Chapter 7

Four-Parton Monte Carlo Studies

Con las flores de un campo encendido
Como un San Francisco entre jarales vivos
De lagartos, vivo.
De quimeras me alimento,
Con simplezas me contento.

7.1 Motivation of the studies

In the context of this thesis many studies on the new four-parton Monte Carlo programs have been performed. In Section 5.3.1 it was already stated that there is a disagreement in the four-jet angular correlations between standard MCs and ALEPH data. For this reason, the new MC programs which allow to start a shower from four-parton configurations have been investigated in order to look for the best corrections for the four-jet angular correlations. As will be shown in the following sections, many aspects of the behaviour of four-parton MCs have been understood, but some problems remain opened at the moment of writing this work.

7.2 Studies on the intrinsic resolution parameter

The resolution parameter $\mathrm{y_{cut}}$ for clustering to four-jet events was chosen to be 0.008 for the angular correlations, based on purity and efficiency criteria. In Section 5.3.1, it was seen that both PYTHIA and HERWIG four-parton options have a key parameter to avoid soft and collinear divergences. This is the intrinsic resolution parameter, $\mathrm{y_{int}}$, which was selected to be 0.004 in the MC simulations used for the calculation of the background and hadronization corrections.

The specifications of the MC programs are $\mathrm{y_{int}} \ll \mathrm{y_{cut}}$, but no best value for $\mathrm{y_{int}}$ is given. In order to check for the dependence of the corrections on the $\mathrm{y_{int}}$ value, the following check was performed. Two samples of 1 million events ("test samples") with different values for $\mathrm{y_{int}}$ were generated using PYTHIA, and the four-jet angular correlations where calculated at three levels: parton level before showering (PL), parton level after showering (PS) and hadron level (HL). The $\mathrm{y_{int}}$ values were 0.003 and 0.005, and the distributions where compared to the ones used for the corrections in Section 5.3.1, where the intrinsic $\mathrm{y_{cut}}$ was set at 0.004 ("standard sample").

The ratios of the distributions for $\mathrm{y_{int}}$=0.003(5) and $\mathrm{y_{int}}$=0.004 at parton level and at hadron level are shown in Fig. 7.1. The ratios were calculated for the normalized angular correlations. In the figure no significant discrepancies are observed between the shape of the angular correlations from the "test samples" with respect to the "standard sample" used for the simultaneous measurement of the strong coupling constant and the colour factors. The discrepancies are only visible at the high edge of the $\cos\alpha_{34}$ distribution, but those bins where not used in the fit.

From this test it can be concluded that the background and hadronizations corrections used for the four-jet angular correlations do not sharply depend on $\mathrm{y_{int}}$, except for some region in $\cos\alpha_{34}$. We expect that if $\mathrm{y_{int}}$ is moved to more extreme values the distributions will be affected. If $\mathrm{y_{int}}$ is increased too much, the condition of $\mathrm{y_{cut}} \gg \mathrm{y_{int}}$ will not be fulfilled and the MC distributions are not reliable anymore. If $\mathrm{y_{int}}$ is too small, the efficiency of the MC generation worsens quickly, and in the limit of very small $\mathrm{y_{int}}$ the soft and collinear singularities will not be cut out efficiently.

7.3 Studies on the Shower Models

The studies on the shower models are performed by comparing the distributions after the shower process from PYTHIA and HERWIG. In both cases the intrinsic resolution parameter was set to 0.004 and the showering parameters were set at the same values as for the standard $q\bar{q}$+PS+hadronization simulation. As both simulations start from the same four-parton level configurations, we can directly compare the normalized distributions after PS.

