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INCLUSIVE CHARGED-PARTICLE DISTRIBUTION IN NEARLY 3-FOLD SYMMETRIC 3-JET EVENTS AT $E_{cm} = 29$ GEV*

A. Petersen, G. S. Abrams, D. Amidei,[a] A. R. Baden, T. Barklow, A. M. Boyarski, J. Boyer, M. Breidenbach, P. R. Burchat, D. L. Burke, F. Butler, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney,[b] M. S. Gold, G. Goldhaber,[c] L. Golding,[d] J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R. J. Hollebeek, W. R. Innes, J. A. Jaros, I. Juricic, J. A. Kadyk, D. Karlen, S. R. Klein, A. J. Lankford, R. R. Larsen, B. W. LeClaire, M. Levi,[e] N. S. Lockyer,[b] V. L. Lüth,[e] C. Matteuzzi,[e] M. E. Nelson,[f] R. A. Ong, M. L. Perl, B. Richter, K. Riles, M. C. Ross, P. C. Rowson, T. Schaad, H. Schellman,[g] W. B. Schmidke, P. D. Sheldon, G. H. Trilling, C. de la Vaissiere,[h] D. R. Wood, J. M. Yelton,[i] and C. Zaiser

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

Department of Physics, Harvard University
Cambridge, Massachusetts 02138

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a Present address: University of Chicago, Chicago, IL 60637
b Present address: University of Pennsylvania, Philadelphia, PA 19104
c Miller Professor, Miller Institute for Basic Research in Science, Berkeley, CA
d Present address: Therma Wave Corp., Fremont, CA 94539
e Present address: CERN, CH-1211 Geneva 23, Switzerland
f Present address: California Institute of Technology, Pasadena, CA 91125
g Present address: Fermilab, Batavia, IL 60510
h Present address: LPNHE, Univ. Pierre Marie Curie, F-75230 Paris, France
i Present address: Oxford University, Oxford, England

ABSTRACT

We report a measurement of the inclusive charged-particle distribution for gluon jets derived from nearly 3-fold symmetric 3-jet events taken at center of mass energy of 29 GeV in e^+e^- annihilation. The charged-particle spectrum for these jets is observed to fall off more rapidly than those of quark jets of the same energy.

Quantum Chromodynamics (QCD) successfully accounts for many features observed in high energy e^+e^- annihilation data, examples of which include violation of scaling in inclusive particle distributions, jet broadening, and multi-jet events. In the world of QCD, the sources of the experimentally observed jets are quarks and gluons. Jets initiated by quarks or antiquarks have been studied in great detail in various experiments. However, little is known experimentally about jets which originate from high energy gluons. The JADE collaboration[1] has presented evidence that particle distributions in 3-jet events which originate from hard gluon bremsstrahlung ($e^+e^- \to q\bar{q}g$) are only described by models in which gluon jets have a broader and softer fragmentation than quark jets of the same energy. Suggestions of differences between quark and gluon jets are now also reported by the UA1 collaboration[2] in $p\bar{p}$ collisions.

In this Letter, we study inclusive charged-particle production in 3-jet events with nearly 3-fold symmetry under the assumption that the distributions originate from two quark jets and one gluon jet. Although the production of such symmetric events is small, this requirement has the following advantages: all three jets have nearly the same energy ($\simeq 1/3\ E_{cm}$ where E_{cm} is the center-of-mass energy), the jets have the best possible angular separation, and the gluon jet has a relatively high energy. It has been shown that quark and gluon jets do not fragment totally independently in an event[3], but these results indicate that it is mainly the soft particles which are affected, whereas the high momentum particles are produced nearly independently. Hence it is interesting to compare the particle distributions of the above mentioned 3-jet events with distributions of events originating from quark jets having the same jet energies.

The data sample used in this measurement was collected at the PEP storage ring by the Mark II detector at $E_{cm} = 29$ GeV. The total integrated luminosity of 215 pb^{-1} corresponds to the production of approximately 90 000 hadronic events. A precise measurement of the inclusive charged-particle cross section for all events was presented in an earlier paper[4] from a subset of these data.

