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Recent QCD Results from LEP-1 and LEP-2

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A summary is given of some recent QCD results from LEP. For LEP-2, the topics include event shape measurements, determinations of α_S, and measurements of the charged particle multiplicity distribution at the recently completed run at $\mathrm{E_{c.m.}}$=189 GeV. For LEP-1, the topics presented are a test of the flavor independence of α_S and a study of gluon jets using a hemisphere definition to correspond to analytic calculations. For the combined LEP data samples, the topics include a test of power law corrections for hadronization effects and the running of α_S.

I. INTRODUCTION

In the LEP-1 period of data collection, from 1989 to 1995, about 170 $\mathrm{pb^{-1}}$ of data were collected by each LEP experiment at energies near the mass of the $\mathrm{Z^0}$ boson, yielding approximately 4×10^6 hadronic annihilation events per experiment. So far at LEP-2, which began in 1996 and is scheduled to run through 2000, a total of 270 $\mathrm{pb^{-1}}$ of data has been collected at center-of-mass (c.m.) energies, $\mathrm{E_{c.m.}}$, of 161, 172, 183 and 189 GeV. Although the luminosity at LEP-2 is large, the event rate is small: the corresponding numbers of QCD events are only about 400, 240, 1300 and 3000 per experiment. By “QCD event,” it is meant a hadronic annihilation event produced through the s-channel decay of a virtual $\mathrm{Z^0}/\gamma$ to a quark-antiquark pair, in which there is minimal initial-state photon radiation so that the hadronic system carries near to the full c.m. energy value. Besides the LEP-1 and LEP-2 data, LEP ran at an energy of about 133 GeV in 1995 and 1997: thus well above the $\mathrm{Z^0}$ mass but below the threshold for $\mathrm{W^+W^-}$ production. This data is sometimes referred to as LEP-1.5. About 10 $\mathrm{pb^{-1}}$ of data were collected at LEP-1.5, yielding about 700 QCD events. The LEP-2 data provide the possibility to study QCD at the highest available $\mathrm{e^+e^-}$ energies, where uncertainties from hadronization and unknown higher order terms in perturbative expressions for experimental observables are relatively small. The large statistics of the LEP-1 data allow tests and measurements not possible with other data samples. The LEP data together allow the energy evolution of QCD quantities to be studied. In the following, we present a summary of some recent work in QCD performed using the LEP data. We first present preliminary results from the recently completed run at 189 GeV. Following this, we discuss some unique and precise tests of QCD made using LEP-1 data. Last, we present results using the combined LEP data samples to test QCD predictions for the energy scaling of several quantities.

II. RESULTS FROM 189 GEV

LEP ran at 189 GeV during 1998. Each LEP experiment collected a data sample of about 190 $\mathrm{pb^{-1}}$, more than the integrated luminosity collected during the entire LEP-1 period. The most basic QCD test which can be performed using these data is to examine variables which measure the distribution of particle energy and momenta and to compare them to the predictions of QCD Monte Carlo event generators. Standard “event shape” variables used for this purpose are Thrust T [1], Heavy Jet Mass $\mathrm{M_H}$ [2], Jet Broadening Variables $\mathrm{B_W}$ and $\mathrm{B_T}$ [3], and $\mathrm{y^D_{23}}$ (sometimes referred to as $\mathrm{y_3}$ or $\mathrm{D_2}$). Thrust is defined as

$$\mathrm{T} = \max \left(\frac{\sum\limits_{\mathrm{i=1,N}} \vec{\mathrm{p}}_\mathrm{i} \cdot \hat{\mathrm{n}}_\mathrm{T}}{\sum\limits_{\mathrm{i=1,N}} |\vec{\mathrm{p}}_\mathrm{i}|} \right) \quad ,$$

where the thrust axis $\hat{\mathrm{n}}_\mathrm{T}$ is the unit vector which maximizes T, as indicted. The sum is over the particles in the event, with $\vec{\mathrm{p}}$ the particle momentum. The quantities $\mathrm{M_H}$, $\mathrm{B_W}$ and $\mathrm{B_T}$ are defined by dividing events into hemispheres using the plane perpendicular to $\hat{n}_T$: M_H is the larger of the two hemisphere invariant mass values, while B_W and B_T are defined by $B_W=\max(B_1,B_2)$ and $B_T=B_1+B_2$ with

