Determination of Centre-of-mass Energy at LEP1 and LEP2

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Vanderbilt University

Paul Bright-Thomas, CERN
(for LEP Energy Working Group)

- Why is LEP Energy important ?
- Energy Calibration
- LEP Energy Model
- LEP1 Energy Determination (1993-95)
- LEP2 Energy Determination (1996–)
- Summary and Prospects

LEP Energy working group

This talk represents the work of the members of the LEP energy working group:

A. Blondel, G. Bobbink, M .Boege, E. Bravin,
P. Bright-Thomas, T. Camporesi, C. Cecchi,
B. Dehning, A .Drees, G .Duckeck, M. Geitz,
K. Henrichsen, M. Hildreth, M. Koratzinos,
E. Lançon, G. Mugnai, J. Mnich, A. Muller,
E. Peschardt, M. Placidi, P. Puzo, G. Quast,
P. Renton, H. Wachsmuth, A. Weber, P. Wells,
J. Wenninger, G. Wilkinson, J. Yamartino, K. Yip

The Energy Working Group would like to thank

CERN SL Division
LEP operations crews

for the construction and operation of the LEP machine, and the successful startup of LEP2.

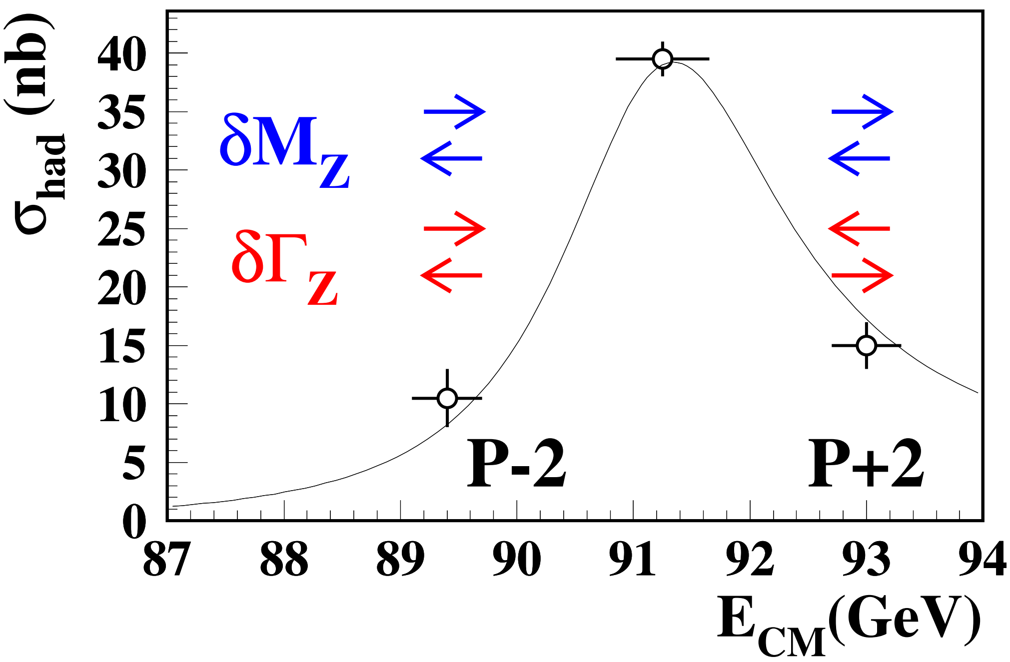
LEP basics

- LEP is $\mathrm{e^+e^-}$ collider at CERN, Geneva
- 27 km storage ring, ~ 100 m underground
- ~ 3000 bending dipoles — plus (de)focusing quadrupoles, RF acceleration etc.
- Peak luminosity $\simeq 4 \cdot 10^{31}\,\mathrm{cm^{-2}\,s^{-1}}$
- 4 experiments: ALEPH, DELPHI, L3, OPAL
- LEP1 – 1989-95: $4 \times 4 \cdot 10^6\,Z^0$
- LEP2 – 1996→: $E_{cm} = 161, 172, 184, 192\,\mathrm{GeV}$

Physics motivations

LEP1

- Precision measurement of Z^0 resonance
- $\Rightarrow Z^0$ mass, M_Z, and decay width, Γ_Z.
- High-precision scans of resonance in 1993, 1995
- 3 energies: close to M_Z ("Peak")
  $\pm 1760\,\mathrm{MeV}$ ("P-2" and "P+2")



- Huge statistics $\Rightarrow$experimental precision now $\delta M_Z = 1.9\,\mathrm{MeV}$ and $\delta\Gamma_Z = 2.6\,\mathrm{MeV}$
- Sets scale for energy uncertainty: $\sigma(E_{beam}) \leq 1\,\mathrm{MeV}$
- $\Rightarrow$ Relative precision of $2 \cdot 10^{-5}$ — challenging.

LEP2

- Precision measurement of W mass, M_W
- In 1996, M_W measured from threshold cross-section at $E_{cm} = 161\,\mathrm{GeV}$
- In 1996, M_W also measured by direct reconstruction of W decays at $E_{cm} = 172\,\mathrm{GeV}$
- From $10\,\mathrm{pb}^{-1}$ each energy, joint LEP precision: $\delta M_W \simeq \pm 150\,\mathrm{MeV}$
- $\Rightarrow \sigma(E_{beam}) \sim 50\,\mathrm{MeV}$ sufficient for 1996
- LEP2 goal: $\sim 500\,\mathrm{pb}^{-1}$ per experiment
- Ultimately $\delta M_W \simeq \pm 30 - 40\,\mathrm{MeV}$
- $\Rightarrow \sigma(E_{beam}) \sim 15\,\mathrm{MeV}$ required — demanding

Energy stability

- Average energy set by integral magnetic field:
  $E^{av} \propto \oint B\, dl$
- LEP beam path length fixed by RF frequency:
  $\oint\, dl \propto f_{RF}$
- Best tool is resonant depolarization of e^- beam
- Measures instantaneous E^{av} over LEP
- precision: $\sigma(E_{beam}) \simeq 200\,\mathrm{keV}$
- Not in physics conditions
- Most P+2/P-2 fills calibrated end-of-fill (EOF)
  Few also beginning-of-fill (BOF)
- 1995 calibrations: RMS spread of $\sim 5\,\mathrm{MeV}$
- Long-term depolarization experiments show
  E variation: dE/dt up to $1\,\mathrm{MeV}/\,\mathrm{hr}$
- If ignored, such behaviour makes desired precision impossible

