LEP Energy Calibration

LEP Energy Working Group Report to the LEPC

31 March 1998 – Pippa Wells

- History and the final word on LEP1
- The LEP2 energy model
  - Polarisation/NMR/flux-loop comparisons
  - Preliminary error estimates for 1997
- Radiative return events
- LEP Spectrometer Project
- Plans for 1998

A brief history...

1986 Predictions: Magnetic calibration $\Rightarrow\ \delta E/E = \pm 3 \times 10^{-4}$, $\delta m_{\rm Z} = 28$ MeV
Polarisation $\Rightarrow\ \delta E = \pm 1$ MeV,
with magnetic stability of $10^{-4}\ \Rightarrow\ \delta m_{\rm Z} \approx 10$ MeV

1990 $\delta m_{\rm Z} = 20$ MeV

- New idea: proton calibration at 20 GeV
- Flux loop correction for magnet aging and extrapolation to 45 GeV
- First observation of transverse polarisation

1991 $\delta m_{\rm Z} = 6$ MeV

- First energy measurements with resonant depolarization, RDP
- Temperature correction
- Correction for local energy differences at IP from RF system
- First calculations of tide effects – improved scatter of RDP measurements, but no controlled experiment or correction.

1992 On peak data.

- More evidence for long term drift in calibration
- First long tide experiment with RDP

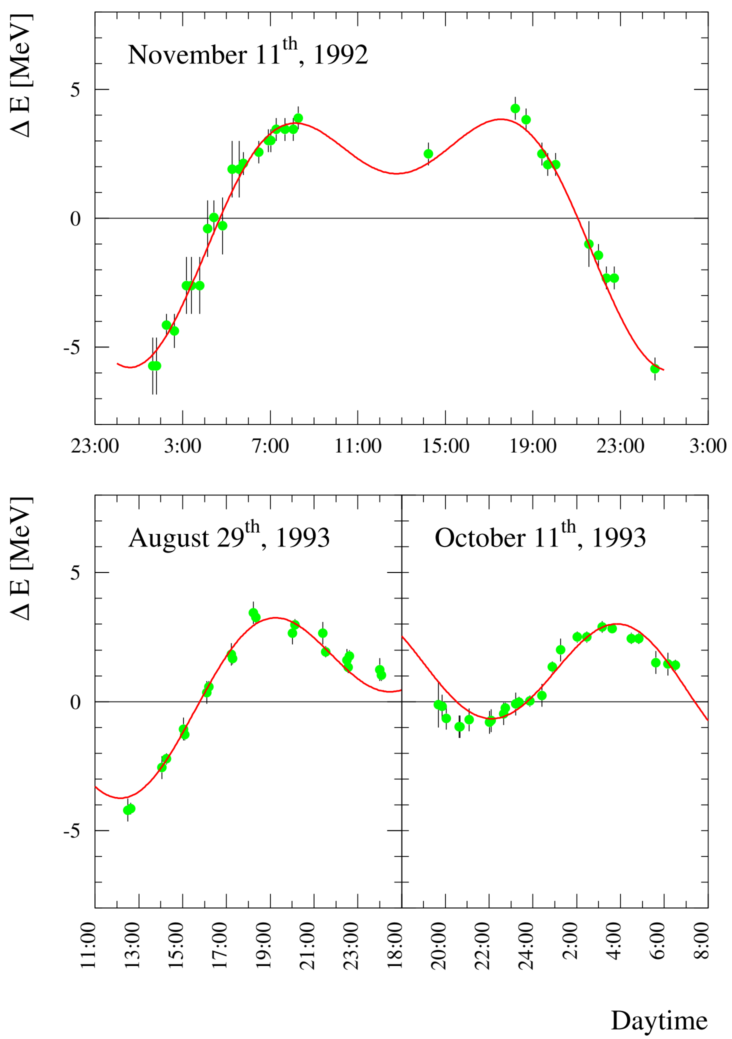
1993 $\delta m_{\rm Z} \approx 1.4$ MeV, $\delta\Gamma_{\rm Z} \approx 1.5$ MeV

- 3 energy point scan with 24 RDP calibrations at end of fill
- Temperature coefficient measured with RDP
- Tide effect well established with RDP
- Improved BOM system $\Rightarrow$
  - $\star$ independent measure of tide effect
  - $\star$ confirmed long term drifts in LEP radius consistent with RDP drift and central frequency.
- Hints of rise/jumps in dipole field seen in reference magnet and during temperature experiments

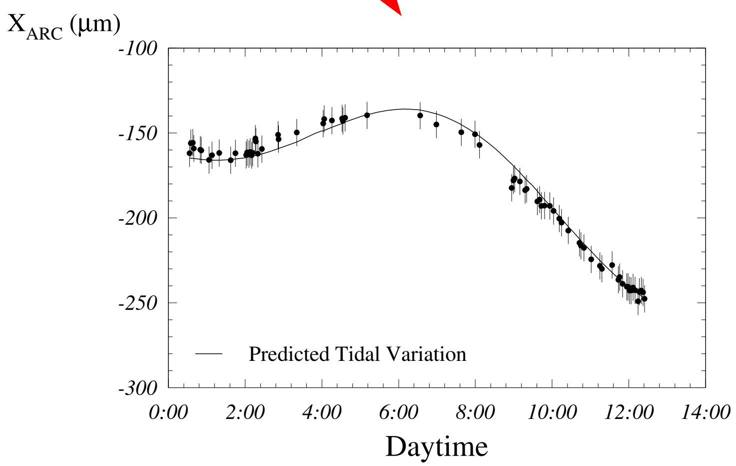
1994 On peak data

Tide model compared to RDP and BOM

Change of energy measured by polarisation vs. time of day.



Change of radius measured by BOMs vs time of day.



