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Precise determination of $\alpha_S(m_{Z^0})$ from a global fit of energy-energy correlations to NNLO+NNLL predictions

A. Kardos[1], *S.* Kluth[2,*], *G.* Somogyi[1], *Z.* Tulipánt[1], and *A.* Verbytskyi[2]

[1]University of Debrecen, Hungary
[2]MPI für Physik, Munich, Germany

Abstract. We present a determination of the strong coupling constant $\alpha_S(m_{Z^0})$ using a global fit of theory predictions in next-to-next-next-leading-order (NNLO) combined with resummed predictions at the next-to-next-leading-log level (NNLL) [1]. The predictions are compared to distributions of energy-energy correlations measured in e^+e^- annihilation to hadronic final states by experiments at the e^+e^- colliders LEP, PETRA, TRISTAN and PEP. The predictions are corrected for hadronisation effects using the modern generator programs Sherpa 2.2.4 and Herwig 7.1.1.

1 Introduction

Data from experiments at e^+e^- colliders have been used since a long time to investigate the theory of strong interactions, Quantum Chromo Dynamics (QCD) and in particular to measure its only free parameter (in the absence of quark mass effects) the strong coupling constant $\alpha_S(m_{Z^0})$ at the reference scale m_{Z^0}, see e.g.[2].

The most important tools to analyse the hadronic final state and compare with QCD predictions are event shape observables and jet production rates. The energy-energy correlation EEC (details below) is an example of an event shape observable, where the observed particles (objects) of the hadronic final state are used to calculate in a theoretically consistent manner quantities, which are representative of the topology of the event.

There are several recent determinations of $\alpha_S(m_{Z^0})$ using data of e^+e^- annihilation to hadronic final states using NNLO QCD predictions combined with resummed calculations and different approaches to treat non-perturbative effects (hadronisation), see [3]. The differences between the measurements using analytic hadronisation models or Monte Carlo generator based models are sometimes significantly larger than the quoted uncertainties which points to possible biases not accounted for in the analyses.

We present here a new measurement of $\alpha_S(m_{Z^0})$ using the energy-energy correlation in hadronic final states of e^+e^- annhilation with NNLO and NNLL QCD calculations [1]. The hadronisation effects are corrected for using modern Monte Carlo generators with NLO QCD matrix elements for the calculation of the primary interaction. Compared to most previous analysis using NNLO + NNLL or NLL with Monte Carlo corrections of hadronisation effects this is a significant improvement. The related observable "transverse EEC in multijet events" has been used by the ATLAS collaboration to measure the strong coupling constant with NLO QCD predictions [4].

*e-mail: skluth@mpp.mpg.de

2 The energy-energy correlation in e^+e^- annihilation to hadrons

The EEC was introduced in [5] and then used frequently. The EEC is defined by

$$\frac{1}{\sigma}\frac{d\Sigma(\chi)}{d\cos\chi} = \frac{1}{\sigma}\int\sum_{i,j}\frac{E_iE_j}{Q^2}d\sigma(e^+e^- \to ij + X)\delta(\cos\chi - \cos\theta_{ij}) \tag{1}$$

where σ is the cross section for $e^+e^- \to$ hadrons, E_i and E_j are the energies of a pair of particles i and j, θ_{ij} is the angle between them, $Q = \sqrt{s}$ is the centre-of-mass energy of the collision, and χ is the angular variable. In the experiments the expression is discretised in χ such that a sum over all pairs of particles with enclosed angle θ_{ij} falling in a given small interval in χ is calculated.

The resulting distribution of the EEC over the range $\chi \in [0, 180]^\circ$ deg. has peaks at $\chi \approx 0$ and $\chi \approx 180^\circ$. For small χ the peak corresponds to particle pairs in the same jet (forward region) and for large χ the peak is due to particle pairs in different and mostly opposite jets (back-to-back region). The peak at small χ is dominated by non-perturbative effects while the peak at large χ is dominated by perturbative effects since e.g. gluon radiation in the primary interaction will change the topology of the final state and thus the EEC distribution at large χ.

