PS RESEARCH PROGRAM II

First report of working groups

At a meeting 28/11 two working groups were set up to study the design of an experiment on the total cross and differential section of pions against protons. The first group, comprising von Dardel, Merrison, Tollestrup, Hine, de Raad and Hagedorn was to study the problem of the target, intensities, beam collection and related problems, while the second group, von Dardel, Merrison, Lundby, Tollestrup would investigate the counters used for defining the incoming pions and distinguish them from other particles.

Chap. I Intensities

I.1 Theoretical (Hagedorn)

In order to design the target and the beam the following information is needed on the production of pions by protons in the target material:

Yield of pions per steradian and MeV/c as a function of pion momentum and angle for various values of the incoming proton energy.

The yield of likely impurities in the beam as a function of these variables.

Effect of the Fermi motion in complex nuclei on these processes, compared to the results on hydrogen.

Once these factors are known the optimum angle of production of a pion beam of the desired properties (momentum and purity) and the trajectories of the beam followed.

We are at present far from having this complete information on the pion production process. Previous estimates by Hine and Citron are essentially based on Cosmic Ray data, covering rather ill defined energy regions up to 40 Gev. It was decided to try to get corraborating information from the pion production spectra at the Bevatron (Tollestrup) and to search Brookhaven reports for corresponding information on the Cosmotron. The latter search produced little additional information.

Theoretical calculations of the pion production process as reported by Hagedorn are based on Fermi's statistical theory, assuming nucleons to be non-relativistic and mesons to be in the extreme relativistic range.

This theory has been preferred in our energy range to the Landau theory which is expected to be strictly valid only above 1000 GeV. Fermi's theory has been used with the obvious improvement to take into account that particles of the same type cannot be distinguished from each other. This reduces the phase space available by large factors in some cases.

It is intended to use this theory to calculate the multiplicity, i.e. the probability for creation of 1,2,3,... mesons in a proton-proton collision at 25 GeV in the laboratory system. The momentum spectrum requires considerable computational work since it has to be obtained as the superposition of the momentum spectrum for creation of 1,2,3,... mesons. The high energy tail of the momentum spectrum, which is of particular importance since it determines the highest pion energy which will be available from the machine with reasonable yield, can however be calculated fairly easily since only processes with 1 or 2 mesons contribute noticeably to this tail. The intensity in the tail may be expected to be small, since single and double meson production occurs only in 0.1 and 2.5% of the cases.

An estimate of the purity of the beam is of considerable importance. Calculations with Fermi theory on the antiproton yield indicate a production of 1 antiproton per 15 pions, for a momentum of 1.7 GeV/c and a primary proton energy of 10 GeV. Extrapolated to the Bevatron energy/this value is a factor of 500 larger than the experimental value from the Bevatron. Chamberlain has however pointed out that the antiproton production on nucleons in copper nuclei seems to be reduced by reabsorption by a factor of about 30. An estimate by Amaldi, based on 3 stars in emulsions, induced by very low energy antiprotons, indicates a yield of antiprotons with cosmic rays 200 times larger than that found in Berkeley.

The yield of K-mesons should be comparable or larger than that of anti-protons.

It can be expected that the purity of the beam will be better at the high energy tail of the pions, and that this advantage may outweigh the considerably lower intensity in the tail.

I.2 Experimental

It must be emphasized that the theoretical treatment, using Fermi statistical theory will yield very uncertain results unless they can be compared with experiments. Comparison with experimental results in the energy region of the Cosmotron and Bevatron is of very limited value for our problem. Bridge has pointed out that it should be possible to obtain reliable information from the cloud chamber photographs of l'Ecole Polytechnique. The maximum detectable momentum in this cloud chamber is 30 GeV, so that 25 GeV interactions can be measured quite reliably. The photographs would however have to be rescanned for events of the type interesting to us, and these events measured. Since high precision is not needed and 50 to 100 events would already give useful information this would not involve very much effort.

Chap. II Beam transport

II. 1 Target area (de Raad and Resegotti)

The beam trajectories have been investigated for particles of 20, 10 and 5 GeV/c momentum. For the higher momenta the yield is expected to drop rapidly with angle of emission, which should not exceed 5° Beams at this angle are best taken from a target in the target chamber between magnets 100 and 1. A diagram of the geometry is shown in fig.