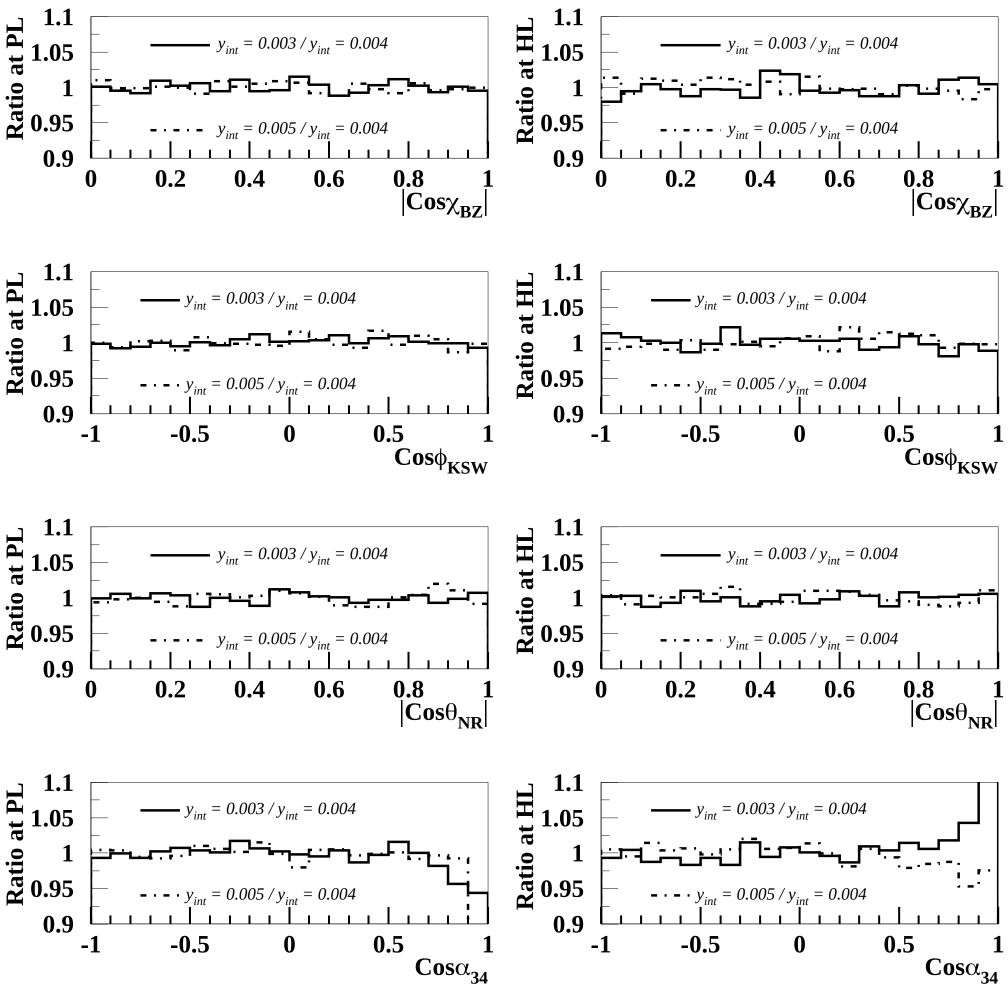

Figure 7.1: Ratios of the angular correlations for y_{int}=0.003 and 0.005 with respect to the standard value y_{int}=0.004 at parton and hadron level.

Figure 7.2 shows the comparison of the distributions coming from PYTHIA and HERWIG. The distributions show significant discrepancies, wich are more pronounced for $\cos\alpha_{34}$. This could be explained either by a better behaviour of one of the showering models, or by the need of retuning one (both) program(s). In principle, the tuned parameters should be “universal” for each Monte Carlo version. However, we have seen that the four-jet angular correlations are not well reproduced by the MC simulations starting from a $q\bar{q}$ pair, only. This might be an indication of a problem in the tuning of the MC programs, as usually the angular observables are not included in this process.

A last observation about the discrepancies observed is presented here. The four-jet angular correlations were thought to be sensitive to the intrinsic properties of the

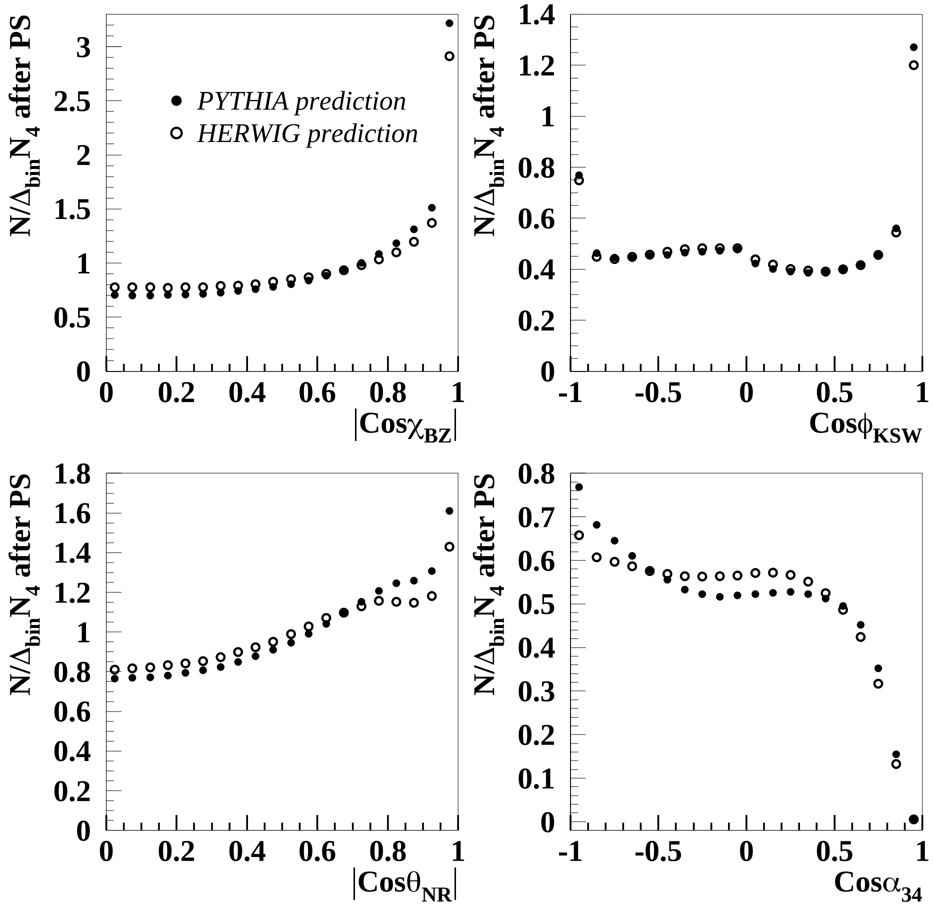

Figure 7.2: Comparison of the predictions after the parton shower from the four-parton option in PYTHIA and HERWIG.

structure of such events. It might be that the investigations so far have led to the point where the approximations and modelizations are not correct anymore (i.e. exact higher order calculations are required for an improvement of the predictions).

7.4 Studies on the Fragmentation Models

As already explained in Section 2.5, PYTHIA and HERWIG model in a different manner the fragmentation of the partons into hadrons at the end of the showering process. The first is based on a string fragmentation, and the second on a cluster fragmentation model. The comparison of the two fragmentation processes is done at hadron level after the shower level has been subtracted, since we are not interested (at this point) in the differences at hadron level which are just a reflection of primary differences at parton level. So, the normalized hadron level distributions over the normalized parton shower distributions from PYTHIA and HERWIG, which are the so called hadronization corrections, are compared in Fig. 7.3. In this case, the discrepancies between both MC simulations are smaller than for the comparison after the showering process. The differences are at the 2-4% level, only going to larger values at the high edge of the forth angular distribution, which is always the most sensitive to all effects encountered in the studies of this thesis. For the comparison after the showering process, the discrepancies where at the 10-20% level for wide range areas, and also going to larger values at the edges of some distributions. It is quite difficult to assess where the discrepancies at hadron level come from. At first approximation, the effects coming from the discrepancies due to the showering

