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A SEARCH FOR RELATIVISTIC PARTICLES WITH FRACTIONAL ELECTRIC CHARGE AT THE CERN $\bar{\text{P}}$P COLLIDER

The UA2 Collaboration

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ABSTRACT

A search for relativistic particles with fractional electric charge has been performed at the CERN $\bar{p}p$ collider using a telescope of scintillation counters to detect particles with abnormally low ionisation. No evidence for such particles has been found. This negative result is used to set an upper limit for the ratio of quark yield to that of particles with unit electric charge. For quark masses below 2 GeV/c^2 the 90% confidence level upper limits range from 2×10^{-4} to 2.5×10^{-3} depending on the quark mass and electric charge.

Many experiments to search for particles with fractional electric charge have been performed since the quark model was first proposed in 1964[1)]. No evidence for such particle has been found so far, either in cosmic ray experiments or at particle accelerators and storage rings[2)]. In accelerator experiments the best upper limits quoted for the quark flux are of the order of 10^{-11} quarks/pion at low transverse momentum[3,4)] and of 10^{-9} at transverse momenta of ~ 2 GeV/c[5)]. In cosmic ray experiments the best upper limits for the quark flux[6,7)] are of the order of 10^{-10} to 10^{-11} $(\mathrm{cm}^2\ \mathrm{sr\ s})^{-1}$, a value eight to nine orders of magnitude lower than that corresponding to the flux of cosmic muons at sea level.

Because of all of these negative searches, there is at present almost no doubt that quarks are confined in hadrons and do not exist as free particles. However, it is conceivable that quarks could be liberated in collisions of extremely high energy[8)]. The existence of such a threshold would not be in contradiction with the negative results of the cosmic ray experiments because the sensitivity of those experiments decreases rapidly as the collision energy increases, due to the steeply falling energy spectrum of the primary cosmic radiation impinging on the atmosphere.

The recent successful operation of the CERN $\bar{p}p$ collider[9)] has opened up the possibility of studying hadron collisions in an energy domain so far accessible only to cosmic ray experiments, but with the advantage, typical of accelerator and storage ring experiments, of a much greater collision rate confined to a small region of space. Only a fraction $\sim 5 \times 10^{-8}$ of the primary cosmic radiation falls above the effective laboratory energy, 155 TeV, of the $\bar{p}p$ collider[10)].

This paper reports a search for relativistic particles with fractional electric charge at the CERN $\bar{p}p$ collider. The experimental apparatus is shown in Fig. 1a and 1b. Its main component is a telescope of five scintillation counters, Q_1 to Q_5, to determine the ionisation of charged particles produced in $\bar{p}p$ collisions and detect events with abnormally low ionisation. This telescope (hereafter referred to as the Q-telescope) is part of the much larger UA-2 detector[11)] installed in a long straight section (LSS4) of the CERN $\bar{p}p$ collider. This detector contains a large single arm magnetic spectrometer at 90°, which consists of twelve drift chamber planes followed by a scintillator-iron-scintillator sandwich and by a wall of lead-glass counters arranged in 28 columns of 10 counters each. For the purpose of the present measurement two adjacent columns are replaced by the Q-telescope, as shown in Fig. 1b.

The drift chambers have an 8 mm gap and are filled with a mixture of 60% A and 40% ethane. Their operating voltage is 50 volts above the knee of the high voltage plateau.

More details on the spectrometer are given elsewhere$^{12)}$.

Each counter of the Q-telescope consists of a plate of plexipop scintillator 30 cm wide, 100 cm high and 4 cm thick, equipped with a 5" phototube at each end (see Fig. 1a). Two additional scintillation counters V are located behing the Q-telescope as shown in Fig. 1a, to reject particles which might simulate abnormally low ionisation by Cerenkov radiation in the light guides of the telescope counters. The anode pulses from the 10 phototubes of the Q-telescope are measured by 12-bit analog-to-digital converters (ADCs).

A 2 cm thick iron plate between two scintillator hodoscopes is located in front of the Q-telescope. This plate shields the phototubes of both the lead-glass array and the Q-telescope from the fringe field of the magnetic spectrometer, and it also acts as a photon converter$^{12)}$. However, as discussed later, it is a source of background events in the present measurement.

Each of the two scintillator hodoscopes is made of 28 vertical counters 15 cm wide by 1 cm thick. For the purpose of this measurement only the two counters located just in front of the Q-telescope are considered. The scintillators of the front hodoscope, named W_F in Fig. 1, are equipped with a phototube at each end and provide an additional measurement of the ionisation. The scintillators of the back hodoscope, named W_B, are equipped with a phototube at the bottom end. The anode pulses from the phototubes of both hodoscopes are measured by 10-bit ADCs.

