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SEARCH FOR THE PRODUCTION OF A NEW QUARK FLAVOR AT THE HIGHEST PETRA ENERGIES

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We report on the results of a study of hadron production in e^+e^- collisions at the highest PETRA energies reached so far. Production of a new quark flavor has been sought at cms energies of 33, 35 and 35.8 GeV. The measured values of the total cross section, the thrust distributions and the study of inclusive muon production show no evidence for the production of a new charge 2/3e quark near threshold. In addition, during an energy scan in the region $29.9 \leq \sqrt{s} \leq 31.6$ GeV, no hadron resonance indicating the existence of a bound state composed of charge 2/3e quarks has been found.

The MARK-J detector[1] has taken data at energies of $\sqrt{s}$ = 33, 35 and 35.8 GeV at PETRA, with time integrated luminosities of 91, 381 and 133 nb^{-1} respectively. The total cross section for the process

$$e^+e^- \rightarrow \text{hadrons} \qquad (1)$$

via one photon annihilation has been measured and the properties of the hadronic final states have been analyzed, to search for the production of a new quark flavor.

In addition to the detector setup reported earlier[1], an inner track detector composed of 992 drift tubes has recently been installed. The tubes, which are arranged perpendicular to the beam line, enable the reconstruction of the event vertex to an accuracy of two millimeters.

Events from reaction (1) are selected by requiring that

- the total visible energy E_{vis} is more than 50% of the available cms energy $\sqrt{s}$.
- The energy is balanced within 50% of E_{vis} in both the longitudinal and the transverse directions with respect to the beam line.
- The shape of the shower development in the layer structure of the detector is incompatible with a purely electromagnetic nature of the final state.

The distribution of the reconstructed vertex position for events selected accordingly (fig. 1) shows that background from beam-gas interactions or synchrotron radiation is <1%. The observed rms width of 1.27 cm is compatible with that expected from the known bunch length of the machine.

The acceptance for reaction (1) has been calculated using a Monte Carlo simulation to provide a phenomenological model of the hadron production process based on perturbative QCD.[2] The model, which incorporates q^2 evolution and the weak decays of heavy quarks[3] in the fragmentation process, also includes the effects of initial state photon bremsstrahlung[4] correct in QED to order α^3. After cuts the acceptance is 89% with little variation as a function of energy.

Background contributions to the hadron sample from the two photon process

$$e^+e^- \rightarrow e^+e^- + \text{hadrons} \qquad (2)$$

and

$$e^+e^- \rightarrow \tau^+\tau^- \qquad (3)$$

have also been calculated and subtracted using Monte Carlo techniques.

The ratio R of the total hadron production cross section to the pointlike cross section for μ-pairs

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

has been measured using a total sample of 28, 133 and 49 events respectively yielding

$$R = 2.9 \pm 0.6 \quad \text{at} \quad \sqrt{s} = 33 \text{ GeV}$$
$$R = 3.8 \pm 0.4 \quad \text{at} \quad \sqrt{s} = 35 \text{ GeV}$$
$$R = 4.4 \pm 0.7 \quad \text{at} \quad \sqrt{s} = 35.8 \text{ GeV}$$

once all corrections and background subtractions mentioned above have been applied. In addition to the statistical errors quoted above, we estimate a systematic error of 10% due to model dependence of the acceptance, event selection criteria and measurement of luminosity.

Fig. 2a summarizes the measurements of R obtained by the MARK-J experiment at PETRA. They are compared with the predictions of QCD for the known five flavors, u, d, s, c, and b as well as for production of a sixth flavor with a quark charge of 2/3e in the continuum. No increase in R is seen corresponding to the opening of a new threshold up to the highest energy of 35.8 GeV. The results at 12 GeV $\leq \sqrt{s} \leq$ 31.6 GeV agree with those reported by other PETRA experiments[5).

