LEP Energy Calibration

Above the WW Threshold

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Outline:

- Introduction
- LEP2 Energy Model
  - Measurement Tools
  - Magnetic Extrapolation
  - Variation of Energy During LEP Fills
- Results
- Prospects for Direct Measurements at Physics Energy

The Bottom Line(s):

$$\frac{\delta M_W}{M_W} \approx \frac{\delta E_{\text{beam}}}{E_{\text{beam}}}$$

$$\delta M_W(\text{stat}) \sim 30\ \text{MeV} \overset{\text{Goal}}{\Longrightarrow} \delta E_{\text{beam}} < 15\ \text{MeV}$$

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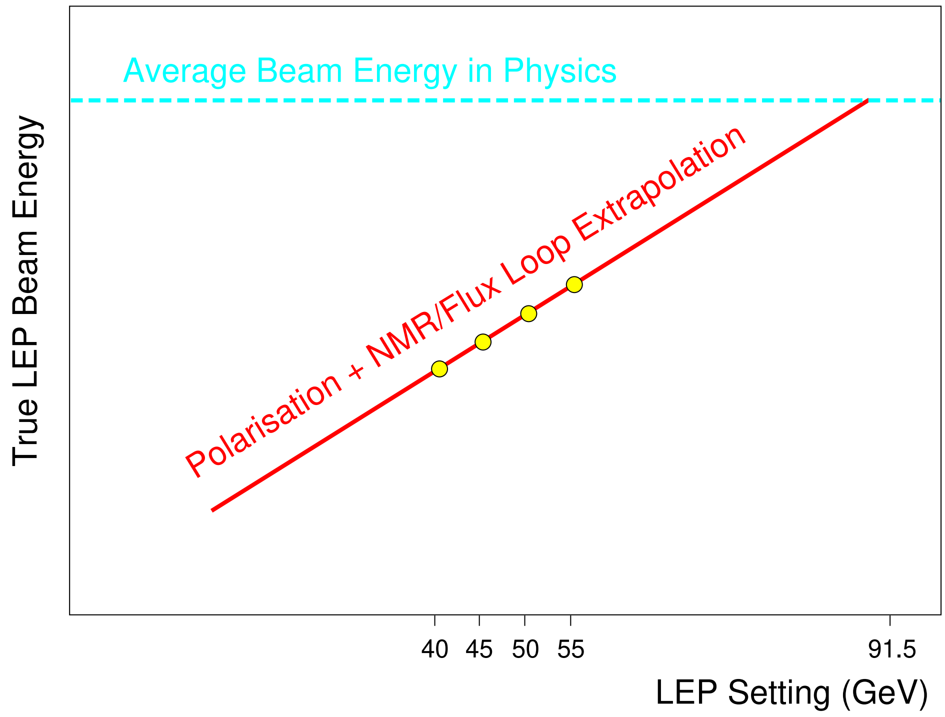
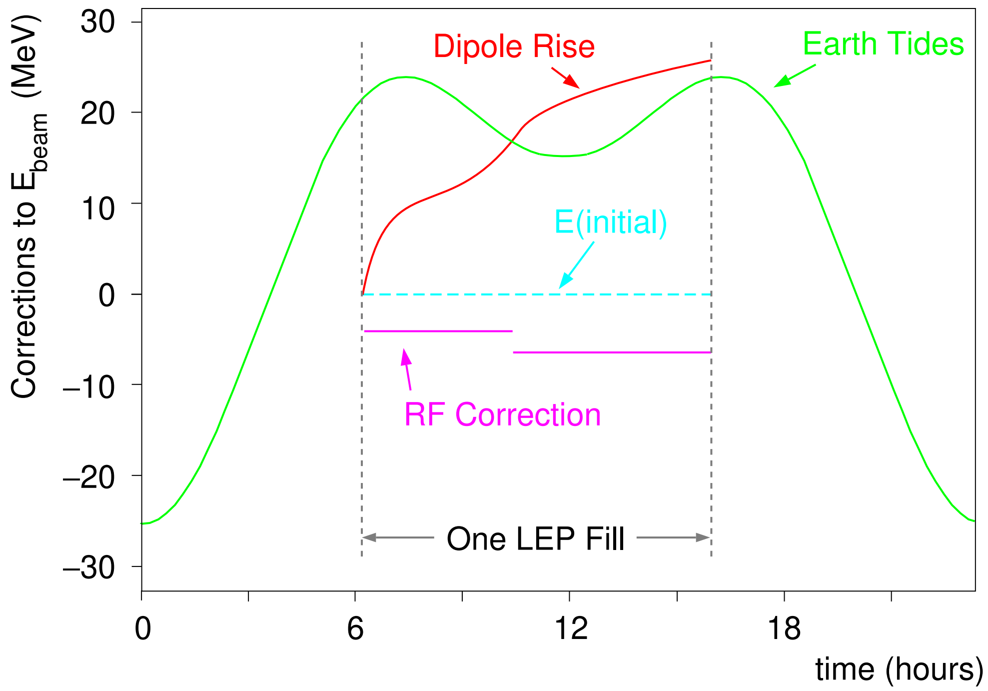
Overview of LEP2 Energy Determination

The LEP 2 Energy Model consists of two parts:

Part 1: Magnetic Extrapolation to set overall Energy Scale



Part 2: Calculation of Time-Dependent Energy Variation at LEP IPs



Effects well-understood at LEPI; some scale with E_{beam}

LEP Energy Measures

Primary Tool: Resonant Depolarization

Measure the spin precession frequency of polarised electrons:

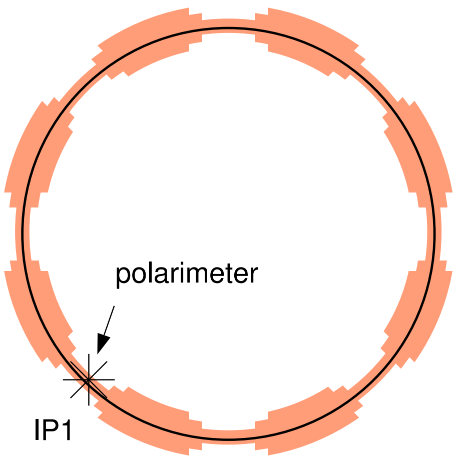
$$\Omega_s = \frac{eB_y}{m_e\gamma_e} \times \frac{g_e - 2}{2}\gamma_e \equiv \Omega_c \nu \quad \Rightarrow \quad \nu = \left(\frac{g_e - 2}{2m_e c^2}\right) E_{\mathrm{beam}}$$

This technique:

- measures the average beam energy $\langle E_{\mathrm{beam}} \rangle \equiv E_{\mathrm{pol}}$ at a specific time
- is *very* precise ($\delta E_{\mathrm{beam}} \sim 200\ \mathrm{keV}$)
- can only be used outside of physics
- DOES NOT WORK at LEP2 Physics Energies

$\Rightarrow$ Alternate energy measurements needed to EXTRAPOLATE

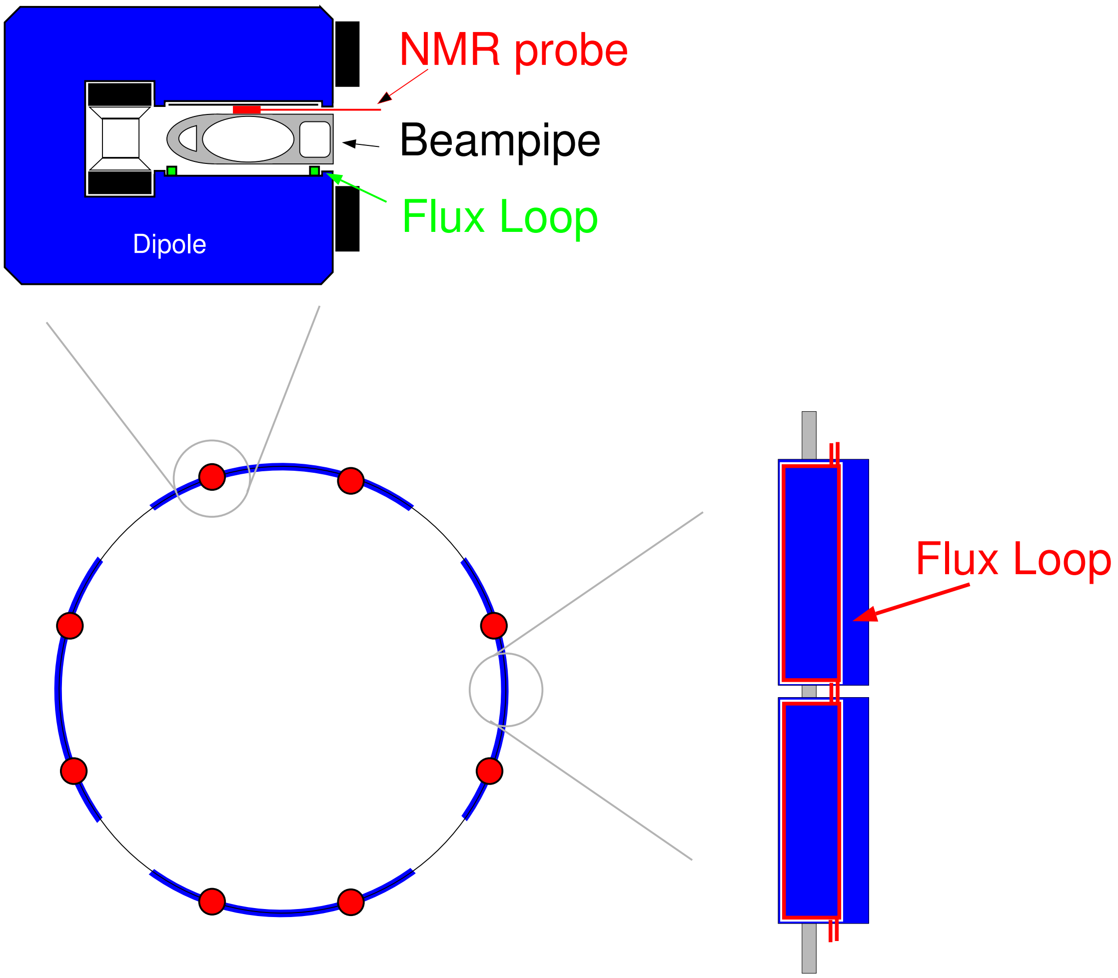
$$E_{pol} \propto \oint B_{\perp} \cdot dl$$



Magnetic Measurements provide means for extrapolation

LEP Energy Measures II

Other Measures of $\oint B \cdot d\ell$:



16 NMRs in LEP Dipoles:

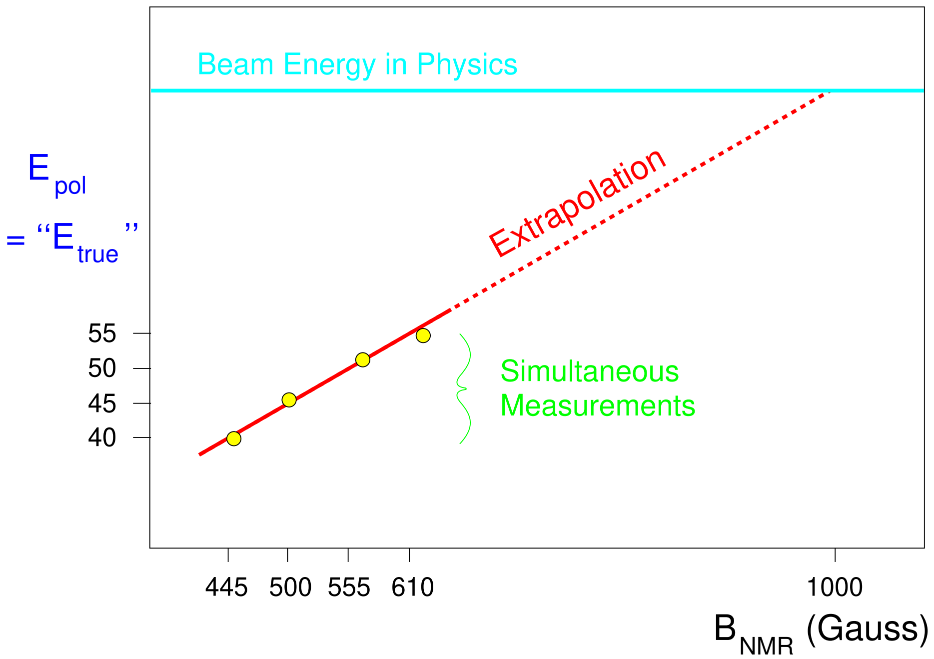
- Precision: $\sim 1 \times 10^{-6}$
- read out: every 30 seconds
- Simultaneous with $E_{\rm pol}$
- only measures B-field over small area (3200 dipoles)

Flux Loop:

- Precision: $\sim 1 \times 10^{-4}?$
- read out: $\sim$ weekly
- Cannot be done with beam
- (only) measures 96.5% of total B-field

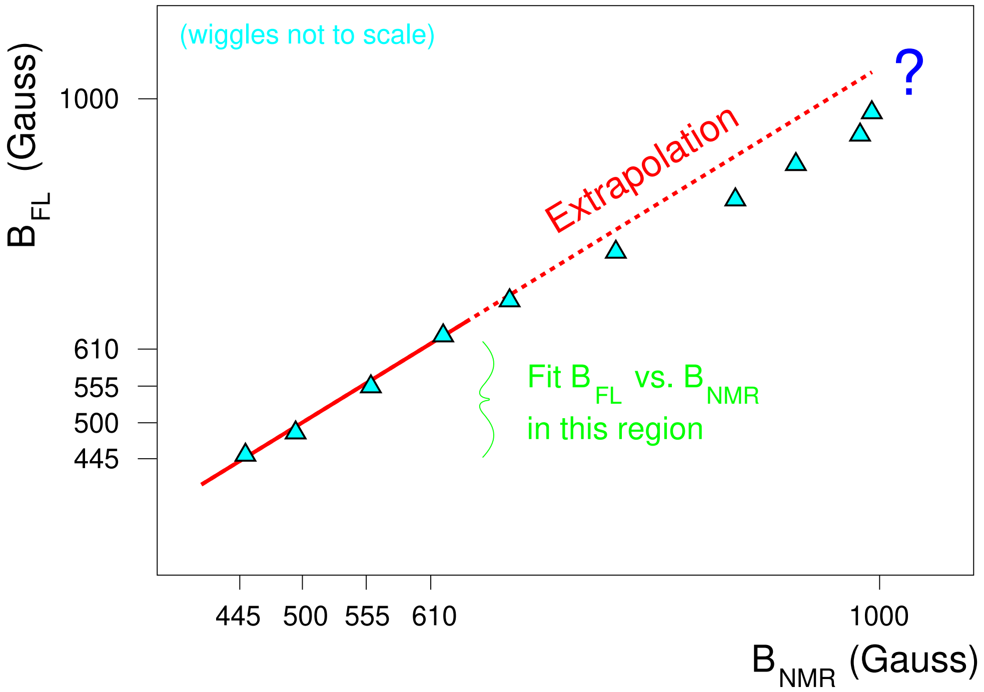
Extrapolation Method

Central Values from Linear Extrapolation using NMRs calibrated with $E_{\rm pol}$



$E_{\rm pol}$ *vs.* "$\oint B \cdot d\ell$"

Cross-check by comparing NMRs and Flux-Loop calibrations



"$\oint B \cdot d\ell$" *vs.* "$\oint B \cdot d\ell$"

Polarisation Data

Used to set Absolute Energy Scale of LEP

- Need a long lever-arm with the highest possible energy to minimise extrapolation uncertainty
- Need as many points as possible to check extrapolation linearity

1996:

Date	41 GeV	44 GeV	50 GeV	55 GeV	Optics
19/08/96			●		90/60
31/10/96		●			90/60
03/11/96		●	●		90/60

1997:

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

1997 saw great progress over 1996:

