The LEP Spectrometer Project

Precision Measurement of the

LEP2 Beam Energy

SL Seminar

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Overview

Introduction/Motivation — Mike

- Why Measure M_W?
- The LEP2 Energy Measurement
- The LEP Spectrometer
- Strategy for Energy Calibration

Implementation — Bernd

- Spectrometer Design and Installation
- Measurements/Goals for 1998
- Magnet Mapping

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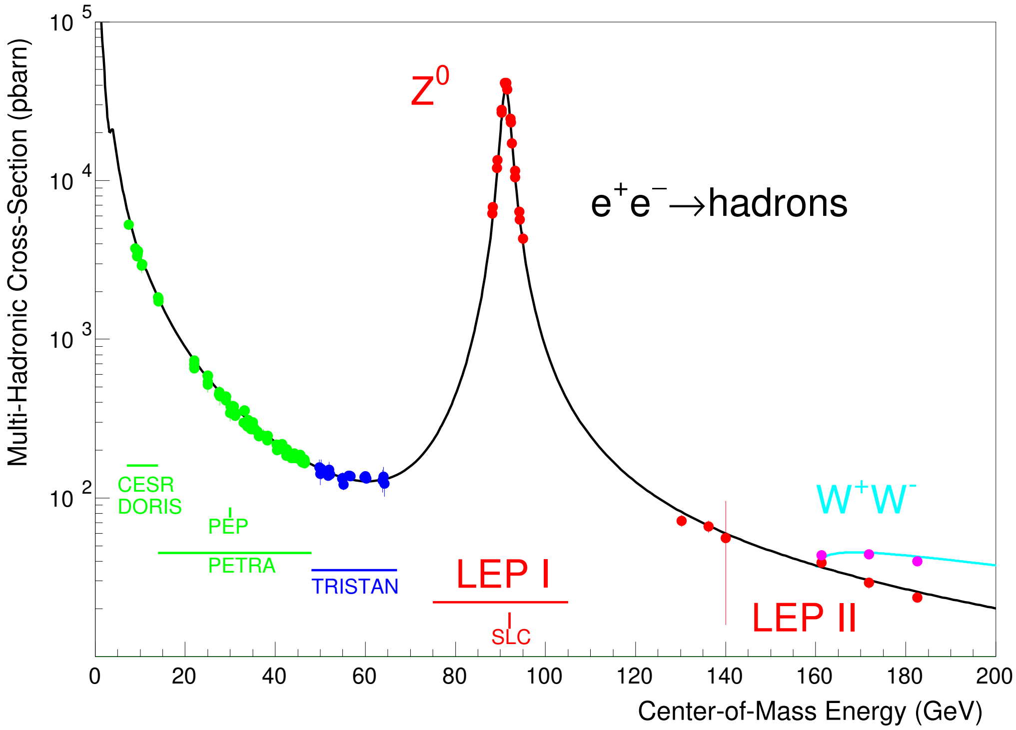
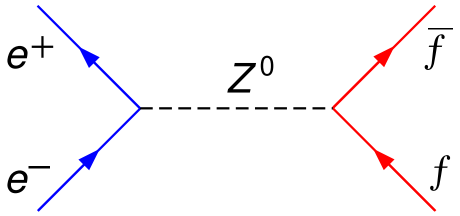
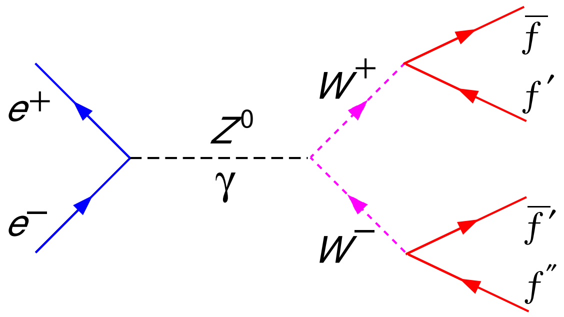
Introduction: LEP Facts of Life

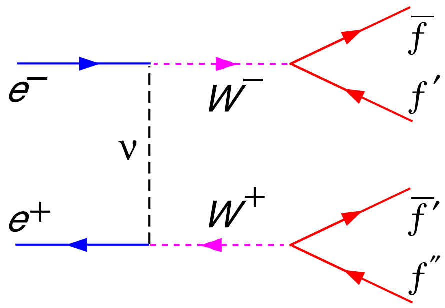


LEP I (1989-1995): 4×10^6 Z/experiment



LEP 2 (1996-2000?): 5000 W pairs/experiment

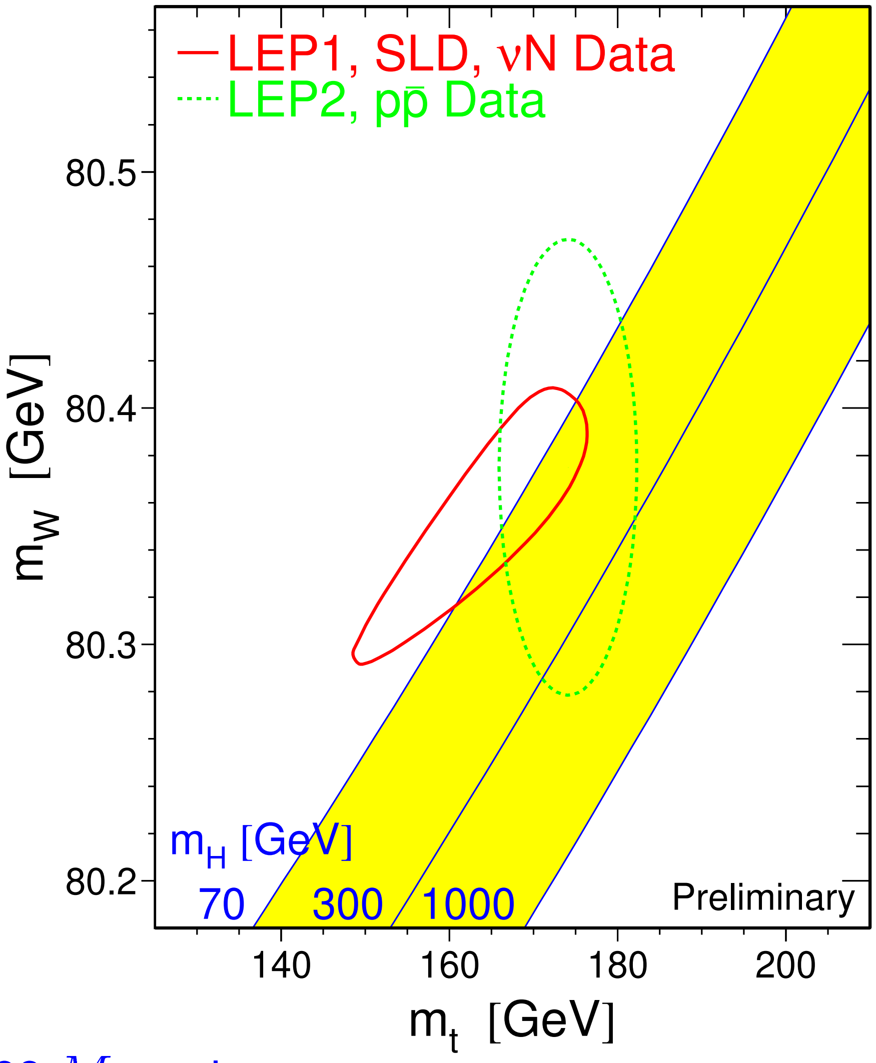




Introduction: Electroweak Observables

Why Measure M_W?

