Determination of the centre-of-mass energies for the years 1993, 1994 and 1995 has recently been finalised and submitted for publication:

Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties

(Submitted to The European Physical Journal C)

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The LEP Energy Working Group

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Final energy calibration at LEP 1

Introduction

- Measuring m_Z and Γ_Z
- Resonant depolarisation
- The need for an energy model
- The 1993 and 1995 scans

Modelling the energy variation

- Fill-to-fill energy variation
- Dipole behaviour during a fill
- Differences between physics and calibration
- Interaction point specific corrections
- Error matrix formalism

Beam energy spread

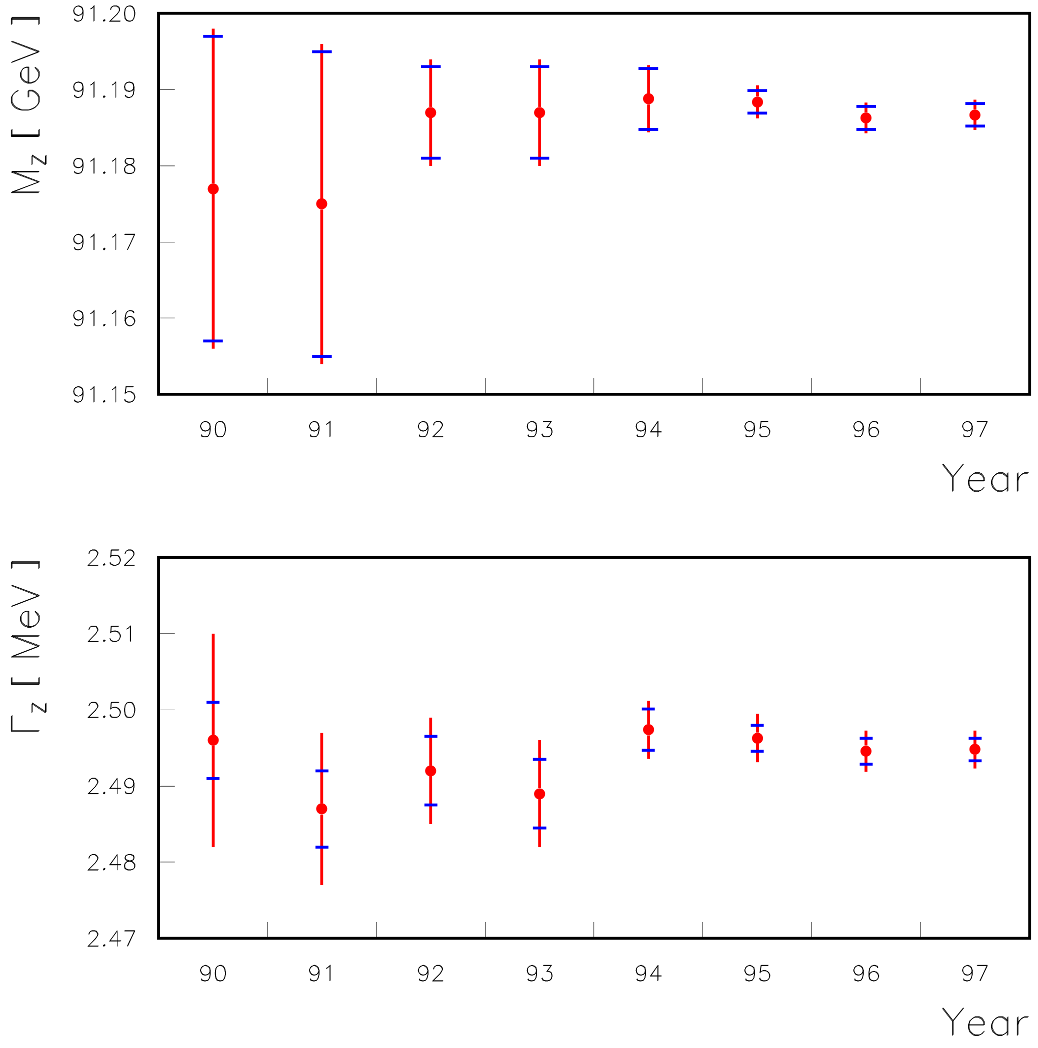
- The energy spread and Γ_Z
- Improved knowledge from 1995

Conclusions

- Summary and lessons for LEP 2

Guy Wilkinson,
20 April 1998

Primary achievement of LEP 1 $\rightarrow$ measurement of Z^0 resonance parameters (in particular m_{Z} and Γ_{Z})



Preliminary *experimental errors*:

$$\Delta M_Z \approx 1.3\,\mathrm{MeV},\ \Delta\Gamma_Z \approx 2.0\,\mathrm{MeV}$$

Collision energy a crucial common systematic

m_{Z} and Γ_{Z} ($+\ \sigma_0$, Γ_{had}, $\Gamma_{l\bar{l}}$, Γ_{inv} etc) determined from resonance scan

Measurements dominated by high luminosity 3 point scans of '93 and '95

In both years offpeak $\sim 20\,\mathrm{pb}^{-1}$ delivered per experiment

It is precision of E_{CM} on offpeak points which matters. Approximately:

$$\Delta m_{\mathrm{Z}} \approx 0.5\,\Delta\,(E_{\mathrm{CM}}^{P+2} + E_{\mathrm{CM}}^{P-2})$$

$$\Delta \Gamma_{\mathrm{Z}} \approx 0.71\,\Delta(E_{\mathrm{CM}}^{P+2} - E_{\mathrm{CM}}^{P-2})$$

