MULTIJETS AT LEP

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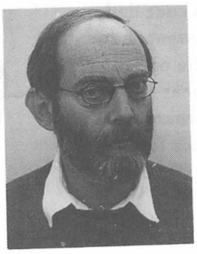

Abstract

At LEP 2, multi-jet events will become an important subject, both for standard physics (measurements of the W boson mass and the three-boson couplings) and in direct searches for new particles within or beyond the Standard Model. This presentation gives a comprehensive report of what has been learnt in this field at LEP 1 and LEP 1.5, emphasizing the measurements of the colour factors in QCD and the difficulties encountered when searching Higgs bosons in multi-jet events.

Presented at the "QCD and High Energy Hadronic Interactions"
Les Arcs, France - March 23-30 , 1996

Introduction

Perturbative QCD has been intensively studied in hadronic final states observed at electron-positron colliders. It is a good time, now that LEP has basically covered its Z^0 campaign, to try to summarize what has been learnt with multi-jet events. Indeed the new energy domain (LEP2) will increase the importance of this type of events, and the recent results from the runs taken last November at 130 and 136 GeV give us a flavour of what will be one of the most interesting topological signature in e^+e^- collisions.
Since three jet events are more or less our daily bread, the presentation will focus on events having at least four hadronic jets, like the one represented on Fig.1. These events appear in two kind of analyses : QCD studies, where they are studied in detail, but also searches for new particles like hA or H^+H^-, where QCD events appear as a background.

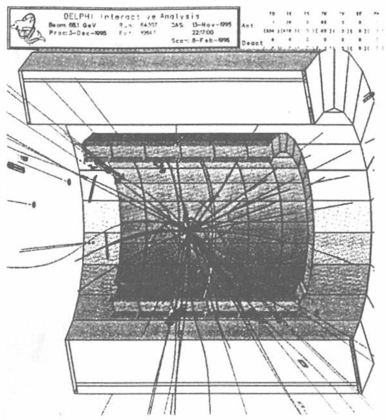

Fig.1

1 QCD studies

1.1 At the Z^0 pole

The next step after the proof of evidence for triple gluon vertex is the measurement of the Casimir or colour factors of the underlying gauge group. Gluon bremsstrahlung is weighted by C_F, the triple gluon vertex by C_A, and quark-antiquark pair creation by T_F or the more directly accessible quantity $T_R = n_f T_F$ where n_f is the number of active quark flavours. At LEP energies $n_f = 5$.

Experimentally the two ratios C_A/C_F and T_R/C_F are determined from a fit of the theory to any multidimensional differential cross-section sensitive to these factors. The most precise results have been obtained from the analysis of the four-jet cross-section [1] but also recently from the investigation of five-jet events [2]. It should be stressed that such tests of QCD can presently be performed at tree level only.

In the analysis of four-jet events two different techniques have been used. DELPHI and OPAL studied angular correlations sensitive to the structure of $q\bar{q}gg$ with respect to $q\bar{q}q\bar{q}$ events (generalized Nachtmann-Reiter angle [4]) while ALEPH and L3 measured the five dimensional differential cross-section as a function of the scaled invariant masses of any bi-jet.

Two new studies have been presented at the Brussels conference. DELPHI [5] tagged for the first time both primary quark jets in four-jet events (1992 and 1993 data) by measuring lifetime and semileptonic decays of hadrons containing b and c quarks. As a result, the differences in the angular distributions and the sensitivity with respect to the colour factor ratios are significantly increased. This is especially important for the ratio T_R/C_F which is the most difficult one to measure since $q\bar{q}q\bar{q}$ events contribute only 5% to the total four parton yield. The price is of course the loss of statistics due to double tagging. L3 [6] analysed up to 100 000 four-jet events (1991 to 1994 data) with a careful investigation of the dependence on the jet resolution parameter y_{cut} used to select the four-jet sample. The final results are :

$$\text{DELPHI} \quad \frac{T_R}{C_F} = 1.48 \pm 0.67\,(stat.) \pm 0.25\,(syst.)$$
$$\text{L3} \quad \frac{T_R}{C_F} = 1.41 \pm 0.24\,(stat.) \pm 0.67\,(syst.)$$

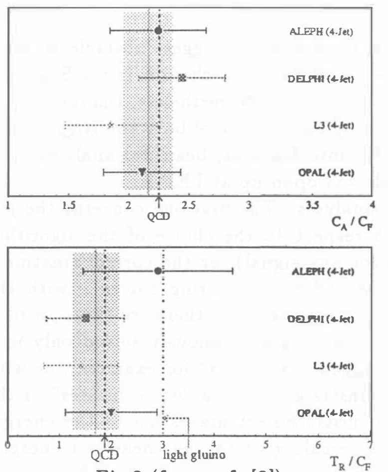

Fig.2 (from ref. [3])

It is worth noting how both sources of errors exchange their magnitude depending on the analysis. The reduction of the systematic uncertainties in the DELPHI result is due to tagging of the primary quark jets.