Precision Measurements of the Electroweak parameters (like M_Z) at low energy allows us to *predict* quantities like M_W :



Moriond '98 M_W values:

$$M_W(\mathrm{LEP2} + \mathrm{pp}) = 80.375 \pm 0.064\,\mathrm{GeV}$$
$$M_W(\mathrm{LEPI} + \mathrm{SLD} + \nu\mathrm{N}) = 80.351 \pm 0.040\,\mathrm{GeV}$$

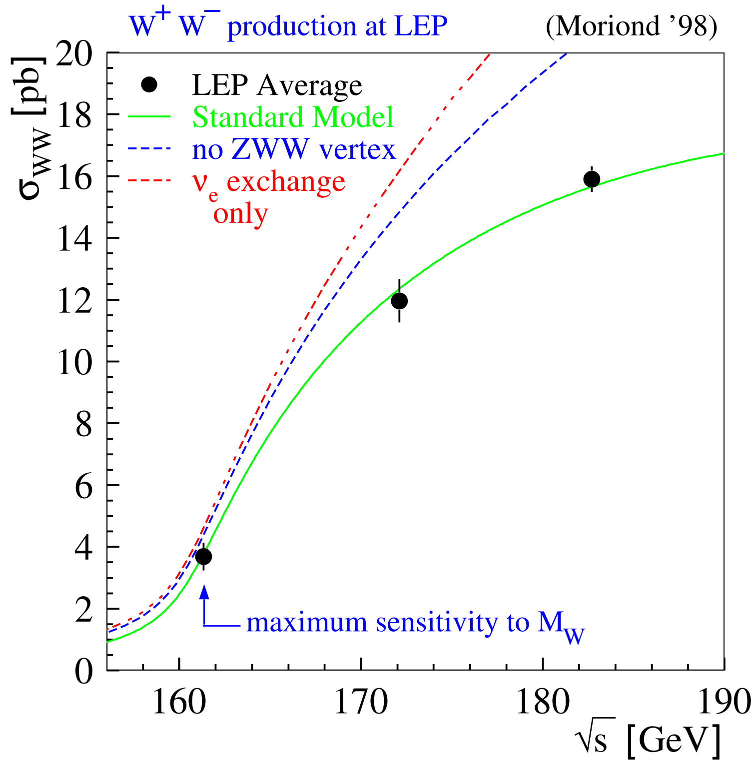
$\Rightarrow$ Test if the Higgs Mechanism is really responsible for mass

$\Rightarrow$ Different Parameters are affected by New Physics differently:

First glimpse beyond the Standard Model?

LEP2: How to Measure M_W

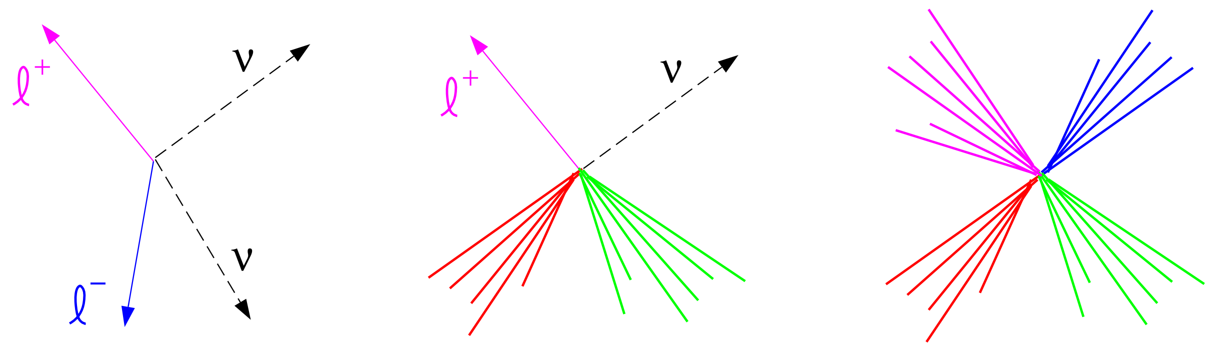
Way # 1: Measure the Production Cross-Section



$\Rightarrow$ Similar to Z^0 Lineshape measurement, many fewer Ws

Way # 2: Direct Reconstruction using Event Kinematics

$\mathrm{W^+W^-} \rightarrow \ell^+\nu_\ell\ell'^-\overline{\nu}_{\ell'}$ $\quad \mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ $\quad \mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$



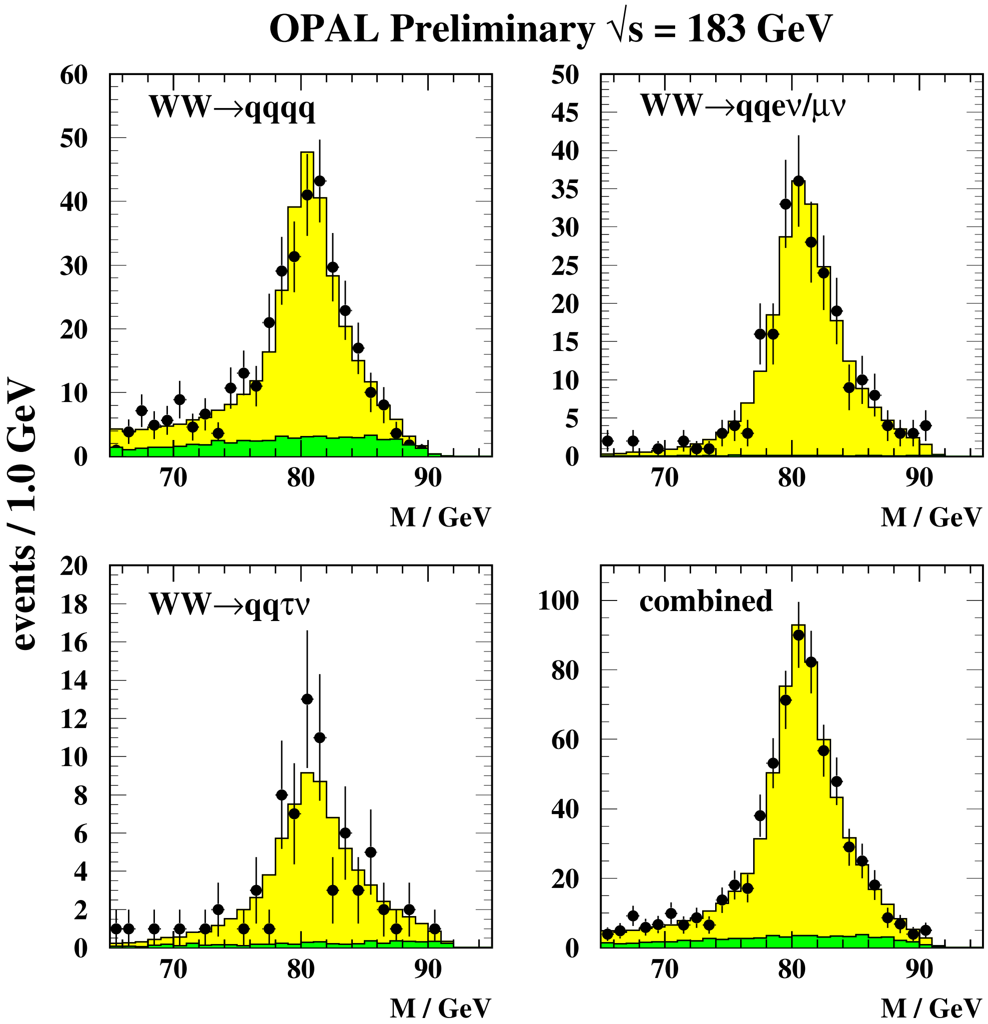
lepton momenta jet-jet mass jet-jet: 3 combinations