The Mark II detector has been described in detail elsewhere[5]. Both the inner and main drift chambers are used in charged track reconstruction and provide a momentum resolution of $(\delta\, p/p)^2 = 0.025^2 + (0.01p)^2$ (p is the particle momentum in GeV/c). The track selection criteria are the following: a well-reconstructed charged track has to pass within 1.6 mm in radius (distance of closest approach) and 60 mm in z from the event vertex and have at least 100 MeV/c of transverse momentum. The measured momentum is corrected for energy loss in the material in front of the tracking chambers assuming the particle to be a pion. Neutral particles assumed to be photons are detected by the central region lead-liquid argon calorimeter modules[6], which are 14 radiation lengths in depth. A neutral cluster with energy greater than 150 MeV and a distance (at the radius of the shower counter) of more than 300 mm from the closest charged track is defined as a photon.

Hadronic events were selected by requiring at least 5 well reconstructed charged tracks, a total charged energy greater than 27.5%, and a total charged and neutral energy greater than 55% of E_{cm}.

The eigenvalues of the sphericity tensor[7] are used to classify the events according to their shape in momentum space. For each event the eigenvalues Q_1, Q_2, Q_3 ($Q_1 < Q_2 < Q_3$) and the corresponding principal axes $\vec{q}_1$, $\vec{q}_2$, $\vec{q}_3$ of the momentum ellipsoid are calculated. The sphericity axis ($\vec{q}_3$) is required to have an angle Θ_3 with respect to the beam axis such that $|\cos\Theta_3| < 0.7$. Obvious 2-jet events with normalized eigenvalues $Q_1 < 0.06$ and $Q_2 - Q_1 < 0.05$ are excluded. A cluster algorithm[8], which uses the vector momenta of charged and neutral particles, is used to partition the data into n-jet events. Only the 3-jet events are retained. Each jet is required to have at least 2 GeV of observed energy and to contain at least 3 (charged or neutral) particles.

The jet axes are defined by the vector sum of the particle momenta within each jet. On the assumption of three massless partons the jet energies (E_j) are calculated from the angles between the jet axes projected onto the event plane ($\vec{q}_2$, $\vec{q}_3$)[9]. To require almost 3-fold symmetry for the 3-jet events, all three angles between the jet axes are required to lie between 100° and 140°. After these selection criteria the data sample consists of 560 events, corresponding to about 0.5% of all hadronic events.

Monte Carlo calculations using models containing QCD plus fragmentation estimate a background of (0.4 ± 0.2)%, mainly from the process $e^+e^- \to q\bar{q}\gamma$ where some low momentum charged-particles are produced in the direction of the photon, thereby simulating a third jet. The model calculations show further that the fraction of heavy quarks in this sample is the same fraction as for all hadronic events.

The inclusive charged-particle distribution is analyzed in terms of the fractional momentum $x_i = p_i/E_j$ where p_i is the momentum of particle i, and E_j the energy of the jet to which it is assigned. The fact that all three jets have nearly the same energy, implies that a wrong assignment of a particle to a jet is not a severe problem.

Corrections for detector inefficiencies were computed from Monte Carlo simulations based on three different models for QCD plus fragmentation: the independent parton fragmentation model of Ali et al.[10] and the Lund string model[11], both of which employ parton emission to second-order in α_s, and the QCD cluster model of Webber et al.[12], which uses leading log evolution for the parton showering including soft gluon interferences and cluster decay for the final hadronisation. As a first step, Monte Carlo events were generated without QED radiative effects and passed through the above mentioned cuts yielding N_{gen} events. These events yield the x distribution $n_{gen}(x)$ of all long-lived, charged-particles with lifetimes greater than $3.\ 10^{-10}$ seconds, produced either at the primary vertex or from the decay of short-lived particles including K_s and Λ. Secondly, events were generated including QED radiative effects[13] and traced through the detector. Energy loss, multiple scattering, photon conversion and nuclear interactions in the material of the detector as well as decays were taken into account. This information was then converted into the measured quantities, such as drift times and pulse heights, taking the properties of the apparatus into account. The events were then passed through the same reconstruction algorithms and analysis used for the real data, yielding N_{det} accepted events and producing the particle distribution

$n_{det}(x)$. The correction factors $C(x)$ are calculated as

$$C(x) = \frac{n_{det}(x)}{N_{det}} \Big/ \frac{n_{gen}(x)}{N_{gen}}. \qquad (1)$$

$C(x)$ increases slightly from 0.85 at low x values to 0.92 at high x values.