In addition to this search for continuum production of a new quark flavor, an energy scan was performed between $\sqrt{s}$ = 29.9 and 31.6 GeV measuring R to search for bound states of a new quark lying below the continuum threshold. Data have been taken with about 25 nb^{-1} average luminosity per point in steps of 20 MeV cms energy (matching the rms energy spread of PETRA). The overall hadron event sample for the scan consists of 807 events corresponding to a time-integrated luminosity of 1945 nb^{-1}. The results of the scan are shown in Fig. 2b, along with the results obtained at 30.0

and 31.6 GeV. The figure shows that the data are consistent with the predictions of QCD for u, d, s, c and b quarks, i.e., with a constant value of R over the whole range. No single point lies more than 3σ above the QCD line, the value of R averaged over the range of the scan is 4.33 ± 0.17. In order to set a quantitative upper limit on the production of a narrow resonance, the data in Fig. 2b were fitted by a constant plus a gaussian distribution

$$R = R_o + R_v \exp \left[- (w - M)^2 / 2 \Delta_w^2 \right] , \quad (w = \sqrt{s})$$

where R_o represents the non-resonant continuum, M is the mass of the resonance, Δ_w the rms machine energy width and R_v the peak value of the resonant contribution. The largest value of R_v consistent with the data was determined by trying fits with M, the center of the gaussian, fixed at all center of mass energies at which data were taken. The largest value of R_v was obtained at 31.32 GeV, corresponding to an upper limit on the resonance strength

$$\Sigma_v \equiv \int (R-R_o)\sigma_{\mu\mu} \, dw$$

of 33 MeV-nb at 90% confidence level. Using the relation between the resonance strength, the width into e^+e^- (Γ_{ee}), the hadronic width (Γ_h), the total width (Γ) and the hadronic branching ratio ($B_h \equiv \Gamma_h / \Gamma$)

$$\Sigma_v \equiv \int \frac{3\pi}{M^2} \frac{\Gamma_{ee} \Gamma_h}{(w-M)^2 + \Gamma^2/4} \, dw = \frac{6\pi^2}{M^2} B_h \Gamma_{ee} ,$$

and taking radiative corrections into account we obtain

$$B_h \Gamma_{ee} < 1.3 \text{ KeV} \qquad (90\% \text{ CL.})$$

This upper limit excludes the production of a vector particle consisting of a $q\bar{q}$ bound state where the quark has charge $2/3\,e$.

On the basis of the experimental fact that Γ_{ee}/e_q^2 is approximately constant for the vector meson ground states ρ, ω, ϕ, J and T as predicted by duality arguments[6], one expects $B_h\Gamma_{ee} \simeq 4$ KeV for the lowest mass meson in the toponium family. Our results for the energy scan are in good agreement with those obtained from the PETRA experiments[7].

A jet analysis of the hadronic events was performed using the spatial distribution of the energy deposited in the detector. The jet-like appearance of events is parameterized in terms of the parameter thrust

$$T = \max \left[\frac{\sum_i |E_\parallel^i|}{\sum_i |E^i|} \right]$$

where E^i is an energy flow vector, whose direction is given by the position of a hit in a counter and magnitude by the corresponding deposited energy. $E_\parallel^i$ is the parallel component of the energy flow vector along the axis which maximizes T and the sums are taken over all counter hits. $\langle T \rangle$ is defined as the mean thrust of all events at a given center of mass energy.

The variation of $\langle T \rangle$ with energy is shown in Fig. 3. No step in $\langle T \rangle$, which is expected from the opening of a new threshold as indicated in the figure, is observed. The normalized thrust distribution $\frac{1}{N} \frac{dN}{dT}$ for the data taken at 35 GeV is shown in Fig. 4. It is compared to data taken earlier at $\sqrt{s}$ = 30 and 31.6 GeV and during the energy scan. Within the limits of statistics, no change in the shape of the distribution is observed. Also indicated in the figures are predictions of the aforementioned QCD Monte Carlo program[2], which includes the effects of gluon bremsstrahlung as required by our data[8]. The data agree well with the prediction for the five quark flavors u, d, s, c and b. The discrepancy between the observed number of events with $T < 0.80$ and the number expected from the production of a new quark of charge 2/3e makes the production of such a quark in the continuum unlikely up to an energy of 35.8 GeV: at 35 GeV 19 events are observed while 16.1 are expected in the case of 5 quarks, and 37.0 in the case of 6 quarks. Similarly, at $\sqrt{s} = 35.8$ GeV, 8 events were observed while 6.2 are expected in the case of 5 quarks and 14.3 in the case of 6 quarks.

