counters, but also the relative time of arrival of the light at each end of any given counter is to be determined. In this way, location of the particle along the counter can be found at least as well as its position in the other direction is known from the counter width. Finding the particle location at four points in space introduces the requirement that the trajectory be straight, tending to eliminate scattering and decay events which could produce confusing results. At the cost of increased complexity, wire planes could be introduced to tighten this requirement.

Several range counters follow the last hodoscope planes. The measurement of range is a powerful discriminant in this case, because the velocity of the particle has been determined and because very heavy particles are to be searched for. For a given velocity and charge the range is longer the heavier the particle. Thus for each event of a certain velocity the lack of signals from certain range counters serves to eliminate known particles of that velocity: electrons, muons, pions, kaons, protons, and antiprotons. It must be emphasized that if interactions occur -- and these will in general be detected from the pulse heights of the range counters -- the shortened ranges can eliminate real events but they do not enable known particles to simulate massive (>3 GeV/c^2) particles. Note also that the ionization-loss measurements eliminate multiply-charged particles, so that of nuclei which might be produced with very small cross sections, only the deuteron and triton (or their antiparticles) could cause confusion in looking for integrally-charged particles. These cannot be mistaken for fractionally-charged particles, but even in the other case the deuteron or triton can be ranged out over a wide band of particle velocities. Thus the velocity band available for the quark search extends somewhat higher than does that for integrally-charged particles.

For very massive particles only the slowest can be brought to the end of their range, giving a mass measurement, but in all cases a lower limit on their mass can be determined. In this connection it is interesting to note that the cosmic-ray experiment[12] discussed above which reported massive particles found that these had very long interaction lengths ($\gtrsim$375 g/cm^2), so that many of these could be ranged out in the proposed experiment, giving a mass measurement.

4. DETECTION CAPABILITIES

The idea of the measurement is to detect slow particles (roughly β=0.1 to 0.8) and to measure the velocity from the time of flight, the ionization loss in four counters, and a range (or at least a minimum range), with particle locations being known so as to insure a straight trajectory. Now we shall discuss in a little more detail the limits of these parameters to be measured and hence the fraction of produced particles which can be detected. This will lead to an estimate of the level of production cross section which can be reached in a given running time.

For quark detection the ionization-loss characteristic of a charge 1/3 or 2/3 of the electronic charge is the signature to be sought. This is usually done by looking for particles with 1/9 or 4/9 of minimum ionization, although the relativistic rise in ionization can introduce problems. Here, however, since the time of flight is measured and thus the particle velocity is known, a specific value for ionization loss is predictable. Furthermore this value is well above minimum ionization, making it more readily measurable than is the case for faster particles. This is not just a matter of photon statistics, which can in any case be made sufficiently good by thickening the scintillator, but rather it concerns collision-loss statistics. Not only are the pulse heights not in the long-tailed Blunck-Leisegang[23] regime, but even the applicable Landau distribution[24] is relatively short-tailed.

Thus in Fig. 3 where the ionization losses rise steeply as the velocity(β) decreases, the pulse-height distribution narrows. The charges e, 2e/3, and e/3 can be readily separated over the whole range of β with four determinations of ionization loss, which incidentally must be logarithmically digitized. The error in β is also small enough to permit the separation of charges, since $\delta\beta/\beta \sim \pm 0.1\beta$ for a time resolution of ±2 nsec., which is a conservative figure.

As can be seen from Fig. 4, at small β the range of heavy particles can be measured, which, together with the ionization measurement, determines the mass of the particles. For example, at $\beta=0.2$ a range of 30 g/cm^2 of copper would correspond to a 5 GeV/c^2 quark if its charge were 1/3, or a 20 GeV/c^2 quark of charge 2/3. For very low β even the energy loss in the counters is significant, but this can be an aid to particle identification.[25]

However, as mentioned above, over the whole useful range of β (about 0.1 to about 0.8, depending a little upon the mass) the range counters serve to exclude the known particles, as may be seen in Fig. 4. For an acceptable event of a given β a certain minimum number of range counters must fire to guarantee that that particle is heavier than any known particle. This permits the search for integrally-charged massive particles, and is in addition a powerful means of certifying a quark event.

One other important feature of this experimental arrangement is that it is sensitive to relatively short-lived particles. The maximum distances involved correspond to a mean life for a particle of 2×10^{-7} sec if it has $\beta=0.1$ and 2×10^{-8} sec if it has $\beta=0.8$. Of course, at least one quark must be stable, but this feature increases the probability of finding other interesting massive particles.

