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SEARCH FOR FRACTIONAL CHARGE AND HEAVY STABLE PARTICLES AT PETRA

JADE - Collaboration

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Abstract

A search has been made for new particles with charge Q = 2/3, 1, 4/3, 5/3 produced in e^+e^- - reactions at PETRA. The energy range was E_{cm} = 27 - 35 GeV. No such particles were found.

Upper limits for the cross-section depending on the assumed mass and production spectrum are given. For Q = 2/3 quarks with mass less than 12 GeV/c^2, upper limits $\sigma(q\bar{q})/\sigma(\mu\mu) \leq 10^{-2}$ (90% C.L.) are obtained both for inclusive and exclusive production. For the lifetime of the B-meson (m_B = 5 GeV/c^2) an upper limit $\tau \leq 2 \times 10^{-9}$ s is obtained.

Introduction

In this paper we report on the search for free quarks and longlived heavy particles in e^+e^- annihilations at PETRA in the center of mass energy range from 27 to 35 GeV. Electromagnetic interactions have been largely ignored in the search for free quarks. The last such search was reported a decade ago [1], and in that experiment, a mass limit of 1.5 GeV/c^2 was obtained from photoproduction of quarks by 12 GeV/c electrons on Cu, assuming a generalized Bethe-Heitler production cross-section.

A search for free particles with charge $Q = 1/3$ or $2/3$ is of general interest. Furthermore, it seems worth-while to look for heavy particles with charge $Q = 4/3, 5/3$ ...... as well: De Rujula et al.[2] studied a version of QCD with unconfined, fractionally charged quarks of large mass (~ 10 GeV/c^2) and large size. In this model the quark-nucleon cross-section is large causing quarks to absorb nucleons in their passage through matter. As a consequence quarks may exist in quark-nucleon complexes with large nonintegral charge and baryon number as is suggested by the experiment of La Rue et al. [3].

Quarks may be produced either exclusively ($e^+e^- \to q\bar{q}$, collinear two-prong events) or inclusively (together with ordinary hadrons inside a jet of particles.) We have searched in both types of reactions. For reasons explained in the next section the results published here concern only $2/3 \leq Q \leq 5/3$ particles. Work on other charge states is in progress.

There also have been speculations about the existence of longlived heavy particles with integral charge. In the gauge theory of Pati and Salam [4] quarks are integrally charged and decay into leptons with lifetimes ranging from 10^{-13} to 10^{-5} s depending on the quark's colour. In addition the possibility has been considered [5] that hadrons containing new quarks (e.g. the bottom meson B) might be rather longlived due to the smallness of mixing between new and old quarks. Also in recent cosmic ray experiments,

indications for a relatively longlived particle with $m > 5$ GeV/c^2 have been reported [6]. If such particles were produced in e^+e^- reactions at about 30 GeV they could be detected in this experiment.

Particle Identification

In the JADE-experiment [7] particles are identified by a simultaneous measurement of the mean energy loss dE/dx, and the "apparent momentum", p/Q. Both quantities are obtained in the JADE-jet chamber [8], a cylindrical drift chamber surrounding the interaction point. The chamber is filled with an argon/methane/isobutane mixture at a pressure of 4 atm and is operated in an axial magnetic field of 4.5 kG.

In the range of polar angle $34^0 < \theta < 146^0$ (with respect to the direction of the e^+e^- beams) 48 points are measured along a track from the interaction point. Outside this angular range a reduced number of points is recorded. At each point, spatial coordinates (r, ϕ, z) as well as the energy loss, ΔE, are obtained. The coordinates r and ϕ are given by the wire position and by the drift-time measurement. z and ΔE are obtained from the signal amplitudes measured at both ends of the wire.

The electronics used for the signal processing has been described elsewhere [9]. Here the following points are relevant. The larger one of the signals derived at both ends of the wire triggers a discriminator circuit giving the timing signal. Furthermore, both amplitudes are integrated during a time equal to the width of the discriminator output pulse. This width (plus a deadtime of 20 ns) determines the double track resolution of the system; set to 140 ns drift-time difference corresponding to 7 mm in space. If two signals arrive within the double track resolution, the timing of the first is properly recorded while the amplitude measurement contains contributions from both tracks. For tracks separated by more than the double track resolution, there is only little interference between the amplitudes.

Fig. 1 shows the (r,ϕ)-view of the hit pattern of a typical jet from e^+e^--annihilation. The tracks reconstructed by the pattern recognition program

[10] are also indicated. On some tracks hits are missing. This is an effect of the finite double track resolution (note that tracks occuring on different sides of the wire planes may give similar drift-times and may, therefore, obscure each other).

The lowest recorded pulse height is determined by the discriminator threshold, which corresponds to 1/7 of the most probable energy loss of a minimum ionizing particle with charge $Q = 1$, emitted at $\theta = 90^0$ from the interaction point. Fast particles with $Q = 1/3$ will give hits with a probability of about 60% and the present pattern recognition program has low efficiency for such tracks. Therefore the results reported here concern only $Q \geq 2/3$ particles. On the other hand heavily ionizing particles may saturate the electronics. The dynamic range extends up to 35 times the most probable amplitude for a minimum ionizing $Q = 1$ particle emitted at $\theta = 90^0$. Because of the Landau fluctuations of the individual samplings and an increase in pulseheight for inclined tracks, an unbiased amplitude measurement is only possible up to 7 times the most probable ionization of a $Q = 1$ minimum ionizing particle. Particles with ionization exceeding this limit require special considerations and are not included in the present evaluation.

To obtain a reliable estimate of the mean energy loss, in the presence of Landau fluctuations, the 60% lowest pulse heights are averaged and used for particle identification (method of truncated mean). Before averaging, each sampling is corrected for the path length of the track in the drift space, for individual electronic- and gas-gain factors, for saturation effects of the gas amplification and for electron attachment in long drift paths. The magnitude of these corrections can be found in ref. [8].

Using pattern recognition results, it is found that some samplings contain signals from two partially unresolved tracks. Such samplings are rejected. In order to maintain a reasonable efficiency for particle identification in jet-like events, the minimum number of useful samplings per track has been fixed at 25. This limit ensures both a momentum-independent efficiency of about 65% (Fig. 2) and, within a jet, a dE/dx resolution of 22% FWHM (for low multiplicity events, e.g. for electrons

from Bhabha-scattering, the resolution is 14% FWHM).

Exclusive Production

The exclusive production of quark-antiquark pairs leads to two nearly collinear tracks. We trigger on such events by a twofold coincidence in the scintillation counter hodoscope surrounding the track detector (see Fig. 1) requiring the two counters to be azimuthally separated by $180^0 \pm 30^0$. Furthermore, two tracks in the jet chamber have to be recognized by a hardwired track-finding logic [11]. This trigger is fully efficient for $Q \geq 2/3$.

Events are selected off line by demanding two tracks, originating from the interaction point, which are collinear to within 10 degrees in space. In this event sample containing mainly Bhabha and $\mu^+\mu^-$ events, $q\bar{q}$ candidates are searched for by plotting the mean energy loss of track 1 vs. mean energy loss of track 2. The lead glass array [12] surrounding the track-chamber is used to distinguish "showering tracks" (mostly Bhabha events, Fig. 3a) from "non showering tracks" (mostly $\mu^+\mu^-$ pairs, Fig. 3b). The first sample includes some events in which a shower is also produced in the beam pipe or in the inner pipe of the pressure vessel, leading to several tracks in the jet chamber. In such events, all possible combinations of two tracks have been used as entries in the scatterplot. In both samples no events are seen corresponding to $Q = 2/3$ particles.

Inclusive Production

The trigger and the selection criteria for multi-hadron events from e^+e^- annihilation have been described elsewhere [7]. The topology of these events is essentially a clear two-jet-structure, modified by the effect of gluon bremsstrahlung [12]. The same selection criteria are used except the cuts for the visible energy and momentum balance described in ref. [7]. These cuts were omitted since they could possibly eliminate quarks reacting in the beam pipe [2].

