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FEASIBILITY OF COMBINING EMULSION, BUBBLE CHAMBER, AND COUNTER TECHNIQUES TO STUDY "NEW SHORT-LIVED PARTICLES" PRODUCED BY NEUTRINOS*)

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ABSTRACT

The feasibility of combining emulsion, bubble chamber, and counter techniques to investigate the nature of dimuon events and to search for new short-lived particles produced by neutrinos, is discussed in the light of concrete facilities already existing or under development at CERN: the wide-band neutrino beam (WBNB); the big European bubble chamber (BEBC); the external muon identifier (EMI). A 30-litre emulsion stack (ES) placed outside BEBC, near its window exposed to the beam, is used as a sensitive target capable of detecting decay paths of a few μm or longer, as expected for the new short-lived particles. The ν interactions in ES will be searched for by scanning a small fiducial region determined by tracing back in ES the tracks of the events observed in BEBC. The momenta of the charged secondaries are all measured in the BEBC 35 kG magnetic field. Time localization of the event is achieved by a counter system enclosing ES and coupled electronically to EMI. Under these conditions EMI allows muon identification with a high confidence level.

Assuming that the CERN Super Proton Synchrotron (SPS) operates with 5×10^{12} ppp and 10^4 pulses/day, one expects to record ∿ 200 ν interactions/day in ES and 10-20 dimuon events in a one-month exposure. The latter could be made on a parasitic basis. The cost of such an experiment is essentially the cost of the emulsion stack.

Using the SPS dichromatic neutrino beam, with BEBC filled either with neon or with the track sensitive target, is another interesting possibility to be further explored.

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*) Partly based on a draft version of a preliminary "Proposal to Investigate Dimuon Events and to Search for Short-Lived Particles from ν Interactions in an Emulsion Stack Coupled to BEBC" (CERN - 11/11/75) written down after a stimulating conversation I had with Dr. J. Ellis about some ideas of his and C.H. Llewellyn Smith.

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1. INTRODUCTION

The field of particle physics has been marked in the last year or so by a number of important findings and discoveries [the J/ψ particles[1], the dimuon events[2], the μe pairs in e^+e^- annihilation[3]] which, even though awaiting a theoretical interpretation, are suggestive of the existence of "more fundamental", or "new" particles, such as "heavy leptons" and "charmed particles".

As is well known, these latter particles are linked to the idea [motivated originally by the suppression of neutral strangeness-changing currents[4] in gauge theories of weak interactions[5]] that a "fourth quark", endowed with a new hadronic quantum number -- the "charm" c -- does "exist". In addition to "charmed candidates" reported at Brookhaven[6] and at CERN[7], indirect indication in favour of "new particles" can be found in e^+e^- colliding beam experiments, where the observed behaviour[8] of the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ cannot be explained by only three fundamental quarks, even allowing for their colour triplets. Another indirect indication can be found in the anomaly in the y distribution at small x and large y, as observed in antineutrino deep inelastic scattering experiments[9].

These experimental facts, however, can by no means be invoked as a *proof* that heavy leptons or charmed particles are a reality. On the other hand, if such new particles do exist they are expected to have masses of a few GeV [10] and, consequently, to decay weakly with lifetimes in the range $\sim 10^{-14}$ to $\sim 10^{-12}$ sec [11]. The corresponding decay paths are then expected to be in excess of 3 μm (up to some 1000 μm if allowance is made for time-dilation effects) and can be recorded therefore in nuclear emulsions. Since neutrino interactions are supposed to violate charm conservation, the charmed particles can be produced singly in processes such as

$$\nu_\mu + N \to \mu^- + C(c = +1) + \text{ordinary hadrons} \qquad (1)$$

$$\bar{\nu}_\mu + N \to \mu^+ + \bar{C}(c = -1) + \text{ordinary hadrons}\ , \qquad (2)$$

which are experimentally "clean", as they do occur without the presence of unwanted background particles. Due to the smallness of the neutrino cross-section, one needs a large emulsion stack even using neutrino beams of the highest attainable intensity. Some external track detector is consequently required in order to locate the interaction point in the emulsion stack, thus reducing the scanning time to a reasonable value.

