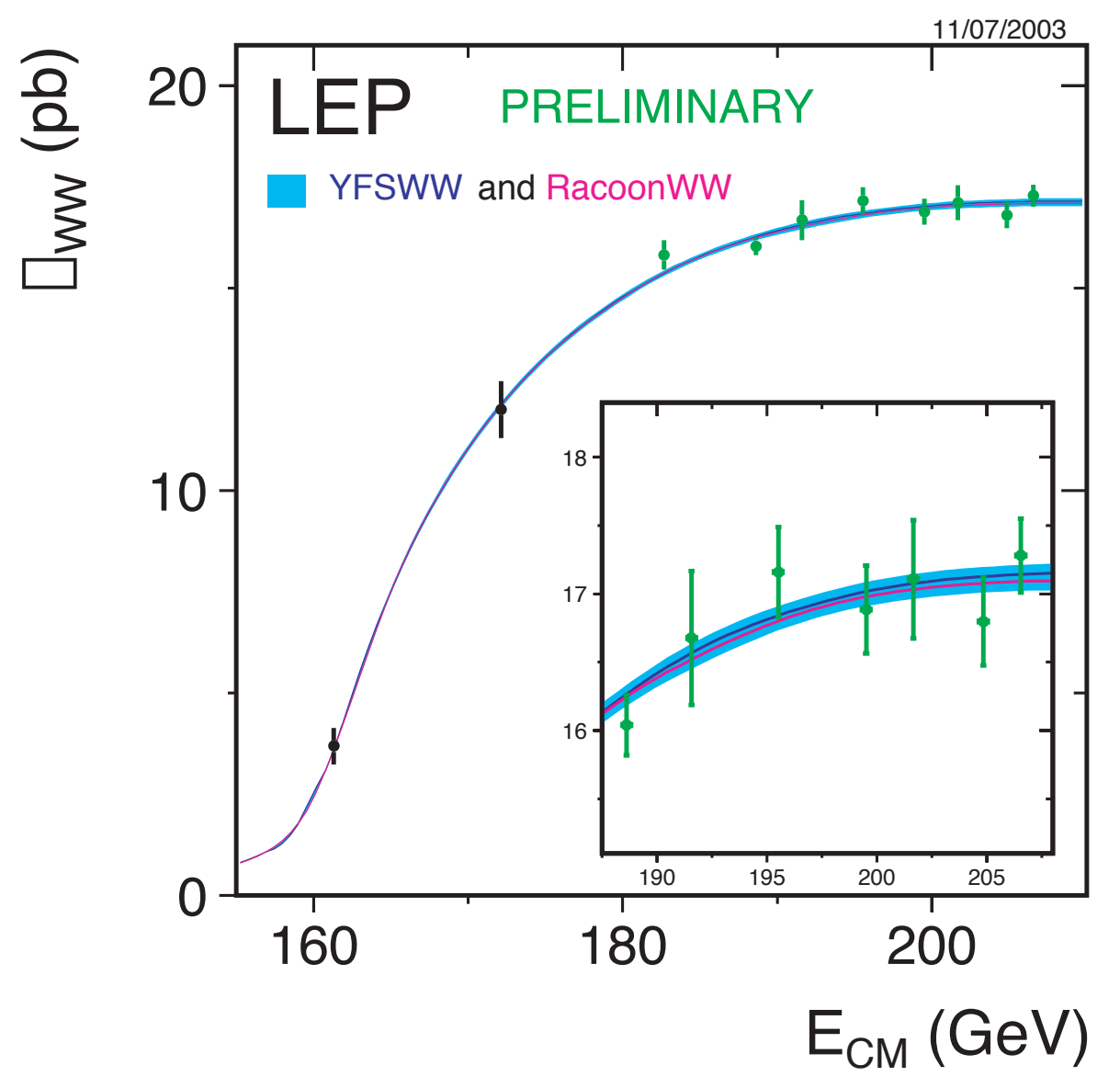
The LEP II Beam Energy Measurement

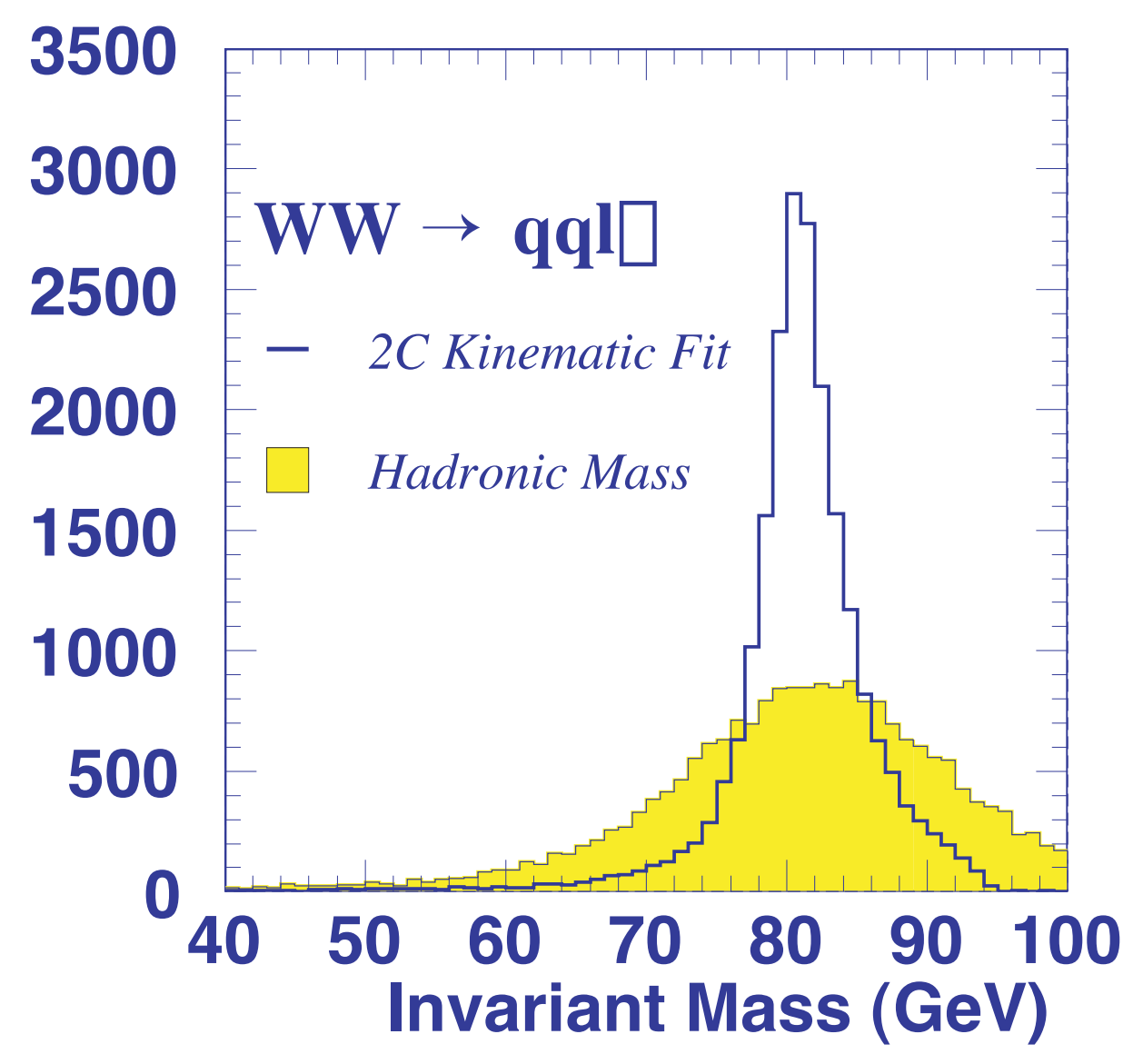
LEP Energy Working Group

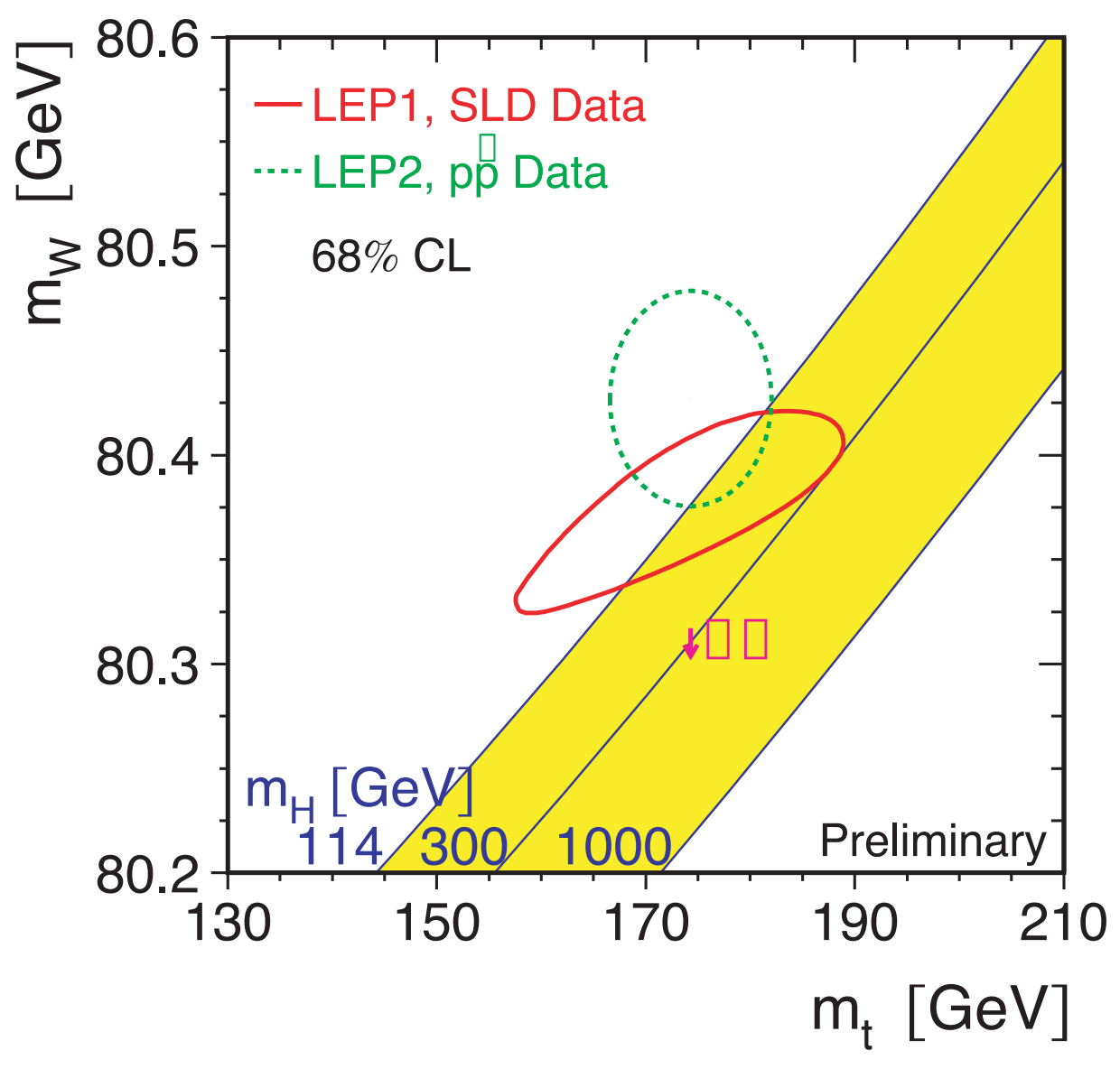
LEP II Electroweak

From 1996 to 2000, the LEP accelerator at CERN ran above the pair-production threshold for W bosons. A key part of the LEP II electroweak physics program was to make precise measurements of W boson properites including the production cross section (shown to the right), decay branching fractions, and the W boson mass. As shown bottom right, precise knowledge of the W boson mass is a critical input in testing the consistency of the Standard Model, and provides important data for predicting the Higgs boson mass.

Production in e^+e^- collisions allows the initial-state beam energy to be used as a kinematic constraint in the analysis of WW events, which improves the resolution on the W mass over the raw invariant mass reconstructed in the detectors by about a factor of 5 per event as shown below. The beam energy, however, ends up setting the overall energy scale for the W mass measurement, and the uncertainty on the beam energy is a common error shared by all four LEP experiments. To match the experimental precision expected from the experiements, the beam energy at LEP II must be determined to about 10 MeV, or 100 parts per million (ppm).







