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Evaluation of the LEP centre-of-mass energy for data taken in 1998

The LEP Energy Working Group [1]

Abstract

The centre-of-mass energy at LEP2, above the W pair threshold, was evaluated in 1996 and 1997 using a magnetic extrapolation method. The average beam energy is measured precisely in the range 41–61 GeV by the method of resonant depolarisation. The beam energy for physics running, is inferred from measurements of the magnetic field in several LEP main bend dipole magnets made by NMR probes, both during the resonant depolarisation measurements and during physics fills. The dominant systematic uncertainty comes from a comparison of the total bending field measured by a flux-loop with the fields measured by the NMR probes. Small corrections are applied to account for magnets other than the main bend dipoles, and for the beam energy variation around the ring to derive the centre-of-mass energy at each interaction point. In this short note, the results of applying this method to the 1998 data are presented. The error on the beam energy in 1998 is determined to be 20 MeV.

1 Introduction

The centre-of-mass energy of LEP above the W-pair production threshold has been determined by the method of magnetic extrapolation for the 1996 and 1997 data samples. This method is documented in Ref. [1]. In this note, the results of applying the same analysis techniques to the 1998 data are presented. The data quality is compared with that seen in 1997, and the systematic uncertainty is evaluated. The calculated centre-of-mass energies and spreads have been distributed to the LEP experiments.

2 Reminder of the extrapolation method

The magnetic extrapolation method used to calibrate the centre-of-mass energy at LEP2 to date [1] relies on 16 NMR probes that measure the local magnetic field in several of the LEP main bend dipole magnets. The field readings of the probes are fit to the beam energy measured by resonant depolarisation in the region of 41 to 61 GeV. The fit is linear, with two free parameters: $E_{\mathrm{pol}} = a + bB_{\mathrm{NMR}}$. From this fit, the beam energy in

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physics can then be predicted from the average field measured by the probes in physics runs. The relationship between beam energy and measured magnetic field is assumed to be linear between the region calibrated by polarisation and the physics regime. Tests of this linearity assumption lead to the dominant systematic errors in the analysis of the 1997 data, as can be seen in table 2

The largest uncertainty comes from a comparison of the total bending field measured by the flux loop and the predicted total bending field from the average over the NMR probes: $B_{\rm FL} = c + dB_{\rm NMR}$. There is also a "statistical" contribution to the error from the scatter in the predicted physics energy over the probes, and a further systematic error from the variation of NMR calibrations from fill to fill through the year.

Other systematic uncertainties from the many other effects that influence the centre-of-mass energy are relatively small. They are also listed in table 2, and more details can be found in [1, 2].

The LEP spectrometer should become operational in 1999. However, until the spectrometer method is proven, the energy calibration will rely on fitting the NMR probes to polarisation measurements over as long a lever arm as possible, and assuming that this normalisation is valid up to physics energy.

3 Energy calibration measurements in 1998

The gradual improvement in the programme to measure the beam energy with resonant depolarisation can be seen from the list of successful measurements between 1996 and 1998, given in table 1. The first measurements away from the Z peak (around 45 GeV beam energy) were made in 1996. In 1997, the lever arm over which measurements were made was extended down to 41 GeV (the lowest energy at which the NMR probes lock reliably) and up to 55 GeV. In 1998 the highest energy with a sufficient level of transverse polarisation to make a measurement increased to 61 GeV.

4 Comparison of 1997 and 1998 data quality

4.1 Initial energy in each fill

The contribution to the initial beam energy in each fill from the main bend dipole fields is shown in Fig. 1 for all the high energy fills in 1997 and 1998. The fills generally show a small scatter with an rms of around 10 MeV, but with a few anomalies. For example, at the beginning of 1998 there were a few fills before the correct magnet calibration curves were loaded, leading to an offset of more than 100 MeV. There are also occasional fills where there is a problem interpolating between the logged values around the start of a fill. The coils of the NMR probes gradually suffer radiation damage so that the probes fail to lock at lower energies. There is no apparent jump in the dipole fields after the NMR coils are replaced in the middle of a year. Even accounting for problem fills, the small scatter and the stable behaviour leads to a small uncertainty.