To determine the systematic uncertainties in the correction, the different models were used and the cuts on $\cos\Theta_3$ and the angles between the jet axes were varied slightly. As an additional check, the axis corresponding to the smallest eigenvalue of the sphericity tensor ($\vec{q}_1$) was restricted to $|\cos\Theta_1| > 0.7$ with respect to the beam axis, so that the total event plane is in the well instrumented area of the detector. The uncertainty in the correction factor is estimated to vary from $\pm$ 0.03 at low x to $\pm$ 0.10 for $x > 0.5$. Figure 1 shows the corrected x distribution (full symbols), where the errors include both statistics and the uncertainty in the correction factor.

To compare this x distribution originating from events containing two quark jets and one gluon jet, each with approximately 9 GeV of energy, with x distributions coming from events containing two quark jets each with about 9 GeV, we use the published data from the HRS collaboration[14] at E_{cm} = 29 GeV, the JADE collaboration[15] and the TASSO collaboration[16] both at E_{cm} = 14, 22 and 34 GeV, and the Mark II collaboration[4] at E_{cm} = 5.2, 6.5 and 29 GeV. In Figure 2 all these cross sections are presented in the form $1/(N_{jet}\sigma_{tot})\ d\sigma/dx$ versus $E_{cm}/\ N_{jet}$ where N_{jet}, the number of jets, is set to two. Within a fixed x interval, all the data points with $N_{jet} = 2$ are fitted to the form suggested by QCD[17]:

$$\frac{1}{\sigma_{tot}} \frac{d\sigma}{dx} = c_1(x)(1 + c_2(x)\, ln(s)) \qquad (2)$$

where $c_1(x)$ and $c_2(x)$ are free parameters. The resulting fits are represented by the curves in Figure 2. Large deviations between the different data points are only visible for low x values, probably due to higher background problems for low momentum tracks.

The cross section of the symmetric 3-jet events with $N_{jet} = 3$ is also plotted in Figure 2. The deviations between these points and the fitted curves (or the data points with $N_{jet} = 2$ themselves) suggest a different slope in the x distribution between 2-jet events and 3-jet events of the same jet energy.

The results of the fits within the twelve intervals from Figure 2 are used to interpolate the cross section at $E_{cm} = 19.3$ GeV. This is shown in Figure 1 as a dotted curve. The 3-jet distribution is observed to fall off faster than that of quark jets, indicated by the curve.

To extract to first approximation an inclusive charged-particle distribution for a gluon jet of $\simeq 9$ GeV energy, we adopted the following ansatz:

$$\begin{aligned}\frac{1}{\sigma_{tot}}\frac{d\sigma}{dx}(\text{gluon jets}) = &\frac{1}{\sigma_{tot}}\frac{d\sigma}{dx}(\text{3–jet events}, E_{cm} = 29\text{ GeV})\\ &-\frac{1}{\sigma_{tot}}\frac{d\sigma}{dx}(\text{all events}, E_{cm} = 19.3\text{ GeV})\end{aligned} \tag{3}$$

where for the events at $E_{cm} = 19.3$ GeV the fit results are again used. This cross section is also shown in Figure 1 (open symbols).

Another way of displaying the data is to calculate the ratio

$$r(x) = \frac{\frac{1}{3\sigma_{tot}}\frac{d\sigma}{dx}(\text{3–jet events}, E_{cm} = 29\text{ GeV})}{\frac{1}{2\sigma_{tot}}\frac{d\sigma}{dx}(\text{all events}, E_{cm} = 19.3\text{ GeV})} \tag{4}$$

as a function of x which is shown in Figure 3.

For comparison, the result of calculations for the three models are also indicated in Figure 3. The quantity r(x) is used for comparison with the models because many of the model parameters and input governing the fragmentation are common to the 3-jet final state at 29 GeV and the 2-jet final state at 19.3 GeV. The effects of the inadequacies in the model features are greatly reduced when the ratio is taken and hence r(x) should be relatively insensitive to how the models are optimized. We have checked that r(x) stays relatively stable in the three models even if the x distributions themselves are changed drastically by adjusting the model features governing the fragmentation process.

The Ali et al. and Lund models do not account well for the trend of the data. A large part of the disagreement comes from the fact that these models use finite order (second-order) for the parton generation. The numerator in r(x) receives only one order of parton radiation because the first order process is used to generate the three parton state. The differences between the two models themselves are mainly due to different assumptions about the gluon fragmentation and the method used to distinguish between 2, 3 and 4-parton events.

