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SEARCH FOR HIGHLY-INTERACTING, FRACTIONALLY-CHARGED PARTICLES IN ELECTRON–POSITRON ANNIHILATION AT 29 GeV

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We have searched for relativistic, highly-interacting fractionally-charged particles using the free-quark detector at the e^+e^- storage ring PEP. No convincing events were seen. For an assumed interaction cross section with matter of 100 times geometric, 90% confidence level upper limits on their production relative to $e^+e^- \to \mu^+\mu^-$ are between 0.025 and 0.49 depending on quark mass (up to 13 GeV/c^2) and reaction type. These are the first published limits on the production of fractionally charged particles with interaction cross sections of 100 times geometric or larger.

Since the quark hypothesis was first introduced nearly 20 years ago, more than 25 accelerator searches have failed to find free particles with fractional charge [‡1]. The usual explanation is that they are always confined in clusters having integral electric charge. But even if the confinement were sometimes broken, quarks might not have been detected in accelerator searches if the confining force causes large interaction cross sections [2]. A factor of 100 increase over normal in the hadronic cross section would have precluded detection in all such previous searches [‡2].

This article describes a search for particles with electric charge $Q < 1(e)$. It used a detector with a thickness of less than 1% of an interaction length and so maintained high efficiency for particles with interaction cross sections of up to several hundred times geometric. It was performed at PEP using e^+e^- beams with a CM energy of 29 GeV. Particle charge, Q, was

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‡1 For reviews see ref. [1].
‡2 Only colliding beam experiments have used thin production targets. Of these, only JADE [3] used tracking detectors sensitive to relativistic quarks and was able to identify a quark in less than 0.1 collision length (0.083).

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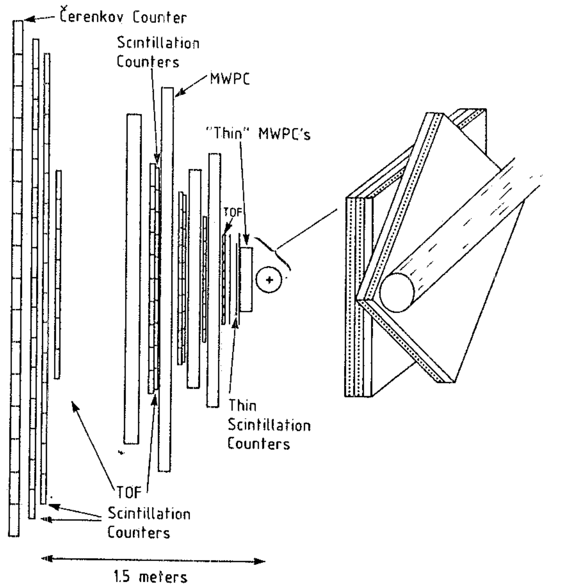

Fig. 1. Elevation view of the left half of the detector in the plane perpendicular to the beam pipe. (The detector is symmetric about the centre line). The innermost chambers and a section of the beam pipe are shown enlarged, and in perspective in the insert.

deduced from $dE/dx = Q^2 f(\beta)/\beta^2$, where $\beta = v/c$ and $f(\beta)$ is a slowly varying function of β. The particle dE/dx was measured in thin-walled proportional chambers that were placed between a thin beam pipe and the rest of the apparatus. Since we could not assume that highly-interacting particles would reach time-of-flight scintillators located in the back part of the apparatus, this search was limited to relativistic particles for which the $1/\beta^2$ increase in dE/dx does not significantly lower the detection efficiency.

The integrated luminosity analyzed was 12.8/pb. There were 1.2×10^6 triggers. We searched for quarks in two types of events: 2 quark ($e^+e^- \to q\bar{q}$, $q\bar{q}$ X) with at least one track in each arm having dE/dx consistent with $Q = 1/3$ or $2/3$, and inclusive ($e^+e^- \to qX$) in which 1 or more tracks fit $Q = 1/3$.

The apparatus is shown in fig. 1. Both it and prior results from our search for free-quark production in e^+e^- collisions are further described in refs. [4–7]. The 5 thin walled chambers had cathodes of 25 μm Al bonded to 38 μm Mylar. The anode-cathode gap was 8 mm. The planes had wires of 20 μm diameter gold plated tungsten set at +45, −45, 90 and 0 degrees to the beam axis. The 64 anode wires in each chamber were spaced 6.35 mm apart, with field wires halfway between, and were connected in pairs to 32 channels of pulse height readout. A $Q = 1$ minimum ionizing particle would make an average of 46 primary collisions in the 80% Ar–20% CO_2 gas at normal incidence [5].