In a sample of 1668 multihadron events recorded in the center of mass energy interval 27-35 GeV, 8500 tracks with more than 25 useful samplings were analysed. Fig. 4 shows the observed energy loss versus the apparent momentum. The absolute energy loss was calibrated with Bhabha electrons. Also shown in Fig. 4 are the lines expected for the known stable particles e, π, K, p, d, t (solid lines) and a hypothetical particle with a mass of 5 GeV/c^2 and charge 2/3 and 1 (dotted lines). The high number of protons in Fig. 4 is due to pions reacting in the beam pipe or pressure vessel (together 1.1 cm of aluminium). On the average one proton is seen per event. Considerably less antiprotons are produced as can be seen from the distribution for negatively charged particles (Fig. 5).(Particles with higher apparent momentum than beam momentum are accounted for by the momentum resolution of $\sigma_p/p = 0.035$ p.)

Out of the 8500 tracks shown in Fig. 4, 65 tracks are found with values for dE/dx and momentum deviating by more than 2.5 standard deviations from the known stable particles π, K, P, e (Fig. 6). All of these, however, can be explained by ordinary particles:
14 candidates fit the hypothesis of positively charged deuterons or tritons. Such particles are only expected from secondary interactions in the beam pipe or in the pressure vessel. A visual check confirms this origin. The occurrence of deuterons and tritons in the proportion seen here has also been observed in proton and pion induced nuclear reactions [14].

Particles emitted with very small azimuthal separation $\Delta\phi$ and having similar curvature appear in the pattern recognition as a single track with an ionization almost twice that of a Q = 1 particle. The probability for a complete overlap of two tracks has been determined in the following way: In Fig. 7, the distribution of the angle between any two tracks within the same jet is plotted for same-charge-tracks and opposite-charge-tracks, respectively. The distribution for same-charge-tracks has a depletion for $\Delta\phi < 15$ mrad attributed to the complete overlap of two tracks. This loss is estimated to be 17 tracks out of 8500. These overlapping tracks appear in Fig. 6 as entries with dE/dx < 2 times that for one high momentum track. Finally, the tails of the dE/dx distribution of π, K, P, e are estimated to be 25 ± 10 events, which account for the remaining events in Fig. 6.

Furthermore we note that all entries in Fig. 6 come from different events. Free quarks would be produced in pairs and both of these should be identified in 10 - 30% of the cases, depending on the quark mass. Therefore, there is no evidence for any tracks with abnormal ionization.

Upper Limit Calculation

Since all entries in figure 6 can be explained by ordinary particles we reduce the background by the following cuts: As candidates for tracks with unusual energy loss we consider only those tracks with an ionisation different from that of π, K, P and e by more than 3.0 standard deviations. In addition, for tracks with more than minimum ionisation we require the energy loss to be at least 17 keV/cm to get rid of background due to overlapping tracks. Although the standard deviation is computed for the individual tracks these cuts can be represented by the dotted lines in Fig. 6.

The detection of a hypothetical particle of mass M and charge Q is then possible only in a certian domain D in the dE/dx - p scatter plot. This domain D is defined by the 2.5 standard deviation contours (dE/dx and p) to both sides of the energy-loss curve of the hypothetical quark and the fact that here ionisation only up to seven times that of a minimum ionizing particle is considered. A typical domain is illustrated in figure 6.

Assuming quarks to be produced in pairs, the number of produced quark tracks is given by

$$2\, L \int_{\Delta p} \frac{d\sigma}{dp}\, dp, \text{ where L is the integrated luminosity.}$$

The range of integration Δp is that covered by the energy-loss curve of the quark in the domain D. Δp as a function of M and Q is given in table 1.

For the extrapolation to the complete momentum range the following momentum distributions are used:

$$E \frac{d^3\sigma}{dp^3} = \sigma_{q\bar{q}} \cdot f_i(p), \quad i = 1,2 \qquad (1)$$

where $f_1(p) \sim \exp(-3.5\,E)$ is the normalized distribution observed for pions, kaons and protons in e^+e^- interactions [15]. As an extreme momentum distribution we alternatively consider $f_2(p) \sim$ const [16].

We determine upper limits on $\sigma_{q\bar{q}}$ using Poisson statistics [17]. Since there are no quark candidates in the domain D, 90% confidence level upper limits are then obtained from

$$2(\Omega/4\pi)L\int 4\pi(p^2/E)\ \sigma_{q\bar{q}}\ f_i(p)\ \ \varepsilon\ dp = 2.3 \qquad (2)$$

Here Ω is the solid angle in which particle identification is possible and ε is the probability that a track with more than 25 ionization samplings (Fig. 2) is found.

This procedure fails for masses around the deuteron mass. For $Q \leq 1$ and masses below 4 GeV/c^2 therefore only tracks which originate from the main event vertex are considered and secondary interactions in the beam pipe or pressure vessel are excluded. For quarks with Q = 4/3 and 5/3, however, interacting tracks are kept since such quarks are expected to come from interactions [2]. In this case the mass range is limited to M > 3 GeV/c^2.

We quote our results in terms of the muon-pair cross-section $\sigma_{\mu\mu} = 4\pi\alpha^2/3s$ and define the quantity R^Q

$$R^Q_{excl} = \sigma\,(e^+e^- \to q\bar{q})/\sigma_{\mu\mu}$$

$$R^Q_{incl} = \sigma(e^+e^- \to q\bar{q} + \text{anything})/\sigma_{\mu\mu} \qquad (3)$$

Upper limits on R^Q are then deduced using equations (2) and (3). Since the data are from runs at different center-of-mass energies $\sqrt{s}$ (see table 2), the quoted value of R^Q corresponds to the average weighted by the factor $L_s\ \sigma_{\mu\mu}(s)$.

The results for R^Q for Q = 2/3 as a function of M for both the exclusive and inclusive case are given in figure 8. Also given, for comparison, is the curve for $Q^2\sigma_{point}/\sigma_{\mu\mu}$ where $\sigma_{point} = 2\pi\alpha^2\beta(3-\beta^2)/3s$ and β is the velocity the quarks would have if they were produced exclusively. This is the curve corresponding to the electromagnetic production of pointlike spin 1/2 particles with Q = 2/3.

Comparing our results with previous limits [20] on the production of $q\bar{q}$ pairs in hadronic interactions via intermediate, virtual photons (Drell-Yan process) we find that for M = 10 GeV/c^2, our limits are better by five orders of magnitude.

In Figs. 9, 10 and 11, we also give upper limits on R^Q for Q = 1 e.g. for Pati-Salam quarks [4], as well as for Q = 4/3 and Q = 5/3.

The present experiment is insensitive to quarks absorbed in the beam pipe or the inner wall of the pressure vessel (3g/cm^2 aluminium in total). We note that even with the large cross-section estimated in ref. [2] an interaction length of the order of 10g/cm^2 is obtained.

Lifetime of Bottom Meson B

To obtain an upper limit on the lifetime τ of the B-meson (Q = 1) we assume a $B\bar{B}$ - pair-production cross section of $\sigma_{B\bar{B}} = 3/9 \cdot \sigma_{\mu\mu}$.
Having observed no B-tracks the 90% C.L. upper limit on τ is calculated from the equation

$$\left(\frac{\Omega}{4\pi}\ \ 3/9\ \sigma_{\mu\mu}\ L\right)\ 2 \int_{\Delta p} \exp(-dM/p\tau)\ 4\pi p^2/E\ f_i(p)\ \varepsilon\ dp = 2.3 \qquad (5)$$

d is the average path length in the detector for a track of at least 25 hits and was determined to be 80 cm. Again two momentum distributions were used:

$f_1(p) \sim \exp(-3.5E)$ as observed for hadrons [15] as well as $(E/4\pi p^2)\, f_2(p) \sim$ const as suggested by ref. [18].

In Fig. 12 we give the 90% C.L. limits on the B-lifetime as a function of B-mass.

Conclusions

No evidence has been found for new longlived Q = 2/3, 1, 4/3, 5/3 particles produced in e^+e^- reactions (E_{cm} = 27-35 GeV).

The cross section ratio R^Q (quark production cross section/$\sigma_{\mu\mu}$) both for pair-production, $e^+e^- \rightarrow q\bar{q}$ and for inclusive production is less than $\sim 10^{-2}$. In the latter case the limit applies to quarks either within or outside a jet of hadrons. The limits for the cross-section ratios for Q = 1, 4/3, 5/3 lie between 10^{-1} to 10^{-2} depending on the mass and the momentum spectrum assumed at production.