The method just outlined -- suitable to yield a *direct* proof of the possible existence of short-lived particles -- was introduced and tested by E.H.S. Burhop and his collaborators a few years ago[12] and is being now applied to a search for short-lived particles to be carried out in 1976 at Fermilab[13]. In this experiment (FNAL-Exp. 247) the neutrino interactions occurring in a 20-litre emulsion

stack will be located either by following the track of the associated muons as in the early work[12], or by area scanning of a small fiducial region around the reconstructed vertex of a more-than-one track event as observed in a wide gap spark chamber. Additional information on the recorded events will be obtained by counter techniques; these will also involve a link to the new complex set-up installed on the FNAL ν line to investigate dimuon and neutral current events (FNAL-Exp. 310).

The importance of pursuing this line of research at CERN essentially by the above-mentioned method has been recently stressed in a "Memo to Members of the SPSC"[14], where the possibility of exploiting some of the existing CERN installations is also mentioned explicitly. It is the purpose of this note to point out that the method can be improved considerably -- so as to yield a powerful tool for the investigation of any possible new short-lived particle produced by neutrinos -- by combining in a feasible way emulsion, bubble chamber and counter techniques. For the sake of concreteness reference will be made, of course, to a specific experiment exploiting large-scale facilities which are either already available at CERN (such as BEBC), or are under construction (such as the EMI for BEBC, and naturally a ν beam from the SPS, which will be assumed to be WBNB).

2. EXPERIMENTAL SET-UP

Figure 1 shows the layout of the proposed experiment. Neutrinos from the WBNB produce interactions in a 30-litre emulsion stack, ES. The rate of ordinary ν interactions in ES is estimated to be (Section 3) of $\sim$ 0.02 event per machine pulse, or $n_\nu = \sim 200$ events/day. The stack is located just in front of the 28 cm × 120 cm BEBC window, which is exposed normally to the ν beam. BEBC has a twofold function:

i) It provides a drastic reduction of the otherwise prohibitive amount of emulsions-scanning work, by allowing one to trace back and locate the interaction point in ES within a small fiducial region;

ii) It provides invaluable information on the momenta of the charged secondaries bent in its 35 kG magnetic field, and on possible interactions, decays, etc., occurring within its large sensitive volume.

All interactions occurring in the stack should be promptly recognized as coming from the 30-litre region occupied by ES, by simple inspection of BEBC photographs. Nevertheless, in order to recognize without ambiguity the ν interactions from other possible interactions occurring in ES, some supplementary information is needed. A veto-coincidence counter system (VCS) made of two scintillation counters placed on opposite sides of ES (a "veto counter" upstream and a "coincidence counter" downstream, see Fig. 1) is sufficient to prove that a neutral particle has produced in ES some charged particles. It is proposed that these counters be viewed by "microchannel photomultipliers"[15], which are insensitive to the large stray magnetic field present near BEBC windows.

If BEBC is filled with liquid hydrogen, then muon identification requires the use of an external detector such as EMI[16], at present being developed at CERN for installation downstream of BEBC. EMI capability to identify unambiguously a muon against other particles is greatly enhanced if EMI is coupled to VCS, since the latter gives with high accuracy the instant at which the ν interaction occurs in ES. It is estimated that, under these conditions, the fraction of "wrong identifications" should be less than 1%.

Liquid neon has a 0.24 m radiation length and a 0.54 m collision length. Hence electrons and muons, possibly emitted in the decay of short-lived particles, would be promptly recognized by inspection of BEBC photographs if BEBC were filled with liquid neon. Nevertheless, because of the large mass of liquid involved in this case (about 40 t total), the WBNB should probably be operated at a reduced rate.

In what follows it will be assumed that BEBC is filled with liquid hydrogen.

Since BEBC sensitive time is about 20 msec, both beam operating modes foreseen at present -- the one-turn, 23 μsec "short spill-out" and the 3 msec "long spill-out" -- are acceptable.

The stack ES could be similar to the one of Exp. 247 at Fermilab, i.e. it could consist of pellicles 0.6 mm thick, of 20 cm × 8.3 cm area, grouped in sub-stacks, each of 20 cm × 20 cm × 8.3 cm volume[13]. These would be obtained by clamping together 333 pellicles in each sub-stack. The dimension of 8.3 cm would be in the direction of the beam.