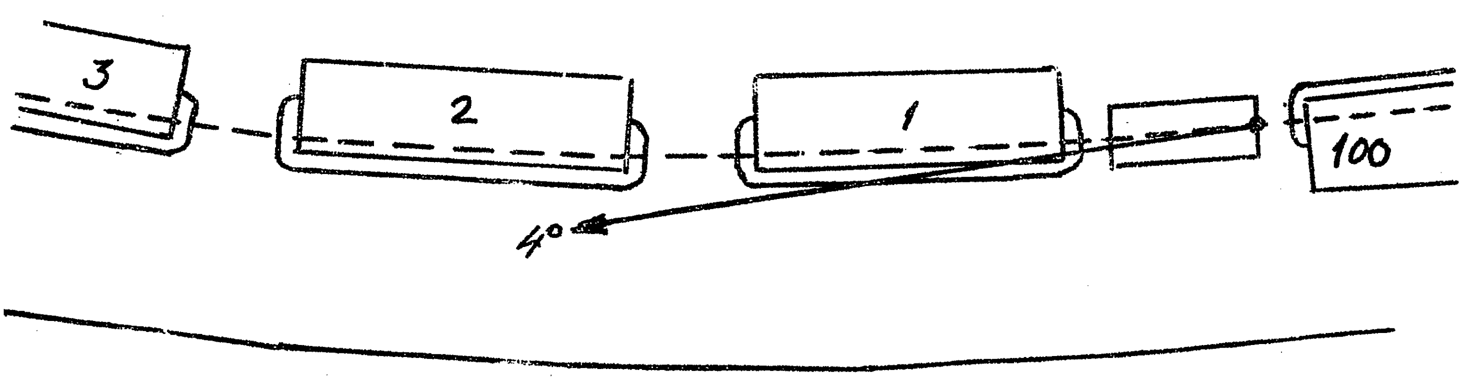

Fig. 1. Geometry in target area. Scale 1:100.

With about 4^o emission angle all particles will clear the next magnet sufficiently that the stray field will not cause serious aberrations, and will also clear the support of the shielding bridge. A focusing channel may start at magnet 2, 7,5 m from the target. The clearance to this magnet allows room for a channel with an aperture of 20 cm. This gives an acceptance angle from the target of 0,1/75 = 0,013 rad. The dimensions of the beam, as limited by the coil of magnet 1 at this point is 20 cm in height by 40 cm in width, but this area is too large to be accepted by the focussing channel. The aperture is large enough to accommodate particles of both signs in the momentum range above 10 GeV/c, so that the momentum analysis can be done after the channel. The angle of emission from the target will be about 3^o5 for negative and 4^o5 for positive mesons of 10 GeV/c.

Particles of 5 GeV/c are best taken out a larger angle, 10^o, which brings them rapidly out of the guiding field and reduces the deflection caused by the field. The target may in this case be put between magnets 5 and 6 and the particles taken out on the inside of the ring, and deflected into the inner experimental hall be a deflecting magnet.

II. 2 Focussing channel (Hine)

Economic considerations indicated that it is better to use relatively weak focussing over long length than to have concentrated lenses which give easier intuitive understanding by the analogy with optics. A positive and negative section tend however to cancel each others effects in part if they come too close together. This and practical consideration indicate that about 50% of the flight path should be covered by lenses, leaving 50% gaps for counters and absorbers.

The acceptance of the channel for particles of momentum P GeV/c is related to the radius of the aperture $\hat{y}$ cm and the peak magnetic field B by the formula

$$A \cong 10^{-4}\, \hat{B}^{\frac{1}{2}} \hat{y}^{3/2} P^{-\frac{1}{2}}$$

For particles of 20 GeV/c and for an acceptance of 0,2 mmrad, e.g. 1 cm x 0.02 rad the following alternatives can be chosen

$\hat{Y}$	$\hat{B}$	L
cm	gauss	m
5	6000	1.7 m
10	700	5 m
15	200	17 m

With small multiple traversal target it may be possible to limit the target size by a factor of 10 or so without affecting the yield. The acceptance of the channel can then be made correspondingly smaller.

If the only problem is to transport the beam over large distances it would seem that the alternative with a large diameter and a low magnetic field (slightly magnetic drainpipe) is the most economic. Very long flight paths, needed to purify the beams by the decay of unstable particles could be envisaged, as suggested by Piccioni.