Assuming 5 GeV/c^2 for the mass of the B meson an upper limit on the lifetime of 2×10^{-9} s is obtained, which is a factor 25 less than the previous limit [19].

The sensitivity of the experiment is essentially limited by the statistics available and not by the experimental double track and dE/dx resolution. (In an ideal experiment with the same integrated luminosity the sensitivity would be higher only by a factor of about two).
A search for Q = 1/3 and Q ≥ 2 particles is in progress.

We acknowledge the efforts of the PETRA machine group, who provide us with the opportunity of doing this experiment, and also the efforts of the technical support groups of the participating institutes in the construction and maintenance of our apparatus. This experiment was supported by the Bundesministerium für Forschung und Technologie, by the Education Ministry of Japan and by the U.K. Science Research Council through the Rutherford Laboratory. The visiting groups at DESY wish to thank the DESY directorate for their hospitality.

Table 1

$Q = 2/3$	$M \geq 2$ GeV/c^2 $M \leq 2$ GeV/c^2	$0.17 \cdot M < p < 0.4 \cdot M$	$0.87 \cdot M < p < (E_{beam}^2 - M^2)^{1/2}$ $1.10 \cdot M < p < (E_{beam}^2 - M^2)^{1/2}$
$Q = 1$		$0.27 \cdot M < p < 0.6 \cdot M$	
$Q = 4/3$		$0.36 \cdot M < p < 0.75 \cdot M$	
$Q = 5/3$		$0.45 \cdot M < p < (E_{beam}^2 - M^2)^{1/2}$	

Interval Δp for true momentum p as used in upper limit calculation

Table 2

$\sqrt{s}$ [GeV]	27.7	30.0	29.9-31.5	35.0
Luminosity [nb^{-1}]	172	427	1937	788

Summary of Experimental Runs

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Figure Captions

Figure 1: (r,ϕ)-view of the hit pattern of typical tracks within a jet.

Figure 2: Probability $\varepsilon(p)$ of a track with more than 25 useful ionization samplings, as a function of momentum.

Figure 3: Energy loss of collinear two prong events.
dE/dx of track 1 versus that of track 2 for
a) showering and b) non-showering tracks.
The cross indicates the expectation for Q = 2/3 particles and the circle the 2.5 standard deviation contour.

Figure 4: Energy loss of positive and negative tracks in multi-hadron events as a function of apparent momentum p/Q. Also shown are the lines expected for the known stable particles e, π, K, p, d, t (solid lines) and a hypothetical particle with mass M = 5 GeV/c^2 and charge 2/3 and 1 (dotted lines).

Figure 5: Same as figure 4, negative tracks only.

Figure 6: Energy loss versus apparent momentum p/Q for tracks deviating by more than 2.5 standard deviations from the energy - loss - curves of π, K, p and e.
Open triangles: negative tracks,
open squares: positive tracks from e^+e^--interaction point.
full symbols: tracks from secondary interactions.
The dotted lines indicate the cuts used for upper limit calculations. The hatched area is a typical domain D as defined in the text.

Figure 7: Angle $\Delta\phi$ between any two tracks within the same jet for same-charge-tracks (full curve) and opposite-charge-tracks (dotted curve). The number of opposite-charge-tracks has been normalized to the number of same-charge-tracks for $\Delta\phi > 20$ mrad. Note that in general both numbers are different for combinatorial reasons.

Figure 8: 90% confidence upper limits on $R^Q = \sigma_{q\bar{q}}/\sigma_{\mu\mu}$ for the exclusive and inclusive production of quarks with Q = 2/3 as a function of particle mass. The dashed line shows the curve expected for Q = 2/3, spin 1/2 pointlike particle.

Figure 9: 90% confidence limits on R^Q for Q = 1 as a function of mass.

Figure 10: 90% confidence limits on R^Q for Q = 4/3 as a function of mass.

Figure 11: 90% confidence limits on R^Q for Q = 5/3 as a function of mass.

Figure 12: 90% confidence limits on the lifetime of the B-meson as a function of mass.