The mechanical support for these sub-stacks presents some problems. One is related to the opportunity of keeping the area of the BEBC window covered as much as possible with emulsions, in order to maximize the rate of events recorded in the ES. Another one has to do with the intense vibrations which occur at BEBC expansions.

3. EXPECTED EVENT RATES

It will be assumed that the SPS operates at 400 GeV with 5×10^{12} ppp and 10^4 pulses/day. The rate of ordinary ν interactions is then computed by integrating the total neutrino cross-section per nucleon[17]

$$\sigma_\nu = 0.83 \times 10^{-38} E_{GeV} \text{ cm}^2 \tag{3}$$

over the neutrino energy spectrum expected for WBNB according to the most recent calculations[18]. The result is the one already reported (see Section 2):

$$\dot{n}_\nu = \sim 200 \text{ events per day} . \tag{4}$$

One arrives at a similar result also starting from the rate of neutrino interactions occurring in the BEBC useful volume ($\sim$ 1 t of liquid hydrogen) which is estimated[19] to be $\sim$ 0.25 events per pulse for 5×10^{12} ppp, 400 GeV protons.

Dimuon events have been observed[2] only for neutrino energies, E_ν, in excess of about 50 GeV [20]. The rate of neutrino interactions from ν's with $E_\nu > 50$ GeV, computed as outlined above, is

$$\dot{n}_\nu(E_\nu > 50 \text{ GeV}) = \sim 50 \text{ events per day} . \tag{5}$$

Assuming that, for $E_\nu > 50$ GeV, about 1% of the interactions contains dimuon events[21], the expected number of such events, recorded in the 30-litre emulsion stack after one month of exposure to WBNB, is found to be

$$N_{\text{dimuon}} = \sim 15 \text{ events per month} . \tag{6}$$

We can recalculate this rate in a slightly different way. The rate of dimuon events observed under the conditions of the Fermilab experiment[2] at the horn-focused neutrino beam, corresponds to about 1 event per ton per 10^{17} protons on target[21]. In the experiment proposed here the detection efficiency of dimuon events should be somewhat higher than in the Fermilab experiment, even though limited by the requirement that at least one muon reaches EMI. (Due to the 35 kG magnetic field present in BEBC this requirement implies in fact that the muon momentum be in excess of $\sim$ 5 GeV.) Nevertheless, we shall assume, for the time being, that the detection efficiency of dimuon events is the same in the two experiments. We then obtain again the rate given by Eq. (6), if we assume the neutrino flux in WBNB to be larger than the flux in the horn-focused neutrino beam at Fermilab by a factor of 8. Such a factor is close to the one expected at CERN, taking into account also the higher repetition rate of the CERN SPS compared to that of the Fermilab machine.

The rate of "spurious dimuons" due to $\pi \to \mu$ decays in flight, from inelastic neutrino interactions, is estimated to be $\sim$ 10% of the rate given by Eq. (6).

4. PROCEDURE FOR SELECTING "CANDIDATE EVENTS"

The procedure for selecting the candidates for the events searched for implies three stages, each corresponding to one of the three techniques employed in the proposed experiment. To be specific, let us consider as an example the case of the dimuon events which are already known to exist[2].

The first stage for selecting a dimuon candidate involves the "electronic component" of the hybrid set-up of Fig. 1. In this stage one merely requires a signal from the veto counter system (VCS) (as expected for any charged weak current neutrino event) and the indication that two muons have reached EMI at the same time as that signal. If, at the occurrence of a given SPS pulse, these requirements are fulfilled, the corresponding photograph of BEBC must then be

inspected. In this second stage, which involves the "bubble chamber component" of the set-up, one requires, first, a confirmation that the event has indeed its origin O inside the volume of the stack ES. If this is the case, then one requires, secondly, that all possible information on the event (such as momenta of all charged secondaries, possible decays occurring in BEBC sensitive volume, etc.) be extracted from the BEBC photograph, and thirdly, that a small fiducial region containing O also be determined by the same photograph. The scanning of the emulsions belonging to this fiducial region will be the start of the third stage -- the one involving the "emulsion component" of the set-up -- which is supposed to end with the identification of the decay of the "new particle" in ES.