In counting experiments a small aperture is desired at the position of the target and the counters. This can be achieved by the use of quarter wave length channels as transformers between the large aperture of the channel and the desired small aperture.

II. 3 Time structure of the beam (Hine)

For a bubble chamber the length of the burst should be short, about 100 µs, so as to be accommodated in the sensitive period of the chamber. To create a short burst the beam should be rapidly pushed on the target by a pulsed magnetic field. It is possible to push the beam 3 cm in 200 µs.

For counter experiments the burst should be as long as feasible to decrease the instantaneous counting rates which have to be handled and the chance coincidences. A long pulse can be obtained from a multiple traversal target if the magnetic field is made to level at the maximum value, while the R.F. field compensates for the energy loss in the target. With a 50 keV target a proton requires about 8 ms to produce a nuclear interaction.

The magnet generators are dimensioned so that they can give a flat top to the magnetic field of 100 - 250 ms.

The extracted beam will probably come in a short burst. An early estimate by Citron indicates a maximum length of the burst of 500 µs. It is very desirable that this limitation on the extracted beam is removed.

II.4 Analysing magnets.

This subject has not yet been discussed to any extent.

II.5 Defining slits.

Although this problem has not yet been touched it should not be forgotten, since large difficulties may be expected if we want to define a certain abeam, for example for momentum selection. The problem will become more important if we want to take advantage of the small acceptance of the beam by using very fine slits.

Chap III Detectors.

Present non-destructive methods of distinguishing particles are all based on simultaneous measurement of momentum in a magnetic field and velocity. Using counters the velocity can be determined from time-of-flight measurements, with Cernkov counters, or from ionisation, making use of the relativistic increase of the ionisation at high energies.

III. 1 Time-of flight methods.

The time of flight differences for various pairs of particles over a 10 m flight path are shown in fig. 2. At present reliable discrimination in time is hardly possible for less than 1 ns separation. Even over a 40 m flightpath this resolution does not lead us very high in momentum, as shown in Table 1.

Table 1

Maximum momentum in GeV/c for which discrimination of particles is possible.

Minimum time separation (ns/40 m)	1	0.1	0.01	
pion-proton	7.5	24	75	GeV/c
pion-kaon	6.6	21	66	GeV/c
kaon-pion	3.8	12	38	
pion-muon	0.75	2.4	7.5	

It can be expected that by the time the PS is working faster detectors should be available, raising the possible time resolution by a factor 10. This leads to the maximum momenta given in the second column. An improvement of this order would make the time-of-flight method usable over part of the energy range we would like to study although a 40 m flight path is rather excessive. It would need an additional factor of 10 of improvement as given in the last column to make the time-of-flight method really convenient.

The speed of the detector depends on the speed of the material giving the light pulse, the speed of the photomultiplier and the speed of the associated electronics.

When pushing towards higher speed it can be expected that scintillation counters will be superseded by Cerenkov counters. In spite of the lower total yield of these counters the peak yield will be much higher since the pulse is much shorter, of the order of 0.01 ns compared to about 4 ns for plastic scintillators. Using Cerenkov counters and with proper care in the design of the optics so as not to broaden the pulse by spherical and achromatic aberrations it can be assumed that the detector itself will be fast enough.

Development program presently foreseen at RCA indicates that photomultipliers with a risetime of 0.1 ns will be available within a year or so. Whether it is possible to go beyond this figure is everybody's guess. It is rather disturbing that the development of fast photomultipliers at present is the sole responsibility of RCA, apart from some development work sponsored by Harwell and Saclay. In the discussions it has therefore been stressed, particularly by Merrison, that CERN should consider to take up or to support development work for faster photomultipliers. In this limited field it should be possible to obtain substantial results with a financial effort which is a very minor fraction of the total budget considering that such improvements are of vital importance for the possibilities to make counter experiments in the energy range of the PS.

The electronic circuits associated with detectors can at present handle time resolutions of the order of 0.3 ns, but it is not clear if this limitation is really inherent in the electronic circuits or due to the relative long pulses supplied by the photomultipliers. A small group in CERN should investigate the ultimate limitations and follow the development outside CERN in this field.