Before installation in LSS4, the response of the Q-telescope as a function of the particle impact point was studied using a charged particle beam from the CERN PS. If we define as unity the most probable pulse height of minimum ionising particles (MIPs) impinging on the centre of the telescope, the response of each phototube varied between the two extreme values of 0.66 and 2.45 over the telescope surface and a suitable parametrisation was obtained to correct the measured pulse heights as a function the particle impact point. The mean of top and bottom phototube outputs showed a much weaker dependence, varying from 1.0 in the centre to 1.55 near the phototubes. The pulse height asymmetry between the two phototubes provided an estimate of the particle impact point along the vertical direction with an uncertainty of ±10 cm. From the width of the asymmetry distribution obtained with MIPs impinging in the centre, the average number of photoelectrons corresponding to unit pulse height was determined to be 165 for each phototube.

A similar study showed that the average number of photoelectrons produced by a MIP in each phototube of a W_F counter is 75.

The gains of all phototubes of the Q-telescope, as well as those of the W_F counters, were adjusted so that one ADC channel corresponded to an ionisation of 8×10^{-3}. Pedestal fluctuations in the ADCs were of the same order of magnitude.

A trigger sensitive to charged particles with fractional electric charge was constructed by linearly adding the amplified signals from the top and bottom phototube of each counter Q_1 to Q_5 and requiring that at least three out of the five signals so obtained exceed a threshold corresponding to an ionisation of 0.05 . A further coincidence requirement was that both phototubes from either one of the two W_F counters in front of the Q-telescope give outputs above a threshold corresponding to an ionisation of 0.03 .

In order to suppress background from sources other than $\bar{p}p$ collisions, the trigger also required a coincidence with a minimum bias event, defined as a signal from each of two scintillator arrays surrounding the vacuum chamber 10.3 metres downstream of the interaction point and covering a pseudo-rapidity interval $\Delta\eta = 1.1$ around $\eta = \pm 4.7$. The probability that a non-diffractive collision produces charged secondaries satisfying this requirement is about 60%$^{13)}$. Its exact knowledge is not needed in the final result because the same two scintillator arrays are used to evaluate the luminosity.

During data taking the typical trigger rate was $0.02\ s^{-1}$ at a luminosity of $10^{26}\ cm^{-2}s^{-1}$. A total number of 15062 triggers was recorded, corresponding to an integrated luminosity of $75\ \mu b^{-1}$.

In the data analysis, events with zero pulse height in either Q_1 or Q_5 are rejected to exclude particles entering or leaving the Q-telescope through the sides. In addition it is required that no more than one of the two W_F counters and no more than one of the two W_B counters located in front of the Q-telescope gives a signal, and that no more than one charged particle, as seen by its track in the drift chambers, traverse the relevant W_F and W_B counters and the Q-telescope. Furthermore, if such a particle does not traverse the entire thickness of the Q-telescope, the event is rejected. Finally, events with signals from either V counter are also rejected.

All phototube pulse heights, in events surviving these cuts, are corrected for the particle impact point and for the different scintillator thickness traversed according to the particle direction. For events with no charged particle track seen in the drift chambers, the impact point is estimated from the pulse height asymmetry of the top and bottom phototubes but no thickness correction is applied. The corrected pulse heights are normalised so that their distributions peak at a pulse height of 1.0 . Ionisation measurements I are then defined for each of the W_F and Q_1 to Q_5 counters as the mean pulse height of the two phototubes. From the six ionisation measurements obtained for each event, the most probable ionisation I_0 is determined by finding the maximum of the likelihood function. This is done in practice by minimising the function

$$\Psi(I_0) = -\frac{1}{6}\sum_{i=1}^{6} \ln\left[P(I_i,\ I_0)\right] \qquad (1)$$

where $P(I_i,\ I_0)$ is the probability density to measure an ionisation I_i when the most probable value is I_0, normalised to unity at $I_i = I_0$. The function $P(I_i.\ I_0)$ is in general dominated by Landau fluctuations$^{14)}$. However, for small ionisations statistical fluctuations resulting from the small number of photo-electrons become important, hence for each value I_i $P(I_i,\ I_0)$ is calculated using both the Landau and Poisson distribution and using the larger of the two values in Eq. (1).

The distribution of the minimum value ψ_0 is shown in Fig. 2a. Events with $\psi_0 > 2.4$ are rejected as being inconsistent with a single I_0 value. Test beam data show that 97% of the MIPs satisfy such cut. The I_0 distribution of the remaining events is shown in Fig. 3a.

Fig. 2b shows the ψ_0 distribution for the events with abnormally low ionisation, $I_0 < 0.7$. This distribution is very different in shape from that of Fig. 2a. There are 23 events with $\psi_0 < 2.4$, whose I_0 distribution is shown in Fig. 3b.

A careful examination of these events shows that six of them have a low ionisation in the W_F counter and ionisations close to 1 in all counters of the Q-telescope. Nine events have ionisations close to 1 in W_F and Q_1 to Q_4, while having low ionisation in Q5. For these events I_0 is found to be abnormally low in spite of the fact that only one out of six ionisation measurements is low, because the shape of the Landau distribution$^{14)}$ falls much more steeply for $I < I_0$ than for $I > I_0$, and so the minimum of the function $\psi(I_0)$ is generally found close to the smallest of the six measurements.

The first class of six events is interpreted as neutral particles interacting in either the W_F counter or the iron plate (when no charged particle track is observed in the drift chambers), or charged particles crossing the W_F counter very close to an edge (as confirmed by the intersection of the charged particle track with the W_F counter). The second class of nine events is interpreted as charged particles interacting in counter Q_4 or early in counter Q_5.

