PROCEEDINGS

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Event Shape Studies at LEP

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Abstract: Infrared and collinear events shapes are suited to directly probe properties of hard QCD. They are traditionally used to measure the strong coupling and to test the gauge structure of QCD. Perturbative predictions exist in several variations all of which depend on the renormalisation scheme leading to large theoretical uncertainties in the determination of α_s. In order to match perturbative predictions with data the non-perturbative effects of hadronisation have to be taken into account. Beside MC models the analytical power corrections are now widely used.

1. Introduction

Event shapes are sensistive to the strong coupling, α_s, and the gauge structure of the strong force. However, the observables investigated (mean values, higher moments and normalised distributions) don't depend on the production rate nor on the event orientation and are therefore independent of the electroweak production process. They are thus directly connected to fundamental properties of the strong force.

QCD predictions for these observables exist in several approximations. Fixed order α_s calculations exist in NLO (in this talk I concentrate on $\mathcal{O}(\alpha_s^2)$, see [1] for $\mathcal{O}(\alpha_s^3)$). NLLA calculations resum all orders of α_s in two jet like configurations. Combination of $\mathcal{O}(\alpha_s^2)$ with NLLA predictions suffer from ambiguities in avoiding double counting. Several so called matching schemes exist, the most popular being the $\log R$-matching. All of these calculations depend on the unphysical renormalisation scale, which is varied in order to estimate theoretical uncertainties.

The conversion of perturbatively accessible partons into hadrons may have a significant impact on the final value of an event shape observable. In order to match perturbative predictions with data these non-perturbative hadronisation effects thus have to be taken into account. Traditionally the only way to correct for these non-perturbative effects was the application of Monte Carlo models, which suffer from a large number of free parameters that need to be tuned. Since a few years the analytical ansatz of power corrections with only one free parameter is used as an alternative.

I will discuss the main aspects of new results obtained with event shapes and presented to this conference [2, 3, 4, 5, 6, 7, 8, 9].

2. Measurements

Experimentally the measurement of event shapes observables in e^+e^- is well established. After the detector dependent selection of tracks and clusters the event selection needs to suppress certain backgrounds. At M_Z the main backgrounds are Bhabha, $\tau^+\tau^-$ and $\gamma\gamma$ events, which can be efficiently suppressed. At LEP2 on top of these initial state radiation (ISR) and boson (W or Z) pair production needs to be taken into account. Especially the suppression of boson pair production is difficult to achieve without biasing the event shape observables. Thus a moderate suppression minimising the bias is combined with subtracting the expected contribution from remaining background. In a final step the measured quantities are corrected for detector acceptance effects to reach results comparable between experiments. However, different experiments use different reference levels in order to minimise systematic errors. As reference levels stable particles including or not including neutrinos and charged particle only are in use. Differences between these levels need to be accounted for when really comparing results.

3. Interpretation

3.1 Strong coupling using MC models

Based on such measurements all LEP experiments have presented a determination of the strong coupling using combined $\mathcal{O}(\alpha_s^2)$+NLLA in $\log R$-scheme with traditional Monte Carlo based hadronisation corrections [2, 3, 8, 9]. DELPHI and L3 used $1-T$, ρ_h, C, B_t and B_w, ALEPH and OPAL used in addition y_{23}. The results are in good agreement with each other. Combination yields

$$\alpha_s(206\,\mathrm{GeV}) = 0.1082 \pm 0.0012_{\mathrm{exp}} \pm 0.0034_{\mathrm{theo}}.$$

Beside combined $\mathcal{O}(\alpha_s^2)$+NLLA DELPHI investigated $\mathcal{O}(\alpha_s^2)$ with optimised scales and also pure NLLA and found good agreement within the large theoretical uncertainties.

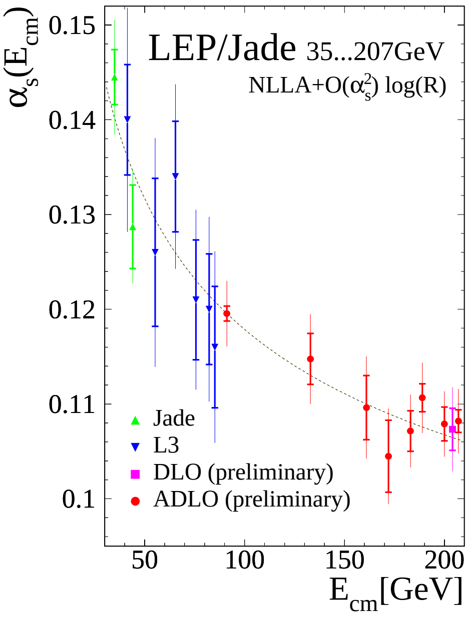

Figure 1: Running of α_s for LEP combined results compared to JADE results. Errors are split into a statistical part and the total error.