III.2 Cerenkov counters

In the high momentum field the gas Cerenkov counter seems best adapted to the discrimination between two particles, since its refractive index can readily be varied within large limits and is in the correct range for our energies. A schematic counter design is shown in fig. 5. The relevant parameters are index of refraction and the pressure the length necessary to give a certain light output, say 100 photons, the diameter necessary to accommodate the Cerenkov cone and the pressure. These parameters are illustrated in fig. 3 and 4 as a function of momentum for various pairs of particles. It is always assumed that the refractive index is chosen such that the heavier particle which we want to discriminate against is at the Cerenkov threshold.

From the curves it is seen that gas Cerenkov counter of reasonable length, less than 10 m will cove the CPS momentum range for all the pairs of particles except for the pion-muon pair where they will only take us up to 7 GeV/c. The diameter of the counter has to be chosen so large that it accommodates the beam and allows the Cerenkov cone to spread. The diameter of the Cerenkov cone at the large end is 20 cm for pion-kaon discrimination at 20 GeV/c and is largest for pion-muon discrimination where it amounts to about 40 cm at 8 GeV/c. If the interior of the counter tube is reflecting the diameter may be made smaller at the expense of some reflection losses and less pronounced directional sensitivity of the counter.

The optical system focuses the Cerenkov light on a ringformed image on the photomultiplier. The radius of this ringformed image is proportional to the relative aperture of the lens, i.e. to f:d. A ring of 2.5 cm diameter is obtained for a f:d-value of 3:1. For large counters it is probably better to use a focussing mirror instead of a lens.

For the comparison with time-of-flight method it is of interest that there exists a unique ratio between the time-of-flight separation over a distance L and the Cerenkov light output of a gas Cerenkov counter of this length. The time-of-flight separation over a length needed to give 100 photons is about 0.004 ns. It is seen that this is considerably better than one can hope to achieve within a foreseeable future with the time-of-flight method. In principle therefore the Cerenkov counter offers more promise.

Apart from the simple threshold Cerenkov counter one should consider the velocity selective counter which can discriminate against higher velocities as well as lower. It is of course possible to use two Cerenkov counters in anticoincidence with different thresholds. This will not give a very narrow band but should be sufficient if the beam is well analysed in momentum. The beam from the CPS may be expected to have a very small angle of divergence. Assuming an acceptance of 0.1 mm. rad the divergence will be only 0.001 rad in a channel of 10 cm aperture. It is tempting to make use of this fact to make a true velocity selective Cerenkov counter. This could be done by covering the face of the photomultiplier except for the ring image corresponding to the selected particle velocity. A rough estimate indicates that with this divergence a velocity selecting Cerenkov counter of 10 m length should be able to distinguish pions and muons up to about 17 GeV/c. There is hope that beams of even smaller divergence can be produced using multiple traversal targets, extending the range even higher. It is however necessary to investigate in more detail the influence of other factors producing divergence of the beam, such as the momentum spread.

Even the long Cerenkov counters should produce a very fast light pulse, whose length is limited essentially only by the dispersion in the lenses and mirrors of the optical system. This broadening may be minimized by proper design of the optics. It seems indicated to make use of these fast pulses to sharpen the selection of discrimination criteria by time-of-flight requirements.

The amount of material in the gas of a Cerenkov counter is proportional to the photon yield but does not depend on momentum of the particle. It is about 1 g/cm^2 for air and 0.1 g/cm^2 for hydrogen for a counter which gives 100 photons for relativistic particles.. The multiple scattering in the gas does not appreciately increase the divergence especially if hydrogen is used. There may however be more serious multiple scattering in the end plates of the counte in particular at low momentum when high pressures and thick walls have to be used.

III. 3 Scintillation counters

A method for discrimination of particles using the relativistic rise in the light output of a scintillator has been suggested by professor Bernardini. Xenon seems to be the most suitable substance since the relativistic increase is particularly high in this gas. An ordinary plastic scintillation counter in which the relativistic rise is insignificant can suitably be used as a reference counter.

Chap.IV Layout of experiments.

On the basis of the previous chapters it is possible to make a very tentative plan for a counter experiment on the total cross section of pions in the momentum region 3-20 GeV. As a basis of discussion a schematic layout is given in fig. 6.

The second bending magnet A2 serves to compensate for the divergence of the beams of different momenta introduced by the momentum analyser A1 so that in the following experimental channel the divergence is small over the entire momentum band accepted by the slit.