Corroborating evidence comes from the study of inclusive muons in the hadron sample. Table I shows the percentage of hadronic events accompanied by a muon. The observed percentages are in good agreement with the rate of production expected from decays of mesons composed of u, d, s, c, b quarks and antiquarks obtained from the above mentioned Monte Carlo program which includes the effects of pion and kaon decay in flight and hadron punch through. The existence of a new quark with charge 2/3e would enhance the number of inclusive muons in the scheme of cascading weak quark decays[3]. As indicated in Table I, this assumption is disfavored by the data.

In conclusion, all data up to a cms energy of 35.8 GeV agree well with the predictions of QCD for the production of the five known quark flavors. The measurement of total cross sections, thrust distributions and inclusive muon production indicate that the continuum production of a new charge 2/3e quark is unlikely up to this energy. The R values obtained during the energy scan show that no narrow resonance with the width expected from a charge 2/3e bound state is produced between 29.9 and 31.6 GeV. The production of a charge 1/3e quark can, however, not be ruled out by the present data.

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Figure Captions

1) Distribution of event vertex along the beam direction reconstructed using drift tube tracks.
   (a) for the scan events.
   (b) for data at $\sqrt{s}$ = 35 GeV.

2) (a) The relative hadronic cross section R as a function of $\sqrt{s}$. The dashed line shows the QCD prediction without open top production. The dot-dashed line shows the prediction with new flavor production.
   (b) R values measured during the energy scan between 29.9 GeV and 31.6 GeV.