On the other hand, the Webber model, which uses leading log evolution for the parton radiation, accounting for multiple parton emission in a more complete way, represents the trend of the data well.

In conclusion we have measured the x distribution for charged particles in nearly 3-fold symmetric 3-jet events produced in e^+e^- annihilation at 29 GeV. On the assumption that these events originate from the quark-antiquark-gluon parton state and using published data on x distributions from quark fragmentation we have obtained the x distribution for gluon jets of 9 GeV energy. When compared with quark jets of the same energy, the gluon x distribution appears to fall off more rapidly for $x > 0.4$.

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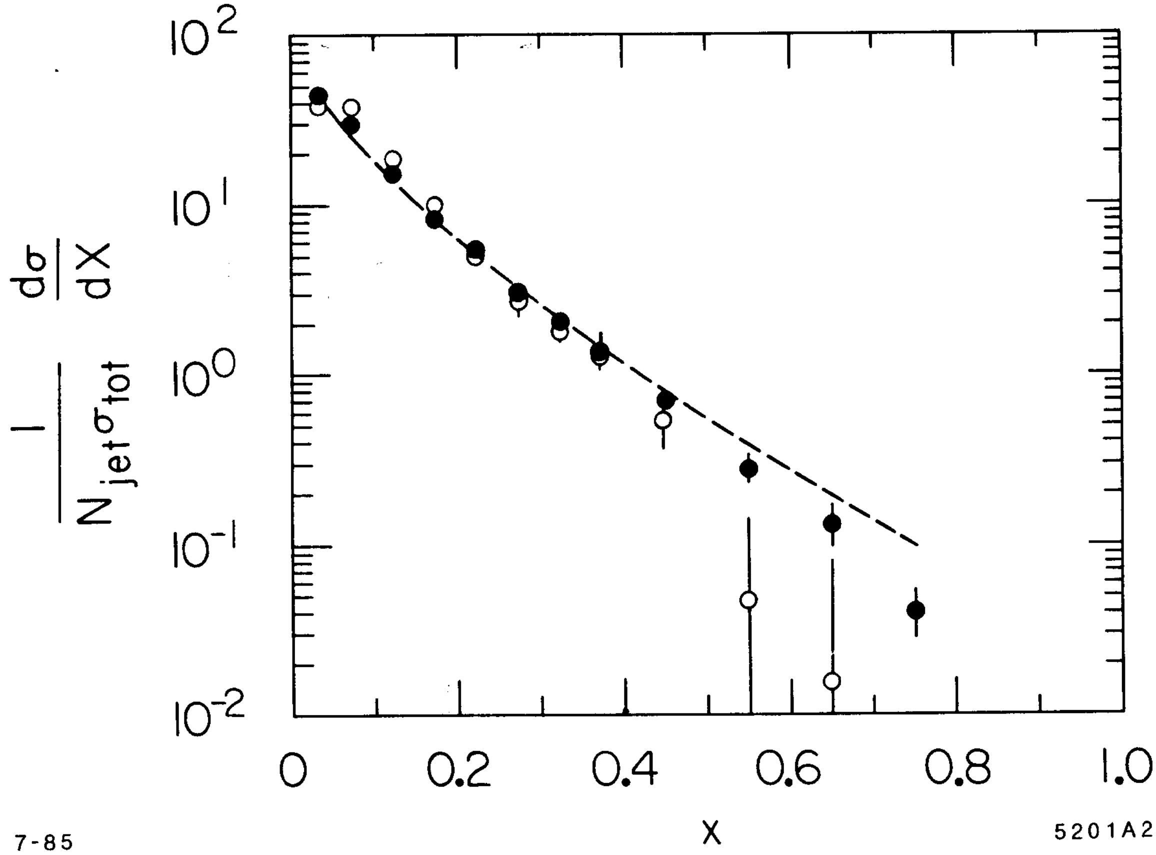
Figure Captions

1. The detector corrected inclusive charged-particle distribution for 3-fold symmetric 3-jet events at E_{cm} = 29 GeV (full symbols) in comparison with the inclusive charged-particle cross section of hadronic events at E_{cm} = 19.3 GeV, extrapolated from the fitted curves in Fig. 2 (dashed curve). The inclusive charged-particle distribution of a gluon jet of E_j = 9 GeV, assuming the subtraction discussed in the text, is shown by the open symbols.