Beyond these chambers on each side were 3 layers of thin (1.5 mm thick) scintillators. Six more layers had their edges aligned to form 10 "roads" radiating from the beam crossing point. Interspersed among them were 4 chambers used for tracking only. Three final layers of scintillators and a layer of lucite Čerenkov counters completed each arm.

The trigger, described in detail in ref. [6], required a charged particle to trigger 5 or more of the scintillators in at least 1 road on each side. The discriminator thresholds were set at 0.05 Δ, where Δ is the most probable value of energy loss for $Q = 1$, normally incident cosmic rays. Thus either the quark, an interaction product or another primary particle had to penetrate at least 0.2 interaction lengths in each arm.

The penetration required for identification was far less. The beam pipe had 1.8 mm of Al for the first 53% of data, and 152 μm of corrugated stainless steel lined with a cylinder of 25 μm copper for the last 47%. The 5 thin chambers were separated from each other by 76 μm of Mylar which was removed after the first 16% of the data. The corresponding thickness, in collision lengths, for the 3 groups of data was 0.011 (0–16%), 0.009 (16–53%), and 0.005. The average was 0.007, comprising the thinnest detector ever used in an accelerator quark-search experiment.

The chamber pulse height readout transmitted all signals greater than 0.02 Δ to the computer. It was calibrated with cosmic rays at full and reduced chamber voltages, and was further monitored with ^{55}Fe sources and variable height pulses injected into each anode. Parallel readout channels, using completely overlapping "wide" gates [5] were used to detect several possible sources of spurious small pulses, such as clipping due to out-of-time input gates.

There were no serious backgrounds from neutrons or gamma rays because of the small conversion thickness of the beam pipe and chambers, or from synchrotron radiation (which has a short mean path) because it produces slow, highly-ionizing electrons. During normal running, the largest source of singles counts came from the ^{55}Fe sources which were distributed across the front and back of the chamber groups and adjusted to give counting rates in the range of several kHz in each channel. Two sources of spurious pulses were found: intermittent electrical noise pickup which may have affected all channels but showed up only on isolated clusters due to the 0.02 Δ threshold, and electrons produced by normal tracks or avalanches that were collected by wires sufficiently removed to produce a signal isolated from the track by one or more vacant channels.

Many background events due to cosmic rays and to beam products such as synchrotron radiation and showers contain many random hits. They were eliminated in the analysis by using a set of preliminary filters (PR1–PR3):

PR1. The 320 thin-chamber channels had to have fewer than 120 (2 quark analysis) or 140 (inclusive analysis) hit channels.

PR2. We required 3 or more hits in the outer (thick) chambers in each arm. Any valid triggering track should satisfy this requirement, but synchrotron radiation, which generally converts in the scintillators, usually does not.

PR3. Loose (and 100% efficient) cuts were placed on time-of-flight signals: the average time in the second layer had to be greater than in the first, and no more than 5 of the 76 counters in the last three scintillator layers could have times earlier than the beam crossing time.

The next step in the analysis was to search for tracks using only the thin-chamber information. Tracks radiating from the beam crossing could project onto 1, 2 or 3 adjacent channels in a given chamber. Signals from adjacent channels were grouped into clusters of up to 3 channels each, and their centers were found by weighting the positions with the corresponding pulse heights. Tracks were formed from combinations of clusters by fitting lines radiating from the e^+e^- interaction region with a chi-squared per degree of freedom less than 5. A cluster in every thin chamber of the arm was required, but any given cluster could be used for more than 1 track. Chamber performance was checked by extrapolating tracks from a sample of two-prong events identified by the outer detector. The individual chambers had a spatial resolution of 3.7 mm. Over 98% of the tracks in the sample were found by the thin chambers.

Since a track was required on each side by the trigger, we also required:

PR4. At least one thin-chamber track be found in each arm.

Five requirements (TR1–TR5) were placed on these tracks prior to the calculation of dE/dx:

TR1. Cluster in at least 4 of the 5 chambers had to be separated from other clusters by zero-pulse height channels. This prevented the construction of fake low-pulse height tracks from the edges of normal ones.