Date	Fill	41 GeV	45 GeV	50 GeV	55 GeV	61 GeV	Optics
19/08/96	3599			•			90/60
31/10/96	3702		•				90/60
03/11/96	3719		•	•			90/60
17/08/97	4000		•				90/60
06/09/97	4121		•	•			60/60
30/09/97	4237		•	•			60/60
02/10/97	4242	•	•	•	•		60/60
10/10/97	4274		•				90/60
11/10/97	4279	•	•	•	•		60/60
29/10/97	4372	•	•				60/60
14/06/98	4666		•	•	•		60/60
18/06/98	4669		•				102/90
15/07/98	4843		•		•		60/60
06/09/98	5137		•				60/60
07/09/98	5141	•	•	•			60/60
20/09/98	5214	•	•	•	•	•	60/60
29/09/98	5232		•				102/90
18/10/98	5337	•	•	•	•	•	60/60

Table 1: The successful resonant depolarisation measurements at LEP2. Energy points measured in a fill are marked •.

4.2 Fits to all polarisation fills in a year

The fields measured by the NMR probes are compared to the energies measured by polarisation, after correcting for tides, horizontal orbit correctors etc. according to the model described in [1]. The residuals from the straight line fits data are shown in Fig. 2. The error bars reflect the scatter over the working NMR probes at each measurement point. In 1997, these data lead to an error of 10 MeV from the scatter in predicted physics energy, plus in quadrature an uncertainty of 5 MeV from the variations from fill to fill. At this stage there is a larger scatter in the preliminary 1998 data. This may be improved once a complete check of the reliability of the probe measurements has been made, and bad measurements have been identified.

4.3 Difference between flux loop and NMR probes

The difference between the total field measured by the flux loop and predicted by the average over the NMR probes can be converted into an energy difference. The two devices are cross-calibrated in the range corresponding to the polarisation measurements, and the discrepancy seen at physics energy gave rise to the largest systematic uncertainty in the 1997 data. The differences for 1997 and 1998 are shown in Fig. 3. The discrepancy is of a similar size in the two years. Time variations during each year are not understood.

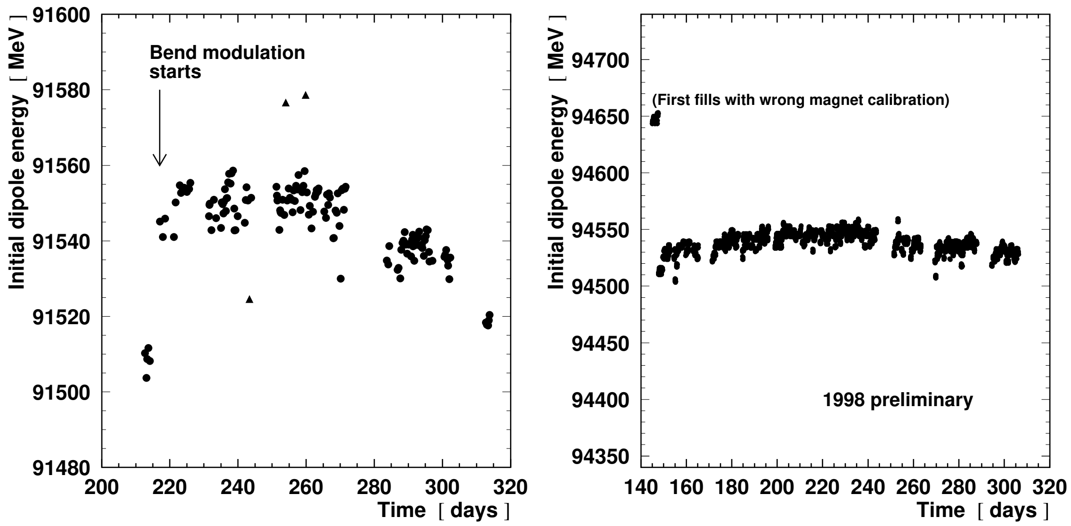

Figure 1: Initial dipole energy in a fill for 1997 (left) and 1998 (right).

