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AN UNSUCCESSFUL SEARCH FOR FRACTIONALLY CHARGED PARTICLES WITH MASS $\lesssim$ 2.2 GeV

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Recent theoretical work$^{(1,2)}$ has suggested the existence of particles with charge 1/3 and 2/3 of the electron charge. Motivated by this suggestion, we have searched unsuccessfully for negative particles with charge $0.2 \lesssim q/e \lesssim 0.7$, mass $\lesssim$ 2.2 GeV and lifetime $\gtrsim 10^{-7}$ sec produced in pairs by 21 GeV/c proton-copper collisions. As is shown in Table I, our negative results indicate that such particles, if they exist, are produced considerably less frequently than the strongly interacting particles; for example, particles with $q = 1/3$ e are produced less than $\sim 10^{-6}$ times as frequently as antiprotons of the same laboratory momentum (5.3 GeV/c).

Gell-Mann$^{(1)}$ and Zweig$^{(2)}$ each consider a unitary triplet for fractionally charged particles as the underlying components of the more familiar particles. The properties of Zweig's aces are shown in Table II. Gell-Mann's quarks also have the properties of the first half of the Table II, but are not specifically assigned those of the second half of the table. The aces are much like the p, n and Λ except that they have baryon number 1/3 and are fractionally charged. Since the aces have coupling at least as strong as that of the strongly interacting particles, we should have seen p_o's and n_o's produced abundantly if they existed with mass $\lesssim$ 2.2 MeV and the lifetimes quoted in Table II.

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In this experiment we have used the method proposed by Morrison and reported by him in the previous paper(3), but our experiment is roughly two orders of magnitude more sensitive than his. An unsuccessful search for fractionally charged particles has also been made among the ~ 300 events attributed to neutrino interactions in the CERN heavy liquid bubble chamber(4). No tracks of bubble density substantially less than that of δ and γ ray electrons in the same photo were observed.

We have looked unsuccessfully for beam tracks with bubble density substantially less than minimum in $\sim 100{,}000$ photos taken at the CERN PS with the Ecole Polytechnique heavy liquid bubble chamber(5). The chamber was placed in an unseparated negative beam(6)(mainly π^-'s) of 16 GeV/c which was produced (from a copper target) at 77 mrad from the direction of the 21 GeV/c internal proton beam.

The $1 \times 1/2 \times 1/2$ m^3 bubble chamber, in a magnetic field of 2.2 Web/m^2, was filled with C_2F_5Cl and was operated under conditions giving ~ 15 bubbles per cm along minimum ionizing tracks. The apparent diameter of the bubbles was ~ 0.3 mm when projected with magnification one. The number of bubbles per cm should be roughly porportional to the number of δ rays with energy in the KeV range which are produced per cm along the track(7), and thus to the square of the charge of the producing particle(8), (for $\beta \approx 1$).

To obtain the flux of fractionally charged particles in the laboratory per interacting proton, we use the formula

$$\frac{d^2N}{d\Omega dp} = \frac{n_q/n_p}{\Delta\Omega\Delta p} \qquad (1)$$

where n_q = the number of fractionally charged particles per machine pulse; $\Delta\Omega$ = the solid angle accepted by the beam transport system = 1.2×10^{-5} steradians; Δp = momentum acceptance of the beam = ± 1 o/o p; and n_p = the number of protons interacting in the target per machine pulse = 2×10^{10}. To compute the last number we have assumed a target efficiency of 12 o/o, estimated by comparing the π^- flux in our beam (tuned to 8 GeV/c) with accepted fluxes(9); this estimate could be in error by a factor of two, and is the dominant uncertainty in our results.