1995 – 2 NMR probes in dipoles in the tunnel – rise/jumps caused by parasitic currents from electric trains

– 6 fills with RDP at beginning and end

– LEP ran with bunch trains – opposite sign vertical dispersion at the IP $\Rightarrow$ control collision offsets

1996/97 – 16 NMR probes in LEP tunnel

– Test facility with LEP dipole in the ISR tunnel

– Major progress in understanding temperature effects – more than one temperature coefficient needed

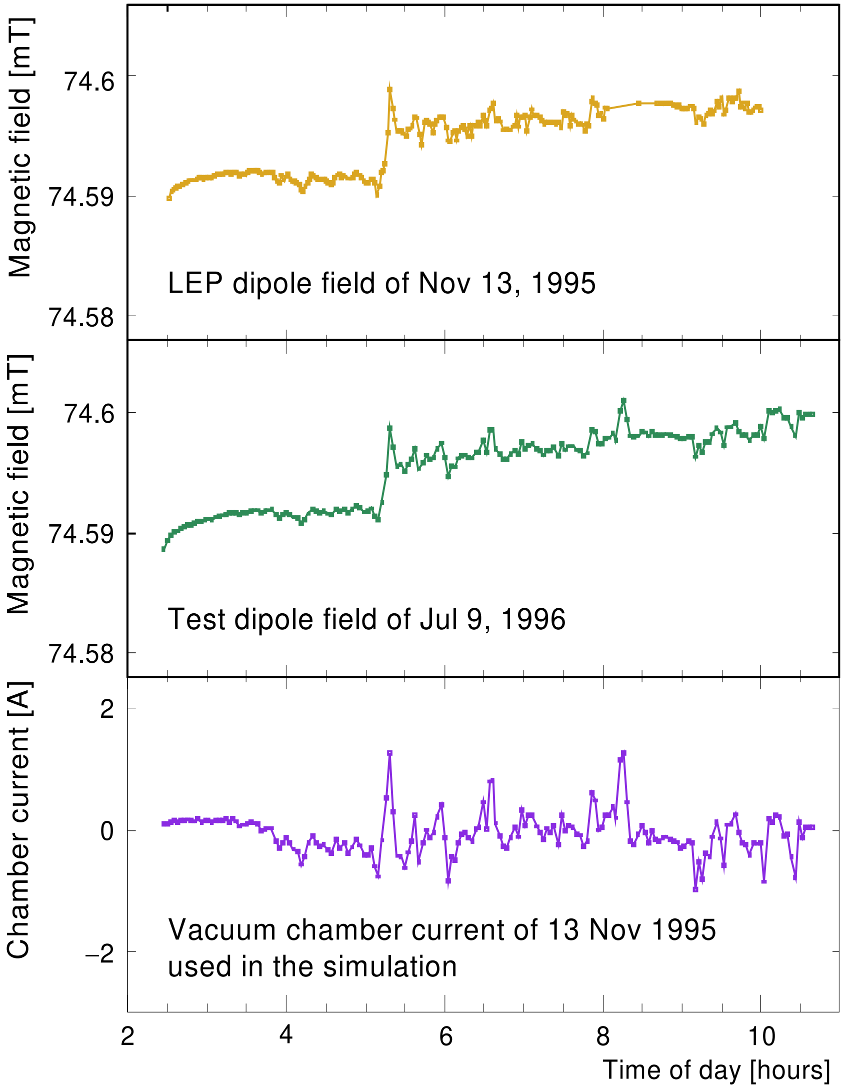
– Interplay of train and temperature effects on dipole field rise understood

1998 – Publication! *Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties*, The LEP Energy Working Group, CERN-EP/98-040, CERN-SL/98-012, submitted to Eur. Phys. J. C

– Expecting $\delta m_{\mathrm{Z}} \approx 1.6$ MeV, $\delta\Gamma_{\mathrm{Z}} \approx 1.2$ MeV

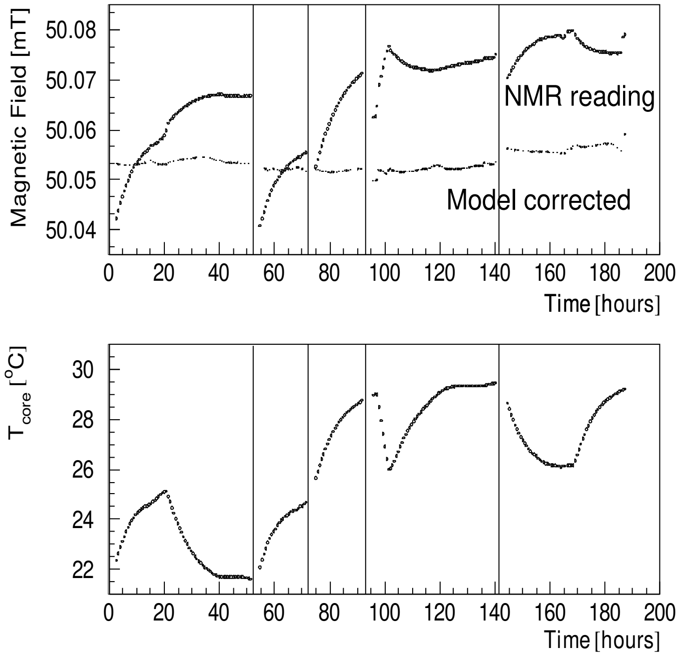
– EP seminar on 20 April by G. Wilkinson

