Fermi National Accelerator Laboratory

FERMILAB-Pub-80/104-THY
December 1980

# Energy Flow In Hadronic Collisions Around $\sqrt{s} \sim 1$ TeV*

by

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ABSTRACT

Simple energy flow measurements at new $\bar{p}p$ colliders are suggested which will reflect the way in which interaction energy is divided between rest mass and kinetic energy of secondaries. Such experiments will contribute to resolution of a fundamental astrophysical problem, the composition of primary cosmic rays around $10^{15}$ eV.

*Extended version of material presented in a talk at Fermilab, December 8, 1980.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

Various interpretations of cosmic ray experiments lead to quite distinct models of hadronic interactions in the energy range $\sqrt{s} \sim 1$ TeV. They range from a conservative one [1] characterized by hadronic scaling [2] for the inclusive cross sections (but with a total cross section that increases with energy) to a picture in which scaling is strongly violated by production of many particles of low energy [3]. An intermediate possibility is a two-component model with a scaling part and an inelastic part that increases in relative importance over the range $\sqrt{s} \sim 0.1$ to 1 TeV and beyond [4].

This is the energy region around $10^{14}$-$10^{15}$ eV in the lab, where the primary flux becomes so low that only indirect measurements of cascades in the atmosphere have been possible [5]. Any conclusion about chemical composition of the primary nuclei depends therefore upon inferences made from properties of the observed cascade rather than on direct observation of the primaries themselves. Thus, on the one hand, conclusions about primary composition depend on unknown features of hadronic interactions around $\sqrt{s} \sim 1$ TeV and above. At the same time uncertainty about primary composition (as well as about the nucleon interaction length) prevent a conclusion as to which interaction picture is correct.

Since development of cosmic ray cascades depends strongly on the most energetic secondaries, and since most secondaries with $x \gtrsim 0.1$ are likely to be inaccessible to early colliding beam experiments, [#1] there has been some pessimism about how much these experiments will contribute to resolving this set of ambiguities [6]. In this letter I wish to point out a calorimetric measurement that can easily be made (for example during the earliest experiments planned for the CERN or Fermilab $\bar{p}p$ colliders) to distinguish among the possibilities described above. Since it is also planned to measure the $\bar{p}p$ total cross section it will then be possible to make definitive conclusions about primary composition at high energy.

A knowledge of chemical composition of the primary cosmic ray nuclei around $10^{15}$ eV is a prerequisite for understanding their origin, acceleration and propagation. For example, the well-known steepening of the energy spectrum may be a rigidity-dependent effect as gyroradii become comparable with the largest scales which govern acceleration or diffusion in the galaxy. Whether or not this is likely to be the case could be determined if the energy dependence of the composition were known in the neighborhood of the bend at $\sim 10^{15}$ eV [7]. #2

Hillas [8] has already argued that if hadronic scaling is valid (but with a rising cross section) that a comprehensive fit to data from extensive atmospheric showers requires a composition which has an energy-dependence more complicated than a simple rigidity effect. Experiments of the type described below are required to confirm the assumptions used in that and similar analyses of cosmic ray cascades. If, on the other hand, hadronic scaling is violated in the manner suggested by Wdowczyk and Wolfendale [3] and many others, or even in some much less drastic way, that also will show up in energy flow measurements which would lead to an exploration of the implications for hadronic interactions.

Models invoked to explain cosmic ray cascades by violation of hadronic scaling typically display significant softening of hadronic interactions as energy increases. Most of the energy not carried away by a leading nucleon is subdivided among many low energy particles rather than among a few fast secondaries as in scaling. This is one way to account for rapid attenuation of cascades in the atmosphere. (Alternatively, in many cases one can accomplish a similar result by increasing the fraction of heavy primary nuclei.) As a representative example, Fig. 1 shows the energy dependence of the inclusive distribution of charged mesons in a model recently used [9] to explain observed uncorrelated fluxes of various cosmic ray components in the atmosphere. Here $F\ (x,\sqrt{s}) = \frac{\pi}{\sigma_{inel}} \int dp_T^2\ f(x,P_T,\sqrt{s})$, where $f = E\,\frac{d\sigma}{d^3p}$ and $x = 2P_{11}^{cm} / \sqrt{s}$. Similar phenomenological models have long been used to explain small air showers and are still advocated by many as a correct representation of hadronic interactions at high energy.