Assume, for example, that the dimuon event is caused by the production and subsequent decay of a $\bar{D}^0$ charmed meson (c = -1):

$$\nu_\mu + N \rightarrow \mu^- + \bar{D}^0 + \text{ordinary hadrons} \tag{7}$$

$$\hookrightarrow \mu^+ + K^- + \nu_\mu \ . \tag{8}$$

Then the dimuon event would appear as illustrated in Fig. 2. Events of this or of some similar types could be unambiguously identified in favourable cases by the combined information of the three "technical ingredients" of the proposed set-up.

5. BACKGROUND

It will be assumed that, during the performance of the experiment discussed in this report, BEBC will be exposed only to particles from WBNB. Nevertheless, this beam will not only contain neutrinos. It is expected, in particular, that muons arising from neutrino interactions will accompany the ν_μ's of the beam. It has been estimated[22)] that when BEBC is exposed to that beam and expanded at the occurrence of each machine pulse, $\sim$ 50 muons will traverse its fiducial volume. These muons are mostly coming from ν interactions occurring either in the neutrino filter or in the dense material surrounding the BEBC body.

The muons from interactions in the neutrino filter will be rejected, of course, by the veto counter of VCS. The other background muons will be recognized as not coming from ES by inspection of BEBC photographs. In general, the tracks of charged particles traversing BEBC will not be confused with those due to events occurring either inside BEBC or in ES.

It may be expected also that several pions will enter the chamber from the coils and interact. This interaction background will mainly be distinguishable at the scanning stage of BEBC photographs and the remainder could be removed by kinematic fitting, if necessary.

The problem of the background to be expected in a large ES, due to cosmic rays and to the ν beam exposure, has been widely discussed in Ref. 13. Preliminary tests on emulsion sample exposures have been made already for Exp. 247 at Fermilab. The background under the conditions of the present experiment should be smaller than in that experiment for a number of reasons:

a) the ES does not need, in our case, to be manufactured much earlier than at the time of its exposure;

b) the ES does not need to be transported by plane overseas as in the case of Exp. 247;

c) the exposure time at the SPS WBNB may be only about 1 month as against a few months foreseen at present for the Fermilab experiment.

Altogether, if Exp. 247 at Fermilab proves to be feasible, there are no reasons to doubt that the experiment proposed here should not be so. Nevertheless, it appears wise to make background tests on emulsion samples for the proposed experiment, especially on account of possible differences between the Fermilab and CERN situations as regards the neutron background in the experimental areas.

6. LOCATING THE INTERACTION POINT INSIDE ES

The dimuon events, and probably all the most interesting neutrino interactions occurring in the stack ES, can be located within a small region inside ES by vertex reconstruction based on BEBC photographs. This method can be applied in fact whenever at least two tracks from a neutrino interaction in ES are observed in BEBC. In the presumably less interesting cases in which only one track is observed, the early method[12] of locating the interaction inside ES by line scanning along the track can be applied. The requirement of having, in this case, less than five muon background tracks per mm^2 of emulsion[13] is fulfilled in the proposed experiment. In fact the WBNB transports $\sim$ 50 muons per pulse (Section 5) through the useful area of BEBC ($\sim$ 7.3 m^2), so that after a one-month exposure ($\sim 3 \times 10^5$ machine pulses) the emulsions should contain less than 2 muons per mm^2.

It has been estimated[13] that, starting from the tracks observed in a wide-gap spark chamber, the interaction points in ES could be located within a cross-sectional area of 5 mm^2 and a depth of 20 mm. The test run to be carried out in December 1975 at Fermilab for Exp. 247 will serve also as a check of this estimate. If the latter is correct, finding a neutrino event by this method should require about 0.7 scanner $\times$ day [13] in the case of Exp. 247. This figure should be smaller in our case, on account of the better space resolution of a bubble chamber compared to that of a wide-gap spark chamber. In fact a preliminary

estimate indicates that, if scattering effects are neglected, vertex reconstruction outside BEBC for an event with at least two long tracks in BEBC can be made within less than 2 mm^2 over a plane normal to the beam direction, and within less than 10 mm along the beam direction. On the other hand, scattering effects are small for muons of momentum greater than 5 GeV/c, the minimum momentum for a muon to be detected by EMI when the 35 kG field is present in BEBC. For example, the displacement caused by a 1 cm thick iron plate (total thickness of the BEBC window) over a plane placed at a distance of 20 cm (the distance between the inner BEBC window plate and ES) is about 0.6 mm.