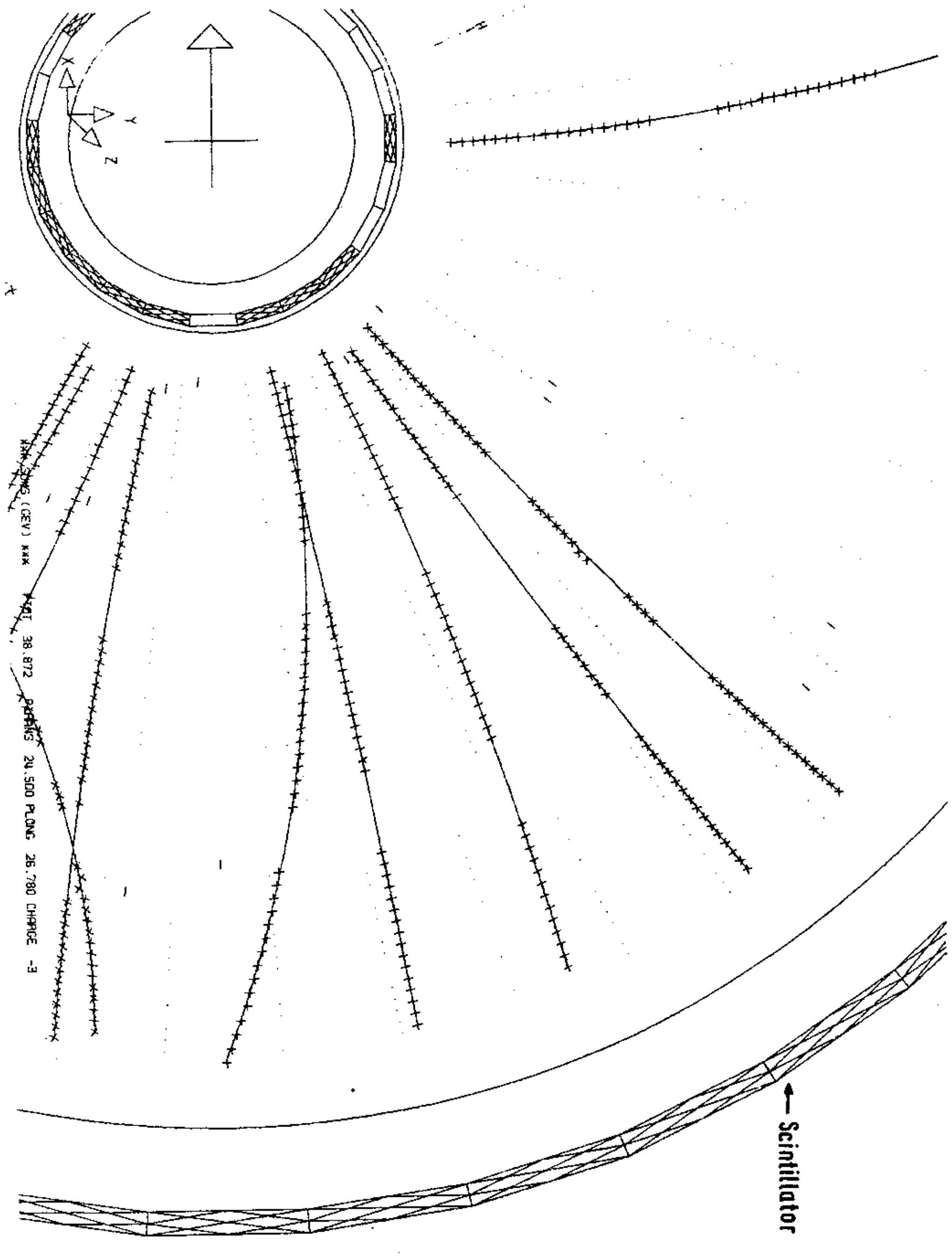


Fig. 1

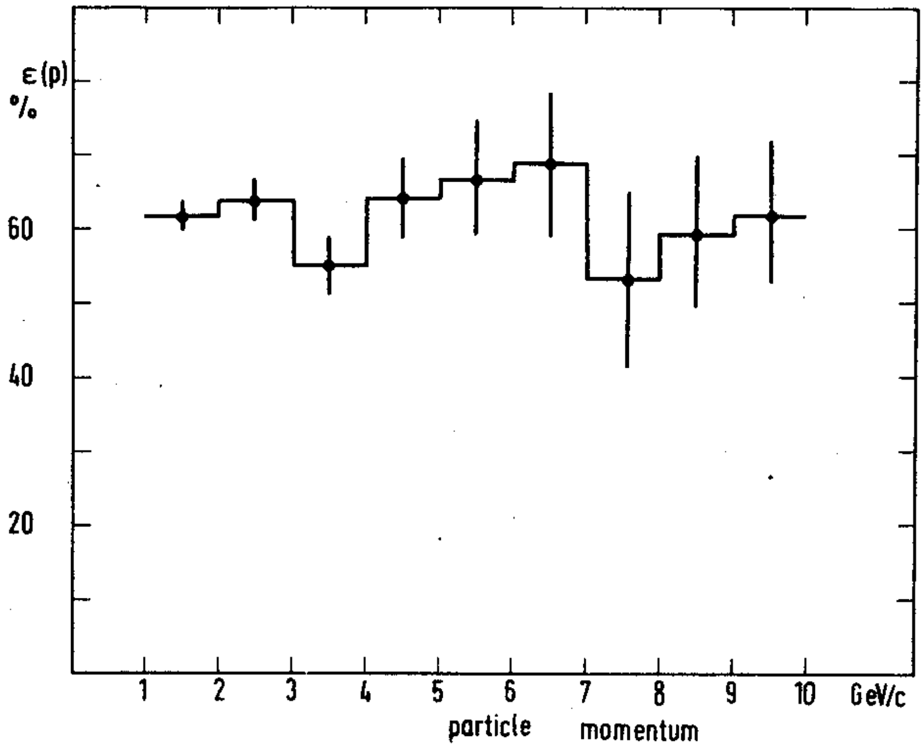


Fig. 2

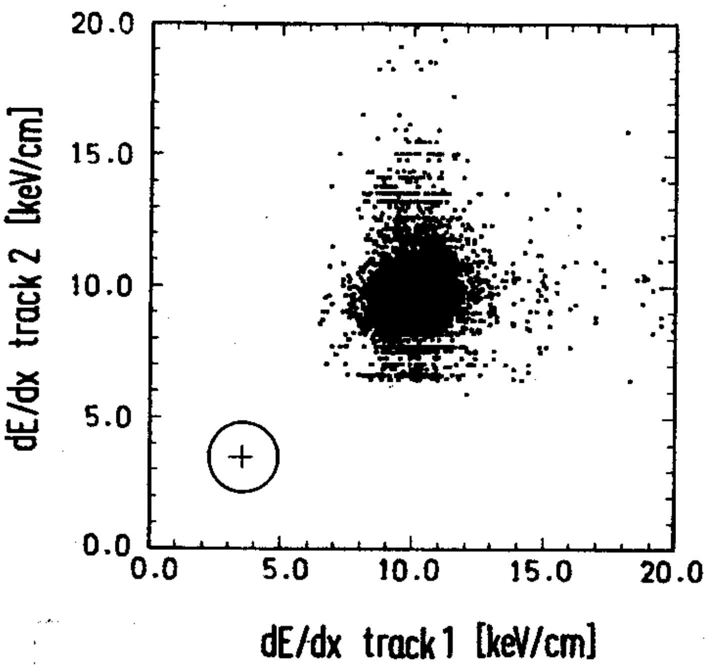


Fig. 3a

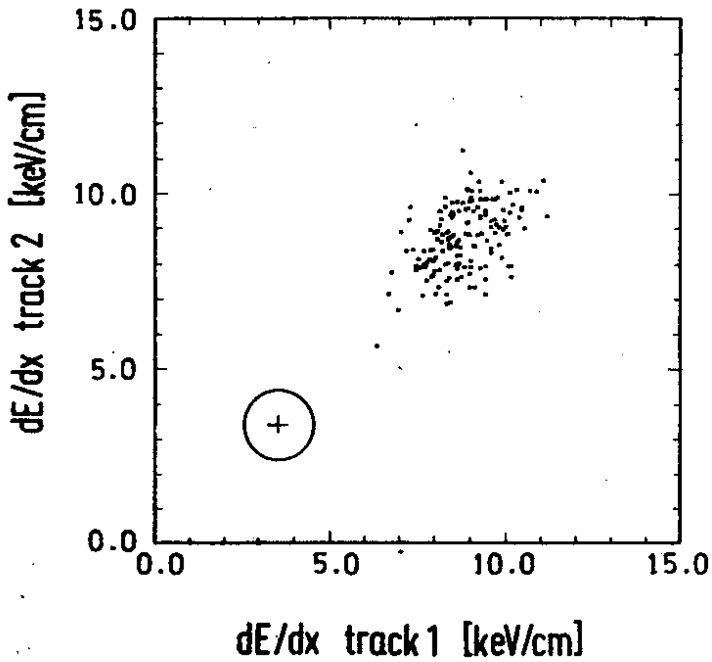
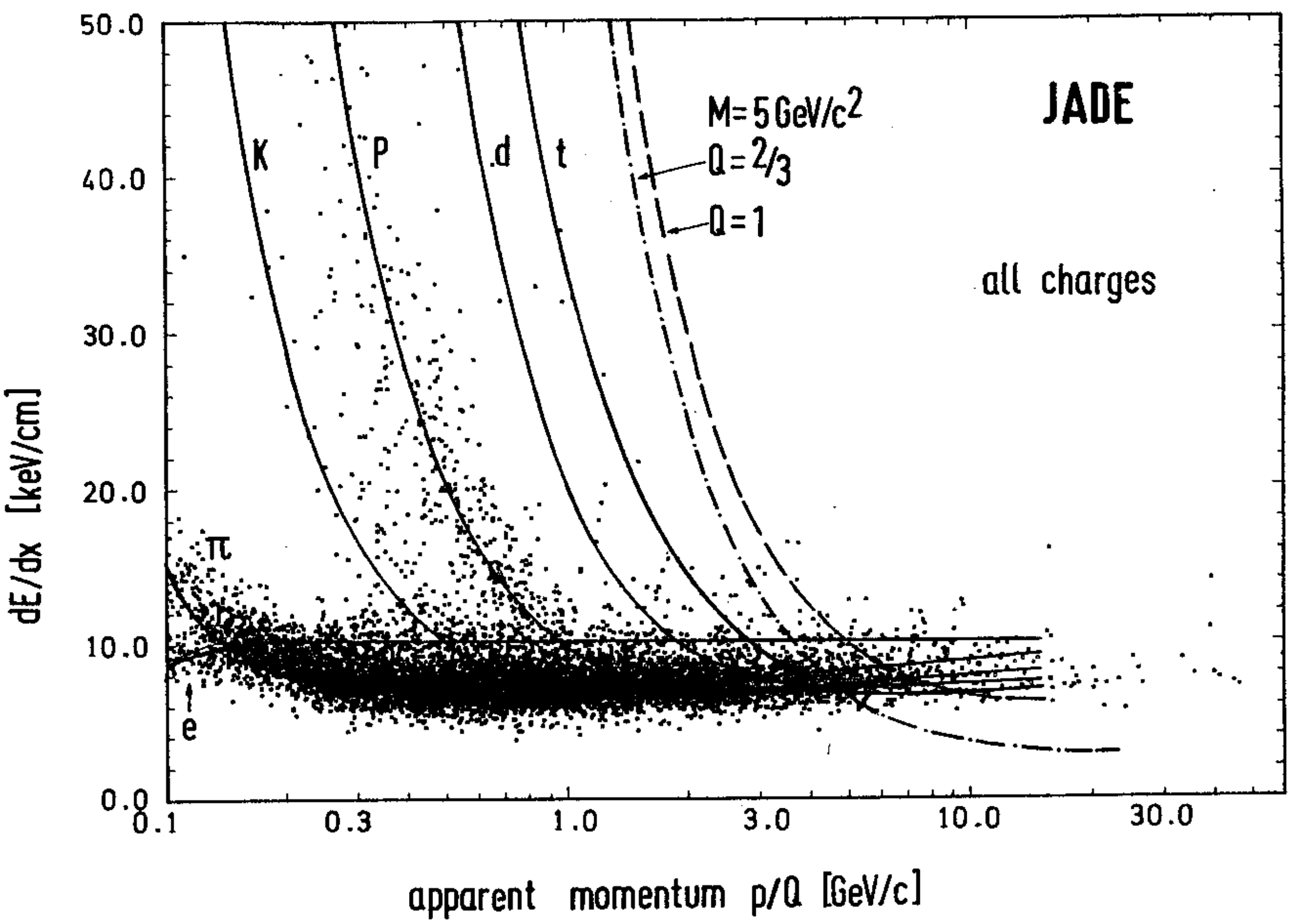


