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W-Mass Reconstruction from Hadronic Events in LEP2: Bose–Einstein Effect

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Abstract

We discuss several aspects of the W-pair production and decay into quarks, taking hadronization into account. We touch upon the influence of the so-called Bose–Einstein effect and colour reconnection on the reconstructed mass of the W boson. The initial-state radiation effect is also revisited. The numerical studies are done using the KORALW Monte Carlo event generator. We find that for the Bose–Einstein effect, which we implement using the "weighting method", has a negligible influence, below 30MeV, on the reconstruction of the W mass.

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1 Introduction

The first experimental results from the LEP2 runs up to the summer of 1996 were presented at this Conference. The mass of the W-boson was measured with a precision of about 200 MeV from the value of the total cross section at fixed centre-of-mass energy. This method is good for energies close to the threshold, where the cross section strongly depends on the W mass. Further away from the threshold, especially at future LEP2 runs, M_W will be deduced from the final-state momenta of jets and leptons. In most cases the WW pair decays into four jets or two jets, lepton and neutrino. The case with both W's decaying into leptons is rather rare. The four-jet final states, from two W's decaying into quarks, are the most difficult, and therefore the most interesting to analyse/discuss. Due to gluon emission, detector limitation and jet-finding procedures we generally have not only four jets in the final state but also more and less. We cannot attribute with decent likelihood any given jet to a given W – we have to take all possible assignments into account. Finally, hadronization of two W's may be not independent because of the space-time overlap of the two hadronization processes – the so called colour reconnection and cross-talk due to the Bose–Einstein effect may take place. Last, not least, the effective mass of the pair of jets will always be biased by the details of the hadronization process, which are not so precisely known.

1.1 Our goals

It should be stressed that the results of the "W mass working group" in the 1995 LEP2 workshop, as summarized in ref. [1], are still the best and up-to-date source of knowledge on the subject of uncertainties in the M_W measurement. Our work, presented here, was completed after the LEP2 workshop; it was strongly influenced (motivated) by the results and discussions of ref. [1] and references therein. Our modest aim in this study is to check if our KORALW Monte Carlo event generator [2] properly describes the final hadronic states in the $e^+e^- \to W^+W^- \to$ 4jets process and to improve, if possible, our understanding of (physical) systematics errors in the measurement of M_W. It seems that we have achieved the latter goal where the uncertainty related to the so-called Bose–Einstein effect is concerned.

1.2 KORALW event generator

The KORALW event generator of ref. [2] is a general-purpose program for the $e^+e^- \to W^+W^- \to f\bar{f}f'\bar{f}'$ process including:

1. initial-state photon radiation with help the of the YFS2 generator,
2. hadronization of quarks using JETSET,
3. decays of final-state tau-leptons with the help of TAUOLA,

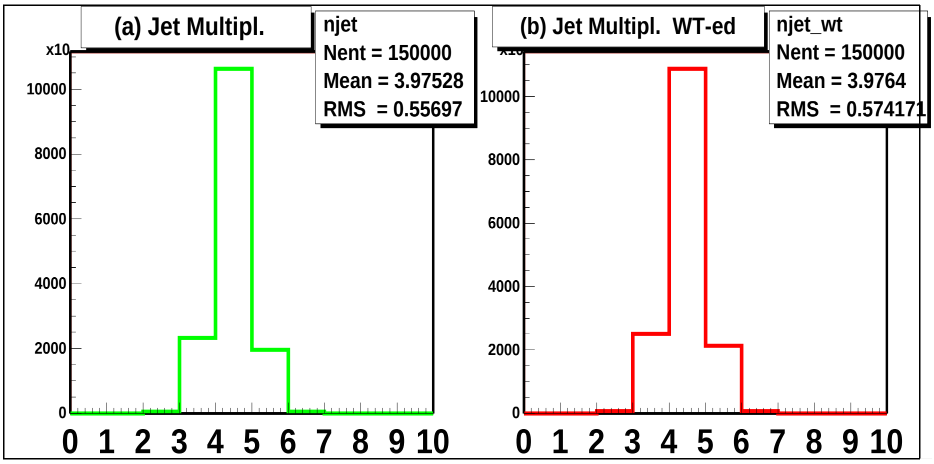

Figure 1: Jet multiplicity distribution at 172 GeV of centre-of-mass energy. The case (a) from standard KORALW/JETSET and (b) with BE weight.

and many other useful features. Within the LEP2 workshop [3] and afterwards [4,5], KORALW was subjected to many tests involving total cross sections and certain distributions at the parton level. However, tests of KORALW involving hadronization in the final state were lacking. This study describes several examples of tests/checks in this class.

1.3 Event selection and fitting M_W

In the process $e^+e^- \to W^+W^- \to J_1J_2J_3J_4$ we do not know which jet originates from which W; we therefore have to take into consideration all three possible assignments ((12)(34)), (13)(24)) and ((14)(23)) without any distinction. In a given event only one of them will be the "correct one" and the other two form what is called a "combinatorial background", which has to be eliminated using clever cuts. Before we even get the 4-jet events we have to define jets using one of the "jet finding algorithms"; as a result we get the entire spectrum of jet multiplicity n_J and we have to decide what to do with events with $n_J \neq 4$. In the present study we use the algorithm LUCLUS of JETSET [6] to define jets. We adjust the parameter d which defines the "fatness" of the jet in terms of transverse momentum in such a way that events with $n_J = 4$ dominate. In fact, we found that for $d = 10$ GeV (the same as in ref. [7]) we obtain the maximum of events (about 70%) with $n_J = 4$ and we have about 15% of events with $n_J = 3$ and another 15% events with $n_J = 5$. See fig. 1 for the actual jet multiplicity distribution from KORALW/JETSET at 172 GeV.

It is common practice [7, 8] to cut also on the separation angle between jets at 0.5 radian and on the minimum energy of the jet at 20 GeV. As we see in fig. 2 for our "fat jets" these cuts would not affect our $n_J = 4$ sample, so we do not apply them[1]. We also include in fig. 2 the distributions for quarks (parton level) as a reference. In

[1]It would perhaps be more worth while to cut on the angle between jet and initial beams, but we leave this for future studies.

