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Measurements of Charged Particle Inclusive Distributions in Hadronic Decays of the Z Boson*

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ABSTRACT

We have measured inclusive distributions for charged particles in hadronic decays of the Z boson. The variables chosen for study were charged particle multiplicity, scaled momentum and momenta transverse to the sphericity axes. The distributions have been corrected for detector effects and are compared with data from e^+e^- annihilation at lower energies and with the predictions of several QCD-based models. The data are in reasonable agreement with expectations.

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In this Letter we present measurements of charged particle inclusive distributions in hadronic decays of the Z boson. These distributions allow us to study fragmentation at higher energies than were previously available in e^+e^- annihilation. The data were taken with the Mark II detector at the SLAC e^+e^- Linear Collider (SLC) running at several center-of-mass energies (E_{cm}) near the Z boson resonance peak at 91.1 GeV.[1] The data correspond to a total integrated luminosity of 19.7 nb^{-1}. Comparisons with lower energy data are presented, in particular with measurements at 29 GeV taken with the same detector.

The Mark II detector has been described in detail elsewhere.[2] Charged particles are measured for $|\cos\theta| < 0.92$, where θ is the polar angle relative to the beam direction, with a 72-layer cylindrical drift chamber in a 4.75 kG solenoidal magnetic field. The momentum (p) resolution was determined from Bhabha scattering events at 29 GeV E_{cm} to be $\sigma(p)/p = 0.0046p$ (p in GeV/c) with an additional expected contribution from multiple scattering in the drift chamber itself of 0.014. When the charged tracks are constrained to originate at the e^+e^- collision point, the momentum resolution improves to $\sigma(p)/p = 0.0031p$. The energy and direction of photons are measured in two electromagnetic calorimeter systems with strip readout geometry. The central region ($|\cos\theta| < 0.72$) is covered by lead-liquid argon sampling calorimeters and the endcap region ($0.69 < |\cos\theta| < 0.96$) by lead-proportional tube calorimeters. The trigger system is described in detail in Reference 2. It includes charged particle and neutral energy triggers and has an estimated efficiency of greater than 99% for hadronic Z decays.[1]

Events were selected for this analysis on the basis of the reconstructed charged tracks and electromagnetic showers. The charged tracks were required to pass through a cylinder around the measured e^+e^- interaction point of radius 1 cm and half-length 3 cm along the beam direction. This reduced the number of beam-gas events and tracks from secondary interactions. The polar angles had to satisfy $|\cos \theta| < 0.82$, in order that the tracks traverse a sufficient number of drift chamber layers to have well-measured momenta. The momenta transverse to the beam direction were required to exceed 0.3 GeV/c, so that the tracking efficiency be well understood. For particles with momenta greater than 10 GeV/c, the tracks were refitted using the interaction point as a constraint. This is not a useful procedure for lower momentum particles because of systematic uncertainties in the amount of multiple scattering.

Electromagnetic showers in the central calorimeter were required to satisfy $|\cos \theta| < 0.68$ and to be within the fiducial volume of the calorimeter in azimuth, a total of 63.5% of the solid angle. The fiducial volume for the endcap calorimeter was defined to be $0.74 < |\cos \theta| < 0.95$. An energy greater than 0.5 GeV was required for all showers in order to ensure high detection efficiency and reduce accelerator-related backgrounds. Showers were retained regardless of any association with a charged track.

Events were required to have at least 7 charged tracks passing these cuts in order to reduce contamination from backgrounds, in particular $Z \rightarrow \tau^+\tau^-$. The visible energy was defined to be the sum of the energies of the selected charged particles, calculated assuming pion masses, and the energies of the showers passing the cuts. Events were selected if the visible energy was greater than $0.5E_{cm}$. Events having small visible energies are primarily those with jets close to the beam line and are thus not well measured in the detector. The number of events passing all selection criteria was 381. The efficiency for detecting events was estimated from Monte Carlo simulations to be 0.77 ± 0.01, where the error represents the systematic uncertainty due to differences in the fragmentation models used. Backgrounds from beam-gas scattering, Z decays into lepton pairs and two-photon scattering were estimated to be less than 0.5 event.[3] Contamination from accelerator-related backgrounds was included by superimposing data from random beam crossings onto Monte Carlo events with detector simulation.