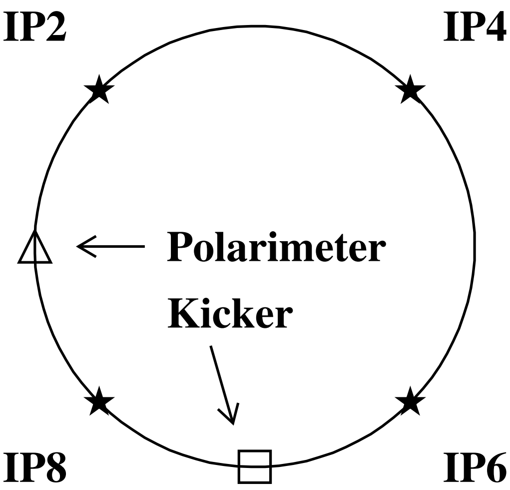
Energy calibration

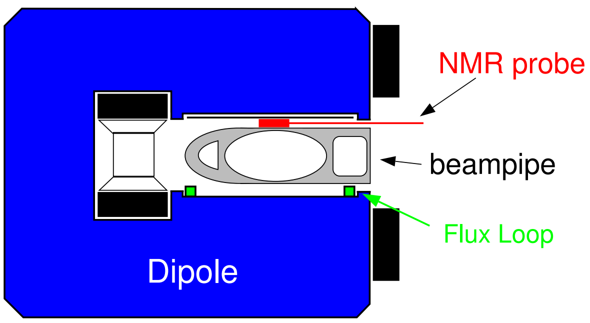
- What is needed:
  - Continuous measurement of E_{cm} at interaction points: $\Rightarrow E^{IP}$
- What is actually possible:
  - Occasional measurement of E^{av}_{beam}
  - Occasional measurement of $\sim \oint B\,dl$
  - Continual measurement of B in few dipoles
  - Calculation of local offsets ΔE^{IP} from E^{av}
- Need energy model to correct time-dependent behaviour and determine IP energies

Instrumentation

Resonant depolarization:

- Natural polarization, $P_{\perp}$
- $E^{av} \propto f$ (spin precession)
- Transverse kicker magnet depolarizes e^+ beam when $f = f_{prec}$
- Detected by polarimeter



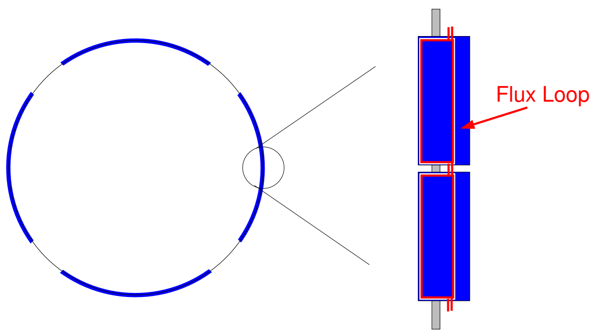


Nuclear magnetic resonance probes:

- NMR's in LEP dipoles
- B measured to 10^{-5}
- Probes in tunnel 1995$\longrightarrow$

Flux loop:

- Loop on each dipole face
- Hysteresis cycle $\Rightarrow$ relative B field
- All dipoles $\Rightarrow \oint B\, dl$



Effects on LEP energy

- Model of time-dependent LEP energy behaviour at each IP
- Includes all effects significant on scale of $1\,\mathrm{MeV}$
- Components of model divided into 3 classes:

	ΔE_{beam}
A. Dipole effects:	
Change dipole $\oint B\,dl$	
Field rise	$\sim 5\,\mathrm{MeV}$
Temperature	$\sim 1\,\mathrm{MeV}$
Correctors	$\sim 1\,\mathrm{MeV}$
B. Quadrupole effects:	
Distort orbit, quadrupole $\oint B\,dl$	
Tides	$\sim 10\,\mathrm{MeV}$
Geological	$\sim 10\,\mathrm{MeV}$
C. IP-specific effects:	
local offsets: $E^{IP} \neq E^{av}$	
RF	$\sim 10\,\mathrm{MeV}$
Dispersion	$\sim 1\,\mathrm{MeV}$

- Above effects incorporated into energy model $\Rightarrow$

Energy model

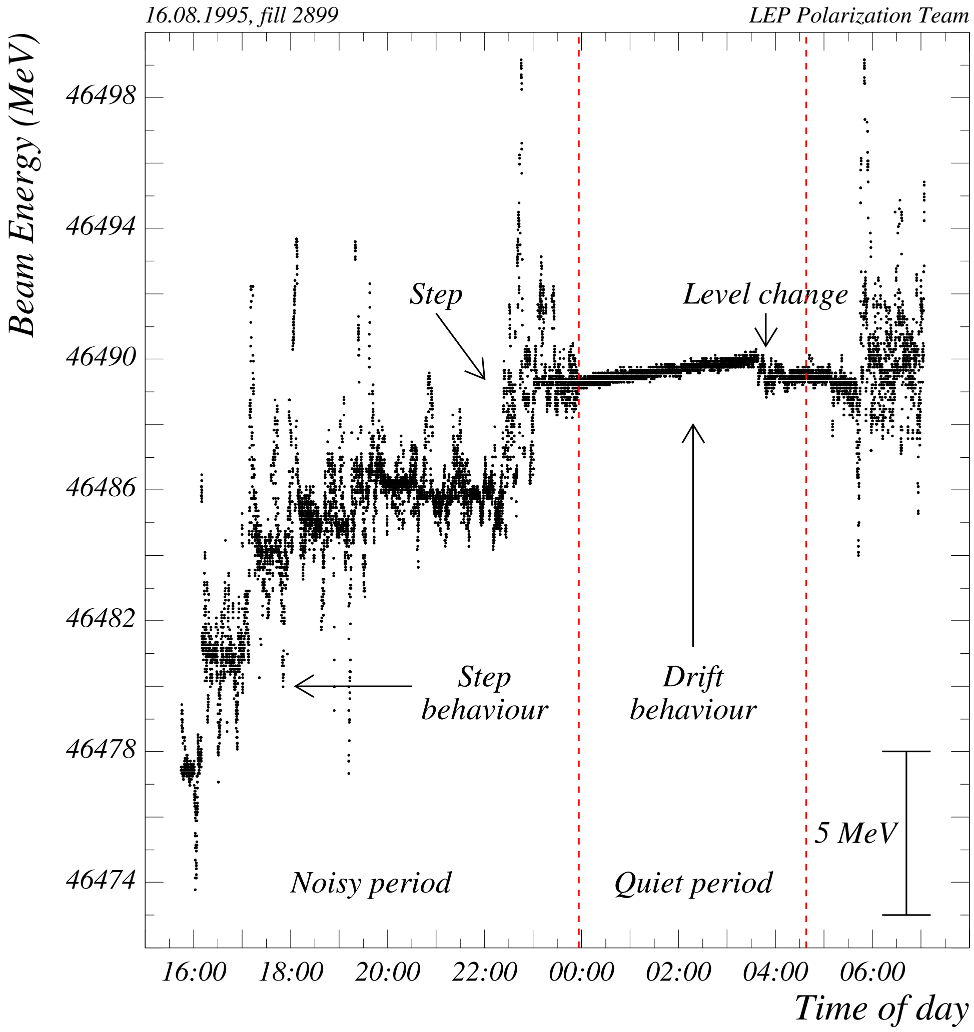
$$\begin{aligned} E_{beam}(t) &= E_{NMR}(t=0) \times A_{norm} \times \\ [1+ & A_{rise}(t_{day}, t_{fill}) + A_{temp}(t) + A_{corr}(t) \\ + & A_{tide}(t) + A_{xarc}(t) \\ + & A_{RF}(t, IP) + A_{disp}(E, IP) \;] \end{aligned}$$