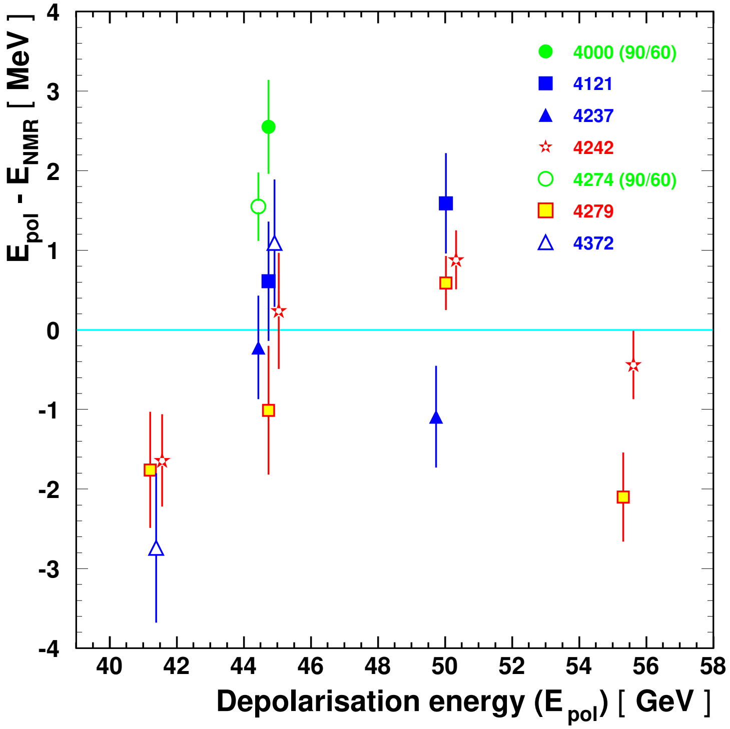
- Developed dedicated LEP optics for Polarisation measurements
- 5 fills with more than one energy point (only one in '96)
- 2 fills with 4 energy points ($\Rightarrow$ first linearity check)
- Lever arm increased from 5 to 14 GeV

Extrapolation Method: Real Data

For Central Values:

Assume $E_{\rm pol} = a^i + b^i B^i_{\rm NMR}$ for each NMR,

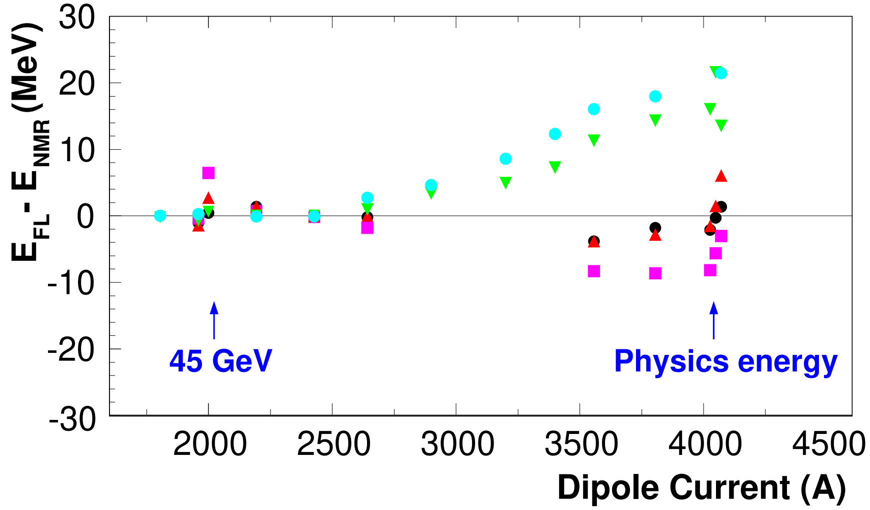
Fit to all Polarisation Data to Calibrate NMRs



- Linearity looks good to 2 MeV/15 GeV
- Small scatter in measurements

Extrapolation Systematic Error:

Cross Check NMRs and Flux Loop by extrapolating from same region where $E_{\rm pol}$ is available



