QCD AT LEP II

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We present LEP results on the study of Quantum Chromodynamics (QCD) at energies above the Z peak. Excellent detector performance and improved theoretical calculations make it possible to study QCD with small experimental and theoretical uncertainties. The energy evolution of the moments of the event shape variables and the strong coupling constant (α_s) from studies of QCD at various energies at LEP have been presented.

Introduction

For the process $e^+e^- \to hadrons$, the initial state is precisely known and QCD corrections apply only to the final state. This establishes a straightforward energy scale for QCD. At high Centre of Mass (CM) energies, the high momentum quarks and gluons form jets, which retain the energy and direction of the primary partons. Hadronisation effects become less significant at higher energies.

At LEP, data have been collected over a large range of CM energy. We can classify the event samples in three categories: events (a) at reduced $\sqrt{s'}$ from Z decay with hard isolated photons (initial and final state radiation), (b) at the Z peak and (c) above the Z peak. All the four detectors (ALEPH, DELPHI, L3 and OPAL) are hermetic and measure the energy and direction of the jets precisely.

The structure of hadronic events can be studied from an analysis of the infra-red and collinear safe global event shape variables which are sensitive to hard gluon emissions and describe the multi-jet topology of events which allows us to determine the strong coupling constant. The variables studied are thrust (T), scaled heavy jet mass (ρ_H), C parameter (C), total and wide jet broadening (B_T and B_W) and 3-jet resolution parameter (y_3) for which improved ($\mathcal{O}(\alpha_s{}^2)$ + NLLA) theoretical calculations are available [1].

We describe the procedure of selection of hadronic events at energies above the Z peak. The corrected event shape distributions are compared to QCD model predictions and analytical calculations. The moments of event shape variables have been explained by perturbative QCD with a power law description for the hadronisation process. Finally we discuss about the extraction of the strong coupling constant from a fit of the data to $\mathcal{O}(\alpha_s{}^2)$ + NLLA analytical expression.

Event Selection

Hadronic events in e^+e^- interactions are characterised by large visible energy and a large number of particles in the final state. At the Z peak, the cross section is large and hadronic events can be selected with very high purity and efficiency. Above the Z peak, however, the production cross section is smaller by several orders of magnitude. Moreover, a large fraction of hadronic events is produced at a reduced CM energy due to emission of hard initial state radiation. At energies beyond W-pair production threshold, $e^+e^- \to W^+W^- \to$ *Jets* becomes a dominant background as well. All these make event selection difficult at energies above the Z peak.

The background due to hard initial state photon is reduced by requiring low longitudinal energy imbalance and absence of energetic photon in the detector. Alternatively, the missing or visible photon direction has been used to reconstruct the reduced CM energy ($\sqrt{s'}$) and events with low $\sqrt{s'}$ are rejected.

Events due to $e^+e^- \to W^+W^-$ have been removed by forcing events into 4-jet configuration and either by using some topological cuts like energies of the most and the least energetic jets or by exploiting compatibility with QCD by computing $\mathcal{O}(\alpha_s{}^2)$ matrix element expressions for different 4-jet configurations using jet energy and direction.

LEP Run	Energy (GeV)	$\int \mathcal{L}\,(\mathrm{pb}^{-1})$/Expt	$\sim$ Events/Expt
LEP I	Z peak	140	4000K
LEP 1.5	130, 136	6+6	600
1996	161	10	400
	172	10	300
1997	181–184	55	1500
1998	189	176	3500
1999	192	29	500
1999	196	80	1500
1999	200	60	1200

Table 1. The energy points, collected integrated luminosity and number of hadronic events observed by each experiment.

Table 1 lists the energy points, the integrated collected luminosity, and the number of hadronic events seen by each experiment during the running of the LEP collider. Hadronic events are selected with $\approx 90\,\%$ efficiency with purity larger than 80 % for high energy events.

Comparison with QCD Predictions

The measured distributions of the event shape variables are corrected for the remaining background, detector and acceptance effects as well as for initial and final state radiation effects using Monte Carlo events. The corrections are done on a bin-by-bin basis or by using a matrix unfolding method. The correction factors are small and smooth.

The corrected distributions are compared with the predictions of QCD models, ARIADNE, COJETS, HERWIG and JETSET, tuned at $\sqrt{s} = 91$ GeV. The models differ in the variables they use for the leading logarithmic expansion of the cross-section and in modelling the hadronisation effects.