$$B_j = \frac{\sum\limits_{i\in j} |\vec{p}_i \times \hat{n}_T|}{\sum\limits_{i=1,N} |\vec{p}_i|}$$

with the index j=1,2 referring to the hemisphere and where the sum in the numerator is over the particles in hemisphere j. Last, y_{23}^D is the resolution value at which an event changes from being classified as a two-jet event to being classified as a three-jet event using the $k_\perp$ ("Durham") recombination jet algorithm [4]. In Fig. 1 (left), ALEPH measurements of 1-T, $(M_H/E_{\mathrm{c.m.}})^2$ and B_W at 189 GeV are shown in comparison to the predictions of the Pythia [5], Herwig [6] and Ariadne [7] Monte Carlo multihadronic parton shower event generators. The parameters of the event generators were tuned using Z^0 data. The event generators are seen to describe the 189 GeV data well, demonstrating that the energy evolution of the variables is as expected from QCD.

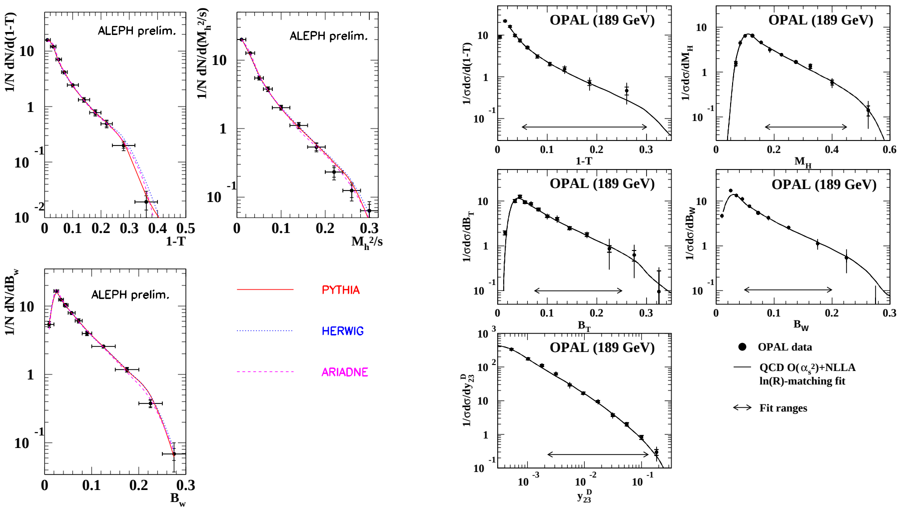

FIG. 1. Measurements of event shape variables at 189 GeV from ALEPH (left) [9] and OPAL (right) [8]. The ALEPH results are shown at the hadron level in comparison to the predictions of QCD parton shower Monte Carlo programs. The OPAL results are shown at the parton level; the solid curves show the results of a fit of $\mathcal{O}(\alpha_S^2)$+NLLA calculations to the data.

The event shape variables defined above have an importance beyond that of comparison to Monte Carlo predictions in that they are stable under the emission of soft and collinear radiation, allowing them to be calculated perturbatively. Calculations of these variables have been performed to two loop order, corresponding to $\mathcal{O}(\alpha_S^2)$ in e^+e^- annihilations. In addition to the $\mathcal{O}(\alpha_S^2)$ calculations, the leading and next-to-leading logarithmically divergent terms have been summed to all orders into analytic functions, an approximation known as NLLA. The combination of the two calculations yields predictions valid to $\mathcal{O}(\alpha_S^2)$+NLLA, the most complete theoretical description of event shape variables which is currently available. In Fig. 1 (right), OPAL measurements of event shapes at 189 GeV are shown after correction for the effects of hadronization (the hadronization corrections are derived from the Monte Carlo programs). The solid curves in Fig. 1 (right) show the results of a fit of the $\mathcal{O}(\alpha_S^2)$+NLLA predictions to the data. The preliminary value of α_S extracted from this fit is $0.106 \pm 0.001(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})$ [8], for which the largest systematic uncertainties are from the hadronization corrections, the matching of the $\mathcal{O}(\alpha_S^2)$ and NLLA calculations, and the ambiguity in the value to choose for the renormalization scale. L3 and ALEPH have also reported preliminary results for α_S at 189 GeV, using a similar technique. The ALEPH and L3 results, $\alpha_S(189\ \mathrm{GeV})=0.110 \pm 0.001(\mathrm{stat.}) \pm 0.003(\mathrm{syst.})$ [9], and $0.1082 \pm 0.0028(\mathrm{exp.}) \pm 0.0052(\mathrm{theo.})$ [10], can be combined with the OPAL value to yield $\alpha_S(189\ \mathrm{GeV})=0.108 \pm 0.001(\mathrm{stat.}) \pm 0.004(\mathrm{syst.})$, which is significantly smaller than the result $\alpha_S(91\ \mathrm{GeV})=0.121 \pm 0.003(\mathrm{stat.+syst.})$ obtained from the ratio of the hadronic to the leptonic decay widths of the Z^0 measured at LEP-1 [11]: this is an example of the running of α_S between LEP-1 and LEP-2. The LEP combined result given above is obtained by taking the statistical uncertainties as uncorrelated and the simple mean of the systematic uncertainties.