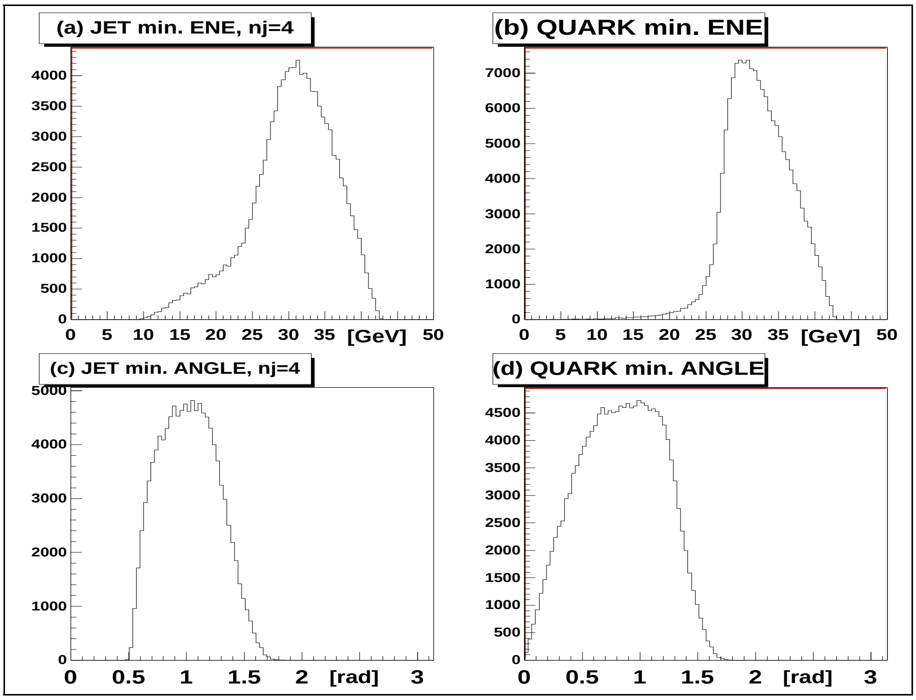

Figure 2: Minimum energy (GeV) and separation angle (radians) distributions of jets ($n_J = 4$) and quarks at 172 GeV of centre-of-mass energy.

the plot of fig. 3 we show the entire double distribution of two pairs of two final-state jets/quark masses without knowing which mass corresponds to the original true W-boson. We see clear resonance bands for quark-pair masses and a less clear but distinctive peak for jet-pair masses. As noticed earlier in many works [8], the efficient yet simple cut that eliminates most of combinatorial background (single resonance bands in fig. 3) is the cut on the difference of masses. In our case we find $|M_1 - M_2| < 10$ GeV, the optimum cut for jets, and $|M_1 - M_2| < 5$ GeV for quarks. In view of the above it is natural to use the distribution of the average mass $M_a = (M_1 + M_2)/2$ for fitting the mass of the W. The other possibility is to plot and fit M_1 or M_2, but we have checked (and this is also a conclusion of other studies [8]) that it yields fitted M_W and Γ_W further away from the true/input values than the fit of the average masses. Let us look, therefore, into the average mass distribution shown in fig. 4. For quarks, the cut on the difference of the masses eliminates the combinatorial background, which is plotted in the figure, almost completely. For jets, we do not plot the combinatorial background in the figure because we do not know it – the jet finding algorithm combines hadrons and knows nothing about their origin (a jet may contain hadrons from different W's). Nevertheless, after the cut on the difference of masses the resonance peak for jets is also much clearer.

We are now ready to fit the mass distributions with the Breit–Wigner function (with constant width). In fig. 5 we show the fitting curve and the fitted M_W and Γ_W. The true input W parameters were $M_W = 80.230$ GeV, $\Gamma_W = 2.034$ GeV. The difference of -65 MeV between the fitted mass from diquark masses and the true (input) value of M_W

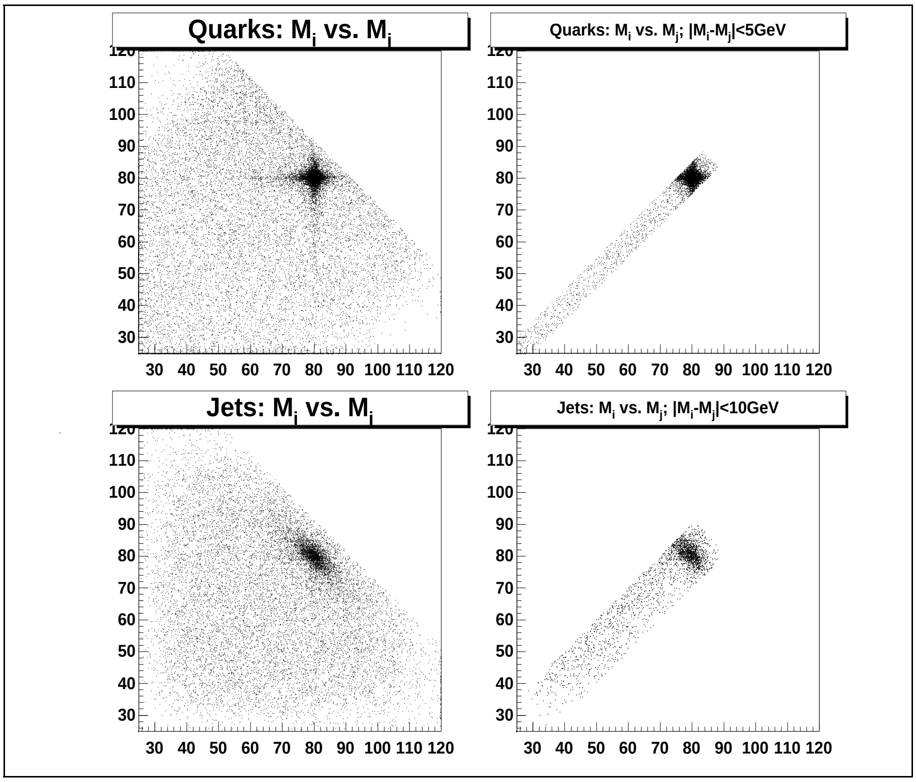

Figure 3: Plot of two effective masses $(M_i, M_j) = (M_{(k,l)}, M_{(m,n)})$ calculated using momenta of the two pairs $((k,l),(m,n))$ of jets or quarks. For each event we plot three points, which correspond to the three combinations ((12)(34)), (13)(24)) and ((14)(23)).