Figure 1(a) shows the corrected distributions of n-jet rate using Durham jet clustering algorithm [2] along with the predictions of PYTHIA obtained by ALEPH at $\sqrt{s} = 196$ GeV. Figure 1(b) describes the CM energy dependence of the mean charged particle multiplicity along-with the model predictions. Distributions of all the event shape variables and their energy evolution are faithfully reproduced by parton shower Monte Carlo models with colour coherence effect.

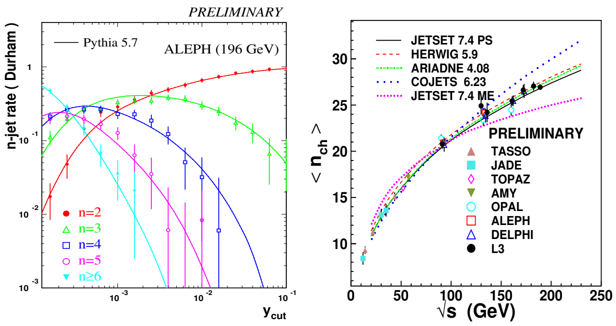

Figure 1. (a) n-jet rate at 196 GeV with predictions of PYTHIA. (b) Mean charged particle multiplicity as a function of CM energy.

Power Law Description of Fragmentation

The non-perturbative contributions to the first and second moments of the event shape variables can be parametrised by power law like terms [3]. This description allows to perform a model independent determination of α_s, and to test the universality of the effective coupling constant (α_{eff}) below a fixed infra-red cut off scale.

The first moment of a variable can be expressed as a sum of perturbative ($\mathrm{f_{pert}}$) and power law ($\mathrm{f_{power}}$) terms as, $\langle \mathrm{f} \rangle = \frac{1}{\sigma_{\mathrm{tot}}} \int \mathrm{f} \frac{d\sigma}{\mathrm{df}} \mathrm{df} = \langle \mathrm{f_{pert}} \rangle + \langle \mathrm{f_{power}} \rangle$. The perturbative term is calculated upto $(\alpha_{\mathrm{s}}(Q)/2\pi)^2$ and the power correction term is $\mathrm{c_f} \cdot \mathcal{P}(\sqrt{\mathrm{s}}, \alpha_{\mathrm{s}}(\sqrt{\mathrm{s}}), \mu_I, \alpha_{\circ}(\mu_{\mathrm{I}}))$, where $\mathcal{P}$ is supposed to be universal and signifies 'a shift $\propto 1/\mathrm{Q}$', for 1-T, C, ρ_{H} and 'a logarithmic-skew' in addition to a shift for $\mathrm{B_T}$, $\mathrm{B_W}$. The factor $\mathrm{c_f} = 2, 2, 1, \frac{1}{2}$ and 3π for 1-T, ρ_{H}, $\mathrm{B_T}$, $\mathrm{B_W}$ and C respectively. $\alpha_{\circ}$ accounts for contributions below matching scale μ_{I} (= 2 GeV).

The above expression has been used to fit the energy evolution of the first moment of all the variables to extract α_{s} and $\alpha_{\circ}$ simultaneously. Table 2 lists the L3 determination of α_{s} and $\alpha_{\circ}$ from invidual variables which supports the prediction of universality of $\alpha_{\circ}$.

Observable	$\alpha_{\circ}$ (2 GeV)	$\alpha_{\mathrm{s}}(\mathrm{m_Z})$	χ^2/d.o.f.
< 1-T >	0.567 ± 0.054	0.1097 ± 0.0047	10.4/11
< ρ_{H} >	0.469 ± 0.041	0.1032 ± 0.0039	5.6/11
< $\mathrm{B_T}$ >	0.480 ± 0.034	0.1148 ± 0.0028	4.5/11
< $\mathrm{B_W}$ >	0.450 ± 0.069	0.1131 ± 0.0035	2.4/11
<C>	0.482 ± 0.031	0.1120 ± 0.0033	6.2/11
Average: $\alpha_{\mathrm{s}}(\mathrm{m_Z}) = 0.1106 \pm 0.0036 \pm 0.0040$			

Table 2. Simultaneous determination of α_{s} and $\alpha_{\circ}$ by L3 from a fit to the energy evolution of the first moment of the events shape variables using perturbative together with power correction terms.

Power law of correction to the second moment of an event shape variable can be described as, $\langle \mathrm{f}^2 \rangle = \langle {\mathrm{f_{pert}}}^2 \rangle + 2 \langle \mathrm{f_{pert}} \rangle \cdot \mathrm{c_f} \, \mathcal{P}(\sqrt{\mathrm{s}}) + \mathcal{O}\left(\frac{1}{\mathrm{Q}^2}\right)$. The first two terms are computed from the fit results of the first moments. The remaining term is obtained from fit for each variable which reveals significant contribution of the $\mathcal{O}\left(\frac{1}{Q^2}\right)$ term as shown for 1-T in figure 2(b).

