MEASUREMENT OF $\alpha_S$ IN $e^+e^-$ COLLISIONS AT LEP AND JADE

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Data from $e^+e^-$ annihilation into hadrons collected by the JADE, the L3 and the OPAL experiment at centre-of-mass energies between 14 GeV and 209 GeV are used to determine the strong coupling $\alpha_S$. Observables in leading order sensitive to $\alpha_S$ as well as $\alpha_S^2$ are used. The evolution of $\alpha_S$ with respect to the centre-of-mass energy as predicted by QCD is studied and confirmed with high precision. All measurements of $\alpha_S$ are consistent with the current world average.

Keywords: QCD, strong coupling constant $\alpha_S$, electron-positron annihilation

1. Introduction

The clean environment of $e^+e^-$ annihilation allows to access the strong coupling $\alpha_S$, the free parameter of Quantum Chromodynamics (QCD), very well. The strong coupling $\alpha_S$ reflects the probability of the radiation of gluons, the vector gauge boson of QCD. General event topologies can be studied or the number of radiated hard gluons, identified by jets, can be counted. To numerically evaluate the strength of the strong coupling $\alpha_S$ the measured observables have to be compared to theoretical predictions. These theoretical calculations predict the radiation of gluons with $\alpha_S$ being the only free parameter. Here the strong coupling $\alpha_S$ is studied in the $e^+e^-$ energy range between 14 GeV and 209 GeV. The energy evolution of the strong coupling $\alpha_S$ is studied and compared to the prediction of QCD. A detailed summary of the results can be found at $^{1,2,3,4}$ and references therein.

2. Data Sample

Data taken with the JADE experiment cover energy points in the energy range between 14 and 44 GeV. At each energy point between 1k and 20k multihadronic events are selected. The L3 collaboration uses events with hard initial or final state radiation (radiative events) to access the energy ranges below the centre-of-mass energy of the colliding beams in the range between 30 and 86 GeV. At every point between 1k and 3k events are selected. For the determination of the strong coupling $\alpha_S$ factorization between the gluon and the photon production is assumed. Theoretically the energy scale of the process is not well defined $^5$. The largest dataset selected at L3 and OPAL is at a centre-of-mass energy of 91 GeV with more than 100k events. Above 91 GeV events are selected with 500-5k events in several energy points up to 209 GeV.

Different sources of background are considered at the various energy points. At JADE $b\bar{b}$ events are subtracted since the electroweak decay of B-mesons fakes events with hard gluon radiation and lead to a bias in the measurement of $\alpha_S$. Above centre-of-mass energies of 130 GeV the large number of radiative events are rejected as background, since they lower the effective centre-of-mass energy. At energies above 160 GeV hadronic decays of W-pair events are subtracted. At the centre-of-mass energy of 91 GeV no background is considered.

3. Event-Shape Observables

The radiation of hard gluons in the $q\bar{q}$ final state alters the topology of the event. Events
without hard gluon radiation look more pencil like, while the radiation of hard gluons make the event look more spherical. The size of the strong coupling $\alpha_S$ therefore has an impact on the event topology. This impact on the topology can be quantitatively described by so called event-shape observables, which are calculated using the charged particle tracks and neutral clusters of the event. The L3 Collaboration uses event-shape observables like Thrust, C-Parameter, the jet broadening variables $B_T$ and $B_W$, the jet resolution parameters $y_{23}$ and the heavy jet mass to determine the strong coupling $\alpha_S$. All these event-shape observables are in leading order proportional to $\alpha_S^2$. In addition the L3 and the OPAL collaboration study the D-parameter and Thrust-Minor, which are proportional to $\alpha_S^3$ in leading order.

The first moments of the event observables $\langle F \rangle = \int F \frac{1}{\sigma} \frac{d\sigma}{dF} dF$, with $F$ being the event-shape observable and $\sigma$ being the cross-section, are used to determine the strong coupling $\alpha_S$. This approach allows to sample the full region of available phase-space. The QCD predictions are available in next-to-leading order (NLO). The hadronization effects are described by power corrections, which predict the changes of the event-shape observable due to hadronization with a single parameter $\alpha_0$. The results of $\alpha_S$ and $\alpha_0$ are shown in Fig. 1. The unweighted average of the six measurements is:

$$\alpha_S(M_{Z^0}) = 0.1126 \pm 0.0045 \pm 0.0039$$

$$\alpha_0 = 0.47 \pm 0.054 \pm 0.024,$$

where the first uncertainty corresponds to the statistical and the second to the theoretical one. The confidence level for a common $\alpha_0$ is 3%, if the systematic uncertainties are treated as uncorrelated. Theoretical uncertainties from the power correction approach are not considered.

In a further measurement fits to the event-shape distributions are performed. In these fits only parts of the available phase-space is used to determine $\alpha_S$. The theoretical predictions are available in NLO combined with resummed calculations (NLLA), leading to an improved description of the data. The hadronization is evaluated using Pythia Monte Carlo and Herwig and Ariadne as a systematic uncertainty. The combined result is

$$\alpha_S(M_{Z^0}) = 0.1227 \pm 0.0012 \pm 0.0058,$$
where the first uncertainty corresponds to the experimental one and the second to the theoretical one. The theoretical uncertainties contain errors from missing higher order terms in the calculation and errors associated to the hadronization correction. The combination of the $\alpha_S$ measurements using event-shape observables at the varies centre-of-mass energies assumes the validity of QCD, in particular the energy evolution of $\alpha_S$ with energy. The combination assuming the energy evolution of $\alpha_S$ according to QCD results a $\chi^2$ value of 17.9/15. A fit with a constant value of $\alpha_S$ returns a $\chi^2$ value of 51.7/15.