Kinematic fits (Conservation of $E, \vec{p}$) used for reconstruction

$$\delta M_W \approx \delta E_{\mathrm{beam}}$$

W Mass by Direct Reconstruction

Example from OPAL:



OPAL Direct-Reconstruction Result for Moriond '98:

$$M_W = 80.34 \pm 0.14 \pm 0.08 \text{ GeV}$$

LEP-Combined Result for Moriond '98:

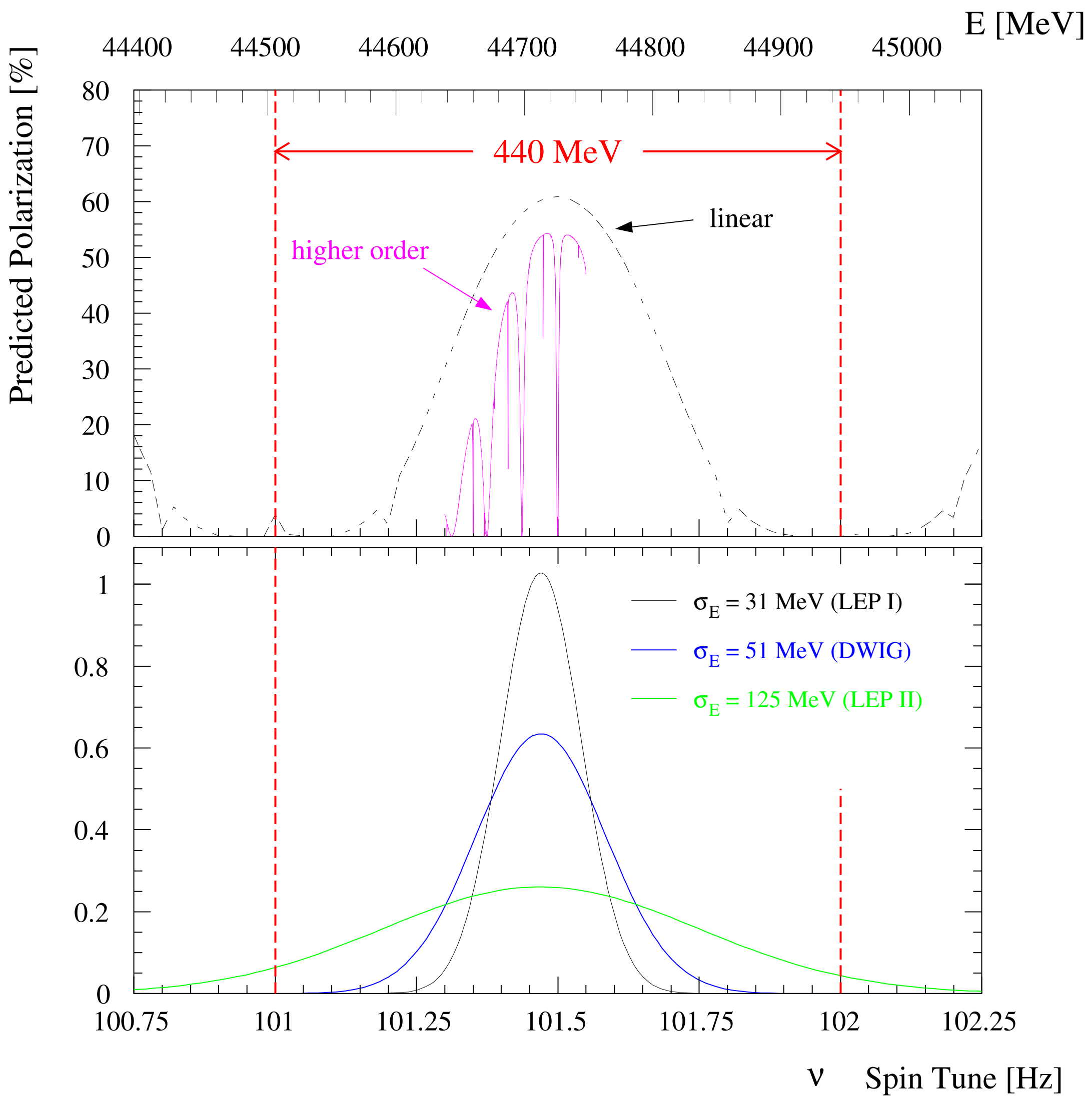
$$M_W = 80.35 \pm 0.09 \text{ GeV}$$

With the complete LEP2 sample of 500 pb^{-1}/experiment the experimental errors on M_W approach 30-40 MeV

$\Rightarrow$ Error on E_{beam} should be 10-15 MeV

Issues for LEP2 Energy Calibration

The Problem:



Natural beam energy spread overlaps the integer depolarising resonances

No resonant depolarisation energy measurements possible at physics energy

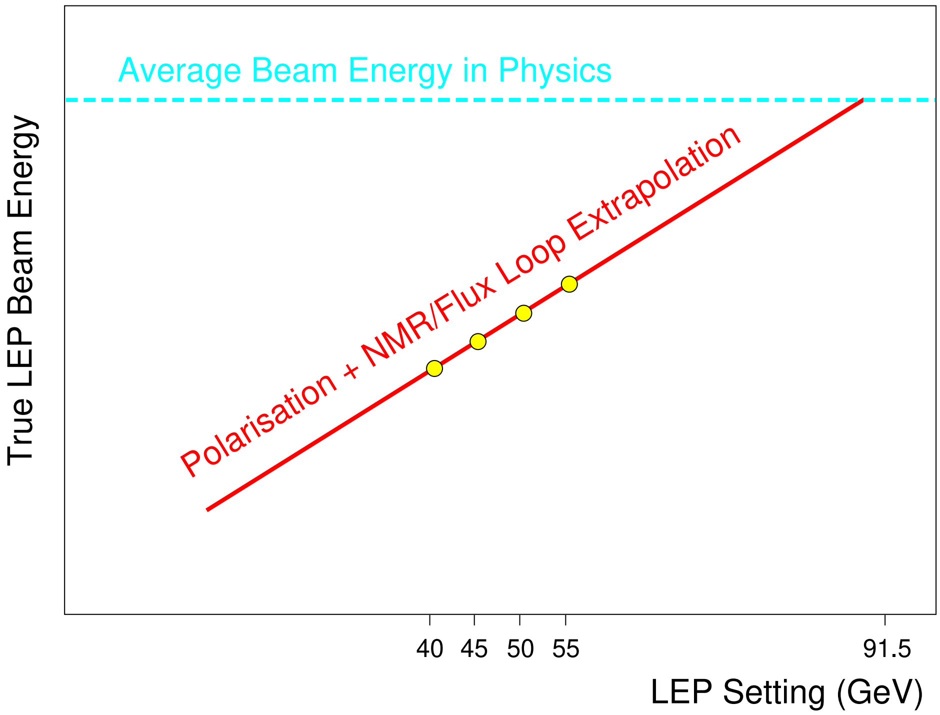
$\Rightarrow$ precise extrapolation from lower energy using other measures of $\oint B d\ell$