Preliminary results for the mean charged particle multiplicity of QCD events at 189 GeV, $\langle n_{\mathrm{ch.}}\rangle$(189 GeV), have been presented by ALEPH and OPAL: the results are 27.37 ± 0.20(stat.)±0.27(syst.) [9] and 26.94 ± 0.17(stat.)±0.41(syst.) [8], respectively, which can be combined to yield 27.12 ± 0.13(stat.)±0.34(syst.). This value is substantially larger than the value measured at 91 GeV: $\langle n_{\mathrm{ch.}}\rangle$(91 GeV)=21.00 ± 0.20(stat.+syst.). A comparison of the 189 GeV result to Monte Carlo predictions and a test of the energy scaling of $\langle n_{\mathrm{ch.}}\rangle$ are presented below in section IV.

III. RESULTS FROM LEP-1

A. Flavor independence of α_S

In QCD, the strong interaction is flavor blind, i.e. gluons couple with equal strength to quarks of all flavors. e^+e^- colliders are well suited to test this aspect of the Standard Model because flavor tagging techniques and α_S measurements are both well developed areas. The procedure is to tag the event flavor "f" in $e^+e^- \to q_f\overline{q}_f \to$ *hadrons* events, where the flavor tags are f=uds, c or b, with uds an undifferentiated sample of light quark (uds) events. In a recent OPAL study [12], uds and b events are identified using the signed impact parameter values of charged tracks with respect to the primary interaction point, b, since the distribution of this variable is strongly skewed towards positive values for b events, and to a lesser extent for c events, but not for uds events. By requiring that there be *no track* in an event with $b/\sigma_b > 2.5$, where σ_b is the uncertainty of b, a uds sample purity of 86% is obtained. By requiring that there be *at least five tracks* with $b/\sigma_b > 2.5$, a b sample with a purity of 96% is selected. c events are identified by requiring the presence of high energy $D^{*\pm}$ mesons, yielding a sample purity of 55%. α_S is measured in the flavor tagged samples using event shape variables such as are discussed above in section II. The results for the flavor independence of α_S are presented in the form

$$\frac{\alpha_S^b}{\alpha_S^{uds}} \quad ; \quad \frac{\alpha_S^c}{\alpha_S^{uds}} \quad ,$$

where α_S^f is the strong coupling strength measured for flavor sample f. The results are presented in this form so that the main uncertainties, from hadronization and the renormalization scale, partially cancel in the ratios. Thus the flavor independence of α_S can be measured with greater precision than α_S itself.

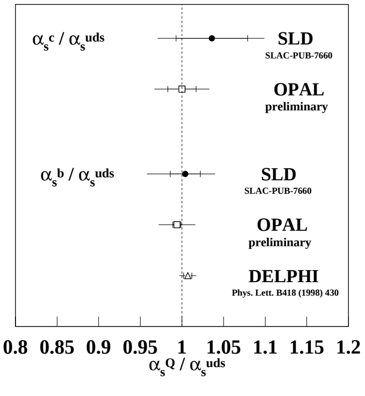

FIG. 2. Results on the flavor independence of α_S from DELPHI [13], OPAL [12] and SLD [14]. These results utilize $\mathcal{O}(\alpha_S^2)$ mass corrections [15] for c and b quarks.

