QCD AND W MASS DETERMINATION AT LEP

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Measurements of hadronic final state interactions in W-pair events at LEP are presented. In particular, different scenarios of colour reconnection are studied. The data agree with moderate colour reconnection effects. Extreme scenarios are ruled out, limiting the systematic uncertainty on the LEP W mass determination due to this effect. An updated measurement of the mass of the W boson at LEP yields 80.412 ± 0.042 GeV.

1 Introduction

At LEP, W bosons are produced in the reaction $e^+e^- \to W^+W^-$ with the subsequent decay of the W's into quark pairs, $q\overline{q'}$, or a lepton and a neutrino, $\ell\nu$. About 10000 W pair events are registered by each of the four experiments ALEPH, DELPHI, L3 and OPAL, corresponding to a total luminosity of 4×700 pb^{-1}.

One of the main goals of the LEP programme is to determine the mass of the W boson, M_W, from the reconstructed invariant mass spectra. In this measurement, the systematic uncertainty turns out to be comparable to the statistical precision that can be reached. Especially in the fully hadronic decay channel, $W^+W^- \to qqqq$, the presence of final state interactions (FSI), like colour reconnection [1] (CR) and Bose-Einstein correlations [2] (BEC), may cause a cross-talk and momentum transfer between the reconstructed W bosons, which leads to a bias in the measured W mass. Therefore, both effects, CR and BEC, are studied in more detail. The latter one is discussed elsewhere [2] in these proceedings.

2 Colour Reconnection

In $W^+W^- \to qqqq$ events, the two quarks originating from each W boson form a colour singlet. In absence of FSI, the fragmentation processes of the quark pairs, measured as hadronic jets in the detector, are independent. Energy-momentum is separately conserved in the two W systems. However, in case of colour reconnection the momentum distribution of hadrons is rearranged. In the string picture of fragmentation this is due to a reconnection of strings between the original colour singlets. Several Monte Carlo (MC) models [1] exist to describe the CR effect in W pair events: the Sjöstrand-Khoze (SKI, SKII) and generalised-area-law (GAL) models implemented in Pythia, and the CR models of Ariadne (AR2) and Herwig (HW). The GAL model is not investigated here since there are strong limits on the size of its CR effect from Z peak data [3].

In the default configuration, all models predict a fraction of reconnected events of about 30%. In the SKI model, which is commonly used as a benchmark, this fraction can continuously be varied. The event reconnection probability is calculated according to $P_{reco} = 1 - \exp(-k_I f)$,

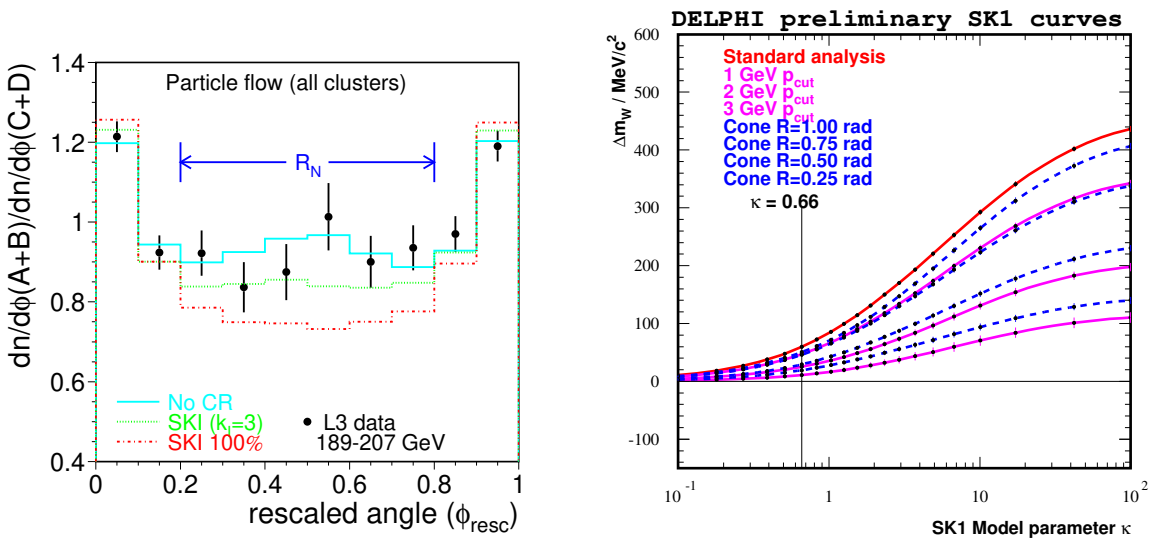

Figure 1: a) Ratio of the particle flow $dn/d\phi$ in the inter-W (A+B) and intra-W (C+D) regions as measured by the L3 experiment and compared to MC predictions with and without CR. The CR measure R_N is determined in the interval indicated by the arrow. b) Applying stronger cuts on particle momenta or on jet cone sizes reduces the W mass bias predicted by the SK1 model.

where k_I is a free parameter and f the overlap integral of the strings that are identified with colour flux tubes in the SKI model.