The first Cerenkov counter C_1 serves as a beam monitor and discriminates against the chief impurities in the beam, kaons, protons, and possibly muons. The second counter C_2 is made to discriminate against particles which have suffered small angle scattering in the target and against particles which have suffered substantial energy loss. Both these features should be possible to obtain by masking the photocathode as described in III.2.

it is suggested to perform the experiment in an x beam with large aperture, perhaps 10 cm radius, but of small angular divergence, with a relatively weak focusing channel (see II.2) to keep the beam together. If the second Cerenkov counter cannot discriminate sufficiently against small angle scattering this discrimination will have to be obtained by increasing the distance between the second counter and the target very much so that the solid angle as seen from the target is small. It is however quite possible that for practical dimensions it will be impossible to discriminate between the very narrow jet in the forward direction.

G. von Dardel

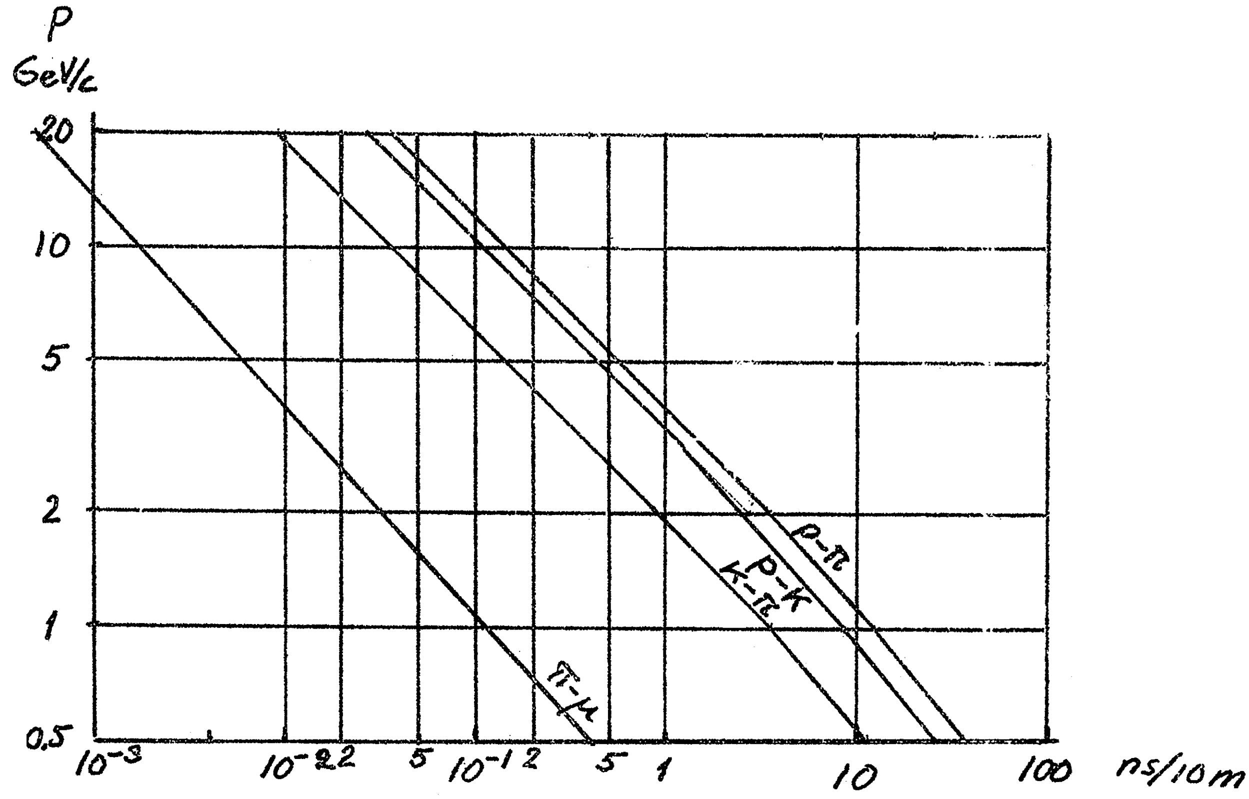

Fig. 2. Time of flight separation between particles with the same momentum for 10 m flight path.