TR2. The weighted centre of gravity of all clusters had to be at least 3.2 cm in from the edge of the gas volume.

TR3–TR5. At least 4 of the 5 chambers had to have good dE/dx information. This required that there be no saturated channels (pulse height greater than 2 Δ in a single channel), that none of the 4 low-gain channels be used, and that no edge channels be used.

The truncated mean energy loss rate ($\langle dE/dx \rangle_t$) was calculated by averaging the 4 smallest dE/dx measurements on each track (all measurements if only 4 passed TR3–TR5). This truncation suppressed the Landau tail and produced a resolution of 55% FWHM for $Q = 1$ minimum ionizing particles.

Cuts based on dE/dx were next used. To determine their efficiency, we calculated the expected dE/dx distributions using a Monte Carlo method [‡3]. The number of primary ionizing collisions was chosen from a Poisson distribution having a mean of Q^2 times the mean number of primary collisions in the gap for a $Q = 1$ particle. The mean contains the detailed β dependence including the expected relativistic rise of 55%. For each collision a number of electrons was then selected and multiplied by a factor chosen from the avalanche fluctuation distribution, $g \times \exp(-1.5g)$, where g is the chamber gain divided by its mean value [8]. Allowance was made for track geometry and possible saturation of the electronics. Factors that were constant from pulse to pulse, such as the average gas gain, the fraction of the total positive ion motion during the 1.2 μs readout gate, and the amplifier gain were included in the overall normalization which was made using cosmic rays and

‡3 The number of electrons is selected from the distribution given in table 2(1) of ref. [8], and extended beyond n = 14 with a $1/n$ tail.

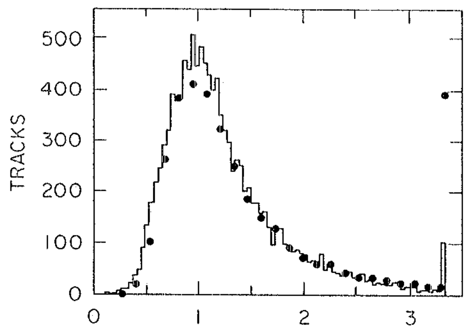

Fig. 2. Cosmic ray d*E*/d*x* distribution taken at lowered high voltage to reduce saturation. Dots indicate Monte Carlo results. The horizontal scale factor is arbitrary.

checked with relativistic electrons. Energy loss distributions calculated in this way for $Q = 1$ agreed well with those observed. Fig. 2, for example, gives a single chamber d*E*/d*x* distribution for cosmic rays.

Three d*E*/d*x* cuts (dE1–dE3) were made:

dE1. At least one track in the event had to have $\langle dE/dx \rangle_t < 0.6$. (All energy loss rates, d*E*/d*x*, will be expressed without units as multiples of the most probable value for $Q = 1$ cosmic rays.)

dE2. At least 3 d*E*/d*x* values on the quark candidate track had to be greater than 0.06. This eliminated most events in which the track was due to noise coincidences.

dE3. The individual d*E*/d*x* values had to be consistent with their mean. This removed false tracks made from a combination of near-zero noise and normal $Q = 1$ values. The probability of observing the 4 d*E*/d*x* values used in $\langle dE/dx \rangle_t$ was calculated from a Monte Carlo distribution in which Q was a variable adjusted to give the observed mean. The 5th (largest) d*E*/d*x* value was not used in this probability calculation since the probability versus pulse height distribution for large pulses depended sensitively on the details of delta ray production and on how the channels went into saturation. The cut was set at a level that passed 98% of the cosmic ray tracks and 93% of the Monte Carlo $Q = 1/3$ tracks.

The cuts through dE1 reduced the number of events to approximately 7000. After the consistency cut dE3, there were no events remaining with at least one track in each arm having $\langle dE/dx \rangle_t < 0.6$. (The closest was above 0.63.) No collinearity cut was needed for this result, and omitting it eliminated one source of systematic error. Inclusive events of the type $e^+e^- \to q\bar{q}X$ could also have been detected in this sample, but with an efficiency dependent on the $q\bar{q}$ opening angle, since we required a low d*E*/d*x* track in each arm.