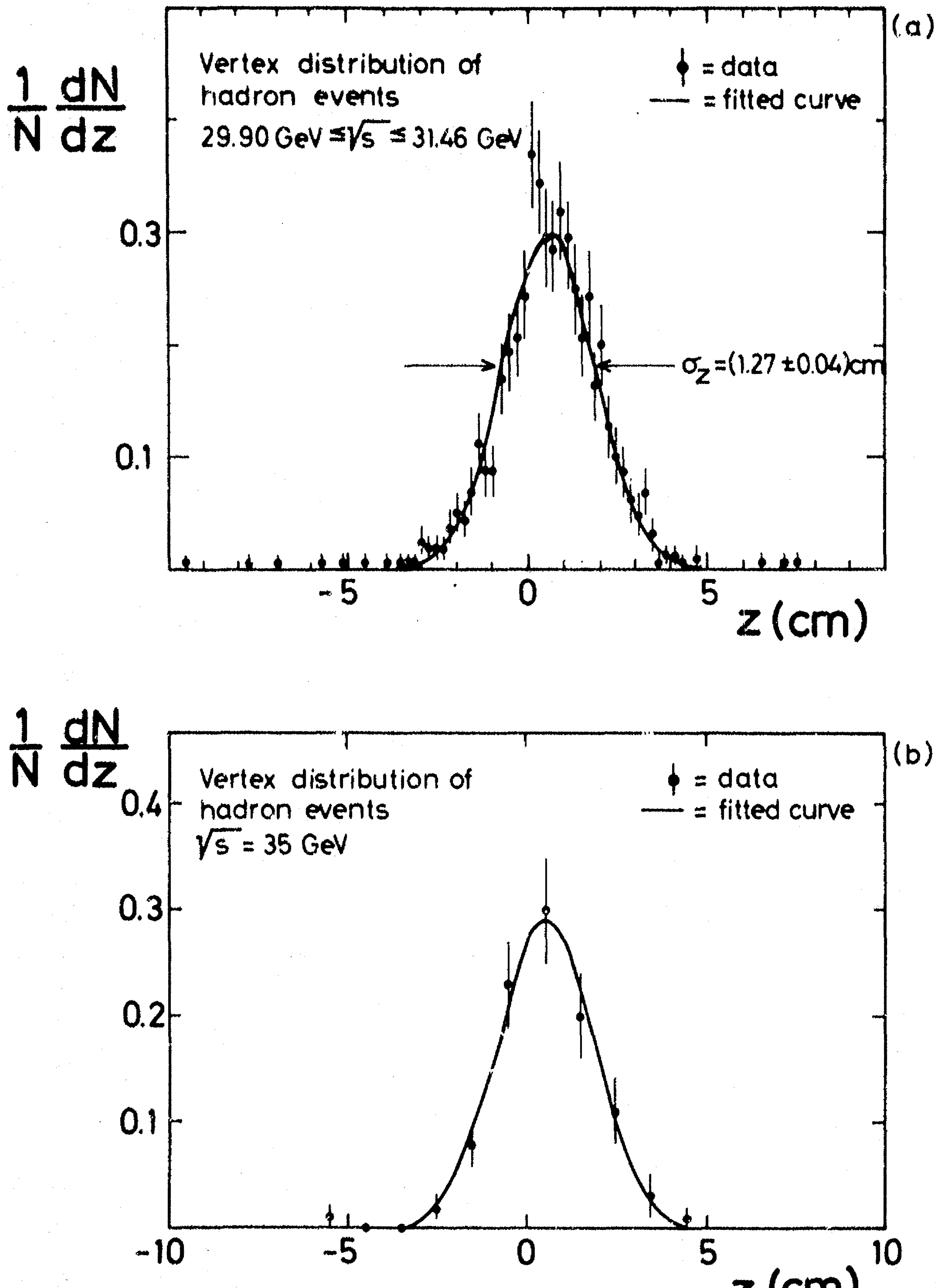
3) Average value of thrust as a function of $\sqrt{s}$ together with the QCD prediction (solid line). The values expected from a QCD model with top quark are also shown.

4) The thrust distribution $\frac{1}{N}\frac{dN}{dT}$ for $\sqrt{s}$ from 29.9 GeV to 31.6 GeV and for $\sqrt{s}$ = 35 GeV. The curves are predictions for QCD models without top (dashed line) and with top (dot-dashed line).

TABLE I

$\sqrt{s}$ GeV	Number of hadron events	Number of muon events	% of muon events	Monte Carlo (no top) %	Monte Carlo (with top) %
29,9-31.6	1147	43	3.7±0.6	5.0±0.4	7.7±0.5
35	133	5	3.8±1.7	5.1±0.4	7.8±0.5

Percentages of hadron events with muons, compared to Monte Carlo estimates with and without the assumption of top quark production.



(a)
$\frac{1}{N}\frac{dN}{dz}$
Vertex distribution of hadron events
29.90 GeV ≤ √s ≤ 31.46 GeV
= data
= fitted curve
σ_z = (1.27 ± 0.04) cm
0.3
0.1
-5
0
5
z (cm)
(b)
$\frac{1}{N}\frac{dN}{dz}$
Vertex distribution of hadron events
√s = 35 GeV
= data
= fitted curve
0.4
0.3
0.2
0.1
-10
-5
0
5
10
z (cm)