$\Rightarrow$ Resonant Depolarization needed at as high an E_{beam} as possible

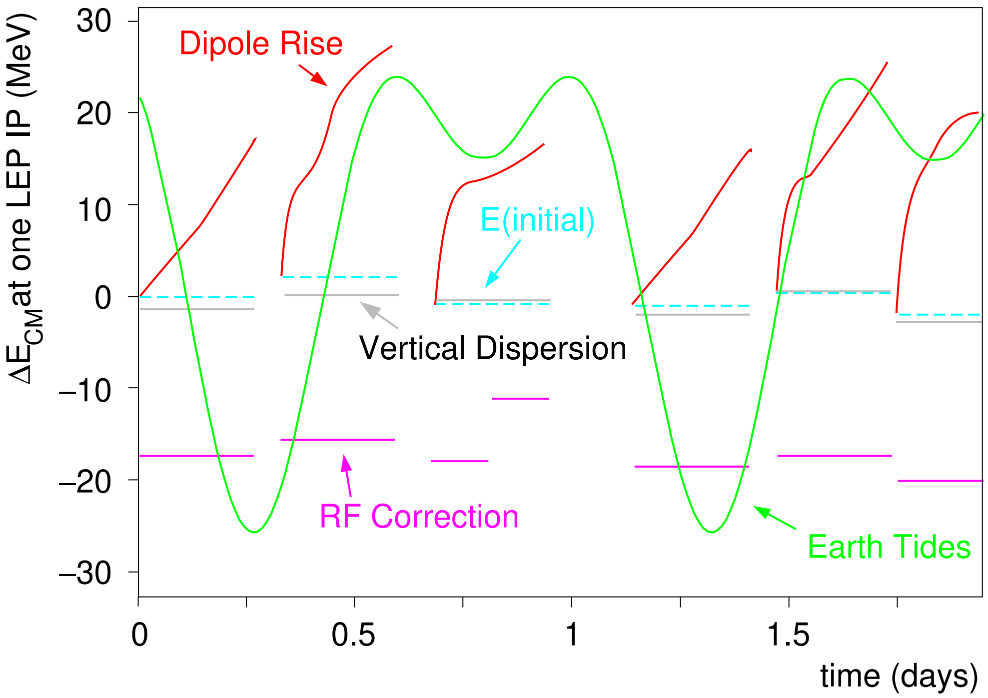
Overview of LEP2 Energy Determination

The LEP 2 Energy Model consists of two parts:

Part 1: Magnetic Extrapolation to set overall Energy Scale



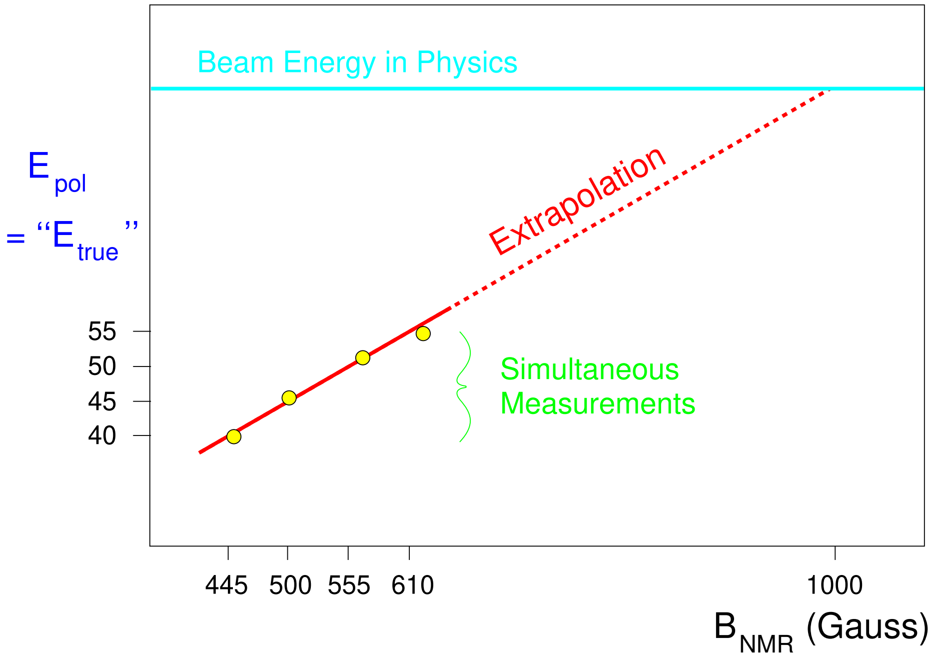
Part 2: Calculation of Fill-to-Fill Energy Variation at LEP IPs