With 90 o/o confidence (taking into account both statistical and systematic uncertainties) the above numbers indicate a flux of $q = 1/3$ e particles (which would thus have a lab momentum of 5.3 GeV/c, $\Delta p = 0.1$ GeV/c):

$$\frac{d^2N}{d\Omega dp} \lesssim 1.4 \times 10^{-9} \,/\, (\text{Ster. GeV/c}) \qquad (2)$$

where we have assumed a scanning efficiency of 70 o/o and lifetime $\gtrsim 10^{-7}$ sec. For q = 2/3 e particles ($p = 10.7$ GeV/c, $\Delta p = 0.2$ GeV/c):

$$\frac{d^2N}{d\Omega dp} \lesssim 0.7 \times 10^{-9} \ / \ (\text{Ster. GeV/c}) \qquad (3)$$

These fluxes are compared with the π^- and $\bar{p}$ fluxes in Table I.

Using $\sigma_T(pp) = 40$ mb, the value given above for $\frac{d^2N}{d\Omega dp}$ implies a centre of mass differential cross section upper limit of

$$\frac{d^2\sigma}{d\Omega' dp'} \lesssim 2 \times 10^{-36} \ \text{cm}^2 \ / \ (\text{Ster. GeV/c}) \qquad (4a)$$

for production of particles with q = 1/3 e and mass $M \gtrsim 1.2$ GeV and

$$\frac{d^2\sigma}{d\Omega' dp'} \lesssim 3 \times 10^{-36} \ \text{cm}^2 \ / \ (\text{Ster. GeV/c}) \qquad (4b)$$

for q = 2/3 e. These limits for the cross section are shown in Fig. 1 as a function of M; the variation with M is caused by the dependance on M of the Jacobian

$$\frac{d\Omega dp}{d\Omega' dp'} = \frac{p'\beta'}{p\ \beta} \qquad (5)$$

For short lifetime, the limits given above must, of course, be divided by the decay factor
$f = \exp\left(-\frac{2 \times 10^{-8}}{\tau} \frac{M}{q}\right)$ where τ = the particle lifetime in seconds; M = its mass in GeV; and q = its charge in units of the electron charge. Thus, for example, only about one q = 1/3 e particle in 10^5 would survive during the 94 meter flight to the chamber if M = 2 GeV and $\tau = 10^{-8}$ sec, in which case our upper limit on the differential cross section would become 2×10^{-31} cm^2 / (Ster. GeV/c).

The kinematic limit of the q = 1/3 e particle mass is ~ 2.2 GeV if they are produced in pairs from a stationary nucleon, and ~ 2.6 GeV if produced in a head - on collision with a nucleon having Fermi momentum of 0.26 GeV/c. One might expect to see strongly interacting particles produced by those few collisions with favorable Fermi momentum, even for masses as high as ~ 2.5 GeV. Making a crude estimate of the fraction of the collisions with Fermi momentum of the target nucleon such that a q = 1/3 e particle with mass 2.5 GeV could be produced and accepted by the beam gives

$$\frac{d^2\sigma}{d\Omega' dp'} \lesssim 3 \times 10^{-35} \ \text{cm}^2 \ / \ (\text{Ster. GeV/c}) \qquad (6)$$

Note, however, that final state annihilation of ace-antiace pairs (into π's etc.) should reduce their probability of coming out from the production region, especially for small relative momentum. But if their annihilation probability depends on relative momentum similarly to that for proton-antiproton,(10) the ace-antiace production cross section would be reduced by less than an order of magnitude for ace masses $\lesssim 2.1$ GeV.

The center of mass momentum and angle for particles in our beam with $q/e = 1/3$ and $2/3$ are shown in Fig. 2 as a function of mass for production from stationary target nuclei. For increasing mass the $e/3$ particles would be emitted more and more backwards in the center of mass system, θ' passing through 90° for $M_q = 1.51$ MeV. The $2e/3$ particles would be emitted somewhat forward, for all masses up to the kinematic limit.

To obtain a rough estimate of the upper limit on the <u>total</u> cross section for ace-antiace production we have made the following assumptions:

1) isotropic angular distribution in the center of mass system; and
2) a four body phase space momentum distribution.

