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AN EXPERIMENT TO MEASURE μ-PAIR PRODUCTION IN NUCLEON-NUCLEON COLLISIONS

G. Matthiae and A. Silverman

Yamaguchi[1], Knoll[2] and Chilton et al.[3], following a suggestion of Van Hove, have calculated the relation between W-meson and μ-pair production in nucleon-nucleon collisions, assuming the validity of the CVC theory. Thus, the observation of μ-pairs, a simpler experimental problem, would be a very useful preliminary to a search for W-production. In this note we propose an experimental arrangement for observing μ-pairs with 2 GeV $< m_{\mu\mu} <$ 4 GeV. $m_{\mu\mu}$ = invariant mass of the muon-pair. We consider this as a first step in a search for the W-meson and have designed the apparatus to be useful in such a search, but we do not wish to minimize the intrinsic interest in the μ-pair production, since it is related to the electromagnetic structure of the nucleon for large time-like momentum transfers.

A section through the experimental arrangement is shown in Fig. 1. The apparatus consists of a conical iron shield with apex at the target covering the angular range $20^\circ - 30^\circ$. Embedded in the iron are scintillation counters to measure the ranges (2 GeV/c $< P_\mu <$ 5 GeV/c), and angles of the two muons observed in coincidence. The mass of the virtual γ-ray, $m_{\mu\mu}$ is to be measured to an accuracy of 15% with reasonably constant efficiency for 2 GeV $< m_{\mu\mu} <$ 4 GeV. (See below for details).

Counting Rate

We have considered two equally unreliable methods for estimating the μ-pair cross section. (a) We relate the μ-pair production to the

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(1) Y. Yamaguchi: CERN TH. 634, 1965.

(2) N. H. Kmoll: Private communication.

(3) F. Chilton, A. M. Saperstein and C. Shraumer (to be published).

Revised November 1965.

production of pion-systems of the same invariant mass, and make use of the rather sparse experimental information available for the pion production. (b) We use published W-meson cross sections and compute the μ-pair from References 1 - 3.

Fig. 2 shows schematically the situation in which a μ-pair (2a) and a π-pair (2b) of the same mass are produced. We assume that for every μ-pair final state, there is a corresponding π-pair final state for which $m_{\mu\mu} = m_{\pi\pi}$ and $E_{\mu\mu} = E_{\pi\pi}$. Then, one might guess that the ratio of the cross sections for these two equivalent configurations is something like

$$\frac{\sigma_{\mu\mu}}{\sigma_{\pi\pi}} \begin{pmatrix} m_{\mu\mu} = m_{\pi\pi} \\ E_{\mu\mu} = E_{\pi\pi} \end{pmatrix} \simeq \frac{\alpha^2 f_\gamma^{\,2}}{f_s^{\,2}}$$

where $\alpha^2 = e^4 = (1/137)^2$ as usual

$f_\gamma^{\,2}$ = electromagnetic form factor for $q^2 = m_{\mu\mu}^2$

$f_s^{\,2}$ = form factor for the strong interactions.

Of course, nothing is known of either $f_\gamma^{\,2}$ or $f_s^{\,2}$.

We shall assume $\dfrac{f_\gamma^{\,2}}{f_s^{\,2}} = 1$. This is probably a better assumption than the usual one that they are separately equal to unity. In fact, since the electromagnetic form factors have their origin in the strong interactions, the assumption may not be completely outrageous. We observe, rather diffidently, that these assumptions give approximately the same branching ratio for the decay of the ρ^0 or ω^0 into 2μ's as do more reliable computations. To obtain information of $\sigma_{\pi\pi}$ we use two sources - the Aachen - Berlin - CERN collaboration(4) (8 GeV πp collisions) and Cavendish - Hamburg collaboration(5) (10 GeV pp collisions). Each of these gives $\dfrac{d\sigma}{dm_{\pi\pi}} \simeq 10^{-28}\ \mathrm{cm}^2/\mathrm{GeV}$

then $\dfrac{d\sigma}{dm_{\mu\mu}} \simeq \alpha^2 \dfrac{d\sigma}{dm_{\pi\pi}} \simeq 5 \times 10^{-33}\ \mathrm{cm}^2/\mathrm{GeV}$

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(4) Aachen - Berlin - CERN collaboration. Phys. Lett. 12, 356 (1965)
(5) Cavendish - Hamburg collaboration. Oxford Conference, Sept. 1965.