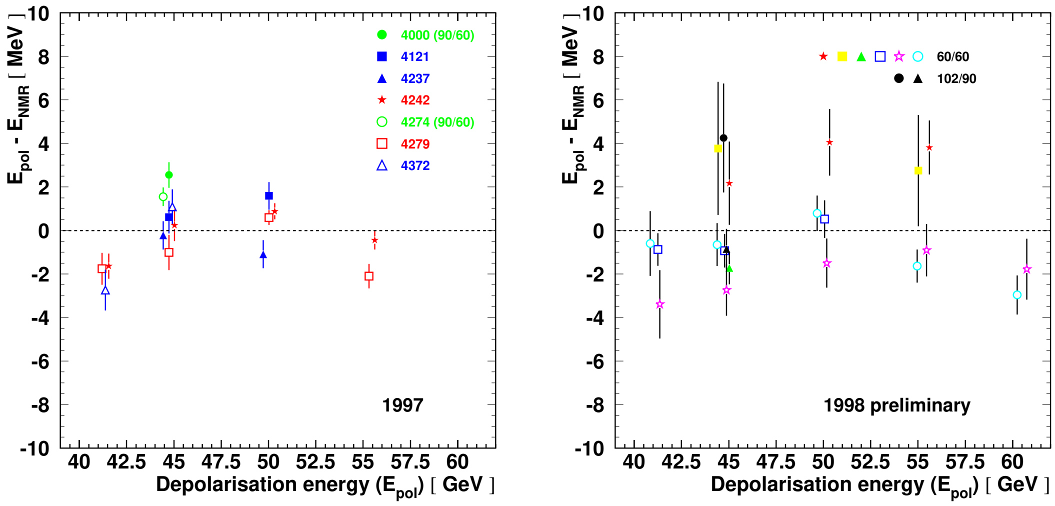

Figure 2: Residuals from the fits to all of the polarisation fills in 1997 (left) and 1998 (right).

There is also a lack of measurements in the middle of the year, when the NMR probes no longer functioned in the range of polarisation energies, although they could still be used in physics running to predict the energy.

Using looser quality criteria for the 1998 data, in particular the number of energy points that must be available before a comparison is made, allows more flux-loop measurements to be compared. Changing the quality cuts in this way does not change the typical values of the bias.

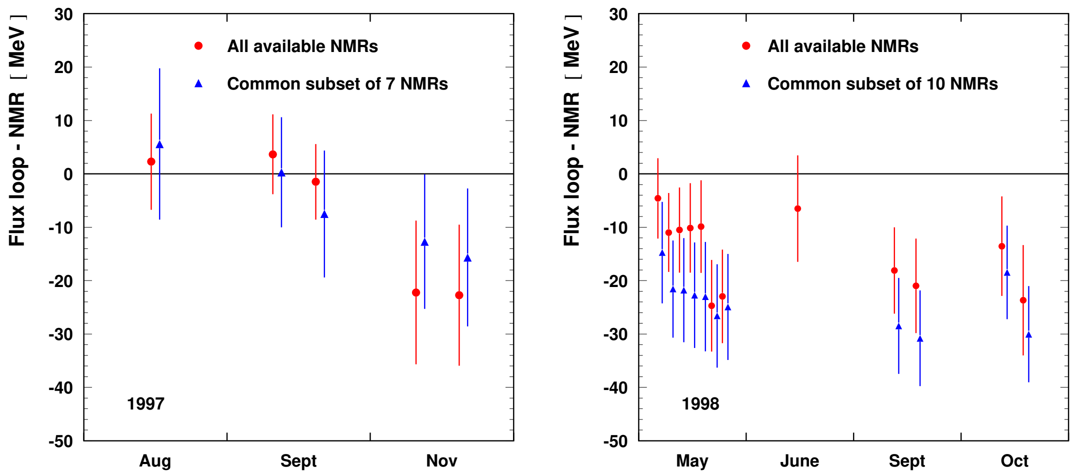

Figure 3: Residual difference between the flux-loop and NMR probes at physics energy in 1997 (left) and 1998 (right).

4.4 Study of non-linearities with five-point fills

The validity of the linearity assumption can be tested by examining the residuals from the fits of NMR measurements to polarisation energies. The residuals from a fit to a single fill can be considered to be the most sensitive test, since any confusion from fill-to-fill scatter is avoided.