Here discuss energy calibration of '93 and '95 scans and peak run of '94

Primary tool of energy calibration is resonant depolarisation (RD)

In LEP beams acquire transverse polarisation. Precession frequency relatable to mean beam energy, E_b

$$\nu_s = \left(\frac{g_e - 2}{2m_e c^2}\right) E_b$$

($\nu_s =$ 'spin tune')

Monitor polarisation with Compton scattered γs, and attempt to deresonate with transverse oscillating B field $\rightarrow\ \nu_s\ \rightarrow\ E_b$

Theoretical error of 0.2 MeV; experimental error 0.5 MeV

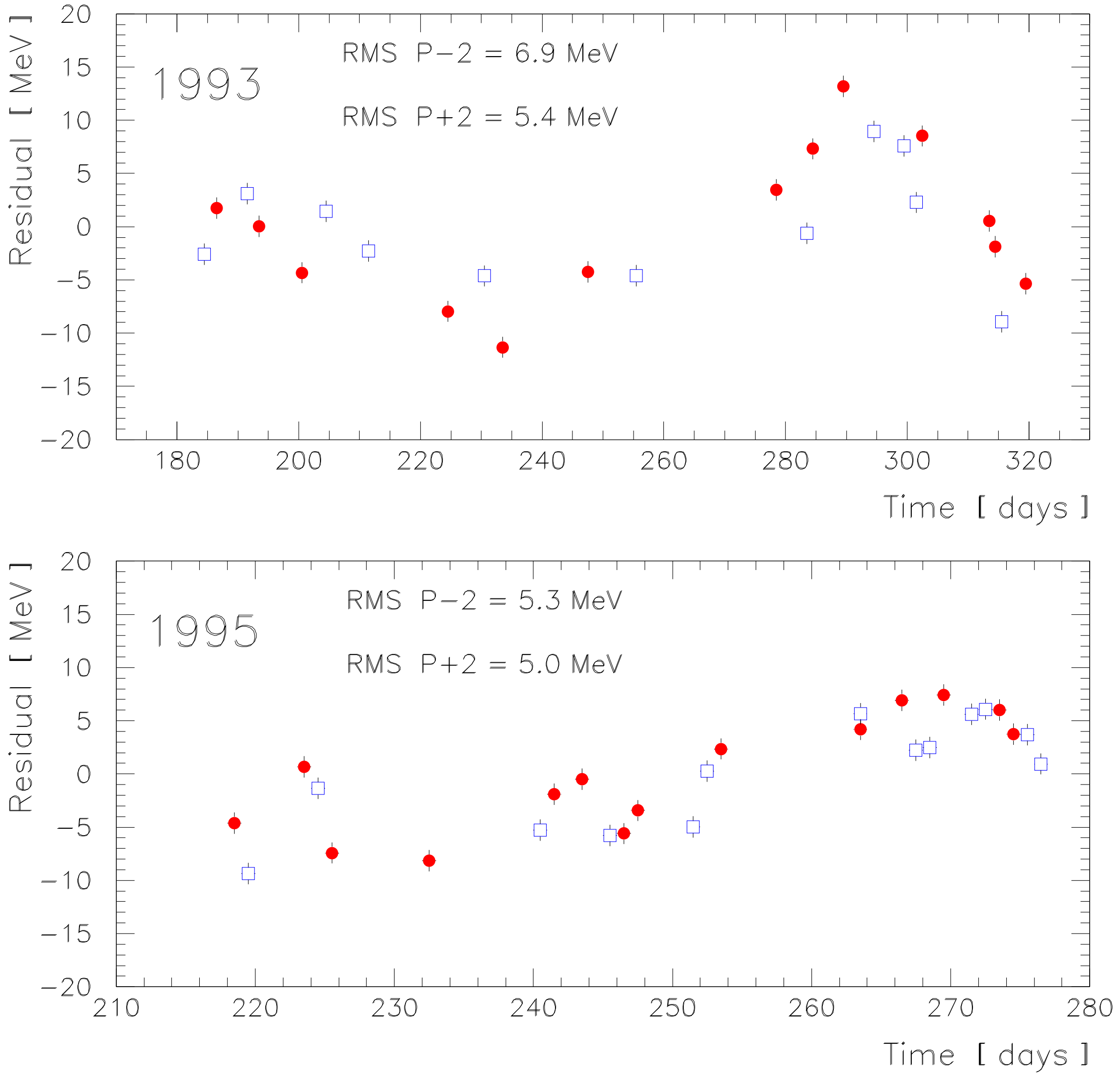
$$\rightarrow \Delta\Gamma_{\mathrm{Z}} \approx 0.4\,\mathrm{MeV},\ \Delta m_{\mathrm{Z}} \approx 0.5\,\mathrm{MeV}$$

But note:

- Performed with separated beams, typically at end of fill
- Difficult procedure $\rightarrow$ not performed every fill
- Typically performed with e^-

But RD is not enough!

Calibrated fills show fill-to-fill scatter:



Energy evolves *between fills*. Assuming same scatter amongst uncalibrated fills implies error of ~ 4 MeV on Γ_Z in '93 ... Unacceptable!

What if conditions during calibration are different from during physics?

What if there is short term energy variation *during fills* ?

What if $2 \times E_b \neq E_{cm}$ at a given interaction point?