Trains and temperature



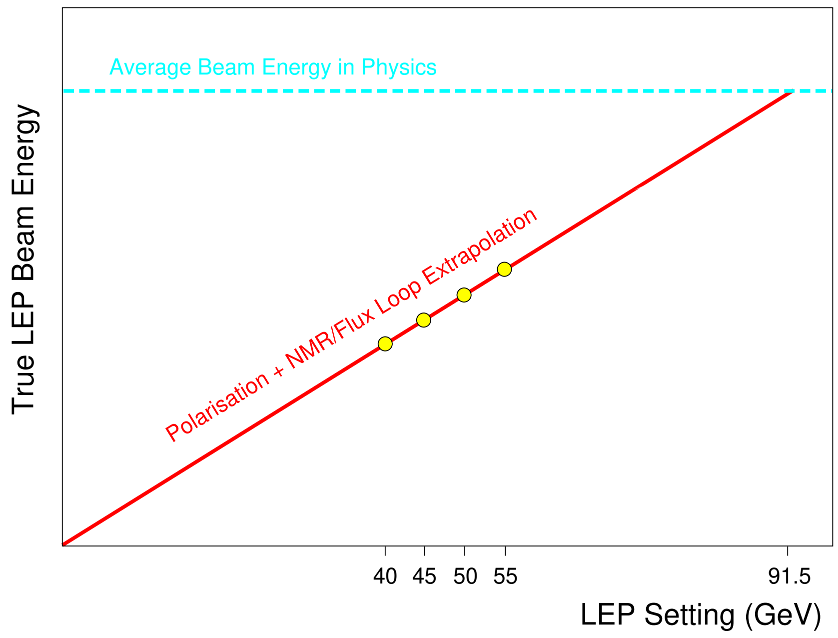
Train effect reproduced

Temperature experiment
in the test laboratory



LEP2 energy model

- Aiming for $\sigma(M_W) \approx 30$ MeV at LEP2
- Polarisation not possible at high energy. Maximum RDP energy so far is 55 GeV. Physics running with $E_{\rm beam}$ 90–100 GeV.
- $\Rightarrow$ Magnetic extrapolation to set energy scale. $E_{\rm beam} \propto \oint B \cdot {\rm d}\ell$
- Other effects are understood from LEP1. Some scale with energy.
- Energy loss per turn scales with E^4, so take particular care with logging RF system status.
- Logging is crucial!



Extrapolation method

- Measure lower energies precisely with RDP

$$\nu \propto E_{\mathrm{beam}} \propto \oint B \cdot \mathrm{d}\ell$$

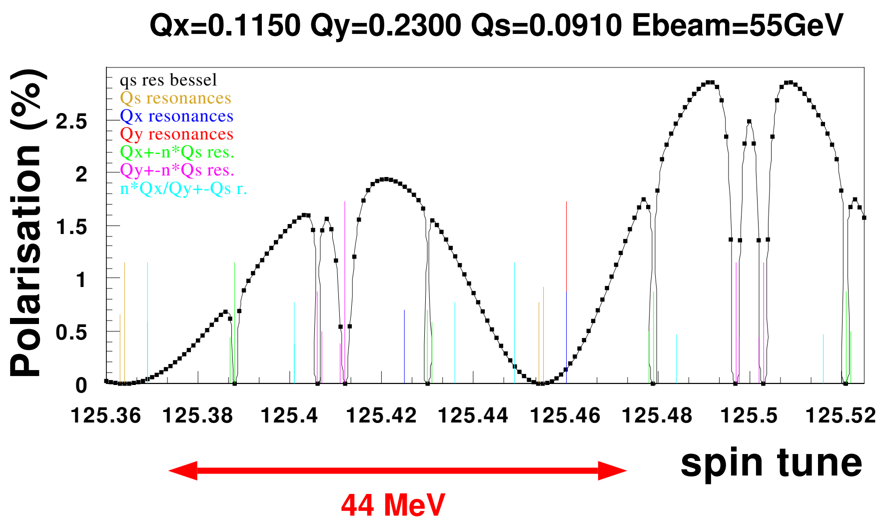
- Compare E_{pol} with B_{NMR} over limited energy range
- Use NMR's to predict E_{beam} at physics energy
- Flux loop measures total $\oint B \cdot \mathrm{d}\ell$, with NMR's read out at steps in the cycle
- Compare B_{NMR} with B_{FL} to test how well NMR's predict total bending field over full energy range
- If NMR's can predict B_{FL}, then they can provide E_{beam} at physics energy from E_{pol} at lower energy

Polarisation

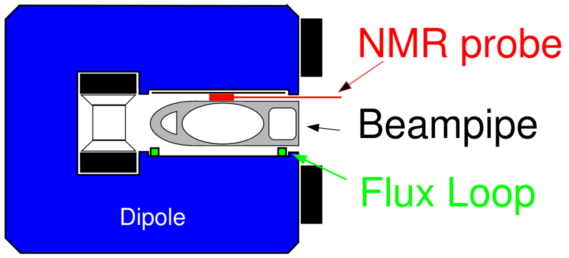
- Natural build up of transverse polarisation by Sokolov-Ternov effect. Spins precess in LEP bending field. Measure spin tune, ν, by RDP.

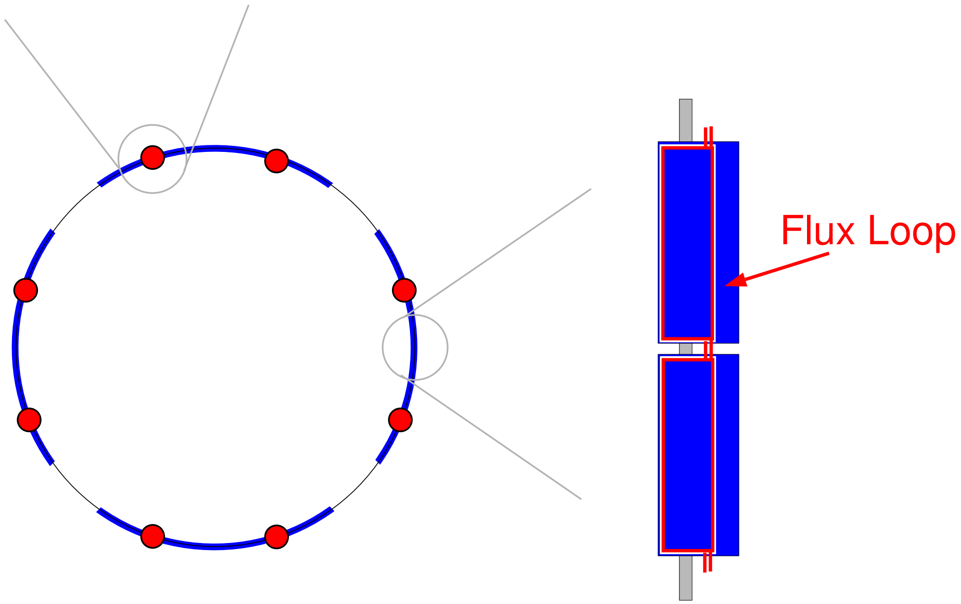
$$\nu = \frac{g_e - 2}{2} \frac{E_{\mathrm{beam}}}{m_e} = \frac{E_{\mathrm{beam}}}{0.4406486(1)}$$