Same effects as LEPI, some scale with E_{beam}

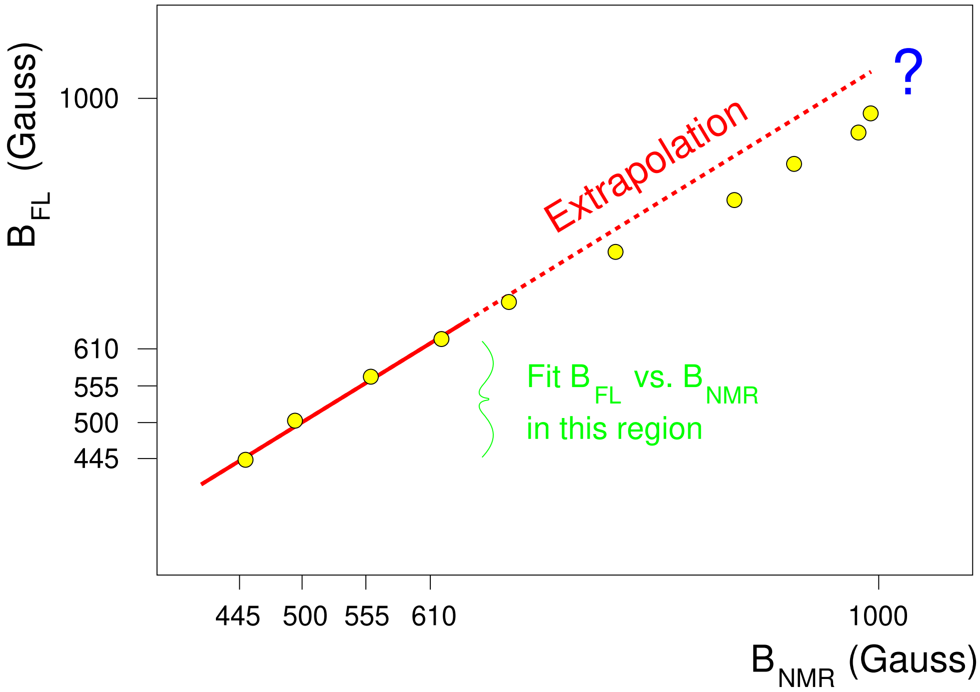
Extrapolation Method

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

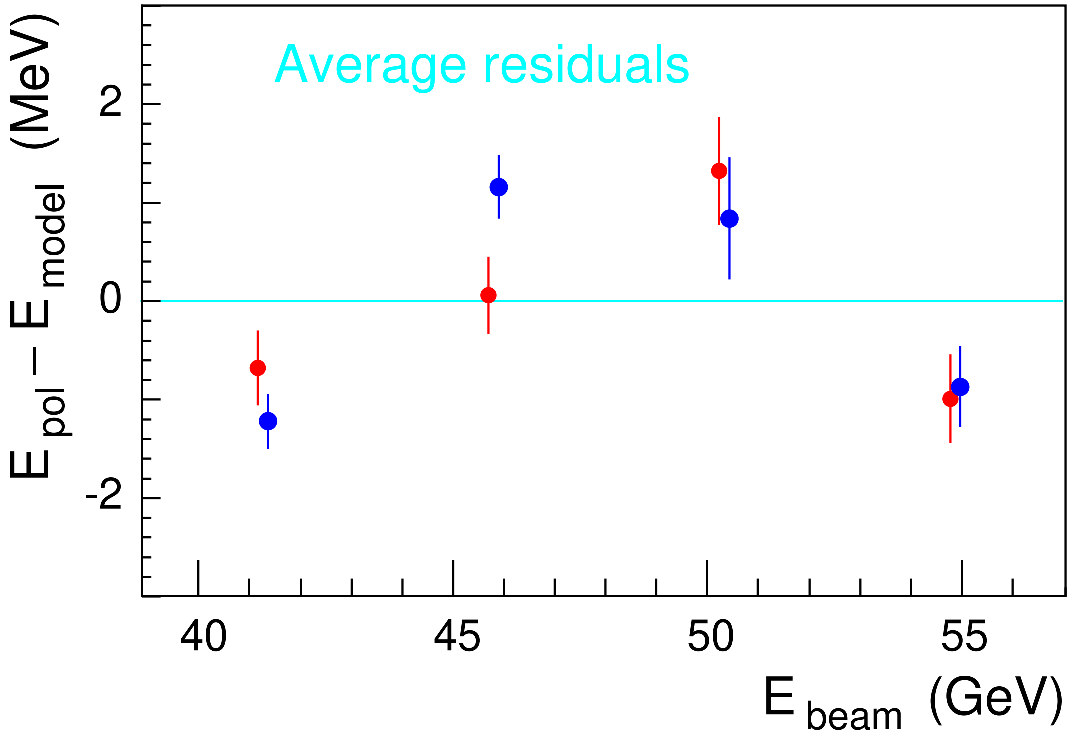


"$\oint B \cdot d\ell$" vs. "$\oint B \cdot d\ell$"

Extrapolation Method: Real Data

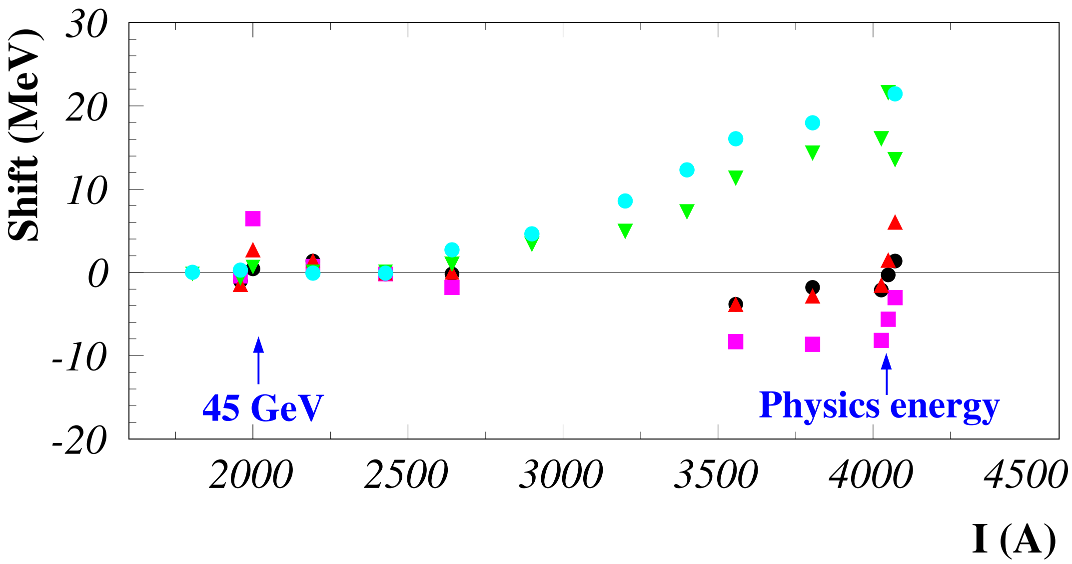
Assume $E_{\rm pol} = a^i + b^i B^i_{\rm NMR}$ for each NMR $i = 1, 16$

Fit to all Polarisation Data



Linearity looks good over 15 GeV

Cross Check NMRs and Flux Loop



Up to 20 MeV Difference at Physics Energy

Preliminary error summary

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

What's the REAL Extrapolation Error?

Can we trust the Magnetic Extrapolation?