A summary of the measurements of these two colour factor ratios is shown in Fig. 2. The combined results : $C_A/C_F = 2.16 \pm 0.20$ and $T_R/C_F = 1.70 \pm 0.45$ are in good agreement with the QCD predictions of 2.25 and 1.875 respectively. The non-Abelian nature of QCD has thus been confirmed with a very high significance, ruling out the possibility of a light gluino.

1.2 At 135 GeV : the n-jet rates

Despite the low luminosity ($\approx$ 6 pb^{-1}) delivered at 130 and 136 GeV during the fall of 1995, many QCD studies have been performed by the LEP experiments (see the presentation by W. Lu in these proceedings). Let us extract from these studies the following figures which show the n-jet rates as seen by ALEPH, OPAL and DELPHI [7]. Despite some discrepancies between measured and predicted four-jet rate, the overall agreement is excellent.

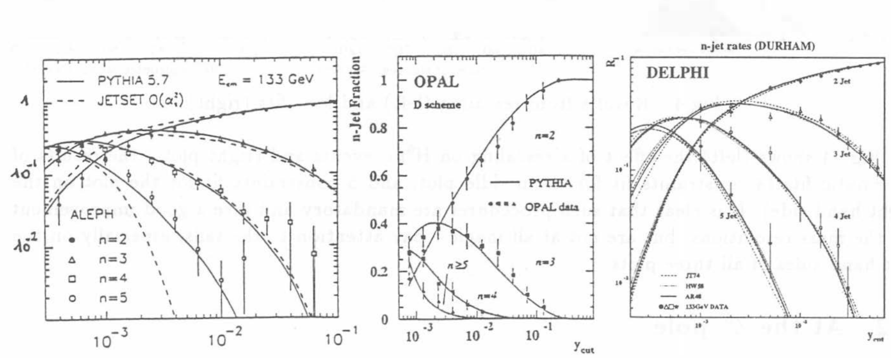

Fig.3 : Measured n-jet rates (Durham scheme) as a function of y_{cut} at LEP1.5

2 Searches in multijet events

2.1 Why is it difficult ?

It is commonly admitted that the huge QCD backgound is the biggest obstacle in these analyses. That is true, especially at LEP 1, where the purely hadronic channel in the Standard Model Higgs boson search has never been used for that reason. Nevertheless, thanks to performant b-tagging techniques (hA into 4 or 6 b-jets) or by making use of both the Higgs boson scalar nature and pair-production in the case of H^+H^- into hadrons, beautiful analyses have already been achieved at LEP 1. Many other channels will open up at LEP 2.

But at least three other difficulties arise in these analyses. The first one concerns the jet-finding algorithm : how to handle instabilities with respect to the choice of the algorithm (which are more frequent in QCD background than for any signal), or the correct treatment of clear 5-jet events are still open questions. The second is the pairing choice : with the prejudice of a two-body final state, each of them decaying into two jets, there are three possible pairings per 4-jet event. Finding the correct pairing can be unambiguously solved only in a few special cases, when two (and only two) jets are tagged (as "b-jets" for example), or with the help of one supplementary hypothesis, used as a constraint, such as "equal masses" or the presence of an on-shell Z^0 boson. Finally, the mass measurement makes use of the energy-momentum conservation by applying either a simple rescaling of the jet measured energies (the jet directions are measured more precisely than their energies), keeping the jet velocities unchanged, or a complete 4-constrained kinematic fit on the jet 4-momenta.

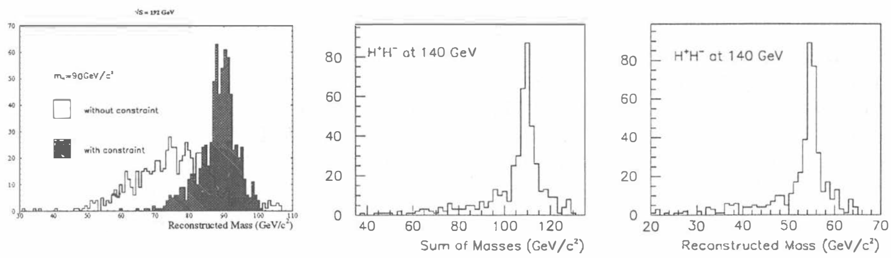

Fig.4 : Results from rescaling (left) and kin. fits (right)

Fig. 4 shows (left) the effect of a rescaling on $H^0\nu\bar{\nu}$ events and (right plots) the results of kinematic fits (4 constraints fit for the middle plot, and 5 constraints fit for the plot on the right hand side). It is clear that such procedures are mandatory and give a good improvement on the mass resolutions, but are not at all magic : pay attention to the tails, especially on the left hand sides of all three plots.