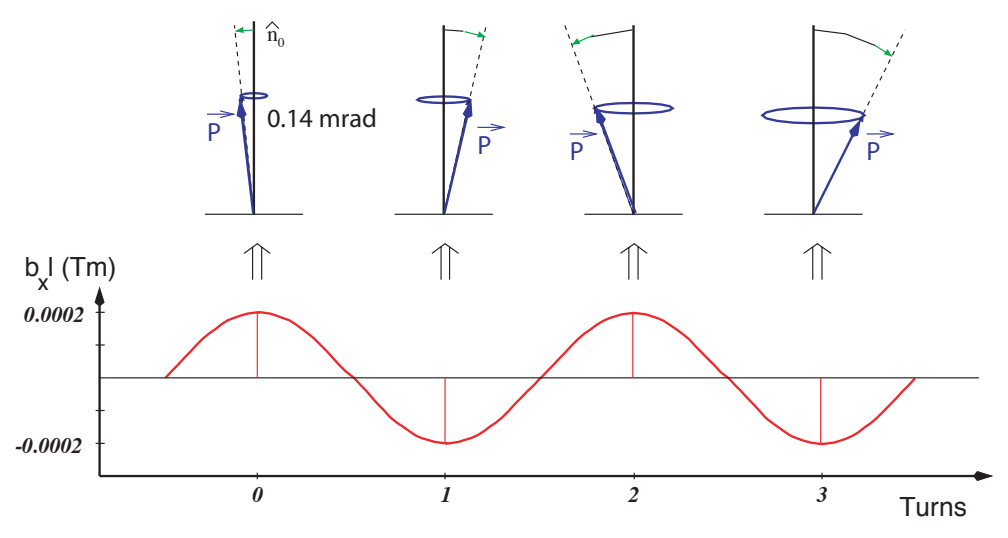
LEP Energy Model

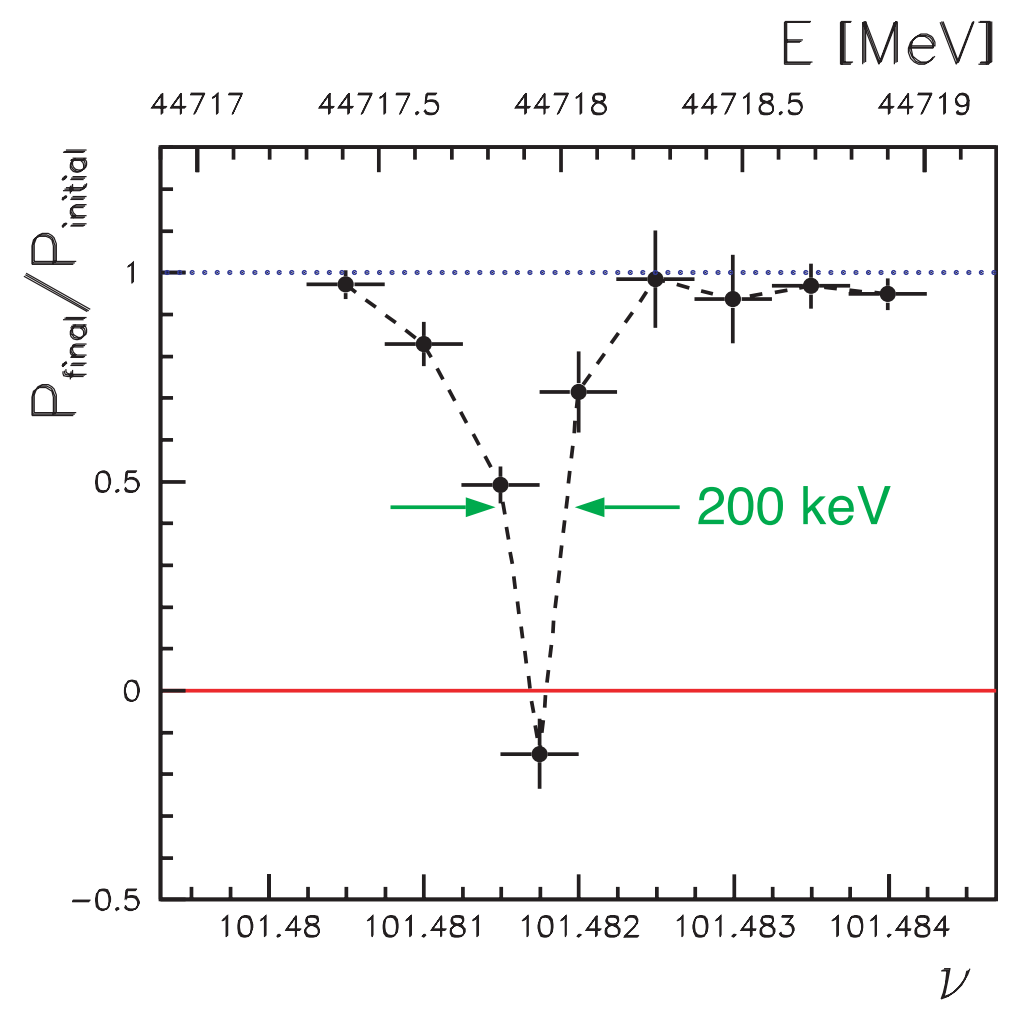
Resonant Depolarization

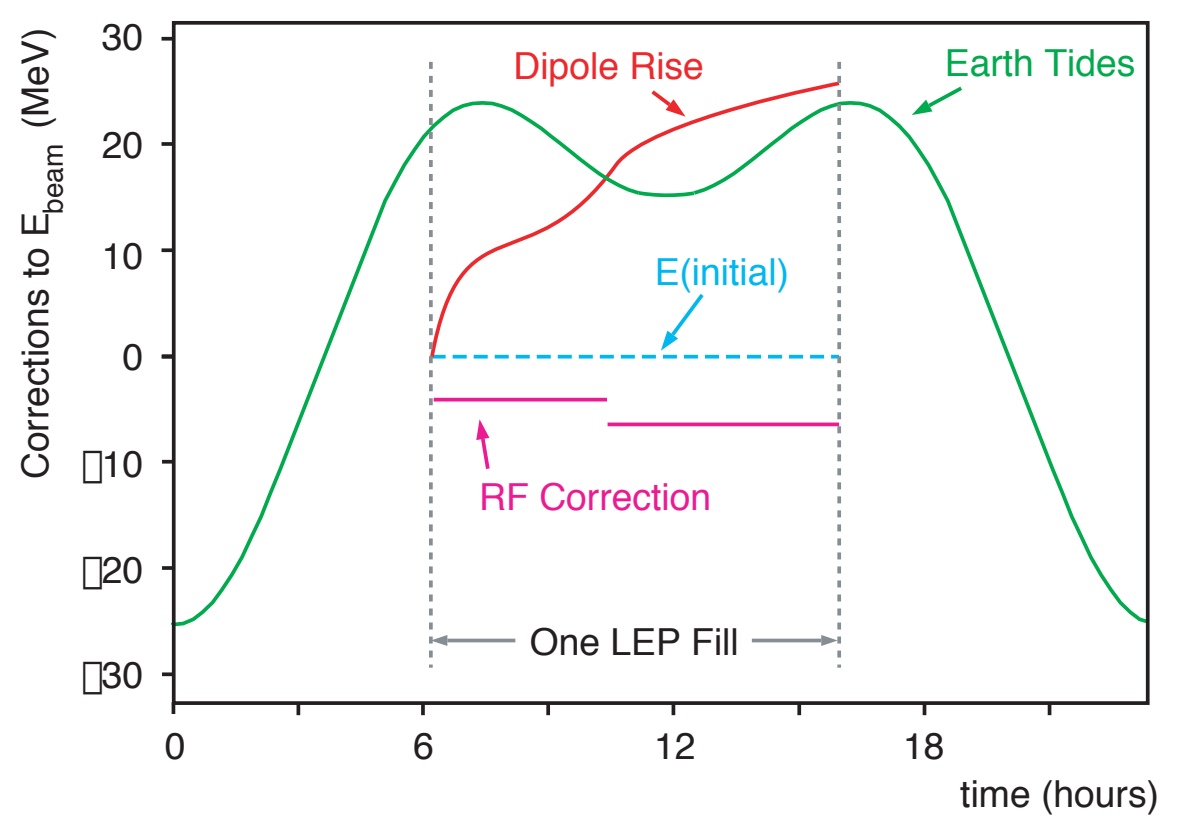
The energy of the beams in LEP can be measured extremely precisely by the Resonant Depolarization (RDP) technique. If a polarized electron beam is given a transverse kick at exactly the spin tune, the polarization will be destroyed, as shown in the top figure. Since the spin tune is directly proportional to the beam energy, the frequency which depolarizes the beam is a direct measurement of the average beam energy.

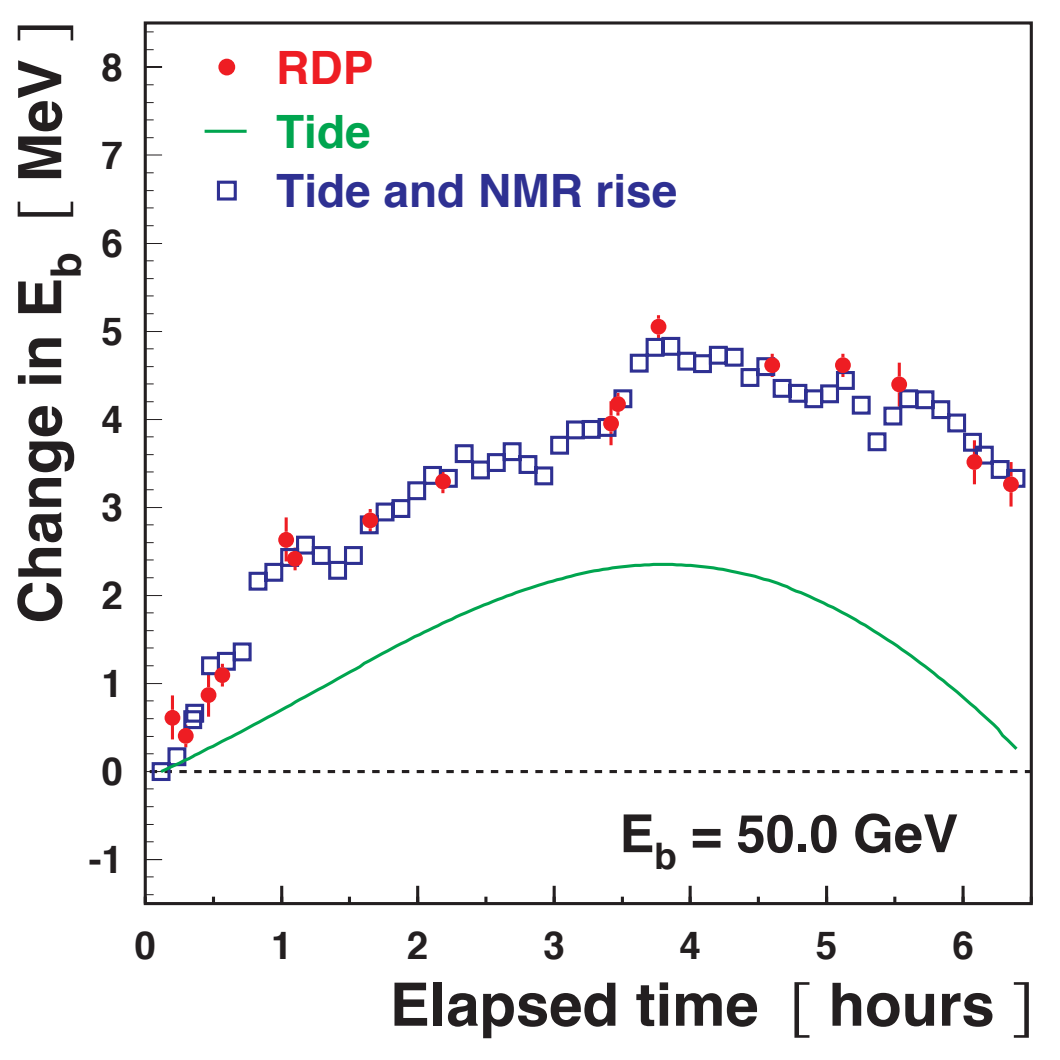
$$\nu_s = \frac{g_e - 2}{2m_e c^2}\langle E_{\text{beam}}\rangle$$