The second method of estimating $\frac{d\sigma_{\mu\mu}}{dm_{\mu\mu}}$ follows Ref. 1 - 3 from which:

$$\frac{d\sigma}{dm_{\mu\mu}} = \frac{e^4 2^3}{G\, 3\sqrt{2}} \frac{1}{M_w^3} \sigma_w \left(M_w = m_{\mu\mu}\right)$$

$$G = 10^{-5} M_p^{-2}$$

For $P_0 = 20$ GeV, and $M_w = 3$ GeV, Chilton gives us $\sigma_w = 7 \times 10^{-32}$ cm^2

from which

$$\frac{d\sigma}{dm_{\mu\mu}} = \frac{10^{-9}\ 3}{10^{-5}\ 3\sqrt{2}} \frac{7}{27} \times 10^{-32}$$

$$= 5 \times 10^{-32} \text{ cm}^2/\text{GeV}.$$

We shall use the smaller estimate of the first method in calculating expected rates since there is good reason to believe that Chilton's cross section is too large. The use of $\frac{d\sigma}{dm_{\mu\mu}} = 5 \times 10^{-33}$ cm^2/GeV is equivalent to inserting a form factor of $F^2 = 0.1$ in Chilton's result.

In order to calculate the expected counting rates we need to know not only $\frac{d\sigma}{dm_{\mu\mu}}$ but the angular and momentum distribution of the virtual γ-rays. We have calculated the efficiency of the detector shown in Fig. 1 for three different assumptions about these γ-ray distributions. (a) They are identical to the distribution computed by Chilton for the W's. (b) They are produced forward and backward in the CM system with a phase space distribution in momentum. (c) They have the same distribution as ~~XXX~~ real particles produced in p-p collisions - which we call the "Cocconi" assumption[6]. In the latter case, the distribution is given by

$$\frac{d^2\sigma}{d\Omega\, dp_\gamma} = \text{constant}\ \frac{p_\gamma^2}{p_T^2 p_1} e^{-p_\gamma/p_1} e^{-p_\gamma \sin\theta/p_T}$$

$$p_1 = 2.8 \text{ GeV/c}. \qquad p_T = 0.18 \text{ GeV/c}.$$

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(6) G. Cocconi, L. J. Koester and D. H. Perkins: High Energy Physics Study Seminars No. 28(2) UCLD - 1444 (1961).

The results of these three calculations are shown in Table 1. The detection efficiencies are shown for various angular intervals as a function of $m_{\mu\mu}$. We shall assume that $\epsilon = 1.0 \times 10^{-2}$ for the interval $2 \text{ GeV} < m_{\mu\mu} < 4 \text{ GeV}$. This is almost certainly a rather pessimistic assumption. These efficiencies are calculated assuming the difference in the azimuthal angles of the two μ's lies in the region $150^\circ < \Delta\phi < 210^\circ$.

We can calculate the expected counting rate from

$$N_{CR} = N_T N_p \frac{d\sigma}{dm_{\mu\mu}} (\Delta m_{\mu\mu}) \epsilon$$

We take $N_p = 10^{11}$ protons $N_T = 4 \times 10^{23}$ protons/cm^2

then $N_{CR} = (4 \times 10^{23})(10^{11})\ 5 \times 10^{-33} .\ 2.\ 10^{-2}$

$= 4$ counts/10^{11} protons.

Background

(a) Accidental rate

We assume the "Cocconi" formula for π-production

$$\frac{d^2\sigma}{d\Omega_\pi dp_\pi} = \frac{N_\pi}{2\pi} \frac{p_\pi^2}{p_1^2 p_1} e^{-p_\pi/p_1} e^{-p_\pi \sin\theta/p_T} \sigma_{inelastic}$$

For $p_0 = 20$ GeV $N_\pi = 2$ $p_T = 0.18$ GeV/c $p_1 = 2.8$ GeV/c.