While a Monte Carlo calculation now in progress will give a more reliable figure, a preliminary estimate including scattering effects would indicate that finding a neutrino event by area scanning requires on average less than 0.3 scanner × day. This means that *if the scanning effort of a two-scanner group is concentrated on the dimuon events, a conclusive result can be reached in a few days* after the emulsion has been processed.

The identification of neutrino events in ES by the other method[12] (track following) requires a much greater amount of work, and should not be applied except for special cases.

Connection between space coordinates inside and outside BEBC is already provided, at present, with an accuracy of less than 0.3 mm [23].

The identification of the fiducial region of ES, where the neutrino interaction must be searched for, starting from the results of measurements on BEBC photographs, will require of course the development of a special computer reconstruction program and experimental tests.

7. FURTHER COMMENTS ON THE EXPERIMENTAL SITUATION CONCERNING "NEW SHORT-LIVED PARTICLES"

The experimental findings recalled at the beginning of this note suggesting the existence of new short-lived particles, all come from experiments with particle accelerators. Mention should be made, however, of results from cosmic-ray experiments which are relevant to the possible existence of such particles.

As early as 1971, a charged particle of a new type, having a mass within about 1.5-3 GeV/c^2 and a lifetime of $\sim 0.4 \times 10^{-13}$ sec, was found[24] in a cosmic-ray jet of many TeV, detected by an "emulsion chamber" technique[25]. Soon afterwards, this particle was interpreted[26] as a new hadron "possessing a second type of strangeness"; namely a new quantum number, like charm.

More recently, very peculiar events have been observed in cosmic-ray experiments carried out deep underground, in the Kolar Gold Mines[27], by a technique

involving plastic scintillator walls with absorbers in between, to signal the passage of charged penetrating particles, and large neon flash tube arrays, to make the trajectories visible. These events can be interpreted apparently as due to the decay in flight of new particles, having a mass within about 3-5 GeV/c^2 and a lifetime greater than $\sim 10^{-9}$ sec, produced in the rock by high-energy cosmic-ray neutrinos. Tentatively, these particles can be related to the dimuon events observed at Fermilab as being in fact at the origin of these events. If this were the case, however, the decay of such a long-lived parent should be observed directly in a large bubble chamber (such as BEBC or the 15 ft bubble chamber at Fermilab) and not in an emulsion stack. The interpretation of these findings has been questioned[28)] since similar events should have been -- but were not -- observed also in experiments with particle accelerators.

8. CONCLUDING REMARKS

The many experimental facts indicating the possible existence of new particles of the type predicted by the phenomenological theories based on the charm idea[10)], demand clear-cut experiments capable of revealing, in particular, the short decay paths expected for such particles. Similar experiments are now carried out at Fermilab[13,29)] and are likely to be concluded within about one year. Except in the case where their conclusion rules out the existence of particles with lifetimes detectable in nuclear emulsion, the type of experiment discussed in this report becomes of primary importance: either to prove or disprove in a conclusive way the existence of the new short-lived particles (should the Fermilab experiments have failed to reach this conclusive stage because of technical difficulties) or to study the new field opened up by the possible discovery of the new particles.

It is worth recalling, in these concluding remarks, that combining the information from the emulsion stack with that from the large bubble chamber with magnetic field provides a "qualitative step" in the investigation of this possible new field. A further step could be achieved if the energy of the primary neutrino was known.

Accordingly, the possibility of using the dichromatic narrow-band neutrino beam, in conjunction with BEBC filled with neon, is now being considered. Operation in conjunction with the track sensitive target (TST) in BEBC is also an interesting possibility. Clearly, should the dimuon events be proved to originate from the decay of short-lived particles, observable in nuclear emulsions, any major technical effort along the lines just outlined would be fully justified by the opening of an entirely new field of research in particle physics.