reflects the influence of the cuts and of the remnants of the combinatorial background. A good-quality Monte Carlo event generator can determine this shift very precisely. The second difference of -40 MeV, between the fitted mass for dijet masses and that for diquark masses is due to hadronization, as implemented in the hadronization in JETSET[2]. This part is uncertain, because there is no precise theoretical prediction for the hadronization process. The conservative approach is to treat JETSET as an intelligent parametrization of the data. In particular the above shift, as coming from JETSET, can be "calibrated" using the experimental dijet mass distribution for the decaying Z resonance. The well-known loophole in such a cross-check is that we are not dealing with the decay of a single W, but the hadronization processes for two quark pairs from two decaying W's may overlap in spacetime, leading to new uncontrolled effects [9]. See ref. [1] and the following sections for more details.

All the above introductory exercises were done using KORALW 1.21 with ISR switched off and with the simple CC03 matrix element. Our main aim was to describe in detail *one example* of the semi-realistic reconstruction of the W mass using four-jet final states. Obviously, in the real experiment, the above procedure will be even more complicated,

[2]Let us remark in passing that the two above shifts are much larger for the case of a fit to a single mass than to the average mass distributions.

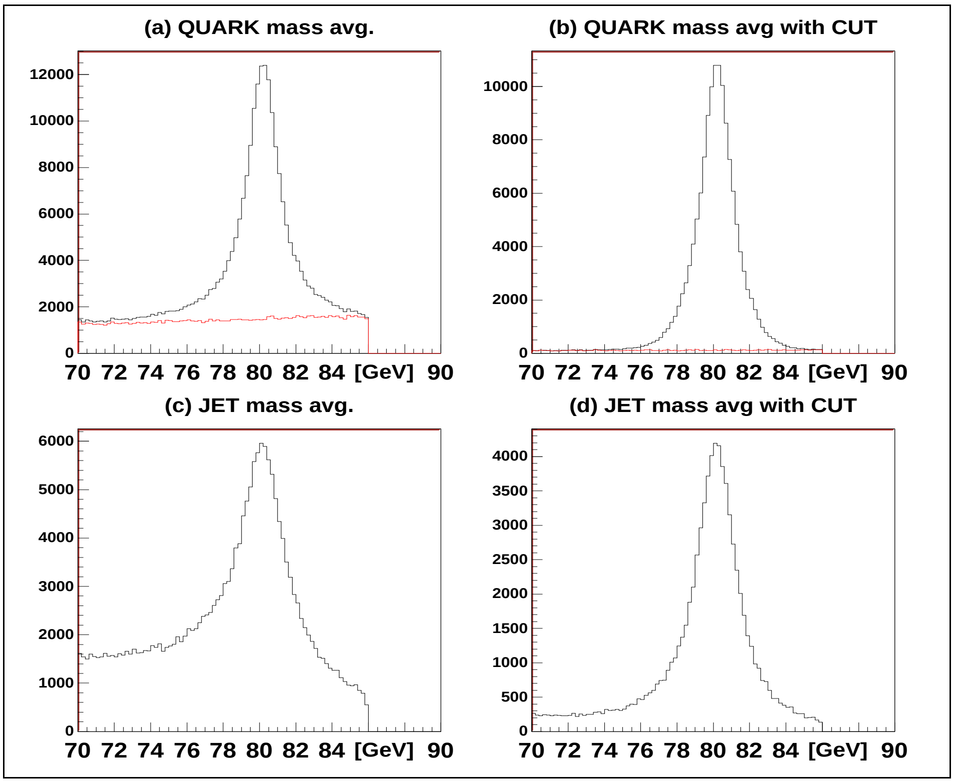

Figure 4: Distribution of the average mass from quarks and jets with and without cuts. Cuts on the difference of masses as in fig. 3. In the case of quarks, the combinatorial background is explicitly shown (non-resonant curve).

see experimental talks at this conference. Nevertheless, the main features will be as in our simplified procedure.

2 ISR effect in reconstructed M_W revisited

Once we have set up the machinery for getting the reconstructed (fitted) W-mass out of 4-jet final states, let us now perform the first, warming up, example of a study on the theoretical uncertainty of the reconstructed M_W. KORALW features QED initial-state radiation up to $\mathcal{O}(\alpha^2 L^2)$, i.e. up to second order in the leading-log approximation. Let us check how big the effect of ISR in the reconstructed M_W is and what would be the higher-order $\mathcal{O}(\alpha^3 L^3)$ correction. Unfortunately, the $\mathcal{O}(\alpha^3 L^3)$ ISR matrix element is not implemented in KORALW (although it would be a fairly simple modification), so we do the other exercise: we degrade ISR in KORALW to $\mathcal{O}(\alpha^1 L^1)$ and we check how big the pure $\mathcal{O}(\alpha^2 L^2)$ correction is. Using the "rule of thumb" scaling law we may guess within a factor of 2 or so the size of the missing $\mathcal{O}(\alpha^3 L^3)$ correction. The results of the above exercise are summarized in table 1. As we see, the shift of the reconstructed M_W due to $\mathcal{O}(\alpha^2 L^2)$ ISR is a non-negligible 174 MeV; the $\mathcal{O}(\alpha^2 L^2) - \mathcal{O}(\alpha^1 L^1)$, "pure second order" part, is not so large, about 45 MeV. It should be strongly stressed, however, that