If the minimisation of the function $\psi(I_0)$ is repeated excluding from the sum of Eq. (1) the W_F ionisation for the first six events, and that measured in Q_5 for the second nine events, a value of I_0 close to 1 is found which reduces ψ_0 from an average value of 2.03 in the original minimisation to 0.48 .

The remaining eight events are shown as shaded areas in the distributions of Fig. 2b and 3b. No event has a reconstructed charged particle track pointing to the Q-telescope, although other tracks are present in other regions of the large angle spectrometer. The drift chambers are 92% efficient for particles of unit electric charge$^{15)}$. Although their efficiency to particles of fractional electric charge has not been directly measured, it appears very safe to assume that these chambers are at least 50% efficient to particles with $I_0 > 0.5$. Of the five events with $I_0 > 0.5$, four have no hit wire in a road defined by the $\bar{p}p$ crossing region and the Q-telescope, the fifth event has two hit wires only out of a total of 12 chamber planes. It can be excluded, therefore, that the five events with $I_0 > 0.5$ are due to particles with fractional electric charge.

The remaining three events have $I_0 = 0.17$, 0.30 and 0.40, and $\psi_0 = 1.83$, 2.39 and 2.32, respectively. In all of these events an electromagnetic shower is present in one of the two columns of lead-glass counters adjacent to the Q-telescope (see Fig. 1b). This observation suggests that the abnormally low ionisations observed in all counters are due to soft photons from these showers, which leak out of the lead-glass counters and either materialise or undergo Compton scattering in the counters.

The additional requirement that no energy deposition be present in either of the two columns of lead-glass counters adjacent to the Q-telescope leaves, therefore, no event in the sample of events with $I_0 < 0.7$.

This null result can be expressed as an upper limit for the ratio R_Q of the quark yield around 90° to that of particles with unit electric charge. The 90% confidence level upper limit is given by the relation

$$2.3 = N_{MB}\, \alpha_Q\, R_Q \qquad (2)$$

where α_Q is the detection efficiency and N_{MB} is the total number of minimum bias events recorded during the experiment.

The detection efficiency is calculated using a Monte-Carlo simulation program. It depends on the geometry of the detector, on the quark mass and momentum spectrum because of the detector thickness of ~ 40 gr cm^{-2} between the $\bar{p}p$ collision point and counter Q_5, and on the deflection of the particle trajectories due to the magnetic field of the spectrometer.

Quarks of various masses m_Q and electric charge equal to $\pm 1/3$ and $\pm 2/3$ are generated in the Monte-Carlo simulation with a flat rapidity distribution around 90°, and with a transverse momentum distribution of the form $p_T \exp(-Bm_T)$, where $m_T = (p_T^2 + m_Q^2)^{\frac{1}{2}}$ and $B = 5\ (\mathrm{GeV}/c^2)^{-1}$. Such a form is typical of thermodynamical models for particle production$^{16)}$ and it is verified experimentally for the production of a variety of known particles also at the energy of the $\bar{p}p$ collider $^{12,13)}$. However, it must be stressed that there is a large arbitrariness in this choice and, furthermore, the Monte-Carlo simulation does not consider a possible strong absorption of the quarks in the detector material$^{17)}$.

In the simulation program the particles are followed through the magnetic field into the counters W_F, W_B and Q_1 to Q_5, and pulse heights are generated taking into account Landau and photo-electron fluctuations. The Bethe-Bloch formula[18] is used to calculate the particle ionisation from its charge and velocity. These simulated data are then analysed with the same code used for the real data to obtain the acceptance α_Q.

A test of the simulation program is made by generating $\pi^{\pm}$'s according to their known momentum distribution[12] and verifying that the acceptance for these particles agrees with the observed number of MIPs in the distribution of Fig. 3a.

The acceptance α_Q decreases rapidly with increasing quark masses, as a result of the dependence of the ionisation on the particle velocity. This decrease is faster for charge $^2/_3$ quarks, because their higher ionisation results in a larger fraction of quarks with $I_0 > 0.7$. These quarks are confused with particles of unit charge.

The behaviour of α_Q is reflected in Fig. 4, which shows the 90% confidence level upper limit for the ratio R_Q as a function of the quark mass m_Q, for both $^1/_3$ and $^2/_3$ quark charges.

In conclusion, no evidence for particles with fractional electric charge has been found at the CERN $\bar{p}p$ collider ($\sqrt{s} = 540$ GeV). The yield of light quarks with charge $^1/_3$ or $^2/_3$ is at most $^1/_{5000}$ of that of particles with unit charge. The sensitivity of the measurement decreases with increasing quark masses and at $m_Q = 2$ GeV/c^2 the upper limit of the ratio of quark yield to that of particles with unit charge becomes 2.5×10^{-3} for quarks with charge $^2/_3$ and 10^{-3} for quarks with charge $^1/_3$.