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Figure captions

Fig. 1 : Schematic view of experimental set-up proposed to investigate dimuon events and to search for short-lived particles. Neutrino interactions occurring in a large emulsion stack (ES) can be located in ES by tracing back the trajectories of associated charged particles observed in BEBC. The events can be kinematically analysed using BEBC photographs, as a 35 kG magnetic field is present. Muons from the ν interactions in ES are identified by the EMI, which is electronically coupled to the veto-coincidence counter system enclosing ES. It is proposed that the veto and coincidence scintillation counters be viewed by "microchannel photomultipliers", which are insensitive to the presence of the stray magnetic field near BEBC.

Fig. 2 : Sketch showing the production and decay of a hypothetical charmed meson $\bar{D}^0$ (charm number c = -1) appearing as a dimuon event.

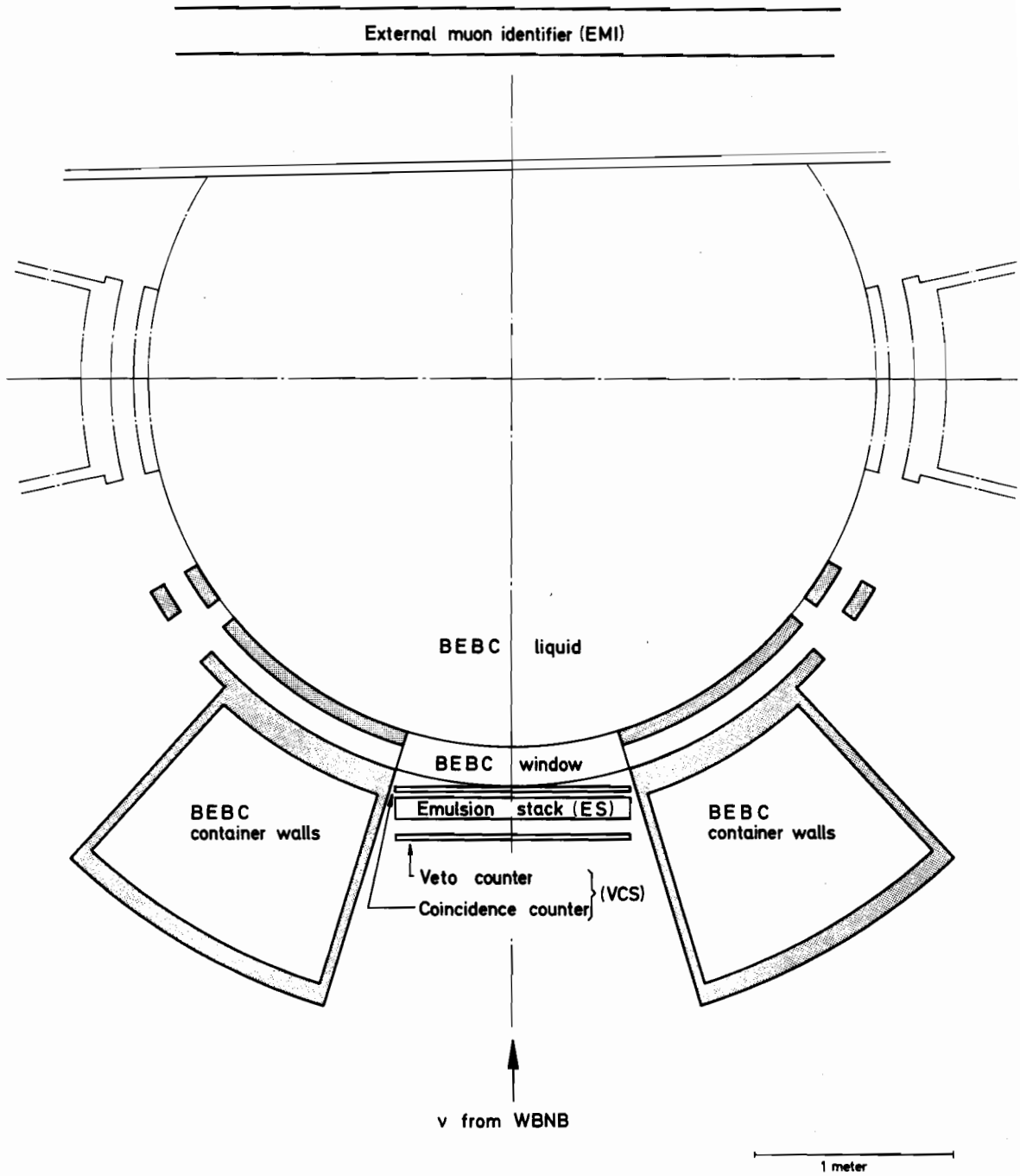
External muon identifier (EMI)
BEBC liquid
BEBC window
Emulsion stack (ES)
BEBC
container walls
BEBC
container walls
Veto counter
Coincidence counter
(VCS)
ν from WBNB
1 meter