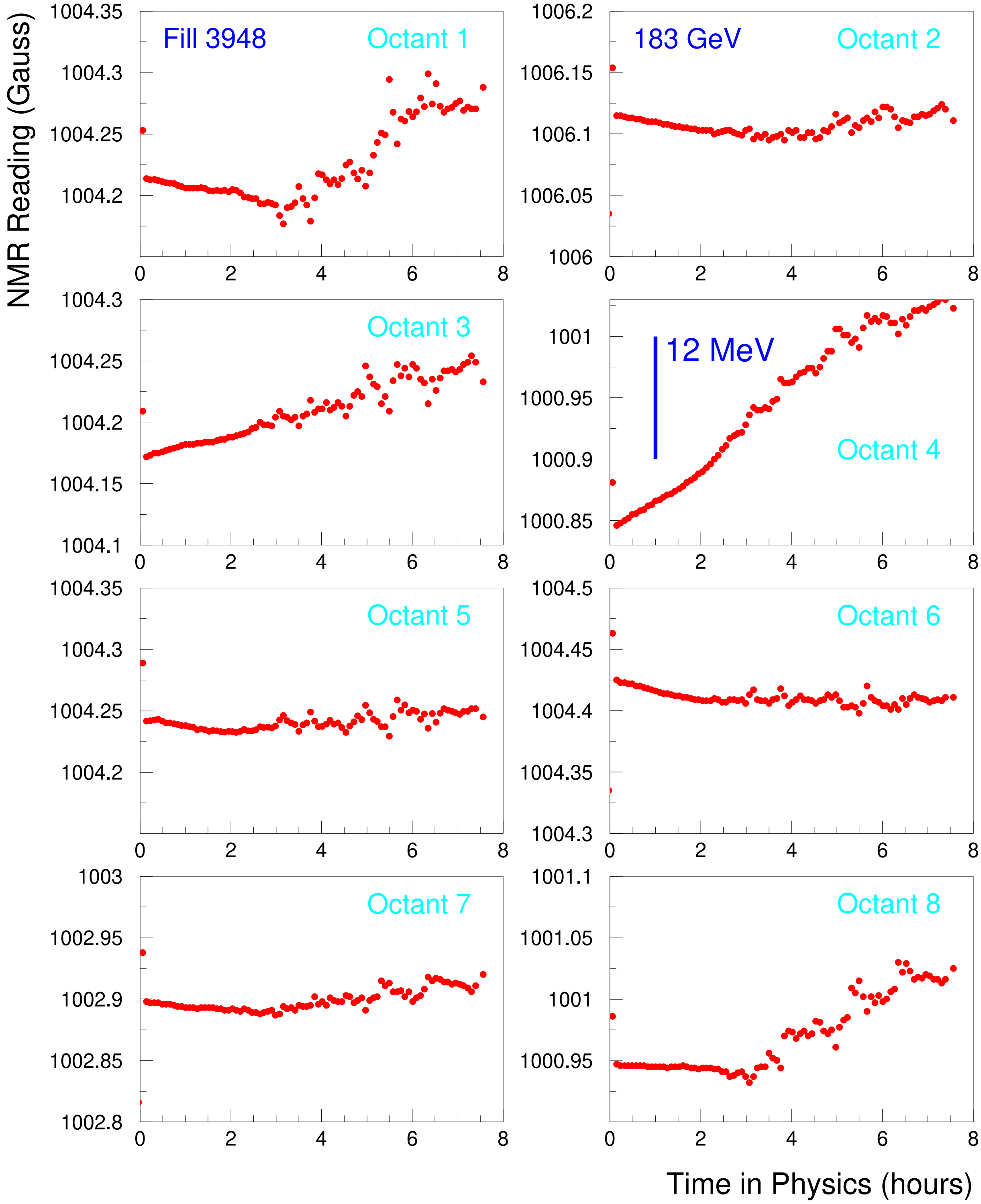
- NMR and Flux Loop agree on Non-Linearity
- Up to 20 MeV Difference at Physics Energy

$\Rightarrow$ Dominant Systematic Error on $E_{\rm beam}$

Energy Variation in a Fill

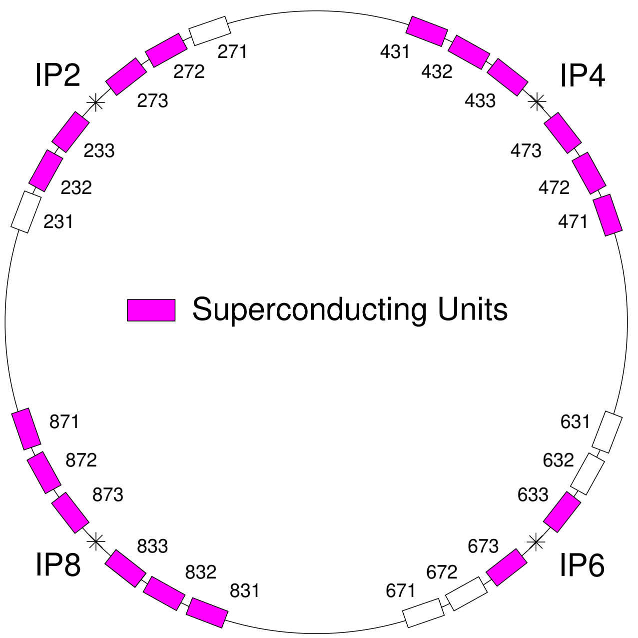
For Example, Dipole Effects ("TGV"+Temperature):

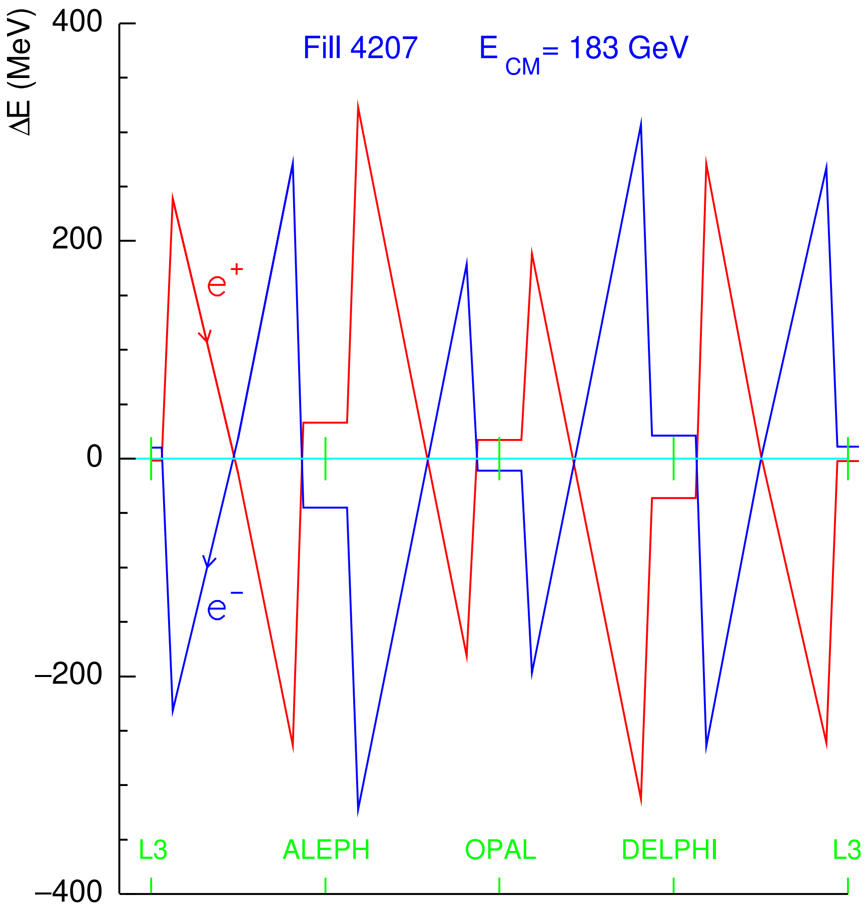
NMRs used to measure any change in the $\oint B d\ell$ of LEP