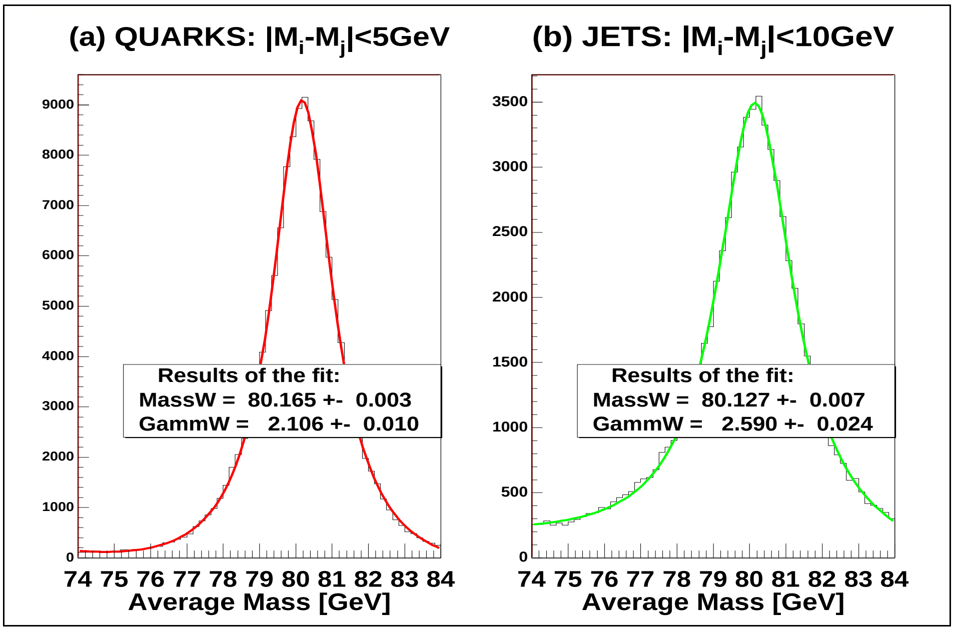

Figure 5: Average mass distribution from quarks and jets fitted with the Breit–Wigner function. Input parameters were $M_W = 80.230$ GeV, $\Gamma_W = 2.034$ GeV. Cut on mass difference as indicated in figures. (No BE effect yet.)

our "pure second order" is in a sense "abnormally small" because we take the difference $\mathcal{O}(\alpha^2 L^2) - \mathcal{O}(\alpha^1 L^1)$ with an exponentiation of the Yennie–Frautschi–Suura (YFS) type where $\mathcal{O}(\alpha^1 L^1)$ as shown in ref. [10] already includes *most* of the $\mathcal{O}(\alpha^2 L^2)$! The naive scaling law would suggest that the missing $\mathcal{O}(\alpha^3 L^3)$ correction in the reconstructed W mass is about 15 MeV; we conclude, therefore, that it would not be worth while to upgrade the ISR in KORALW to the $\mathcal{O}(\alpha^3 L^3)$ level[3]. This conclusion is most probably *not true* for other M.C. generators and integration programs that do not employ YFS exponentiation. Of course, the very interesting question is: How big is the non-leading $\mathcal{O}(\alpha^1 L^0)$ correction in the reconstructed W mass? For the moment we do not have any firm answer to this question[4].

3 Bose–Einstein effect in reconstructed M_W

3.1 What is the Bose–Einstein effect?

In short, the famous Bose–Einstein (BE) effect [12] is a type of short-range (< 400 MeV) positive correlation in the momentum space, among particles of the same-kind in the hadronization process (typically charged pions of the same sign) attributed to an inco-

[3] Note that the YFS-exponentiated LL electron structure functions for the ISR are known analyticaly to the fifth order [11]!

[4] It seems that we have little prospect for the completion of the full $\mathcal{O}(\alpha)$ off-shell calculation for the W-pair production and decay process before the end of LEP2 operation.

	Absolute		Original subtracted	
Type of calcul.	M_W^{av}	Γ_W^{av}	$M_W^{av} - M_W^{input}$	$\Gamma_W^{av} - \Gamma_W^{input}$
Without ISR	80.127 ±.007	2.590 ±.024	-0.103 ±.007	0.556 ±.024
ISR $\mathcal{O}(\alpha^2 L^2)$	80.301 ±.016	2.798 ±.058	0.071 ±.016	0.764 ±.058
Difference	+0.174 ±.017	0.208 ±.020	+0.174 ±.017	0.208 ±.020
Without ISR	80.127 ±.007	2.590 ±.024	-0.103 ±.007	0.556 ±.024
ISR $\mathcal{O}(\alpha^1 L^1)$	80.258 ±.016	2.849 ±.059	0.028 ±.016	0.815 ±.059
Difference	0.131 ±.017	0.259 ±.022	0.131 ±.017	0.259 ±.022
$\mathcal{O}(\alpha^2 L^2 - \alpha^1 L^1)$	+0.043 ±.021	-0.051 ±.083	+0.043 ±.021	-0.051 ±.083

Table 1: Study of the effect of ISR at 172 GeV. W masses and widths values are from Breit–Wigner fits to distributions of jets. M_W^{avg} and Γ_W^{avg} are from a fit to the distribution of the average jet–jet mass, for which the difference is below 10 GeV (cut on combinatorial background). The "difference" of the fitted masses is due to ISR. The difference in the bottom row corresponds to the pure ISR $\mathcal{O}(\alpha^2 L^2)$ effect.

herent emission at space distances of about 1 fermi. Although the effect is clearly seen in the data, see refs. [1, 13] and the review [14], the actual physical process responsible for was never unambiguously identified. In any case, it seems to be related to a quantum-mechanical interference effect (hence the importance of the BE symmetrization principle) in the unknown multipion wave function in the quark hadronization process.