The result of these assumptions is shown as a function of mass in Fig. 3, again for the 90 o/o confidence limit for particles with $q/e = 1/3$ and $2/3$. For $q/e = 1/3$ and $1.3 \lesssim M \lesssim 2.1$ the result is

$$\sigma_T \lesssim 4 \times 10^{-35} \text{ cm}^2, \qquad (7)$$

and for $q/e = 2/3$, $1.0 \lesssim M \lesssim 1.9$ GeV

$$\sigma_T \lesssim 7 \times 10^{-35} \text{ cm}^2. \qquad (8)$$

Alternately, following Morrison(3), we could assume fractionally charged particles are produced with transverse momentum distributed similarly to that of other heavy particles. Total cross sections estimated in this way are approximately the same as those above.

We conclude that if particles of charge $0.2 \lesssim q/e \lesssim 0.7$ exist, and would be pair produced in proton-copper collisions with cross sections similar to those of other strongly interacting particles (e.g. $\bar{p}$'s), then they must have mass above ~ 2.2 GeV, or lifetime less than $\sim 10^{-7}$ sec.

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TABLE I.

Upper limits (90 o/o confidence) on the laboratory fluxes of particles with $q = 1/3$ e and $2/3$ e, mass $\lesssim 2.2$ GeV, and lifetime $\gtrsim 10^{-7}$ sec. compared with the π^- and $\bar{p}$ fluxes(9) of the same laboratory angle and momentum.

Charge	1/3	2/3
Laboratory Momentum	5.3 GeV/c	10.7 GeV/c
Laboratory Angle	4.4°	4.4°
(Fractionally chgd.flux)/(π^- flux)	$\lesssim 5 \times 10^{-9}$	$\lesssim 4 \times 10^{-8}$
(Fractionally chgd.flux)/($\bar{p}$ flux)	$\lesssim 1 \times 10^{-6}$	$\lesssim 5 \times 10^{-5}$

TABLE II

Summary of the properties of the quarks(1)(first six properties only) and aces(2) : the isotropic spin and its z projection, baryon number, strangeness, charge, spin, parity, mass, mass difference, lifetime, and coupling strength.

Nomemclature quark	ace	I	I_z	B	S	Q	J	P	M (MeV)	ΔM (MeV)		coupling
u	p_o	1/2	1/2	1/3	0	2/3	1/2	+	>400	~ 2	stable	of the order of strong interactions or greater
d	n_o	1/2	-1/2	1/3	0	-1/3	1/2	+	>400	~ 150	~minutes	
s	Λ_o	0	0	1/3	-1	-1/3	1/2	+	>560		$\sim 10^{-10}$ sec	

FIGURE CAPTIONS

Fig. 1 The upper limit (90 o/o confidence) of the center of mass differential cross section as a function of the mass of $q = 1/3$ e and $2/3$ e particles; the target nucleon has been assumed at rest.

Fig. 2 The center of mass momentum and angle of $q = 1/3$ e and $2/3$ e particles, A, which would be seen in the bubble chamber; the target nucleon has been assumed to be at rest.

Fig. 3 The upper limit (90 o/o confidence) of total cross section for the production of $q = 1/3$ e and $2/3$ e particles based on assumptions discussed in the text and including a rough estimate of the effects of Fermi motion of the target nucleon.