The fixed order QCD prediction in NNLO is expressed as a power series in the strong coupling

$$\frac{1}{\sigma_0}\frac{d\Sigma(\chi)}{d\cos\chi} = \hat{\alpha}_S\frac{dA}{d\cos\chi} + \hat{\alpha}_S^2\frac{dB}{d\cos\chi} + \hat{\alpha}_S^3\frac{dC}{d\cos\chi} \tag{2}$$

where $\hat{\alpha}_S = \alpha_S/(2\pi)$. The A, B and C are the LO, NLO and NNLO coefficient functions determined by integration of the QCD matrix elements using the CoLorFulNNLO scheme [6]. The neccessary corrections for normalisation to the total cross section for $e^+e^- \to$ hadrons and the variation of the renormalisation scale are included in the analysis [1]. The default QCD prediction will be evaluated at a renormalisation scale $\mu_R = \sqrt{s}$, where $\sqrt{s}$ is given by the cms energy of the e^+e^- collision.

The data from e^+e^- annihilation contain a fraction of events where a primary pair of b-quarks was produced in the interactions varying from about 11% at energies below the Z^0 peak to about 21% on the Z^0 peak. The large mass of the b-quark of $m_b(m_b) = 4.2$ GeV [3] leads to significant effects on event shape observable distributions. Since the data are inclusive the predictions are modified for b-quark mass effects by adding the complete NLO prediction with mass effects with a relative weight given by the predicted fraction of b quark production to the NLO part of the massless prediction shown above. The predictions with mass effects are calculated using the program described in [7].

At large values of χ in the back-to-back region of the EEC distribution the fixed order predictions will diverge $\approx \alpha_S^n(\log^{2n-1}(y) + \log^{2n-2}(y) + \log^{2n-3}(y) + \ldots)$, $y = \cos^2(\chi/2)$. For the first few towers of logarithms, a summation of the infinite series in n is possible, the so-called resummation. In this analysis resummation results for ECC at NNLL are used. An extension of the resummation to N3LL may appear in the future [8]. The combination of the NNLO fixed order predictions with the resummed predictions, the so-called matching, involves identifying all terms proportional to powers of α_S^n, $n = 1, 2, 3$, in the resummed prediction and subtracting them from the combined (added) prediction in order to avoid double counting. The $\log(R)$-matching procedure for the EEC used in this analysis is described in [9]. The resummation variable y can be rescaled by setting $L = \log(y) = \log(yx_L^2) - \log(x_L^2)$ with a resummation scale parameter x_L different from unity.

3 Hadronisation corrections

The experimental data are published by the collaborations "at the hadron level" with corrections for experimental effects such as limited acceptance of the experiment and the event selection and limited resolution for the measurements of particle momenta and energies. The theoretical predictions are at the level of the partons (quarks and gluons) of QCD and are known to not give an adequate description of the data. This is due to the presence of non-perturbative corrections connected with the transition of partons to hadrons, i.e. the hadronisation process. There is no perturbative understanding of this process and models are used instead. In this analysis we use the hadronisation models implemented in the Monte Carlo event generators Sherpa and Herwig 7. In the Sherpa program the Lund string model as well as the cluster model are available while in Herwig 7 the cluster model is available.

The Sherpa program version 2.2.4 is used with the MENLOPS procedure to simulate and merge samples for the processes $e^+e^- \to 2, 3, 4, 5$ partons and NLO matrix elements for 2-parton final states. The Herwig program is used in version 7.1.1 with unitarised merging for $e^+e^- \to 2, 3, 4, 5$ partons to generate combined samples, also with a NLO calculation for 2 parton final states. For both programs $\alpha_S(m_{Z^0}) = 0.1181$ is set and otherwise the default settings are used, for details see [1]. We refer to Sherpa with the Lund string model as S^L and with the cluster model as S^C while Herwig 7 is labelled H^M.

The simulated samples are reweighted to the data for the EEC distributions at hadron level for each data set in order to improve the description of the data by the simulations. The hadronisation corrections are calculated as the ratio of EEC distributions at parton and hadron level in the simulations using the weighted events. These corrections are applied to the perturbative predictions before they are compared with the data.