The data are compared with events simulated by three QCD-based Monte Carlo event generators. The models used are the Lund parton shower model with string fragmentation (Lund 6.3 Shower),[4] the Webber-Marchesini parton shower model with cluster fragmentation (Webber 4.1),[5] and the parton shower model of Gottschalk and Morris (Caltech-II 86) with a combined fragmentation method.[6] The parameters of these models were tuned to fit Mark II data at 29 GeV.[7] The Lund model based on the second-order QCD matrix element calculated by Gottschalk and Schatz, again with string fragmentation,[4,8] was not used because an extrapolation to 91 GeV is not possible without changing parameters which should be kept constant.[9]

The variables studied were the charged particle multiplicity distribution, the inclusive charged particle distributions in the scaled momentum ($x = 2p/E_{cm}$) and the momentum transverse to the axes of the sphericity tensor[10] both in the event plane ($p_{\perp in}$) and out of the event plane ($p_{\perp out}$). The sphericity axes were calculated using all charged tracks and calorimeter showers passing the selection criteria.

The data were corrected for detector inefficiencies, resolutions and machine backgrounds using bin-by-bin correction factors derived from the Lund 6.3 Shower Monte Carlo with full detector simulation. Charged particles from all K_S^0 and Λ decays were included in the corrected distributions. Typical correction factors were ~ 1.2, with a spread of $\sim 30\%$ for the different bins in each distribution. The correction factors were compared with those derived from the other QCD models and the differences were included in the systematic errors. Corrections for QED radiative effects were included but were less than 2% for these data. All errors shown for these data, except for the first figure, have statistical and systematic uncertainties added in quadrature.

The multiplicity distribution was not corrected using this bin-by-bin method because the correlations between bins are large. Figure 1(a) shows the uncorrected charged particle multiplicity distribution compared with the predictions of several models after detector simulation. An unfold procedure[11] has been used to measure the mean corrected charged particle multiplicity to be 20.1 ± 1.2. Figure 1(b) shows the mean charged particle multiplicity *vs.* E_{cm} for several e^+e^- experiments.[11,12] The solid line is the prediction of the Lund Shower model. Only one model is shown for clarity.

Figure 2(a) shows the corrected inclusive distribution $1/\sigma_{had}\ d\sigma_{trk}/dx$ compared with the predictions of the models, where σ_{had} and σ_{trk} are the total hadronic and charged particle inclusive cross sections, respectively. All of the models predict a spectrum consistent with the observed distribution. Figure 2(b) shows $1/\sigma_{had}\ d\sigma_{trk}/dx$ *vs.* E_{cm} for several x bins, comparing the results of this analysis with data from other e^+e^- experiments at lower E_{cm}.[7,11,13] The solid line is the prediction of the Lund Shower model. Small scaling violations, in agreement with this model and qualitatively expected from QCD, are seen in the higher x bins. The scaling violations in the lower x bins are due to the increase in available phase space for particle production.

Figures 3(a) and 3(b) show the distributions of $p_{\perp in}$ and $p_{\perp out}$ together with the model predictions at 91 GeV and Mark II data taken at 29 GeV.[7] The 91 GeV data agree with the predictions of the models, within errors, over the range shown. A clear increase in transverse momentum at 91 GeV compared with 29 GeV is seen for both $p_{\perp in}$ and $p_{\perp out}$ in the perturbative region ($p_\perp \gtrsim 1$ GeV/c). In contrast, the distributions show little difference in the low $p_\perp$ region, where E_{cm}-independent fragmentation effects are expected to dominate. The corrected mean square values were measured to be $<p^2_{\perp in}> = 0.70 \pm 0.05$ (GeV/c)^2 and $<p^2_{\perp out}> = 0.121 \pm 0.005$ (GeV/c)^2, and these are compared with the results from other experiments in Figure 3(c).[7,11,12,13] The solid lines show the Lund Shower model predictions, which are below our measured values for both $<p^2_{\perp in}>$ and $<p^2_{\perp out}>$. The differences arise mainly from the tails of the data distributions which are broader than the MC predictions.

The charged particle inclusive distributions presented here for hadronic decays of Z bosons are consistent with our extrapolations of the three models and lower energy data. These models also described the detected event shapes, such as sphericity, thrust, aplanarity and number of jets.[3] However, there are indications, e.g. from the momenta transverse to the sphericity axes, that the models tuned at 29 GeV may not fully describe the data at Z energies without further adjustment.