- $P_\infty = 92.4\%/(1 + \tau_p/\tau_d)$. Depolarising effects increase with E^4_{beam}.
- Vertical kicks minimised with Harmonic Spin Matching $\Rightarrow$ measure pickup positions wrt quads with k–modulation
- New 60/60 optics with smaller vertical phase advance
- Resonances require careful choice of energy and tunes to maximise P_∞



Magnetic measurements





NMRs:

- Precision: order 10^{-6}
- Read out: every 30 seconds
- Only measures B-field over small area, 16 probes for 3200 dipoles

Flux Loop:

- Precision: few 10^{-4}
- Read out: every few weeks. NMR's lock at steps in cycle
- Measures 96.5% of B-field. Missing:
  - "10%" dipoles (end of arcs)
  - injection dipoles
  - fringe fields
  - quadrupoles

Extrapolation error with 1996 data

Error in 1996 at E_{beam}=86 GeV was 30 MeV

- Largely based on a single fill with resonant depolarisation (RDP) measurement at 45 and 50 GeV.
- Apparent precision of FL/NMR vs RDP was around 2 MeV over this 5 GeV interval (relative error 4×10^{-4}).
- "Linear extrapolation" with this precision would give error of 15 MeV at 86 GeV.
- Error inflated to 30 MeV because
  - No estimate of reproducibility from fill to fill
  - No fills with more than two energy points $\Rightarrow$ No check of non-linearity
  - No work on the possible precision for the 3% of bending field outside the flux loop

Application to 1997

- With no improvements, error at E_{beam}=91.5 GeV would be about 35 MeV

1997 polarisation measurements

Date	41 GeV	44 GeV	50 GeV	55 GeV	Optics
17/08/97		•			90/60
06/09/97		•	•		60/60
30/09/97		•	•		60/60
02/10/97	•	•	•	•	60/60
10/10/97		•			90/60
11/10/97	•	•	•	•	60/60
29/10/97	•	•			60/60

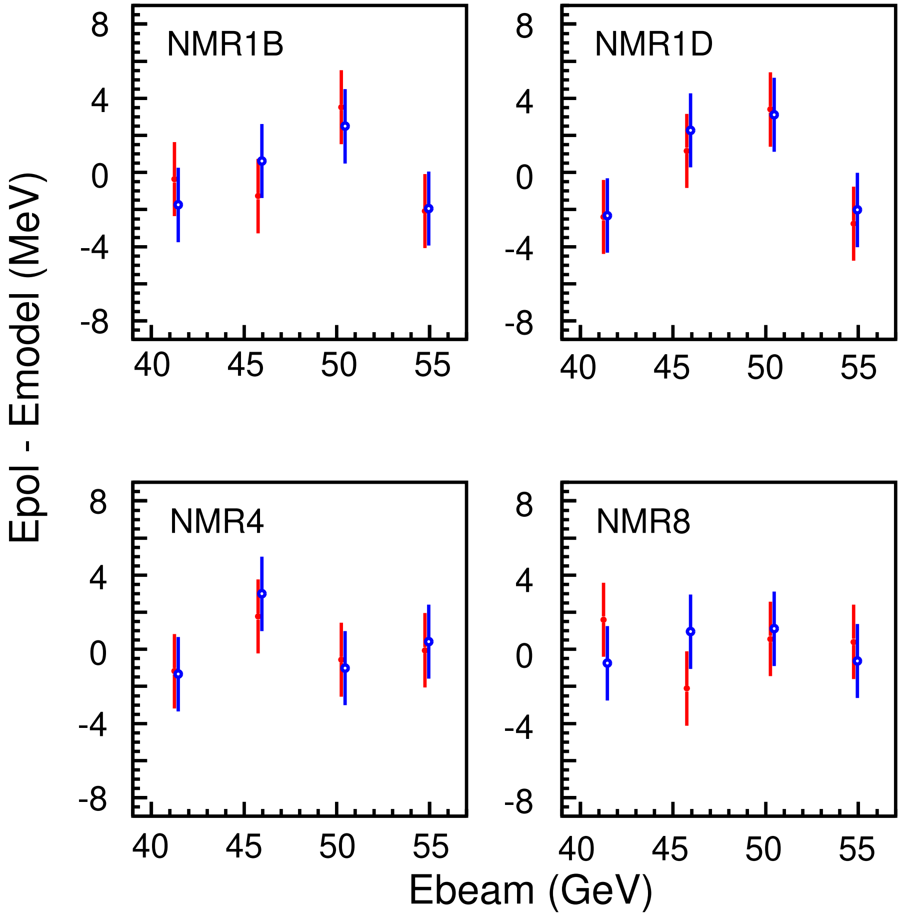
- 5 fills with more than one energy point,
- 2 fills with 4 energy points ($\Rightarrow$ first linearity check)
- Lever arm increased from 5 to 14 GeV
- Maximum measured energy increased from 50 to 55 GeV (2% polarisation at 60 GeV).

