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Measurement of the Strong Coupling Constant α_s at the Z^0 Resonance Using Modified Jet Mass Difference

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JUN 15 1992

ABSTRACT

A modified jet mass difference (Thrust Criterion) technique is used to extract the value of $\alpha_s(M^2_{Z^0})$. This new technique suppresses fragmentation uncertainty, reducing the overall systematic error. Based on this method and using results from 2 LEP experiments we determine $\alpha_s(M^2_{Z^0}) = 0.127 \pm 0.004$, where the errors have been added in quadrature.

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1 Introduction

The strong coupling constant, α_s, is a key parameter for testing QCD theory and for understanding other aspects of hadronic physics. The value of α_s, for example, is sensitive to the SUSY model [1] and may also be used to put a limit on the mass of the top quark [2]. Moreover, to test if α_s is running with energy as the QCD theory predicts, the value of α_s measured at $s = M_{Z^0}^2$ is needed in order to compare it with values of α_s measured at lower energies.

Electron-positron colliders provide an excellent environment for determining the value of α_s. Measurements made by e^+e^- detectors tend to have less systematic uncertainties than similar measurements made with detectors on hadron colliders. This permits a decrease in systematic error for many QCD analyses, including the determination of α_s.

A precise value of α_s is difficult to determine even at e^+e^- colliders. There are intrinsic uncertainties in this measurement due to the fact that QCD theory describes hadron physics in its early stages, when there are only quarks and gluons (partons), while detectors observe a final state of color singlet hadrons. Mapping between the parton level and the hadron level is not well understood, although Monte Carlo models exist which attempt to bridge this gap by implementing a scheme for fragmentation of the partons. Two examples are the string fragmentation scheme [3] implemented in Lund Jetset and the cluster fragmentation scheme [4] implemented in Herwig.

Most analyses attempt to minimize the effect of the theoretical uncertainty by measuring observables that are sensitive to α_s but insensitive to fragmentation. One parameter typically chosen for this purpose is R (the ratio of hadronic to leptonic Z decay widths). This parameter has the advantage of being insensitive to fragmentation but has the disadvantage of being relatively insensitive to α_s, as well. As a result, a small systematic error in the measured value of R contributes to a large error in the value of α_s. It is worth mentioning here that analyses extracting α_s from R [5] appear to measure a larger mean value for α_s than analyses based on other QCD event shape variables [6]. It is not yet known if this discrepancy is due to experimental errors in measurements of R or underestimation of fragmentation and other nonperturbative effects in the QCD event shape variables. The more recent results [24] [26] [27] [28] show that the values α_s from R and the other QCD event shape variables are in better agreement. In this paper we present a new method for determining α_s which is insensitive to fragmentation and gives very small systematic errors.

2 The Modified Jet Mass Difference

Heavy jet mass was proposed as an event shape variable in ref [7] because it is infrared insensitive and is not very sensitive to high order corrections. There are commonly two definitions for jet mass: Mass Criterion and Thrust Criterion. The former definition divides the final state of an hadronic event into two groups, I and II, in such a way that the sum of the invariant mass of the two groups is minimal. The larger of (M_I^2, M_{II}^2) is called the heavy jet mass, the smaller the light jet mass. This method, however, has been

found to contain biases [8] and is not employed in our analysis. The latter (and more common) definition of jet mass divides an hadronic event according to its thrust [9] axis. The invariant mass of each of two hemispheres, defined by a plane perpendicular to the thrust axis, is measured and then scaled by the square of the Center of Mass energy of the event. The larger of the two quantities is called the heavy jet mass, $< M_h^2/s >$, the smaller the light jet mass, $< M_l^2/s >$.

The observables $< M_h^2/s >$ and $< (M_h^2 - M_l^2)/s >$ as defined by the Thrust Criterion may be expressed in QCD theory to second order [10] in α_s:

$$< M_h^2/s >= 1.05(\alpha_s/\pi) + (4.7 \pm 0.1)(\alpha_s/\pi)^2 \tag{1}$$

$$< M_d^2/s >\equiv< (M_h^2 - M_l^2)/s >= 1.05(\alpha_s/\pi) + (-0.1 \pm 0.1)(\alpha_s/\pi)^2. \tag{2}$$

The modified jet mass difference, $< MM_d^2/s >$, presented in this analysis as an event variable for determining α_s, is the following linear combination of these two quantities:

$$< MM_d^2/s >\equiv< (3M_h^2 - M_l^2)/s >= 3.15(\alpha_s/\pi) + (9.3 \pm 0.3)(\alpha_s/\pi)^2. \tag{3}$$

This particular linear combination is chosen for its ability to minimize the effect of the fragmentation (section 4), while preserving agreement between the theoretical expectation and observation at the parton level in the Monte Carlo program (section 3).