RF Corrections

LEP2 RF in 1997:





The Real Worry:

Energy loss at 91.5 GeV is $\sim$ 2 GeV/turn $\approx 2\%$ of $E_{\rm beam}$!

$\Rightarrow$ The energy loss per arc must be understood at the 1-2% level

Preliminary error summary

For the 1997 Running at $E_{\mathrm{CM}} = 183$ GeV

Source	Error on E_{beam} [MeV]
Extrapolation from NMR–polarisation:	
NMR rms/$\sqrt{N}$ at physics energy	10
Different E_{pol} fills in fit	5
Flux-loop test of extrapolation:	
NMR Flux Loop difference at physics energy	20
Field not measured by Flux Loop	5
Optics difference (90/60 *vs.* 60/60)	4
Polarisation systematic	1
$\mathrm{e^+e^-}$ energy difference	2
Corrector effects	3
Tide	1
Dipole rise modelling	1
IP specific corrections ($\delta E_{\mathrm{CM}}/2$):	
RF model	4
Dispersion	2
Total	25

$\Rightarrow$ Error small enough for *NOW*, but not yet down to 10–15 MeV

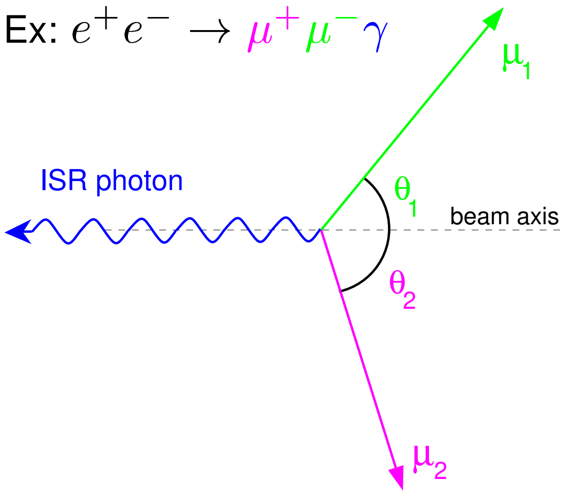
$\Rightarrow$ Need More Precise Check of Extrapolation at Physics Energy