An absolute accuracy of 200 keV is possible, as shown to the right. The resonant depolarization measurements were used to cross-calibrate magnetic field measurements by NMR probes located in the LEP dipoles, relating the measured dipole field to the average beam energy. Under the assumption that the average beam energy is also proportional to the total bending field, the NMRs were in turn used to predict the beam energy corresponding to a pure dipole field at 10-minute intervals during each fill.









Time Dependent Effects

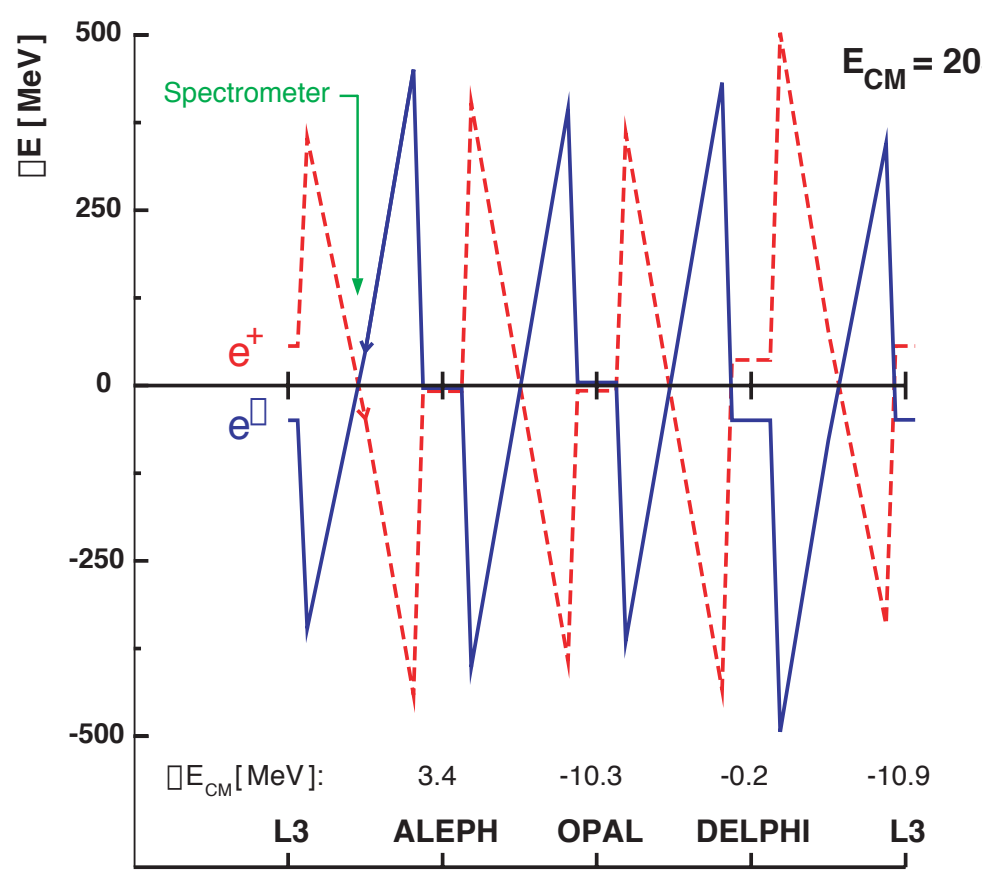
The dipole component of the field must be corrected for several effects that vary with time in a predictable way:

1) tidal distortion of the earth's crust;
2) extra bending field from horizontal corrector magnets;
3) extra bending field from the quadrupole magnets if the orbit frequency is not equal to the central frequency;
4) increasing dipole bending field due to parasitic currents on the beam pipe which modulate the magnets (measured by the NMRs);
5) extra bending field from cables supplying the quadropole magnets in the LEP tunnel;
6) variation in the beam energy at the interaction point from the Radio Frequency acceleration cavities;
7) modifcation of the beam energy due to opposite sign vertical dispersion at the collision point.

A diagram giving the approximate magnitude of these corrections is shown to the left, as is a long experiment comparing the beam energy measured by RDP with the LEP energy model. The component due to the earth tides is shown by the solid curve, demonstrating the size of the other corrections.

RF Sawtooth

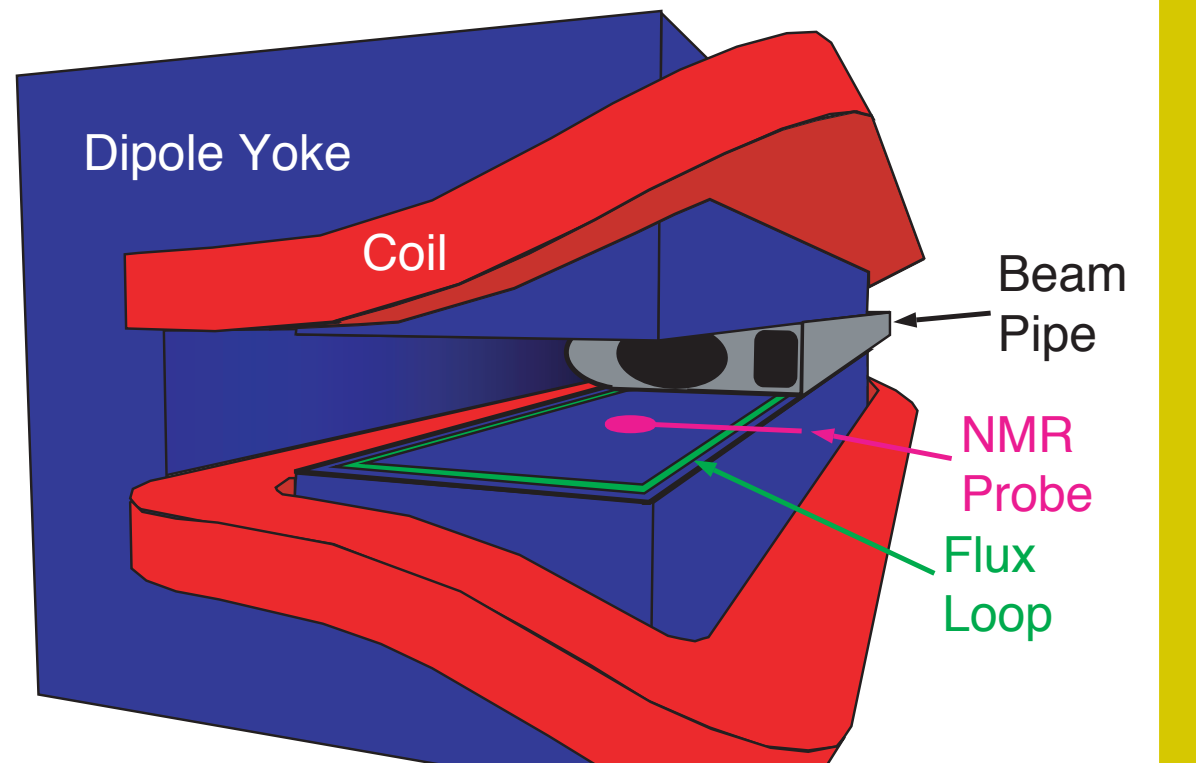
At 100 GeV, the LEP beams lose almost 3% of their energy to synchrotron radiation on each turn around the machine. This energy is replenished by superconducting RF cavities installed in the straight sections on either side of the four LEP detectors. The beam energy as a function of ring position, shown to the right, exhibits a characteristic "sawtooth" shape as the energy is lost through the arcs then restored in two steps by the RF cavities on either side of each interaction point.