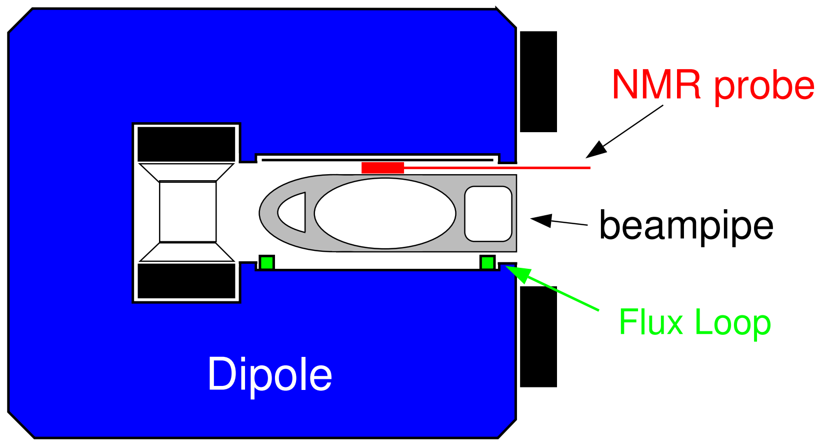
Need to understand and then model

Operation, instrumenation and measurements different in '93 and '95 scans ('94 situation similar to '93)

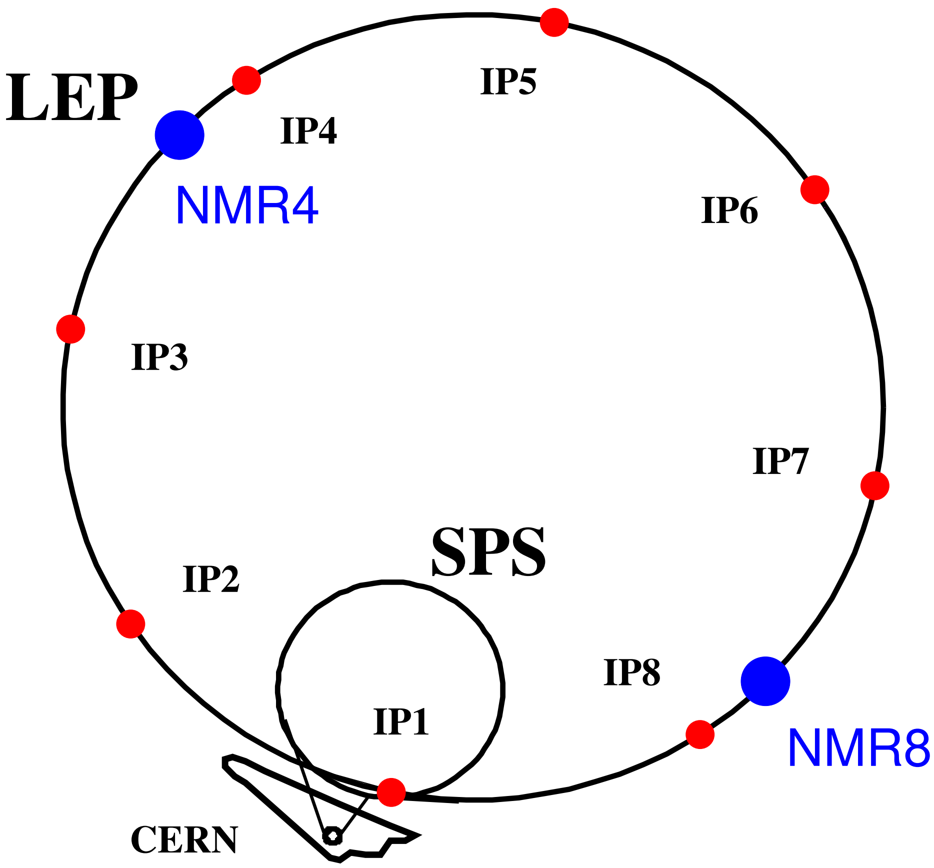
1993	1995
$\sim 40\%$ offpeak lumi calibrated	$\sim 70\%$ offpeak lumi calibrated
	4 physics fills calibrated at end and beginning (+ 2 MD fills)
NMR probe in reference magnet outside tunnel	2 NMR probes installed in tunnel dipoles (NMR4 and NMR8)
Pretzel operation	Bunch train operation
Cu RF	Cu + SC RF
Regulate cooling w.r.t. T of cooling water	Regulate cooling w.r.t. T of dipole cores
	Magnet cycling prior to physics
Varying QFQD current	Constant QFQD current

Additional instrumenation and measurements in '95 throws light on '93

Monitoring the dipole field



In '93 NMR in reference magnet; '95 two NMRs in tunnel



Growth in understanding far from linear (and not always positive)!

Truthful narrative will be attempted, but occasionally sub-plots will be omitted

Model ingredients and considerations

Modelling E_b

Fill-to-fill energy evolution

- eg. ring deformations

Dipole behaviour during a fill

- Trains and temperature

Differences between physics and calibration

- eg. correctors

$$E_{\mathrm{cm}} = 2 \times E_b + ?$$

Interaction point specific corrections

- RF effects
- Dispersion effects

All these & more used to produce energy files (E_{cm} per experiment every fifteen minutes)