Wdowczyk and Wolfendale [3] have suggested a parametrization of the inclusive cross section which, while not exhaustive, encompasses models that have traditionally been used in cosmic rays, as well as conventional hadronic scaling. It is

$$F\ (x,\sqrt{s}) = (s/s_0)^{\frac{1-\beta}{2}}\ F\ ((s/s_0)^{\frac{1-\beta}{2}}\ x) \qquad (1)$$

for $s \gtrsim s_0$, where $\sqrt{s_0} \sim 20 - 40$ GeV is the total center of mass energy at some normalization point where accelerator data is used to determine F. Hadronic scaling corresponds to the choice $\beta = 1$ and energy conservation requires $\beta > 0$. The energy dependence shown in Fig. 1 corresponds to $\beta = 0.62$, with the normalization point taken as $\sqrt{s_0} = 43.3$ GeV.

A quantity that can be readily measured in proposed calorimeter experiments at $\bar{p}p$ colliders is the fraction of energy deposited within some angular region excluding cones along the beam pipes. The energy could be subdivided into electromagnetic ($\pi^{\circ}$) and hadronic components as well as into angular bins. The illustration in Fig. 2 shows the average fractions of total energy deposited within the angular regions indicated as a function of the parameter $\beta$. The visible energy increases as interactions soften (decreasing $\beta$). The choice of energies and angles in this example is motivated by designs of central and forward detectors at CERN [10] and FNAL [11]. The inclusive cross sections used to normalize $f\ (x,p_T,\sqrt{s})$ for these simulatopms are based [12] on Fermilab and ISR data and include the x-dependence of the $p_T$-distribution. A fragment nucleon has been chosen independently in each hemisphere from a flat distribution in x. This corresponds to an average of one-half the interaction energy going into produced particles. If this value were energy dependent it also would contribute to the visible energy fraction. These two possible sources of an increase in visible energy might be difficult to distinguish without either (a) measurement of fast secondaries or (b) particle identification to distinguish p from $\bar{p}$, pions and kaons at small x. Either source of increased inelasticity would, however, have a similar effect on cosmic ray cascades.

Finally, Fig. 3 shows the expected distribution of hadronic energy for $\beta = 1$ and $\beta = 0.62$. The presence of two or more components in hadronic interactions could conceivably give rise to structure in this distribution. It is clear from the Figures that simple analysis of a set of minimum bias events should be sufficient to distinguish between conventional hadronic models with $\beta = 1$ and the models with $\beta < 0.75$, thus making possible a clear determination of overall features of composition of primary cosmic rays around $10^{15}$ eV.

Acknowledgements. I am grateful to Prof. Ch. Y. Christov, Prof. P. K. Markov and Todor Stanev for their hospitality at the Institute for Nuclear Research and Nuclear Energy in Sofia, where this work was begun, and to Chris Quigg and J. D. Bjorken for the invitation to visit Fermilab, where it was completed. This research was supported in part by the U. S. Department of Energy (Contract #DE-AS02-78ER05007) and by the National Science Foundation under the U.S.-Bulgaria Cooperative Science Program.

Footnotes

#1 Designs generally plan for detection of particles with $\theta > 1°$. For $p_T$ = 500 MeV $\theta = 1°$ corresponds to Feynman $x \cong .11$ at $\sqrt{s}$ = 540 and $\cong .03$ at $\sqrt{s}$ = 2000 GeV. Most secondaries are expected to have $p_T$ < 500 MeV.

#2 This is because a rigidity-dependent effect affects nuclei of different mass at different total energies.

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## Figures

Fig. 1 Integrated inclusive cross sections of Ref. 9 for production of charged mesons vs. Feynman x at a variety of energies. If hadronic scaling is valid the cross section will be identical to the curve labelled $\sqrt{s}$ = 43.3 GeV at all higher energies.

Fig. 2 Average fraction of total energy in particles produced outside cones surrounding the beam pipes.