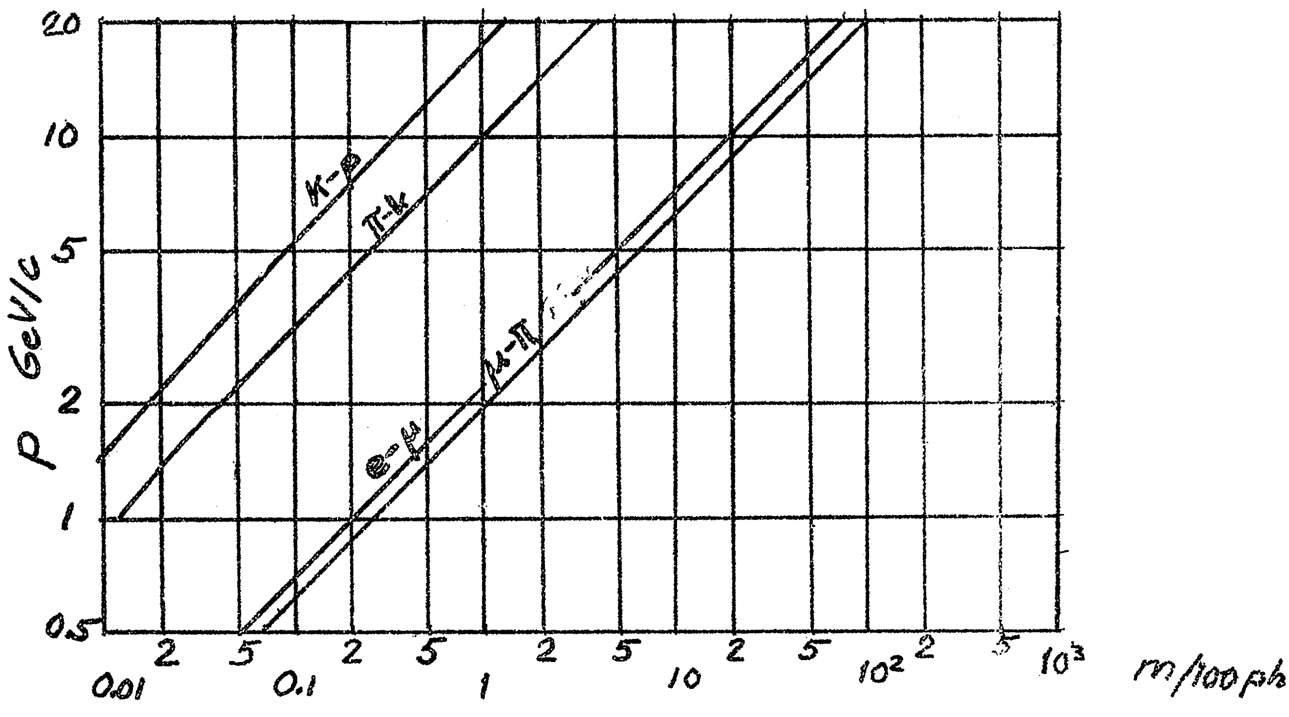

Fig. 3. Length of Cerenkov counter producing 100 photons for the lighter of two particles with the same momentum, the heavier being just at threshold.