The successful completion and installation of the UA2 detector is the result of the unwearing efforts of the technical staff of the collaborating Institutes, whom we deeply acknowledge. Invaluable help as been provided by G. Bertalmio and his team, L. Bonnefoy, J.M. Chapuis, Y. Cholley, G. Gurrieri, M. Lemoine and A. Sigrist in assembling the detectors used in the present measurement. Special thanks are due to F. Bourgeois and his team and to M. Hess for their contribution to the data acquisition and trigger electronics.

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FIGURE CAPTIONS

Fig. 1 a) Side view of the experimental apparatus.

b) Top view of the experimental apparatus.

Fig. 2 Distribution of the minimum value ψ_0 of the variable ψ, as defined in Eq. (1), for all events (a) and for the events with $I_0 < 0.7$ (b). The shaded area in Fig. 2b represents the ψ_0 distribution for the eight events which cannot be explained as interactions in the iron plate or in the last two planes of the Q-telescope.

Fig. 3 a) Distribution of the most probable ionisation I_0 for all the events with $\psi_0 < 2.4$.

b) Expanded view of the I_0 distribution in the region of abnormally low ionisation. The shaded area represents the distribution for the eight events which cannot be explained as interactions in the iron plate or in the last two planes of the Q-telescope.

Fig. 4 The 90% confidence level upper limit for the ratio R_Q, defined as the ratio of quark yield to the yield of particles with unit electric charge, as a function of the quark mass m_Q. The curves labelled $^2/_3$ and $^1/_3$ refer to the absolute values of the quark charges, respectively.

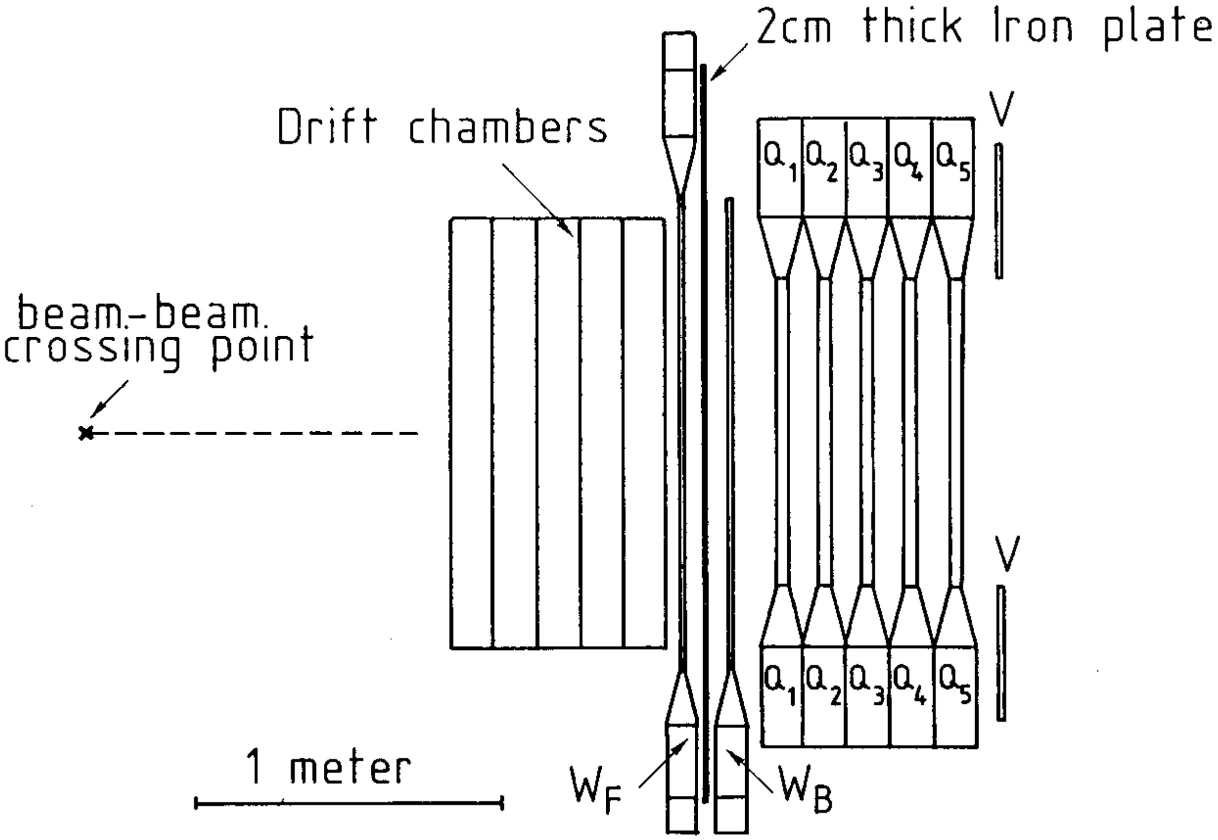

2cm thick Iron plate
Drift chambers
V
a_1
a_2
a_3
a_4
a_5
beam.-beam.
crossing point
V
a_1
a_2
a_3
a_4
a_5
1 meter
W_F
W_B