Fig. 3b


JADE
M=5 GeV/c2
Q=2/3
Q=1
all charges
K
P
d
t
π
e
dE/dx [keV/cm]
apparent momentum p/Q [GeV/c]
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3.0
10.0
30.0

Fig. 4

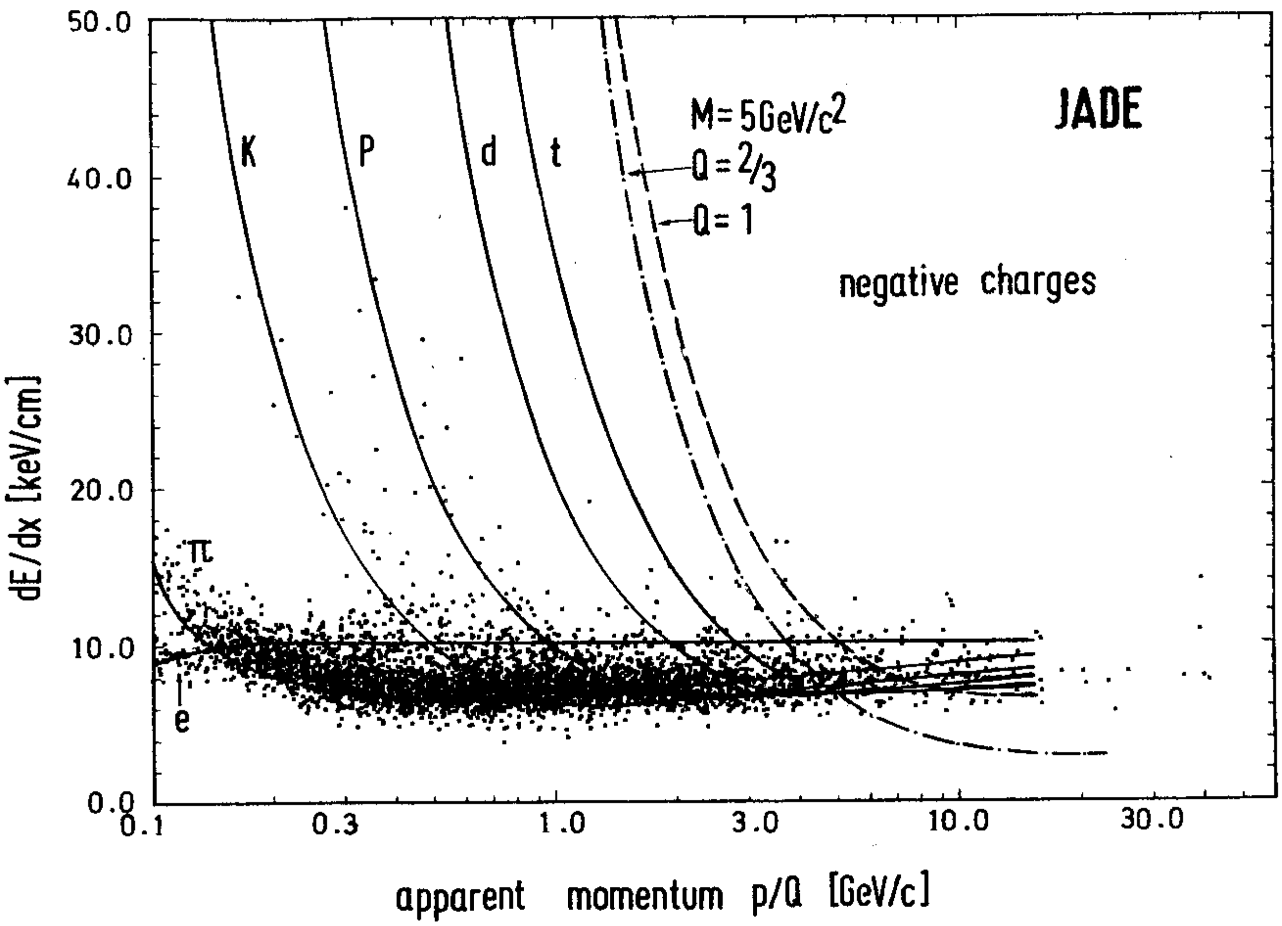
JADE
M=5 GeV/c2
Q=2/3
Q=1
negative charges
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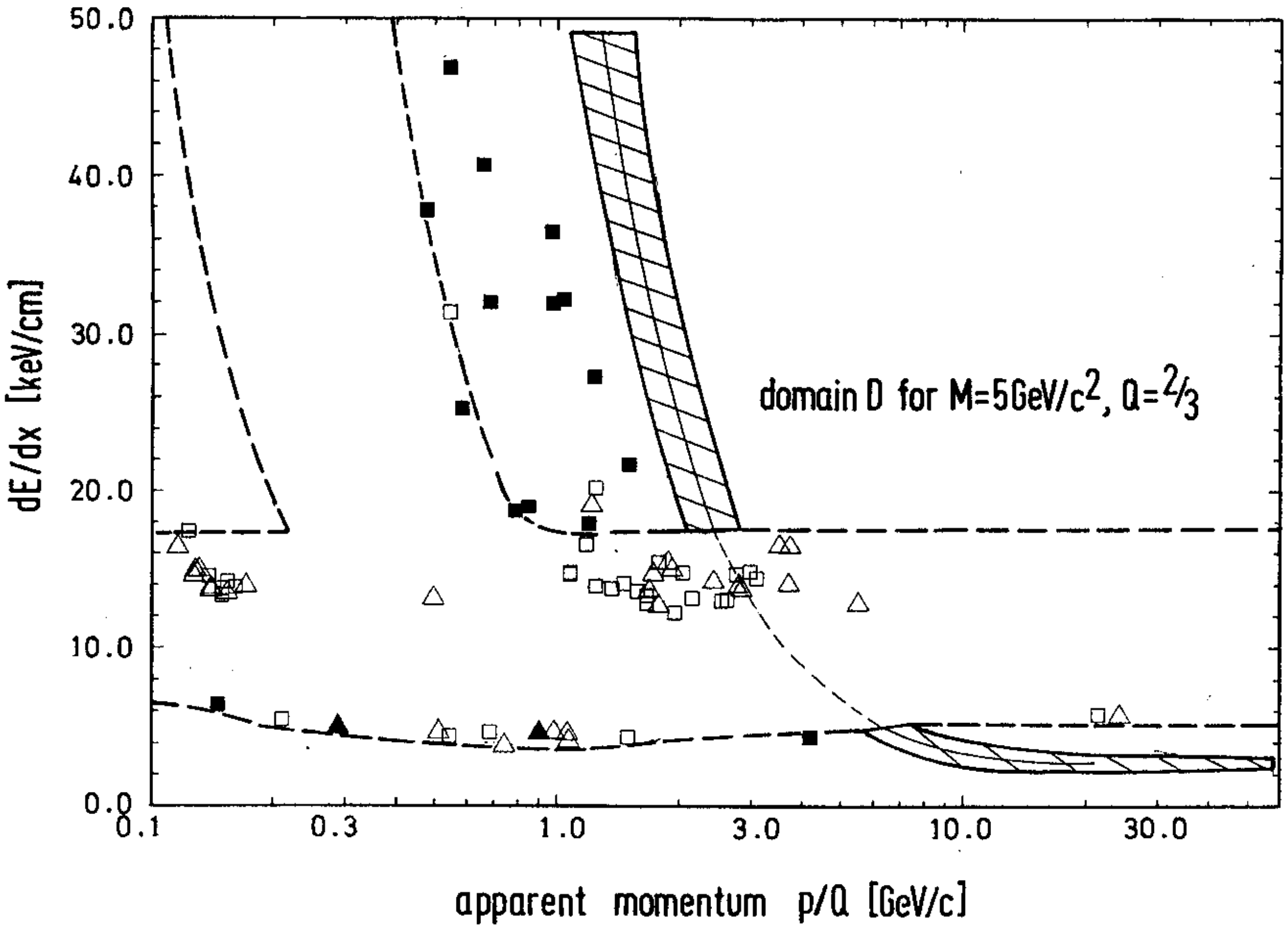
Fig. 5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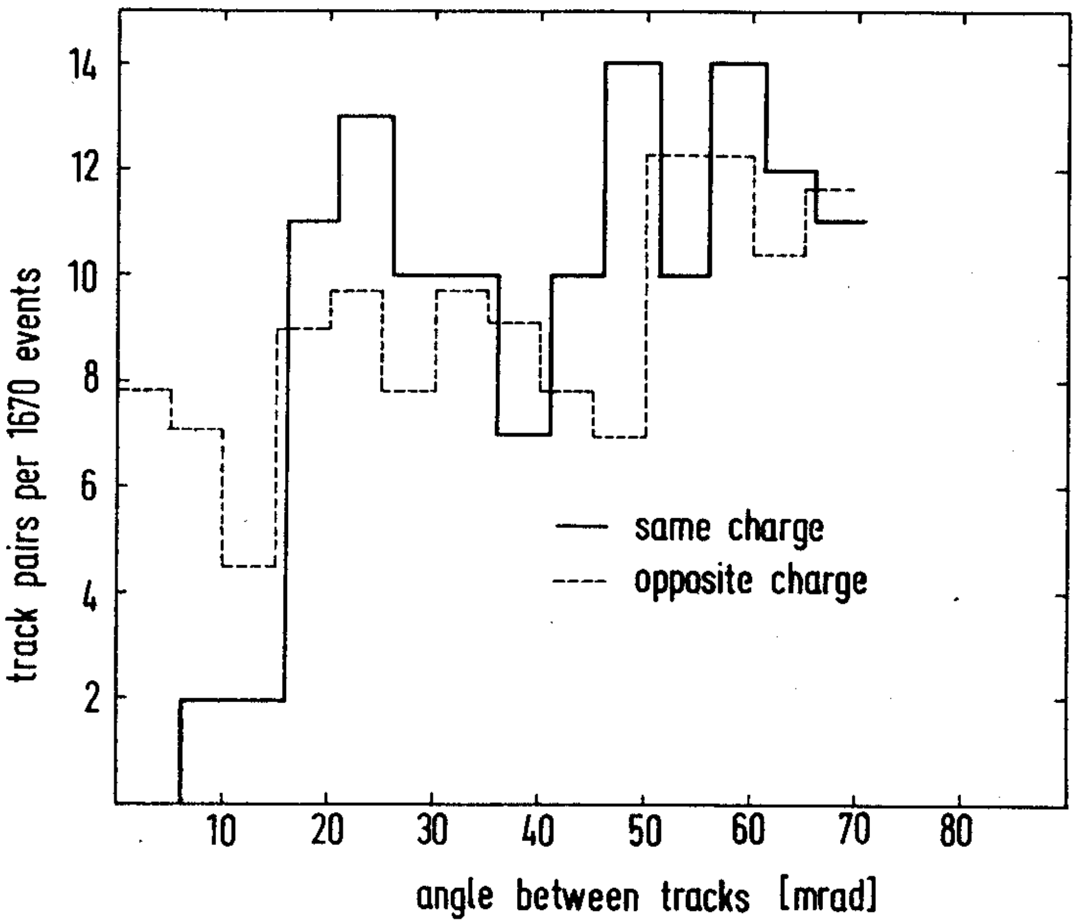
dE/dx [keV/cm]
domain D for M=5GeV/c2, Q=2/3
apparent momentum p/Q [GeV/c]