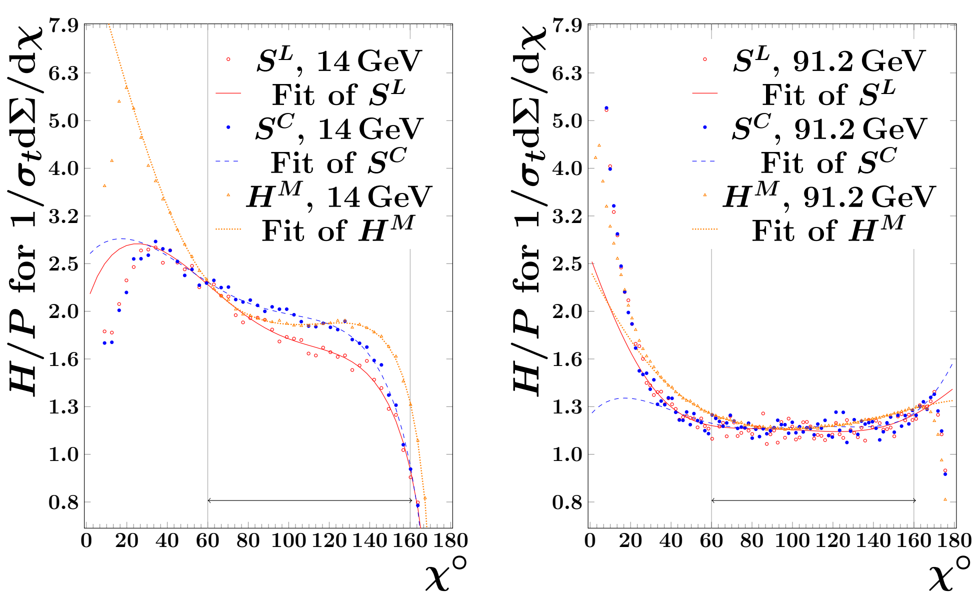

Figure 1. (left) The figure shows predictions for the ratio of EEC values at parton and hadron level at $\sqrt{s} = 14$ GeV by various generators as indicated. The solid lines are parametrisations of the distributions. (right) The same as for (left) but at $\sqrt{s} = 91.2$ GeV [1].

Figure 1 (left) shows the hadron over parton level ratio for the JADE data at 14 GeV centre-of-mass (cms) energy. The predictions of the different simulations are indicated by the points. The lines are the results of parametrisations performed to supress the influence of statistical fluctuations. At the lowest available cms energy of 14 GeV the corrections are between a factor of 1.3 to 2 in the range used in the fits indicated by the horizontal arrows and vertical black lines. The different simulations agree reasonably well with each other. The differences will be studied as a systematic uncertainty. Figure 1 (right) shows the same results for the OPAL measurement of the EEC at 91.2 GeV, i.e. on the Z^0 peak. The corrections are now predicted to be about 10 to 20% with much reduced dependence on the value of the variable χ compared to the 14 GeV results. The agreement between the different simulations has improved as well.

4 Fits to the data

In total 20 datasets corrected to the hadron level and with sufficient detail about statistical and experimental uncertainties are available for analysis [1]. The statistical correlations between bins of the distributions are estimated using simulation at hadron level and can be as high as about 0.5 for neighboring data points.

The combined NNLO+NNLL calculations corrected for hadronisation effects are compared to the data with $\alpha_S(m_{Z^0})$ as the only free parameter. The optimisation is based on a χ^2 method:

$$\chi^2 = (\vec{D} - \vec{P}(\alpha_S)) \cdot V^{-1} \cdot (\vec{D} - \vec{P}(\alpha_S))^T \tag{3}$$

where $\vec{D}$ is a vector with the data points, $\vec{P}$ is a vector with the predictions corresponding to the data points and corrected for hadronisation, and V^{-1} is the inverse of the sum of the statistical and systematic covariance matrices for each data set. For the global fit the sum of the χ^2 for each data set is optimised.

The data points in the fits are chosen in fit ranges, i.e. in contiguous regions of the distributios. Within the fit ranges the hadronisation corrections and the resummation calculations are reliable. The default fit range is given by the interval 60 to 160°. The default fit uses the S^L, i.e. the Sherpa with Lund string model, hadronisation corrections. The result of the default fit with all uncertainties is

$$\alpha_S(m_{Z^0}) = 0.1175 \pm 0.0002(fit) \pm 0.0010(had.) \pm 0.0026(ren.) \pm 0.0008(res.) \ . \tag{4}$$

The *fit* error is from the fit and contains the statistical and experimental uncertainties of the data. The *had.* error is the hadronisation uncertainty estimated by comparing to a fit using the S^C, i.e. Sherpa with cluster model, hadronisation. The *ren.* error is the renormalisation scale uncertainty estimated by varying the renormalisation scale μ_R in the theory predictions by a factor of 1/2 or 2 from the default scale $\mu_R = \sqrt{s}$. The *res.* error is the resummation scale uncertainty given by variation of the resummation scale parameter x_L by a factor of 1/2 or 2. The total uncertainty is $\Delta\alpha_S(m_{Z^0}) = 0.0029$ corresponding to a 2.5% relative error. The total uncertainty is dominated by the renormalisation scale and the hadronisation errors. Several other effects have been studied such as variation of the fit ranges, and leaving out data sets from the fits [1] and have been found to have no significant effect on the result.