Fig. 1a

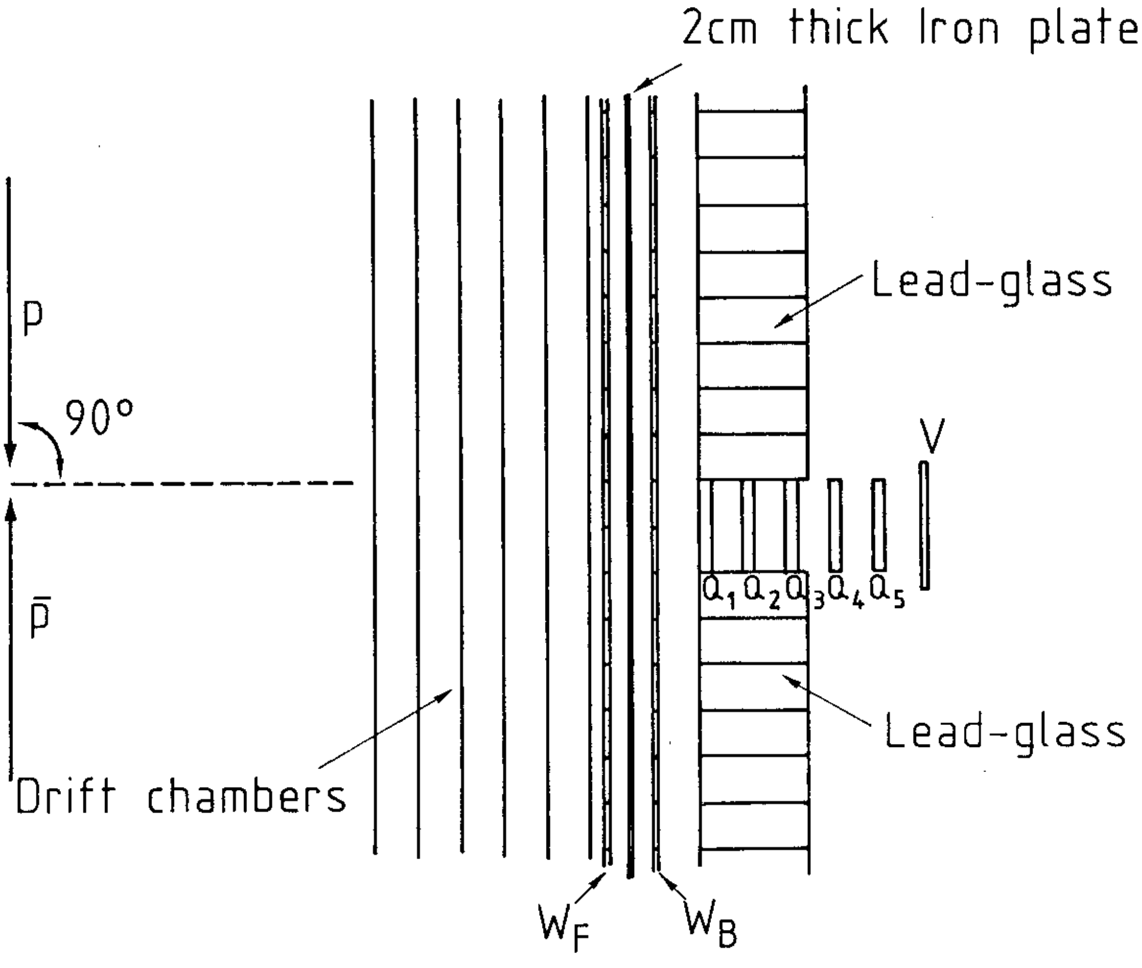
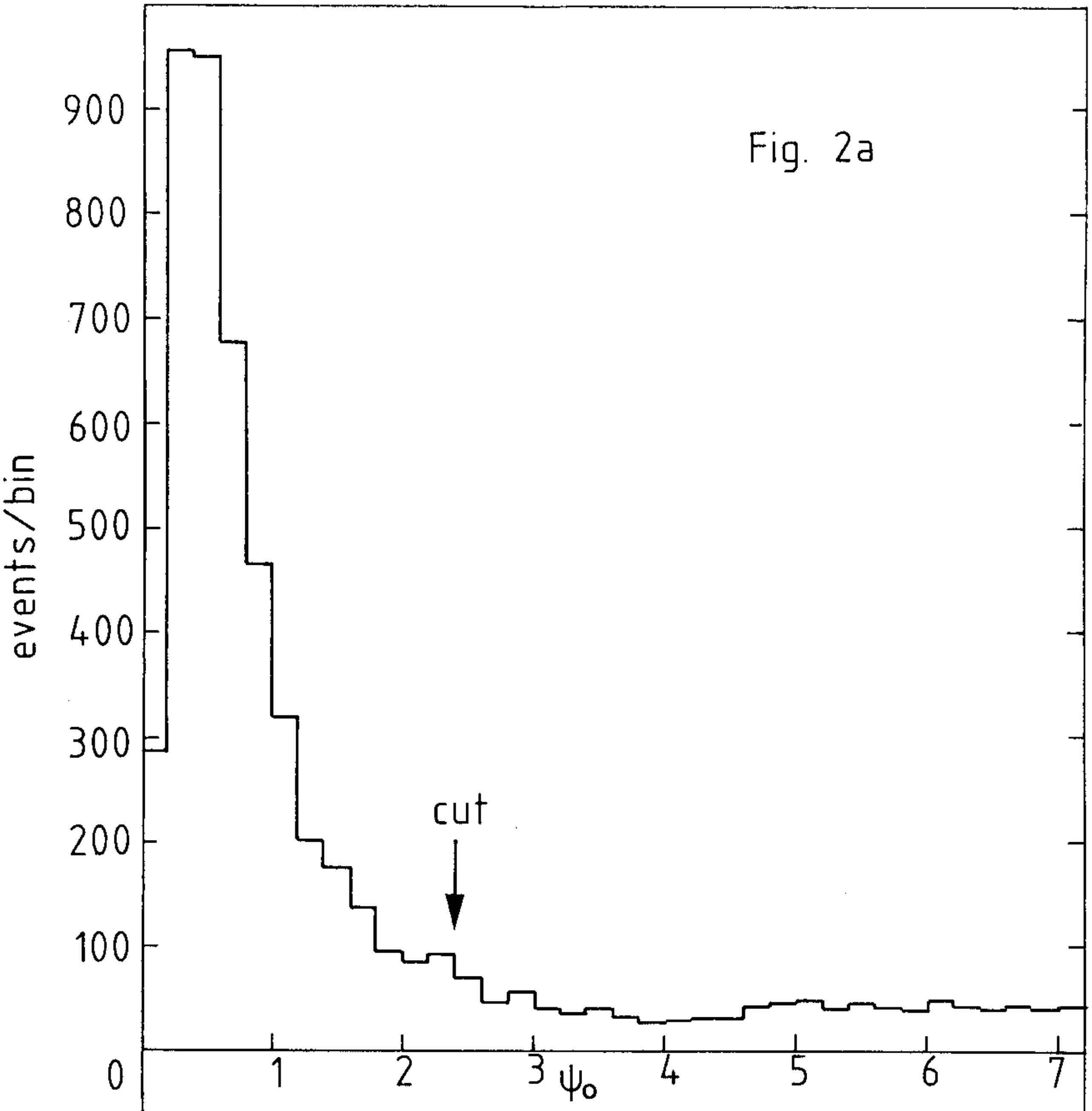