3 Comparison Between Theory and Monte Carlo

We have tested the ability of eq.(3) to reproduce the expectation value $< MM_d^2/s >$ measured from events generated by Lund Jetset 7.3 using the ERT Matrix Element [11]. A total of 100,000 (hadron) events were generated at each of five different values of $\Lambda_{\overline{MS}}$ [12] ranging from 0.1 GeV to 0.5 GeV with $y_{min} = 0.01$. For each value of $\Lambda_{\overline{MS}}$, the value of α_s is fixed by the following equation:

$$\alpha_s = \frac{1}{b_0 \log(\mu^2/\Lambda^2)}\left(1 - \frac{b_1 \log(\log(\mu^2/\Lambda^2))}{(b_0^2 \log(\mu^2/\Lambda^2)}\right) \tag{4}$$

where $b_0 = \frac{33-2N_f}{12\pi}$, $b_1 = \frac{153-19N_f}{24\pi^2}$, and N_f is the number of flavours [13]. The quantity $< MM_d^2/s >$ is then measured for each event at the parton level and at the hadron level.

Results of this check can be seen in fig.(1) and fig.(2). The plots indicate that eq.(3) agrees very closely at parton level with the ERT Matrix Element implemented in Lund Jetset 7.3. From fig.(2) we assign the deviation between the Monte Carlo at parton level and eq.(3) to be the theoretical uncertainty in the value of α_s and which is equal to 0.0017 [14]. Moreover, it appears that it is possible at the hadron level to extract the input value of α_s from the measured $< MM_d^2/s >$ to a very good precision over the large range of 0.1 GeV$< \Lambda_{\overline{MS}} <$0.5 GeV.

4 Sensitivity to Fragmentation

Sensitivity of the theory to Monte Carlo fragmentation was studied by measuring $< M_h^2/s >$, $< M_d^2/s >$, and several linear combinations of these quantities in events generated using Lund Jetset 7.3 with ERT Matrix Element , Lund Jetset 7.3 with Parton Shower [15], and Herwig 5.1 [16]. For each value, 100,000 events were generated at each of five different values of $\Lambda_{\overline{MS}}$ for Lund-Matrix, Λ_{LLA} for Lund-Parton Shower, and Λ_{QCD} for Herwig ranging from 0.1 GeV to 0.5 GeV.

Figures (3-5) compare the fragmentation effects (plotted as $\frac{|<O>_{qrk}-<O>_{had}|}{<O>_{qrk}}$) of $< M_h^2/s >$, $< M_d^2/s >$,and $< MM_d^2/s >$. The quantity $< MM_d^2/s >$, defined in eq.(3) as the modified jet mass difference, is selected because it is the linear combination of $< M_h^2/s >$ and $< M_d^2/s >$ with smallest sensitivity overall to fragmentation. The figures show relatively small deviations in the modified jet mass difference $< MM_d^2/s >$ due to fragmentation, regardless of the model. Both $< M_h^2/s >$ and $< M_d^2/s >$, however, have larger fragmentation effects in all three models, with $< M_d^2/s >$ being the least stable of the three quantities, deviating by more than 20% from nominal value when the ERT Matrix Element method is employed.

The modified jet mass difference is demonstrated in fig.(3) to be less sensitive to fragmentation effects than $< M_h^2/s >$ and $< M_d^2/s >$; however, there is still some variation evident when $\Lambda_{\overline{MS}}$ is scaled from parton level (high values of $\Lambda_{\overline{MS}}$) to hadron level (low values of $\Lambda_{\overline{MS}}$). The same is true when the fragmentation effects are measured over the same range of Λ_{LLA} using the Lund Jetset 7.3 Parton Shower (fig. 4) and over the same range of Λ_{QCD} using Herwig 5.1 (fig. 5). Variations in $< MM_d^2/s >$ due to fragmentation give rise to variations in the extracted value of α_s. This relationship, derived from eq.(3), is