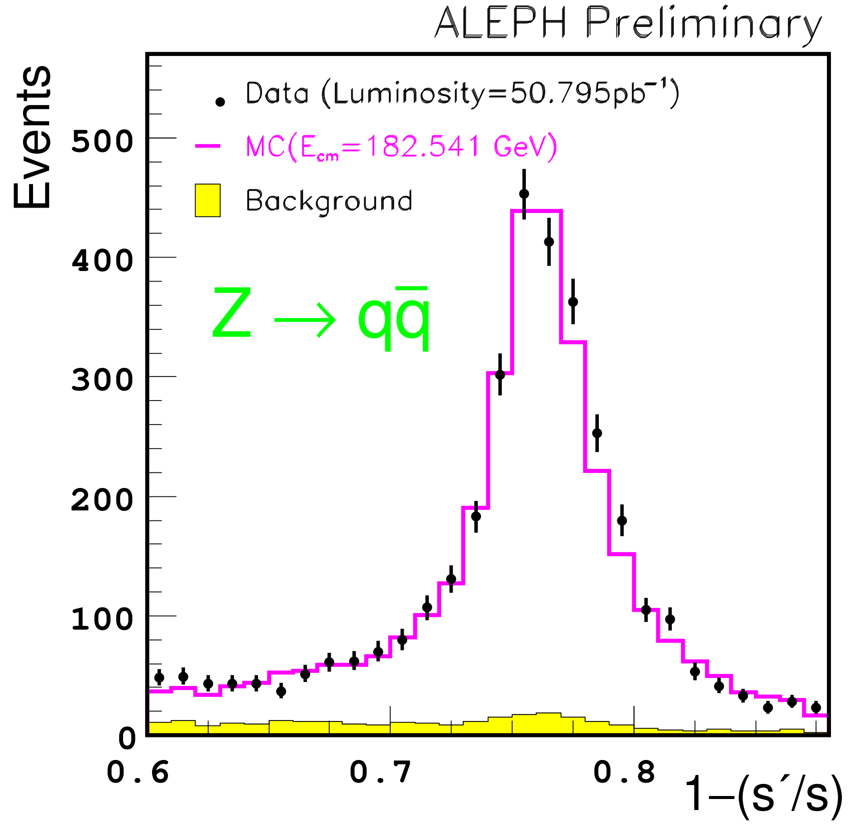
Measuring E_{beam} at Physics Energy

Radiative Return Events in Data

Use the incredibly precise M_Z measurement to get the beam energy

Ex: $e^+e^- \to \mu^+\mu^-\gamma$



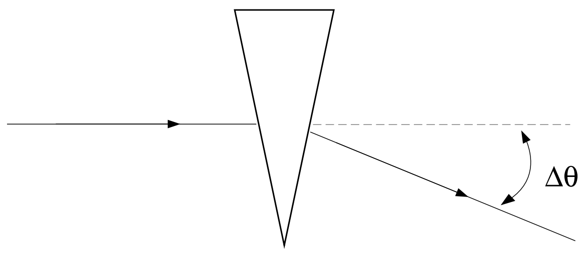


+ independent measure of E_{beam}
+ statistics scale with WW events
+ μ-pairs: $\delta E_{\mathrm{beam}} \sim 40\ \mathrm{MeV}$ (Σ LEP2)
+ hadrons: $\delta E_{\mathrm{beam}} \sim 16\ \mathrm{MeV}$ (Σ LEP2)
+ ISR Systematics look OK (YSF3ff/Jadach)
− Hadronisation Systematics?

183 GeV Result from ALEPH:

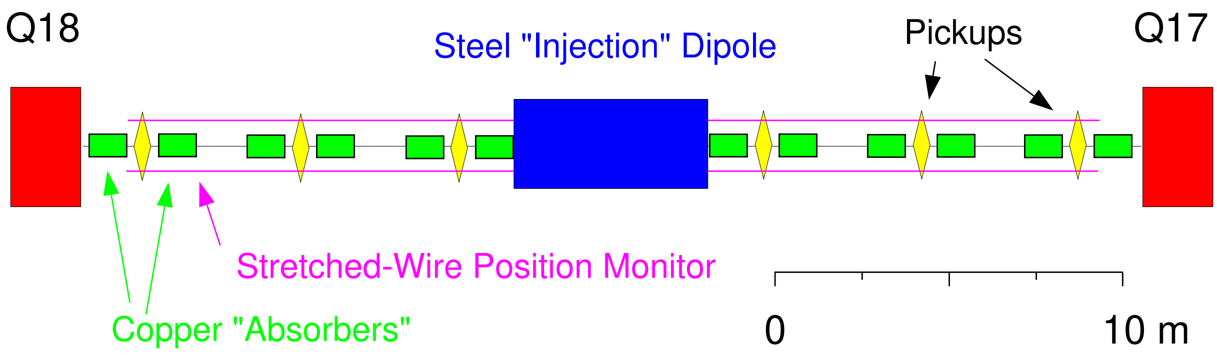
$$\delta E_{\mathrm{beam}} = \pm 0.110(\mathrm{stat}) \pm 0.53(\mathrm{syst})$$

Measuring $E_{\rm beam}$: Spectrometer Concept



$$\Delta\theta \propto \frac{\oint B \cdot d\ell}{E_{\rm beam}}$$

LEP Implementation:



GOAL: Measure change in $\Delta\theta$ at different energies to

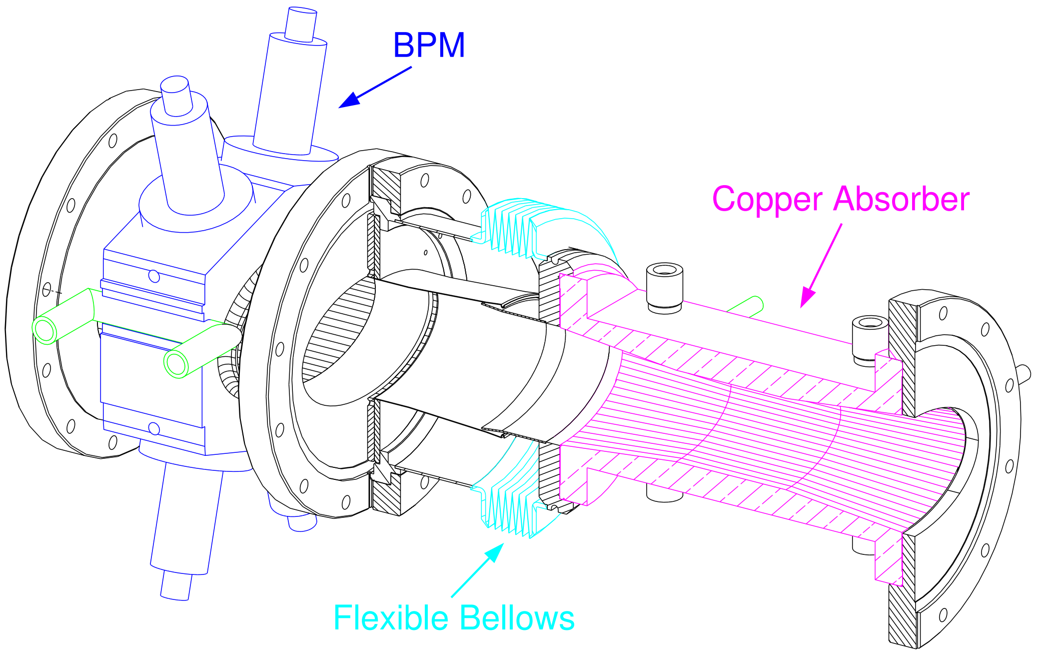
1×10^{-4} precision (10 MeV at $E_{\rm beam}$ of 100 GeV)