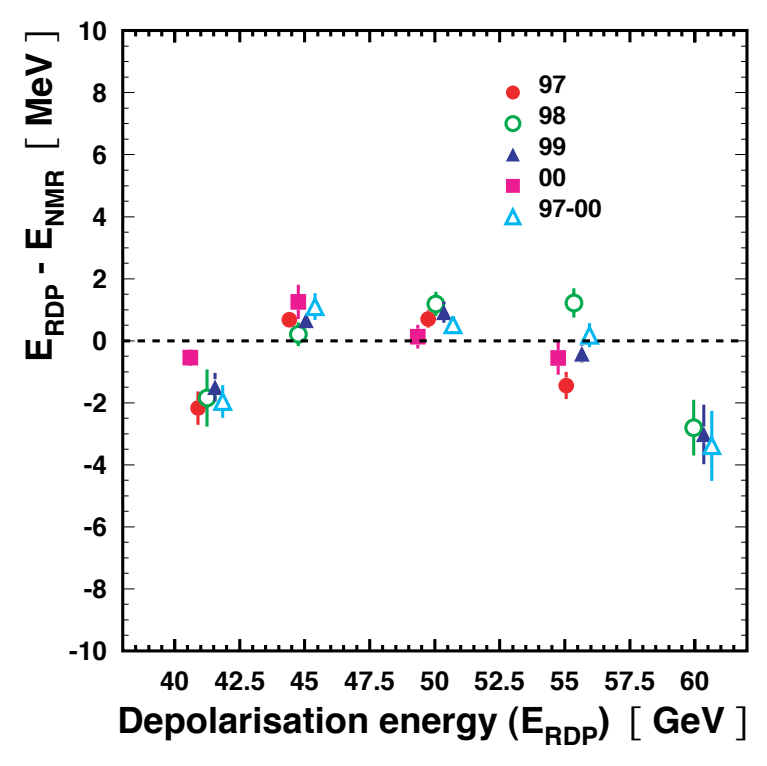
Magnetic Extrapolation

Instrumentation

RDP only works in LEP for beam energies up to about 60 GeV. Because LEP is a storage ring, any measure of the total bending field will also give a measure of the beam energy. In 1996, 16 NMR probes were installed in dipole magnets around the LEP ring to provide a high precision measurement (1 ppm intrinsic resolution) of the total bending field. The NMRs only sample a small fraction of the total field, however, and a second device known as the Flux Loop (FL) is used to verify the NMR prediction. The FL system encloses 96.5% of the LEP bending field and is installed in all standard LEP dipoles. The voltage induced in the FL as the magnets are ramped allows a measure of the field to 100 ppm.