A measurement [4] of the charged particle multiplicity, N_{ch}, in qqqq events is found not to be sensitive enough to CR. ALEPH measures a multiplicity difference in qqqq and qq$\ell\nu$ events of $\Delta_{ch} = N_{ch}(\mathrm{qqqq}) - 2N_{ch}(\mathrm{qq}\ell\nu) = 0.31 \pm 0.23(stat.) \pm 0.10(syst.)$, to be compared with a maximal effect from CR of $\Delta_{ch} = 0.46 \pm 0.03$ in the Herwig model. All other models predict even smaller values of Δ_{ch}. The analysis of the particle momentum distribution yields that differences between the fragmentation models are larger than the expected CR effect, even in the soft momentum regime.

The string reconnection picture proposes that sensitivity is gained by studying the ratio of the particle flow in the region between the jets of each hadronically decaying W (intra-W) and in the region between jets of different W's (inter-W). To determine the flow in the two regions, the particle momenta are projected on planes that are spread between the directions of the four jets, where the first two jets belong to one W and the last two jets to the second W. The angles, ϕ, of the particles to the jet directions are normalised such that the rescaled angular difference between two neighbouring jets is one. Figure 1a shows the measured ratio of the particle flow $dn/d\phi$ in the intra-W and inter-W regions. The SKI model predicts a clear depletion of the flow in the central angular interval.

To quantify the CR effect, the ratio $R_N = \int_{0.2}^{0.8} dn/d\phi(\mathrm{intra-W})d\phi / \int_{0.2}^{0.8} dn/d\phi(\mathrm{inter-W})d\phi$ is calculated and normalised to the expectation without CR, $r = R_N^{data}/R_N^{no-CR}$. Combining the results of the LEP experiments and taking their different CR sensitivities due to different W pair purities into account, the following values of r are found for LEP data [5] and MC:

$$
\begin{aligned}
r^{\mathrm{LEP}}_{\mathrm{AR}} &= 0.959 \pm 0.010(stat.) \pm 0.010(syst.)\,, & r^{\mathrm{MC}}_{\mathrm{AR2\,CR}} &= 0.989\,;\\
r^{\mathrm{LEP}}_{\mathrm{HW}} &= 0.950 \pm 0.011(stat.) \pm 0.010(syst.)\,, & r^{\mathrm{MC}}_{\mathrm{HW\,CR}} &= 0.987\,;\\
r^{\mathrm{LEP}}_{\mathrm{SKI}} &= 0.969 \pm 0.011(stat.) \pm 0.011(syst.)\,, & r^{\mathrm{MC}}_{\mathrm{SKI100\%\,CR}} &= 0.891\,.
\end{aligned}
$$

The main systematic uncertainties are due to hadronisation modelling (± 0.008) and $\mathrm{e^+e^-} \to \mathrm{q\bar{q}gg}$ background shape and scale (± 0.003). Data deviates from the AR2 and HW CR predictions by -2.1σ and -2.6σ, respectively. The extreme 100% SKI scenario can be excluded at 5.2σ.

Source	Uncertainties on M_W in MeV		
	qq$\ell\nu$	qqqq	ffff
Colour Reconnection	–	90	9
BE Correlations	–	35	3
Hadronisation	19	18	18
ISR/FSR	8	8	8
Detector Syst.	14	10	14
LEP Beam Energy	17	17	17
Other	4	5	4
Total Systematic	31	101	31
Statistical	32	35	29
Total	44	107	43
Statistical in absence of Systematics	32	28	21

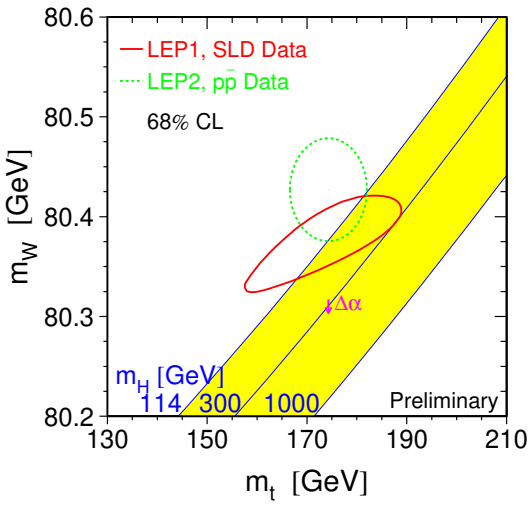

Figure 2: a) Systematic uncertainties in the W mass measurement. b) Contour curves of the direct and indirect determinations of the W boson and Top quark masses, together with the predictions of the Standard Model for different values of the Higgs boson mass, M_H. Direct and indirect measurements prefer small values of M_H.