From this we calculate the differential cross section for the decay muons $\frac{d^2\sigma}{d\Omega_\mu dp_\mu}$. The results for a decay path of 1 cm are shown in Fig. 3. We integrate these curves and average over angles to find the mean differential cross section for $p_\mu > 2$ GeV/c.

$$\left(\frac{d\sigma}{d\Omega}\right)_{p_\mu > 2 \text{ GeV}} \simeq 3 \times 10^{-32} \text{ cm}^2/\text{ster}$$

for a decay path of one centimetre. We will assume a 20 cm decay path which allows 5 cm free flight before the muon absorber. Then, the counting rate in each telescope of the detector is

$$N = N_T N_p \left(\frac{d\sigma}{d\Omega}\right)_{p_\mu > 2 \text{ GeV}} (d\Omega)$$

$$\frac{N}{10^{11} \text{ proton}} = (4 \times 10^{23})(10^{11})(3 \times 10^{-32})(20)(.037)$$

$$\simeq 10^3$$

The number of π's that survive the absorber without interacting is less than this by a factor of 10 or more. We double this number to take into account muons from K-meson decay, so that the counting rate for each telescope is

$\mathcal{N} = 2 \times 10^3$ counts/10^{11} protons. Then,

the accidental rate between any pair of telescopes is given by

$$(\mathcal{N}_{Acc})_{\text{pair}} = \frac{(3 \times 10^{-9})\ (2 \times 10^3)\ (2 \times 10^3)\ (10)}{1.5}$$
$$= 8 \times 10^{-2}$$

Here, we have assumed $2\tau = 3\,ns$ and the pulse duration = 150 msec. Since we insist that the difference in azimuth between the two μ's be in the region $150^\circ < \Delta\phi < 210^\circ$, and each telescope subtends 30° in azimuth, there are six possible pairs. Thus, the total accidental rate $(N_{acc})_{\text{Total}} = (6)(8) \times 10^{-2} = 0.5$ counts/10^{11} protons.

Background - (b) Detection of π's as μ-pairs according to our earlier assumption

$$\frac{\left(\dfrac{d\sigma_{\mu\mu}}{dm_{\mu\mu}}\right)}{\left(\dfrac{d\sigma_{\pi\pi}}{dm_{\pi\pi}}\right)} \simeq \alpha^2 \qquad \text{for} \qquad \begin{aligned} M_{\mu\mu} &= M_{\pi\pi} \\ E_{\mu\mu} &= E_{\pi\pi} \end{aligned}$$

Then, let $\mathcal{N}_{\pi\pi}$ be the number of charged π-pairs which decay into μ's and are detected as μ-pairs. Let $\mathcal{N}_{\mu\mu}$ be the true μ-pairs, then

$$\frac{\mathcal{N}_{\mu\mu}}{\mathcal{N}_{\pi\pi}} \simeq \frac{\alpha^2}{P_D^2}$$

where P_D = probability that a 2 GeV/c π will decay in 20 cm.

$$P_D = \frac{20 \times 1.4}{2.5 \times 20 \times 300} \simeq 2 \times 10^{-3}$$

$$\therefore \frac{\mathcal{N}_{\mu\mu}}{\mathcal{N}_{\pi\pi}} \simeq \frac{1}{2 \times 10^4 . 4 \times 10^{-6}} \simeq \underline{\underline{10}}$$

The situation should be considerably better than this, since the energy carried off by the neutrinos will cause the apparent mass of the decay μ-pair to be about half the mass of the parent π- pair. Thus, if our assumption about the cross sections is correct to an order of magnitude, we can expect the charged π-pair background to be small at all $m_{\mu\mu}$.

It is easily shown that the background contributed by the neutral pions is an order of magnitude smaller than the charged pions.

It is perhaps unnecessary to point out that there are decisive experimental checks to determine whether the observed rates are due to directly produced μ's or the decay of charged π's.

We make the following observations about backgrounds:

(a) The present arrangement is not optimized for signal to noise.

(b) The counting rates will be limited by the randoms. Our estimates indicate that if the $f_\gamma^2 \simeq 10^{-3}$, the random rate and real rate will be approximately equal when they are both ~ 10 counts/hour.

f_γ^2 = electromagnetic form factor

(c) The present calculations refer to the mass interval 2 GeV < $m_{\mu\mu}$ < 4 GeV. A rough calculation indicates that the rate at which data can be obtained is not a strong function of $m_{\mu\mu}$. Therefore, it is likely that measurement can be made down to quite low $m_{\mu\mu}$, in particular in the region of the ρ-meson. This would appear to be very desirable.