Since the range of $\beta \approx 0.1$ to about 0.8 is usable in the experiment, the other parameter needed to determine the detection efficiency is the angular distribution, which is of course unknown. We shall consider here two extreme cases which surely bracket the true situation. First, let us assume an isotropic distribution, which is clearly not correct for such an energetic process. Since the counter arrangement of Fig. 2 covers $\pm 30^{\circ}$ in the forward and backward directions, the solid angle is 13.4% of 4π steradians. The particle energy distributions for an isotropic angular distribution were obtained by Monte Carlo calculations, and it was found that the acceptance range of β included about 0.1 of the 5 GeV/c^2 particles, about 0.5 of those having 10 GeV/c^2 mass, and essentially all of the particles with a mass greater than 15 GeV/c^2. These values with a luminosity of 4×10^{30} interactions$\cdot$ cm$^{-2}\cdot$ sec^{-1} correspond to cross sections of 2×10^{-34} cm^2 for 5 GeV/c^2, 4×10^{-35} for 10 GeV/c^2, and 2×10^{-35} above 15 GeV/c^2 for one observed particle per day.

The other extreme case is more realistic: very small angle production of the quark pair. Because of the massiveness of the particles, essentially any known high-energy particle production momentum-transfer distribution will force these particles close to the forward direction. One example of such a distribution is that used by Chilton, Horn, and Jabbur[14] in their calculation of quark production using an absorptive peripheral model; it is $(e^{7.7t} + e^{3.2t})/2$, where t is the exchanged-pion four-momentum in $(\mathrm{GeV}/c)^2$, and was chosen to fit much high energy data. Another estimate is a distribution proportional to e^{3t}, which is based on an extrapolation to larger masses of heavy-isobar production,[26] and even this gives a very forward spike for heavy particles. One can also argue on the basis of cosmic-ray evidence[9] that the probability of having a transverse momentum $\gtrsim$ 1 GeV/c is small for all known reactions. For pair production kinematics in the proton-proton collision such a 1 GeV/c transverse momentum corresponds to an angle of about 5° for a particle of 10 GeV/c^2 mass. Thus for any of these restrictions on momentum transfer or transverse momentum the counter acceptance of ±30° is much too large, and a more important limitation is the size of the beam pipes. For a 1 cm x 7 cm beam and a 5 cm x 14 cm beam pipe, typically about half of the particles do not get out of the beam pipe into the first hodoscope for these extreme exponential t distributions.

The massive pair of particles going at a small angle take close to half of the available energy, regardless of the directions of the recoiling protons. Thus, rather like the case of the proton in backward pion scattering, the distribution in total energy of the two massive particles is also a spike, so much so that if the velocities of both members of the pair are observed their masses are remarkably well determined. This energy spike gives at least one, and usually both, of the particles a velocity within our acceptance range for all particles of mass 9 GeV/c^2 or greater for the top energy of the storage rings. To reduce the mass limit to 5 GeV/c^2 requires some running with protons of 16 GeV. Within the accepted mass range the detection probability is about one half and again for one detected particle per day the cross section would be roughly 2×10^{-36} cm^2.

The latter cross section, which is from three orders of magnitude at 5 GeV/c^2 to five orders of magnitude at 25 GeV/c^2 lower than present cosmic ray limits, is surely more realistic than the isotropic-distribution value, and since the true production mechanism should lie between these two extremes, it is clear that the experiment can reach significantly low cross sections. Running times of the order of a few days could produce extremely important results.

5. ISR REQUIREMENTS

While the drawing of Fig. 2 assumes the apparatus is symmetric about the median plane of the beams and hence that it be in an interaction area containing a pit, this is not a stringent requirement. With a small loss in detection efficiency (essentially no loss for the case of small-angle production), counters can be removed from the lower hodoscopes and perhaps added to the upper ones, if scheduling considerations require this.

The experiment is in general rather non-demanding. Gas-scattered backgrounds are quite unimportant in this all-counter experiment, since even with relatively poor vacuum the accidental rates are very small. There are no stringent monitor requirements, since absolute cross sections are of quite secondary importance. Most of the running should be with protons near the top energy, but to cover the 5-9 GeV/c^2 mass range for the small-angle production case, there should be some running at about half energy.