3.2 Previous implementations of BE effect in M.C.

Since the effect most probably has a genuine quantum-mechanical interference origin, related to the phase of the wave function of the multihadron final state, it is therefore by construction absent from any typical hadronization Monte Carlo event generators; simply because they are based on the probabilistic (stochastic chain) models without any quantum-mechanical interferences. There were attempts to modify existing hadronization event generators in order to incorporate (parametrize) the BE effect in them. In JETSET there is a special subroutine LUBOEI that does this job, see refs. [6] and [15]. Very briefly the LUBOEI takes a hadronic event as produced by JETSET (before the decay of long-lived resonances) and manipulates four-momenta of all pairs of the equal-sign pions in such a way that they come a bit closer (the angle between them gets smaller). This "mechanical" procedure generally violates four-momentum conservation. In order to cure this violation, *all* momenta are rescaled at the end of the procedure, so that four-momentum is again conserved. The above procedure is quite successful in reproducing (parametrizing) BE effect in the experimental data. As its authors rightly point out, the correction of the total four-momentum non-conservation introduces spurious long-range correlations. For the description of the typical hadronic inclusive data, this is probably unimportant.

3.3 Is BE effect relevant for M_W measurement?

Similarly, as the so-called colour reconnection phenomenon [9], the physical process that is the source of the BE effect may also introduce a "cross-talk" between hadrons in jets originating from two W's. This "cross-talk" may disturb the effective dijet masses, leading to an additional bias in the reconstructed M_W. Our prejudice is that the "cross-talk" effect should be small, because it affects the intersecting part of jets, i.e. low-energy hadrons and the ends of jets (fast hadrons), which are critical for the dijet masses, should not be affected. As we have already noted, the experimental study of the single-Z decay at LEP1 cannot help us to assess the magnitude of the "BE cross-talk" effect among decay product of two W's. What we may do is only to try to estimate this effect theoretically and hope that it is much smaller than the LEP2 ultimate experimental error of $\sim$ 40 MeV in the reconstructed M_W. The first, and up to now the only quantitative theoretical study of BE effect, in the reconstructed W mass, was presented in ref. [15] and is based on the LUBOEI algorithm in JETSET. It gives us, however, the estimate that the "BE cross-talk" effect is up to 200 MeV, in the reconstructed M_W. A further study of this effect is therefore urgently needed.

3.4 Our implementations of the BE effect in M.C.

As pointed out by the authors of ref. [15], the main problem with the LUBOEI recipe, in the context of the M_W measurement from the dijet masses, is that the rescaling necessary to correct for the four-momentum conservation introduces spurious long-range correlations among fast particles at the ends of the different jets. They subtract this effect, but doubts may remain as to whether this subtraction is good enough. In our opinion one disturbing feature of the results in ref. [15] is that the effect grows with energy, while we know that at very high energies, when two W's decays far away in the space-time, the "cross-talk" among decays should die out completely. The authors of ref. [15] also point out that it would be better to imprint the BE effect on the M.C. hadron distributions not by momenta manipulations but by the "weighting" method, i.e. for pairs of equal-sign particles closer in momentum space one should attribute slightly bigger weight than for the distant ones. They see, however, three main obstacles in the practical realization of such a method. (i) The total weight, being typically the product of the weights for all pairs of equal-sign pions, would fluctuate wildly, destroying the convergence of the M.C. method. (ii) The hadronization process is believed to be well space-time-separated from the hard-parton underlying process, in the same way as the decay of the long-lived particle is not interfering with its production process[5]. The hadronization process is not allowed to disturb parton distributions (for instance quark energy and gluon multiplicity distributions). There is always a danger that the weight used to introduce the BE effect may disturb the parton distribution. (iii) The basic hadronization M.C. is usually tuned to very well describe hadron distributions (for instance hadron multiplicities) in the experimental data. Weighting events may destroy this agreement, and in principle the basic

[5]Watch out! Quantum mechanics may always strike back, see the Einstein–Podolsky–Rosen effect.

M.C. should be laboriously retuned in order to regain the agreement with the data. In view of the above potential *pitfalls* the authors of ref. [15] did not pursue the otherwise very attractive "weighting method".

In this talk we present our method of introducing the BE effect by means of the weighting method, feeling confident that we have avoided the above three pitfalls. Our recipe for the BE weight is based on refs. [16, 17] and it is the following:
(1) Form *clusters* where a cluster is a group of identical particles (in our case pions of the same sign) that are *connected*, i.e. each of them has at least one neighbour belonging to the cluster. The particle j is a neighbour of particle i if $Q_{ij} < z$ where

$$Q_{ij} = \sqrt{-(p_i - p_j)^2} \tag{1}$$

and $z \simeq 0.2$ GeV is a free parameter.
(2) Calculate the total weight as the product of the component weights for each cluster:

$$W_{BE} = \prod_{clusters} W_c^{(n)}(p, R, Q_c). \tag{2}$$

The weight of a cluster depends on the cluster multiplicity n and two model parameters p and R. For $n = 1, 2, 3$ the component weight for one cluster reads as follows:

$$\begin{aligned} &W_c^{(1)}(p, R, Q) = 1, \\ &W_c^{(2)}(p, R, Q) = 1 + 2p(1-p)e^{-R^2Q^2} + p^2 e^{-2R^2Q^2}, \\ &W_c^{(3)}(p, R, Q) = 1 + 6p(1-p)e^{-\frac{1}{3}R^2Q^2} + 3p^2(3-2p)e^{-\frac{2}{3}R^2Q^2} + 2p^2 e^{-2R^2Q^2}. \end{aligned} \tag{3}$$

The general definition of $W_c^{(n)}$ for arbitrary[6] n can be found in ref. [17] The total Q_c^2 of the cluster is defined as follows:

$$Q_c^2 = \sum_{1 \le i < j \le n} Q_{ij}^2. \tag{4}$$

(3) We apply the above weight for events from KORALW/JETSET for all π^0's and $\pi^\pm$'s adjusting the total pion multiplicity back to its original value with the simple power factor

$$W_{BE} \to \lambda^n W_{BE}, \tag{5}$$

where $n = n(\pi^0) + n(\pi^+) + n(\pi^-)$ is total pion multiplicity. The adjustment is done either for a single W, the resulting λ being fed into the WW calculation, or λ is adjusted separately for the single W-decay and for the W-pair decay (at each energy separately). In the first case the total multiplicity of the W-pair is increased by 4% due to BE weight (mainly in the high-multiplicity tail). This very simple adjustment of the average multiplicity does not prevent a slight modification of the shape of the multiplicity distribution.