Squashing and stretching LEP

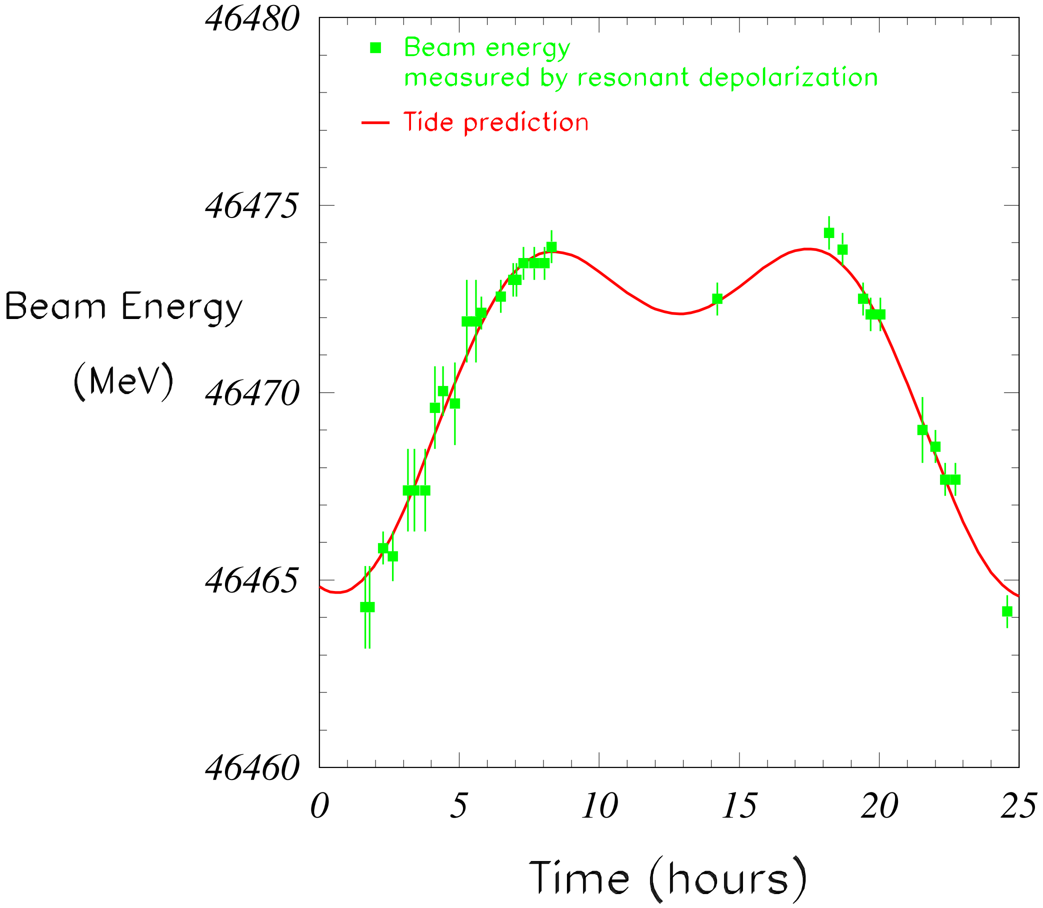
Deformations in the shape of LEP → changes in E_b. Why?

- Beam orbit length fixed by f_{RF}
- LEP changes shape → beams no longer pass through quadrupole centres
- Sees additional bending field → change in energy

$$\frac{\Delta E(t)}{E_0} = \frac{-1}{\alpha} \frac{\Delta C(t)}{C_0}$$

($\alpha = 1.86 \times 10^{-4}$, momentum compaction factor)

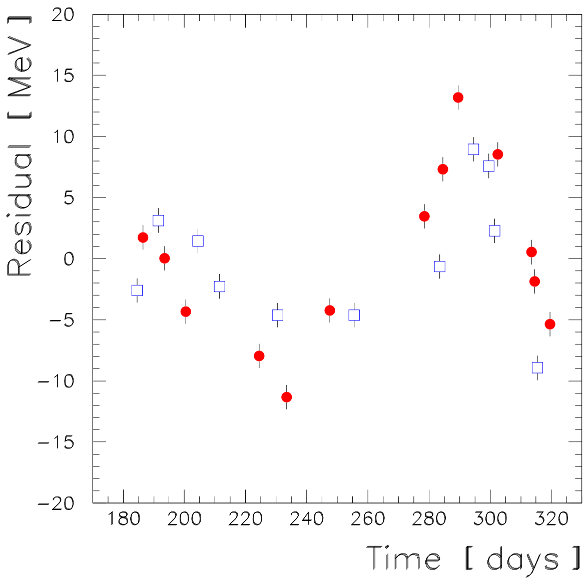
Deformations famously caused by tides (→ ΔE_b with $\tau \sim 1$ hour, amplitude ~ 10 MeV)