Experimental tune-up can be done at any energy.

Most of the apparatus could come from UCSB, probably including a PDP-15 computer to determine ionization losses, ranges, and particle trajectories quickly. The electronics could also be supplied mostly by UCSB. Although the number of potential digitizations for pulse height and time could be very large, there are important simplifications. To begin with, counters other than those in the first planes would be gated off during the passage of fast ($\beta \gtrsim 0.9$) particles, so that the number of digitizations would be reduced. The 100% duty cycle of the ISR is also extremely useful in this regard. Those digitizations which do occur can be handled on an event basis, rather like wire-plane spark chambers. For any one event the number of digitizations is not large but it would be prohibitively expensive and complex to have analog-to-digital converters on each counter for time and pulse height. Instead, by employing time delays and appropriately routing the pulses only a few ADC's are needed for each function. This idea is demonstrated in Fig. 5 for the time information and a similar scheme would be employed for pulse heights.

Because the set-up is quite simple, it could be ready at least as soon as the ISR is available. While we realize that the ISR schedule already appears quite full, we would urge strongly that consideration be given to slipping this short, simple experiment in early in the program, since the potential pay-off is so very great.

6. COLLABORATION WITH ANOTHER GROUP

While we are proposing this experiment as an individual external group, we do not consider this an appropriate way to operate at the ISR and we would expect to collaborate with a group already working there. Our full manpower (six postdoctoral people, plus students) if necessary could be utilized at CERN during a summer or during a short running period, but at other times the numbers would be fewer than this. We could also afford to bring essentially all equipment for the experiment, but it would be desirable to reduce transportation costs if some items were available at CERN. A collaboration is particularly advantageous because we lack expertise in the local operation.

We have discussed the possibilities for collaboration with CERN groups, and at present it appears that our interests mesh most closely with those of the Winter group. A sharing of equipment and manpower appears quite feasible, and we clearly have mutual interests in the physics. In particular it was a talk by Winter at the Wisconsin Conference in March which inspired us to try to find a simple way to search for massive particles.