[6] In practical calculations one may encounter $n = 30$ or even higher, so we have written a general program calculating $W_c^{(n)}$ for arbitrary n.

For our purpose this modification is negligible, but one may treat it as real and try to compare it with the data. The other approach would be to rescale $\sigma(n(\pi^0), n(\pi^+), n(\pi^-))$ back to its original value. This would "retune" the entire multiplicity distribution to its original shape. We did not attempt to do this. We find a rescaling with power of λ fully acceptable for our purposes.
(4) Finally, we adjust the average weight to be $\langle W_{BE}\rangle \equiv 1$ simply by multiplying it with a suitable constant[7]: $\langle W_{BE}\rangle \to \mathrm{const}\langle W_{BE}\rangle$.

3.5 Numerical results: BE effect

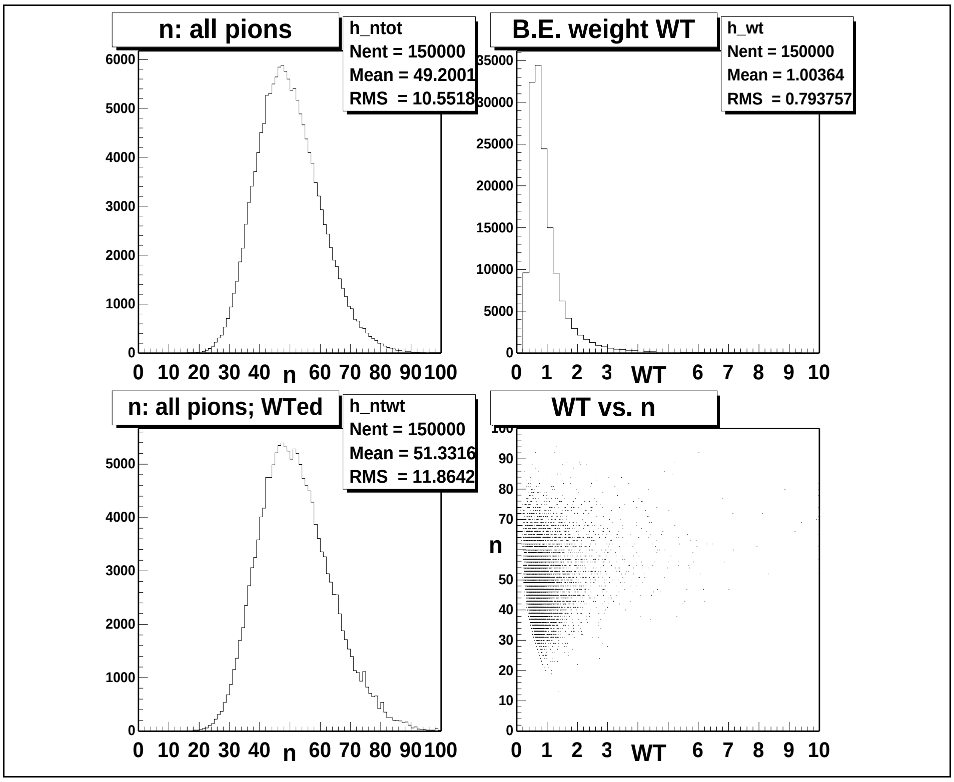

Figure 6: Plots of the total-multiplicity distribution without and with BE weight. The distribution of the BE weight and the scattergram of pion multiplicity versus BE weight. Results are for WW $\to$ $4J$ at 172 GeV with BE weight adjustment done for WW $\to$ $e\nu 2J$.

We shall now present our numerical results illustrating the "adjustment procedure", and show the 2-particle and 3-particle distributions with the BE effect due to our weight. In fig. 6 we see the original multiplicity distribution and the one with the "adjusted" BE weight. The average multiplicities are not exactly the same, because we show the more interesting case of WW $\to$ $4J$ (at 172 GeV) with BE weight adjustment done for WW $\to$ $e\nu 2J$. As we see, the multiplicity distribution with the BE weight is stlightly

[7]For each energy we perform two MC runs; in the first one we run with $\lambda = 1$, const=1 and in the next runs we use λ and const adjusted to multiplicity and weight distributions of the first run.