2cm thick Iron plate
Lead-glass
p
90°
V
$\bar{p}$
a_1
a_2
a_3
a_4
a_5
Lead-glass
Drift chambers
W_F
W_B

Fig. 1b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800
700
600
500
400
300
200
100
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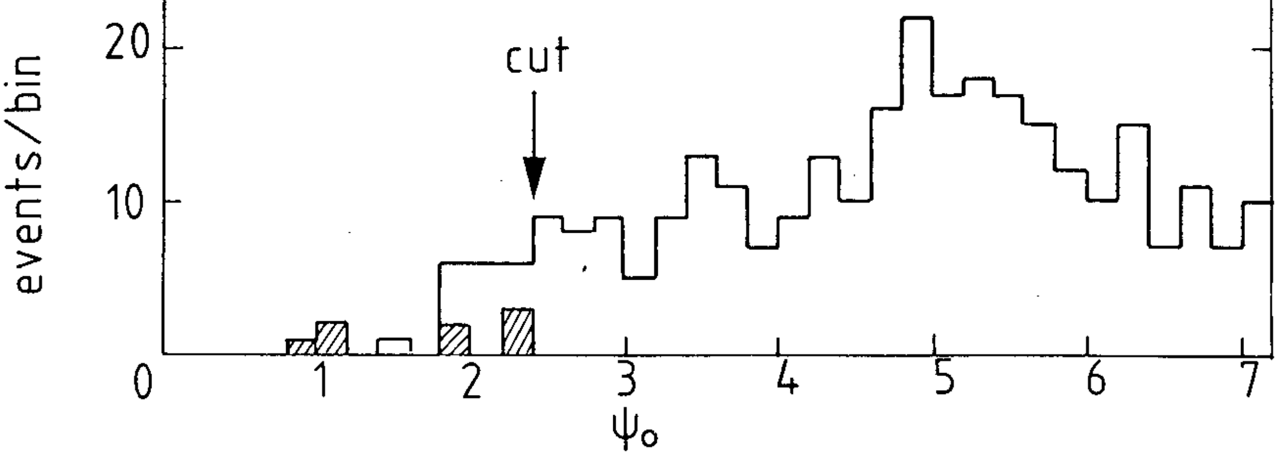
cut
1
2
3
4
5
6
7
ψ_o