Figures 2 (left) and (right) show as examples the results of the default fit compared to the data from JADE at 14 GeV and from OPAL on the Z^0 peak. The red line shows the default fit, which describes the data at 14 GeV and the data at 91.2 Gev reasonably well. The blue lines indicate a fit using a NLO+NNLL prediction in order to investigate the impact of the NNLO contribution. The NLO+NNLL fit describes the OPAL noticably less well. The full analysis with a NLO+NNLL prediction yields $\alpha_S(m_{Z^0}) = 0.1220 \pm 0.0054$, with significantly larger

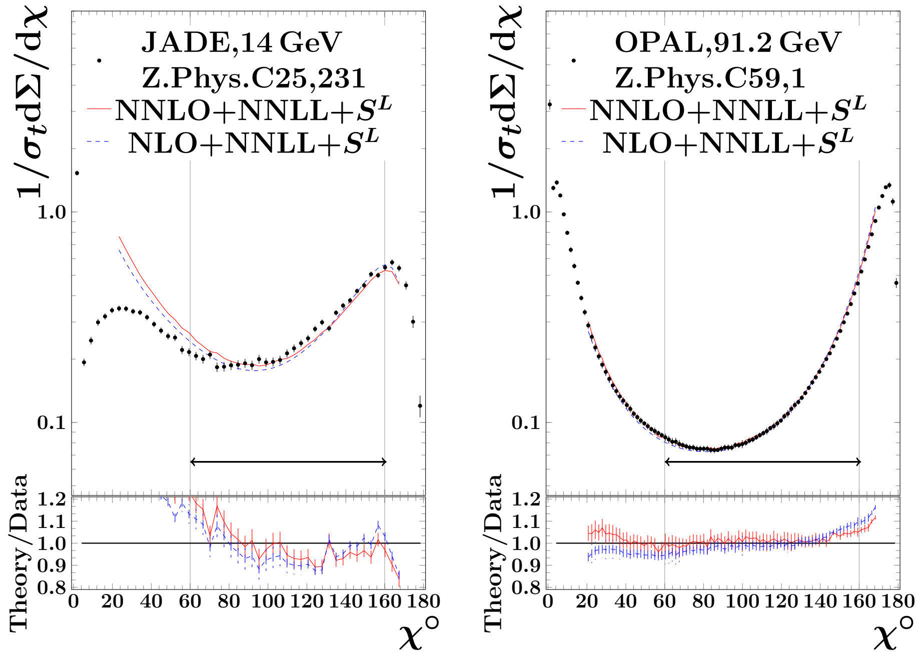

Figure 2. (left) The figure shows the data for the EEC from JADE at 14 GeV together with the results of the default fit (solid red line) and the NLO+NNLL fit (dashed blue line). The lower plot presents the ratio of the theory prediction and the data. (right) Same as for (left) but with data from OPAL at 91.2 GeV.

values of χ^2 compared to the default analysis [1]. This result is conistent with the world average value of $\alpha_S(m_{Z^0})$ [3] and in particular the uncertainty is in line with uncertainties of related measurements using event shapes with NNLO+resummation analyses and Monte Carlo generator based hadronisation corrections.

Figure 3 shows the dependence of the default NNLO+NNLL and the NLO+NNLL fits on the renormalisation scale (left) and the resummation scale (right). The default NNLO+NNLL fit has weaker dependence on the theory scales compared with the NLO+NNLL fits. This is evidence that adding the NNLO contribution to the prediction improves the convergence of the perturbative series.

5 Truncated parton shower bias

In a recent publication [10] a calculation of the effects of a truncated parton shower as implemented in the Herwig 7 generator using the coherent branching algorithm was shown. Truncation refers to the stopping criterion present in any parton shower implementation.