Fig. 3 Distribution of fraction of visible hadronic energy in particles produced outside cones of 1°.

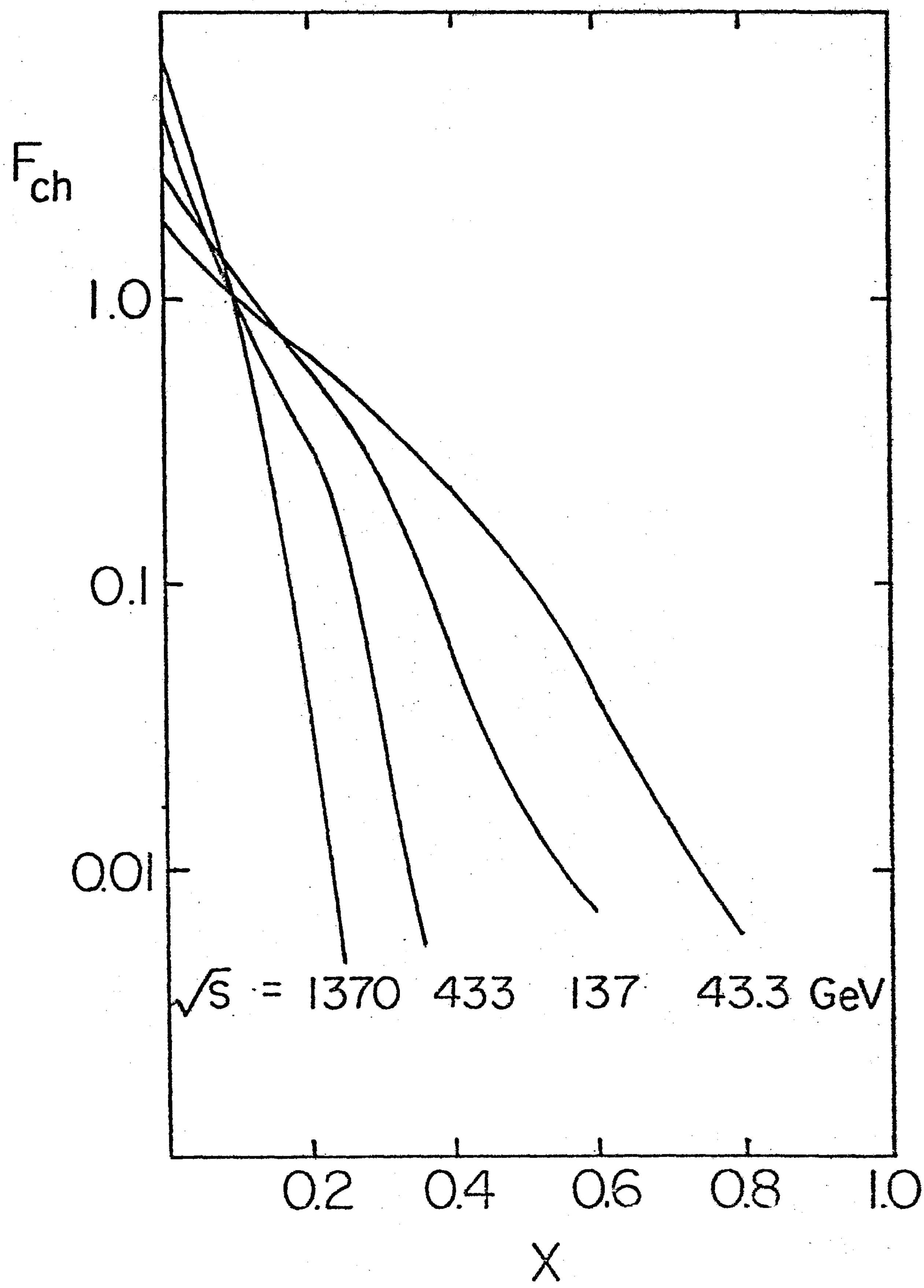
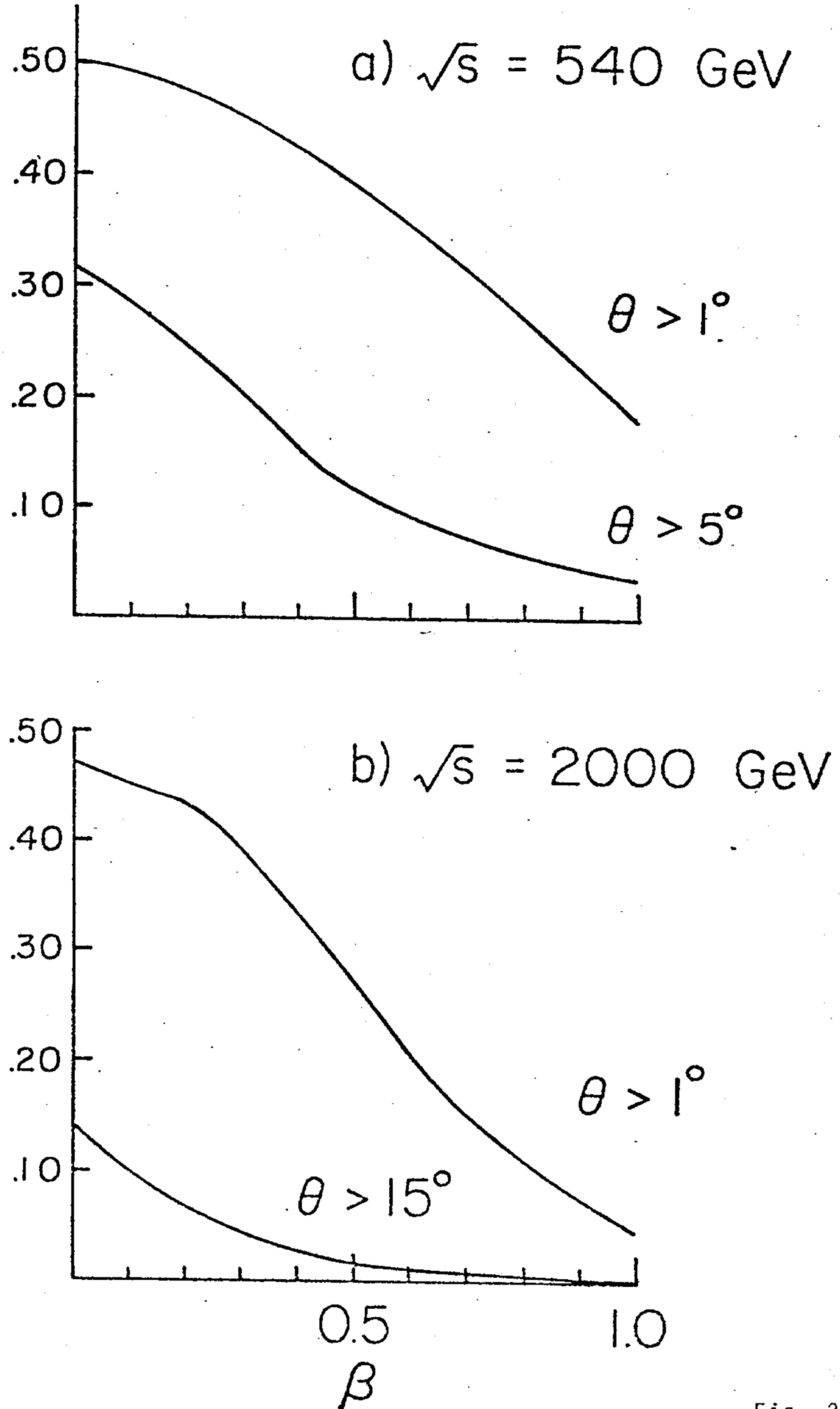
