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# STUDY OF HADRONIC FINAL STATES OF $Z$ BOSON DECAYS*

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We have studied hadronic final states produced in the decays of $Z$ bosons using the Mark II detector at SLC. We have measured the distributions of global shape parameters, inclusive charged particle distributions, charge particle multiplicity and jet multiplicity. The results are compared to predictions of QCD-based models optimized at the PEP energy. The data and models agree within the present statistical precision. We have also investigated a new method to determine the QCD scale parameter $\Lambda_{\overline{MS}}$ using differential jet multiplicity.

## 1. Introduction

In this report we present the initial studies of the hadronic final state of $Z$ boson decay. With increasing center-of-mass energy ($E_{CM}$) of $e^+e^-$ collisions, fragmentation effects relative to $E_{CM}$ decrease much faster ($\sim 1/E_{CM}$) than $\alpha_s$ ($\sim 1/\log E_{CM}$); hence perturbative QCD effects, that were masked by the fragmentation effects at lower energies, become more visible. The $Z$ boson peak is an ideal place to study these perturbative QCD effects[1] since background from two photon processes and initial state radiation effects are very small.

Our results are compared with predictions of the QCD-based Monte Carlo generators.[2][3][4][5] Fragmentation parameters of the models are optimized at 29 GeV using PEP data.[6]

## 2. Detector, Trigger and Event Selection

The Mark II detector has been described in detail elsewhere.[7] It triggers on hadronic $Z$ events by a combination of charged particle and neutral energy triggers which are described in detail in Ref. 7. The two triggers have considerable redundancy and have an estimated combined efficiency of 99.8% for hadronic events from $Z$ boson decay. Events are selected by requiring at least 7 well-reconstructed charged tracks and that the sum of charged particle energies and shower energies ($E_{\text{vis}}$) greater than 0.5 $E_{CM}$. The selection criteria must be simple, unbiased and give events that are well contained within the sensitive regions of the detector. The criteria given above select 269 events. The selection efficiency is estimated using QCD-based Monte Carlo generators[2,3,4,5] to be $0.78 \pm 0.02$. Background events resulting from beam-gas scattering, lepton pairs, and two-photon production are negligible. All the measured distributions shown in this report are corrected for detector effects by applying bin-by-bin correction factors determined from the Monte Carlo simulation.

## 3. Global Event Shape

Sphericity ($S$), Aplanarity ($A$) and Thrust ($T$) are commonly used among the observables for studying global event shape. The individual particle momentum quadratically contributes to $S$ and $A$, whereas $T$ depends on momentum linearly. Both $S$ and $T$ distributions are sensitive to the rate of planar three jet events from the $\mathcal{O}(\alpha_s)$ gluon radiation process but $A$ is sensitive to non-planar multi-jet events expected in $\mathcal{O}(\alpha_s^2)$ and higher

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order QCD processes. The variables $S$ and $T$ fit very well to the prediction of all the models. The tail of the $A$ distribution is slightly underestimated by the Lund model based on $\mathcal{O}(\alpha_s^2)$ matrix elements, because only the leading order term is available for the four jet rate in the $\mathcal{O}(\alpha_s^2)$ calculations. Conversely, the parton shower models naturally incorporate much higher order QCD effects but have more ambiguities in the theory since the parton shower is based on leading-log approximation. These ambiguities somehow help the model to fit the data.

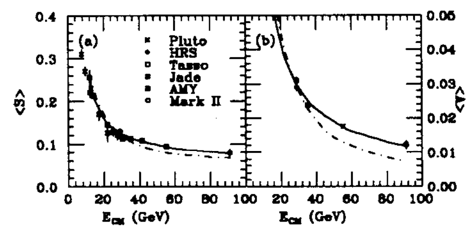


Fig. 1 . The average values of sphericity $S$ and aplanarity $A$ as a function of $E_{CM}$. The solid curve is the Lund shower model prediction. The dot-dashed curve corresponds to the Lund model based on $\mathcal{O}(\alpha_s^2)$ matrix elements.

In Fig. 1 , the average values of $S$ and $A$ are plotted as a function of $E_{CM}$ for the Mark II data as well as data from lower energy $e^+e^-$ experiments.

## 4. Multiplicity and Inclusive Distributions of Charged Particles

The averaged charged multiplicity of hadronic events at the $Z$ boson peak corrected for detector effects is $20.8 \pm 0.8 \pm 0.5$. This value fits the extrapolation from the lower energy data using the Lund shower model.