Detector

The detector shown in Fig. 1 consists of 11 x 12 = 132 scintillators embedded in 85 tons of iron. The first scintillator in each telescope is a "Charpak" counter which, together with the target position, determines θ_μ to $\pm 2^\circ$ for a 10 cm long target. The range is determined to ± 7%, and the difference in azimuth between the two muons $\Delta\phi = \pm 30^\circ$. The invariant mass of the μ-pair is given by (neglecting $2 m_\mu^2$)

$$m_{\mu\mu}^2 = 2E_1E_2 \,(1 - \cos\theta_{12})$$

E_1 = energy of one muon

E_2 = energy of other muon

θ_{12} = angle between the two muons

then
$$\sqrt{\left(\frac{\Delta m_{\mu\mu}}{m_{\mu\mu}}\right)^2} = \frac{1}{2}\sqrt{\left(\frac{\Delta E_1}{E_1}\right)^2 + \left(\frac{\Delta E_2}{E_2}\right)^2 + \left(\frac{\Delta(\cos\theta_{12})}{1-\cos\theta_{12}}\right)}$$

Putting in the errors given above
$$\sqrt{\left(\frac{\Delta m_{\mu\mu}}{m_{\mu\mu}}\right)^2} = \pm 0.15$$ as stated earlier.

Cost estimate of everything new

Iron	85 t at 700 fr/ton	=	60,000 fr.
	132 56 AUP at 800 fr.	=	105,000 fr.
	132 bases at 600 fr.	=	80,000 fr.
	40 power supplies at 900 fr.	=	36,000 fr.
Misc.			50,000 fr.
			330,000 fr.

Electronics

The electronics can be very simple. We trigger on any coincidences between the first three scintillators in any of the appropriate six pairs of telescopes, and look at the output of all the scintillators. This type of electronics exists in sufficient quantity so that probably very little new would be required.

Of course, one could imagine beginning more modestly. Two telescopes, which, of course, reduces the counting rate by a factor of six, could certainly be assembled out of available components. Perhaps a reasonable compromise would be to buy the necessary iron for the total detector, but to start with only two telescopes.

Table I

a) Chilton

$\vartheta_{\text{degrees}}$	$M_\gamma =$ 2.0	2.5	3.0	3.5	4.0 GeV
0°–10°	$1.4\ 10^{-2}$	$4.25\cdot10^{-3}$	0.0	0.0	0.0
10°–20°	$1.56\cdot10^{-2}$	$3.5\cdot10^{-2}$	$7.15\cdot10^{-2}$	$12.0\cdot10^{-2}$	$14.6\cdot10^{-2}$
20°–30°	$1.27\cdot10^{-2}$	$2.04\cdot10^{-2}$	$2.98\cdot10^{-2}$	$2.96\cdot10^{-2}$	$0.58\cdot10^{-2}$

b) "γ" forward and backward in the c.m.s. with phase space momentum distribution.

$\vartheta_{\text{degrees}}$	$M_\gamma =$ 2.0	3.0	4.0 GeV
0°–10°	$11.8\cdot10^{-2}$	$0.95\cdot10^{-3}$	0.0
10°–20°	$2.3\cdot10^{-3}$	$5.1\ 10^{-2}$	$15.3\cdot10^{-2}$
20°–30°	$2.18\cdot10^{-2}$	$4.7\cdot10^{-2}$	$2.56\cdot10^{-2}$

c) "Cocconi" formula

$\vartheta_{\text{degrees}}$	$M_\gamma =$ 2.0	3.0	4.0 GeV
0–10°	$6.5\cdot10^{-4}$	$1.5\cdot10^{-4}$	0.0
10°–20°	$8.25\cdot10^{-3}$	$2.1\cdot10^{-3}$	$6.\ 10^{-4}$
20°–30°	$2.16\cdot10^{-2}$	$1.37\cdot10^{-2}$	$7.3\cdot10^{-3}$
30°–40°	$9.7\cdot10^{-3}$	$7.75\cdot10^{-3}$	$5.05\cdot10^{-3}$
40°–50°	$9.25\cdot10^{-3}$	$7.85\cdot10^{-3}$	$5.75\cdot10^{-3}$