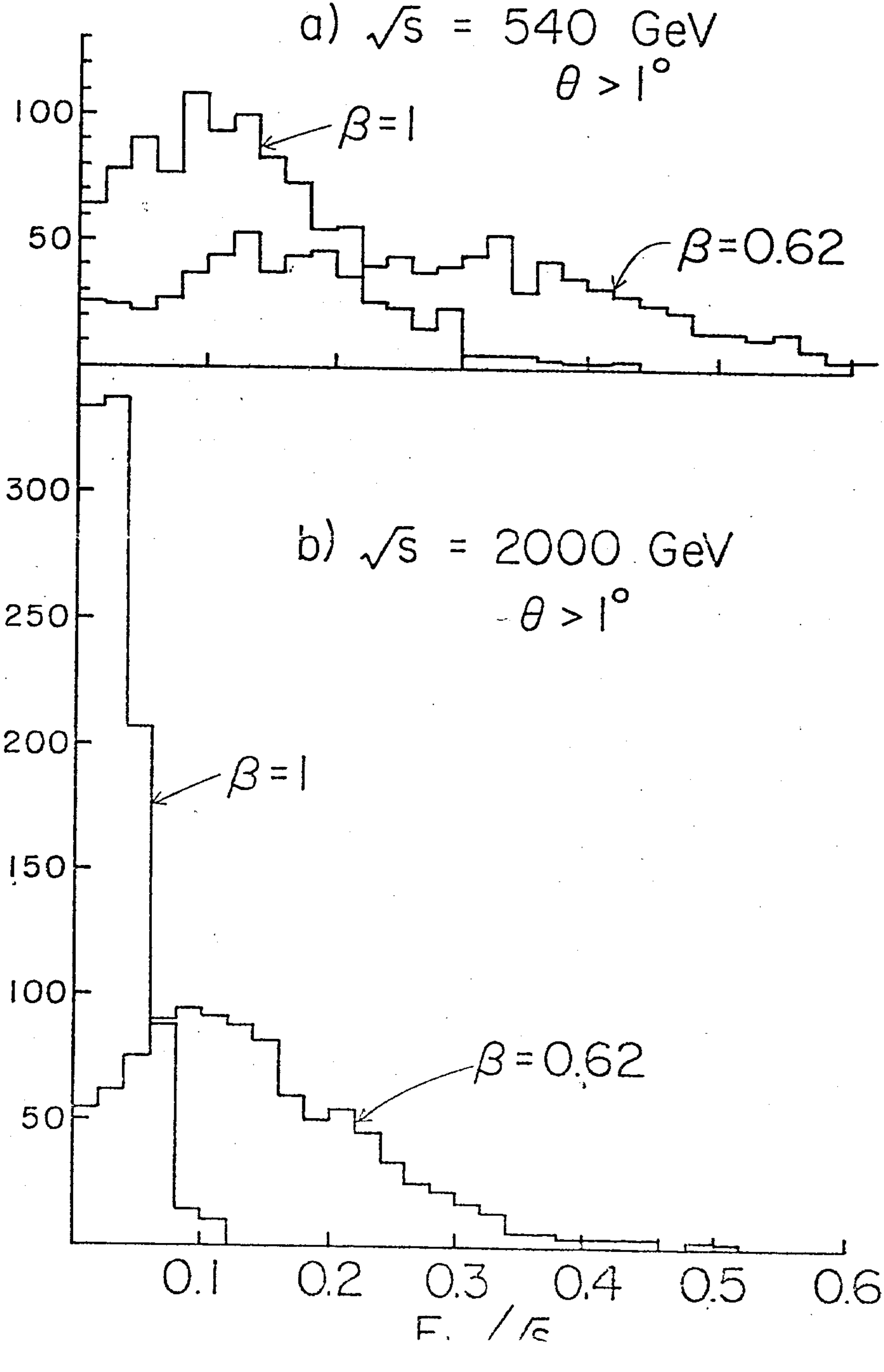



Fig. 1



.50
.40
.30
.20
.10
a) $\sqrt{s}$ = 540 GeV
$\theta > 1°$
$\theta > 5°$
.50
.40
.30
.20
.10
b) $\sqrt{s}$ = 2000 GeV
$\theta > 1°$
$\theta > 15°$
0.5
1.0
$\beta$


Fig. 2


a) √s = 540 GeV
θ > 1°
β=1
β=0.62
b) √s = 2000 GeV
θ > 1°
β=1
β=0.62
100
50
300
250
200
150
100
50
0.1
0.2
0.3
0.4
0.5
0.6