2. The inclusive charged-particle cross section for a jet as a function of the jet energy, as measured by various experiments. The curves represent fits to the different data points for twelve x intervals which are defined by a = $0.03 < x < 0.05$, b = $0.05 < x < 0.10$, c = $0.10 < x < 0.15$, d = $0.15 < x < 0.20$, e = $0.20 < x < 0.25$, f = $0.25 < x < 0.30$, g = $0.30 < x < 0.35$, h = $0.35 < x < 0.40$, i = $0.40 < x < 0.50$, j = $0.50 < x < 0.60$, k = $0.60 < x < 0.70$, l = $0.70 < x < 0.80$. The detector corrected inclusive charged-particle distribution for 3-fold symmetric, 3-jet events at E_{cm} = 29 GeV is also shown.

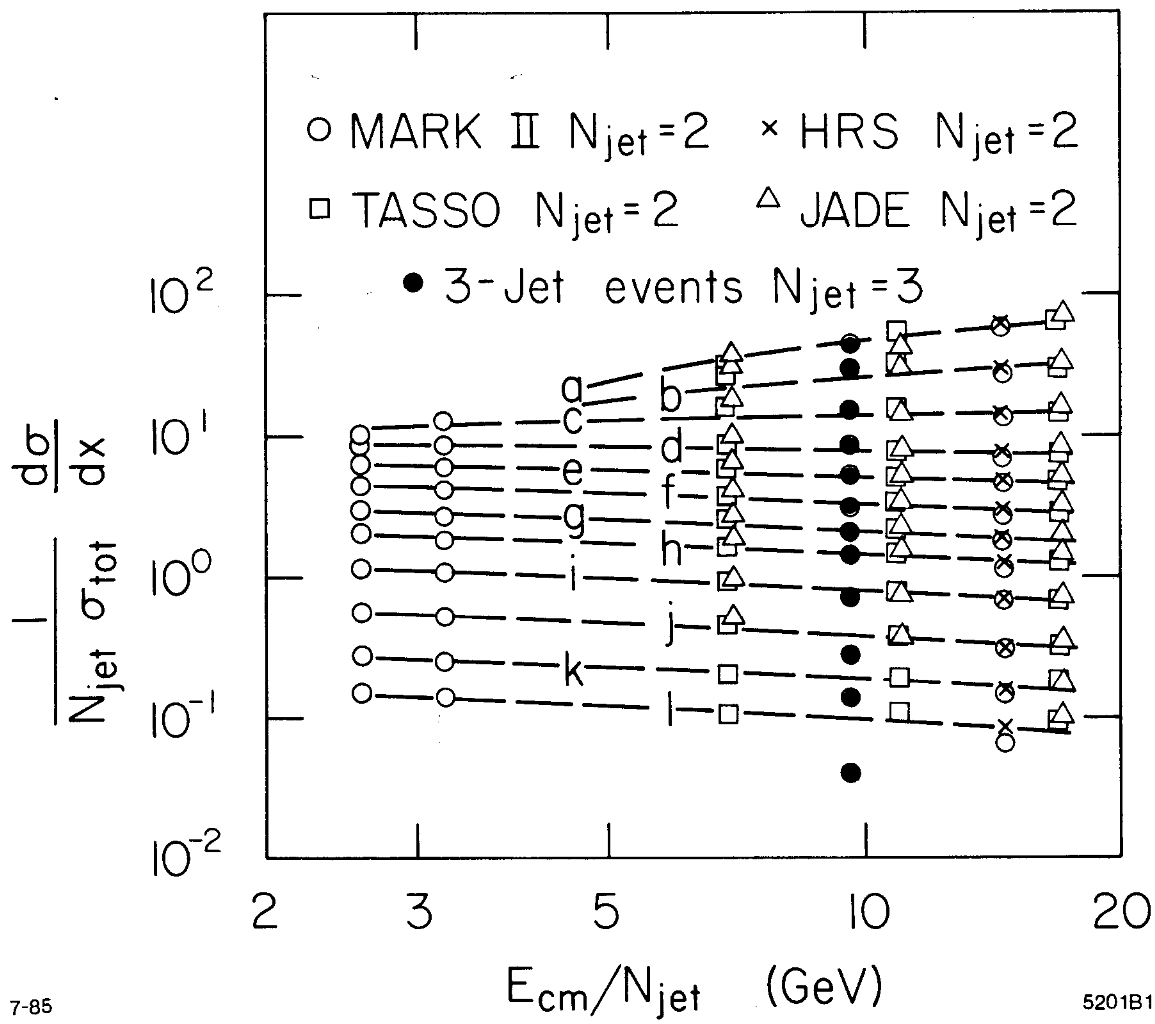
3. The ratio of the detector corrected inclusive charged-particle distribution

for 3-fold symmetric, 3-jet events at $E_{cm} = 29$ GeV to the inclusive charged-particle cross section of hadronic events at $E_{cm} = 19.3$ GeV, together with several model predictions.