Previous results on the flavor independence of α_S have been based on leading order mass corrections for the heavy c and b quarks. DELPHI [13], OPAL and SLD [14] have now presented studies which utilize recent $\mathcal{O}(\alpha_S^2)$ mass corrections [15] for c and b quarks. The results are summarized in Fig. 2. The flavor independence of α_S is verified to better than 1% for the b/uds flavors and to 3% for the c/uds flavors.

B. Gluon jet studies

Most studies of gluon jets are from e^+e^- annihilations. Recent results on gluon jets include a study of unbiased gluon jets by OPAL [16], a study of the scale evolution of gluon jet multiplicity by DELPHI [17], and a study of the splitting of gluons to $b\overline{b}$ pairs by SLD. These latter two topics are presented in separate talks at this conference (see the contributions by Oliver Klapp and Toshinori Abe, these proceedings); hence only the OPAL study is discussed here.

To test theoretical predictions in a meaningful manner, the experimental definition of jets should match the theroetical one. Theoretical predictions of gluon jet properties are based on the production of a virtual gluon jet pair, gg, from a color singlet point source. The jet properties are obtained inclusively by summing over the event hemispheres: thus there is no selection of a specific event topology. In contrast, most studies of gluon jets employ a jet finding algorithm to identify $e^+e^-\rightarrow q\overline{q}g$ events with a prominent three-jet structure, interpreted as arising from two quark jets and a gluon jet. Results from these "3-jet events" cannot be used to test QCD predictions in a quantitative manner since the experimental selection does not satisfy the inclusive requirements of the calculations. In particular, results based on 3-jet events usually exhibit a strong dependence on the jet finding algorithm employed for the analysis.

gg production from a color singlet point source is a process which has been practically unobserved in nature. One channel where the experimental selection of gluon jets matches the theoretical criteria is e^+e^- hadronic annihilation events in which the quark jets q and $\overline{q}$ from the electroweak Z^0/γ decay are approximately colinear: the gluon jet hemisphere against which the q and $\overline{q}$ recoil is produced under the same conditions as gluon jets in gg events [18,19]. OPAL selected events of the type $e^+e^-\rightarrow q_{tag}\overline{q}_{tag}g_{incl.}$, in which $g_{incl.}$ refers to a gluon jet hemisphere recoiling against two tagged quark jets q_{tag} and $\overline{q}_{tag}$ in the opposite hemisphere. The OPAL result is obtained for a for $g_{incl.}$ jet energy of E_{jet}=40 GeV.

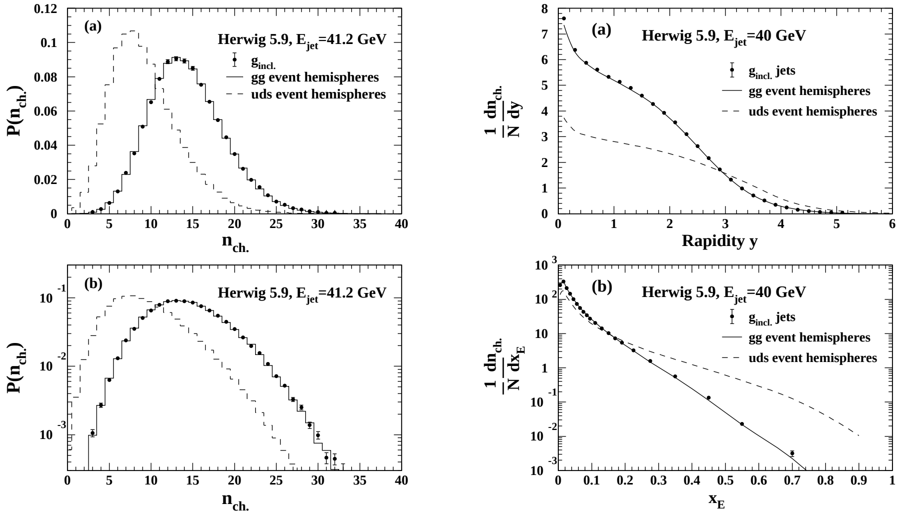

FIG. 3. The prediction of the Herwig parton shower Monte Carlo event generator for $g_{incl.}$ gluon jet hemispheres from e^+e^- annihilations, in comparison to the Herwig predictions for hemispheres in gg and uds events produced from a color singlet point source [16].