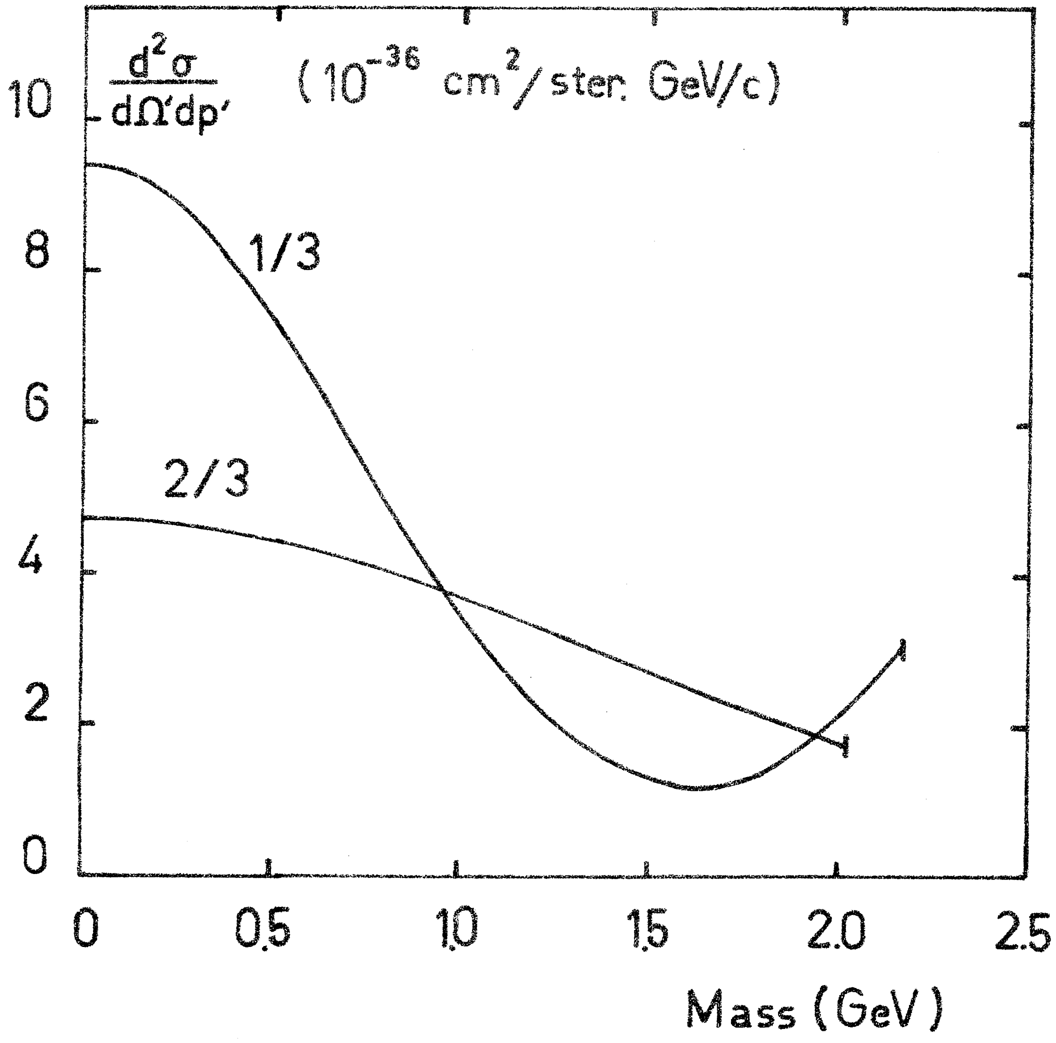
$\frac{d^2\sigma}{d\Omega' dp'}$ $(10^{-36}$ cm^2/ster. GeV/c)
10
8
6
4
2
0
1/3
2/3
0
0.5
1.0
1.5
2.0
2.5
Mass (GeV)