Normalization
Dipole
Orbit
IP-specific
The most important effects now examined in detail

Energy Determination at LEP1

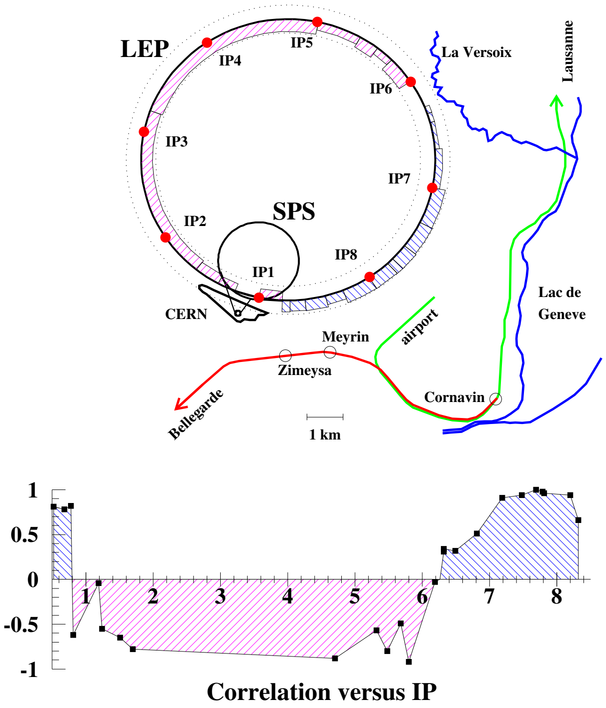
Dipole field rise

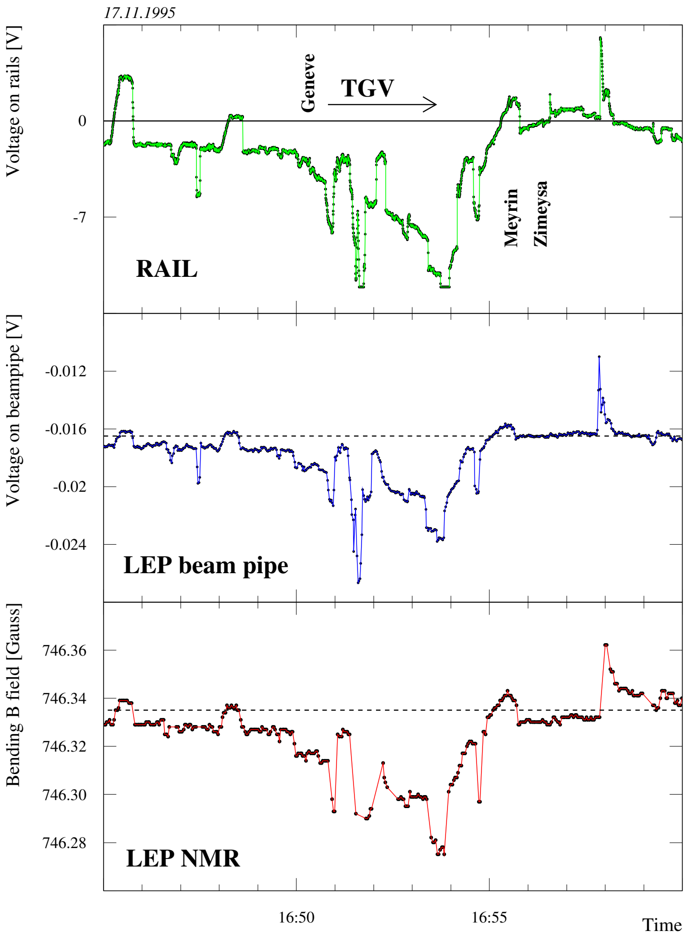
- 1993: long-term polarization experiments showed E^{av} rise over fill
- Rise not tracked by NMRREF:
- 1995: tunnel NMRs installed — NMR4 and NMR8
- Weird behaviour: rise, jumps, spikes, anti-correlated noise, quiet period (00:00–04:00)



Beampipe current

- Parasitic current $(1\mathrm{A})$ found on LEP beampipe: bi-directional, noise consistent with NMR's
- Source identified as leakage current from Genève–Bellegarde railway line $\Rightarrow$ "train effect"