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9. T. Sjöstrand, Int. J. Mod. Phys. **A3**, 751 (1988), see page 764. When changing energies in the Lund second-order matrix element model, the parameter specifying the minimum invariant mass, M_{min}, between two partons should be kept constant. However, the value used in reference 7 at 29 GeV, $M_{min} = 3.5$ GeV, gives a negative two parton cross-section at 91 GeV. The smallest value which could be used at both energies is $M_{min} = 9.3$ GeV, but this value would not allow sufficient soft gluon radiation at 29 GeV.

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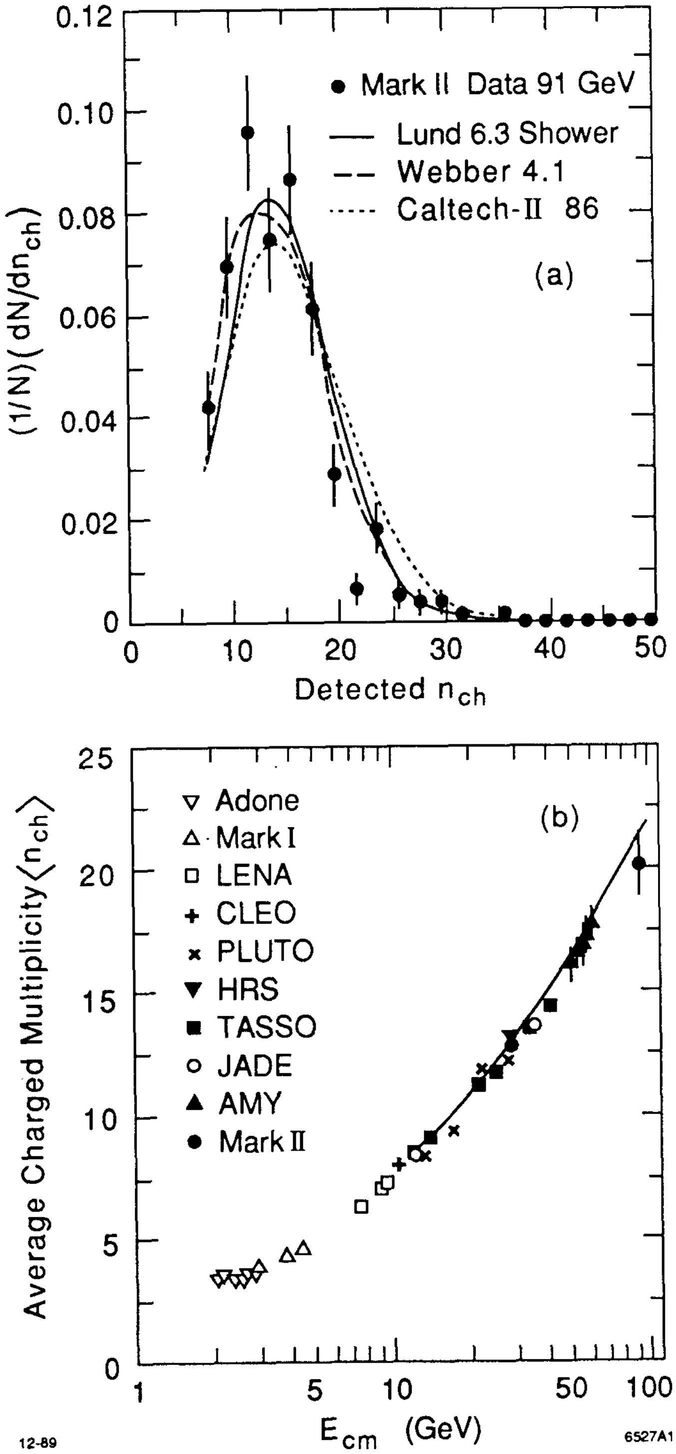
FIGURE CAPTIONS

Fig. 1. (a) Uncorrected charged particle multiplicity distribution for detected hadronic events. Comparisons with several QCD models are shown. (b) Mean corrected charged particle multiplicity *vs.* E_{cm} for various e^+e^- experiments. The solid line is the Lund Shower model prediction.