The LEP QCD working group has performed a combination of direct measurements of the strong coupling for centre-of-mass energies between 41 and 205 GeV. The inputs collected from existing publications were given by the four LEP experiments with an agreed error split, so that correlations between the experiments and between different energies could be taken into account. An overall $\mathcal{O}(\alpha_s^3)$-fit yields

$$\alpha_s(M_Z) = 0.1195 \pm 0.0007_{\mathrm{exp}} \pm 0.0048_{\mathrm{theo}} \quad ,$$

see line in Fig. 1. The result for 206 GeV doesn't enter the fit, yet. The quality of the fit with $\chi^2/\mathrm{ndf} = 31.3/36$ shows that the data are in excellent agreement with the running expected from QCD.

An improved combination including the highest energies is in preparation. It will be based on refitted results with an unified theoretical basis and a more homogenous error estimation.

3.2 Power Corrections

Power corrections are an analytical description of the influence of hadronisation on event shape observables. The power correction ansatz of Dokshitzer and Webber [10, 11] describes the hadronisation by an additive term for the mean $\langle f \rangle$ of an observable f and by a shift for its distribution $\mathcal{D}_f(f)$:

$$\langle f \rangle = \left\langle f^{\mathrm{pert}} \right\rangle + c_f \mathcal{P}(\alpha_0) \qquad\qquad \mathcal{D}_f(f) = \mathcal{D}_f^{\mathrm{pert}}(f - c_f \mathcal{P}(\alpha_0)) \quad , \tag{3.1}$$

where the superscript 'pert' shall indicate the perturbative prediction. The size of the power correction term is defined by two parts.

All dependence on the variables is put in the coefficient c_f, which is computed for several observables, see e.g. [6] for a table. The other factor, $\mathcal{P}(\alpha_0)$, is the same for all observables. It is falling off like the inverse centre-of-mass energy and depends on an unknown parameter α_0. α_0 is interpreted as the average strong coupling below the intermediate scale μ_I where the perturbative prediction is replaced by the power correction.

An application of power corrections will always have to fit α_0 from data at low centre-of-mass energies, which have the highest sensitivity on this parameter.

3.2.1 Structure constants

To measure the structure constants, one needs to use predictions in which the structure constants are still parameters. Second order predictions will have terms proportional to C_F, C_F^2, $C_F C_A$ and $C_F T_R = C_F \frac{1}{2} n_\mathrm{f}$.

In previous measurements MC based hadronisation corrections were used, in which the hadronisation is described assuming of QCD. MC tuning to real data should have minimised the resulting bias.

In [5] for the first time power corrections are used and the structure constants were allowed to vary also in the description of the hadronisation. The combined results of event shape distributions with centre-of-mass energies between 14 and 189 GeV obtained for fixed α_0 are in good agreement with the QCD expectation, as shown in Fig. 2.

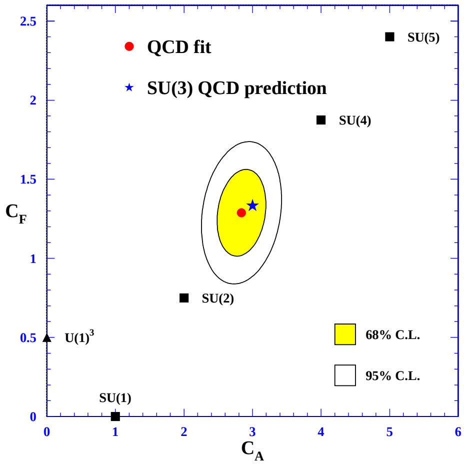

Figure 2: Measurement of structure constants using power corrections [5].

3.2.2 Hadron Masses

As QCD calculations for both the perturbative and the power corrections were carried out for massless partons, power correction analyses don't take the influence of hadron masses into account. Replacing the four-momenta of the particles according to

$$p = (\vec{p}, E) \rightarrow (\vec{p}, |\vec{p}|) \quad (p\text{-scheme}) \quad (3.2)$$

$$\text{or } p = (\vec{p}, E) \rightarrow (\hat{p}E, E) \; (E\text{-scheme}) \quad (3.3)$$

doesn't change the predictions, but it does change the observable values calculated with massive particles.

For the jet masses at M_Z the difference between the usual and the p-scheme definition is around 10%, the difference between E- and p-scheme 2.5%.

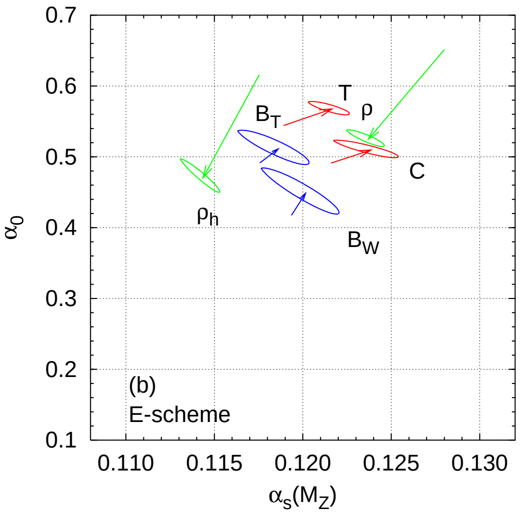

Figure 3: Two parameter fits to α_0 and α_s. Ellipses show the result of using the E-scheme definition, the arrows indicate the change of the central values wrt. their standard definitions.