Fig. 2a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1
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3
4
5
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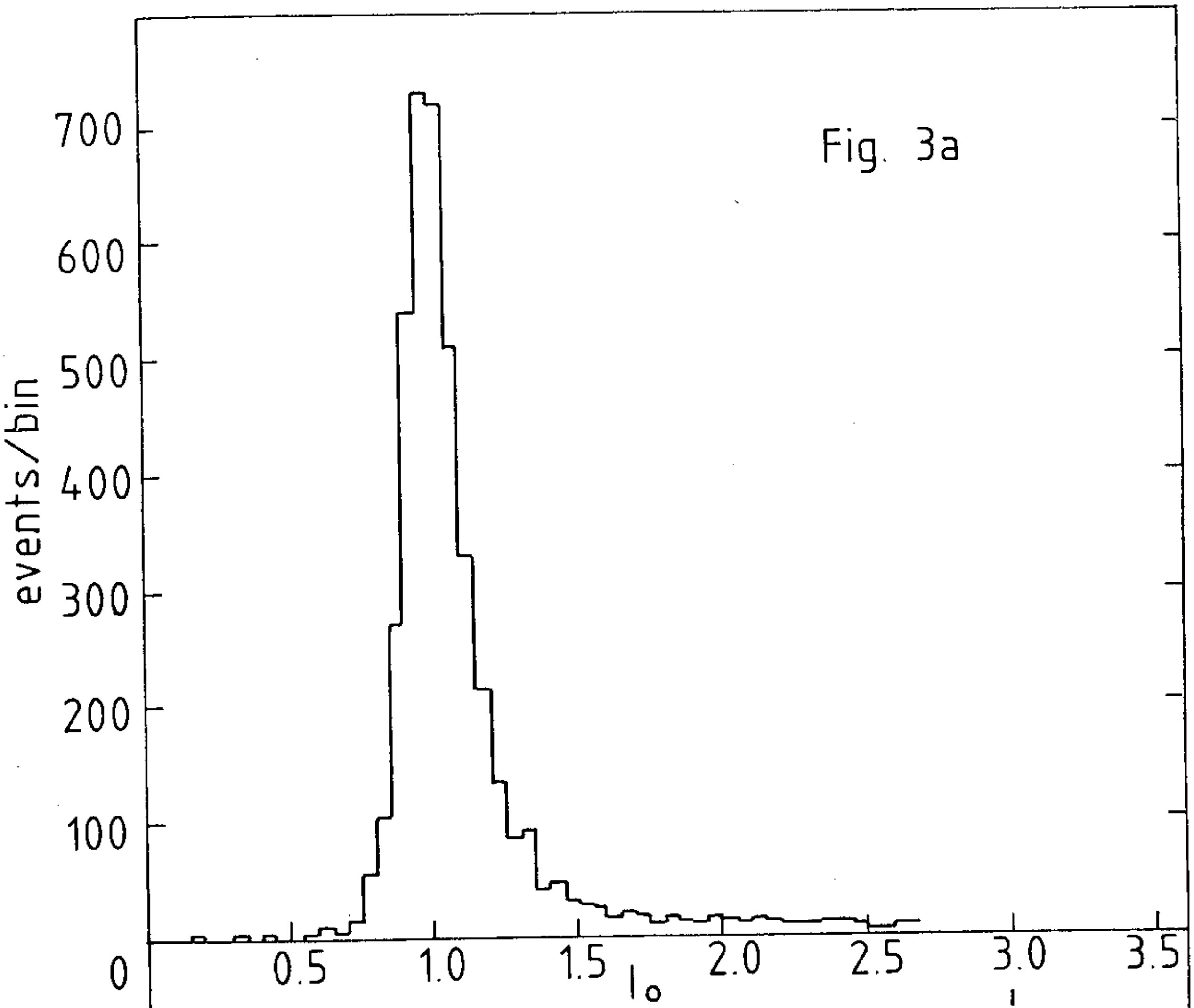
7
ψ_o

Fig. 2b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600
500
400
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200
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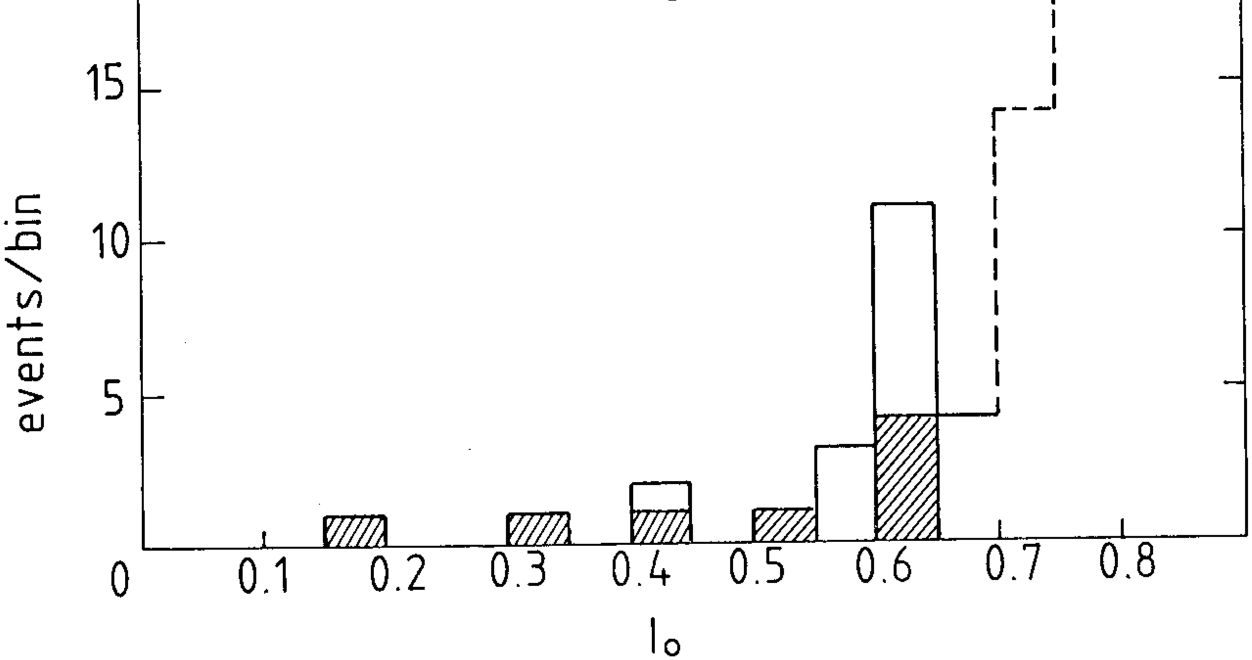
0.5
1.0
1.5
2.0
2.5
3.0
3.5
I₀