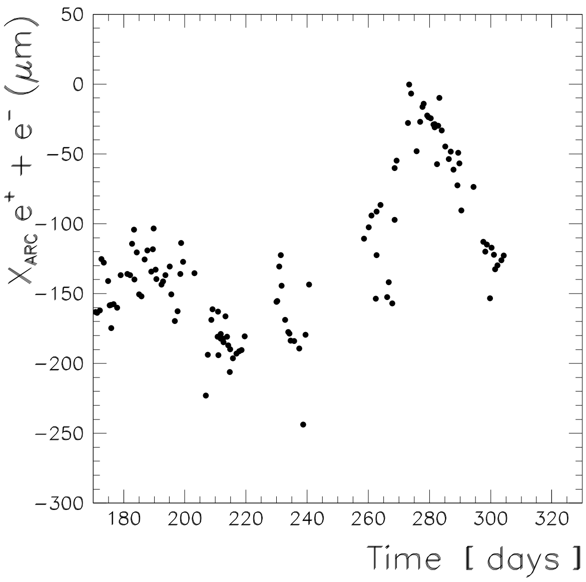


Include tide predictions in model

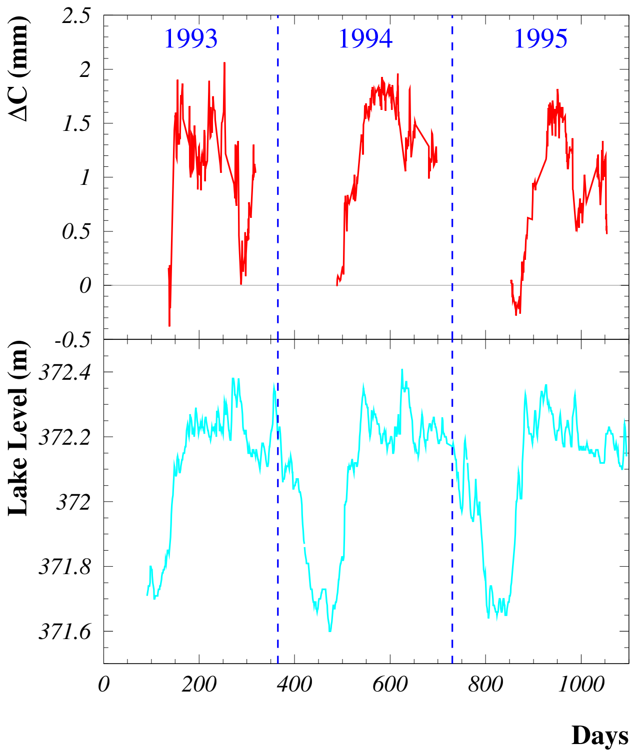
Squashing and stretching LEP (ctd)

Additional long term variation ($\rightarrow \Delta E_b$ with $\tau \sim 1$ week, amplitude ~ 10 MeV) seen by beam orbit monitors (BOMs)





Possibly caused by variations in level of Lac Léman...



...but correction made empirically from BOM data

Uncertainty in modelling of fill-to-fill E_b variation

How to quantify error on modelling of fill-to-fill energy variation?

- Compare model with RD measurements
- Scatter of model-RD now reduced by factor of $\sim 2-3$ w.r.t. original scatter of RD measurements

RMS [MeV]	'93		'95	
	Before	After	Before	After
P-2	6.9	3.9	5.3	3.3
P+2	5.4	1.9	5.0	1.6

- How well mean E_b can be modelled for *calibrated fills* can be used to estimate uncertainty induced by *uncalibrated fills*. Approximately:

$$\Delta E_b = \frac{RMS\sqrt{N_{\mathrm{uncal}}}}{\sqrt{N_{\mathrm{total}}}\sqrt{N_{\mathrm{cal}}}}$$

This contributes errors of (in MeV):

	Δm_Z	$\Delta\Gamma_Z$
'93	1.0	1.4
'95	0.4	0.7
Combined	0.5	0.8

This error accounts for imprecisions in modelling and all unknown effects in fill-to-fill variation

Dipole behaviour in a fill

Pre-'95 orthodoxy:

- Dipoles ramped to a field and remain at that field...
- ...apart from effects of temperature variations which induce monotomic changes

$$\Delta B/B = c_T \, \Delta T$$

where $c_T \sim 10^{-4}$

Bear in mind:

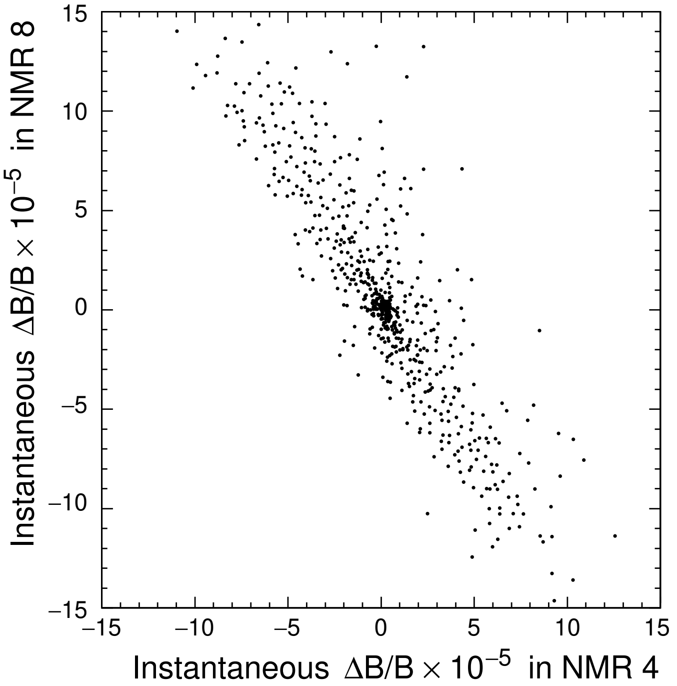
- end of fill depolarisation measurements have (essentially) no sensitivity to dipole evolution during fill

Faint worries:

- NMR in reference magnet exhibited jumps and a small rise (~ 1 MeV in E_b)
- Dedicated MD in '93 to study temperature behaviour had shown energy evolution which did not agree well with this description