FOOTNOTES

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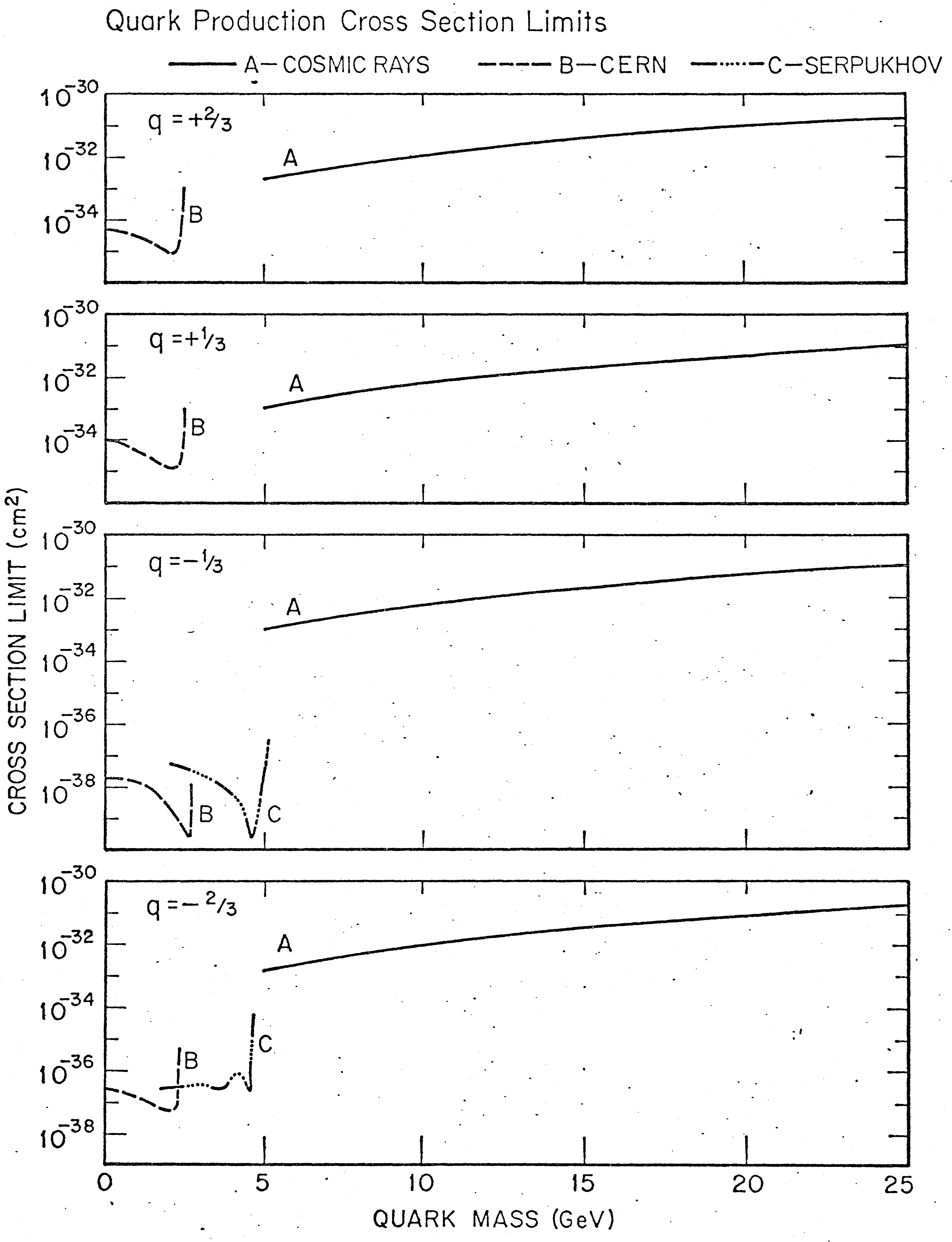
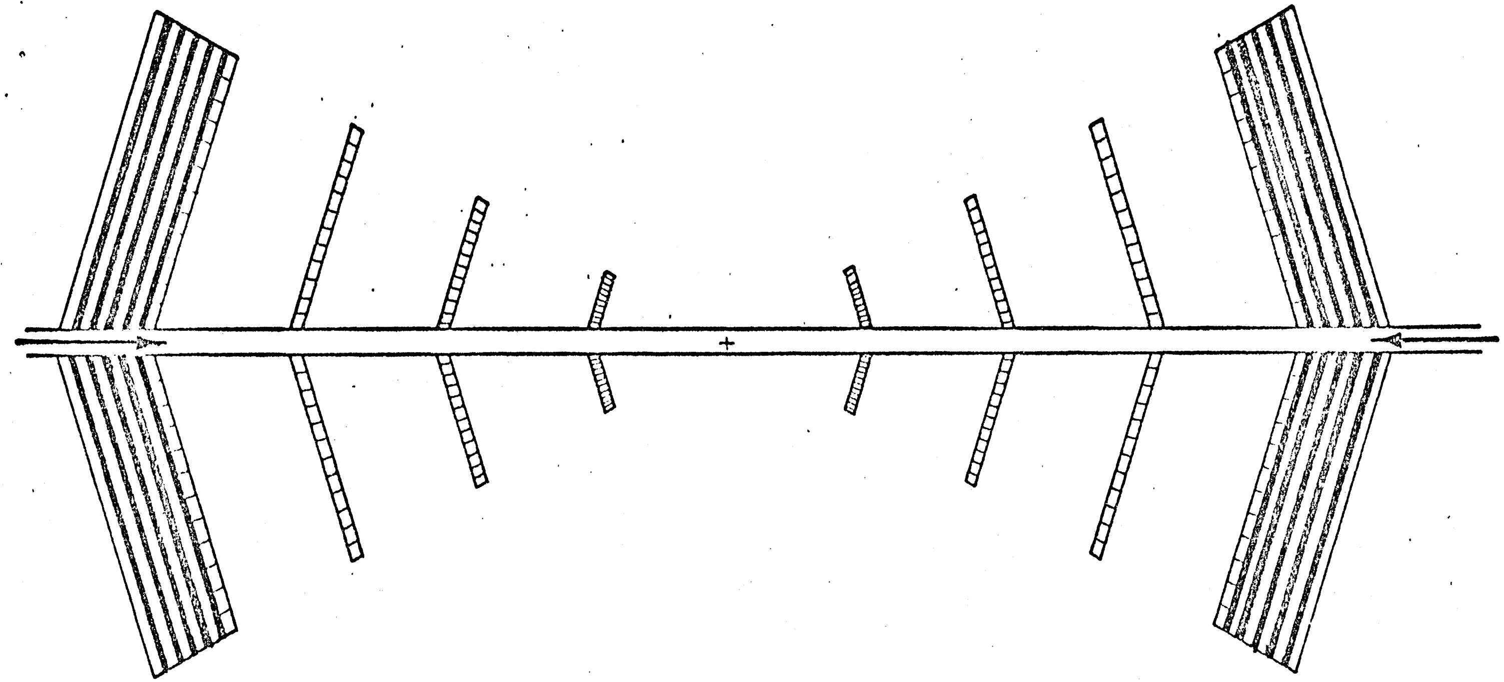