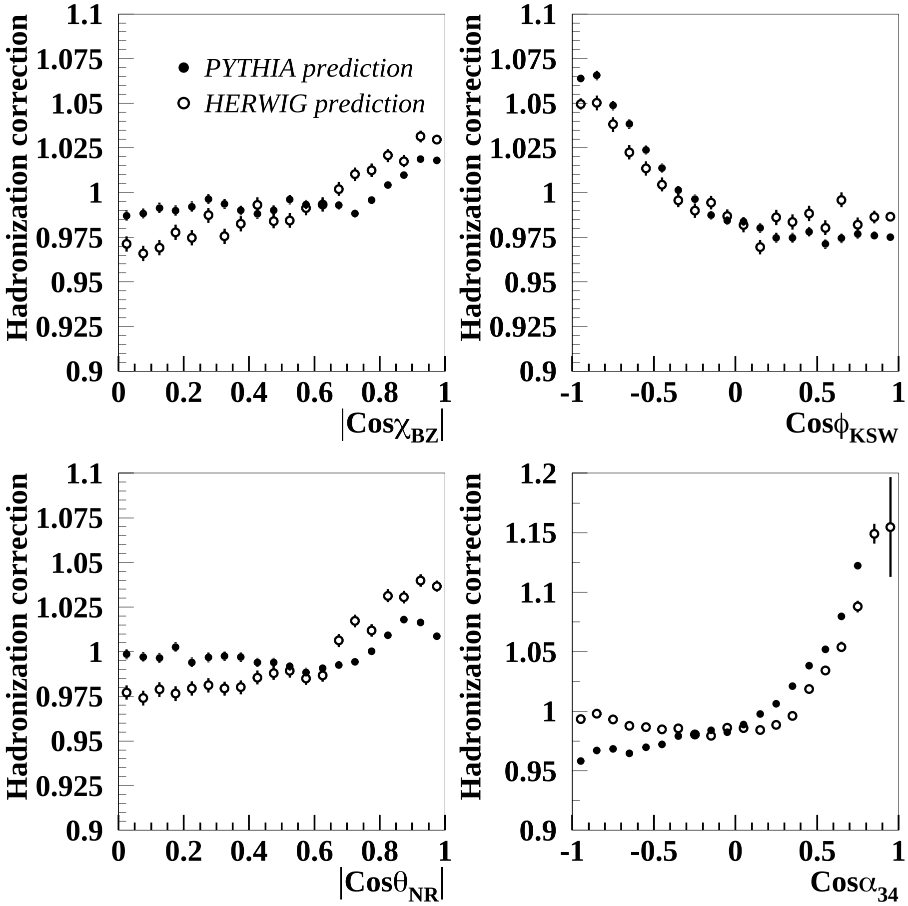

Figure 7.3: Comparison of the predictions for the hadronization corrections, i.e. hadron level over parton level distributions, from the four-parton option in PYTHIA and HERWIG.

process, already observed in the previous section, are taken out by the normalization. However, it could happen that the hadronization of the "non-common" configurations, i.e. the configurations present after the parton shower in PYTHIA but not in HERWIG (and vice-versa), is the source of the differences observed in Fig. 7.3.

However, the most obvious explanation would be to refer to the different models used in both Monte Carlo programs to simulate the hadronization. However, these fragmentation models have been shown to behave very similarly for the four-jet rate (see Fig. 6.1) and, once more, the parameters used are supposed to be universal. To exclude this second explanation the following test could be performed: take a set of events after the showering (either from PYTHIA or from HERWIG) and force them to hadronization first with PYTHIA and then with HERWIG. If a better agreement between the distributions at hadron level is obtained, then either the tuning or the remaining effects from the showering process should be further investigated in order to understand the disagreement. This possibility has not been studied here.

7.5 Studies on Quark Mass Effects

The only MC program with MEs including quark masses is FOURJPHACT, which showers and fragments through PYTHIA. The study described in this section arrived to the conclusion that small mass effects where expected for the observables used in the analyses. This explains why the PYTHIA simulation, without further corrections, was used to calculate the hadronization corrections.

In Section 5.3.1 the FOURJPHACT MC program was briefly described, and the possibility of simulating the different channels of a four-parton configuration was stated. This was exploited to investigate for mass effects in the four-jet angular correlations. Such distributions were calculated separately for the following channels: *(i)* $u\bar{u}u\bar{u}$, *(ii)* $u\bar{u}gg$, *(iii)* $b\bar{b}b\bar{b}$ and *(iv)* $b\bar{b}gg$. The resulting distributions were compared, $u\bar{u}u\bar{u}$ vs $b\bar{b}b\bar{b}$ and $u\bar{u}gg$ vs $b\bar{b}gg$, at parton level and at hadron level.

The comparison is done between channels *(i)* and *(iii)*, or *(ii)* and *(iv)* in order to make the mass effects visible. The other possible comparisons where already shown in Chapter 3 to stress the difference between "abelian" and "non-abelian" channels. Fig. 7.4 and 7.5 shows the comparison of the two four-quark channels for two of the angular correlations. If we first concentrate on the parton level distributions, the mass effects observed are small, but more important than the ones of the $q\bar{q}gg$ channels, for which an example can be found in Fig. 7.6. This is an indication that the total mass effects, i.e. the effects when all channels are added with their corresponding weights, are much smaller than the ones observed when comparing the $u\bar{u}u\bar{u}$ and the $b\bar{b}b\bar{b}$ channels. First, because the production of $q\bar{q}gg$ dominates over the four-quark one. Second, because the channels containing a primary $b\bar{b}$ pair are only found in 20% of all hadronic events.