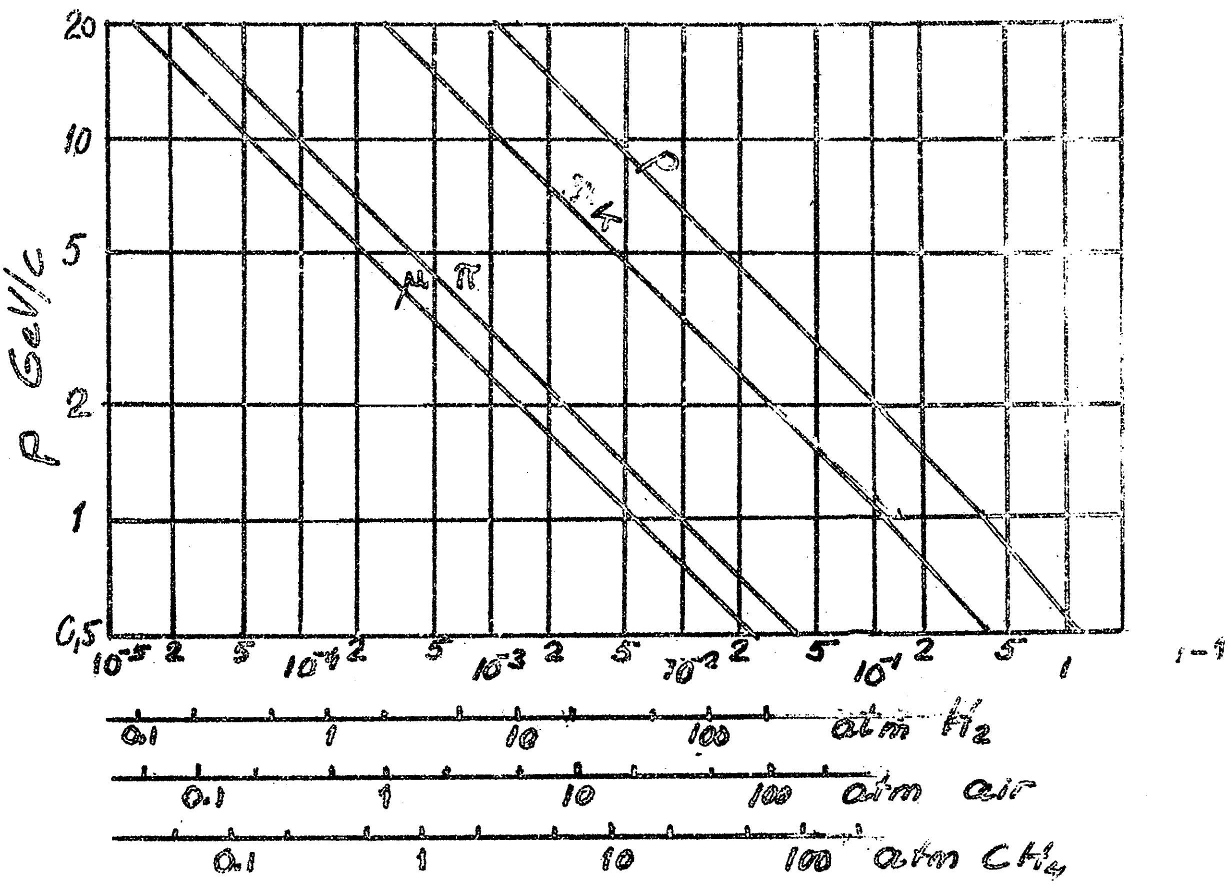

Fig. 4. Index of refraction of Cerenkov counter as a function of momentum threshold. Auxiliary scale gives pressure for various gas fillings.

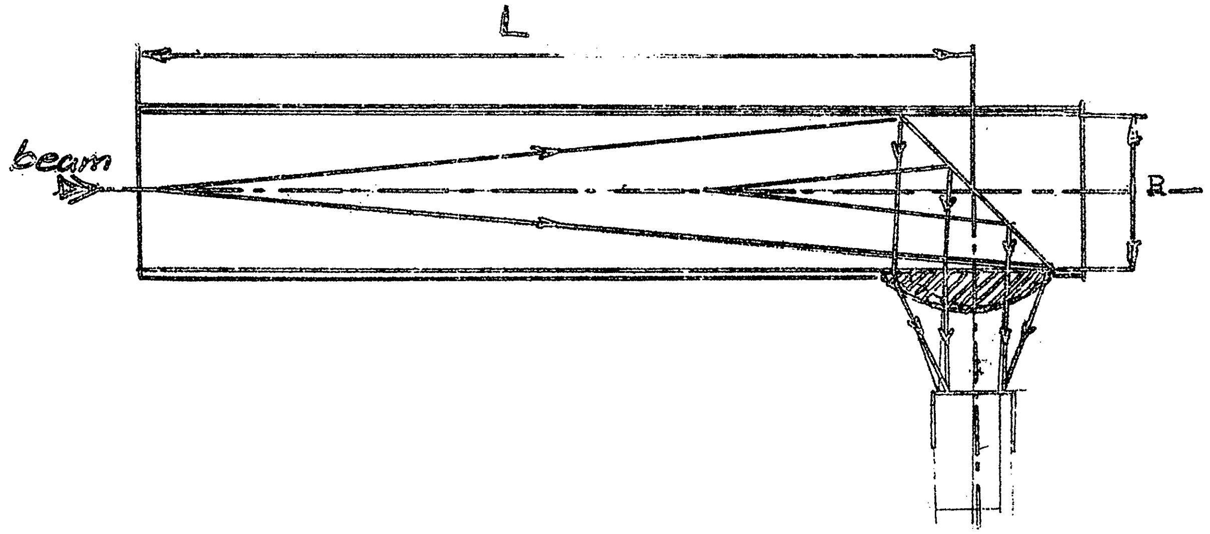

Fig. 5. Schematic design of gas Cerenkov counter.