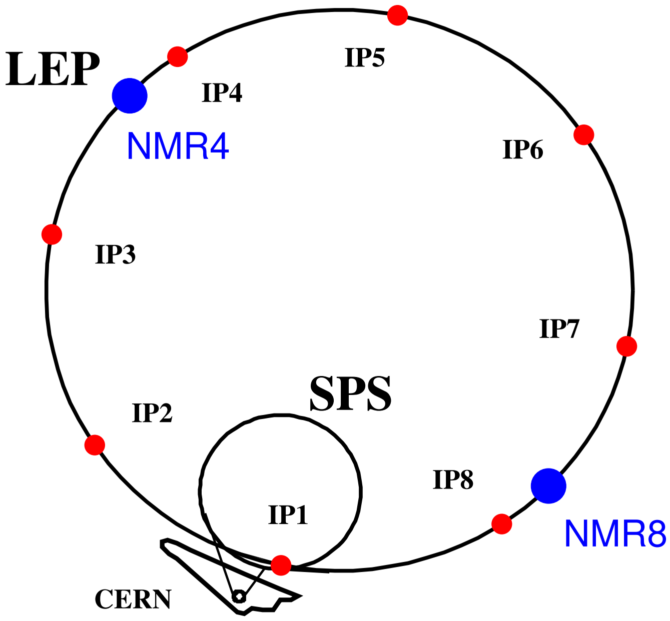
NMR data from tunnel more dramatic than expected

- Significant noise and jumps, particularly in NMR8
- Noise/jumps strongly anticorrelated between magnets

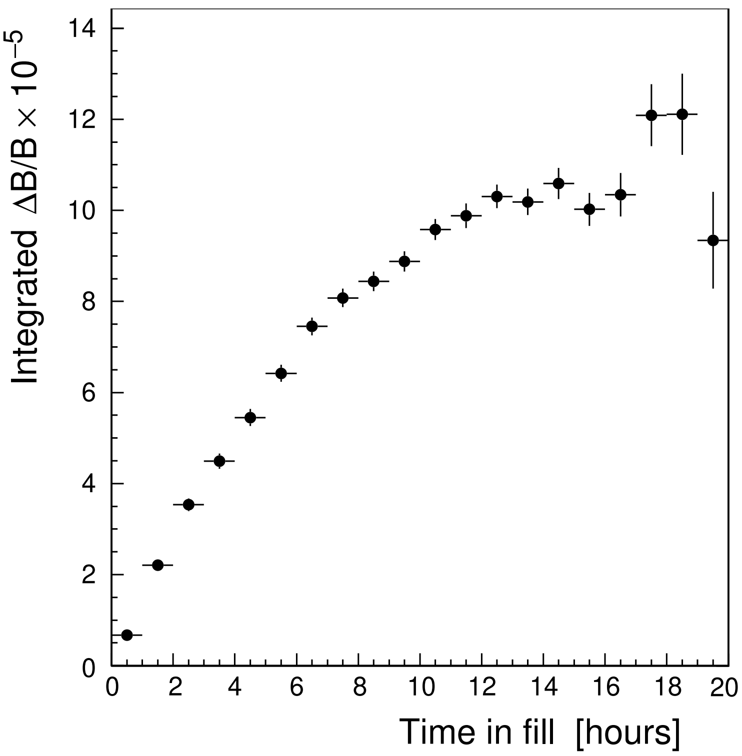


- Noise shows significant dependence on time of day (virtually absent 0–5 am)

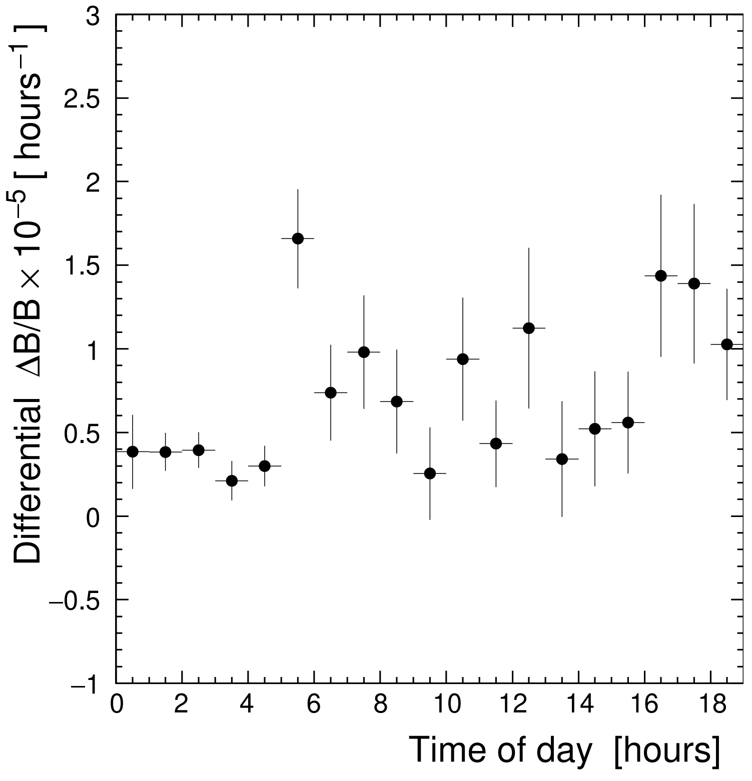
Also seen - a fluctuating current on beampipe itself (magnitude ~ 1 A) with identical behaviour



More worryingly, noise accompanied by rise far in excess of that expected from temperature changes-