Fig. 1

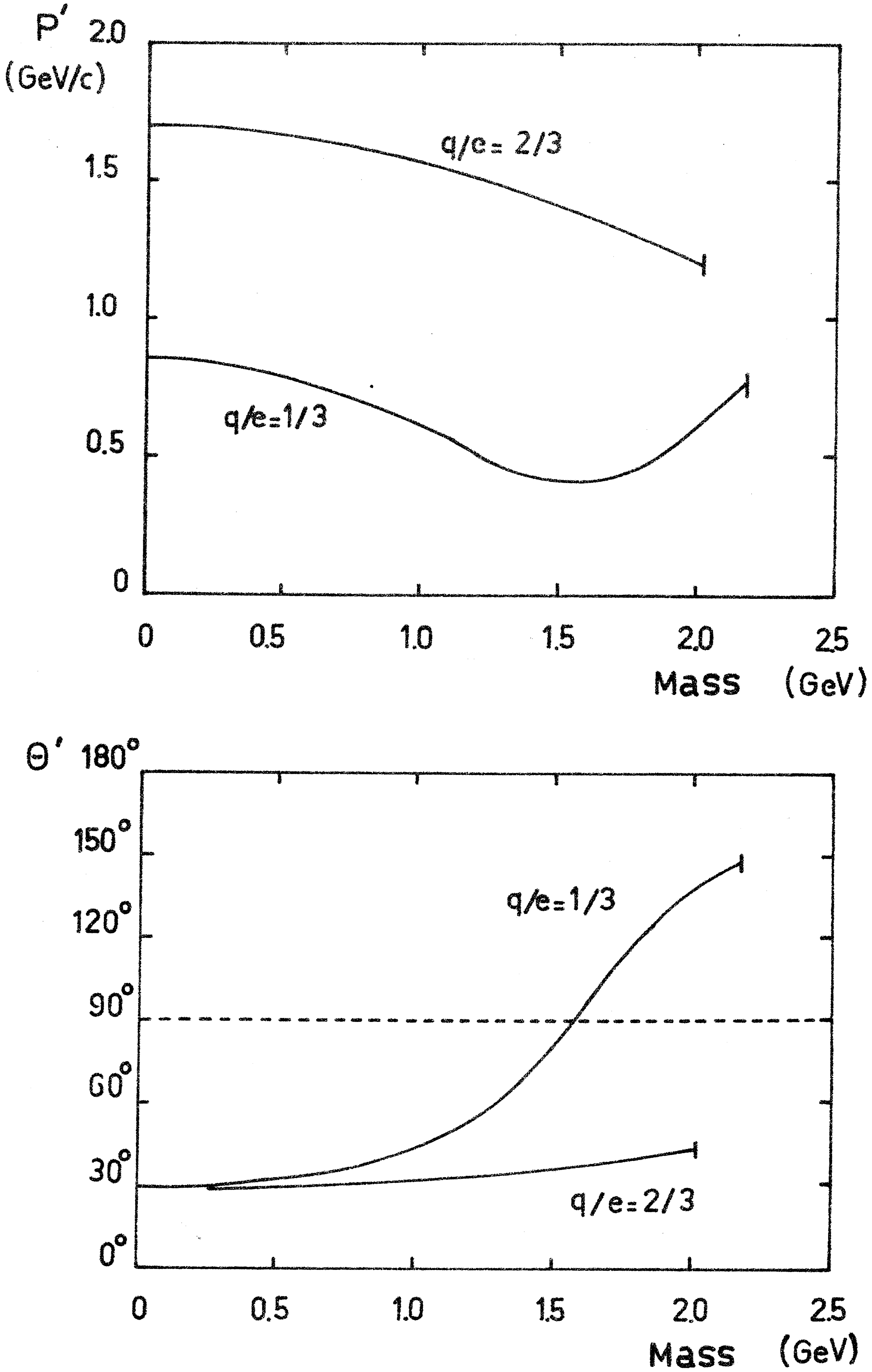
P′
(GeV/c)
2.0
1.5
1.0
0.5
0
q/e= 2/3
q/e=1/3
0
0.5
1.0
1.5
2.0
2.5
Mass
(GeV)
Θ′
180°
150°
120°
90°
60°
30°
0°
q/e=1/3
q/e=2/3
0
0.5
1.0
1.5
2.0
2.5
Mass
(GeV)