$\frac{1}{N_{jet}\sigma_{tot}} \frac{d\sigma}{dX}$
10^2
10^1
10^0
10^-1
10^-2
0
0.2
0.4
0.6
0.8
1.0
X
7-85
5201A2

Fig. 1



○ MARK II N_jet=2
× HRS N_jet=2
□ TASSO N_jet=2
△ JADE N_jet=2
● 3-Jet events N_jet=3
10^2
10^1
10^0
10^{-1}
10^{-2}
a
b
c
d
e
f
g
h
i
j
k
l
$\frac{1}{N_{jet}\ \sigma_{tot}} \frac{d\sigma}{dx}$
2
3
5
10
20
E_{cm}/N_{jet} (GeV)
7-85
5201B1

Fig. 2

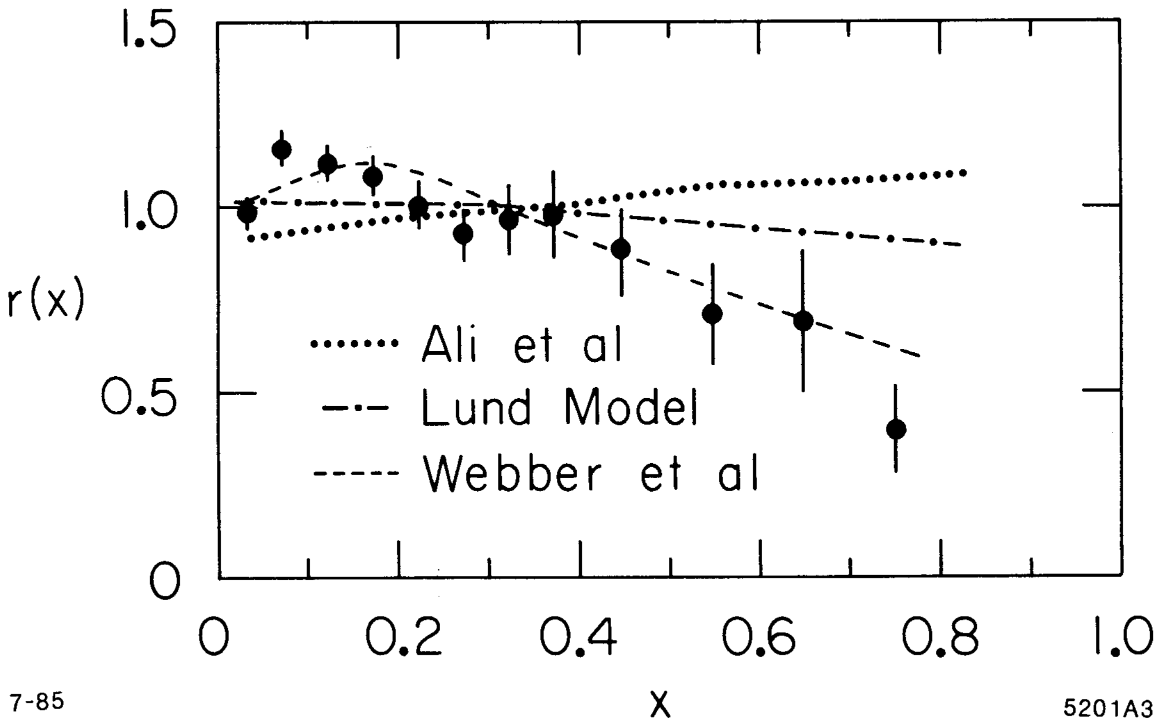

1.5
1.0
0.5
0
r(x)
Ali et al
Lund Model
Webber et al
0
0.2
0.4
0.6
0.8
1.0
X
7-85
5201A3

Fig. 3