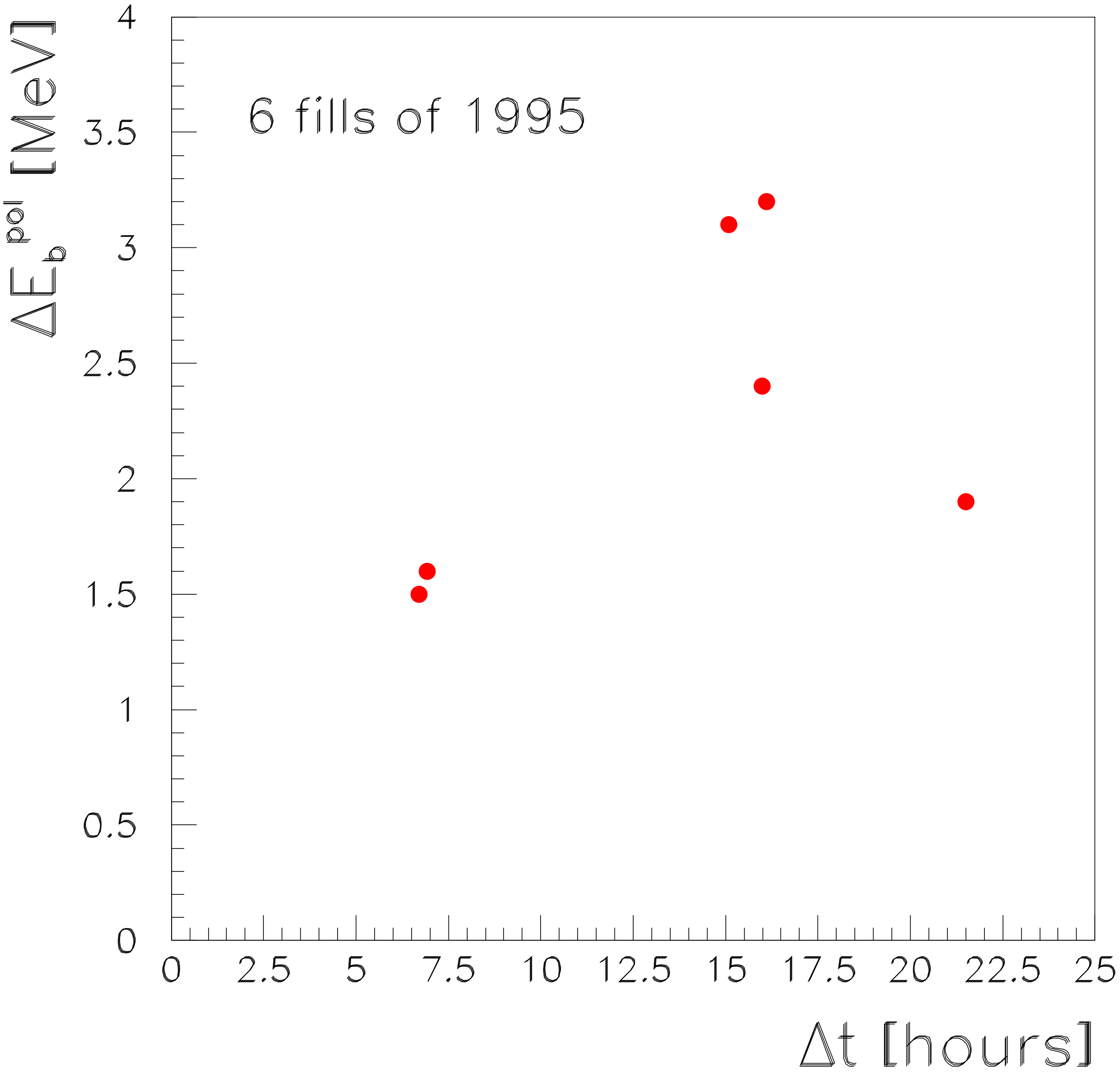
Rise shows same dependence on $t_{\rm day}$ as noise



If seen by beam overestimate $E_{\rm cm}$ scale (and $m_{\rm Z}$) by ~ 5 MeV

So does beam see such a rise?

Yes! Seen in 6 multiple depolarisation fills



Important effect - presumably present in '93 (and '94) also!

Source of rise?

Leakage of current from Geneva-Bellegarde railway back to generator station via LEP...