Optics difference

- Measured energy difference at 45 GeV: $E(90/60) - E(60/60) = -4$ MeV
- Predicted difference at 45 GeV from QFQD and horizontal corrector settings $E(90/60) - E(60/60) = -6 \pm 1$ MeV
- Assign uncertainty of 2 MeV at 45 GeV from the discrepancy
- Difference is expected to scale with energy $\Rightarrow$ correction

-8 ± 4MeV at physics energy

NMR–polarisation comparison

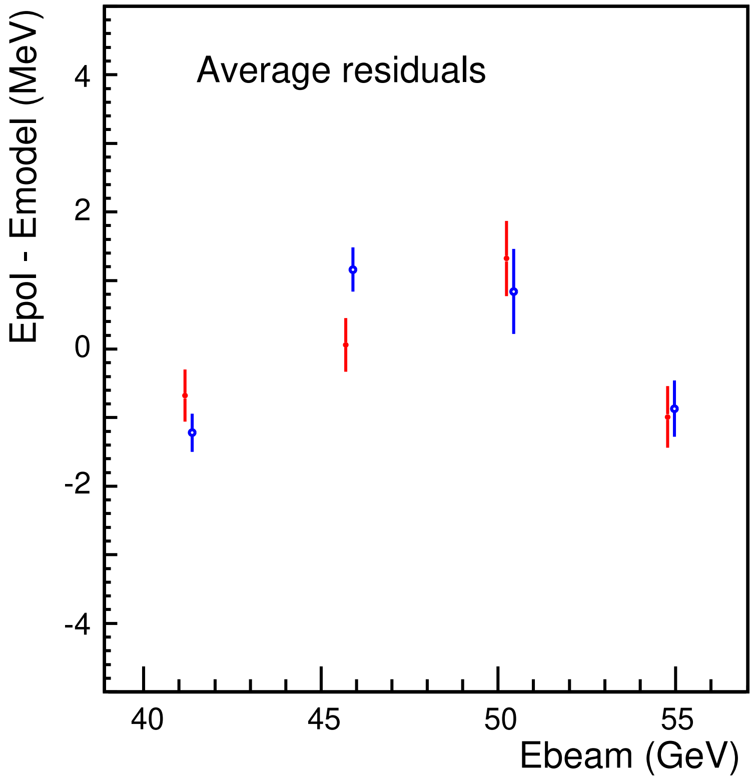


Example residuals for 4 NMR's

blue and red points for different fills

- Make fit to $E_{\rm pol} = a^i + b^i B^i_{\rm NMR}$ for each NMR $i = 1, 16$
- $\Rightarrow$ Need two or more $E_{\rm pol}$ values in same fill
- Use $E^i_{\rm NMR} = a^i + b^i B^i_{\rm NMR}$ and plot residuals $E_{\rm pol} - E^i_{\rm NMR}$
- Different probes show different behaviour, but reproduced from fill to fill.

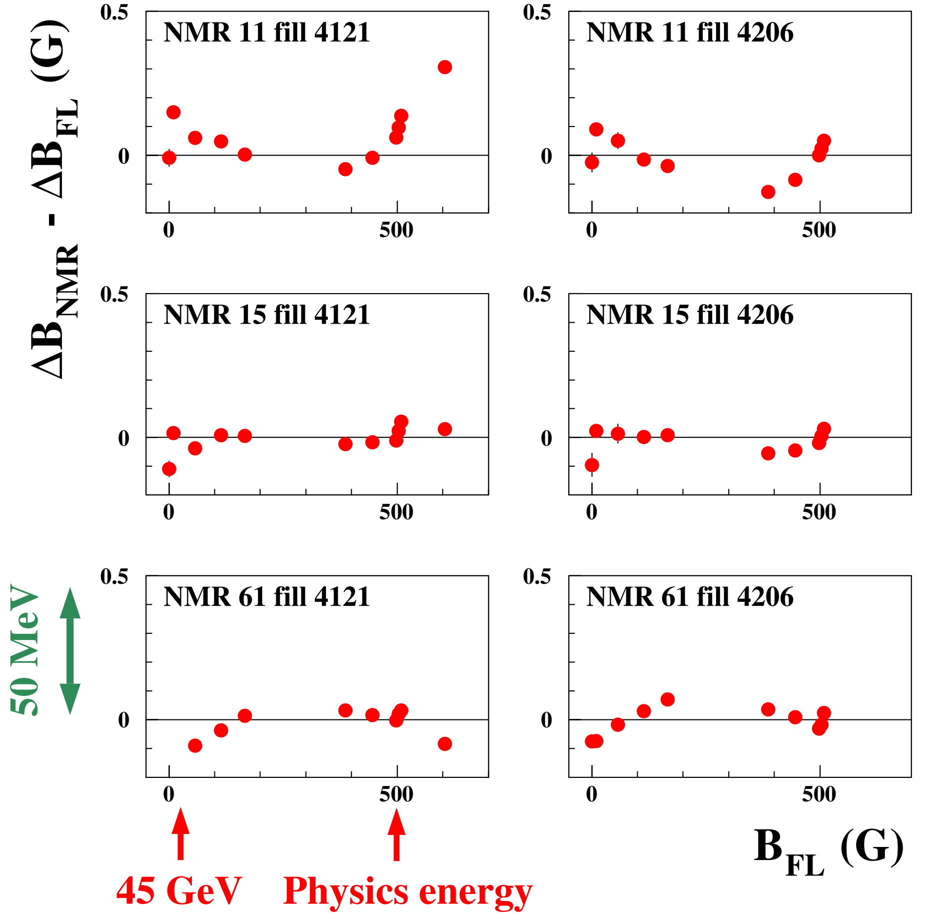
NMR–polarisation comparison



- Error bars shown are the rms residuals over NMR's.
- The red/blue points correspond to the two 4-energy RDP fills.
- Characteristic shape $\Rightarrow$ test of non-linearity
- Further increase $E_{\rm pol}^{max}$ in future?