Quark Production Cross Section Limits
A— COSMIC RAYS
B— CERN
C— SERPUKHOV
q = +2/3
q = +1/3
q = −1/3
q = − 2/3
A
B
C
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
CROSS SECTION LIMIT (cm²)
0
5
10
15
20
25
QUARK MASS (GeV)

FIG. 1



HODOSCOPE ARRANGEMENT
SCHEMATIC SIDE VIEW

FIG. 2

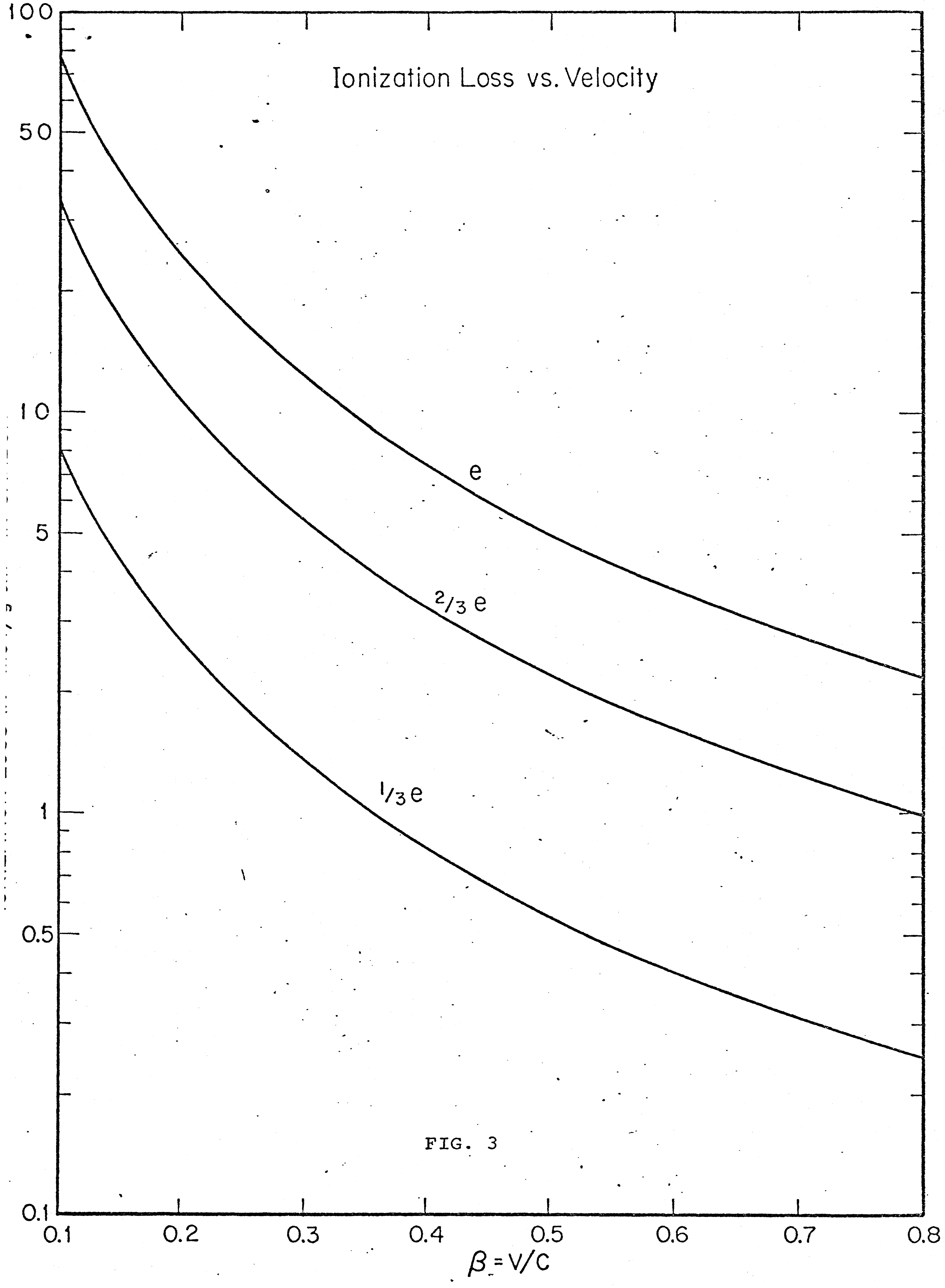
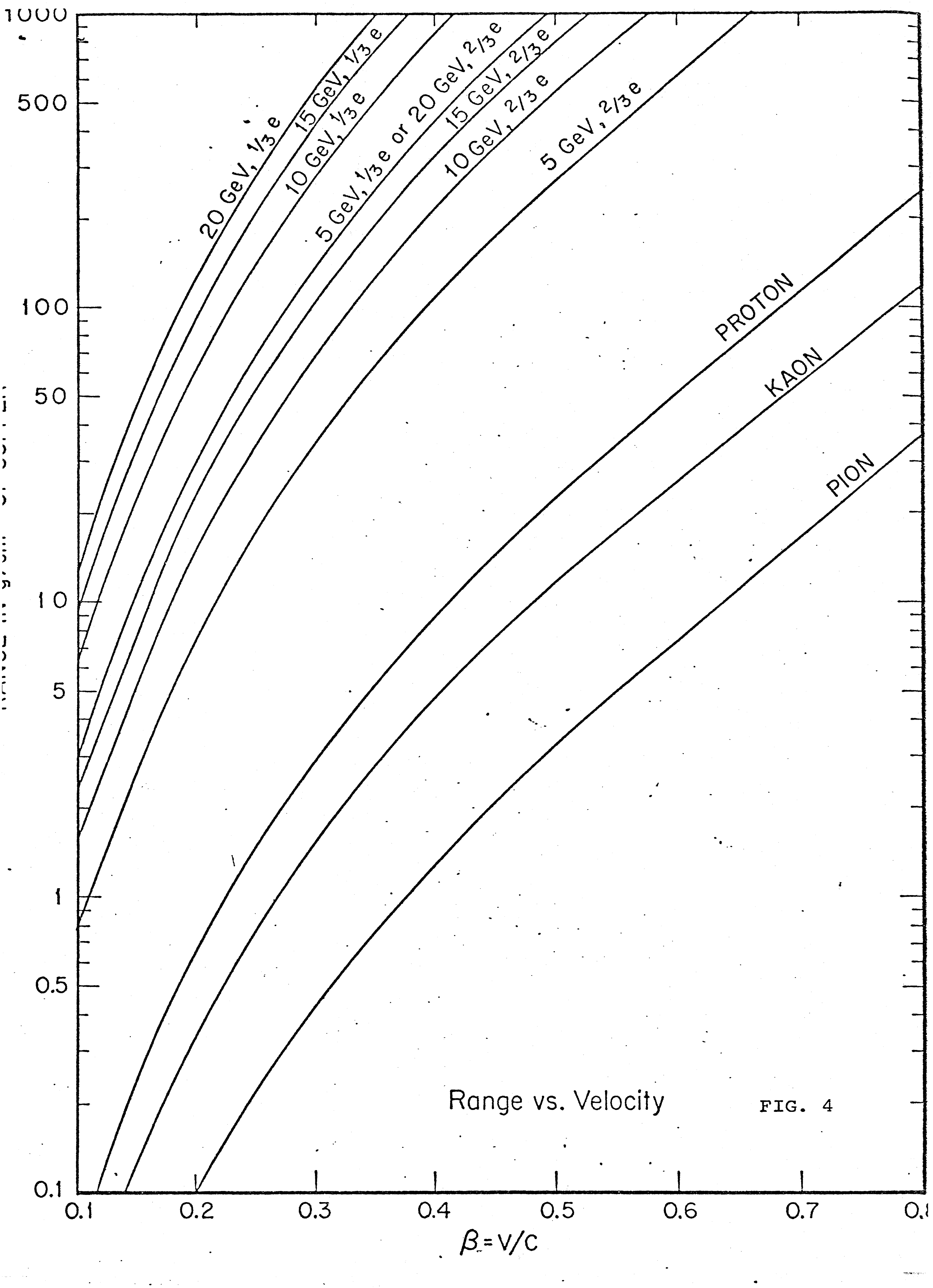