Fig. 3a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10
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0.5
0.6
0.7
0.8
I₀

Fig. 3b

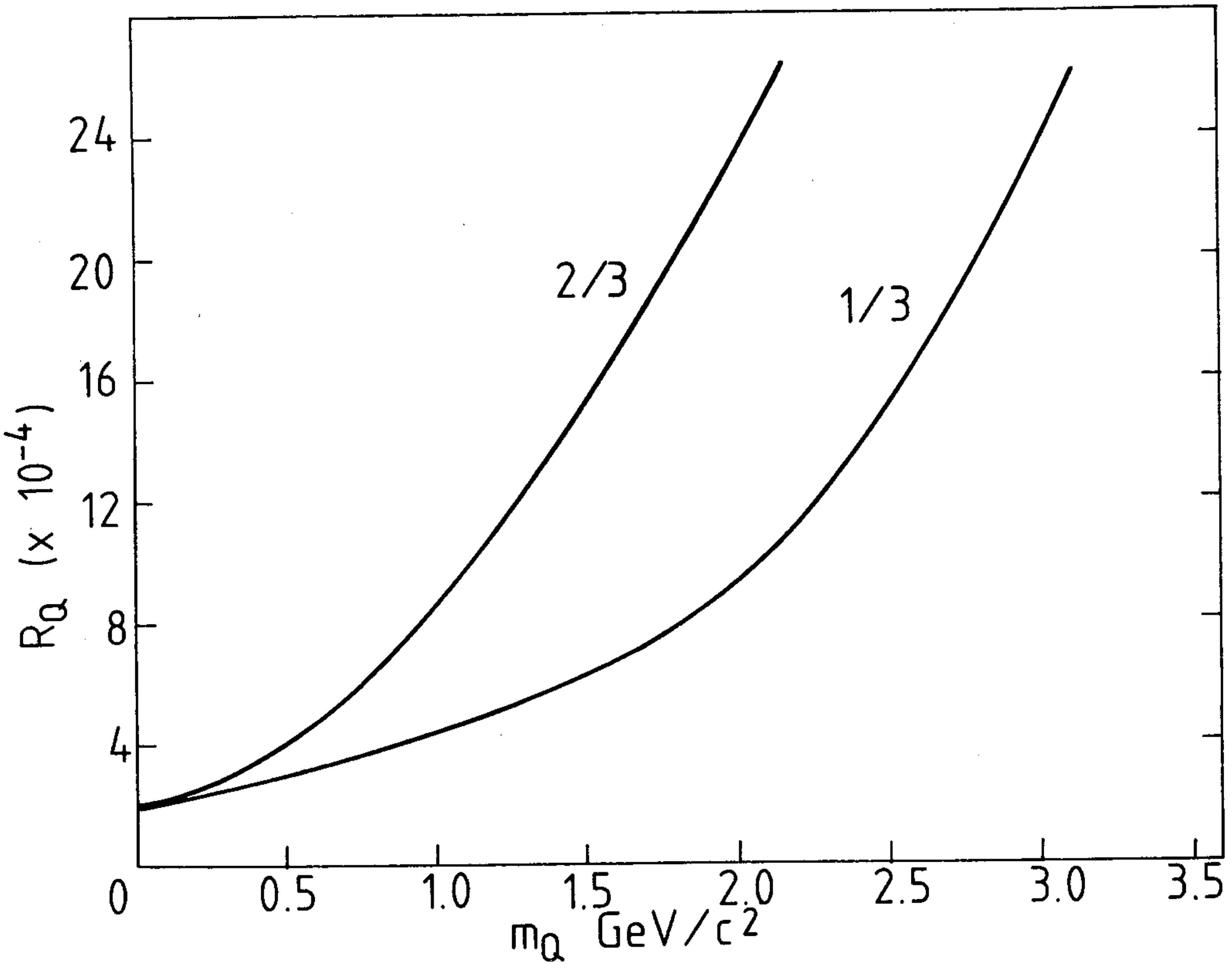

Fig.4