Efficiency for detecting the μ-pair with arrangement of Fig. 1. The efficiency applies only to those μ-pairs whose relative azimuthal angle $150^\circ \leq \phi_1 - \phi_2 \leq 210^\circ$

Fig 1

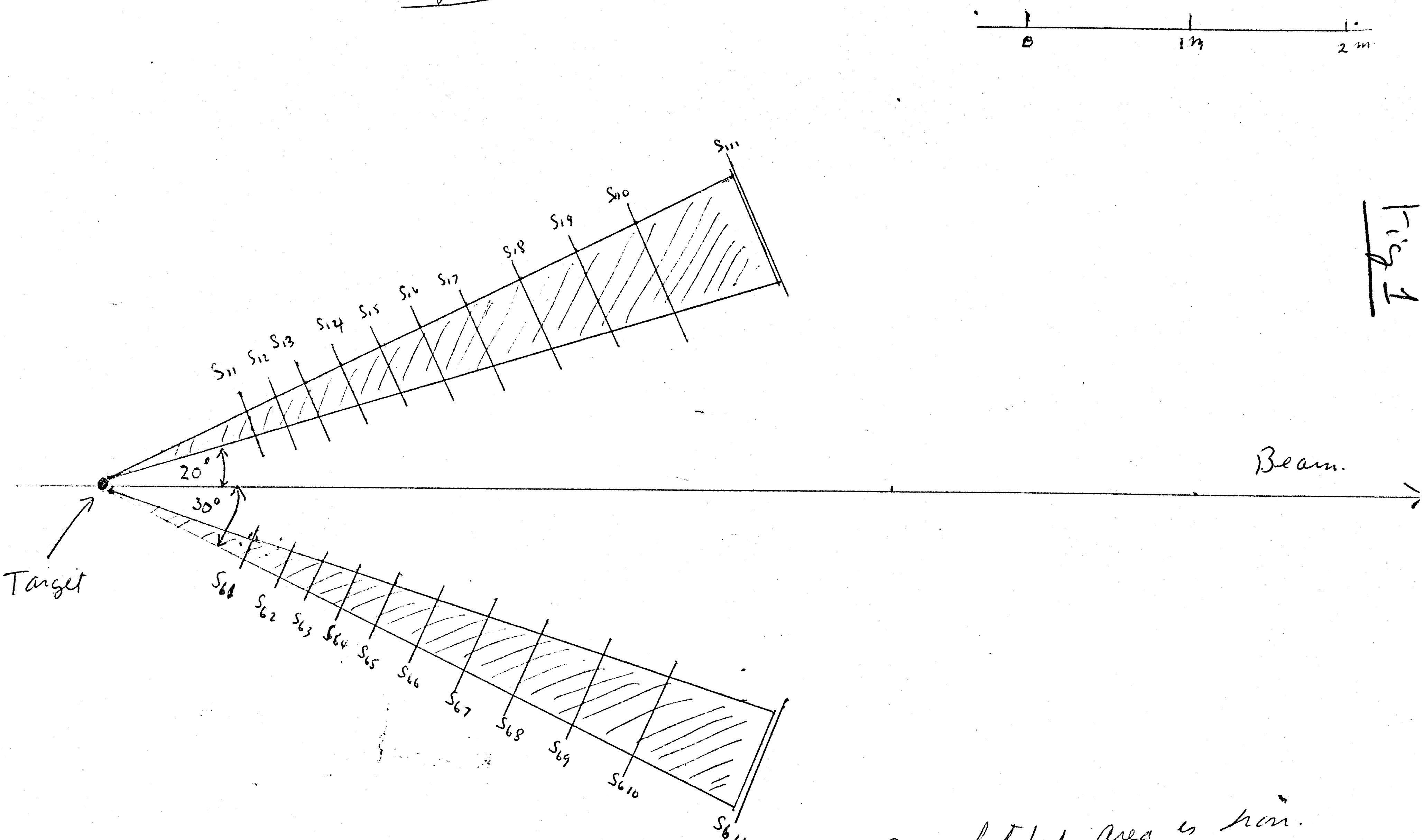
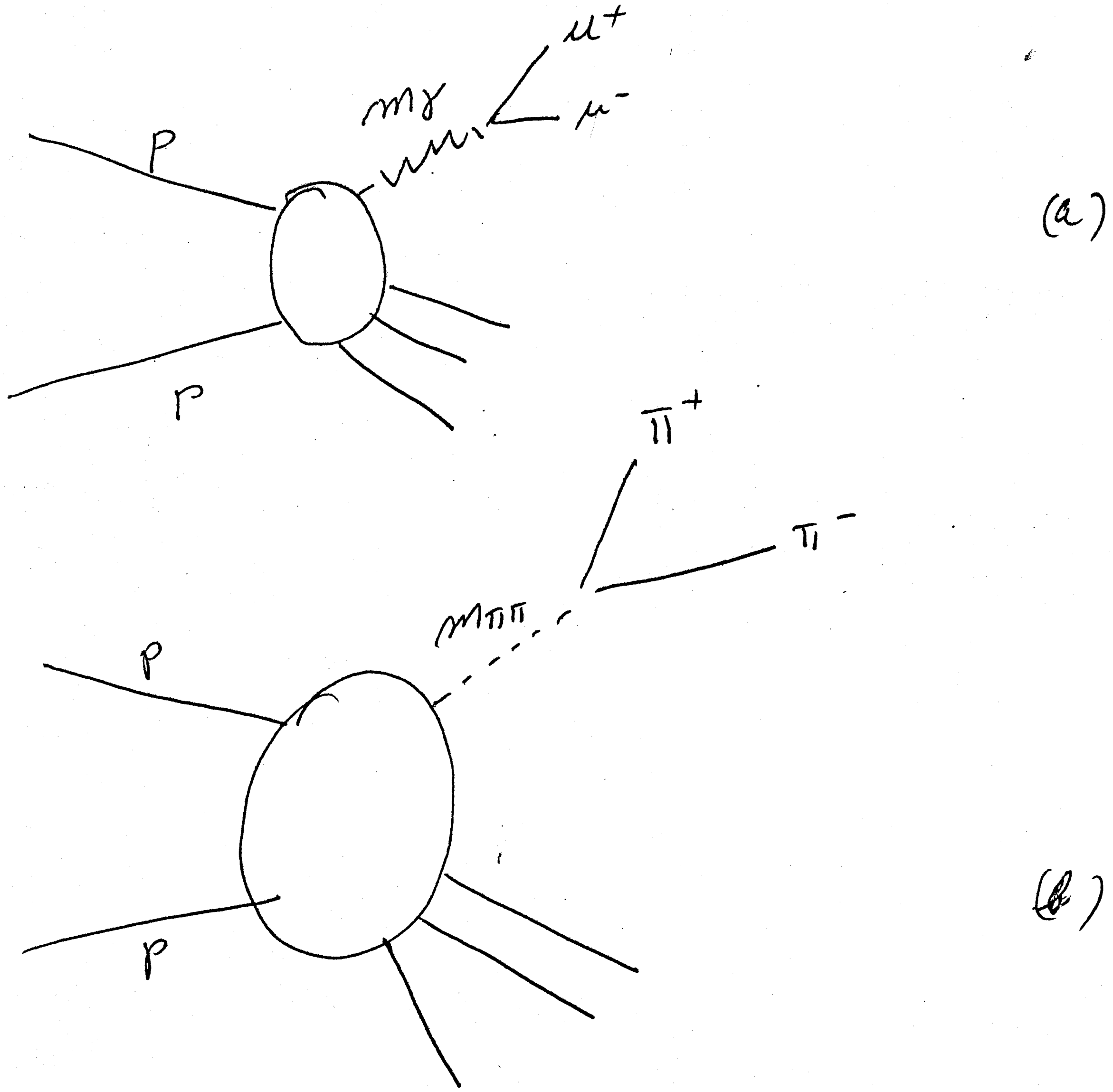