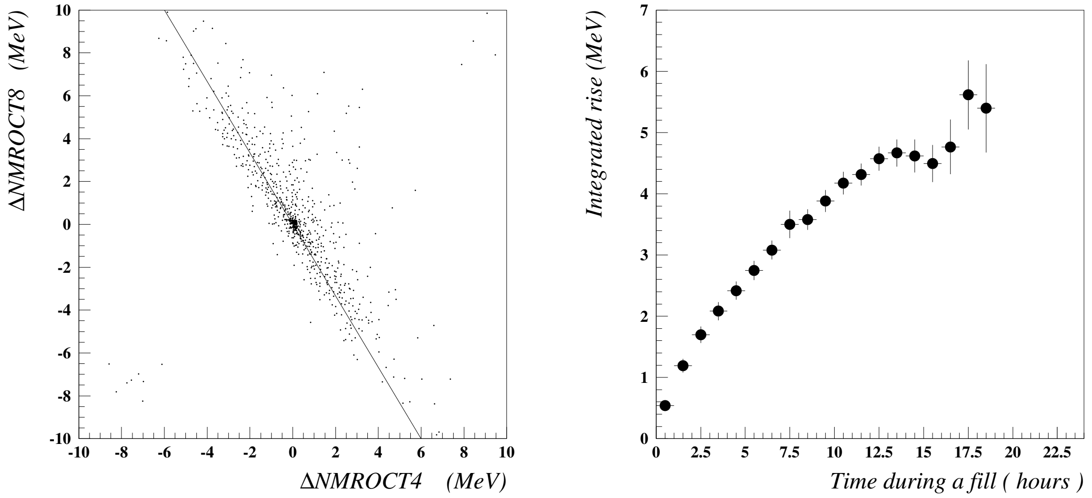
B. Dehning, M. Geitz

Dipole Model: Rise term

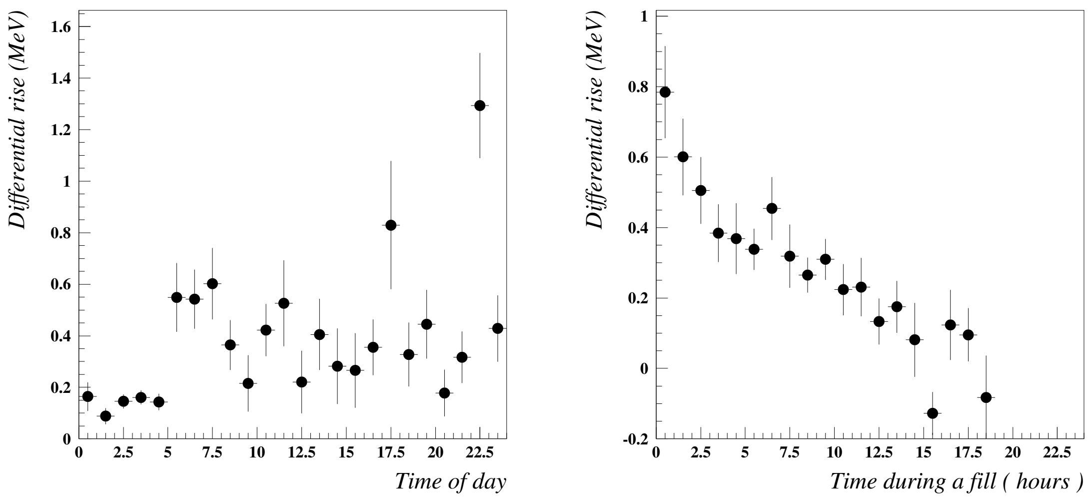
- Composite pseudo-device most representative

$$\mathrm{NMR48} = \tfrac{5}{8}\mathrm{NMR4} + \tfrac{3}{8}\mathrm{NMR8}$$

- Noise $\sim$ cancelled, rise consistent with 1993



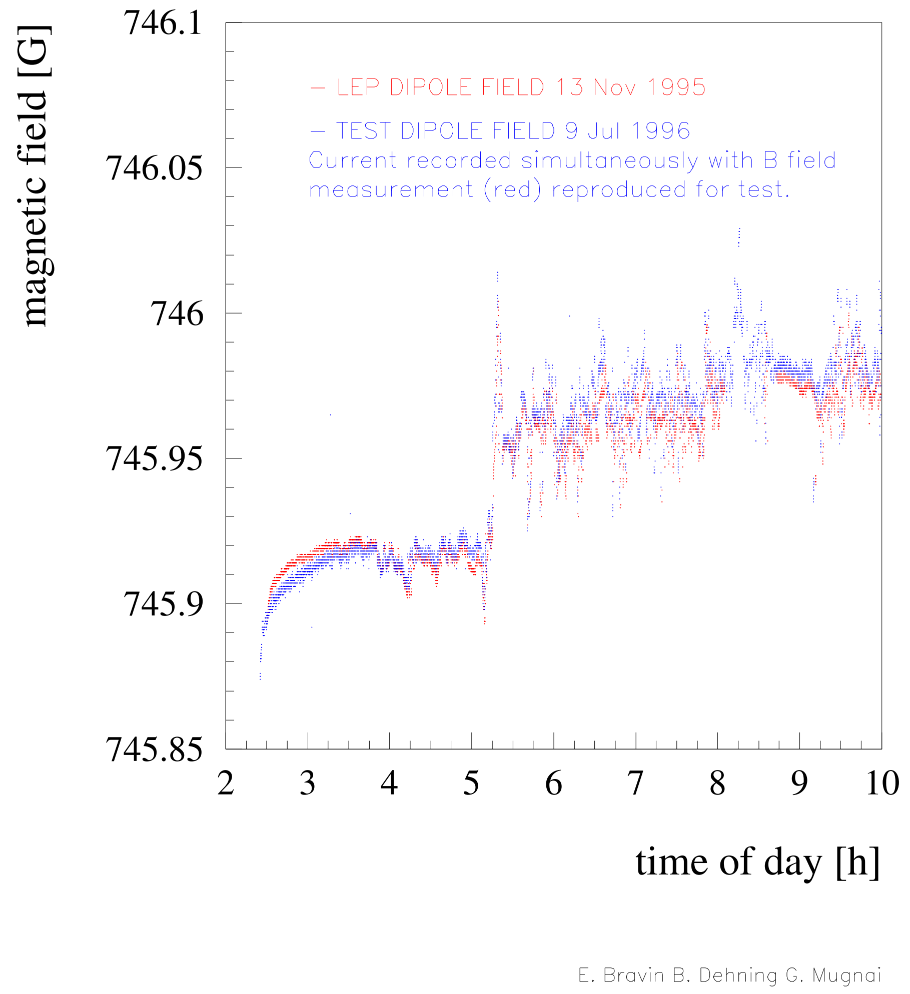
- Phenomenological model based on behaviour with time-of-day and time-into-fill