The Mark II experiment is the only one which has measured the inclusive momentum distribution in a very wide $E_{CM}$ range (at SPEAR, PEP and SLC). The scaled momentum distributions ($x_p = \frac{2\,p}{E_{CM}}$) is shown in Fig. 2, where scaling violation in the large $x_p$ region ($x_p \geq 0.3$)

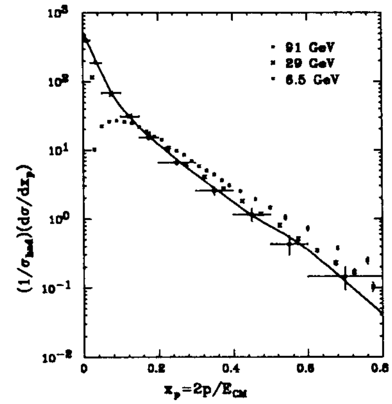


Fig. 2 . The scaled momentum distribution measured by Mark II at $E_{CM} = 6.5$ GeV, 29 GeV and 91 GeV.

is clearly observed from the PEP data to the SLC data. The scaling violation can be explained by emissions of soft gluons, which reduce the momentum of the primary quarks and soften the momentum of leading hadron coming from the primary quark.

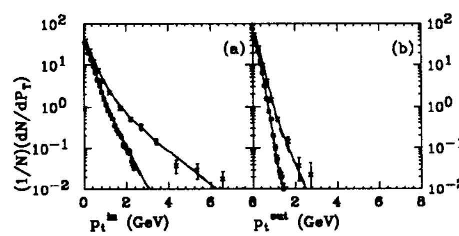


Fig. 3 . The $p_t^{in}$ and $p_t^{out}$ distribution at SLC (crosses) and PEP (circles). Also shown are the predictions of the Lund shower model.

The inclusive distributions of transverse momentum within the event plane ($p_t^{in}$) and out of event plane ($p_t^{out}$) measured at SLC (cross points with error bars) are shown in Fig.3(a) and (b). The event plane is defined from sphericity analysis. In the figures, the PEP data (circle points with error bars) and the Lund shower model predictions (solid curves) are also shown. In the small

$p_t$ region ($p_t$ < 1 GeV) for both $p_t^{in}$ and $p_t^{out}$, the distributions for the SLC data and for the PEP data are fairly similar. This indicates that the $p_t$ distribution of soft fragmentation region does not depend on the $E_{CM}$ of the hard processes where the high momentum quarks and gluons are produced. The long tail of the $p_t^{in}$ distribution at SLC is expected to be mainly due to the $e^+e^- \to q\bar{q}g$ process. We checked using the Lund shower model that a factor two difference of the $b\bar{b}$ event fraction from PEP to SLC does not affect the $p_t$ distributions.

## 5. Studies of Methods to Determine the Coupling of Strong Interaction

One of the classical methods for measuring $\alpha_s$ is to count the number of hard three jet events. We use the algorithm proposed by the JADE collaboration.[8,9] A good feature of this algorithm is that mapping from a parton jet into a corresponding hadron jet is almost one-to-one. The Lund shower model prediction for the jet multiplicity agrees very well with the data, whereas a deficit of the four jet events is observed in the case of the model based on the second order QCD calculations as discussed earlier. Note that the measurement of n-jet fractions at different $y_{cut}$ values are highly correlated since the same events contribute at different $y_{cut}$ values. Therefore it is not straight forward to fit the $f_3(y_{cut})$ distribution as a function of $y_{cut}$. This problem can be solved if a differential distribution is used. The differential jet multiplicity is defined in the following way. For each event, particles are forced to be clustered into $n$-jets using the jet algorithm, and $y_n$ is defined as the minimum value of $y_{ij}$'s ($i \neq j,\ i,j = 1,2,...,n$). If $g_3(y_3)$ is integrated over $y_3$ from 0 to $y_{cut}$, one recovers $f_2(y_{cut})$, therefore $g_3(y_3)|_{y_3=y_{cut}} = \frac{\partial}{\partial y_{cut}} f_2(y_{cut})$. Similarly, $g_4$ can be defined but it does not have the next-to-leading order corrections in the $\mathcal{O}(\alpha_s^2)$ calculation. Therefore the only reliable differential jet fraction is $g_3(y_3)$ in $\mathcal{O}(\alpha_s^2)$.

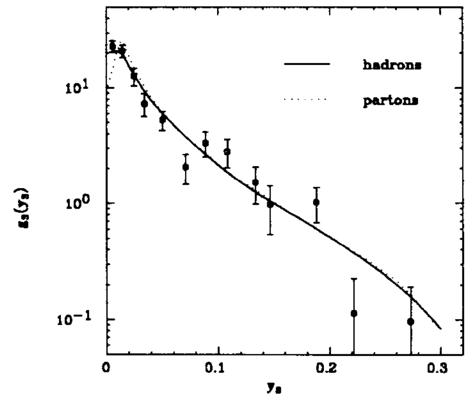


Fig. 4 . $g_3(y_3)$ distribution at SLC: the solid curve is the prediction of the Lund model based on $\mathcal{O}(\alpha_s^2)$ matrix element for partons (dotted curve) and for hadrons after fragmentation (solid curve).