Fig. 1

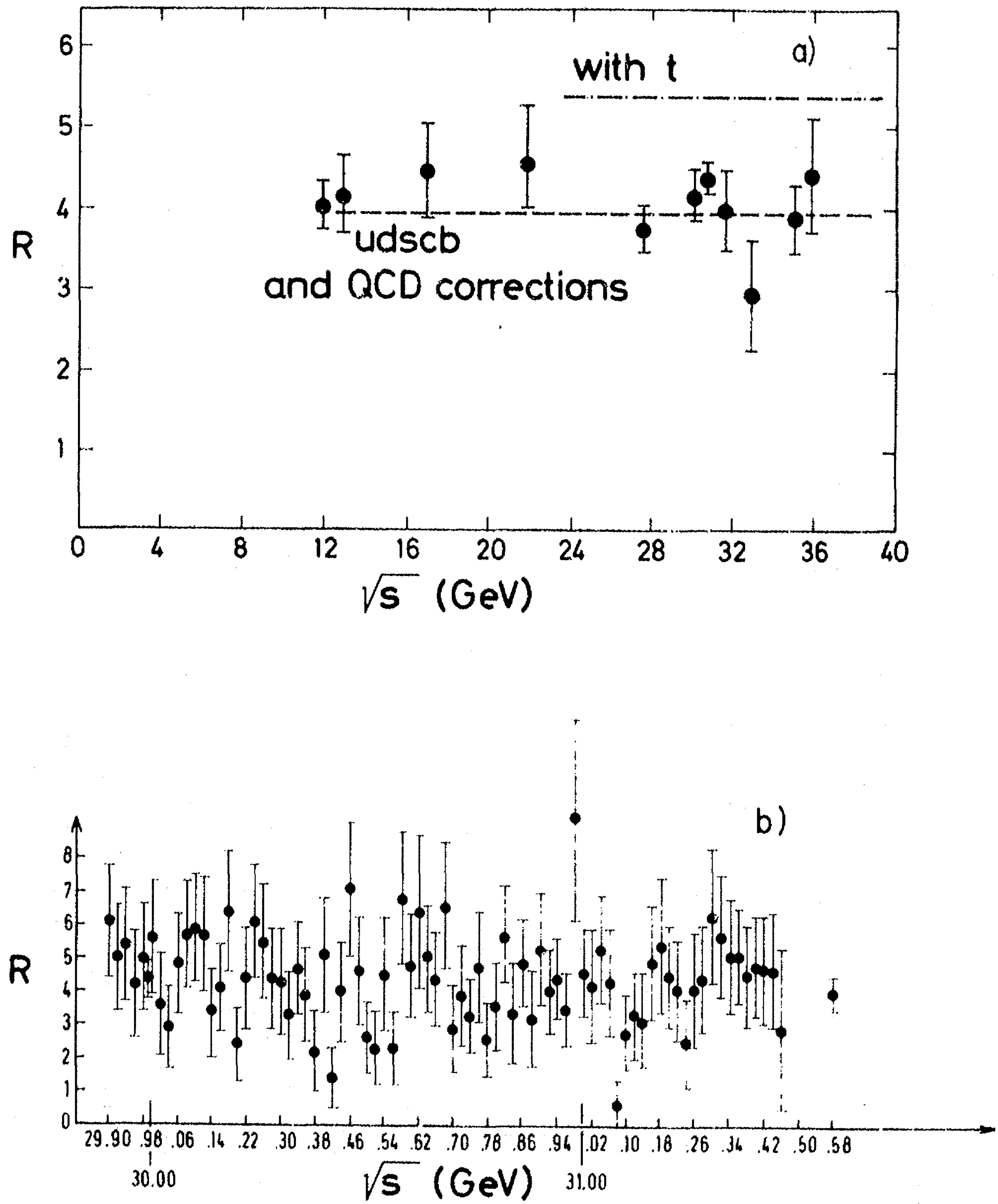

a)
with t
udscb
and QCD corrections
R
0 4 8 12 16 20 24 28 32 36 40
√s (GeV)
b)
R
30.00
31.00
√s (GeV)