Fill 5214 in 1998 was exemplary, in that the full set of 16 NMR probes functioned at the five energy points between 41 and 61 GeV. The residuals to the straight line fit for this fill alone are shown in Fig. 4. The error bars are small, and any deviations are less than 1 MeV. However, larger residuals, with a characteristic banana shape have been observed in other fills.

If only those NMR probes that worked in the later fill 5337 are used in the fit to the fill 5214 data, then larger residuals are seen (Fig. 5). The deviations may therefore be explained as being due to the different characteristics of the local field as a function of excitation current of the particular set of magnets and positions that the NMR probes occupy. This observation extends back to 1997 - if only four energy points are used in the fit, and only the common probes, then the fill 5214 data can mimic the four-point fill 4242 from 1997 (Fig. 6).

5 Systematic error evaluation

The preliminary estimate of the error breakdown for 1998 is given in table 2, together with the breakdown for 1997 and the correlation coefficients between the two years. The systematic checks leading to any new evaluations and the arguments behind the choice of correlation coefficient are given in the following sections.

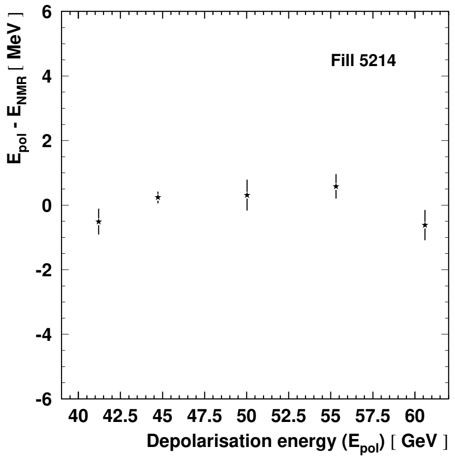

Figure 4: Residuals from a straight line fit to polarisation fill 5214, with five energy points and all NMR probes working.

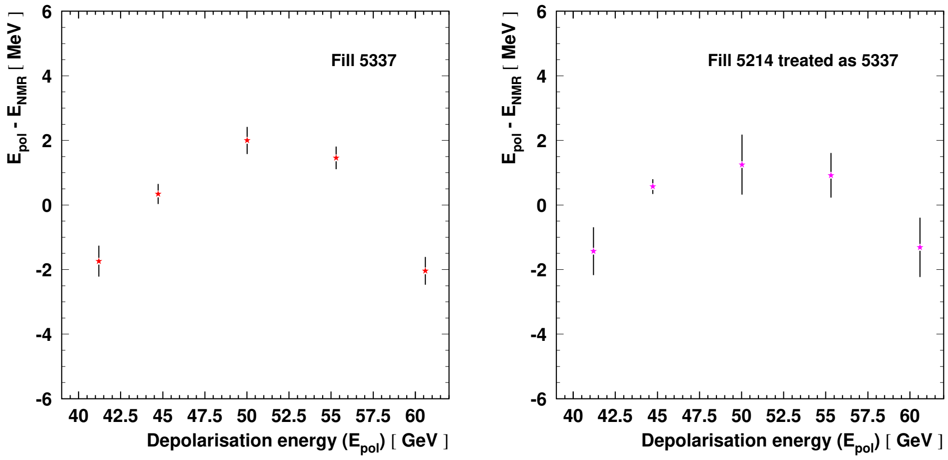

Figure 5: Comparison of residuals for fill 5337, and fill 5214, using only the common subset of probes.