Tolerances/Requirements:

- A precisely-mapped dipole in the LEP lattice with NMR(s) to track B-field
  Dipole ramps with LEP ($\Delta B/B \sim 5 \times 10^{-5}$)
- Precision Beam Position Monitors to measure the beam trajectory
  (Mechanical/Thermal/Electronic stability $\sim 1\ \mu$m over $\sim$ hours)

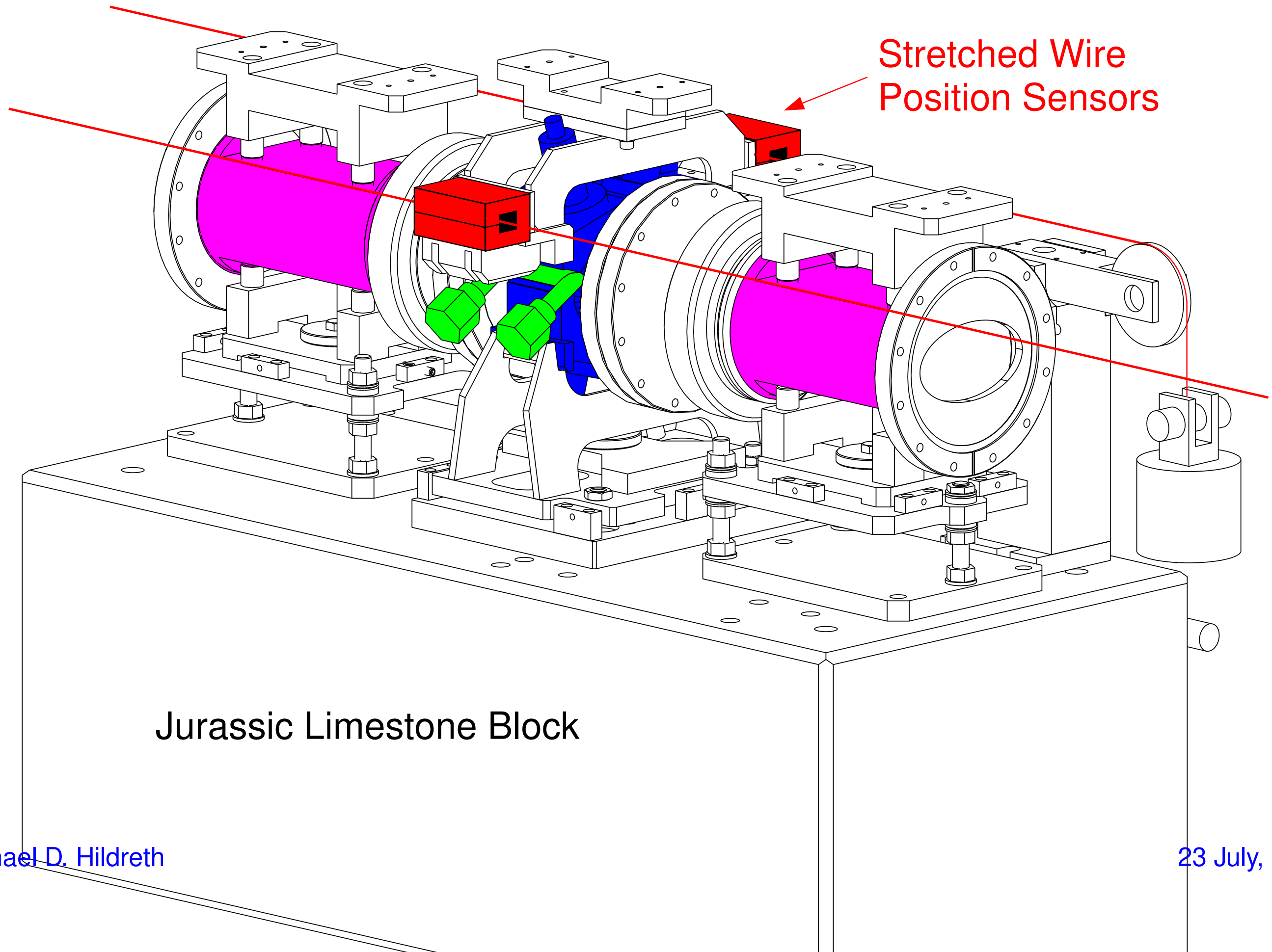
Spectrometer Installation

Beam Pickup and Absorber Assembly:



Measurement Station:

("One Arm" installed for '98)



LEP2 Beam Energy: Conclusions

- **Great Success for Polarisation measurements in 1997**
  - ⋆ 5 Fills with multiple energy points
  - ⋆ Triple the extrapolation “lever arm” from 1996
  - ⋆ First real test of magnetic “linearity” at LEP2 Energies
  - ⋆ Error fine for now, *too big* for final LEP2 result
- **Independent Cross Check(s) of Beam Energy will be available**
  - ⋆ Radiative Returns will provide a measurement from data
  - ⋆ Spectrometer will be partially operational in 1998, ready in 1999

Stay Tuned!