FIG. 2

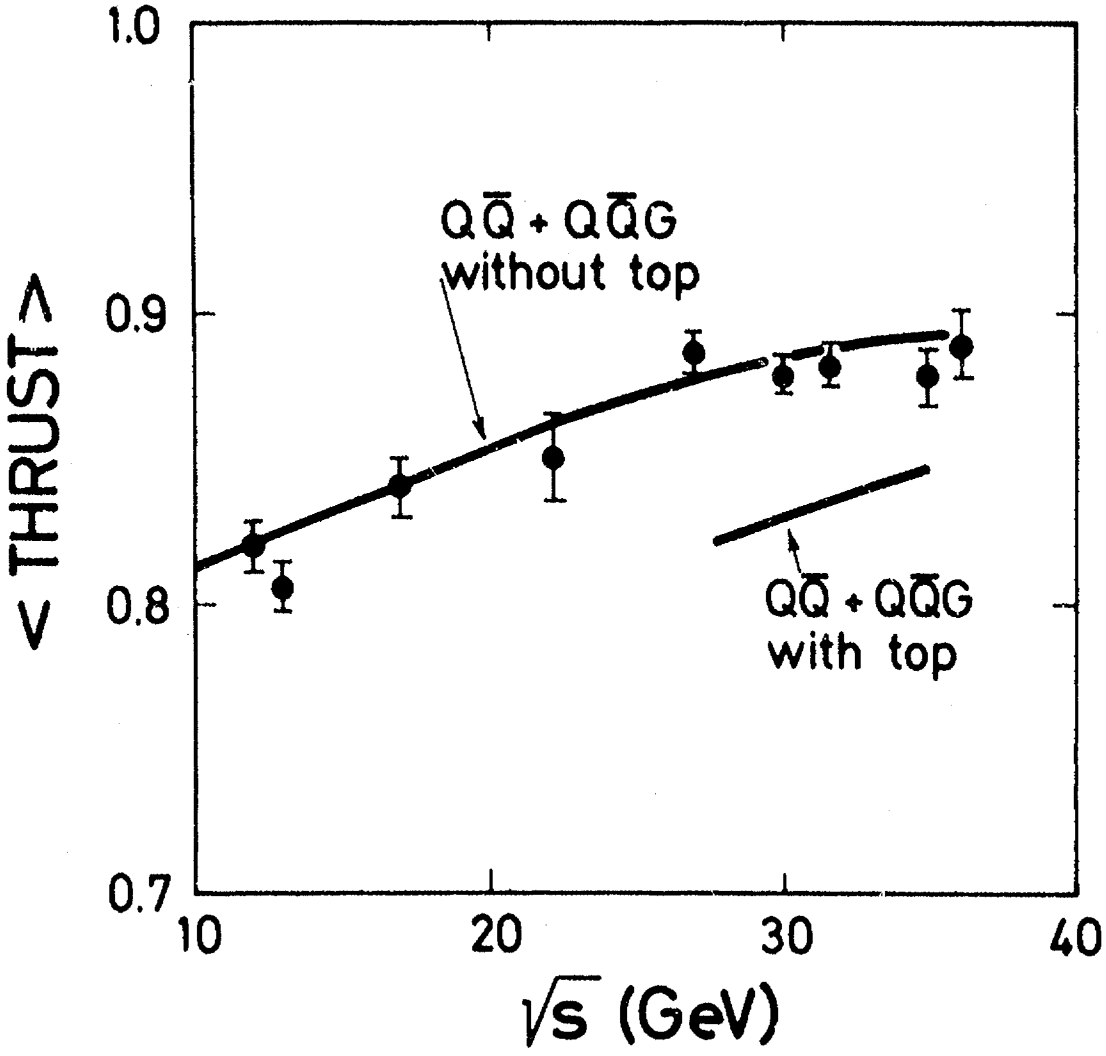
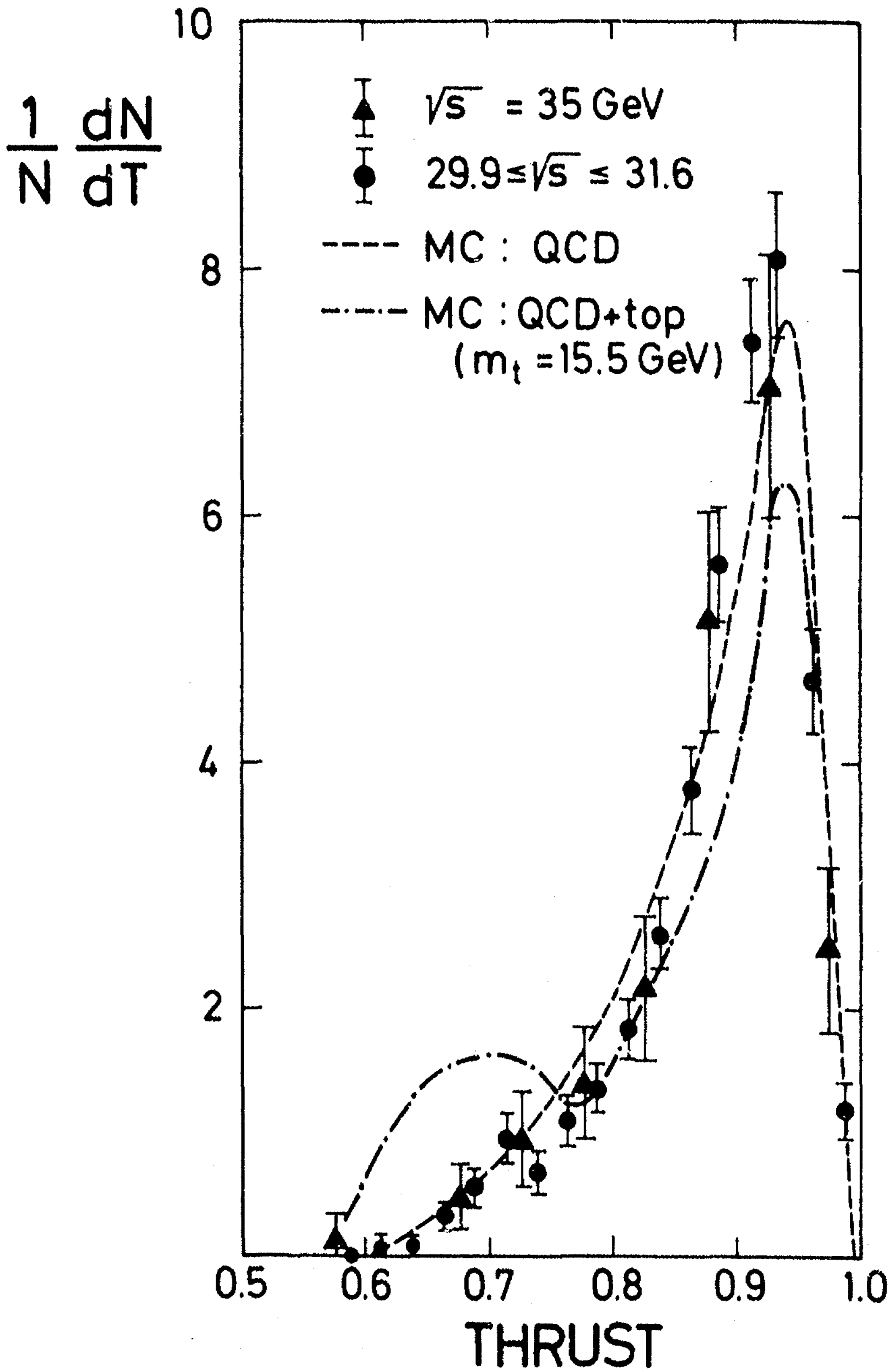

1.0
0.9
0.8
0.7
< THRUST >
$Q\bar{Q} + Q\bar{Q}G$
without top
$Q\bar{Q} + Q\bar{Q}G$
with top
10
20
30
40
$\sqrt{s}$ (GeV)

Fig. 3



$\frac{1}{N}\frac{dN}{dT}$
10
8
6
4
2
$\sqrt{s}$ = 35 GeV
$29.9 \leq \sqrt{s} \leq 31.6$
MC : QCD
MC : QCD+top
(m_t =15.5 GeV)
0.5
0.6
0.7
0.8
0.9
1.0
THRUST

Fig. 4

END

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