$$\Delta\alpha_s = 0.814\ \Delta(< MM_d^2/s >) \tag{5}$$

for small variations in α_s around the value $\alpha_s = 0.120$. The uncertainty of this relationship is less than 2.2% when α_s is varied over the range corresponding to the values of $\Lambda_{\overline{MS}}$ plotted in fig.(3). Although there is no straightforward relationship between $\Lambda_{\overline{MS}}$, Λ_{LLA}, and Λ_{QCD} [17], relatively small contributions to $\Delta\alpha_s$ due to higher order corrections (section 5) permit the use of eq.(5) to estimate the uncertainty of α_s due to fragmentation for all three Monte Carlo fragmentation methods. These values are presented in table (1). An overall uncertainty of $\Delta\alpha_s = 0.003$ due to fragmentation is estimated from this table.

The value of α_s extracted from the modified jet mass difference, in addition to being less sensitive to fragmentation and less dependent on the fragmentation model employed, is stable with respect to variations of the Monte Carlo fragmentation parameters. Varying the parameter A in the Lund Jetset with Matrix Element, for example, by ± 0.3 from its central value 0.9 gives

$$\Delta\alpha_s = (6 \pm 3) \times 10^{-4}$$

Varying σ_q, the gaussian width of the P_t distribution, by ± 0.045 from its central value 0.325 gives

$$\Delta\alpha_s = (3 \pm 3) \times 10^{-4}$$

Estimation of the sytematic error of α_s due to fragmentation also appears to be more stable when α_s is extracted from $< MM_d^2/s >$ than when it is extracted from $< M_h^2/s >$. Events generated using Herwig 5.1 with input values: QCDLAM=0.2 GeV (QCD scale parameter Λ), VQCUT=0.48 GeV (quark virtuality cutoff), and VGCUT=0.06 GeV (gluon virtuality cutoff), give

$$\frac{| < M_h^2/s >_{qrk} - < M_h^2/s >_{had} |}{< M_h^2/s >_{qrk}} = 2.1\% \tag{6}$$

and

$$\frac{| < MM_d^2/s >_{qrk} - < MM_d^2/s >_{had} |}{< MM_d^2/s >_{qrk}} = 1.3\%. \tag{7}$$

Inputting the values: VQCUT=0.90 GeV and VGCUT=0.47 GeV while keeping QCDLAM=0.2 GeV gives

$$\frac{| < M_h^2/s >_{qrk} - < M_h^2/s >_{had} |}{< M_h^2/s >_{qrk}} = 6.1\% \tag{8}$$

and

$$\frac{| < MM_d^2/s >_{qrk} - < MM_d^2/s >_{had} |}{< MM_d^2/s >_{qrk}} = 1.3\%. \tag{9}$$

Changing the input value of QCDLAM to 0.3 GeV and using VQCUT=0.90 GeV and VGCUT=0.47 GeV gives

$$\frac{| < M_h^2/s >_{qrk} - < M_h^2/s >_{had} |}{< M_h^2/s >_{qrk}} = 3.2\% \tag{10}$$

$$\frac{| < MM_d^2/s >_{qrk} - < MM_d^2/s >_{had} |}{< MM_d^2/s >_{qrk}} = 0.6\%. \tag{11}$$

Finally, inputting VQCUT=1.20 GeV and VGCUT=0.77 GeV while holding QCDLAM at 0.3 GeV gives

$$\frac{| < M_h^2/s >_{qrk} - < M_h^2/s >_{had} |}{< M_h^2/s >_{qrk}} = 5.1\% \tag{12}$$

and

$$\frac{| < MM_d^2/s >_{qrk} - < MM_d^2/s >_{had} |}{< MM_d^2/s >_{qrk}} = 0.5\%. \tag{13}$$

It is evident when comparing eq.(6) to eq.(8), eq.(7) to eq.(9), eq.(10) to eq.(12), and eq.(11) to eq.(13) that the calculated systematic error of α_s due to fragmentation is both smaller and less sensitive to Monte Carlo when α_s is extracted from the modified jet mass difference than when it is extracted from the value of $< M_h^2/s >$.