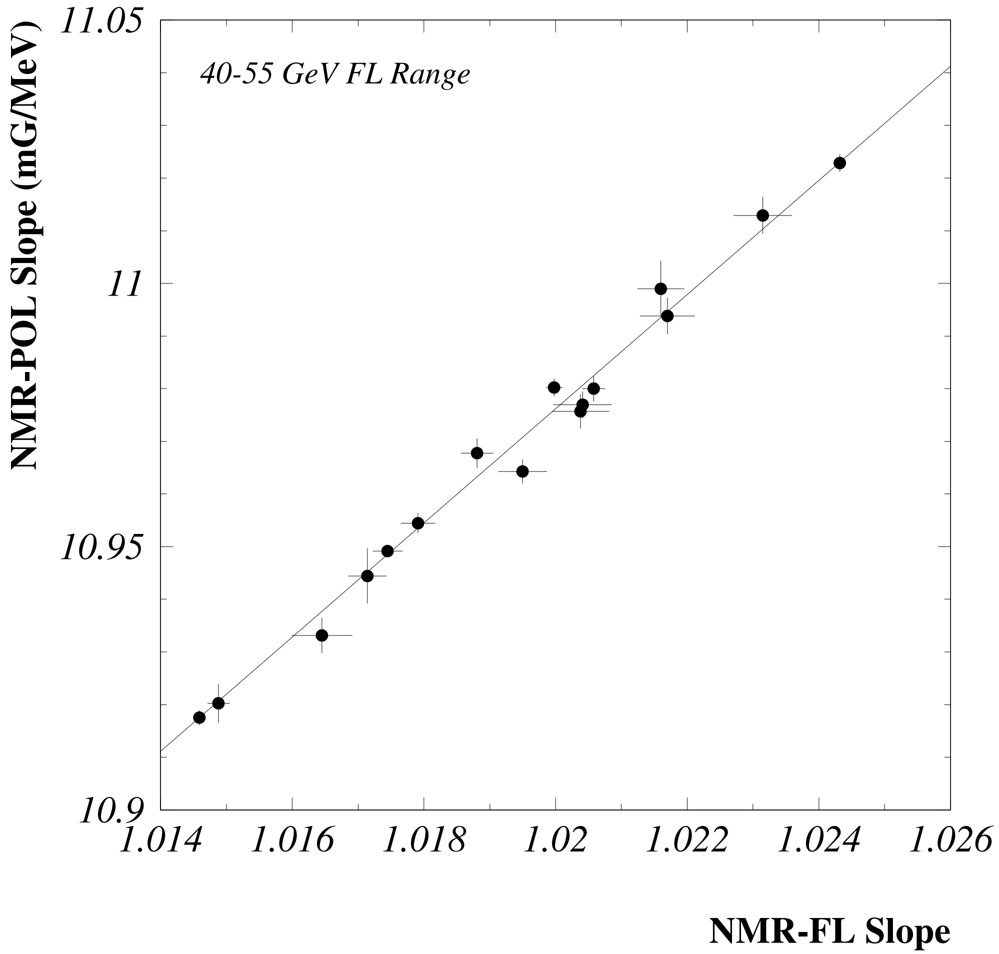
- Best estimate of physics energy from fit to all fills with $\geq$ 2 RDP energies.
- Scatter (rms) over 16 NMR's is 40 MeV, $\Rightarrow$ 10 MeV uncertainty.
- Fitting to subsets of RDP fills $\Rightarrow$ additional 5 MeV uncertainty.

NMR flux-loop comparison



- Fit $B_{\mathrm{NMR}} = c + dB_{\mathrm{FL}}$.
- Plot residuals from this line as a function of ΔB_{FL} (0 G at 40 GeV, 500 G at physics energy)
- Octant-to-octant and magnet-to-magnet, behaviour varies.
- Slopes are not constant with energy
- But behaviour is reproduced from fill-to-fill