- "Average behaviour" model — applied to 1993

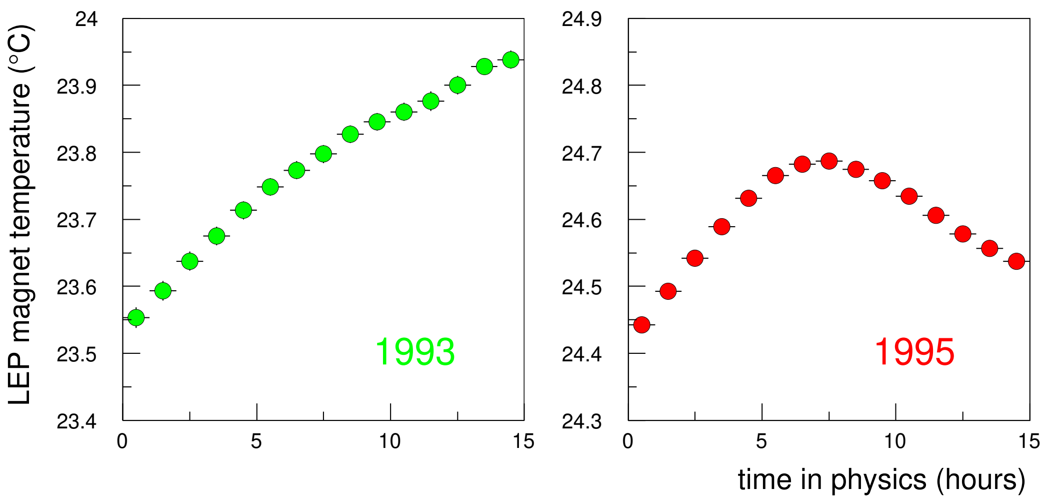
Dipole test bench

- Excitation of dipole hysteresis curve by current spikes/noise $\Rightarrow$ field rise, saturation
- Dipole test bench: magnet, beampipe, NMR
- Recorded current “played back” on beampipe
- Reproduces rise behaviour of tunnel NMR’s



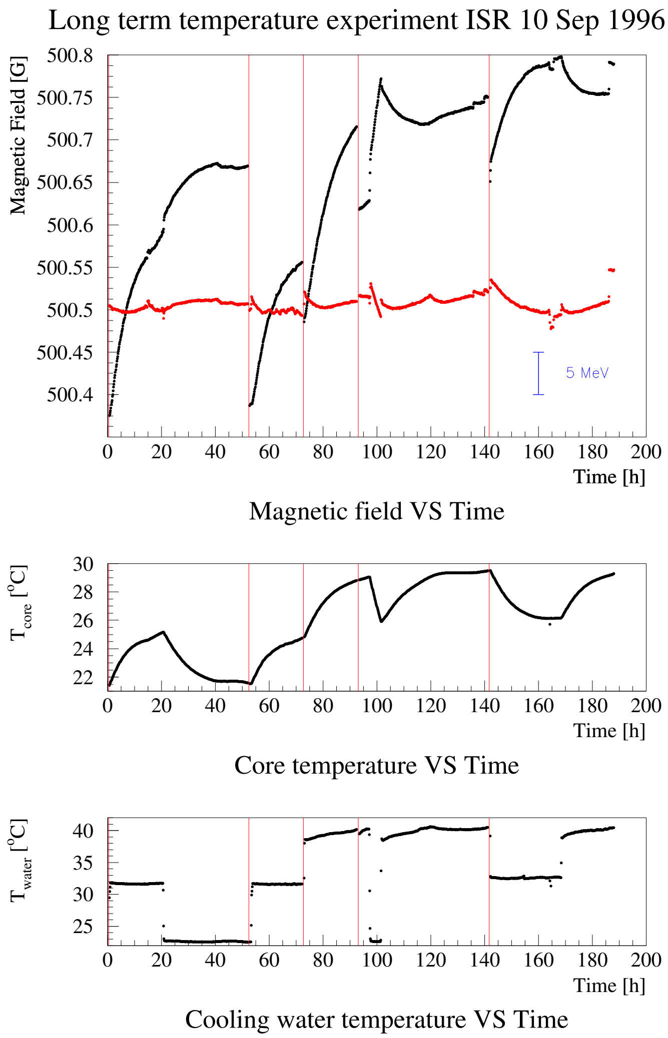
Temperature

- Dipole field dependent on temperature — water cooled
- Train rise and temperature closely linked
- Original model: $\Delta E = 1 \cdot 10^{-4} \Delta T$
- Temperature profiles different in 1993 and 1995



New temperature model

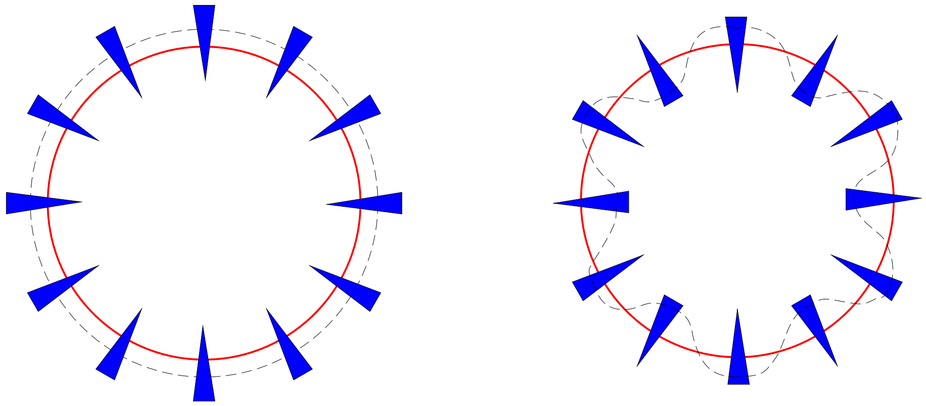
- Test bench shows more complex T behaviour



- $\Rightarrow$ 5-parameter temperature model:
  $\Delta E_T = f(T, T_{max}, T_{min}, T_0, T_{water})$
- Temperature profiles in physics $\Rightarrow$ simpler description:

$$C_{eff} = \begin{cases} C_T + C_{Tmax} & \text{for } dT/dt > 0 \\ C_T & \text{for } dT/dt < 0 \end{cases}$$