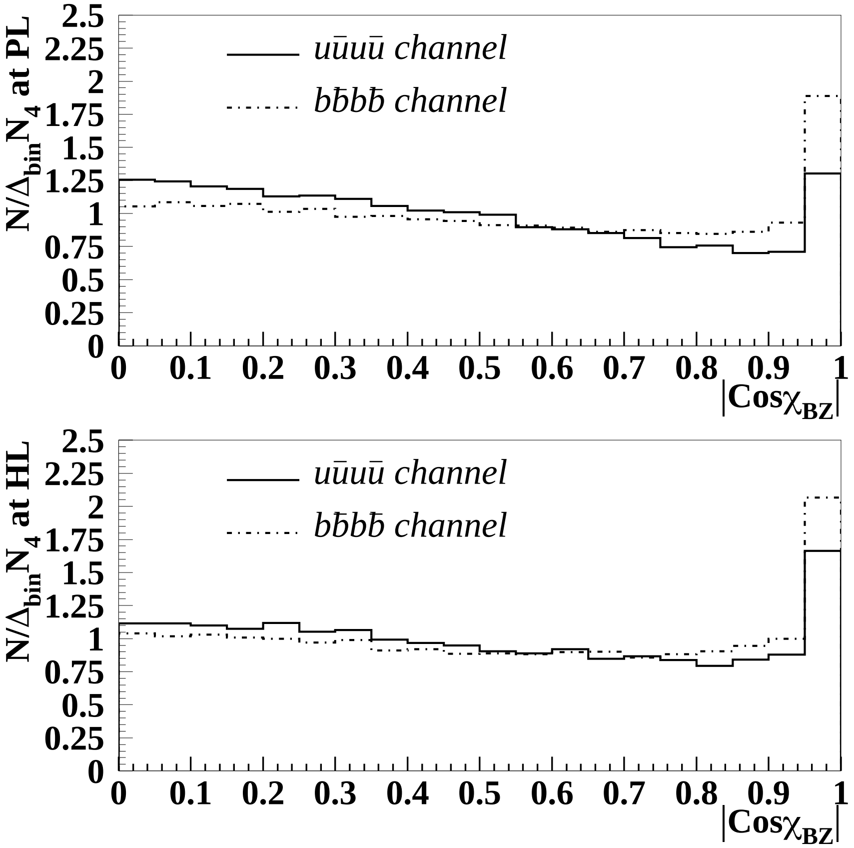

Figure 7.4: Comparison of the normalized distribution of $|\cos\chi_{\rm BZ}|$ between a "massive" and a "massless" four-quark channel. The comparison is presented at parton level (upper plot) and at hadron level (lower plot).

When the comparison is done at hadron level (lower plots in the figures) we observe that the showering and hadronization processes reduce the discrepancies between partons of different mass, and so also between a massless and a massive simulation. Therefore, it is clear that a mass systematic uncertainty estimated at the parton level is a conservative estimate of the uncertainty at hadron level.

The discussion above indicates that the massive and massless distributions for the four-jet angular correlations do not present large discrepancies. However, it is difficult to

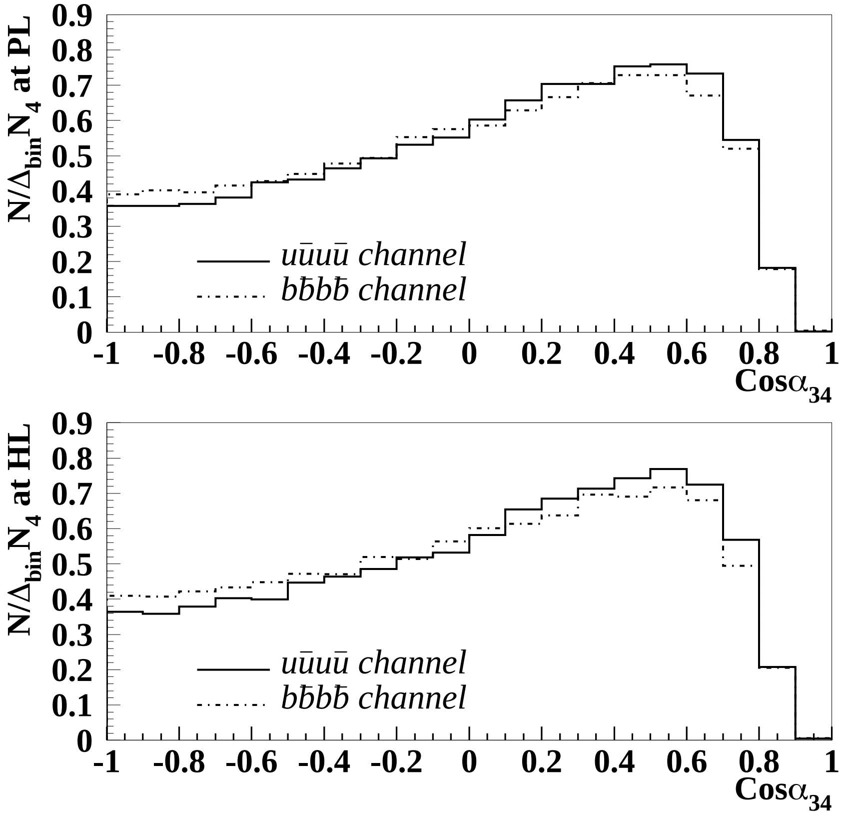

Figure 7.5: Comparison of the normalized distribution of $\cos\alpha_{34}$ between a "massive" and a "massless" four-quark channel. The comparison is presented at parton level (upper plot) and at hadron level (lower plot).

give an estimate of the mass effects in the measurement of the strong coupling constant and/or the colour factors. The effects on the strong coupling constant are expected to be very small because we are using normalized NLO angular correlations. However, the colour factors determine the shape of the distributions and they have been shown to be very sensitive to small variations in it. An estimation of such effects was presented in Section 6.2.3, but for a better estimation new MC programs with a precise treatment of masses in the whole chain of the event simulation are needed.