However, the agreement with the no-CR scenarios is in all cases only at a level of about -2σ. When the SKI parameter k_I is left free, the best agreement with data is found for $k_I = 1.18$, corresponding to a reconnection probability of 49%. The 68% confidence level lower and upper limits are 0.39 and 2.13, respectively. Thus, data favours a moderate reconnection fraction, as it is modelled in SKI. However, in the case of AR2 and HW no conclusion can be drawn, because these models do not predict significant changes in the colour flow.

3 Measurement of the W Boson Mass

The W boson mass is determined in a maximum likelihood fit by comparing data to MC samples with different underlying W masses. The W mass variation is implemented by means of MC reweighting or convolution techniques. The most sensitive W mass estimator is the average invariant mass, which is calculated from the reconstructed final state fermions. A kinematic fit, imposing energy-momentum conservation and equal invariant masses of the two decaying W's, improves the resolution on the measured quantities.

With the current techniques a comparable statistical precision [6] on M_W is reached in the qq$\ell\nu$ and qqqq channel, of 32 and 35 MeV, respectively. However, using the measured limits on the SKI parameter k_I, the systematic uncertainty due to CR is ranging between 75 and 105 MeV in the hadronic channel, increasing with centre-of-mass energy. This reduces the weight of this channel in the combined W mass result to just 11%.

Since recently, alternative W mass estimators are investigated that are based on modified jet reconstruction algorithms. By removing low momentum particles or restricting the cone size of the quark jets the CR bias is found be reduced in the SKI model, which is illustrated in Figure 1b. This observation is turned into a measurement of CR. By comparing the W mass bias in data and MC as a function of momentum or cone cut, the CR scenario that fits best to data can be determined. The DELPHI CR measurement [7] improves from $k_I = 2.4^{+14.6}_{-2.2}$ using only the colour flow method to $k_I = 1.96^{+2.60}_{-1.30}$ combining it with the result using the alternative mass estimator. The results of both methods are practically uncorrelated because different event samples are used in the analyses. Also the correlation with the W mass measurement is found to be only

about 10%. The analyses by the other LEP experiments are still in preparation. Therefore, the current W mass measurements do not yet include information from the alternative W mass estimators.

The current statistical and systematic uncertainties on the W mass are given in Figure 2a. In the hadronic channel, uncertainties on CR and BEC dominate. For the combined results the fragmentation uncertainties become important because they are correlated between the qq$\ell\nu$ and qqqq channels. These uncertainties are derived from comparisons between different fragmentation models [8], Pythia, Ariadne and Herwig, and from a variation of the model parameters, that are tuned with Z peak data. The uncertainty due to the LEP beam energy is expected to be reduced with the final energy calibration.

Finally, the results on the LEP combined W mass measurements [6] are

$$\begin{aligned} M_{\mathrm{W}}(\mathrm{qq}\ell\nu) &= 80.411 \pm 0.032\ (stat.) \pm 0.030\ (syst.)\ \mathrm{GeV} \\ M_{\mathrm{W}}(\mathrm{qqqq}) &= 80.420 \pm 0.035\ (stat.) \pm 0.101\ (syst.)\ \mathrm{GeV} \\ M_{\mathrm{W}}(\mathrm{ffff}) &= 80.412 \pm 0.029\ (stat.) \pm 0.031\ (syst.)\ \mathrm{GeV}\,, \end{aligned}$$

where the qq$\ell\nu$ and qqqq results are 18% correlated. The mass difference between the qqqq and qq$\ell\nu$ channels is found to be $+22 \pm 43$ MeV, neglecting FSI uncertainties. This indicates that there are no extreme CR effects present in data. However, a better understanding of the QCD effects in the hadronic W decay is needed to improve the current W mass result. Combining the LEP result with the M_{W} measurements at $p\bar{p}$ colliders, yields [9] $M_{\mathrm{W}} = 80.426 \pm 0.034$ GeV.

The mass of the W boson is an important parameter in the Standard Model of electroweak interactions. In Figure 2 the direct measurements of the masses of the W boson and the Top quark [10] are compared to the values that are determined in a Standard Model analysis [9] of all remaining LEP and SLD data, probing the Standard Model at the level of its radiative corrections. Good agreement between direct and indirect measurements is found. Also shown is the Standard Model prediction for different values of the Higgs boson mass. Both data sets prefer small values of M_{H}, close to the current lower limit from Higgs boson searches [11] at LEP.

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