Fig. 2. (a) Corrected charged particle inclusive distribution $1/\sigma_{had}\ d\sigma_{trk}/dx$, where $x = 2p/E_{cm}$, compared with several models. (b) Comparison between charged particle inclusive distribution in x for hadronic Z decays and various e^+e^- experiments at lower center-of-mass energies. The solid lines are the Lund Shower model prediction.

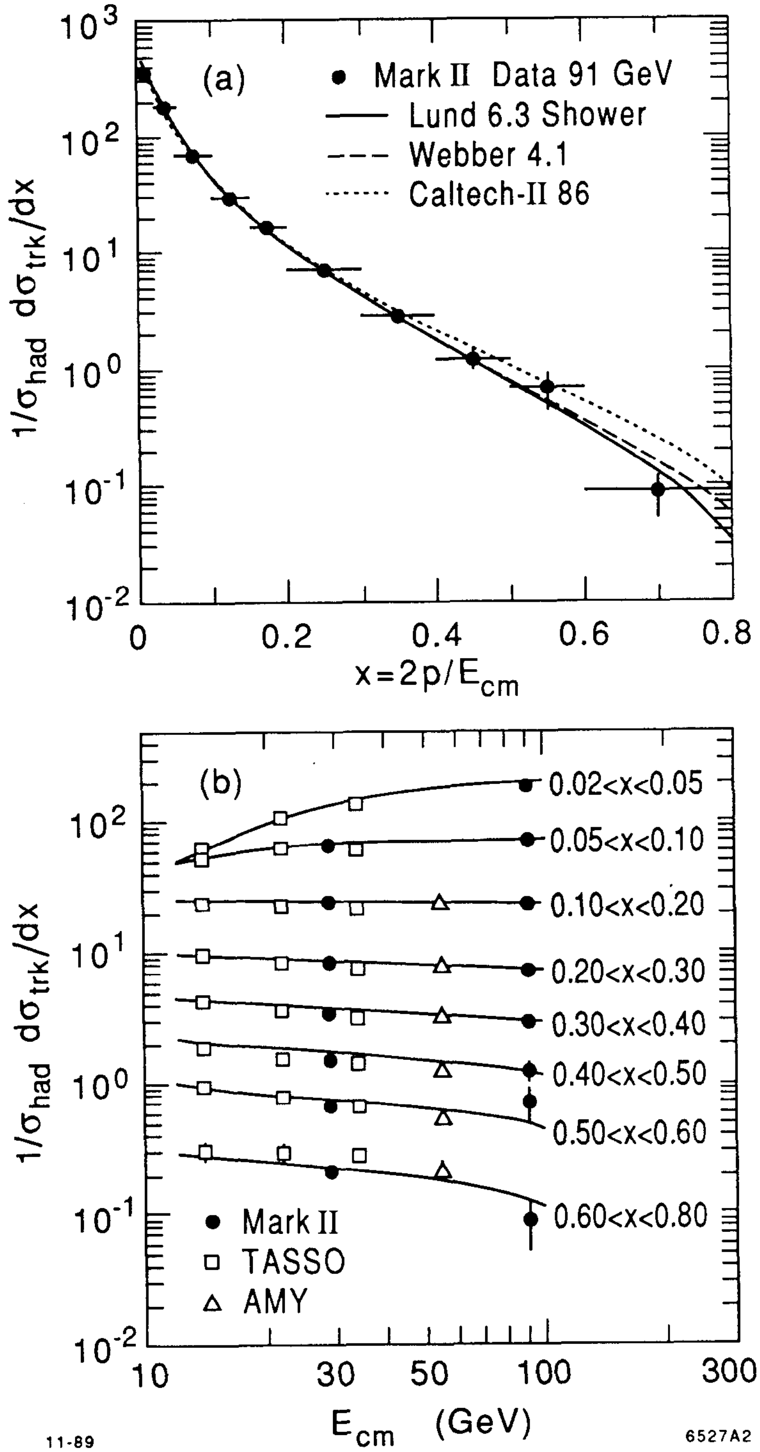
Fig. 3. (a) Corrected charged particle inclusive distribution $1/\sigma_{had}\ d\sigma_{trk}/dp_{\perp in}$ compared with the predictions of several models and with Mark II data at 29 GeV. (b) Corrected charged particle inclusive distribution $1/\sigma_{had}\ d\sigma_{trk}/dp_{\perp out}$ compared with the predictions of several models and with Mark II data at 29 GeV. (c)

Comparison between means of charged particle inclusive distributions in $p^2_{\perp out}$ and $p^2_{\perp in}$ for hadronic Z decays and various e^+e^- experiments at lower center-of-mass energies. The solid lines are the Lund Shower model predictions.