Fig. 2

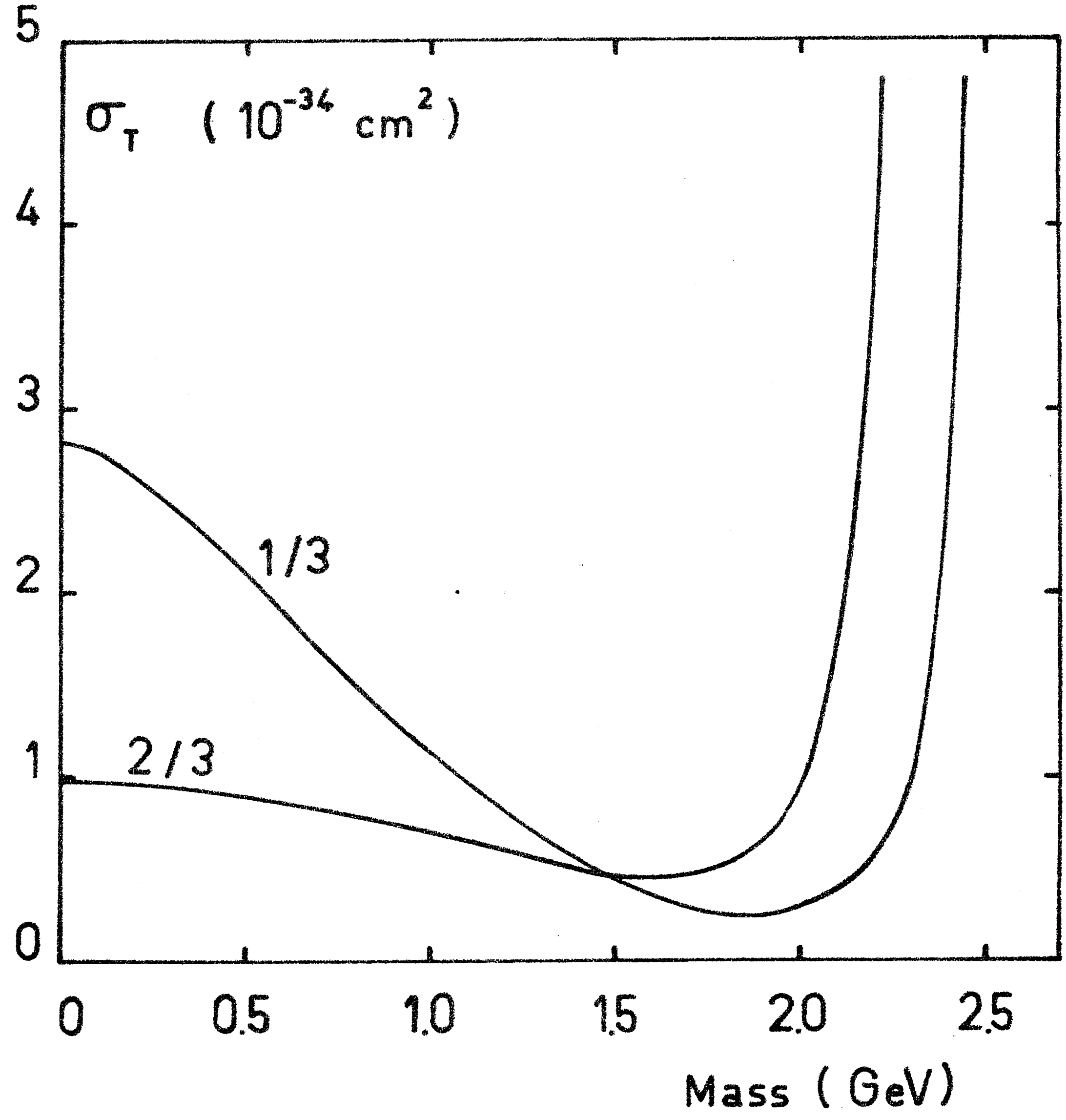

Fig. 3