Fig. 3 shows a Monte Carlo comparison of $g_{incl.}$ hemispheres from e^+e^- annihilations and hemispheres of gg events, for the distributions of charged particle multiplicity $n_{ch.}$, rapidity y, and scaled particle energy $x_E = E/E_{jet}$. The solid points show Monte Carlo predictions for $g_{incl.}$ jets. The solid curves show Monte Carlo predictions for gg event hemispheres with the same energy as the $g_{\mathrm{incl.}}$ jets. The results for $g_{\mathrm{incl.}}$ jets and gg event hemispheres are almost indistinguishable, establishing the validity of this technique to identify gluon jets in a manner which corresponds to point source production from a color singlet.

In the most recent OPAL study of $g_{\mathrm{incl.}}$ jets [16], 439 gluon jets are identified with a purity of 83%. The gluon jet hemispheres are compared to hemispheres of light quark (uds) events, selected as explained above for the analysis on the flavor independence of α_S. The ratio $r_{\mathrm{ch.}}$ of the mean multiplicity in gluon jets to that in quark jets is measured to be $r_{\mathrm{ch.}} = 1.514 \pm 0.019\,(\mathrm{stat.}) \pm 0.034\,(\mathrm{syst.})$, in excellent agreement with recent QCD calculations of this quantity [20].

The measured distributions of y and x_E for the gluon and uds hemispheres are shown in Fig. 4. A striking feature of these results is the nearly factor of two difference between the mean multiplicities of gluon and quark jets at small values of rapidity and x_E. The ratio of the mean gluon to quark jet charged particle multiplicity for $|y| \leq 1$ is measured to be $r_{\mathrm{ch.}}(|y| \leq 1)$=$1.919 \pm 0.047\,(\mathrm{stat.}) \pm 0.095\,(\mathrm{syst.})$. For *soft* particles, i.e. particles with energies $E << E_{\mathrm{jet}}$, QCD predicts that the mean multiplicities in gluon and quark jets differ by a factor of $r = \mathrm{C_A}/\mathrm{C_F} = 2.25$ [21]. Monte Carlo study demonstrates that the experimental variable $r_{\mathrm{ch.}}(|y| \leq 1)$ does indeed yield 2.25 at the parton level for a large energy (E_{jet}=5 TeV): hence the experimental variable $r_{\mathrm{ch.}}(|y| \leq 1)$ corresponds to the multiplicity ratio r between gluon and quark jets as it is defined for analytic calculations. Because the experimental definition of gluon jets in this analysis corresponds to the theoretical one, these results provide the most direct test to date of QCD predictions for gluon jets.