Only 5 chamber pulse height measurements were available for the analysis of a single track. Therefore, for the inclusive channel $e^+e^- \to qX$, we limited the search to $Q = 1/3$, as the expected d*E*/d*x* was well removed from that for $Q = 1$.

Fig. 3a shows the $\langle dE/dx \rangle_t$ distribution for all tracks in the events remaining in this sample after cuts PR1–PR4, TR1–TR5, and an initial looser d*E*/d*x* cut of 0.64 (rather than 0.6). The low pulse height peak, below where quarks were expected, was probably due to noise pickup. It often appeared in many channels simultaneously and came at a frequency of about 10^{-4} per trigger. Fig. 3b shows the distribution after most of these events were removed by cut dE2. Fig. 3c shows the distribution after cut dE3. The drop at 0.64 is due to the initial d*E*/d*x* cut which was used to remove the bulk of normal events. The $Q = 1$ peak (0.75–1.51) from the additional normal tracks in these events contains 3684, 3677, and 3431 tracks in the 3 distributions. This consistency serves as an indication that the losses due to the cuts were small and that most of these tracks were valid ones. Fitting the peak (due primary to highly relativistic electrons) with the same Monte Carlo used for fig. 2 indicates an increase in ionization over that for cosmic rays (primarily several GeV muons) of approximately 1.3. This is in agreement with the expected relativistic rise. The reduced high d*E*/d*x* tail was due to saturation of the electronics as well as to the truncation procedure. Fig. 3d shows the Monte Carlo prediction for $Q = 1/3$ tracks.

The data regions below 0.25 in fig. 3a, b, c contain respectively 999, 51, and 29 events. Two final requirments (INC1–INC2) were used in the inclusive analysis only, to select events caused by particles and eliminate those caused in part by noise:

INC1. At least 2 of the 3 thin-scintillator hodoscopes were required to show d*E*/d*x* signals larger than 0.05 Δ when summed over the counter on the track projection and the 2 adjacent to it.

This requirement should have been satisfied with

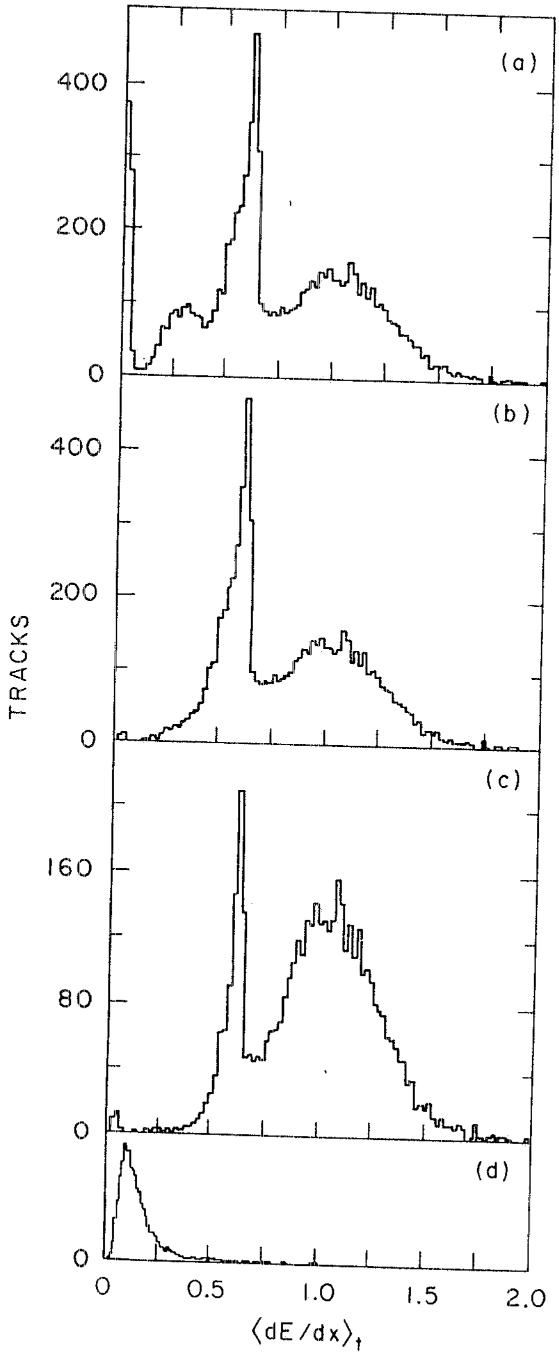

Fig. 3. Distribution of $\langle dE/dx \rangle_t$ for all tracks in events remaining after cuts (a) PR1–4, TR1–5, dE1 (8548 tracks), (b) dE2 (7052 tracks), (c) dE3 (4636 tracks), and (d) Monte Carlo distribution for relativistic $Q = 1/3$ tracks before any cuts are applied (arbitrary vertical scale).