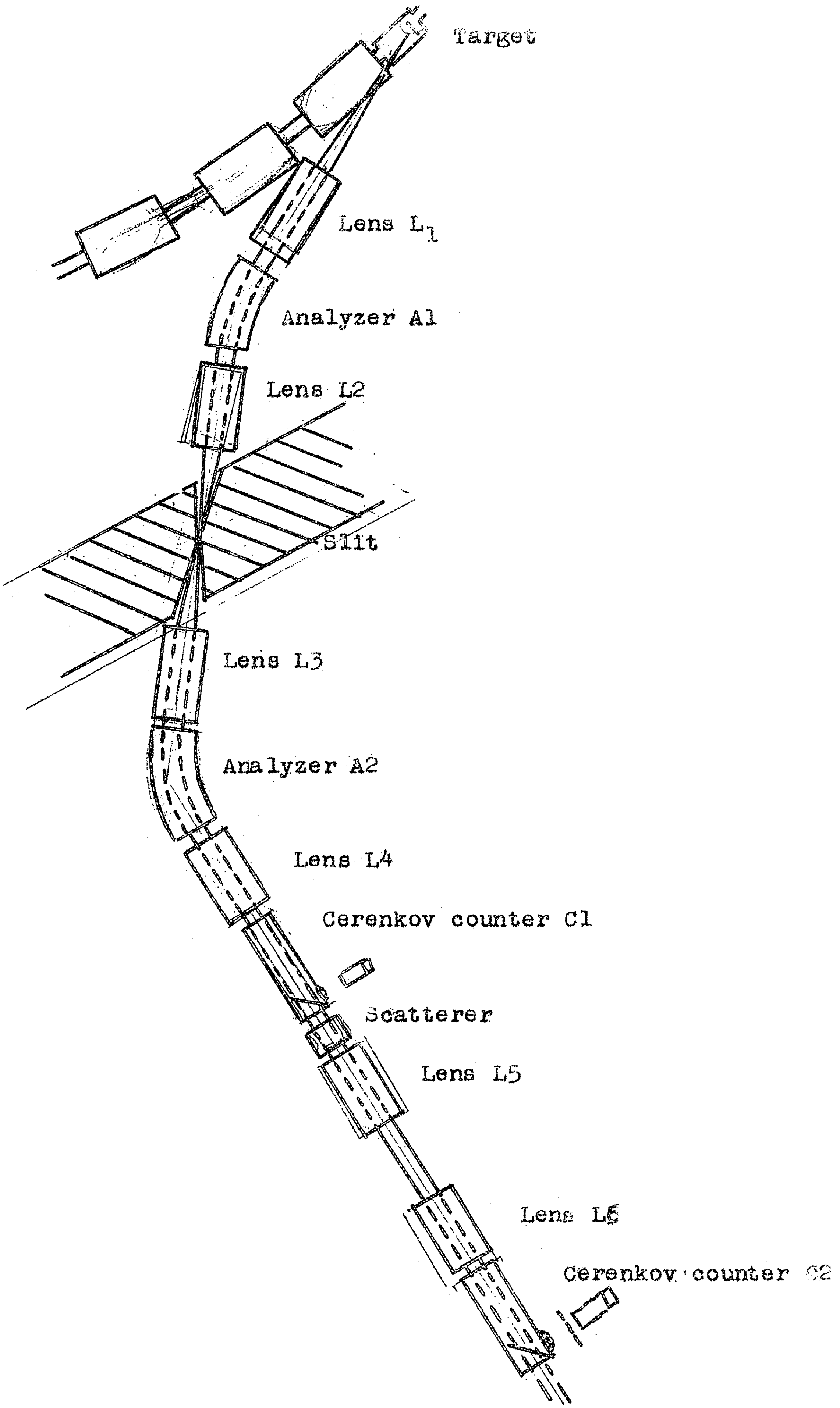

Fig. 6 Tentative suggestion for experiment on the total cross section of pions.