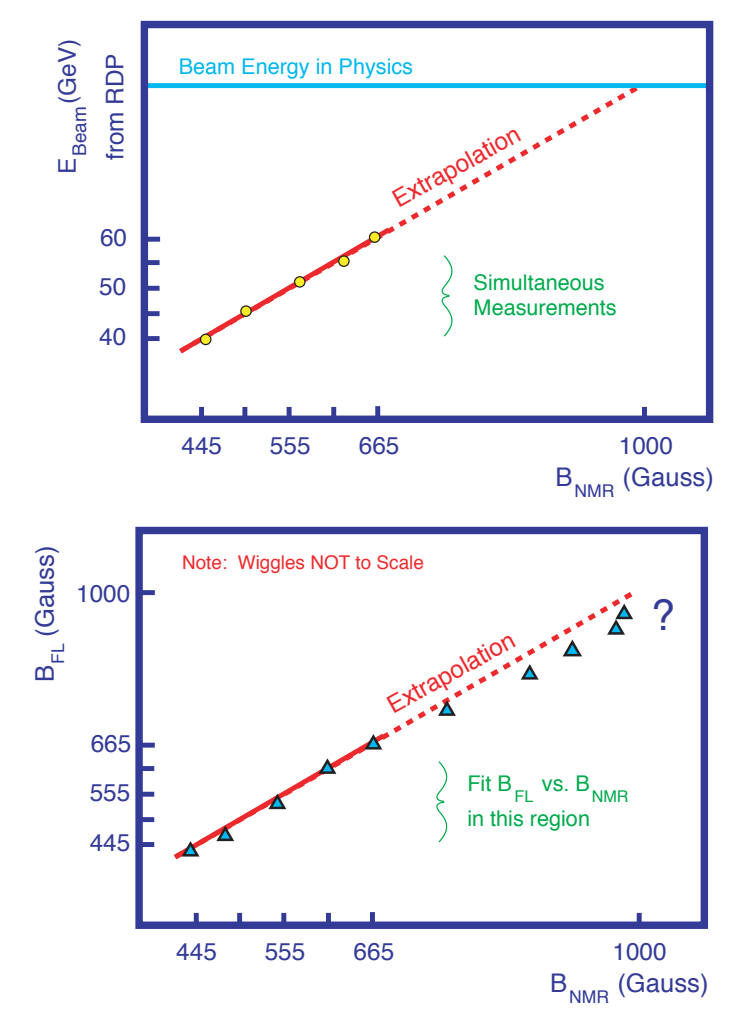
NMR Calibration

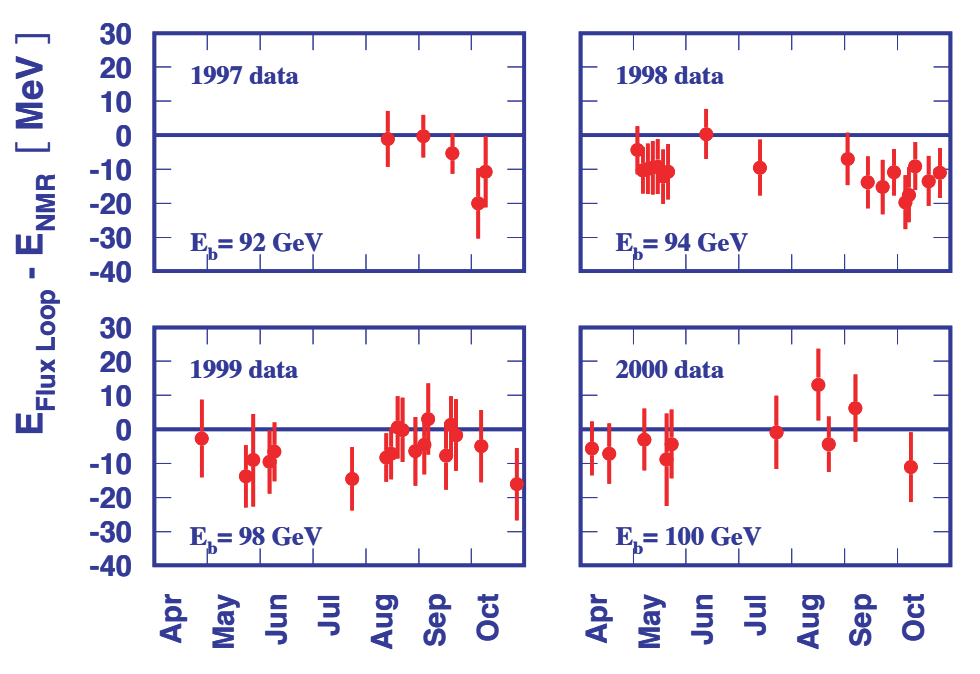


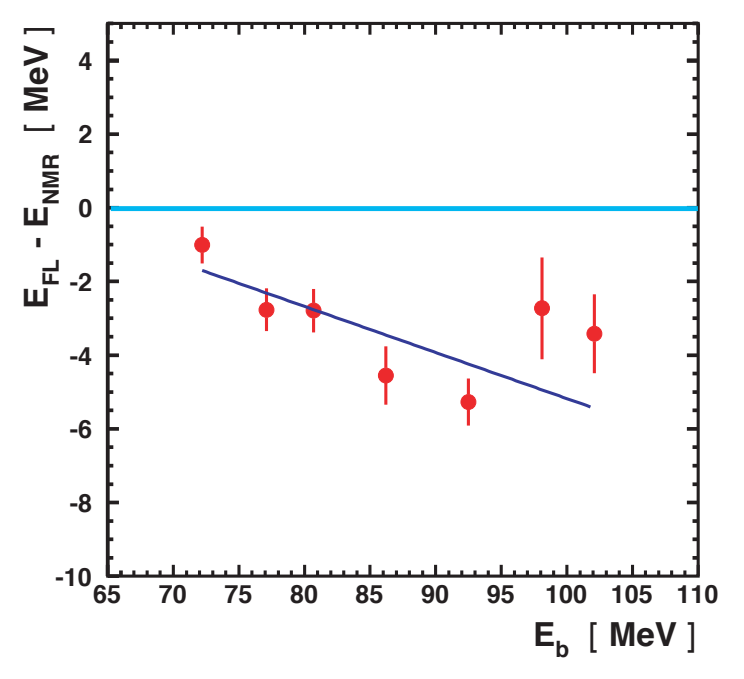
The 16 NMR probes are calibrated against RDP at low energy using a linear relation between NMR reading and beam energy. A plot of the residuals between the beam energies measured by RDP and those predicted by the NMR probes for several years of LEP running is shown to the left. Note the impressive reproducibility. The RMS of the probe predictions at Physics energies is 11 MeV at a beam energy of 100 GeV. Energies determined with NMR coefficients from other years of LEP running shift the average energy by less than 3 MeV.

Extrapolation Checks

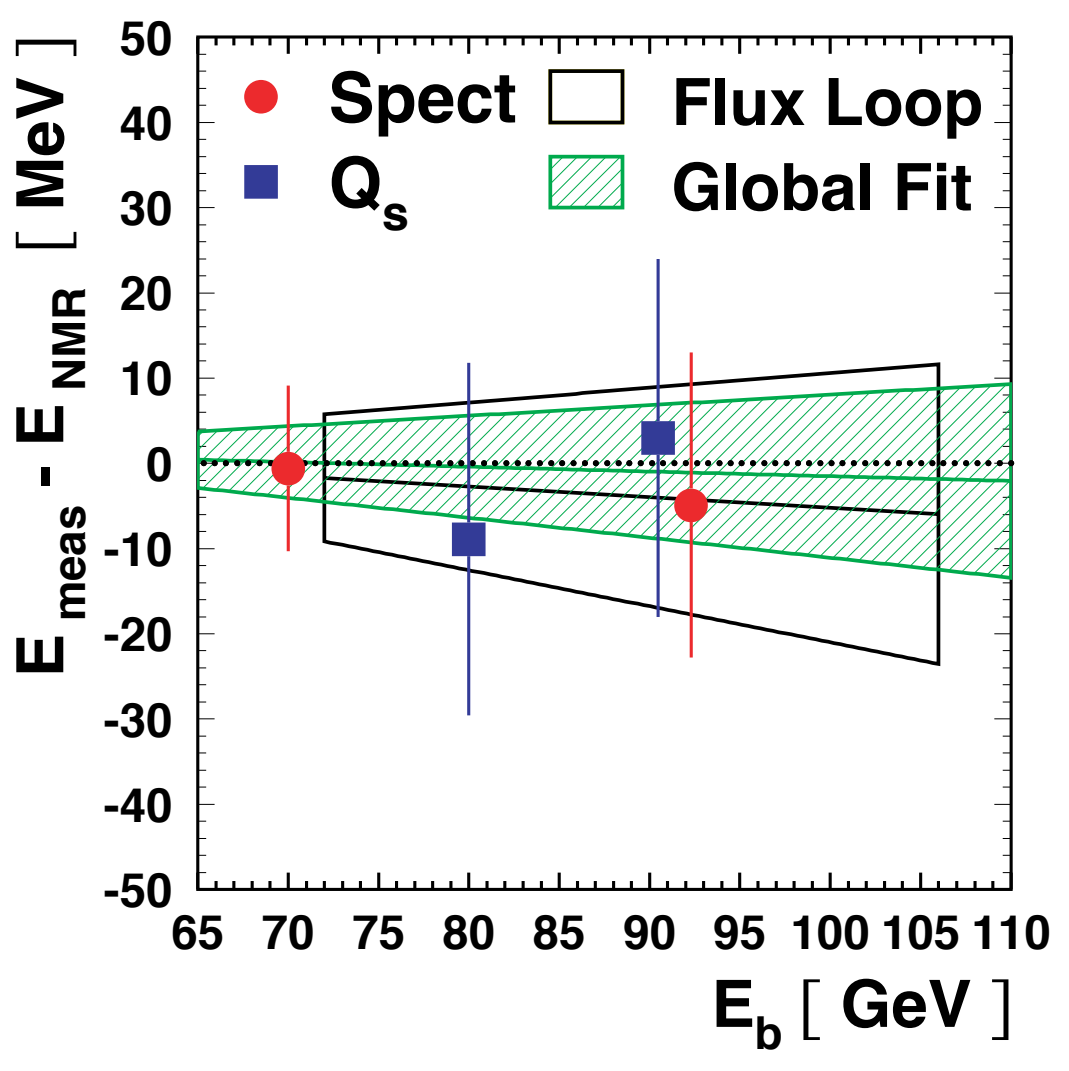
To check that the linear assumption made in calibrating the NMR probes holds to the highest LEP energies, an equivalent calibration is made against the field measured by the FL. As shown to the right, this calibration is done in the same field range where RDP is available, and then the NMR and FL fields are compared at the values used in Physics running. The discrepancy between the NMR and FL fields is shown below as a function of time. Averaged over all high energy data, this descrepancy is approximately 4 MeV as shown below right.