7.6 Other Studies to be performed

In the previous sections studies of the new Monte Carlo programs that allow to start a parton shower from four-parton matrix elements were shown. They are quite well understood, but more effort is needed in order to trust them at the same level than standard $q\bar{q}$ simulations. Detailed studies, that go beyond the purpose and time-scale of this thesis,

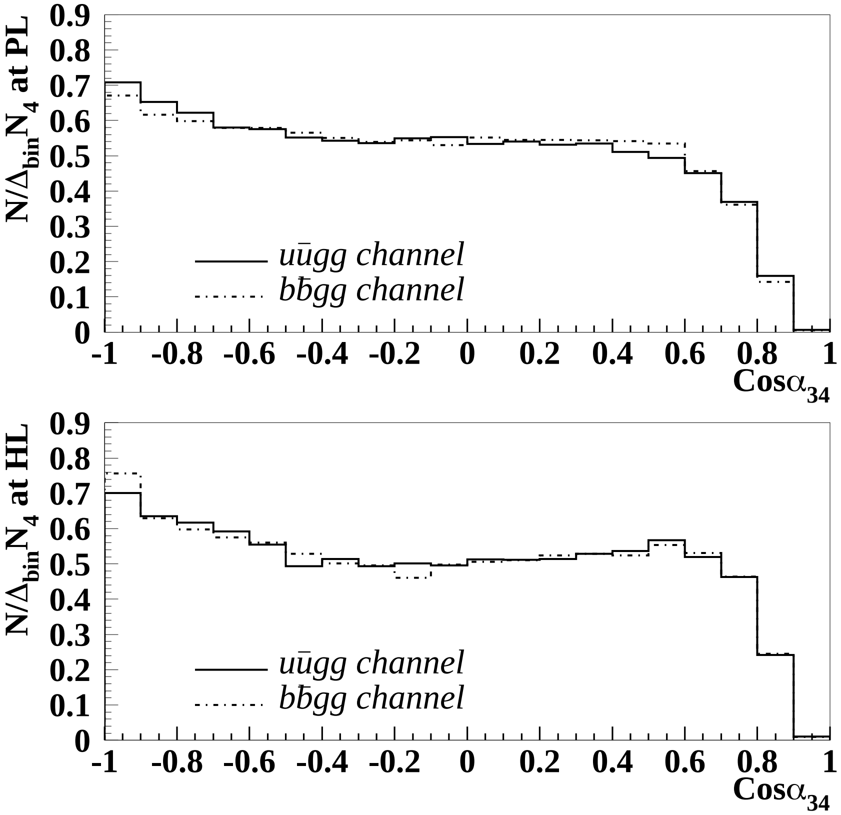

Figure 7.6: Comparison of the normalized distribution of $\cos\alpha_{34}$ between a "massive" and a "massless" two-quark two-gluon channel. The comparison is presented at parton level (upper plot) and at hadron level (lower plot).

should be performed, which will give a better comprehension of the properties of four-jet events.

More precisely, there is a new Monte Carlo program, APACIC, which is currently under development. Its basic ideas were already presented in Chapter 2, and preliminary tests showed a good performance of the new program [43]. Here no other studies will be shown as there is no tuning for the ALEPH detector, and for the time being there are different versions with their corresponding initial tunings that make any estimation of the performance of the APACIC program quite difficult and time consuming, for what concerns our analysis. As stated before, the colour factors are very sensitive to variations in the shape of the angular correlations. We would prefer to wait for a more definitive version of the APACIC program before testing its performance in the simultaneous measurement of the strong coupling constant and the colour factors.

Chapter 8

Summary and Outlook

> *Si lo que vas a decir*
> *no es más bello que el silencio*
> *no lo vayas a decir.*

Two different kind of measurements have been presented in this thesis. First, three measurements of the strong coupling constant from the four-jet rate were described. Second, the simultaneous measurement of the strong coupling constant and the QCD colour factors was detailed. The analyses used ALEPH data from 1994 and 1995 and NLO predictions corrected to detector level.

The measurement of the strong coupling constant using NLO resummed predictions for the four-jet rate is the first measurement of α_s from a four-jet observable. The calculations that allow for a NLO prediction were finished some years ago. They allowed for a measurement of the strong coupling constant from new observables. In this thesis three different methods were tried. In the first case, taken as the nominal one, the result

$$\alpha_s(\mathrm{M_Z}) = 0.1170 \pm 0.0001(stat) \pm 0.0014(sys)$$

represents one of the most precise measurements on α_s at present. It is in perfect agreement with previous measurements by ALEPH and other collaborations which used two- and three-jet observables. Also, recent preliminary results by DELPHI using the four-jet rate are in excellent agreement with those presented here. The other two methods, based on the experimentally optimized scale method, lead to results compatible with the previous one.

Then, a stringent test of QCD was performed by measuring simultaneously the strong coupling constant and the colour factors. To do so, NLO predictions, corrected to detector level, for five four-jet observables are used: the four-jet rate and the four-jet angular correlations. A similar analysis had been performed in ALEPH before. The measurement presented in this thesis is the first combined measurement based on four-jet observables only. The new calculations and the new Monte Carlo programs available allow for a more precise measurement. The results,

$$\begin{aligned} \alpha_{\mathrm{s}}(\mathrm{M_Z}) &= 0.119 \pm 0.006(stat) \pm 0.022(sys) \\ C_A &= 2.93 \pm 0.14(stat) \pm 0.50(sys) \\ C_F &= 1.35 \pm 0.07(stat) \pm 0.22(sys) \end{aligned}$$

are in agreement with the expectation from QCD as well as with the previous results by ALEPH. A similar analysis, using the four-jet rate and the four-jet angular correlations, but also the differential two-jet rate, was performed by the OPAL Collaboration [55]. Our results show a good agreement with OPAL's results, however, a smaller statistical error is achieved here.

Finally, in the context of the simultaneous measurement of the strong coupling constant and the colour factors, the existence of a massless gluino has been excluded up to 95% CL. To do so, the simultaneous measurement was repeated taking into account the gluino contributions in the NLO predictions. For this test the assumption that hadronization corrections are quite independent of the existence of the light gluino is made. An improvement of this test will be possible as soon as full Monte Carlo simulations with the inclusion of the light gluino contributions become available.