Strong Coupling Constant

The event shape distributions have been compared to the analytical calculations, complete to $\mathcal{O}({\alpha_{\mathrm{s}}}^2)$ together with resummation of leading and next-to-leading log terms [4]. The combined calculations describe data over a wide kinematical range. Hadronisation effect has been folded in using parton shower Monte Carlo and a fit to the data yields a value of α_s at the corresponding CM energy.

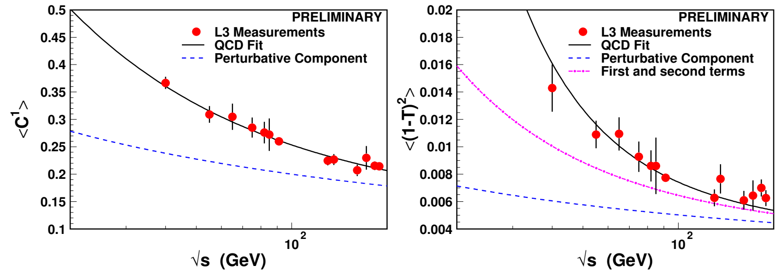

Figure 2. (a) Fit to energy evolution of the first moment of C parameter, (b) Fit to energy evolution of the second moment of 1-T.

Figure 3(a) shows the α_s values determined by L3 from event shape distributions as a function of the CM energy. As the theoretical errors at all the energy points are fully correlated, only experimental errors have been used to perform fit to the QCD evolution equation. The statistical errors are assumed to be uncorrelated whereas the experimental systematic errors, dominated by the background uncertainties, are uncorrelated among the three data sets (Z peak, high energy and reduced CM energy), but are fully correlated within individual data sets. The fit gives a χ^2 of 15.4 for 12 degrees of freedom corresponding to a confidence level of 0.22 with a fitted value of α_s:

$$\alpha_s(m_Z) = 0.1220 \pm 0.0015\,(\mathrm{expt}) \pm 0.0060\,(\mathrm{theory})$$

On the other hand, a model with constant α_s gives a χ^2 of 115 for 12 d.o.f which corresponds to a confidence level of 1.5×10^{-5}.

The fit has also been carried out with the slope of the energy evolution of α_s as a free parameter together with α_s which results in the number of active flavours given by, $N_f = 4.4 \pm 1.0\,(\mathrm{exp}) \pm 2.0\,(\mathrm{theo})$.

Figure 3(b) summarises $\mathcal{O}({\alpha_s}^2)$ + NLLA α_s values from the four LEP experiments [5], evaluated at the m_Z scale according to the QCD evolution equation. All the measurements are consistent among themselves and to a value of $\alpha_s(m_Z) = 0.1188 \pm\ 0.0009\,(\mathrm{expt})$ obtained from a fit which ignores correlation among the experiments.

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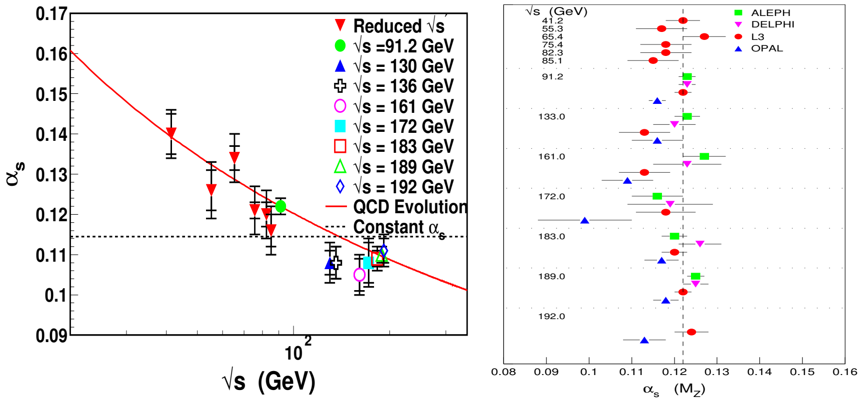

Figure 3. a) L3 measurements of α_s from event shape distribution as a function of the CM energy. The errors correspond to experimental uncertainties. The solid and dashed lines are fits with and without energy evolution as given by QCD. b) $\alpha_s\,(m_Z)$ measured from event shape distributions by the four LEP experiments.

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