Fig. 6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30
40
50
60
70
80
track pairs per 1670 events
same charge
opposite charge
angle between tracks [mrad]

Fig. 7

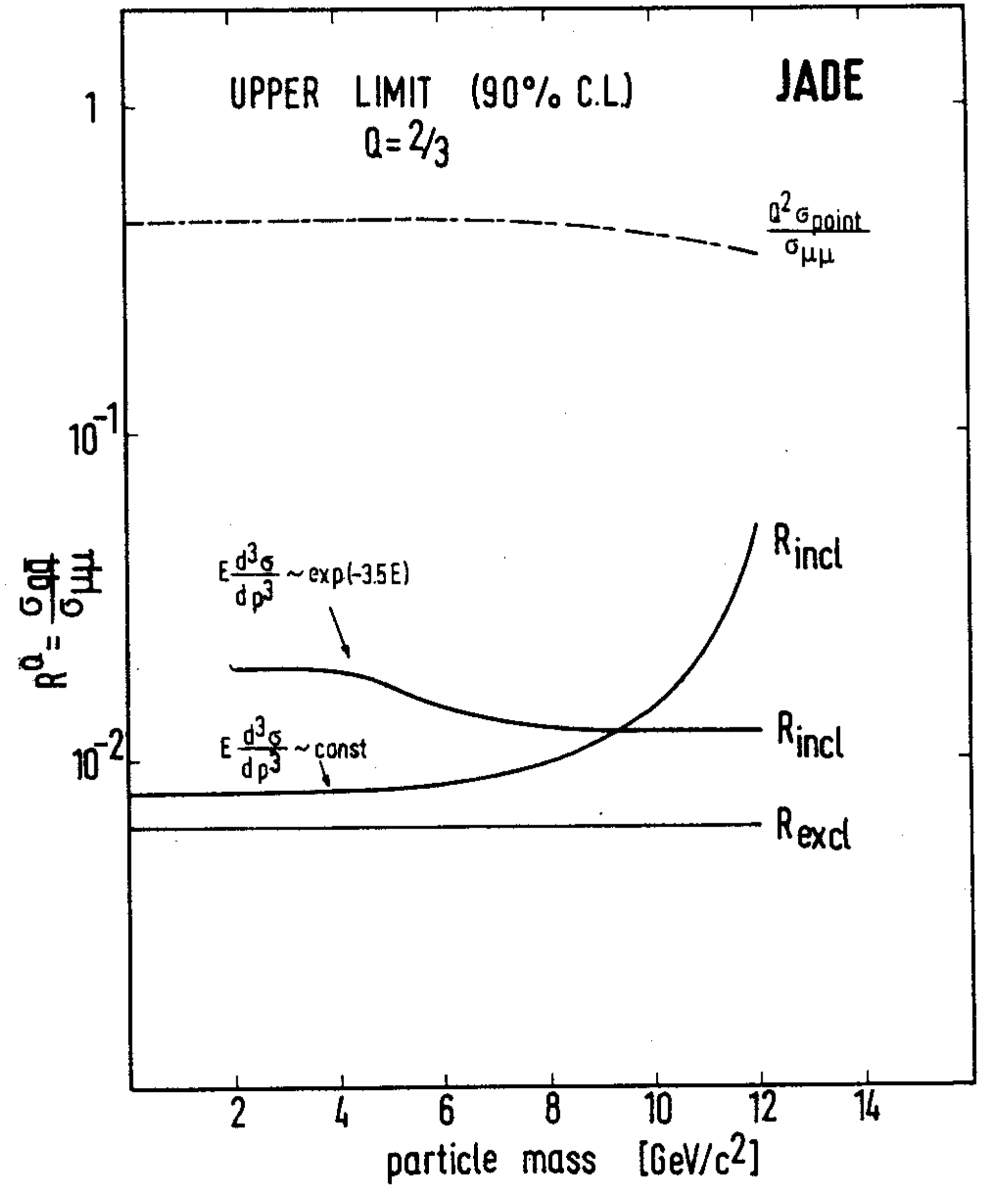

UPPER LIMIT (90% C.L.)
Q=2/3
JADE
1
10^-1
10^-2
R^Q = σqq̄/σμμ
Q^2 σpoint/σμμ
E d^3σ/dp^3 ~ exp(-3.5E)
E d^3σ/dp^3 ~ const
R_incl
R_incl
R_excl
2 4 6 8 10 12 14
particle mass [GeV/c^2]