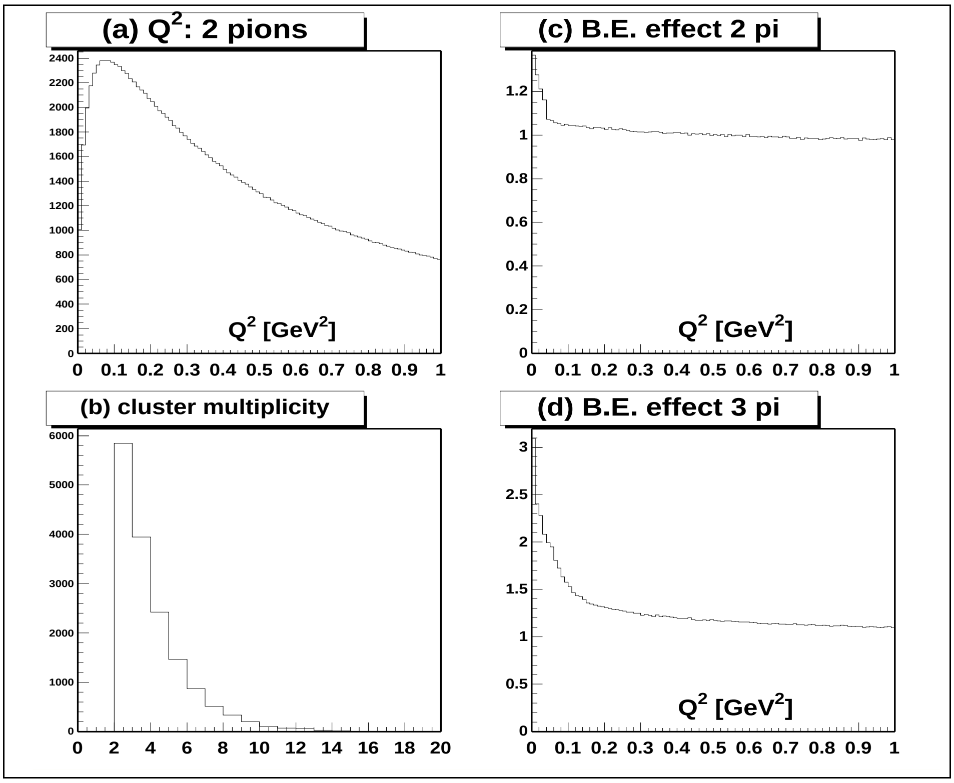

Figure 7: (a) The raw distribution of the Q_{ij}^2 for 2 equal-sign π's. (b) The cluster multiplicity distribution. (c) The BE effect for 2 equal-sign π's. (d) The BE effect for 3 equal-sign π's. Results are for WW $\to$ $4J$ with BE weight adjustment done for WW $\to e\nu\ 2J$.

(about 4%) larger. The distribution of the total BE weight is also shown. The BE weight has a sharply falling tail, assuring good Monte Carlo convergence. These results are from a run at 172 GeV with $\lambda = 1.0510$, const $= 0.511$ for $z = 0.2$ GeV, $p = 0.2$ GeV and $R = 1$ fm. The scatterplot weight versus multiplicity in fig. 6 shows that, as expected, the weight distribution is slightly worse for higher multiplicities.

In fig. 7 we show the BE effect induced by our weight. We do not attempt to compare it very precisely[8] with the experimental data but BE effect in our M.C. exercise looks fairly close to the typical experimental data of UA1 [18] or LEP1 [19]. For two equal-sign π's the enhancement of about 30–40% is located at small Q^2 and for three equal-sign π's we observe a healthy factor 2–3 enhancement, as in the real data. We therefore conclude that we were able to reproduce the BE effect with a precision of about 50%! This is good enough for our studies of the BE effect in the reconstructed M_W in the next section but, of course, the more precise/complete comparison of the BE effect of the presented model with the experimental data remains to be done. Let us finally note that the strength of the BE effect generated by our method is about the same for the WW-pair decay as for the single-W decay.

[8]The small value of the cut-off $z = 0.2$ is instrumental in getting the reasonably looking BE effects in our plots. This point requires further discussion.

	Absolute		Original subtracted	
Type of calcul.	M_W^{av}	Γ_W^{av}	$M_W^{av} - M_W^{input}$	$\Gamma_W^{av} - \Gamma_W^{input}$
Without BE	80.165 ±.003	2.106 ±.010	-0.065 ±.003	+0.072 ±.010
With BE wt	80.168 ±.003	2.118 ±.011	-0.062 ±.003	+0.084 ±.011
Difference	+0.003 ±.004	+0.012 ±.010	+0.003 ±.004	+0.012 ±.010
Type of calcul.	M_W^{sg}	Γ_W^{sg}	$M_W^{sg} - M_W^{input}$	$\Gamma_W^{sg} - \Gamma_W^{input}$
Without BE	80.177 ±.004	2.057 ±.012	-0.053 ±.004	+0.023 ±.012
With BE wt	80.181 ±.004	2.088 ±.013	-0.049 ±.004	+0.054 ±.013
Difference	+0.004 ±.006	+0.031 ±.011	+0.004 ±.006	+0.031 ±.011

Table 2: W masses and widths values are from Breit–Wigner fits to distributions of quarks (prior to hadronization). No ISR. M_W^{av} and Γ_W^{av} are from fits to the distribution of the average quark–quark mass, for which the difference is below 5 GeV (cut on combinatorial background). M_W^{sg} and Γ_W^{sg} are from fits of a single quark–quark mass for the same cut on the mass difference. Results with BE weight as in fig. 6.

Now let us come back to the question: *Did we manage to avoid the pitfall of disturbing parton distributions with our BE weight?* In fig. 1 (b) we see that the number of jets (related to quark/gluon multiplicity) changes very little, less than 1%! In table 2 we list reconstructed/fitted W masses from diquark masses (similarly to fig. 5 (a)) with and without the BE weight. The fitted values of M_W and Γ_W are almost the same in the two cases, the difference being less than 15 MeV. In another exercise of the same kind we switched to the BE weight, which was adjusted to reproduce WW $\rightarrow$ $4J$ pion multiplicity. We could see a shift in M_W up to 20 MeV in such a case. Perhaps, more tests of this kind should be done, but the above two already give us enough confidence that the weighting method is not nonsense and does not lead us to the pitfall of disturbing the parton distributions. Finally, let us mention that the introduction of the B.E effect by weighting events is also employed in refs. [14, 20–22].

3.6 The BE effect in the reconstructed W mass

We are now fully armed to attack the question of the size of the BE effect in the reconstructed M_W. In fig. 8 we show the actual fit of the distribution of the average dijet mass (with the usual cut $|M_i - M_j| < 10$ GeV) in the case without and with BE weight. The difference is below the statistical error of about 12 MeV.

In table 3, we summarize results for centre-of-mass energies of 172 GeV and 200 GeV. We see that the BE effect in the reconstructed mass is consistent with zero.