Final Results



Extrapolation Consistency

The three methods for checking the magnetic extrapolation, the Flux Loop, the Spectrometer, and the Qs analysis, all give consistent results at high energy as shown to the left. The final uncertainty on the NMR-based energy model extrapolation at high energy is determined from a global fit to this data, and is more precise than the uncertainty from any one method alone.

Final Uncertainties

The final uncertainty on the LEP beam energy, shown to the right, is dominated by the uncertainty on the NMR-based energy model, but other uncertainties also contribute, most notably the uncertainty on the RF sawtooth. Bend field spreading (BFS) was a technique employed in 2000 to distribute the dipole bending field around the ring by powering corrector magnets as bending dipoles and increase the total beam energy. Since this field is outside of the region sampled by the FL, there is a large uncertainty associated with this data.

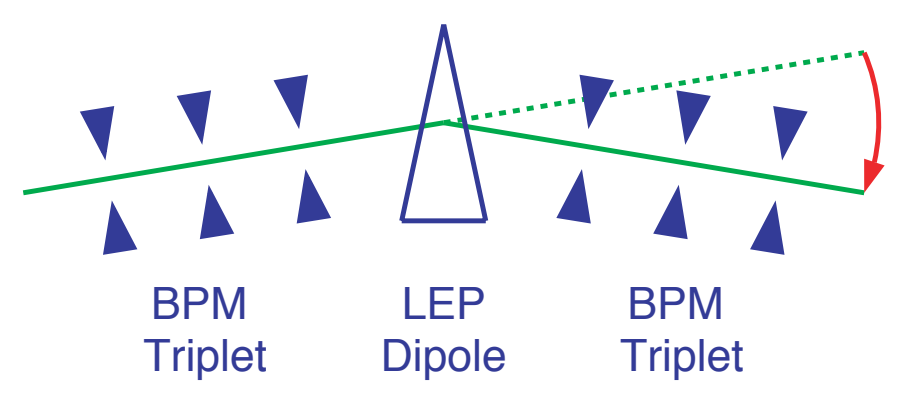
Uncertainties (in MeV) for selected LEP II collision energies