2.2 At the Z^0 pole

This is not the place to recall here the theoretical backgrounds of the Minimal Supersymmetric Standard Model. Let us simply say that all four LEP experiments have reported analyses of the associated production (hA) of neutral Higgs bosons, where the dominant signature is four (or even six) b-jets if $\tan\beta$ is high, and of the pair production of charged Higgs bosons, where the hadronic decay is important only if $\tan\beta$ is low. All these studies [8] [9] developped sophisticated statistical methods to look for a localised excess of events with respect to QCD simulation. It is interesting to note (see Fig. 5 as examples) that nearly all analyses found discrepancies (not localised !) between data and simulation, which give an idea of the size of the systematics due to our imperfect modeling of multijet events.

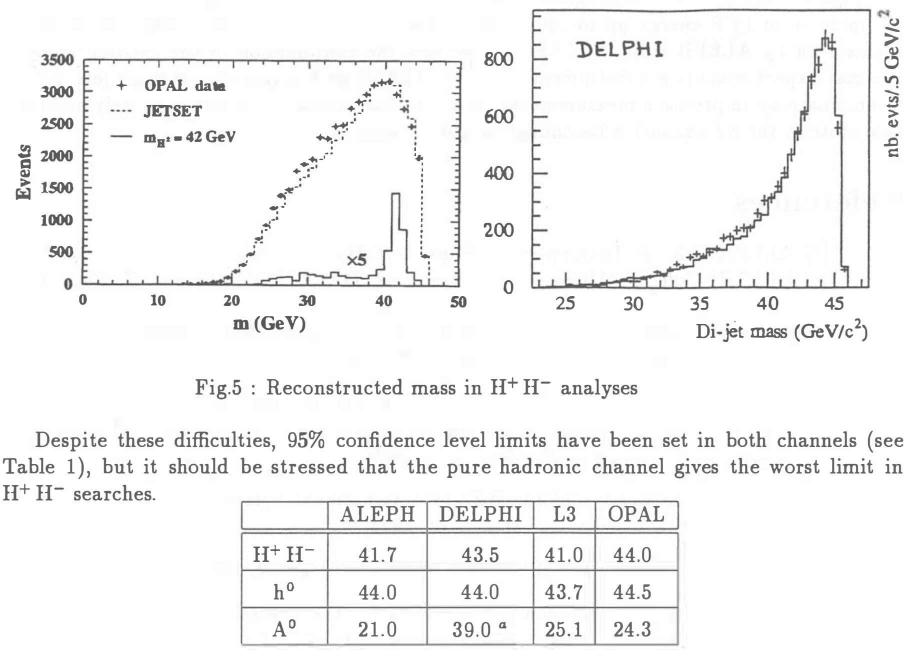

Fig.5 : Reconstructed mass in H^+H^- analyses

Despite these difficulties, 95% confidence level limits have been set in both channels (see Table 1), but it should be stressed that the pure hadronic channel gives the worst limit in H^+H^- searches.

	ALEPH	DELPHI	L3	OPAL
H^+H^-	41.7	43.5	41.0	44.0
h^0	44.0	44.0	43.7	44.5
A^0	21.0	39.0 [a]	25.1	24.3

Table 1: 95% CL lower limit (in GeV/c^2) on masses of the MSSM Higgs bosons obtained in 4-jet events analyses.

[a] Radiative corrections to the Higgs boson mass have been calculated including two-loop effects.

2.3 At 135 GeV

Given the accumulated luminosity ($\approx$ 6 pb^{-1}) at 130 and 136 GeV and the small cross-sections (below 1 pb), one cannot expect to improve the LEP1 limits for a given experiment. For a 1 pb cross-section, an overall signal efficiency of 50% is needed to set a limit at the 95% confidence level, provided that no event is seen in the data ! But the cross-sections lie around .35 pb for any SUSY Higgs mass around 55 GeV/c^2. The only way to enlarge the domain covered by LEP1 would be to combine the four experiments. At the time of this meeting, DELPHI [10] analysed its data for hA and H^+H^-signals and OPAL [11] for hA only.

In hA analyses, both experiments found no candidate event in the data, with signal efficiencies running from 23% (OPAL) to 46% (DELPHI), leading in that last case to a 95% confidence level exlusion limit of 1.3 pb. In the H^+H^-analysis, again no event is left, with a signal efficiency around 30%, thus allowing to put the 95% CL limit at 1.6 pb. As expected, the LEP 1 limits are not improved yet.

Conclusion

The study of multijet events is already a very active field in e^+e^- collisions, from both vue points of QCD understanding and searches beyond the Standard Model. Recently, with the increase of LEP energy up to 140 GeV, it has become even exciting with the excess of events seen by ALEPH [12]. At LEP 200, besides the continuation of the existing studies, one may expect some new developments in pure QCD (Bose-Einstein effects inside jets, colour recombination), in precision measurements (W mass) and in searches where the purely hadronic final state in the hZ channel is becoming the golden signature.

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