Our result differs substantially from that of ref. [15], where the effect was found to be $100-200$ MeV. Of course, further studies are necessary in order to consolidate our results. (In particular one should check it with other variants of the BE weight.) Nevertheless, our result not being prone to the spurious long-range correlation of the LUBOEI method seems to be potentially better founded. It would be interesting to see if some variant of the LUBOEI method, which would not rely on the global rescaling of the four-momenta[9],

[9] One could think about compensating four-momentum non-conservation “locally”, for instance within

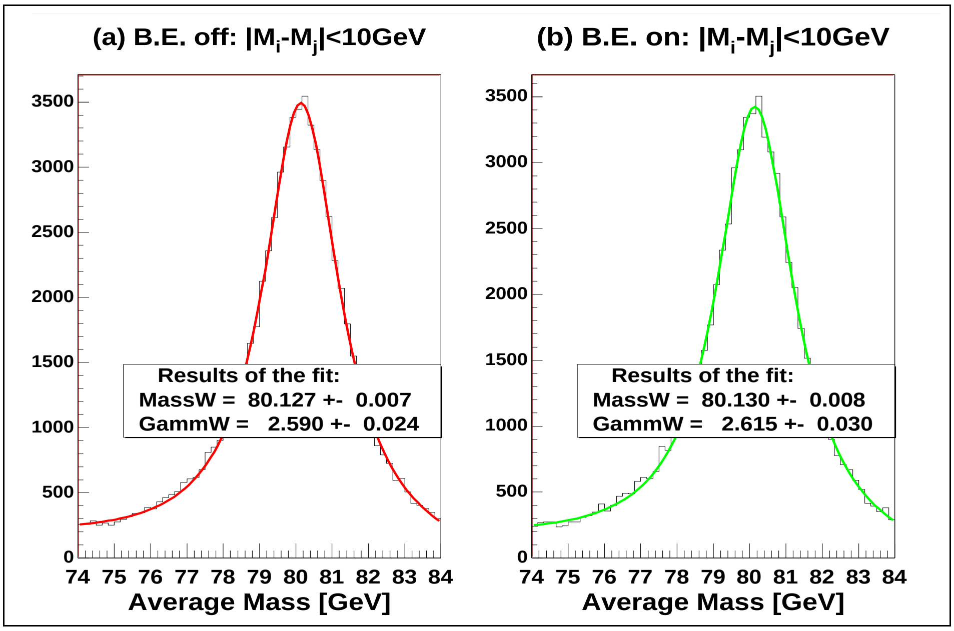

Figure 8: Average dijet mass distribution without and with the Bose–Einstein effect.

does confirm our result. The message for LEP2 experiments is clear: we see a clear prospect that the BE effect in the reconstructed M_W is below the ultimate experimental error of ~ 40 MeV.

4 Colour reconnection, as implemented in KORALW

The colour reconnection is another kind of "cross-talk" between simultaneous hadronization processes of the two decaying W's. Contrary to the BE effect the reconnection effect at the 100 GeV scale has not been seen before in the data. Its theoretical description is equally uncertain. A rich menu of theoretical models was available at the time of the 1995 LEP2 workshop [1]. A typical prediction of 50-100 MeV was quoted for the additional shift in the reconstructed W mass. The largest estimate, up to 500 MeV, was predicted from yet another model, see ref. [7], later on. Our aim is to model just *one* kind of colour reconnection in the KORALW program. We did implement it in the simplest possible way: if one W from the WW pair decays into $q_1\bar{q}_1$ and the second one into $q_1\bar{q}_1$, then there is normal colour connection (for the CC3 matrix element) among $(q_1\bar{q}_1)$ and $(q_2\bar{q}_2)$ pairs. This is what is done[10] in the original KORALW 1.21. What we do now is to allow with some probability p_{rec}, an input parameter of KORALW, a reconnection to the $(q_1\bar{q}_2)$ and $(q_2\bar{q}_1)$ configuration. We employ the routine LUJOIN of the JETSET to set up the colour flow, and the hadronization is done with the help of LUSHOW, as usual. In this

a cluster defined as in our method.

[10]For the matrix element beyond CC03 (for ZZ contributions) some kind of re-connection is already implemented in KORALW 1.21, according to the prescription in [13].

	Absolute		Original subtracted	
	172 GeV			
Type of calcul.	M_W^{av}	Γ_W^{av}	$M_W^{av} - M_W^{input}$	$\Gamma_W^{av} - \Gamma_W^{input}$
Without BE	80.127 ±.007	2.590 ±.024	-0.103 ±.007	0.556 ±.024
With BE wt	80.130 ±.008	2.615 ±.030	-0.100 ±.008	0.581 ±.030
Difference	+0.003 ±.010	+0.025 ±.038	+0.003 ±.010	+0.025 ±.038
	200 GeV			
Type of calcul.	M_W^{av}	Γ_W^{av}	$M_W^{av} - M_W^{input}$	$\Gamma_W^{av} - \Gamma_W^{input}$
Without BE	80.066 ±.007	2.561 ±.024	-0.164 ±.007	0.527 ±.024
With BE wt	80.059 ±.007	2.635 ±.026	-0.171 ±.007	0.601 ±.026
Difference	-0.007 ±.010	0.074 ±.035	-0.007 ±.010	0.074 ±.035

Table 3: W masses and widths values are from Breit–Wigner fits to distributions of jets at two different centre-of-mass energies. No ISR. M_W^{av} and Γ_W^{av} are from fits to the distribution of the average jet–jet mass, for which the difference is below 10 GeV (cut reducing combinatorial background).

simplistic scenario we did not attempt to implement parton/hadron shower in the time-position space. We find that for $p_{rec} = 1/N_c^2 = 1/9$ the reconstructed W mass changes by $+30 \pm 10$ MeV. This result is consistent with the typical estimate quoted in the 1995 LEP2 workshop summaries [1].

5 Conclusions

We conclude in the following way:
(a) The ISR effect in the reconstructed M_W is under control due to YFS exponentiation; it would be good to include the third-order LL correction and first-order sub-leading corrections to be on safe side.
(b) The Bose–Einstein effect in the reconstructed M_W is negligible, independently of centre-of-mass energy. This result was found for the BE effect introduced in the M.C. with additional weight. This method seems to be superior to other methods.
(c) A primitive ansatz for colour reconnection was introduced and tested in the KORALW Monte Carlo.

While results (a) and (c) are compatible with the 1995 LEP workshop summaries [1], the result (b) is novel and therefore more interesting.

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[11] See http://root.cern.ch for more details on the new ROOT histogramming package.

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