Fig 1

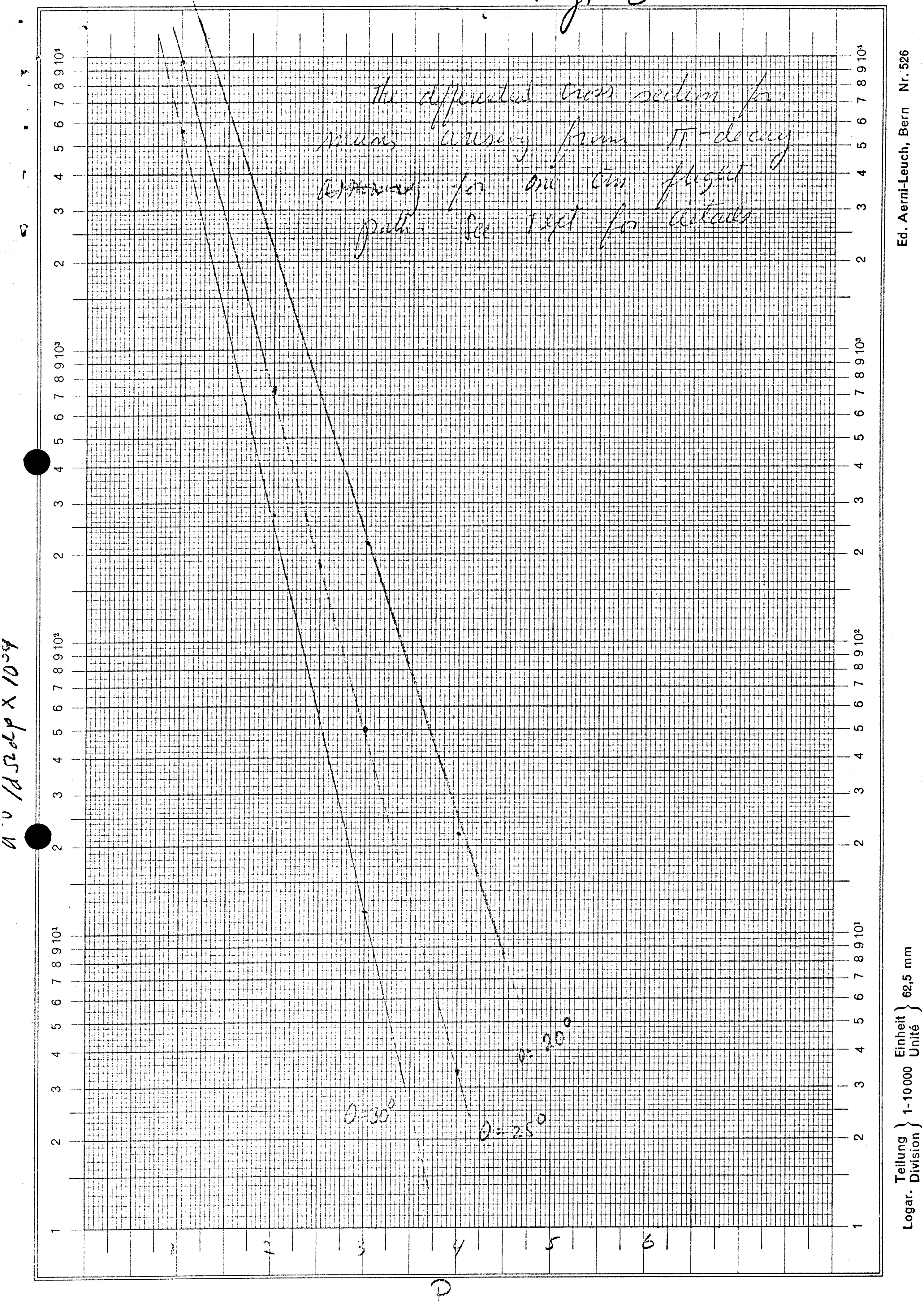
Experimental Arrangement for μ-pair experiment: Cross hatched area is iron. S11 etc are scintillation counters embedded in iron. For clarity shown extending beyond iron but ~~secondary~~ intended to be completely shielded by the iron. The complete apparatus is obtained by revolving section shown about Beam. There are 12 telescopes each subtending 30° in

Fig 2.



The graph ~~of~~ (a) is intended to represent a final state in which a pair of μ's is ~~found~~ produced. Graph B is intended to represent the same final state with the μ-pair replaced by a π-pair of the same invariant mass.

Fig. 3


the differential cross section for
muons arising from π-decay
allowing for one cm flight
path see text for details
θ=20°
θ=25°
θ=30°
d²σ/dΩdp × 10⁻⁴
Pμ
1
2
3
4
5
6
Ed. Aerni-Leuch, Bern Nr. 526
Logar. Teilung Division } 1-10000 Einheit Unité } 62,5 mm