$+$ NMRs and Flux Loop agree on possible non-linear behaviour

BUT

$-$ Large scatter on Flux Loop comparison (30 MeV)

$+$ NMRs/Depolarisation/Flux Loop agree at low energy

BUT

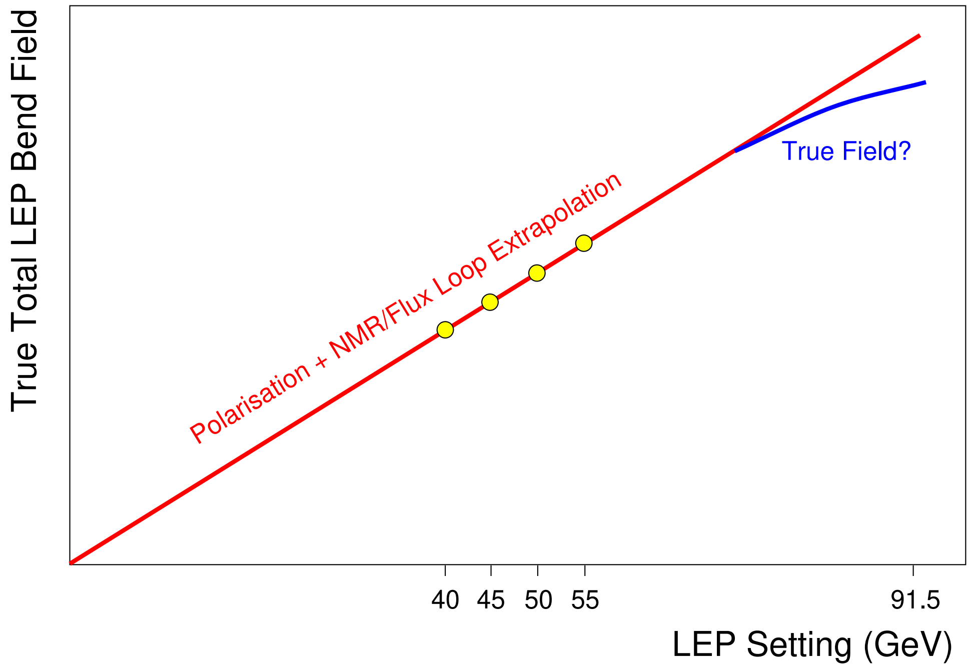
$-$ Flux Loop measures $\sim 97\%$ of the total $\oint B \cdot d\ell$ of LEP

$\rightarrow$ Flux Loop comparison is sufficiently precise IF the unmeasured $\oint B \cdot d\ell$ has the same (non-) linear behaviour as the measured flux to within 1%.

$\star$ more measurements needed to insure that this is true

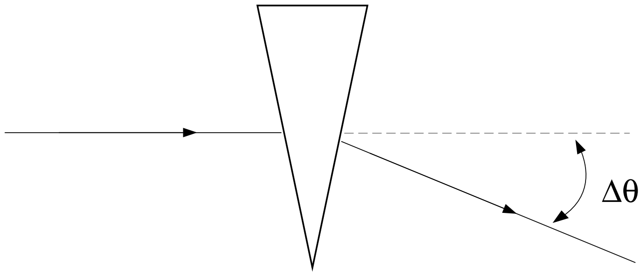
$\Rightarrow$ No Real Cross Check of Extrapolation at Physics Energy

THE WORRY:



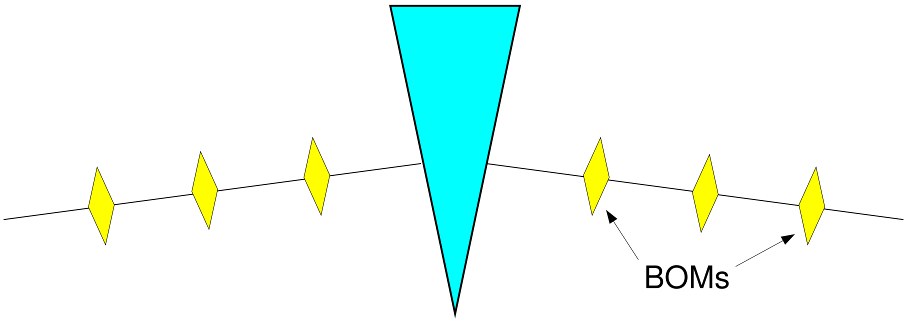
More constraints needed to control extrapolation error

Spectrometer Concept



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

In reality, a spectrometer in LEP is more likely to look like this:



To first order, what is needed is:

- A precisely-mapped dipole somewhere in the LEP lattice with NMR(s) to track B-field and space for BPMs (Dipole ramps with LEP)
- Precision Beam Position Monitors to measure the incoming and outgoing trajectories

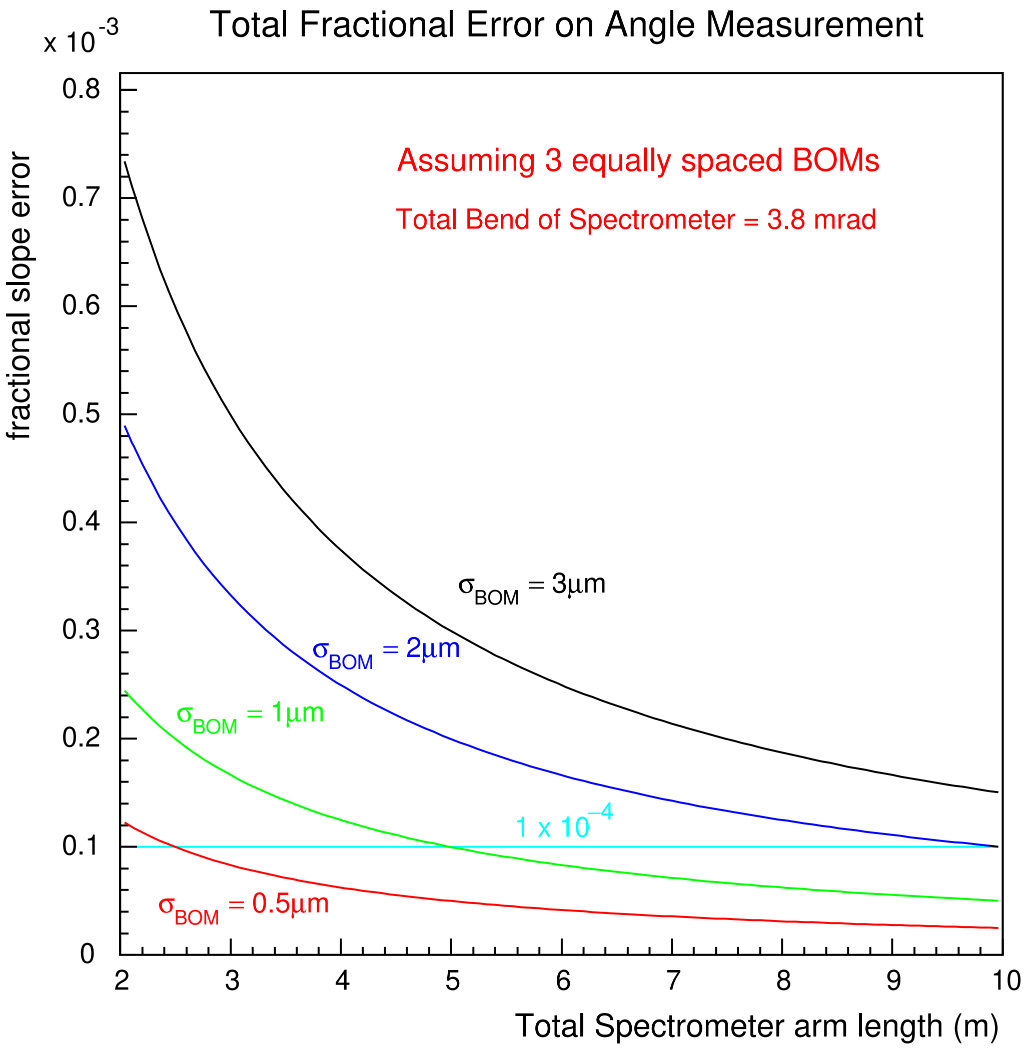
Absolute Positioning not possible $\rightarrow$
Cross-calibrated with Resonant Depolarisation

Measurement of change in $\Delta\theta$ at different energies can provide a linearity check on the $\oint B \cdot d\ell$ of LEP to 1×10^{-4} precision

Tolerances/Requirements

- Map of $\oint B \cdot d\ell$ with a relative precision better than 10^{-4} between polarisable and physics energies (?)
- BOMs with stable resolution on horizontal beam position of $\sim 1\mu m$ ($\surd$)
- Mounting for BOM/beampipe assembly that is stable to a micron (?)
- Position verification so that we know they haven't moved by a micron ($\surd$)
- Special beam pipe with flexible bellows and protection collimators ($\surd$)
- Stability of the entire system for two hours or more (?)