Mark II Data 91 GeV
Lund 6.3 Shower
Webber 4.1
Caltech-II 86
(a)
(1/N)(dN/dn_ch)
Detected n_ch
Adone
Mark I
LENA
CLEO
PLUTO
HRS
TASSO
JADE
AMY
Mark II
(b)
Average Charged Multiplicity ⟨n_ch⟩
E_cm (GeV)
12-89
6527A1

Fig. 1



(a)
Mark II Data 91 GeV
Lund 6.3 Shower
Webber 4.1
Caltech-II 86
1/σhad dσtrk/dx
x=2p/Ecm
0
0.2
0.4
0.6
0.8
(b)
0.02<x<0.05
0.05<x<0.10
0.10<x<0.20
0.20<x<0.30
0.30<x<0.40
0.40<x<0.50
0.50<x<0.60
0.60<x<0.80
Mark II
TASSO
AMY
10
30
50
100
300
Ecm (GeV)
11-89
6527A2

Fig. 2

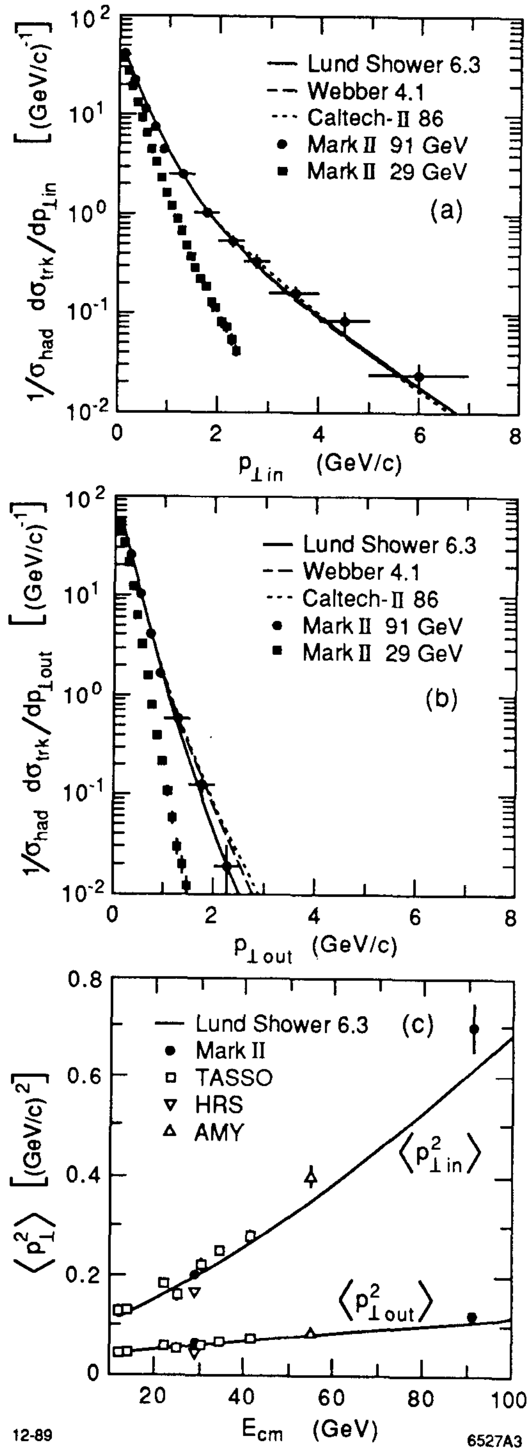

Lund Shower 6.3
Webber 4.1
Caltech-II 86
Mark II 91 GeV
Mark II 29 GeV
(a)
1/σhad dσtrk/dp⊥in [(GeV/c)-1]
p⊥in (GeV/c)
(b)
1/σhad dσtrk/dp⊥out [(GeV/c)-1]
p⊥out (GeV/c)
Lund Shower 6.3
Mark II
TASSO
HRS
AMY
(c)
⟨p²⊥in⟩
⟨p²⊥out⟩
⟨p²⊥⟩ [(GeV/c)²]
Ecm (GeV)
12-89
6527A3

Fig. 3