Fig. 8

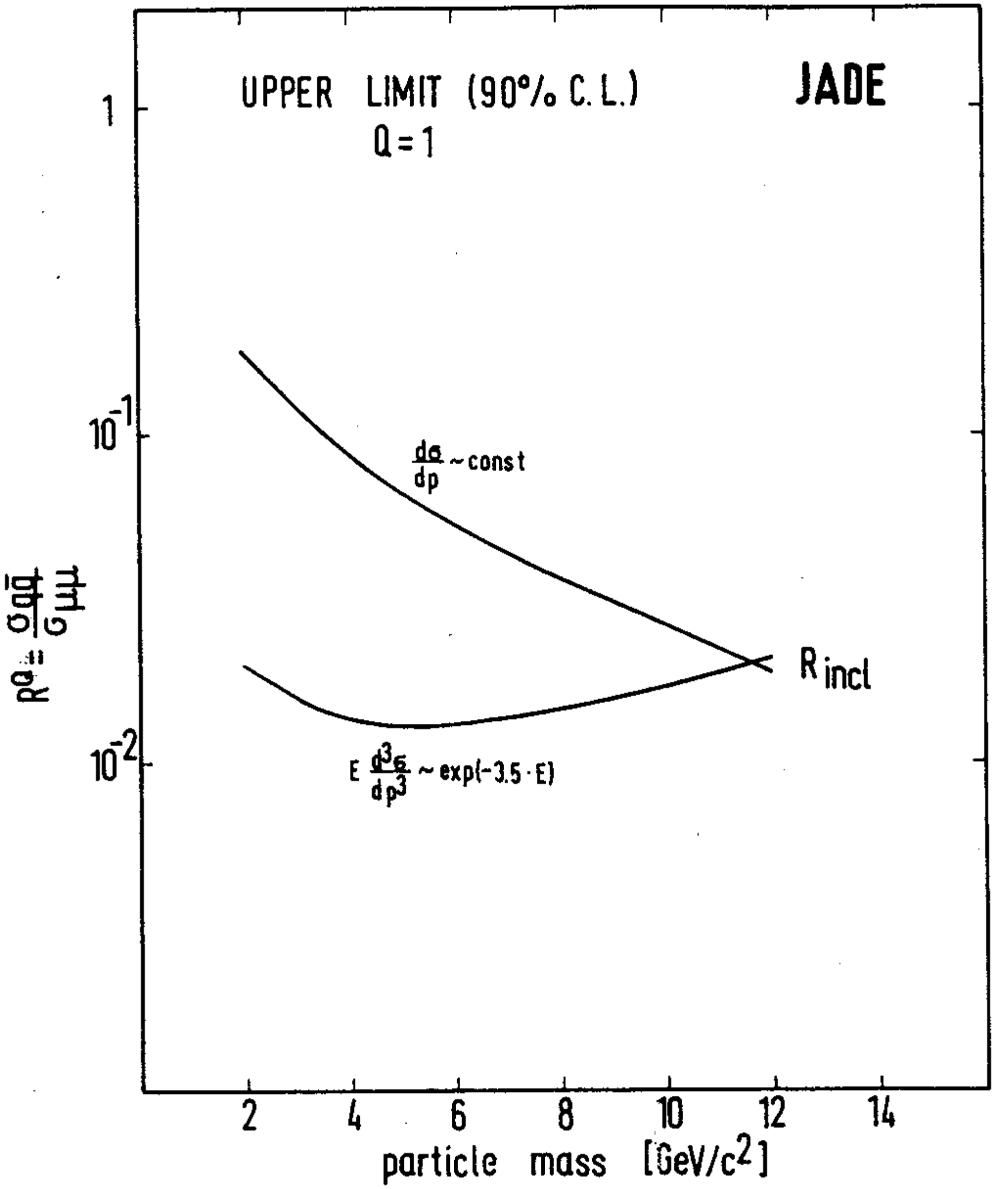

UPPER LIMIT (90% C.L.)
Q=1
JADE
1
10^-1
10^-2
R^Q = σqq̄/σμμ
dσ/dp ~ const
E d^3σ/dp^3 ~ exp(-3.5·E)
R_incl
2 4 6 8 10 12 14
particle mass [GeV/c^2]

Fig. 9

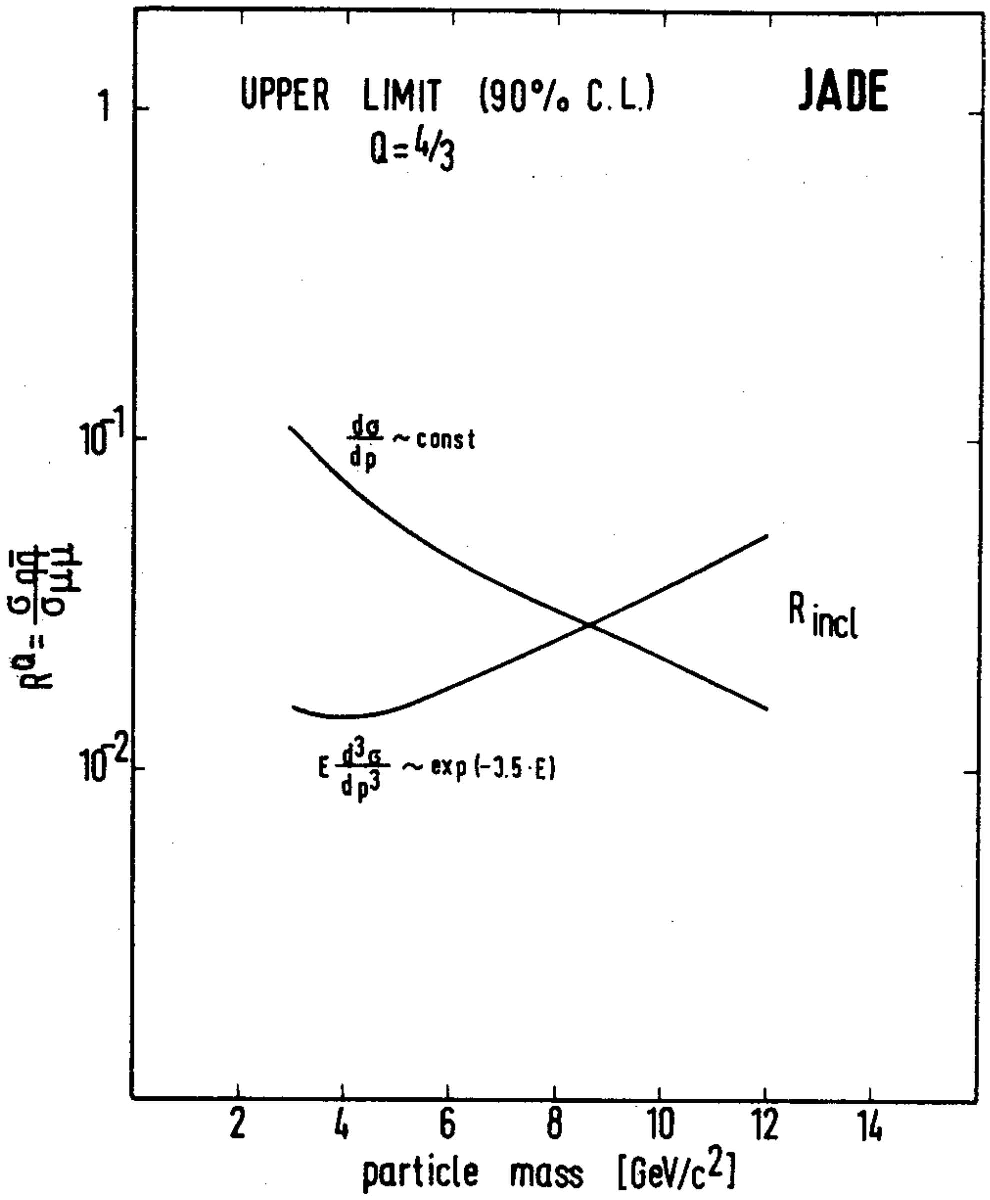

UPPER LIMIT (90% C.L.)
Q=4/3
JADE
1
10^-1
10^-2
$R^Q = \frac{\sigma_{q\bar{q}}}{\sigma_{\mu\mu}}$
$\frac{d\sigma}{dp}$ ~ const
$E\frac{d^3\sigma}{dp^3}$ ~ exp(-3.5·E)
R incl
2
4
6
8
10
12
14
particle mass [GeV/c^2]