($\surd$ means we think we know how to do this now...)

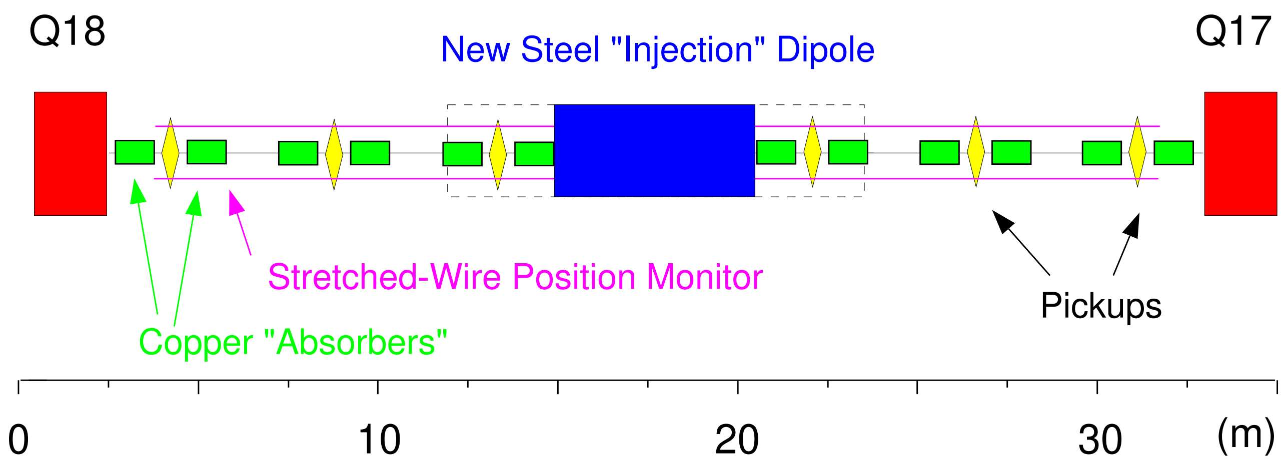


Spectrometer Components

Candidate Technologies:

- LEP Injection Dipole (MBI)
    - + “nice” steel magnet, no ageing effects
    - + standard aperture, easy to accommodate
- Standard LEP pickups, customised electronics
    - + tests results from modified LEP pickups gave $1\ \mu\mathrm{m}$ resolution
    - + new electronics for long-term stability
- Stretched wire (CLIC)
    - + rad-hard, can do $\sim 0.4\ \mu\mathrm{m}$

Final Design (for 1999 Running):



Spectrometer Calibration Strategy

1. Cross-Calibration with Polarisation Measurements

- Magnetic Field ($\oint B \cdot d\ell$) known, but
- No way to measure position of BOM electric center to $1\ \mu\mathrm{m}$
- No way to mechanical position of BOMs to $1\ \mu\mathrm{m}$

$\Rightarrow$ Straight line provided by beams

$\Rightarrow$ Bend Angle from Polarisation Energy

2. Ramp LEP to High(er) Energy

- Magnetic Field known
- Positions of BOMs relative to Polarisation Measurements known

$\Rightarrow$ Measure $E_{\mathrm{HE}} - E_{\mathrm{POL}}$

Procedure can be Cross-Checked with Polarisation

- Stop at intermediate energies where Depolarisation is possible

$\Rightarrow$ Measure $E_{\mathrm{HE}} - E_{\mathrm{POL}}$, compare with $E_{\mathrm{POL}} - E_{\mathrm{POL}}$

The Crucial Issue is Stability:

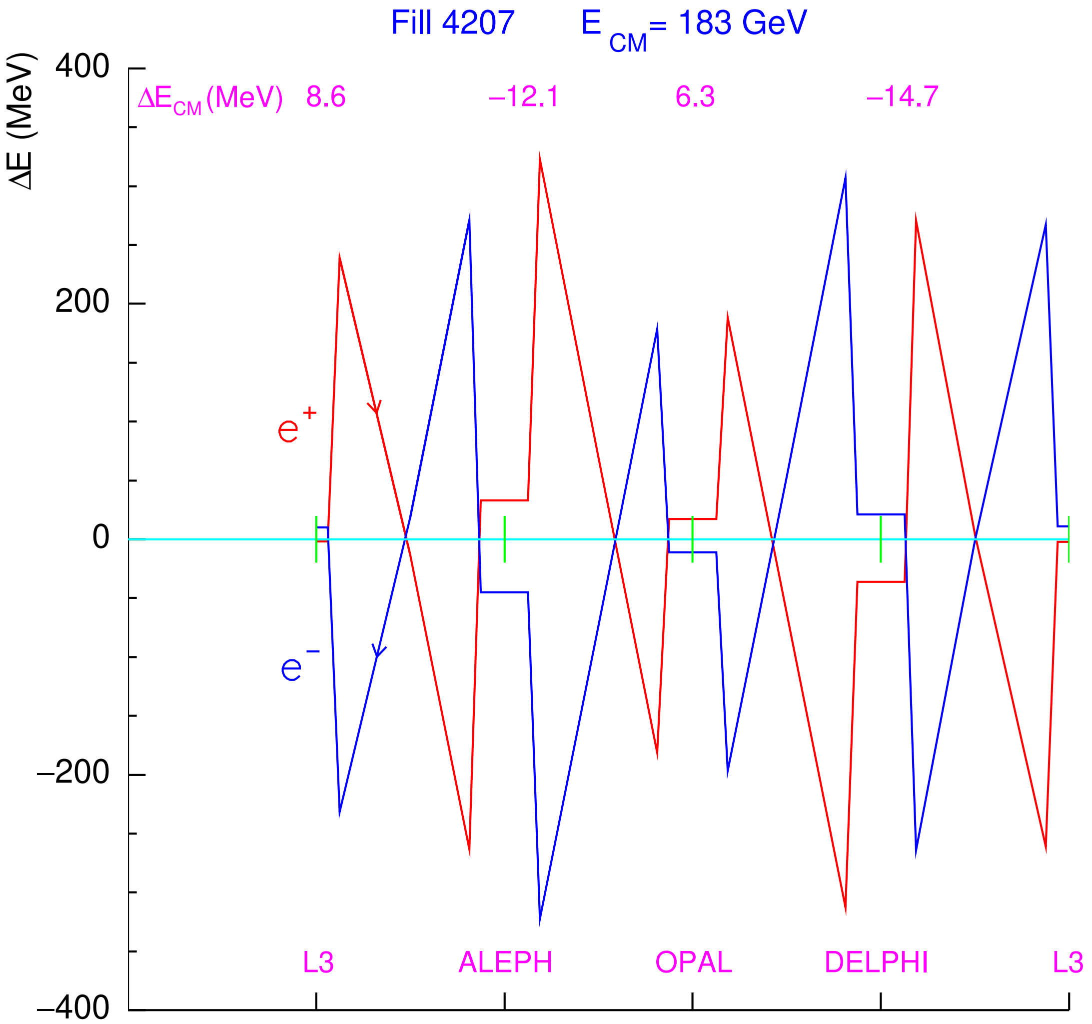
- Large Temperature Gradients will tax mechanical structure
- BOM electronic drift over time?
- In priciple, stability over several hours is required
- Monitoring every LEP fill not required

A Caveat...