Measurements of $\alpha_S$ using event-shape distributions of event-shape observables proportional to $\alpha_S^2$ in leading order, like the D-Parameter and Thrust minor are performed as well. Only NLO predictions are available, leading to an increased theoretical uncertainty.

4. Measurements of $\alpha_S$ using Jet Rates

Another way to determine the strong coupling $\alpha_S$ is to measure the number of selected jets. For this all particles have to be clustered according to a certain jet-finder scheme. The OPAL collaboration applies two different schemes, the Durham scheme and the Cambridge scheme, both with $y_{\text{cut}}$ as a free parameter. The average jet-rate $\langle N(y_{\text{cut}}) \rangle = \frac{1}{y_{\text{cut}}} \sum_n n \sigma_n(y_{\text{cut}})$ and the differential 2-jet rate $y_{23}$ is used, both being sensitive to $\alpha_S$ in leading order. The theoretical prediction applied here are combined NLO+NLLA calculations. Hadronization correction are determined with Monte Carlo. The combined value of both jet-finder schemes applied to the energy range between 91 and 209 GeV is

$$\alpha_S(M_{Z^0}) = 0.1182 \pm 0.0003 \pm 0.0015$$
$$\pm 0.0011 \pm 0.0012 \pm 0.0013,$$

with the first uncertainty being the statistical one, the second the experimental one, the third due to the hadronization and the last the theoretical one.

The OPAL and the JADE collaboration uses the number of selected four-jet events to determine the strong coupling $\alpha_S$. The theoretical predictions are NLO combined with NLLA calculations. The leading order prediction is proportional to $\alpha_S^2$ and therefore the theoretical uncertainty due to higher order missing terms is proportional to $\alpha_S^3$. A decreased theoretical uncertainty compared to leading order $\alpha_S$ observables is expected. The combined value of $\alpha_S$ determined by OPAL using the Durham jet-finder scheme and data between 91 and 209 GeV is

$$\alpha_S(M_{Z^0}) = 0.1159 \pm 0.0004 \pm 0.0012$$
$$\pm 0.0024 \pm 0.0007,$$

with the first uncertainty being the statistical one, the second the experimental one, the third due to the hadronization, the fourth due to higher order missing terms and the last due to effects originating from the b-quark mass.

A similar measurement is performed by the JADE collaboration also using the Durham jet-finder and data between 22 and 44 GeV. The combination returns a value of

$$\alpha_S(M_{Z^0}) = 0.1191 \pm 0.0007 \pm 0.0011$$
$$\pm 0.0024 \pm 0.0007,$$

with the first uncertainty being the statistical one, the second the experimental one, the third due to the hadronization and the last the theoretical one. Both $\alpha_S$ measurements have a similar precision, dominated by systematic uncertainties. The theoretical uncertainty due to higher order missing terms is decreased compared to measurements of $\alpha_S$ using observables sensitive in leading order to $\alpha_S$. Fig. 2 shows the result and the variation of $\alpha_S$ with respect to the centre-of-mass energy. In the case of the $\alpha_S$ measurements
The values of $\alpha_S$ at the various energy points. The errors show the statistical (inner part) and the total error. The full and dash-dotted lines indicate the world average value of $\alpha_S$ with error.

Fig. 2. The values of $\alpha_S$ at the various energy points. The errors show the statistical (inner part) and the total error. The full and dash-dotted lines indicate the world average value of $\alpha_S$ with error.

using four-jet events two alternative methods to evaluate the theoretical uncertainty are studied. First, both, the renormalization scale factor and the strong coupling $\alpha_S$ are varied within the fit. Second, the renormalization scale factor is determined as the one with the least sensitivity with respect to $\alpha_S$. Both alternative methods return values of $\alpha_S$ which are well within the theoretical uncertainty of the default method. The natural choice of the renormalization scale factor is close to the renormalization scale factor having the least sensitivity to the renormalization scale factor. This leads to smaller theoretical uncertainties determined by varying the scale factor, compared to fits to event-shape observables sensitive to $\alpha_S$ in leading order.

Measurements at OPAL and JADE alone return no significant proof for the running of $\alpha_S$. However, a combined fit to the OPAL and JADE data points confirms the running with high significance with a $\chi^2$ value of 12.0/18, compared to 149.5/18 assuming a constant value of $\alpha_S$.

5. Summary

Studies of the strong coupling using event-shape observables and jet-rates in $e^+e^-$ are presented. All measurements return values of $\alpha_S$ consistent with the world average $^6$. A summary of all measurements is shown in Fig. 3. The determination of $\alpha_S$ using the four-jet rate leads to a decreased theoretical uncertainty. The combination of data taken at LEP experiments and the JADE experiment confirm the running of $\alpha_S$ with high significance.

Fig. 3. A summary of all measurements of $\alpha_S$ discussed in this article. All measurements are consistent with the current world average.

References

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