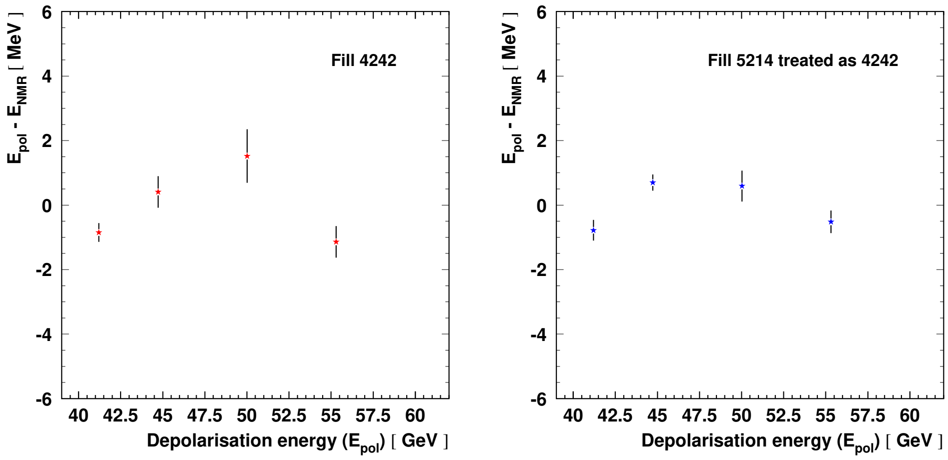

Figure 6: Comparison of residuals for fills 4242 and 5214, omitting the 61 GeV point, and only using the common probes.

Source	Error [MeV] 1997	1998	Correlation
Extrapolation from NMR–polarisation:			
NMR rms/$\sqrt{N}$ at physics energy	10	8	100%
Different E_{pol} fills	5	4	0%
Flux-loop test of extrapolation:			
NMR flux-loop difference at physics energy	20	15	75%
Field not measured by flux loop	5	5	100%
Polarisation systematic	1	1	100%
e^+e^- energy difference	2	2	100%
Optics difference	4	6	50%
Corrector effects	3	4	50%
Tide	1	1	100%
Initial dipole energy	2	1	0%
Dipole rise modelling	1	1	100%
IP specific corrections ($\delta E_{\mathrm{CM}}/2$):			
RF model	4	4	100%
Dispersion	2	2	100%
Total	25	20	

Table 2: Table of errors for 1997 and 1998, including the correlation coefficients between the two years.

5.1 Scatter in predicted physics energy over NMR's

The rms scatter of the average initial energy per NMR in physics runs for the 1998 data is 33 MeV, compared to 41 MeV in 1997. This implies a slightly reduced uncertainty of 8 MeV.

The average initial dipole energy per NMR shows a strong correlation between 1997 and 1998. This is understood to mean that the scatter reflects the intrinsic properties of the magnets in the positions measured by the NMR's, and is therefore preserved when the probes are exchanged.

5.2 Different Epol fills

NMR4 has been seen to have a strange behaviour, leading to a larger scatter of residuals in polarisation fills. If this NMR is omitted, the scatter and error bars are reduced, and the energy shifts by 3.3 MeV.

Using different groups of polarisation fills also causes shifts in the mean energy. The largest come from splitting the data into July and earlier, and September and later. NMR4 was exchanged between these two, so the difference is largely a reflection of the NMR4 strange behaviour. The shifts are $+4$ and -2.3 MeV w.r.t. the default fit to all fills. An error of 4 MeV is therefore assigned, and this is almost entirely driven by the unexplained strange behaviour of NMR4 in 1998.

Using coefficients calculated in an independent analysis gives consistent results to 1.5 MeV. In this second analysis, all polarisation points at the same nominal energy are averaged together, rather than used as separate measurements. A different procedure is used to synchronise NMR readings with other data, and rather than taking into account an average rise term, the instantaneous NMR values are taken. This therefore also tests that the analysis is insensitive to several procedural choices.

The equivalent error in 1997 was dominated by one strange fill, rather than one unusual NMR, so these uncertainties are taken to be uncorrelated.

5.3 Flux-loop/NMR difference at physics energy

The typical bias observed during 1998 is -15 MeV using all available NMR's, or 20 MeV using only the common subset of NMR's. There is no strong trend through the year. Using the common subset of NMR's, the maximum difference in bias during the year is also around 15 MeV.

To reduce the sensitivity to probes failing during the year, the average bias per probe can be calculated first, and then these values combined with equal weight. The average bias calculated in this way is -11 MeV. The error on this mean from the rms over the probes is 7.8 MeV, which could be combined in quadrature with the typical scatter over flux-loops for one probe, which is 6.4 MeV, to give a total error of about 10 MeV, i.e. only a one sigma significance for the bias.