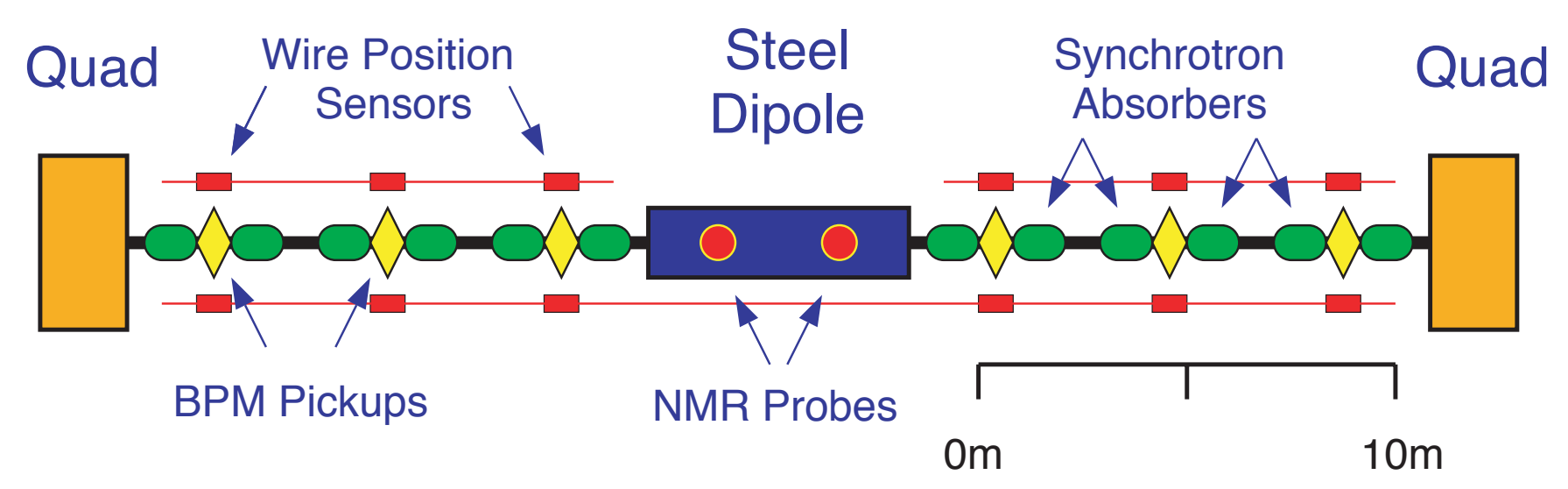
CM Energy [GeV]	189	200	207
NMR Model	9	10	10
RF Sawtooth	4	5	5
Correctors (BFS)	2	0	17
Cent. Freq.	3	3	0
e^+e^- diff.	2	2	2
Dispersion	1	1	1
Other	2	2	1
Total [MeV]	11	12	21

LEP Spectrometer

A project was initiated in 1997 to install an in-line energy spectrometer into the LEP ring with the goal of making a 100 ppm measurement of the LEP energy scale. The concept is simple, as shown to the right. With a pair of BPM triplets, the bend angle through a precision-mapped dipole can be measured which gives a direct measure of the beam energy:

$$\Delta\Theta = \frac{1}{E_{\text{beam}}}\int B\cdot dl$$

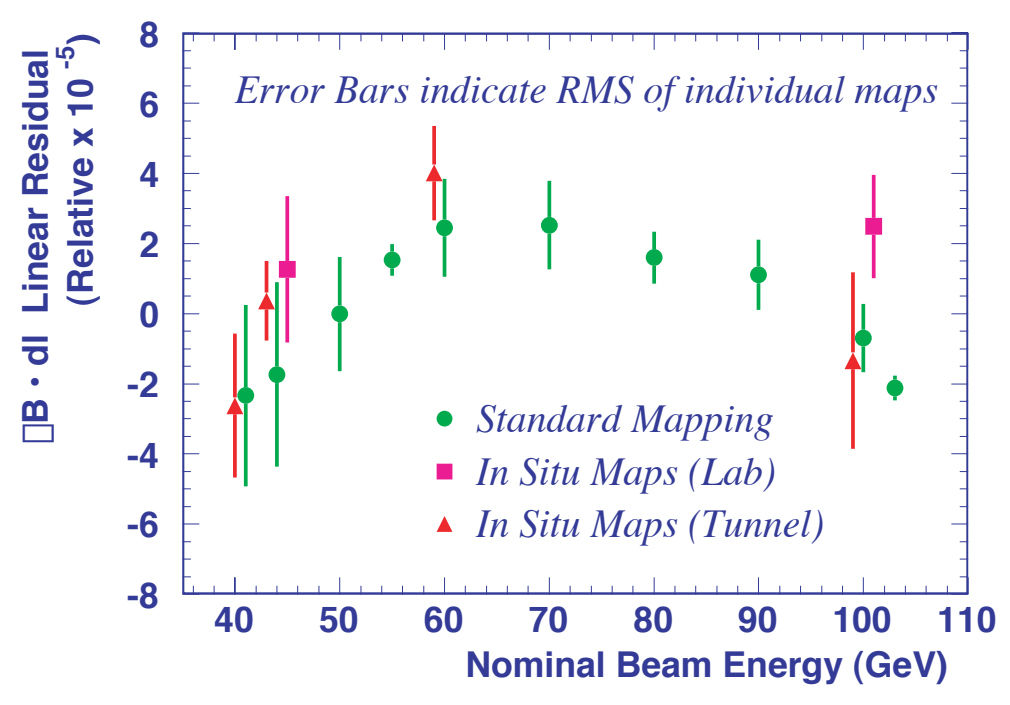


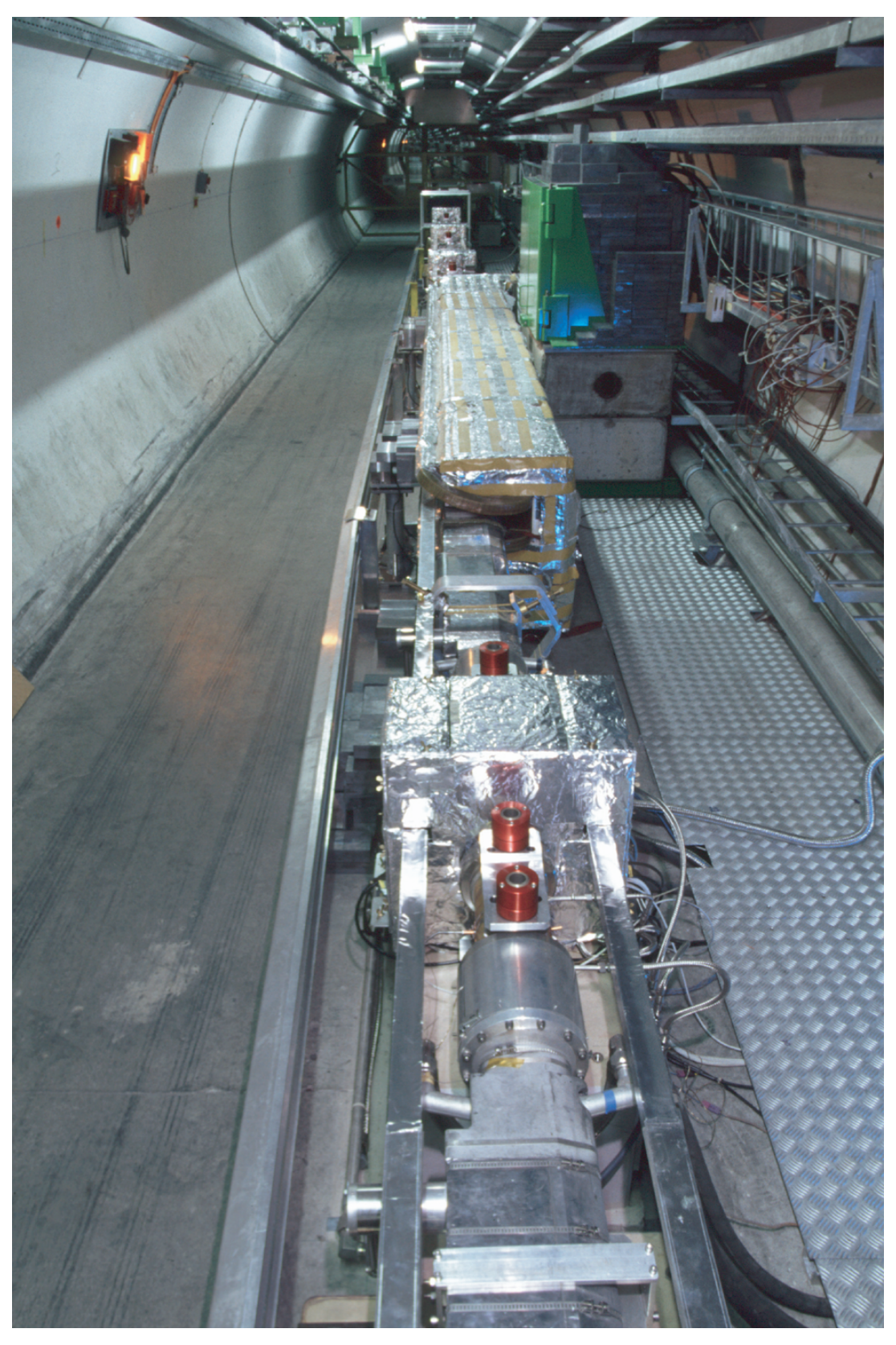


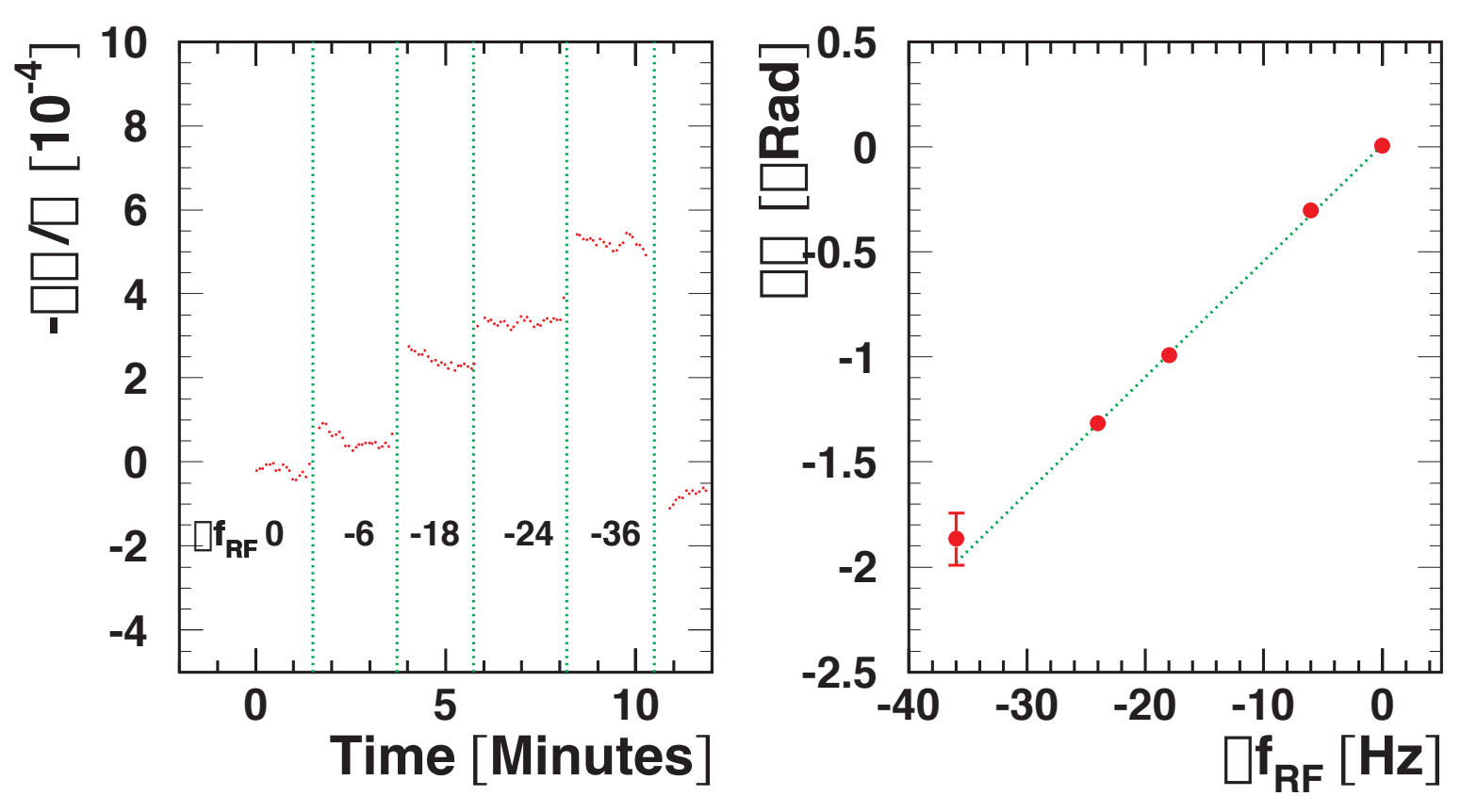
With a 3.8 mRad bend angle and 10 m lever arm, a precision and stability of about 1 micron is required from each BPM. Special synchrotron absorbers were installed to shadow the BPM blocks from the intense radiation produced by the LEP beam, and independent cooling circuits were employed to stabilize the BPMs to 0.1 degree C. Capacitive wire position sensors with an intrinsic resolution of ~200 nm are used to monitor the stability of the system. The spectrometer is calibrated using RDP data at lower energy, and then immediately used to check the energy scale at physics energy compared to the NMR model.

Magnetic Mapping

To achieve 100 ppm precision, the total bending field is determined by a set of four NMR probes installed locally in the spectrometer dipole which have been calibrated over the period of several months during a magnetic mapping campaign. A temperature dependent model of the total bending field as a function of NMR value describes the true bending field to better than 50 ppm. In situ measurements made with a special probe after dipole installation also agree well.







RF Frequency Changes

The LEP beam energy changes by a well understood amount with changes in the RF frequency. This fact is exploited to calibrate the sensitivity of the spectrometer to changes in beam energy. As shown above, 6 Hz changes in the RF frequency produce roughly 100 ppm changes in beam energy, or 10 MeV at 100 GeV.

Synchrotron Tune

The synchrotron tune (Qs) is related to the beam energy (Eb) by the following expression:

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

where V_{RF} is the total RF voltage and U_0 is the energy loss per turn due to synchrotron radiation in the dipole bending field. In principle, fitting this expression to a measurement of Qs as a function of RF voltage can yield the beam energy. However, this expression must be refined to include other corrections such as the energy lost in quadropoles and corrector magnets, a realistic distribution of RF cavities around the LEP ring, phasing errors in the RF system, and parasitic mode losses.

The corrected expression which is fit to the data is:

$$Q_s^4 = \left(\frac{\alpha_c h}{2\pi}\right)^2\left\{\frac{e^2g^2V_{RF}^2}{E_c^2} + Mg^4V_{RF}^4 - \frac{1}{E_c^2}\left(\frac{C_\gamma}{\rho}E^4 + K\right)^2\right\}$$

Momentum Compaction — RF Voltage Calibration — Realistic RF Distribution — Dipole Losses — Other Losses

The behavior of Qs versus energy was obtained by first measuring the Qs at lower energies to determine the absolute scale of the RF voltage by using the NMR energy measurement to determine the beam energy. Then, the beams were ramped to higher energies, and the RF voltage stepped through the maximum range allowed by beam stability, with the Qs measured at each voltage point. This is shown in the figure to the right, where the Qs versus RF Voltage curves are shown for several energies. From 1998-2000, 6 fills were used to measure the energy using this technique, with other experiments to constrain various energy-loss effects.