At the end of this work we have presented studies performed with the new Monte Carlo programs that allow to start a parton shower from four-parton leading order matrix elements. Such programs are more suitable for our analysis as they are expected to better describe the shape of the four-jet angular correlations, shown to be badly described by the standard Monte Carlo simulations. The new four-parton Monte Carlo programs have been used in the present thesis, but some problems have appeared, such as the discrepancies between the corrections obtained from PYTHIA and HERWIG.

Detesto el tiempo, la ansiedad lamento.
Descansar sólo quiero, junto al calor del fuego.

Appendix A

The Experimentally Optimized Scale Method

The understanding of the role played by the renormalization scale parameter μ in the α_s measurements is the main goal of the coming sections. Such a parameter appears in the perturbative series of the QCD predictions, which for any observable is independent of this unphysical parameter if all the orders are known. However, usually only the first two terms are known, and for some observables also the resummation of large logarithms exists. The truncated perturbative prediction is then a function of the renormalization scale.

In many experiments, as well as in this thesis, the standard method for the measurement of the strong coupling constant is to perform the analysis with the scale μ fixed to some physical scale Q of the process, which for measurements at LEP1 is $\mathrm{M_Z}$. Then, to test the dependence of the results on the renormalization scale, its value is varied from $Q/2$ to $2Q$. However, this is a somehow arbitrary estimation and some methods for a better estimation have been proposed.

The ratio of the NLO contribution with respect to the LO one can be used to estimate the importance of the unknown higher order terms. In many cases it is found to be close to unity, see Figs. A.1 and A.2, which is a clear indication of the poor convergence of the perturbative series. One can think of a value of the renormalization scale chosen in order to match the theoretical predictions to data. Such an optimal scale is found, without any theoretical assumption, by a combined fit of α_s and the scale, parametrized through x_μ defined in Section 3.2. This is the so called Experimentally Optimized Scale method (EOS), which was used for the measurement of the strong coupling constant from the four-jet rate in Chapter 6 (called Method III).

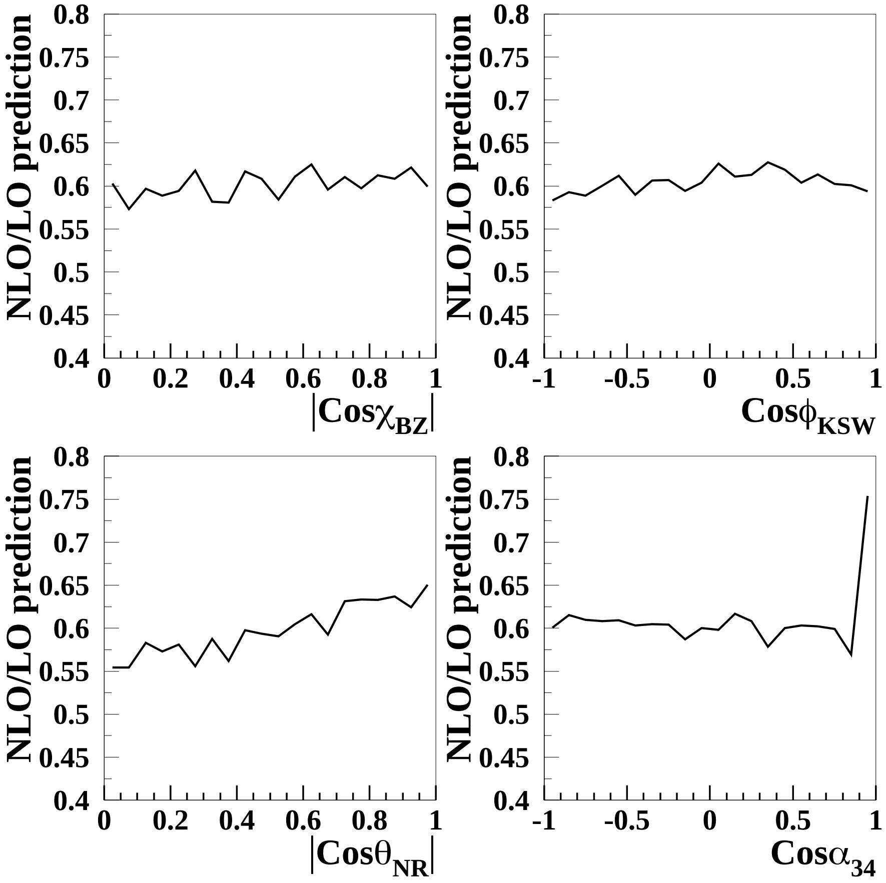

Figure A.1: K factor, NLO over LO prediction, for the four-jet angular correlations.

Other approaches, based on theoretical assumptions, have been proposed to find the best value for the renormalization scale so that fixed-order theoretical predictions better describe the data. More details can be found, for example, in Ref. [59]. Briefly, the methods try to find a general property for all observables which is an indication of a good convergence of the theoretical description. For example, in the FAC (fastest apparent convergence) method the scale is chosen to be the one that causes the NLO contributions to vanish. However, this has been proved not to work properly since the next-higher order terms are neither zero nor small for many observables.

Going back to the EOS method, it has been used for different measurements performed