Compare slopes NMR–polarisation and NMR–FL

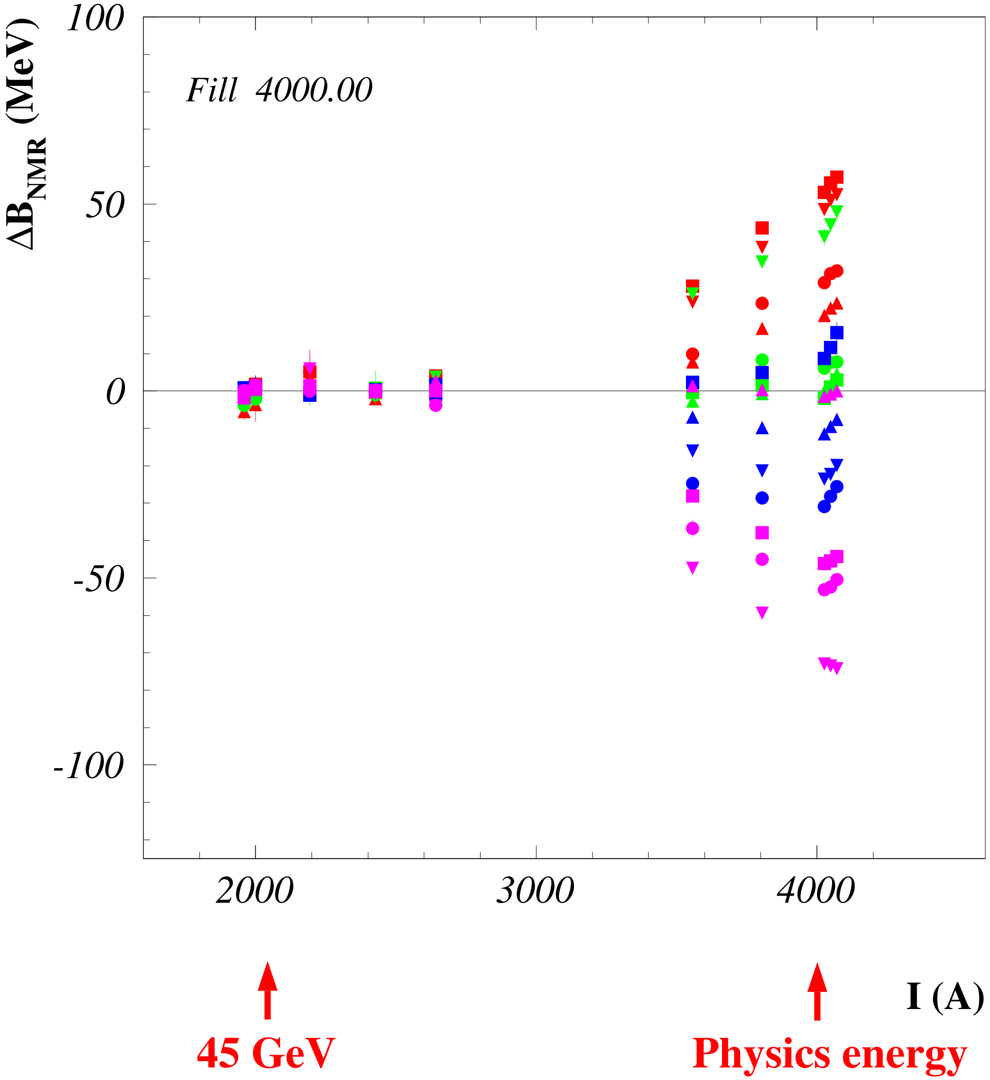


- Make the NMR-FL fit in the restricted range corresponding to 40–55 GeV.

  $B_{\mathrm{NMR}} = \alpha + \beta E_{\mathrm{pol}}$

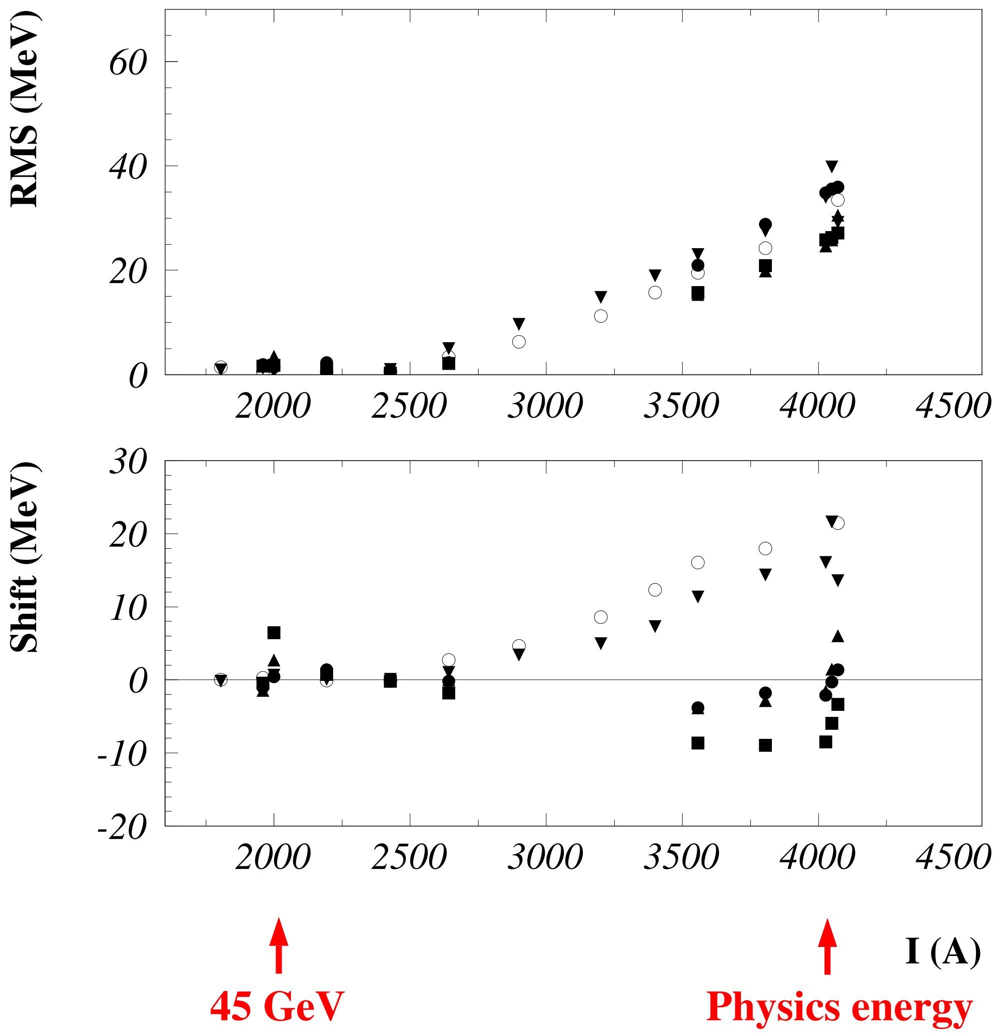
  $B_{\mathrm{NMR}} = c + d B_{\mathrm{FL}}$
- Plot β vs d for each NMR (one point per probe)
- Error is fill-to-fill scatter
- Good correlation

FL test of extrapolation with NMR's



- Compare NMR prediction of FL magnetic field from $B_{\rm NMR} = c + dB_{\rm FL}$ (fitted in 40–55 GeV range) with direct flux-loop measured $\Delta B_{\rm FL}$
- Plot is for one flux-loop measurement
- Each symbol corresponds to a different NMR

FL test of extrapolation with NMR's



- Find average over NMR's of discrepancy in B field
- Convert to energy difference
- Each symbol corresponds to one flux loop measurement
- At physics energy, average shift in the range –10 to +20 MeV and RMS over NMR's is 30–40 MeV.

