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MEASUREMENT OF THE BEAM ENERGY AT LEP2

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The status of the determination of the beam energy at LEP2 is discussed.

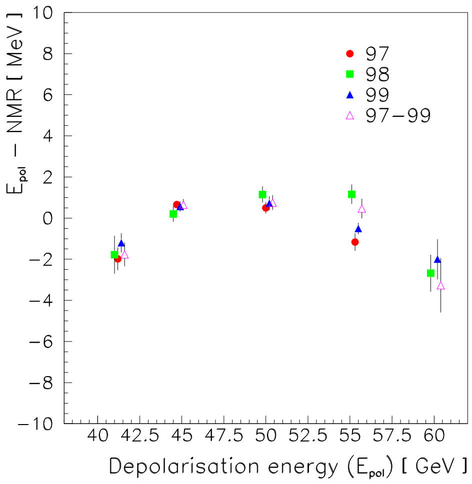
1 Extrapolation method

At LEP1 the uncertainties due to the beam energy on the Z mass and width are 1.7 and 1.2 MeV respectively, to be compared to the combined experimental errors from all other sources of 1.2 and 2.0 MeV. The main tools used for this excellent precision were *resonant depolarisation*, which gives the instantaneous beam energy to a fraction of an MeV, and extensive logging and monitoring for the many environmental effects which were found to influence the beam energy[1].

At LEP2 the determination of the mass of the W boson sets the requirements The experimental uncertainty from the combined LEP data is expected to be $\Delta m_{\rm W} \simeq 30$ to 40 MeV, depending on progress with the understanding of final state interaction effects. This sets the target of $\Delta m_{\rm W} \simeq$ 10-15 MeV for the desired uncertainty from the LEP beam energy. Unfortunately there is insufficient transverse polarisation above $\rm E_b \simeq 60$ GeV to use this method directly at LEP2.

The method currently used to determine the beam energy is based on the readings of 16 NMR probes, which are located in dipole magnets around the LEP ring. These are read out almost continuously and are calibrated assuming a linear relationship between the NMR field and the beam energy from resonant depolarisation, in the region $\rm E_b$ 40 to 60 GeV. There are 20 fills with 2 or more energy points and the residuals of a linear fit to all the data is shown in fig 1. It can be seen that the residuals are less than

Figure 1. Residuals of NMR energy versus $\rm E_{\it pol}$.



2 MeV and reproducible from year to year. The additional corrections applied to determine $\rm E_b$ for physics fills are described in [2]. The main disadvantages with this method is that it only samples 16 out of 3300 dipole magnets and the uncertainty in how any non-linearities will extrapolate.

The ring dipole magnets contain single turn flux loops which can be used to make a direct measurement of the field integral seen by the beam (in fact 96.5%), using dedicated machine current cycles [2]. The flux-loop integral is determined for each LEP octant and the mean then found. The beam energy is proportional to the total field integral but the flux-loop is not accurate enough to make a precise independent measurement of $\rm E_b$. In-

Figure 2. Differences in MeV between the measured and extrapolated flux-loop values for the 1999 data.

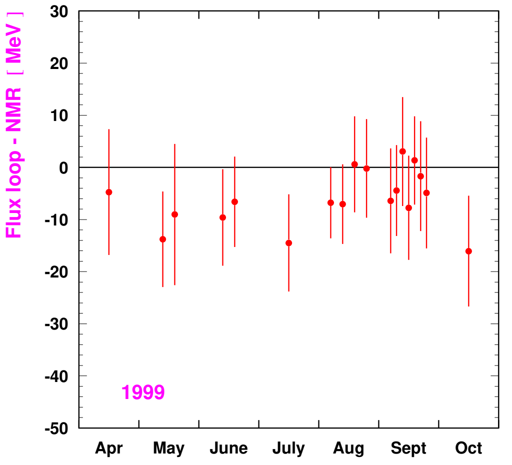
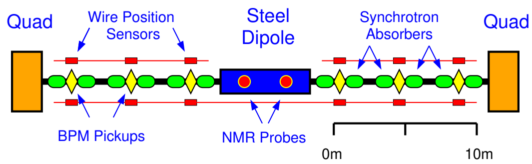


Table 1. Error breakdown for 1999 data.

source	error (MeV)
NMRs plus extrap.	19
E_{pol}, e^+e^- diff, optics diff	4
other(tide, correctors..)	3
IP specific (RF,dispersion)	5
TOTAL	21

Figure 3. Layout of the spectrometer.



stead it is calibrated against NMR measurements in the region 40-60 GeV. At high energies ($\simeq$ 100 GeV) the extrapolated values can be compared with the directly measured flux-loop values. The results for the data of 1999 are shown in fig 2.

It can be seen that the difference flux-loop - NMR is stable with time and, on average, is slightly negative, but there is no indication of any large non-linearity. It is also stable year-to-year, both averaged over all octants, and octant by octant. Based on these studies an extrapolation error of 15 MeV at LEP2 physics energies is assigned. The flux-loop is not used directly in assigning the central energy values, but is used as a cross-check and to assign the extrapolation error.