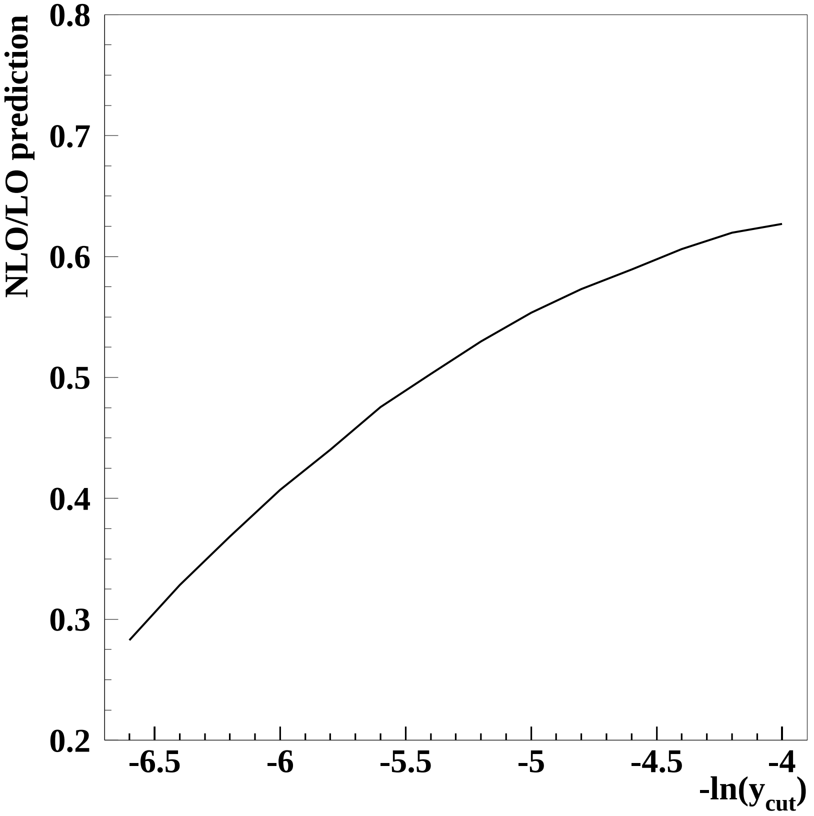

Figure A.2: K factor, NLO over LO prediction, for the four-jet rate.

by various experiments within and outside LEP. Some of these results are discussed in the following sections, as the validity of the method is still under investigation. As will be shown, different measurements have arrived to different conclusions.

In order to understand the discussions below two things have to be outlined. First, the experimentally optimized scale can differ for different observables, as the convergence of the truncated series does not have to be the same. Second, the scale is measured in a different way at different experiments. For example, we have been using the definition $x_\mu \equiv \frac{\mu}{\mathrm{M_Z}}$, but in other collaborations the definition $x_\mu \equiv \left(\frac{\mu}{\mathrm{M_Z}}\right)^2$ was chosen. The exact definiton of x_μ will be indicated when needed and has to be kept in mind when comparing results from different experiments.

A.1 Results with Optimized Scales from DELPHI

DELPHI has recently updated a LEP1 study on the EOS method using a set of 16 event-shape observables [60]. Results are compared from fits using $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^2)$+NLLA predictions. In Fig. A.3 the dispersion of the fitted α_s is shown to be much smaller for EOS at $\mathcal{O}(\alpha_s^2)$. Furthermore, in EOS the uncertainty due to hadronization corrections becomes the largest, since the scale uncertainty is heavily reduced. The scale uncertainty is measured in EOS as the largest deviation in α_s when x_μ is varied between 0.5 and 2 times the experimentally optimized value. EOS at $\mathcal{O}(\alpha_s^2)$, following the DELPHI conclusions, has then a small scale uncertainty with the total error heavily reduced. In Fig. A.4 the large dispersion of the experimentally optimized scales is shown, going from x_μ (here defined as $\frac{\mu^2}{{\rm M_Z}^2}$) around 0.003 to 7.10, i.e. μ from 5 GeV to 240 GeV.

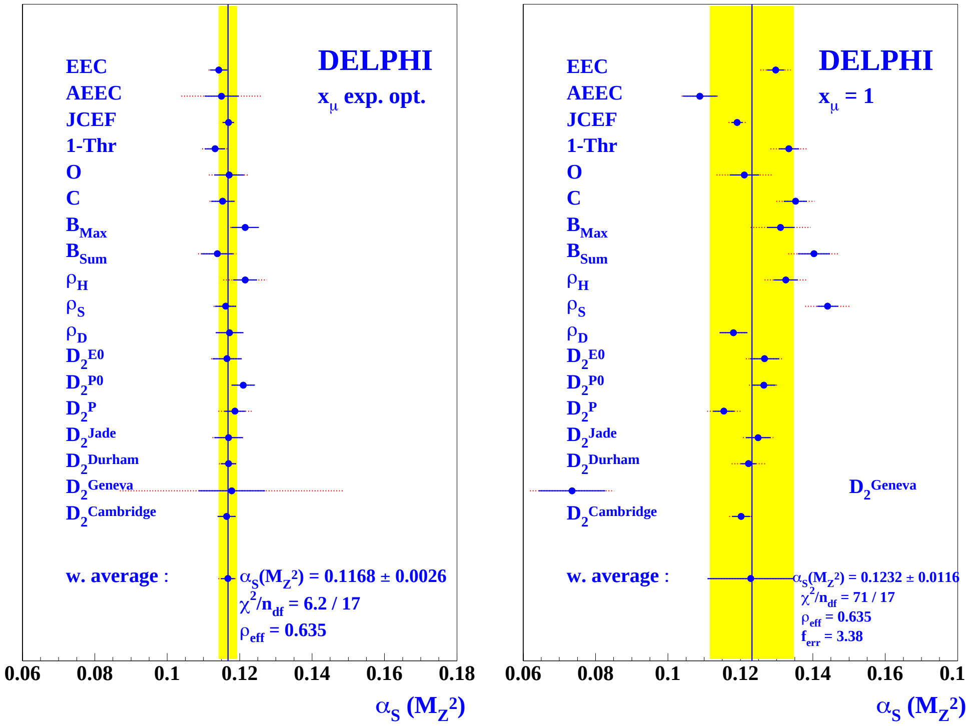

Figure A.3: DELPHI results using EOS.

Other conclusions drawn by DELPHI are that EOS at $\mathcal{O}(\alpha_s^2)$ describes the data over the whole fit range better than resummed predictions. Average results from the 16 observables show a good agreement between the EOS method and the fits to resummed predictions as seen in Table A.1.