From these studies and arguments, and error from the flux-loop bias test of 15 MeV is taken for the 1998 data. This 15 MeV is assumed to be fully correlated with 15 MeV in 1997, leading to an effective correlation coefficient of 75%.

The field outside the flux loop is the same for both years.

5.4 Polarisation and e^+e^- energy difference

These small uncertainties are the same in each year, and fully correlated between years.

5.5 Optics difference

The residuals w.r.t. the fit to all polarisation points for the two measurements with the physics optics, 102/90, are $+4$ and -1 MeV if NMR4 is included, but shift to $+5$ and -3 MeV excluding NMR4.

NMR4 is used for the central values, suggesting an average optics difference of 1.5 MeV, with an rms of 3 MeV. However, the data without NMR4 have an average shift of 1 MeV, and an rms of 4 MeV. The optics difference scales with beam energy, so an uncertainty of 6 MeV has been assigned, based on the rms with NMR4 included.

The optics dependence has some systematic uncertainties in common between the years, but is driven by imperfections, so a 50% correlation coefficient has been chosen.

5.6 Corrector effects

The average shift from horizontal orbit correctors was 7.9 MeV, evaluated by removing the correction. Following the same prescription as for 1997, the uncertainty is half of the effect, i.e. 4 MeV.

The systematic uncertainties affecting the corrector error are partly in common between years, and partly depend on the golden orbit adopted for optimal physics running, so a 50% correlation has again been chosen.

5.7 Initial dipole energy

The rms is 8 MeV for 440 fills, leading to an uncertainty of less than 1 MeV. Following tradition, an entry remains in the table with the negligible 1 MeV contribution (as was already done for polarisation uncertainty, for example).

The scatter is evaluated independently in the two years, and the corresponding uncertainty is treated as uncorrelated.

5.8 Dipole rise modelling

The average energy in phyiscs changes by -0.8 MeV if the dipole rise term is ignored. The corresponding systematic uncertainty is therefore expected to be much less than 1 MeV, and following the convention of other such negligible uncertainties, we retain an entry of 1 MeV in the error table. The uncertainty is taken to be fully correlated between years, since the effects driving the rise are the same.

5.9 RF and dispersion effects

The evaluation of these uncertainties uses the same criteria as for 1997, and the errors are taking to be fully correlated between the years.

6 Errors and correlation matrix for different years

Year	Centre-of-mass energy	Error in Ebeam
1996	161 GeV	27 MeV
1996	172 GeV	30 MeV
1997	183 GeV	25 MeV
1998	189 GeV	20 MeV

Table 3: The uncertainty in the beam energy for the four sets of data taken at LEP2 to date.

The total systematic error for the four main samples at LEP2 to date are given in table 3. The total errors from 1997 and 1998 are assumed to be fully correlated with the 1996 data points. This approximation is adequate, given the lower statistics at the lower energy points. The detailed error breakdown from table 2 for 1997 and 1998 is used to calculated the correlation coefficient between these two years. This is dominated by the

NMR/flux-loop bias uncertainty. The full correlation matrix is calculated to be

$$\begin{pmatrix} 1.00 & 1.00 & 0.91 & 0.75 \\ 1.00 & 1.00 & 0.82 & 0.67 \\ 0.91 & 0.82 & 1.00 & 0.75 \\ 0.75 & 0.67 & 0.75 & 1.00 \end{pmatrix}$$

The luminosity weighted centre-of-mass energy spread has also been calculated for the 1998 data sample, following the same procedure as in [1]. The energy spreads are listed in table 4 for the main LEP2 data samples.

Year	Centre-of-mass energy	spread
1996	161 GeV	144 ± 7 MeV
1996	172 GeV	165 ± 8 MeV
1997	183 GeV	219 ± 11 MeV
1998	189 GeV	237 ± 12 MeV

Table 4: The luminosity weighted centre-of-mass energy spread for LEP2 data.

References

[1] LEP Energy Working Group, "Evaluation of the LEP centre-of-mass energy above the W-pair production threshold", CERN-EP/98-191, CERN-SL/98-073, December 1998, submitted to Eur. Phys. J. C.

[2] "Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties", LEP Energy Working Group, Eur. Phys. J. C 6 (1999) 2, 187-223.