These differences, which demonstrate the influence of hadron masses, behave like a (logarithmically enhanced) power correction. Only in the E-scheme is this correction proportional to the *same* coefficient as the standard power correction: c_f. Thus performing the power corrections analysis in the E-scheme should improve the consistency obtained when fitting α_0 from different observables.

Fig. 3 shows that indeed, when using observables measured in or corrected to the E-scheme, the range of α_0-values reduces from ±25% to ±12% [6].

3.3 Renormalisation Group Invariant Perturbation Theory

Renormalisation group invariant perturbation theory (RGI) is based on the idea to use the observable itself as expansion parameter. With this one avoids any dependence on a renormalisation scheme. The energy dependence of an event shapes mean value can still be predicted and is given by the β-function. The constant from integrating the corresponding relation can be connected to $\alpha_s(M_Z)$ using the Celmaster-Gonsalves equation.

The application of RGI contributed by DELPHI [7] provides a good description of seven observables, when the E-scheme definitions is used for the jet masses, and yields $\alpha_s(M_Z) = 0.1172 \pm 0.0040$. Hadronisation is described by fitting a power correction term, which contributes of the order of only 2% and is consistent with zero.

For the final result the power correction term is set to zero. This application of pure RGI even reduces the spread on the strong coupling: $\alpha_s(M_Z) = 0.1195 \pm 0.0020$. For the β-function a fit including low energy and DELPHI data points yields

$$\frac{\beta_0}{2\pi} = 1.25 \pm 0.05 \quad \text{or, assuming QCD} \quad n_{\mathrm{f}} = 4.75 \pm 0.44 \qquad (3.4)$$

with surprisingly small systematics and in perfect agreement with QCD, from which 1.27 is expected.

4. Comparison of the various methods

As in other fields it is useful to compare the direct measurements with the results from more indirect methods. In Fig. 4 I have assembled several measurements of the strong coupling performed at LEP and compared them to the current PDG world average [12].

Beside the results from the LEP QCD working group [13], a combination of pure NLLA results [14, 15], an application of $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ with MC models and optimised scales [15, 16] and results from $\mathcal{O}(\alpha_s^2)$ with power corrections [6]. The error contribution from the renormalisation scale was adapted to use a consistent variation of $\mu/Q = 0.5 \ldots 2.0$. The increase, if any, is shown as extra (red) error bars.

The different methods show a good consistency within the quoted errors which are in all cases dominated by the contribution from the renormalisation scale variation.

The indirect determinations of the strong coupling stem from the investigation of τ hadronic branching ratio R_τ [12], from the hadronic width of the Z [17] and from a five parameter fit to electroweak precision data [18]. They show a good consistency with the direct results and with the world average within the given errors.

5. Conclusions

Event shapes provide a means for directly probing properties of hard QCD. There are still many different options on both the perturbative and the non-perturbative side. Experimentalists and theorists are interacting to improve the understanding. The incredibly good description of mean event shapes with pure RGI gives new input to this discussions.

Measurements of the strong coupling from event shapes are in good agreement with results from more indirect measurements. The dependence on the renormalisation scale is used to estimate theoretical uncertainties, which limits the precision of current direct measurements of the strong coupling.

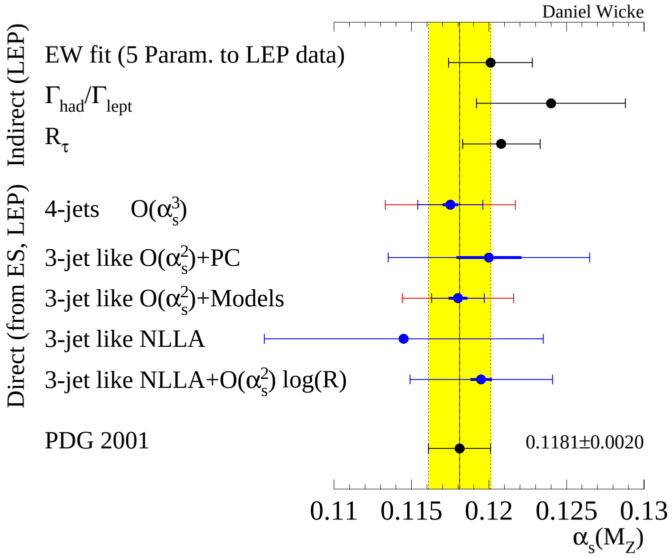

Figure 4: Comparison of direct measurements of the strong coupling from event shapes at LEP with indirect results from LEP and the current world average.

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