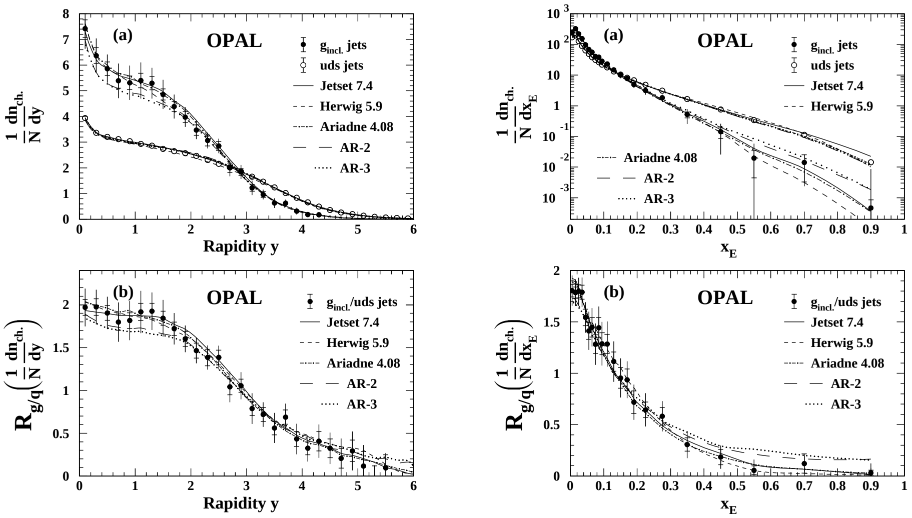

FIG. 4. (Left) Corrected distributions of charged particle rapidity, y, for 40.1 GeV $g_{\mathrm{incl.}}$ gluon jets and 45.6 GeV uds quark jets. The ratio of the gluon to quark jet rapidity distributions for 40.1 GeV jets. (Right) The corresponding results for charged particle scaled energy, $x_E = E/E_{\mathrm{jet}}$. The top plots show the separated gluon and quark jet results; the bottom plots show the ratio between the two [16].

IV. ENERGY SCALING OF QCD VARIABLES

A. Power law corrections for non-perturbative effects

A power law ansatz has been presented [22] to treat hadronization corrections analytically. The ansatz takes the form

$$\langle y \rangle = \langle y_{pert.} \rangle + \langle y_{non-pert.} \rangle \tag{1}$$

where $\langle y \rangle$ represents the mean value of an event shape variable such as Thrust, with $\langle y_{pert.} \rangle$ a term calculable in perturbative QCD, and $\langle y_{non-pert.} \rangle$ a non-perturbative term meant to replace the Monte Carlo derived hadronization corrections often used in the experimental analysis of e$^+$e$^-$ data. The perturbative term $\langle y_{pert.}\rangle$ has been calculated to $\mathcal{O}(\alpha_S^2)$. The non-perturbative term is given by

$$\langle y_{non-pert.}\rangle = \frac{C_y f(\alpha_S,\alpha_0)}{E_{\rm c.m.}}$$

where f is a universal function of α_S and α_0, with α_0 a non-perturbative parameter predicted to have the same value for all variables y. This ansatz has been tested by DELPHI and ALEPH by fitting expression (1) to e$^+$e$^-$ measurements of $\langle y\rangle$ versus E$_{\rm c.m.}$, with α_S and α_0 as fitted parameters. The renormalization scale is chosen to be the mass of the Z^0 for this fit. The DELPHI study, using LEP and lower energy e$^+$e$^-$ data, is summarized in Fig. 5 (left). DELPHI base their analysis on the energy evolution of the mean Thrust and Heavy Jet Mass values. The solid lines in Fig. 5 (left) show the results of the fit. The contribution of the perturbative term is shown by the dashed lines. The corresponding ALEPH results for the mean Thrust value are shown in Fig. 5 (right). ALEPH also includes the mean C-parameter [23] value in their study.

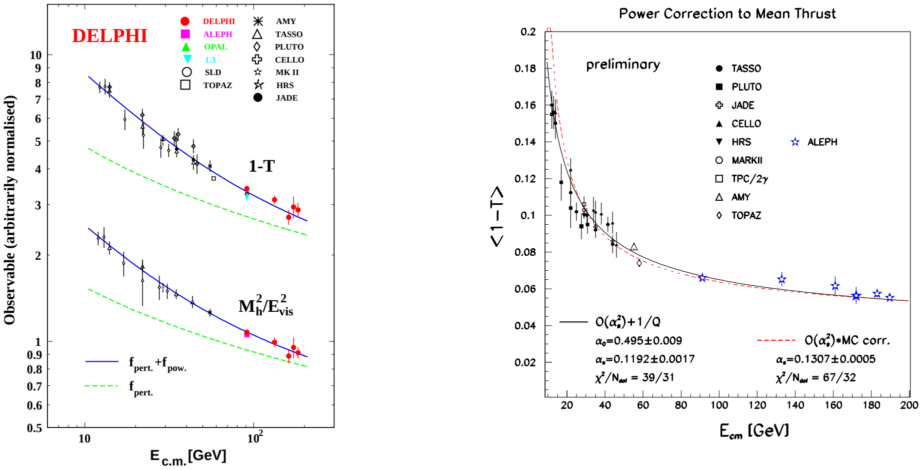

FIG. 5. Results on the energy evolution of the mean values of Thrust and Heavy Jet Mass in e$^+$e$^-$ annihilations [24].