Preliminary error summary

Source	Error [MeV]		
	Hi E	LEP1.5	Z
Polarisation systematic	1	1	1
e^+e^- energy difference	2	2	2
Optics difference	4	3	2
Extrapolation from NMR–polarisation			
NMR rms for two parameter fit	10	5	0
Different E_{pol} fills	5	3	2
Flux-loop test of extrapolation			
NMR flux-loop difference per fill	20	10	0
NMR scatter	10	5	0
3.5 % of field not measured by FL			
with 1 % uncertainty over 55 to 90 GeV	12	6	0
Corrector effects	6	6	6
Tide	1	1	1
Dipole rise modelling	1	1	2
RF frequency shift (15 min sampling)	3	0	0
IP specific corrections ($\sigma(E_{\mathrm{CM}})/2$)			
RF model	3	3	3
Dispersion	2	2	2
Total	29	16	8

Precision using radiative return events

Beam energy derived from $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma$ events and well known Z mass.

Statistical errors estimated from preliminary studies of 183 GeV data and large Monte Carlo samples.

For 500pb^{-1}, 4 experiments, assuming all data at 183 GeV

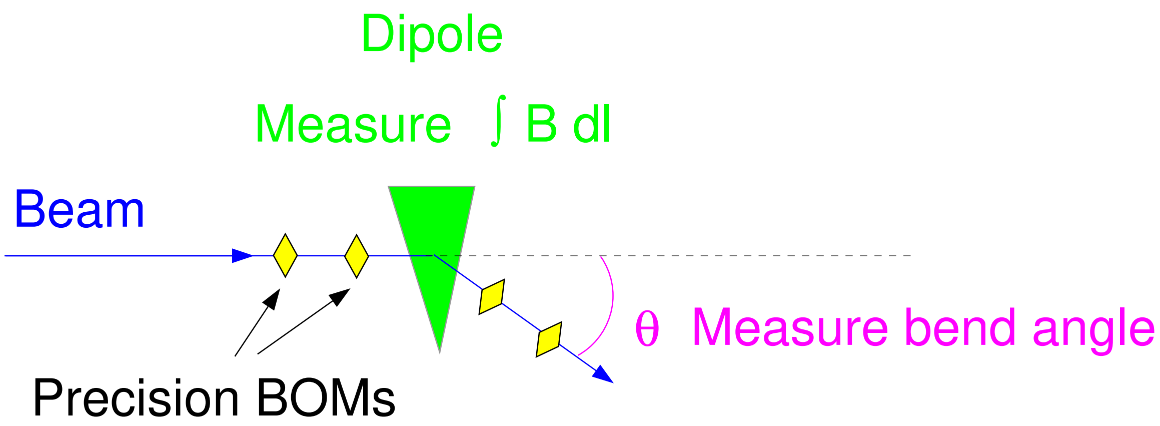
- $qq\gamma$ events $\Rightarrow$ stat error $\approx$16 MeV in Ebeam
- $\mu\mu\gamma$ events $\Rightarrow$ stat error $\approx$40 MeV in Ebeam
- $ee\gamma$ events are expected to have worse precision from the extra background
- Dominant reduction in stats from running at higher energy is from the fall off of the cross section. Reduction in detection efficiency at 200 GeV typically $\approx$5%

Potentially LARGE systematic errors

- Most important is modelling of ISR. Large differences (> 100MeV) have been seen between some different MC generators (work in progress: S. Jadach et al.)
- Jet modelling uncertainties - these also enter for the W mass measurement.

LEP Spectrometer Project

- Measure bend angle of electron and positron beams each time they go through a particular dipole.



$$\theta \propto \frac{\int B \mathrm{d}\ell}{E_{\mathrm{beam}}}$$

- Cross calibrate with RDP at low energy.
- Dipole current ramps with E_{beam}, along with the rest of the machine.
- Monitor $\theta \Rightarrow$ calculate change in E_{beam} relative to nominal setting value.

Spectrometer realisation

- Aim for 10^{-4} precision $\Rightarrow$ ± 10 MeV at 100 GeV
- Find a place in the LEP lattice with space for BOMs
  - 1998: two concrete dipoles near point 3. Equip with 4 NMR's
  - 1999: replace with a single, precisely mapped, steel "injection" dipole
- $\theta \approx 3.8$ mrad, lever arm ≈ 10 m $\Rightarrow$ required BOM precision 1 micron

  Possible with standard pickups, equipped with new electronics
  - 1998: only one side equipped with new readout
  - 1999: both sides equipped
- Stretched wire system to measure relative alignment
- Thermal and mechanical stability an issue
  - 1998: phase 1 – check relative precision of BOM measurements
  - 1999: available for energy calibration

Conclusions and plans for 1998

- Progress in 1997
  - Successful polarisation campaign
  - Consistency of polarisation data and flux-loop vs. NMR's firmly established at the 20–30 MeV level at physics energy
- Magnetic extrapolation in 1998
  - Attempt to increase lever arm with RDP at 60 GeV (60/60 optics)
  - More fills with many energy points in the same fill
  - Cross-calibrate polarisation (60/60) and new physics (102/90) optics
  - Further study of the flux loop (ISR test facility and LEP with no beam)
  - Measure field outside flux loop
- Improve Monte Carlo modelling of radiative returns
- Spectrometer commissioning and tests parasitic on physics and on RDP
- 8 days of machine development time have been allocated for energy calibration