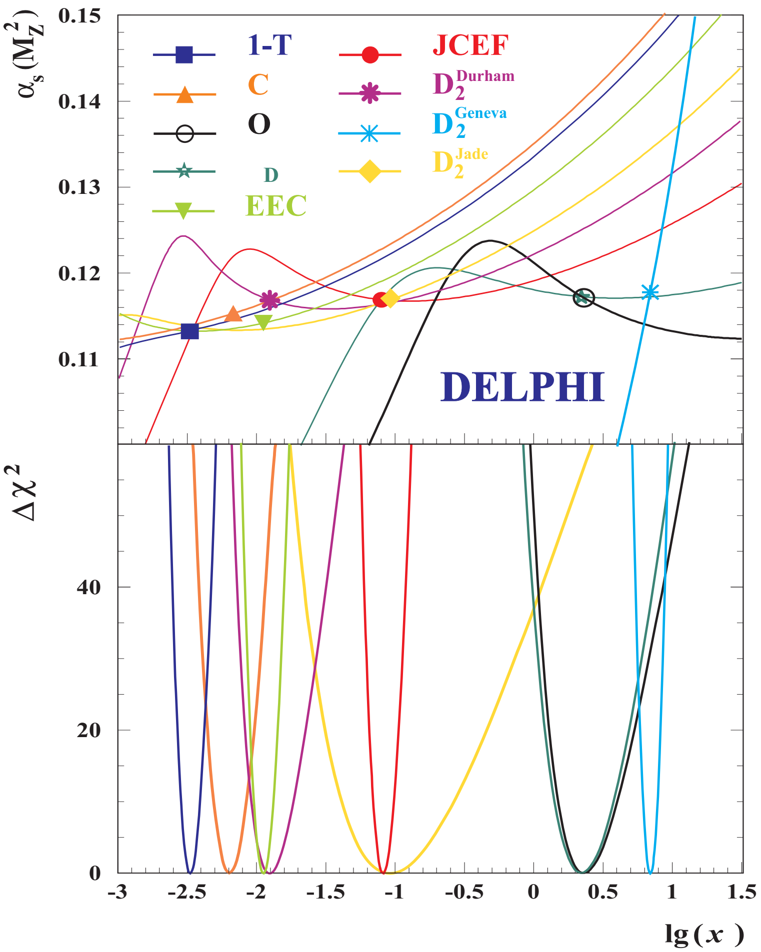

Figure A.4: Scale dependence for different observables in the EOS method.

	α_s	Total Error
EOS	0.117	0.003
$\mathcal{O}(\alpha_s^2)$ + NLLA	0.119	0.005

Table A.1: α_s results from DELPHI.

The study also includes results obtained when choosing the optimal scale according to some theoretical assumption (such as vanishing NLO terms). A larger dispersion in the fitted α_s is found, but the results are fully compatible with EOS. The study concludes that the best method for an α_s measurement from two- and three-jet observables is EOS at $\mathcal{O}(\alpha_s^2)$.

A.2 Other Results with Optimized Scales: OPAL and SLD

A recent analysis by OPAL[61] has lead to different conclusions (and results from SLD[62] confirm such discrepancies). They show that $\mathcal{O}(\alpha_s^2)$ predictions describe better the data if the scale is also fitted. However, one can not arrive to a definitive conclusion concerning the comparison to resummed predictions, as the best prediction depends on the observable. Following this analysis resummed predictions have a smaller x_μ dependence, and therefore the smallest scale uncertainty. They show that the shape of both α_s and χ^2 depend strongly on the scale, but with a stable minimum. Following OPAL's studies the best method for an α_s measurement from two- and three-jet observables would be EOS at $\mathcal{O}(\alpha_s^2)$ +NLLA.

A.3 α_s from the 4-jet rate: ALEPH and DELPHI

In this section the results of the α_s measurements from the four-jet rate are summarised, see Section 6.1 and Ref. [56]. This observable has an attractive characteristic when compared to previously used three-jet observables. Since the LO term for four-jet observables is proportional to α_s^2, these observables have less sensitivity to possible large sources of systematics, as $\frac{\Delta\alpha_s}{\alpha_s} = \frac{1}{2}\frac{\Delta\sigma}{\sigma}$, where σ is the four-jet cross section and $\Delta\sigma$ its variation due to some systematic uncertainty source.

In the measurements performed by ALEPH a NLO+NLLA four-jet rate prediction, corrected to detector level, was fit to ALEPH data. The results when fitting only α_S (Method I) and when doing a combined fit of α_S and x_μ (i.e. EOS at NLO+NLLA) can be seen in Tables 6.2 and 6.3. The χ^2 of the two fits show an agreement with the conclusions from the OPAL collaboration, i.e. NLO predictions describe the data better if the scale is also fitted. Figure. 6.7 shows a strong dependence of the χ^2 with the renormalization scale, but with a clear minimum around 0.7. The scale dependence of α_s is small when compared to previous results using two- and three-jet observables. The smaller dependence is found with the EOS method.

The DELPHI Collaboration has performed a similar measurement, but fitting only NLO predictions to LEP1 DELPHI data [56]. Their results can be found in Table A.2 and show a good agreement with those presented in this thesis.

Observable	α_s	±	exp.	±	hadr.	±	scale
R_4	0.1178	±	0.0012	±	0.0023	±	0.0014

Table A.2: α_s results from the four-jet rate by DELPHI.

A.4 Conclusions

Two analyses by DELPHI and OPAL on Experimentally Optimized Scales have been discussed, showing some discrepancies in the final conclusions. However, they both agree on the reduction of the renormalization scale uncertainty when a combined fit of both α_s and μ is done. Finally, the α_s measurement by DELPHI from the four-jet rate has been presented briefly and compared to the one by ALEPH, already described in Chapter 6. The results from both experiments are in agreement with previous two- and three-jet measurements, and show an important reduction in the scale uncertainty. Such a reduction of the scale uncertainty is more important if the EOS method is used, but it is significant with the standard method (i.e. with x_μ fixed to 1), indicating that four-jet observables may have a smaller scale dependence than two- and three-jet variables.

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