high probability by the quark or, if it interacted in the thin scintillators (each 0.003 collision lengths thick), by its interaction products. The solid angle covered was nearly 2π and since $Q = 1$ particles were highly efficient at $9 \times 0.05\ \Delta$, we would expect $Q = 1/3$ particles to be efficient at $0.05\ \Delta$. (A lower limit of 40–70 for the number of photoelectrons from each $Q = 1$ traversal of a thin scintillator is estimated by fitting the pulse height distribution with the convolution of a Landau and a Poisson distribution. No allowance was made in this lower limit calculation for other contributions such as those from photomultiplier gain fluctuations.) This cut passed 3134 $Q = 1$ and 12 low pulse height tracks.

At no stage in the analysis was there an identifiable peak in $\langle dE/dx \rangle_t$ in the expected region for $Q = 1/3$. All but 2 of these last 12 events were littered with pulses, typically in the range 0.02–0.04 Δ. Such pulses combined with ones from $Q = 1$ tracks to make combinations in which the 4 non-truncated values passed height consistency cut dE3, while the $Q = 1$ track traversed the thin scintillators, satisfying INC1.

The last cut was:

INC2. Events having, in the arm containing the quark candidate, 15 or more channels *not* used for any quark candidate (to prevent bias against quarks) with pulse heights in the range 0.02 to 0.05 Δ were excluded.

Most of the 10 events eliminated had considerably more than 15 such pulses. The probability that a valid event would have as many as 15 or more was estimated, using the two-prong sample selected by the main detector from the same data set, to be 0.0096 ± 0.0003.

The final 2 events were formed in a similar way: one pulse from a valid $Q = 1$ track (which was the one truncated in the dE/dx calculation) and 4 other small ones separated from normal sized pulses by only 1 blank channel. Both events had small energy-loss rates $\langle dE/dx \rangle_t$ of 0.050 and 0.061. There was no indication in the rest of the detector either of an interaction or of continuing tracks other than the $Q = 1$ ones seen in the thin chambers.

We examined the $Q = 1$, two prong sample to see if energy (presumably a photon) emitted from a track or its avalanche could jump one channel and make such pulses. A clear clustering of small pulses peaking at 0.025 Δ and mostly confined to below 0.05 Δ was seen in 5% of the crossings in each chamber. A uniform background of comparable height also appeared over the entire chamber at the rate of 0.006 per channel per crossing. A Monte Carlo using normally constructed events with small pulses added around each track and throughout the chambers at the observed rate, however, predicted only 0.2 events. The added pulses were too small by a factor of 2 to produce 2 events; thus for the purpose of calculating an upper limit we accept these 2 and used 5.3 events for the 90% confidence level.

The efficiency for $e^+e^- \to q\bar{q}$ was calculated assuming a $(1 + \cos^2\theta)$ angular distribution for the quarks. The dE/dx Monte Carlo previously described was used. The efficiencies for counting in the electronics and passing each cut were essentially unity in $e^+e^- \to q\bar{q}$ ($Q = 1/3, 2/3$) except for:

1. Passing the pulse height threshold (0.02 Δ) in all chambers: >0.9 per track for light (highly relativistic) and heavy (10 GeV/c^2) $Q = 1/3$ quarks, decreasing to 0.52 per track in between at minimum ionization.

2. Cut TR4 (no low-gain channels): 0.96 for $q\bar{q}$ and 0.98 for qX events.

3. Cut dE1 ($\langle dE/dx\rangle_t < 0.6$): 0.91 per track for light and heavy $Q = 2/3$ quarks, increasing to 0.97 in between, at minimum.

4. Cut dE2 (3 dE/dx values above 0.06): >0.94 per track for light and heavy $Q = 1/3$ quarks, decreasing to 0.63 in between, at minimum.