Fig. 1

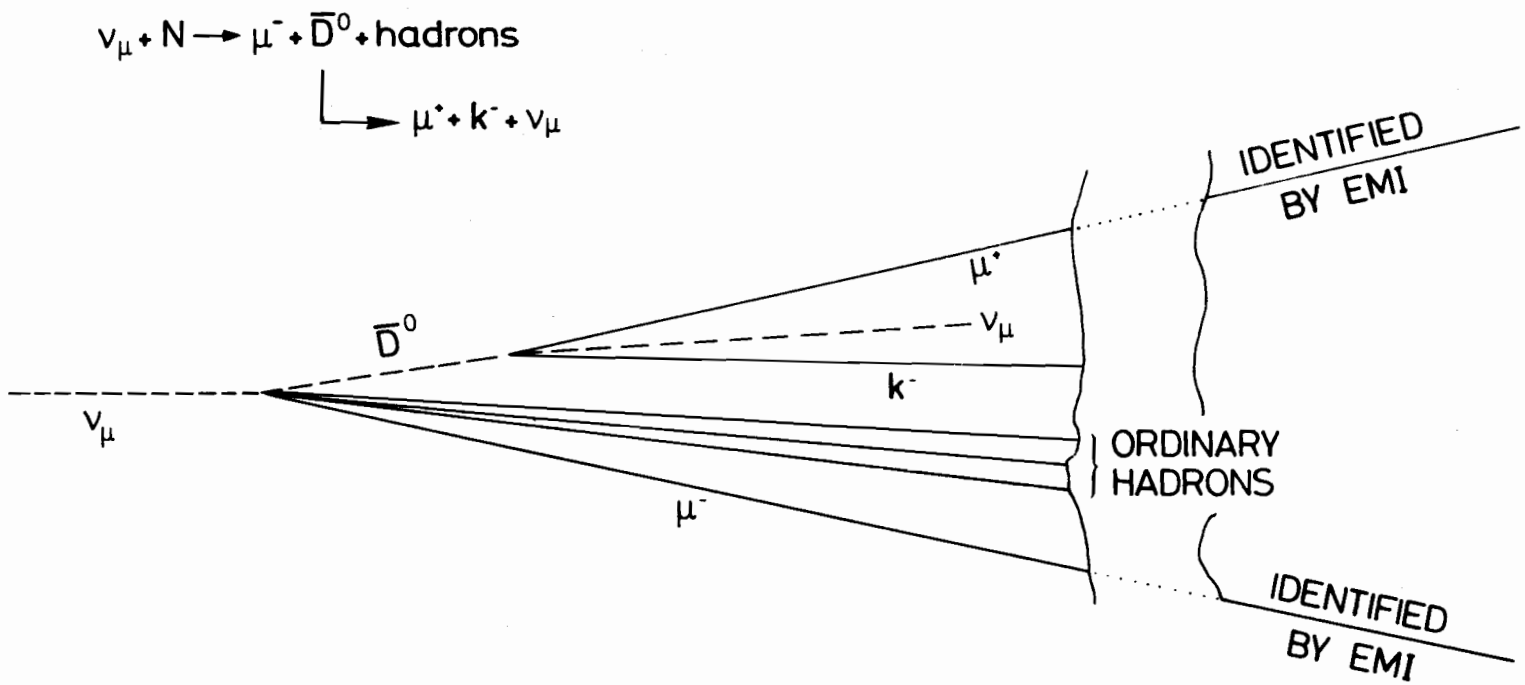
$\nu_\mu + N \rightarrow \mu^- + \bar{D}^0 + \text{hadrons}$
$\mu^+ + k^- + \nu_\mu$
IDENTIFIED BY EMI
μ^+
ν_μ
$\bar{D}^0$
k^-
ν_μ
ORDINARY HADRONS
μ^-
IDENTIFIED BY EMI

Fig. 2