5 Higher Order Corrections

Higher order corrections are estimated in this analysis by comparing the modified jet mass difference determined from events generated with and without the full parton shower. Values of $< MM_d^2/s >$ were measured at the parton level from events generated by the Lund Jetset 7.3 Parton Shower Monte Carlo with Λ_{LLA}=0.3 GeV varying Q_0 from 1.0 GeV, which yields an average of about 9.4 partons per event, to Q_0=8.0 GeV, which yields 3.0 partons per event. Effects of the parton shower on the values of $< M_h^2/s >$ and $< M_d^2/s >$ are seen in fig.(6). The plot shows an increase in $< M_h^2/s >$ of $3.9 \pm 0.5\%$ with increased showering, while the value $< M_d^2/s >$ decreases by $6.4 \pm 0.6\%$. This indicates that higher order effects of $< M_l^2/s >$ dominate those of $< M_h^2/s >$ causing an overall decrease in the value of $< M_d^2/s >$:

$$(< M_d^2/s > |_{Q_0=1.0\ GeV}) \ < \ (< M_d^2/s > |_{Q_0=8.0\ GeV}) \tag{14}$$

The effect of the parton shower [18] on $< MM_d^2/s >$ is seen in fig.(7), where $< MM_d^2/s >$ peaks near Q_0=5 GeV. The maximum variation of $< MM_d^2/s >$ due to these effects is $\Delta < MM_d^2/s > = +0.0039$ at Q_0=5 GeV. Based on this, we estimate a higher order correction to $< MM_d^2/s >$ of +0.002. We assign a systematic error due to these effects of $\Delta < MM_d^2/s >= \pm 0.002$ and which corresponds to $\Delta\alpha_s = \pm 0.0016$.

The PMS method [19] for minimizing sensitivity to higher order corrections, is not used in this analysis. Since, as was shown in ref. [20], its application to the analysis of the factorization scale ambiguities is rather complicated [21]. In addition, it is important to note that $< MM_d^2/s >$ is not a single observable; rather, it is a composite of two observables: $< M_h^2/s >$ and $< M_l^2/s >$. The variable $< M_h^2/s >$ receives contributions from the first and second order in α_s while $< M_l^2/s >$ has contributions from only second order in α_s. As a result, higher orders in $< M_h^2/s >$ are unknown and may not necessarily dominate those of $< M_l^2/s >$. A study of the observable $< M_d^2/s >$ [10], in fact, indicates that higher order effects of $< M_l^2/s >$ dominate those of $< M_h^2/s >$. Moreover, the PMS method sometimes yields a very small renormalization scale, causing the Monte Carlo to operate in a phase space where results are not reliable [22].

6 Results

An event shape analysis [23] of L3 data measures

$$< M_h^2/s >= 0.0539 \pm 0.0002(stat.) \pm 0.0014(sys.) \tag{15}$$

and

$$< M_l^2/s >= 0.0203 \pm 0.0001(stat.) \pm 0.0007(sys.) \tag{16}$$

Inserting these values directly into eq.(3) gives α_s=0.126. The ranges of M_h^2/s and M_l^2/s used in [23] are different from those used in [10] to calculate $< M_h^2/s >$ and $< M_l^2/s >$.

This contributes an uncertainty term to eq.(3) corresponding to $\Delta\alpha_s = 0.0011$. If we apply the higher order correction determined in section 5, we get

$$\alpha_s = 0.1276 \pm 0.0005 \pm 0.0034 \pm 0.0011 \pm 0.003 \pm 0.0017 \pm 0.0016, \tag{17}$$

where the first and second errors are, respectively, statistical and experimental, the third is due to the ranges of M_h^2/s and M_l^2/s used, the fourth is due to fragmentation, the fifth is due to the theoretical uncertainty of eq.(3), and the sixth is due to higher order corrections. The statistical and systematic errors here are scaled according to eq.(5). Adding all the errors in quadrature gives

$$\alpha_s = 0.1276 \pm 0.0052 \tag{18}$$

Repeating the same exercise with DELPHI results [24], we find that:

$$< M_h^2/s >= 0.05324 \pm 0.00039(stat.) \pm 0.00046(sys.) \tag{19}$$

and

$$< M_d^2/s >= 0.03405 \pm 0.00028(stat.) \pm 0.00042(sys.) \tag{20}$$

The systematic errors given in ref. [24] for $< M_h^2/s >$ and $< M_d^2/s >$ in eq.(19) and eq.(20) are added in quadrature and then scaled to take into account correlations between the bins. Using eq.(3) we get