Correctors



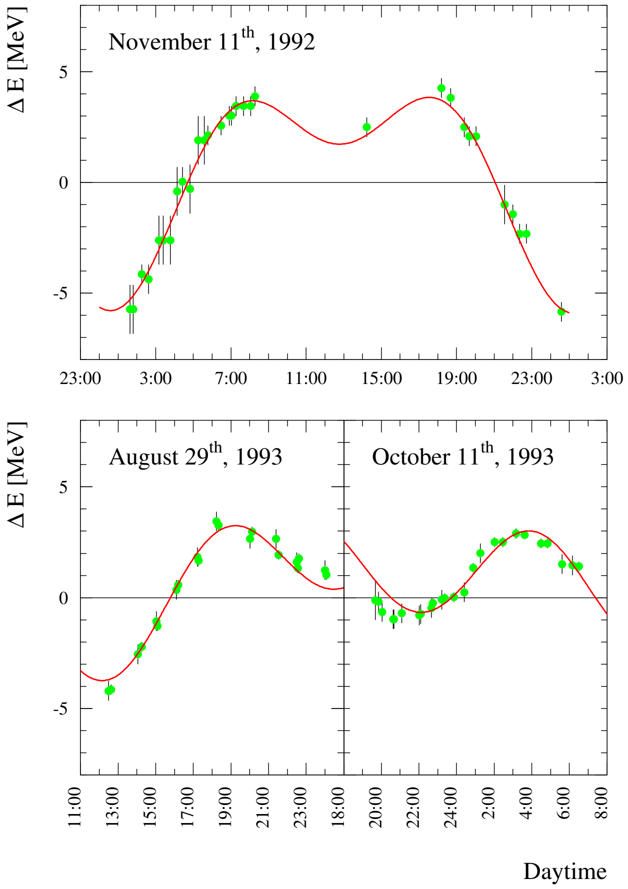
- Orbit correctors improve polarization level
- $\Rightarrow$ differences between calibration and physics
- Horizontal correctors add dipole field
change orbit radius
- Experiments confirmed machine simulation
- $\sigma(\Gamma_Z)$ reduced from $1.1\,\mathrm{MeV}$ to $0.5\,\mathrm{MeV}$

Tides

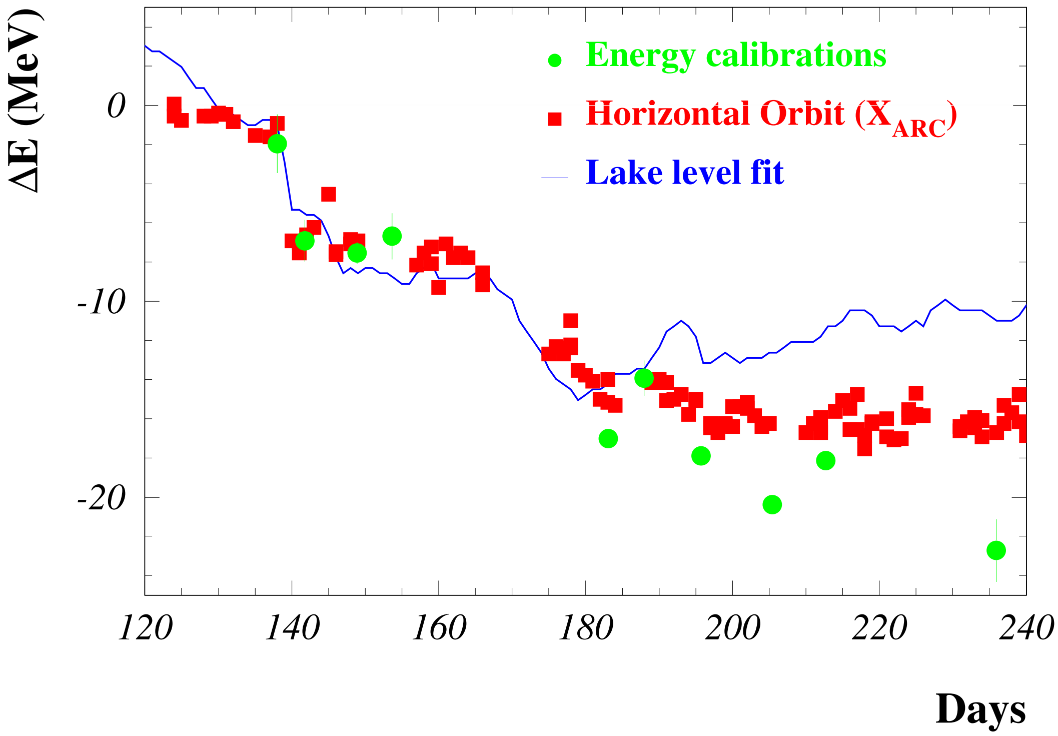
- Earth tides cause local distortions of earth's crust
- $\oint B\,dl$ fixed: LEP ring stretched $\Rightarrow$ off-centre orbit
- Beam sees field component from quadrupoles

$$\frac{\Delta E}{E} \simeq -1 \cdot 10^4 \frac{\Delta C_{ring}}{C_{ring}}$$
$$\Delta C = 0.5\,\mathrm{mm} \Rightarrow \Delta E = 5\,\mathrm{MeV}$$

- Δ beam position seen by orbit monitors (x_{arc})
- Large ΔE seen by depolarization experiments
- Described by tide model: $\sigma(E_{cm}) \simeq 0.4\,\mathrm{MeV}$