Since in this analysis, as in many previous determinations of $\alpha_S(m_{Z^0})$, hadronisation corrections are calculated with Monte Carlo generator programs, there could be a possible bias on the result. This bias would be caused by the discrepancy of the perturbative prediction, which contains resummation without a cutoff and the parton level in the generator including the cutoff.

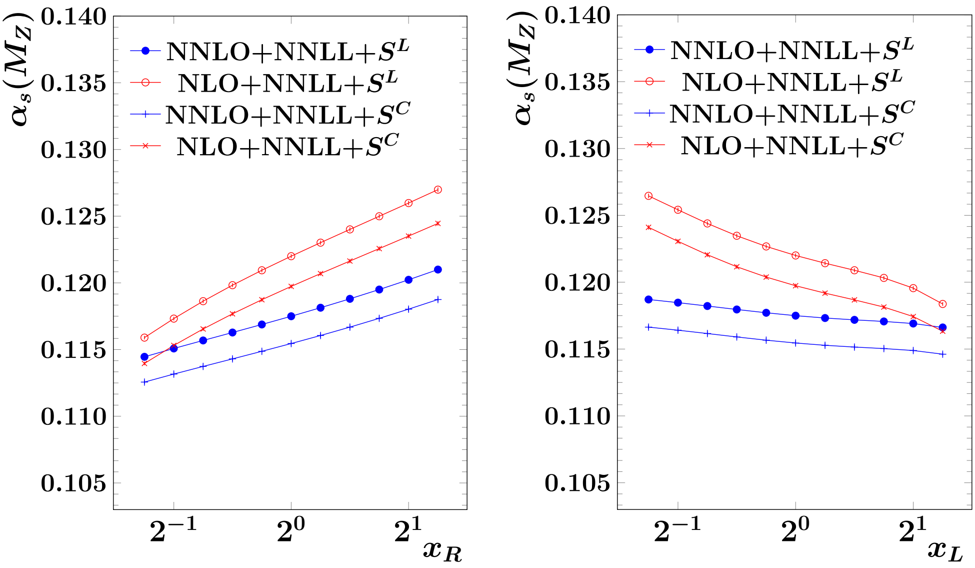

Figure 3. (left) The Figure shows as blue lines the dependence of the fit results on the value of the renormalisation scale $\mu_R = x_R\sqrt{s}$ for the default fits NNLO+NNLL with the S^L and S^C hadronisation corrections, as indicated on the figure. The red lines show the results for the NLO+NNLL fits. (right) The same as (left) but for the dependence of the results on the value of the resummation scale x_L.

This effect was already studied by the OPAL collaboration in their determination of $\alpha_S(m_{Z^0})$ using event shape observables including the EEC and NLO+NLL resummation predictions [11]. In this analysis the parton shower cut parameter in the JETSET 7.3 generator was varied from its default value of $Q_0 = 1$ GeV to 2 GeV and the determination of $\alpha_S(m_{Z^0})$ was repeated. Since a difference in Q_0 of 1 GeV corresponds to an extrapolation for $Q_0 = 1$ GeV to 0 GeV, i.e. no parton shower cut, this test can estimate the size of a possible bias, if the dependence of the results on the value of Q_0 is approximately linear. The approximate linearity was confirmed in the OPAL analysis.

The result for the deviation from OPAL was $\Delta\alpha_S(m_{Z^0}, Q_0 = 1 \to 2GeV) = -0.0009$ [11]. Even though there are differences in the parton shower algorithm and the precision of the perturbative prediction, we thus conjecture that a possible bias in this analysis due to the truncated parton shower in the simulations has about this size. Future analyses using Monte Carlo generator based hadronisation corrections aiming for precision on $\alpha_S(m_{Z^0})$ at the 1% level should study this effect explicitly.

6 Summary

We have shown a determination of the strong coupling constant $\alpha_S(m_{Z^0})$ using the event shape observable EEC using NNLO combined with NNLL resummed QCD predictions. The non-perturbative predictions are determined using modern Monte Carlo generators reweighted to describe the data for the EEC well. The result is $\alpha_S(m_{Z^0}) = 0.1175 \pm 0.0029$ consistent with the world average and with competetive uncertainties compared to similar analyses. The inclusion of NNLO QCD predictions is important as observed by the significant reduction of the total uncertainty. Future improvements to this analysis might be possible by including

N3LL resummation and by performing measurements of the EEC with the high energy LEP2 data samples.

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