The Spectrometer measures at one point in LEP, but

Polarisation measures the Average Energy...

Modelling of Energy Sawtooth is Crucial!



- RF Model needed to get from $E_{\rm POL}$ to $E_{\rm SPECT}$ at Z^0 energy
- Needed again to get from $E_{\rm SPECT}$ to $E_{\rm AVE}$ at High Energy
- Dominant Uncertainty $\rightarrow$ RF Phase on cavities nearest Spectrometer
- $E(e^+) - E(e^-)$ can be measured $\rightarrow$ another constraint

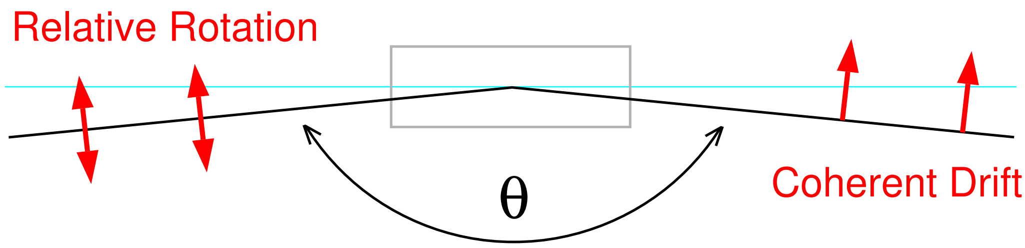
  $\Rightarrow$ additional $\sim 5\ \mathrm{MeV}$ Energy Error from this

Spectrometer Systematic Errors

Errors from BOM Measurement

- BOM Resolution (Measureable)
- Physical or electronic distortions of BOM positions

Anything that changes the apparent measured angle is a problem:



⇒ In principle, available from wire position measurement

Estimation of these errors mainly from data analysis

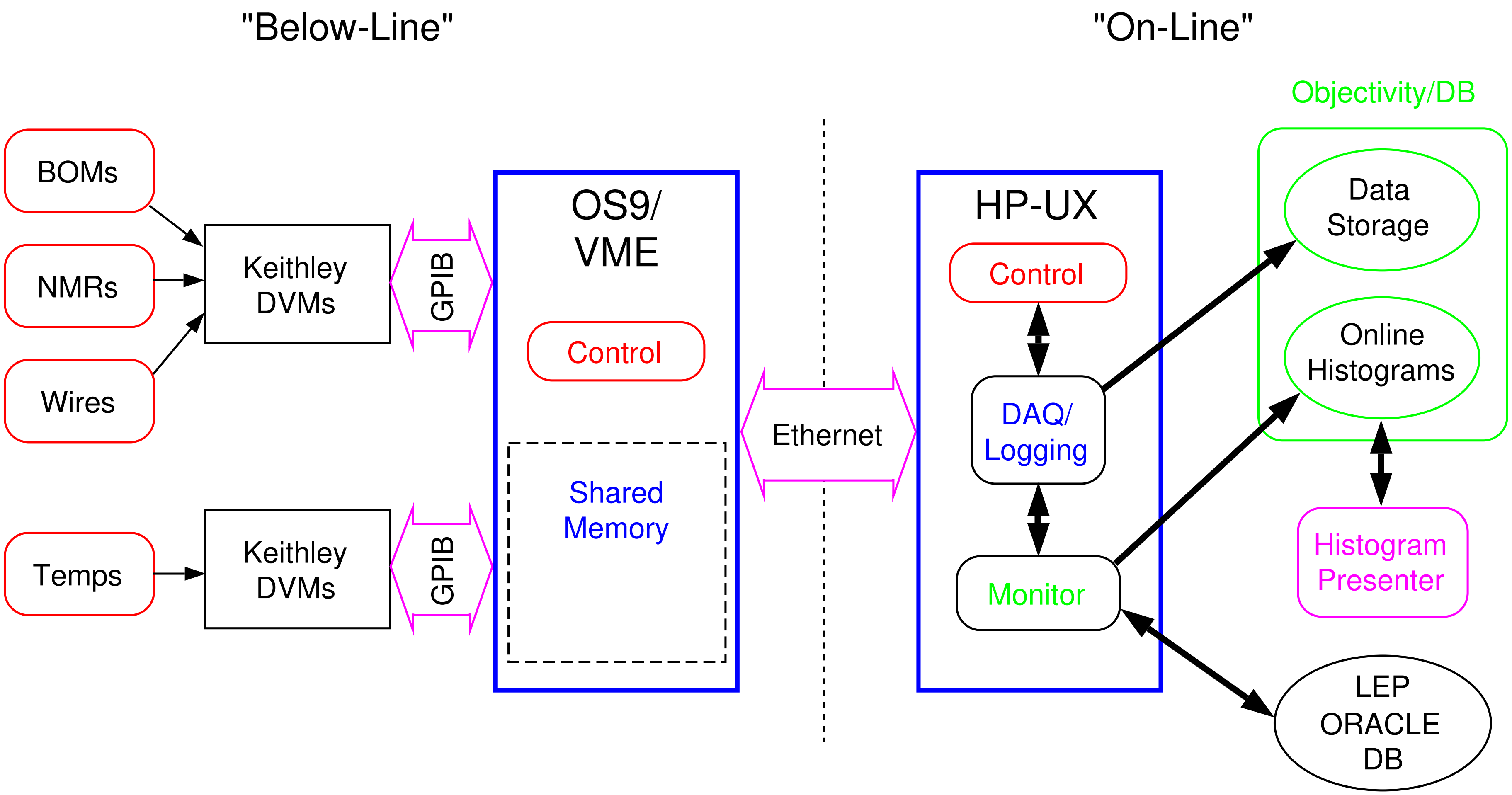
Errors from Magnetic Field Measurement

- Overall Scale Error
- NMR-to-$\oint B \cdot d\ell$ reproducibility
- Fill-to-fill reproducibilty
- Temperature Dependence
- Transport of Magnet Map from Test Stand to Tunnel Environment
- Stray fields in LEP tunnel

⋮

Estimation of these errors mainly from many measurements

Spectrometer DAQ



All this for a few kbytes/sec...