Ionization Loss vs. Velocity
100
50
10
5
1
0.5
0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$\beta = V/C$
e
$^2/_3$ e
$^1/_3$ e

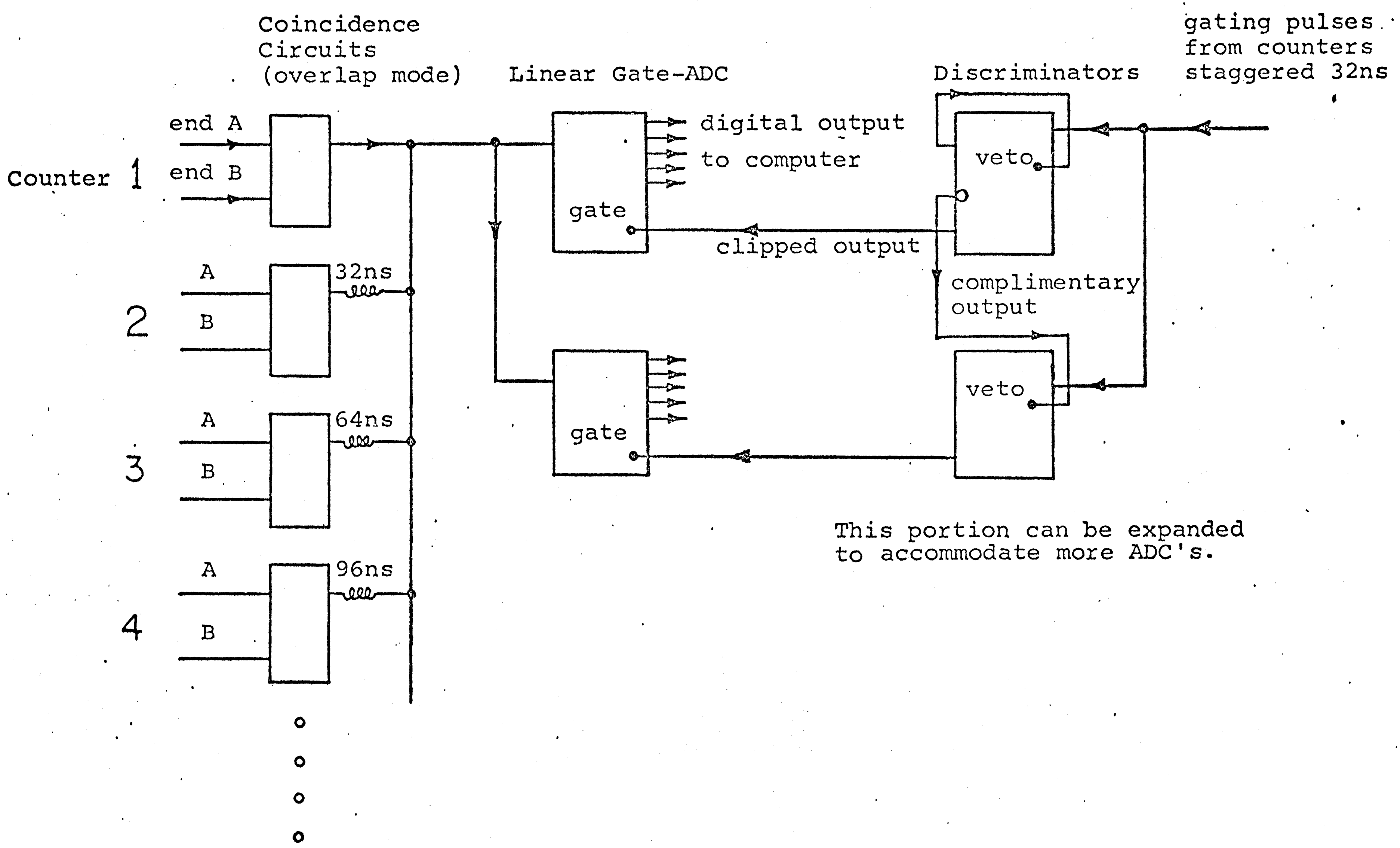
FIG. 3



Range vs. Velocity

FIG. 4

ELECTRONICS TO RECORD TIMING INFORMATION



This portion can be expanded to accommodate more ADC's.

FIG. 5