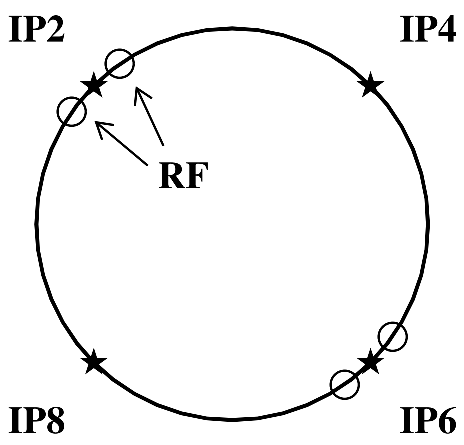
Quadrupole: Geological shifts

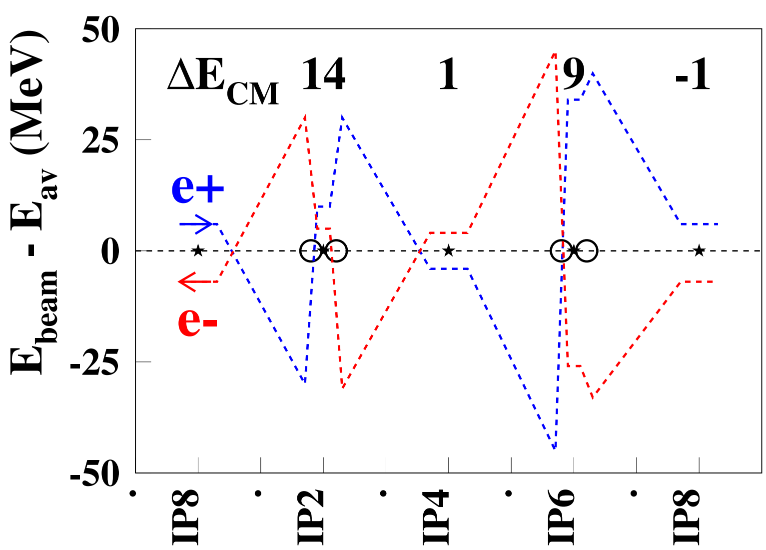


- EOF calibrations "drifted" during 1993
- Correlated with measured orbit shifts, Δx_{arc}
- Part of effect identified as changing level of Lake Geneva
- Weight of water distorts local geology
- Also affected by rainfall and water table in Jura mountains
- x_{arc} used to correct E_{cm} for orbit shifts

RF corrections

- $\Delta E \simeq -120\,\mathrm{MeV}$/turn due to synchrotron radiation
- Lost energy restored by RF accelerating units
- Energy around LEP described by "sawtooth"

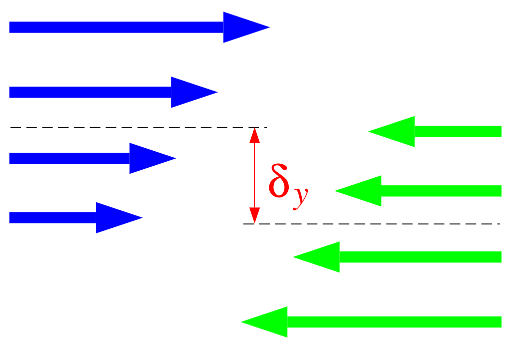




- RF alignment offset $\Rightarrow$IP2,IP6: $\Delta E \sim 20\,\mathrm{MeV}$
  Cancellation $\Rightarrow$IP4,IP8: $\Delta E \sim 0$
- ΔE depends on IP2–IP6 path length, RF alignment and phasing, distribution of RF voltage
- LEP2 superconducting RF $\Rightarrow$ ΔE unstable (1995)
- RF Effects modelled by balancing energy losses and gains — compare to measureed Q_s and x_{arc}
- Data–model agreement $\Rightarrow \sigma(E_{cm}) \simeq 1\,\mathrm{MeV}$

IP-specific: Dispersion

- Bunch train scheme since 1995
- 4 “trains” $\times$ 2(3) bunches/train in each beam
- Parasitic collisions prevented by vertical orbit “bumps”
- Bumps cause momentum dispersion — opposite sign in e^+ and e^- beams
  $\Rightarrow E_{cm} = 2E_{beam} + \Delta E_{disp}$
- Vertical collision offset $\Rightarrow \frac{dE_{cm}}{d\,\delta y} \simeq 1.5\,\mathrm{MV}/\,\mu\mathrm{m}$



- Offset minimised by vertical beam scans — optimal collisions when $\mathcal{L}$ maximised
- Energy dispersion measured from scans, knowing beam size
- Mean $\mathcal{L}$-weighted offset used for ΔE_{disp}
- Energy uncertainty: $\sigma(E_{cm}) \simeq 0.7\,\mathrm{MeV}$

Systematic uncertainties

- Uncertainties for E_{CM}^{IP} in 1995 (illustrative values):

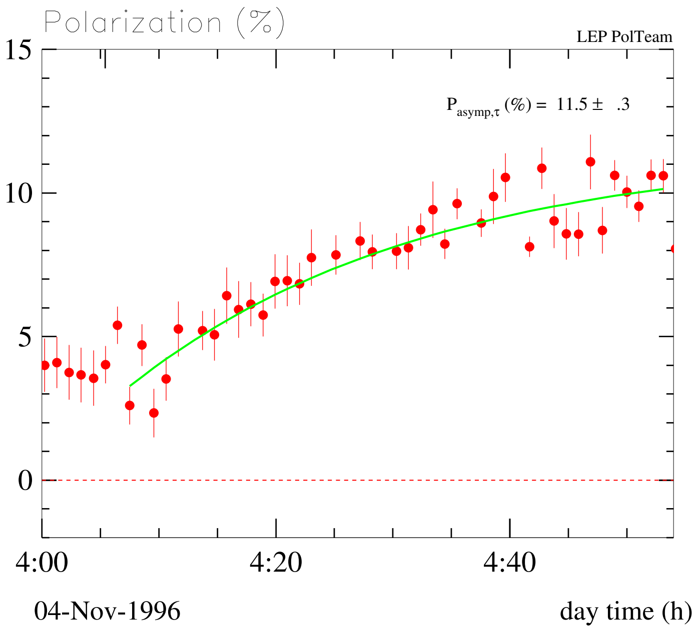
Source	$\sigma(E_{cm})$, MeV
Depolarization	$\sim 0.2\,\mathrm{MeV}$
$\mathrm{e}^+ - \mathrm{e}^-$ difference	$\sim 0.3\,\mathrm{MeV}$
Calibration statistics	$\sim 1.0\,\mathrm{MeV}$
Dipole rise model	$\sim 1.0\,\mathrm{MeV}$
Temperature model	$\sim 1.0\,\mathrm{MeV}$
Horizontal correctors	$\sim 0.3\,\mathrm{MeV}$
Tide	$\sim 0.4\,\mathrm{MeV}$
Orbit drifts	$\sim 0.5\,\mathrm{MeV}$
RF corrections	$\sim 1.0\,\mathrm{MeV}$
Dispersion	$\sim 0.7\,\mathrm{MeV}$
Total	$\sim 2.0\,\mathrm{MeV}$