Fragmentation effects on $g_3$ are estimated to be typically a few percent for $y_3 > 0.04$ at 91 GeV. In Fig.4, the $g_3(y_3)$ distribution is plotted together with QCD predictions for various $\Lambda_{\overline{MS}}$ values. The data still have too large statistical errors for obtaining an accurate $\Lambda_{\overline{MS}}$ value.*

Fitting Energy-Energy-Correlation (EEC) asymmetry with model predictions while letting $\alpha_s$ free to vary is an established method to determine $\alpha_s$. The EEC ($\Sigma(\chi)$) is essentially the opening angle distribution between any two particles weighted by the product of their energies of the two particles:

$$\Sigma(\chi) = \frac{1}{N_{ev}} \sum_{n=1}^{N_{ev}} \sum_i \sum_j \frac{E_i}{E_{\text{vis}}} \frac{E_j}{E_{\text{vis}}} \delta(\chi - \chi_{ij}).$$

In Fig.5, the EEC asymmetry $A(\chi) = \Sigma(\chi) - \Sigma(\pi - \chi)$ is plotted for the data at SLC. Also shown in the

* After the meeting, having accumulated more data and we determine the strong coupling $\alpha_s$ to be 0.123±0.09±0.05 GeV at the SLC, choosing the renormalization point $Q^2$ to be $E_{CM}^2$. By using the same analysis method, $\alpha_s$ was measured to be $0.149 \pm 0.002 \pm 0.007$ at PEP. The running of $\alpha_s$ from PEP to SLC is consistent with the QCD prediction.

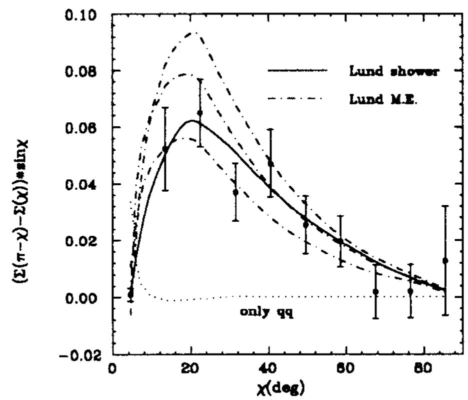


Fig. 5 $A(\chi) = \Sigma(\chi) - \Sigma(\pi - \chi)$ is plotted for the SLC data. The solid curve is the prediction of Lund shower model with $\Lambda_{LLA} = 0.4$ GeV. The dot-dashed curves are the prediction of the Lund model based on $\mathcal{O}(\alpha_s^2)$ matrix element with $\Lambda_{\overline{MS}} = 0.5$ GeV, 0.33 GeV and 0.1 GeV. The dotted curve is the asymmetry for $\alpha_s = 0$ (only two jets).

figure are the predictions of the Lund shower model (solid curve) and of the Lund model based on $\mathcal{O}(\alpha_s^2)$ matrix elements calculated by Gottschalk and Shatz for three $\Lambda_{\overline{MS}}$ values (broken curves). Both models fit the data well with the $\Lambda_{\overline{MS}}$ value obtained at PEP. Fragmentation effects are not negligible for $A(\chi)$ even for large $\chi$ values. At $\chi = 30°$, these effects account for about 30 % at SLC. Therefore an extensive study of the fragmentation effects is needed to estimate the corresponding systematic uncertainties.

## 6. SUMMARY

We have measured properties of multihadron events from $Z$ boson decays. The distributions of global shape parameters (sphericity, aplanarity, thrust), charged multiplicity, scaled momentum ($x_p$), $p_t^{in}$ and $p_t^{out}$, jet multiplicity as a function of jet resolution, differential jet multiplicity, and energy-energy-correlation and its asymmetry are measured. The distributions are compared with data from lower energy $e^+e^-$ experiments and with predictions of QCD-based models. Fragmentation parameters in the models are optimized at 29 GeV and fixed to those values, whereas the QCD part is evolved naturally by the models with increasing $E_{CM}$. The data agree well with these model predictions. In particular, predictions of the parton shower models fit the data very well. We have developed a method to measure the QCD scale parameter $\Lambda_{\overline{MS}}$ using a differential jet multiplicity distribution, which is very insensitive to the fragmentation effects.

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