5. Cut dE3 (consistent pulse heights): 0.93^2 for $q\bar{q}$ and 0.93 for qX.

The overall efficiency for $e^+e^- \to q\bar{q}$ including solid angle, was 0.21 for both light and 13 GeV/c^2 $Q = 1/3$ quarks, decreasing in between to 0.05 at minimum. For $Q = 2/3$ light and 10 GeV/c^2 quarks, it was 0.05, increasing to 0.23 in between.

The total inclusive efficiency was calculated with the aid of a simple all-pion two-jet production Monte Carlo [9] in which 2 pion masses were replaced with quark masses. Including solid angle, it was 0.088 for low mass $Q = 1/3$ quarks, and decreased of 0.011 for 10 GeV/c^2 quarks. Most factors in this calculation were similar to those in the exclusive analysis except for the probability of having at least 4 out of 5 clusters separated from all neighbouring ones, which, averaged over all multiplicities, was 0.66. Radiative corrections were not incorporated since there were no significant angle or energy cuts.

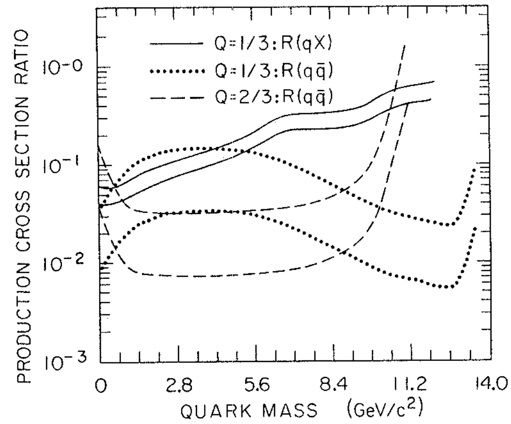

Fig. 4. 90% confidence level upper limits on production of free quarks, relative to muon pairs, as a function of assumed quark mass. The pairs of curves are for assumed interaction cross sections of geometric (lower curves) and 100 times geometric.

The results of this experiment are summarized in figs. 4 and 5. Fig. 4 shows the upper limits on production of quarks with interaction cross sections of geometric and 100 times geometric.

We can characterize the sensitivity of this experiment in another way. We assume hadron events initiated by $e^+e^- \to q\bar{q}$ are produced with a cross section of 3 (for color) × $(\Sigma_{udscb} q_i^2 \sigma_{ee\to\mu\mu})$, and define p_{escape} as the probability, averaged over all hadron

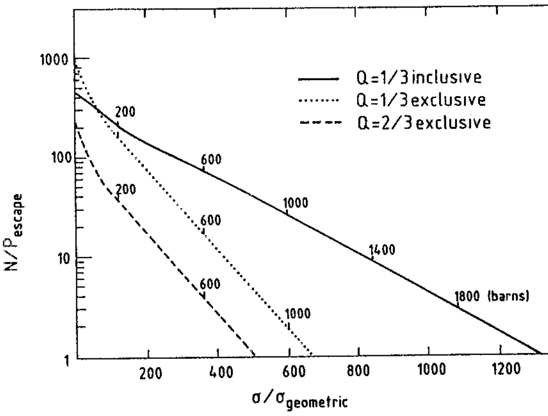

Fig. 5. Ratio of number of events expected to have been seen in this experiment (N), to the probability of emergence from interaction region of free quarks (p_{escape}) as a function of assumed interaction cross section in the apparatus.

events, that a quark pair of the type under investigation (1/3, 2/3 back-to-back or 1/3 inclusive) will escape. We include, in the definition of p_{escape}, any probability of fast decay of a heavy quark to an escaping lighter one. Then the number of observed events of a given type, N, passing all cuts will be proportional to the integrated luminosity, to p_{escape}, to our detection efficiency, and to the unknown interaction cross section of the quark (in inclusive events) or quarks (in back-to-back events) in our apparatus.

The ratio (N/p_{escape}) for relativistic quarks is shown as a function of that interaction cross section in fig. 5. For instance, if 10% of the hadronic production events resulted in the escape of a $Q = 1/3$ pair (plus possibly other particles), then we would have seen 10 $Q = 1/3$ inclusive events ($N/p_{escape} = 10/0.1 = 100$) for an interaction cross section of 280 times geometric. If one rather assumes a fixed interaction cross section per nucleus, the labeled cross sections on the line are used instead to give 460 b.

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