$$\alpha_s = 0.1271 \pm 0.0007 \pm 0.0011 \pm 0.00005 \pm 0.003 \pm 0.0017 \pm 0.0016, \tag{21}$$

or

$$\alpha_s = 0.1271 \pm 0.0040 \tag{22}$$

Combining the two results in eq.(18) and eq.(22), this will yield

$$\alpha_s = 0.1271 \pm 0.0040 \tag{23}$$

which corresponds to

$$\Lambda_{\overline{MS}} = 360^{+70}_{-60} \text{ MeV} \tag{24}$$

The final value of α_s is dominated by the DELPHI result because it has small experimental error in comparison with that of L3. The value of $\Lambda_{\overline{MS}}$ is in good agreement with the recent value reported in ref. [25].

7 Conclusion

We have presented a new event shape variable $< MM_d^2/s >$, called the modified jet mass difference, for determining α_s from hadronic events measured at the Z^0 resonance. Monte Carlo studies indicate that α_s can be extracted from this variable to a

very good precision and that effects due to fragmentation are small and relatively model-independent. The effect of higher order α_s terms on the modified jet mass difference is estimated from a comparison of events generated using full parton showering with events generated using shower suppression. Finally, the result in this paper is in good agreement with the recent results [24] [26] [27] [28] reported by the 4 LEP experiments.

8 Acknowledgements

I would like to thank K. Riles, S. Goldfarb, J. Qian, T. Azemoon, and the L3 QCD group for their help, suggestions, and constructive criticism. This work has been supported by the U.S. National Science Foundation.

Figure Captions

Figure 1: α_s measured from $< MM_d^2/s >$ at hadron level (no detector simulation) and at parton level is plotted vs the value of α_s used in the Lund Jetset 7.3 M.E. (ERT) Monte Carlo program. The solid straight line shows the ideal case.

Figure 2: The deviation of the value of α_s measured at hadron level and parton level with respect to the input value of α_s used in the Monte Carlo generator. The solid line shows the ideal. The maximum deviation at both hadron level and parton level is about 0.0025. The error bars shown in this figure as well as in fig.(3-5), and fig.(7) are the statistical errors.

Figure 3: Comparisons of the fragmentation effects, which are measured as $\frac{|<O>_{qrk}-<O>_{had}|}{<O>_{qrk}}$, for the observables $< M_h^2/s >$, $< M_d^2/s >$, and $< MM_d^2/s >$. The result is based on the Lund Jetset 7.3 M.E. (ERT) Monte Carlo program. The fragmentation of this model affects the value of $< MM_d^2/s >$ by 4% at most.

Figure 4: Same as fig.(3) but using the Lund Jetset 7.3 PS Monte Carlo program. The fragmentation of this model affects the value of $< MM_d^2/s >$ by 5% at most.

Figure 5: Same as fig.(3) but using the Herwig 5.1 Monte Carlo program. The fragmentation of this model affects the value of $< MM_d^2/s >$ by 3% at most.

Figure 6: The change in the values of $< M_h^2/s >$ and $< M_d^2/s >$ as a function of Q_0, the shower cutoff parameter (PARJ(82)) in Lund Jetset 7.3 PS. Higher order corrections are estimated from the maximum variation shown.

Figure 7: Same as in fig.(6) but for the observable $< MM_d^2/s >$.

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Λ $\overline{MS}, LLA, QCD$	JETSET 7.3 PS	JETSET 7.3 ME	HERWIG 5.1	AVERAGE VALUE
0.1 GeV	5.0 ± 0.5	0.6 ± 0.5	2.4 ± 0.5	2.7 ± 0.3
0.2 GeV	4.4 ± 0.5	1.8 ± 0.5	1.4 ± 0.5	2.5 ± 0.3
0.3 GeV	4.4 ± 0.5	3.9 ± 0.5	0.6 ± 0.5	3.0 ± 0.3
0.4 GeV	3.9 ± 0.5	4.7 ± 0.5	0.1 ± 0.5	2.9 ± 0.3
0.5 GeV	4.0 ± 0.5	4.9 ± 0.5	0.4 ± 0.5	3.2 ± 0.3

Table 1: The values of $\Delta\alpha_s \times 10^{+3}$ for each value of Λ and for each model. The average value is also presented. An error of 0.003 in the value of α_s is a good approximation for the error due to the fragmentation.