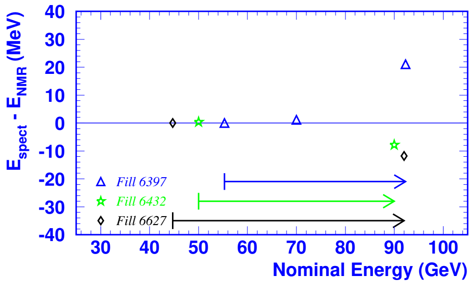
Central values and errors on E_b have been determined up to 1999, and a breakdown of the errors for 1999 is given in Table 1. In previous years the total error on E_b was 25 MeV in 1997 and 20 MeV in 1998, with a correlation $\simeq$ 70-90 % between years[2]. These uncertainties translate into an uncertainty on the W mass of $\Delta m_W \simeq \pm$ 17 MeV.

2 Magnetic Spectrometer

In order to try and improve the accuracy the LEP Spectrometer project was conceived in 1997. The idea is to measure the deflection of the beam in the LEP ring by measuring the trajectory before and after a special steel dipole magnet. The beam energy is proportional to the field integral of the magnet divided by the angular deflection. A schematic of the apparatus is shown in fig 3. The magnet used was accurately mapped outside of the LEP tunnel and later in situ to ensure the field remained stable. Good accuracy and stability is achieved and an error on $E_b \simeq 3$ MeV from this source is estimated.

The most demanding requirement is that on the Beam Position Monitors (BPMs), which must achieve an accuracy of $\simeq 1\mu$m. Special electronics were needed and the BPMs are shielded against synchrotron radiation and must work in a very hostile environment. To achieve the required 10^{-4} accuracy the device is calibrated against resonant depolarisation. From measurements made in 1999 a preliminary attempt has been made to determine E_b and its error. The uncertainties which are related to the NMRs and

Figure 4. Comparison of Spectrometer and NMRs at physics energies.



the normalisation are $\simeq$ 3 MeV. The uncertainties in computing $\mathrm{E_b}$ from the spectrometer readings (RF model etc) amount to 5.5 MeV and the estimated uncertainty from the BPMs is $\simeq$ 8 MeV; giving a total estimated systematic uncertainty at physics energies of $\simeq$ 11 MeV. The uncertainty in the region of 40-60 GeV is about 6 MeV, and this is compatible with the 8 MeV rms observed between the spectrometer and resonant depolarisation measurements in the energy range.

Spectrometer measurements of $\mathrm{E_b}$ have been obtained from three fills in 1999, in which they were normalised to resonant depolarisation at low energy and then a ramp to physics energies made. The spectrometer measurements are compared to the usual NMR model in fig 4. The mean difference E_{spect}-E_{NMR} = 0.5 MeV, with an rms of 15 MeV. This is the first direct measurement at the LEP2 energy scale and supports the extrapolation method.

For 2000 more measurements are being made to gain statistics and understand systematics. However the early data obtained seem to show some internal BPM inconsistencies, the cause of which is yet to be resolved.

3 Beam energy from $\mathbf{Q}_s$ v $\mathbf{V}_{RF}$

A second direct method has also been employed. In this, $\mathrm{E_b}$ is extracted from the energy loss $U_0 \propto E_b^4/\rho$, by measuring the synchrotron tune Q_s versus V_{RF}:

$$Q_s^2 = \left(\frac{\alpha_c\, h}{2\pi \mathrm{E_b}}\right) \sqrt{(e^2\, V_{\mathrm{RF}}^2\; - \; U_0^2)}$$

In practice a more detailed model is used. Three measurements have been made in 1998/9 above 80 GeV and these give E_{QS}-E_{NMR} = -9 MeV, with an rms of 11 MeV; again confirming the NMR method. More measurements are being performed in 2000 to gain statistics and measure the effective LEP bending radius ρ.

4 Beam energy from event data

Since the Z boson mass is well known a study of $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$ events, in which there is an ISR photon such that the $\mathrm{f\bar{f}}$ system 'returns' to the Z, can be used to estimate $\mathrm{E_b}$. A new study by DELPHI using $\mu^+\mu^-$ events [3] gives E_{data}-E_{NMR} = 80 $\pm$ 101(stat) $\pm$ 58(syst) MeV. An earlier study using $\mathrm{q\bar{q}}$ events by ALEPH [4] gives E_{data}-E_{NMR} = -15 $\pm$ 95(stat) $\pm$ 40(syst). The average is E_{data}-E_{NMR} = 27 $\pm$ 77 MeV; again in good agreement with the NMR method.

5 Summary and Outlook

The contribution of the beam energy to the uncertainty on m_{W} is $\Delta m_{\mathrm{W}} \simeq$ 17 MeV. The final step is to complete and fully analyse the direct measurements from the Spectrometer and Q_s v V_{RF}.

References

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