The preliminary results for α_S and α_0 from DELPHI and ALEPH are given in the table below. The fits yield generally consistent results for α_S(M$_Z$) and α_0: in this sense the power law ansatz provides a successful description of the data.

B. Energy scaling of α_S and mean multiplicity

Last, we present studies of the energy scaling of α_S and $\langle n_{\rm ch.}\rangle$ at LEP. Fig. 6 (left) shows measurements of α_S from L3. The measurements for E$_{\rm c.m.}$>M$_Z$ are determined using the LEP-1, LEP-1.5 and LEP-2 data in the manner described in section II. The measurements below E$_{\rm c.m.}$=M$_Z$ are obtained from LEP-1 events in which the initial-state e$^-$ or e$^+$ radiates a photon, thus reducing the energy of the hadronic system. The uncertainties shown are statistical only, i.e. the correlated systematic terms are omitted to emphasize the running character of α_S. The solid line shows the evolution predicted by QCD, which agrees well with the data. It is interesting that the high luminosity 183 and 189 GeV points fall directly on the solid curve which also passes through the high statistics LEP-1 point. Fig. 6 (right) shows measurements of $\langle n_{\rm ch.}\rangle$ versus E$_{\rm c.m.}$. The top portion of this figure shows the $n_{\rm ch.}$ distribution measured by

Experiment	Event Shape Variable	α_0	α_S(M$_Z$)	χ^2/d.o.f.
DELPHI	T	0.49 ± 0.1	0.119 ± 0.005	1.9
DELPHI	$(\rm M_H/E_{c.m.})^2$	0.55 ± 0.03	0.119 ± 0.004	0.2
ALEPH	T	0.45 ± 0.08	0.119 ± 0.006	1.3
ALEPH	C	0.46 ± 0.06	0.113 ± 0.004	0.8

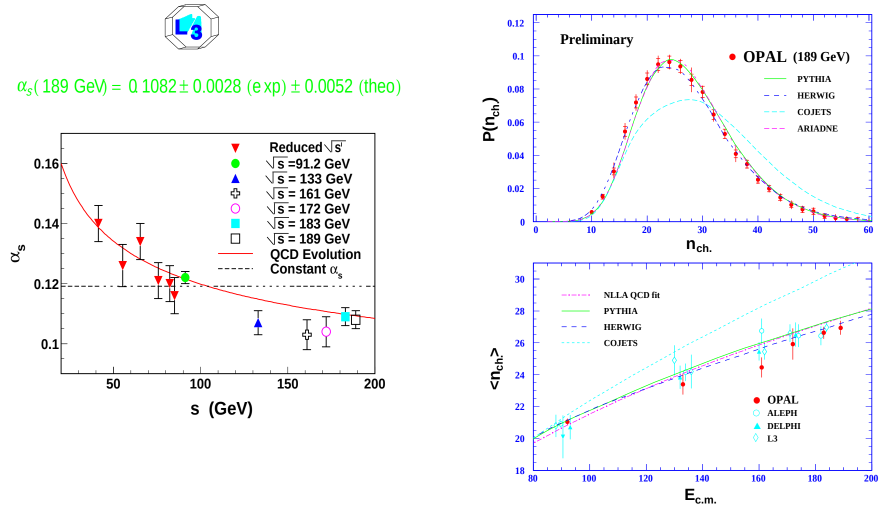

FIG. 6. (Left) L3 results on the running of α_S [10]. (Right) OPAL measurements the charged particle multiplicity distribution at 189 GeV and of the energy evolution of the mean charged multiplicity [8].

OPAL at 189 GeV. Shown in comparison to the data are the predictions of the principle QCD Monte Carlo programs, tuned to provide an approximately equivalent description of global event properties at the Z^0. Pythia, Herwig and Ariadne, all based on parton showers with coherence (soft gluon interference), are seen to describe the energy evolution of the mean multiplicity well. Cojets [25], based on a parton shower without coherence, describes the high energy data poorly and thus does not exhibit the correct energy scaling behavior. A similar result is obtained by ALEPH using a variant of Pythia without coherence [9]. These results are highly suggestive of the need to include coherence effects in QCD predictions to obtain an accurate description of multiplicity in e^+e^- data.

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