Fig. 10

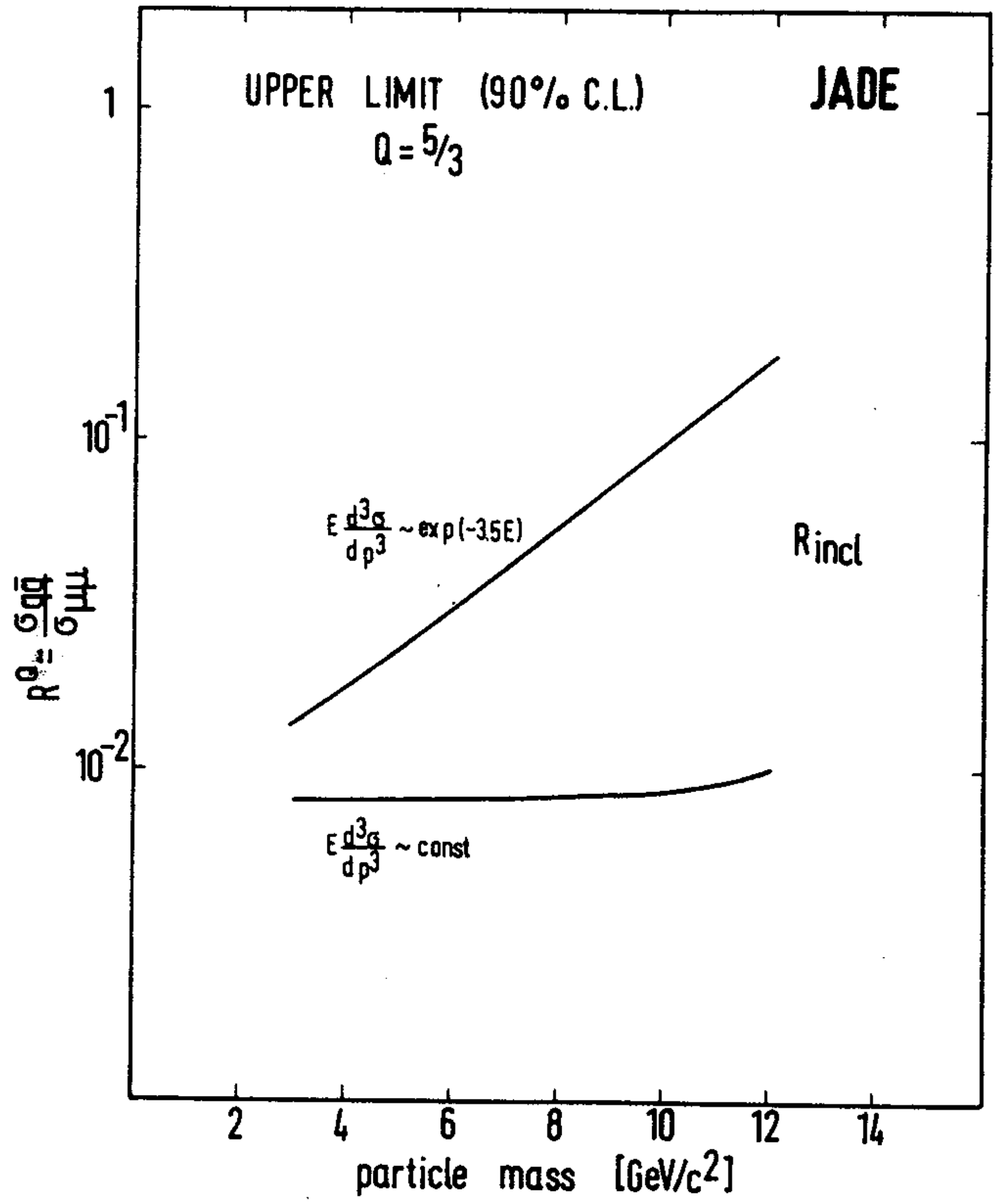
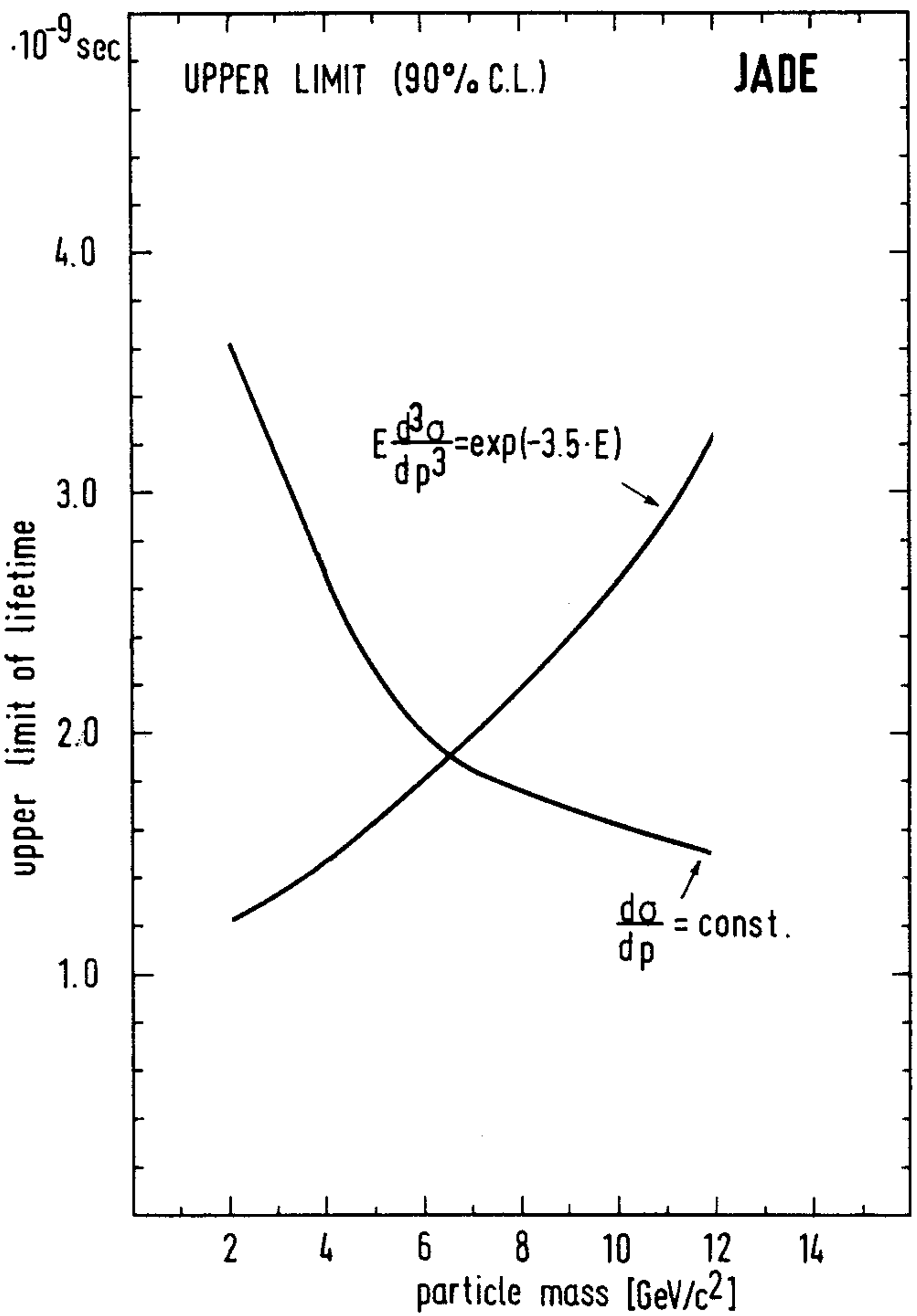

UPPER LIMIT (90% C.L.)
Q=5/3
JADE
1
10^-1
10^-2
$R^Q = \frac{\sigma_{q\bar{q}}}{\sigma_{\mu\mu}}$
$E\frac{d^3\sigma}{dp^3}$ ~ exp(-3.5E)
$E\frac{d^3\sigma}{dp^3}$ ~ const
R incl
2
4
6
8
10
12
14
particle mass [GeV/c^2]

Fig. 11



·10^-9 sec
UPPER LIMIT (90% C.L.)
JADE
4.0
3.0
2.0
1.0
upper limit of lifetime
$E\frac{d^3\sigma}{dp^3}=\exp(-3.5\cdot E)$
$\frac{d\sigma}{dp}$ = const.
2
4
6
8
10
12
14
particle mass [GeV/c²]

Fig. 12