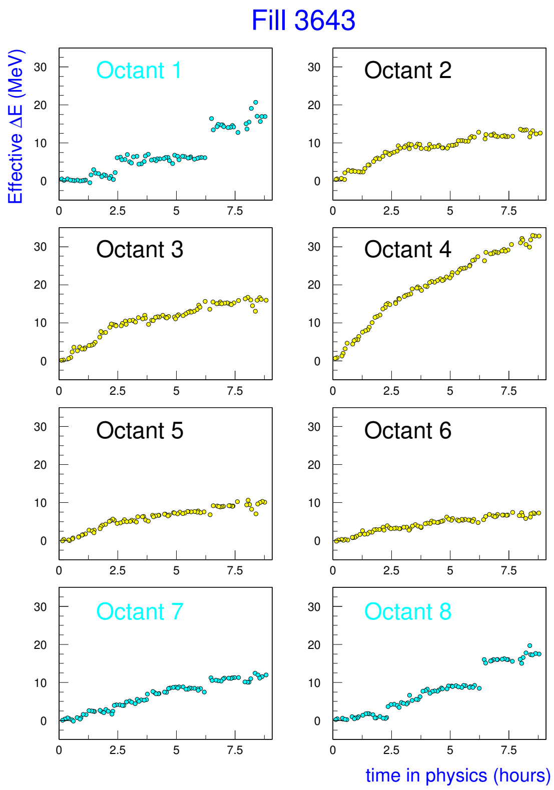
- Corrections and errors calculated for each dataset
- Uncertainties correlated by year, energy point, IP
- Combined as error matrix for each experiment
- Beam energy spread determined: $55 \pm 1.5\,\mathrm{MeV}$ (2^{nd} order effect on M_Z)
- Energy errors on Z^0 parameters (Warsaw 96)

1993		1995		
$\sigma(M_Z)$	$\sigma(\Gamma_Z)$	$\sigma(M_Z)$	$\sigma(\Gamma_Z)$	
2.6	2.1	1.6	1.6	MeV

Energy Determination at LEP2

- LEP2 began at WW threshold in 1996: $E_{cm} = 161\,\mathrm{GeV}$
- Lower precision sufficient — still challenging
- Similar calibration technique employed for LEP2
- But depolarization only possible (so far) up to $E_{beam} = 50\,\mathrm{GeV}$
- $\Rightarrow$No direct calibration of physics energies
- Additional NMR's in LEP dipoles: ≥ 1/octant
- 1995 model of rise behaviour confirmed
- NMR's calibrated at low energy
- Calibration extrapolated to $80+\ \mathrm{GeV}$





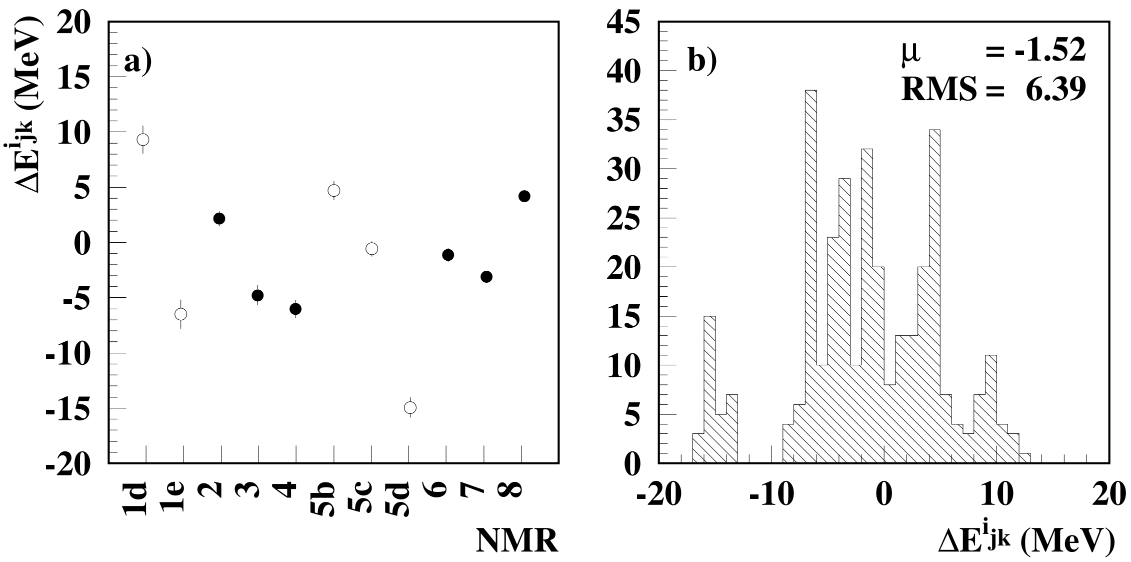
Extrapolation

- Depolarization at 44 and $50\,\mathrm{GeV}$ only
- Single fill with calibrations at both energies
- 5 NMR's damaged by radiation, ≥ 1 per octant ok
- Extrapolate NMR readings from 44 to $50\,\mathrm{GeV}$

$$E^{ext}_{44-50} = \frac{E^{depol}_{44}}{B_{44}} B_{50} - E^{depol}_{50}$$

- Check E linearity with NMR i reading:

$$\Delta E^{i} = E^{ext,i} - E^{depol}$$



- Extrapolation–polarization discrepancy consistent with zero
- Scale for extrapolation from 50 to $80.5\,\mathrm{GeV}$ $\Rightarrow \sigma(E_{beam}) \simeq 24\,\mathrm{GeV}$
- Cross-check with NMR–flux loop comparison

1996 Systematic errors

$\sigma(E_{beam})$ [MeV] at	80.5 GeV	86 GeV
E scale/Dipole model:		
Polarization systematic	1	1
e^+e^- energy difference	1	1
Extrapolation	24	29
Fill-by-fill normalisation	10	5
Correctors	1	1
NMR/temperature model	2	2
Orbit:		
Tide model	1	1
IP-specific:		
Dispersion	1	1
RF	5	5
Total	27	30

- Extrapolation is dominant uncertainty
- RF model updated for superconducting cavities
- Precision exceeded goal for 1996

Prospects for LEP2

- Test extrapolation with more calibration fills
- Check NMR linearity $\Rightarrow \geq$ 3 polarization energies
- Polarization at higher energies — up to $60\,\mathrm{GeV}$?
- Improve polarization efficiency — work in progress
- Aim for $\sigma(E_{beam}) \simeq 15\,\mathrm{MeV}$ — optimistic

Summary

- Precision of Z^0 scan dependent on $\sigma(E_{cm})$
- Energy calibration based on resonant depolarization — very precise, E^{av} only
- Model energy time-evolution and IP-specific offsets
- Dipole model of field rise due to beampipe current and temperature
- LEP ring distorted by tides and geological shifts
- Detailed model of RF effects
- LEP1 analysis almost finalised
- LEP2 precision dominated by extrapolation of NMR calibrations
- Outlook good for precision of M_W 1997$\longrightarrow$