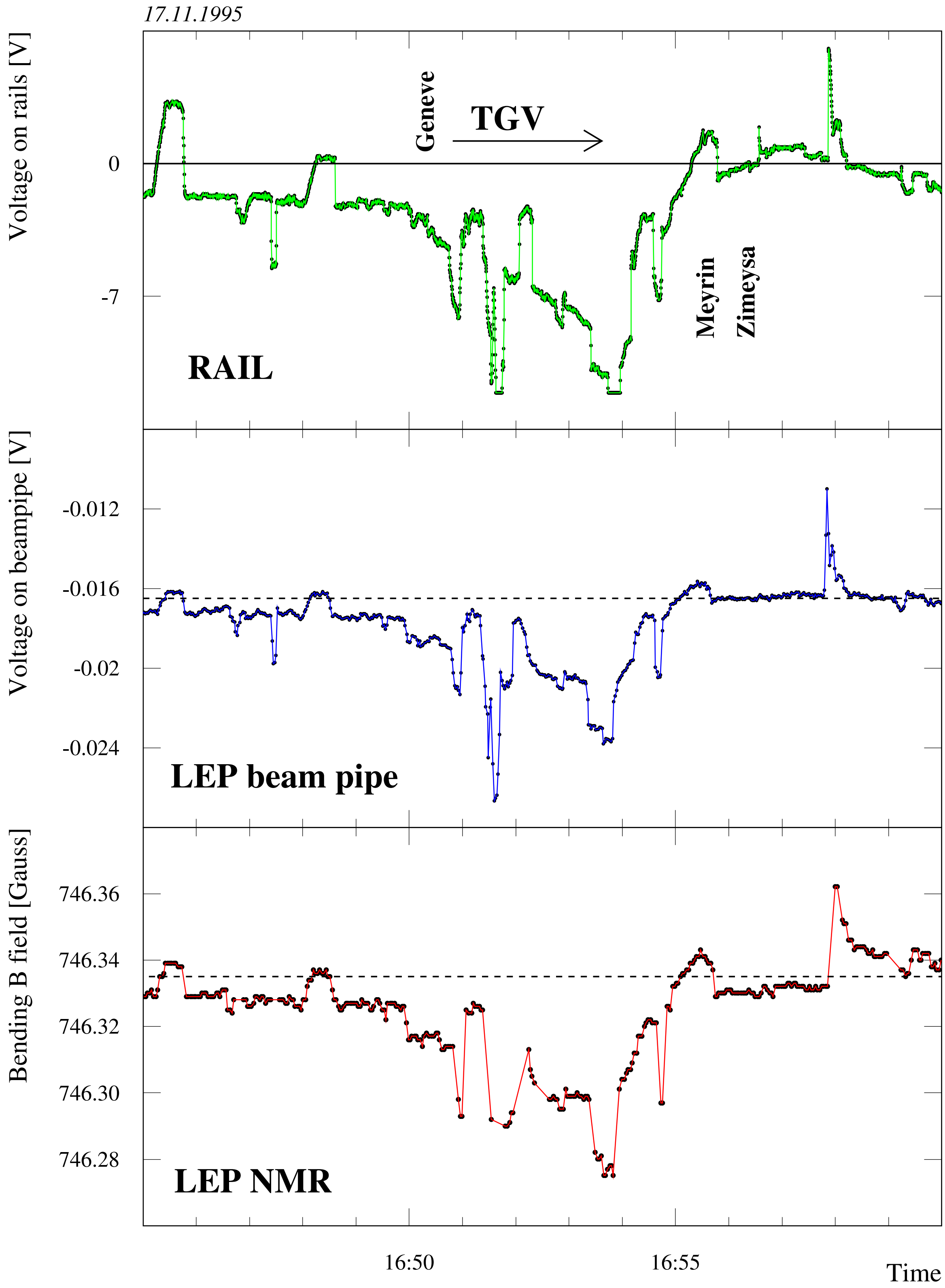
1. Current on beampipe
2. Noise observed by NMRs
3. Stimulates magnets, causing climb up hysterisis loop

(NB no trains between 0 & 5 am!)

Proof and supporting observations:

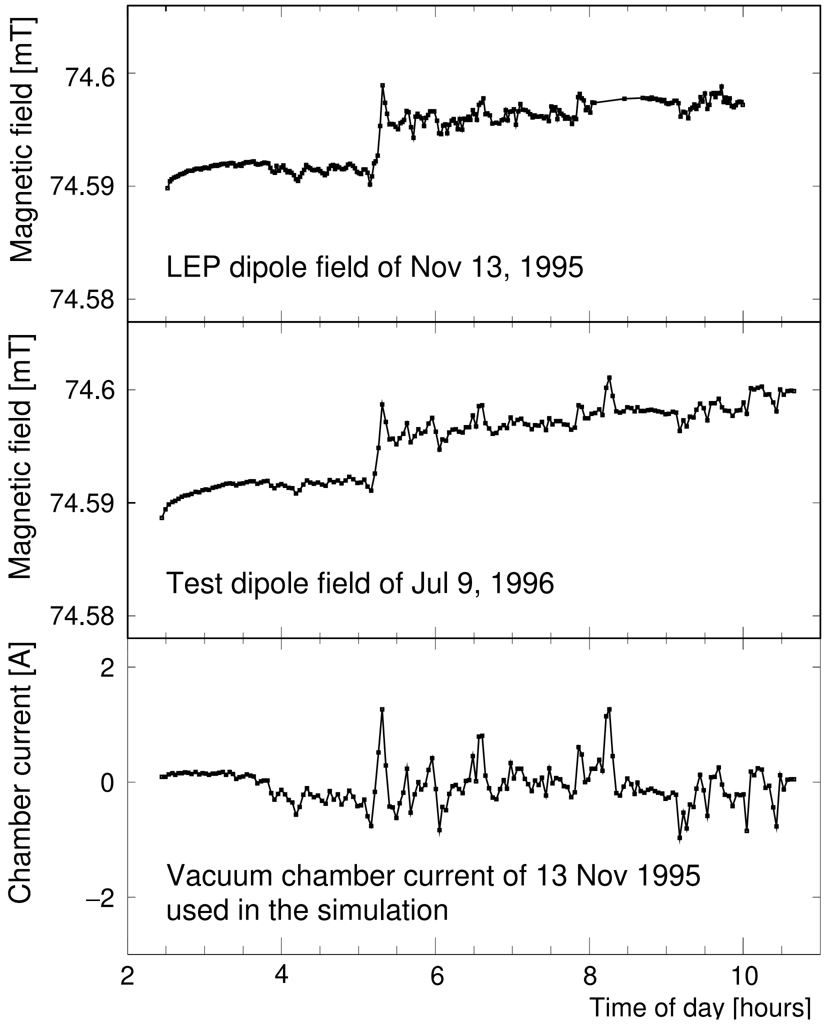
- 'TGV experiment'
- Magnet replay in laboratory
- NMR behaviour in '96 $\rightarrow$

TGV experiment



Magnet replay in laboratory

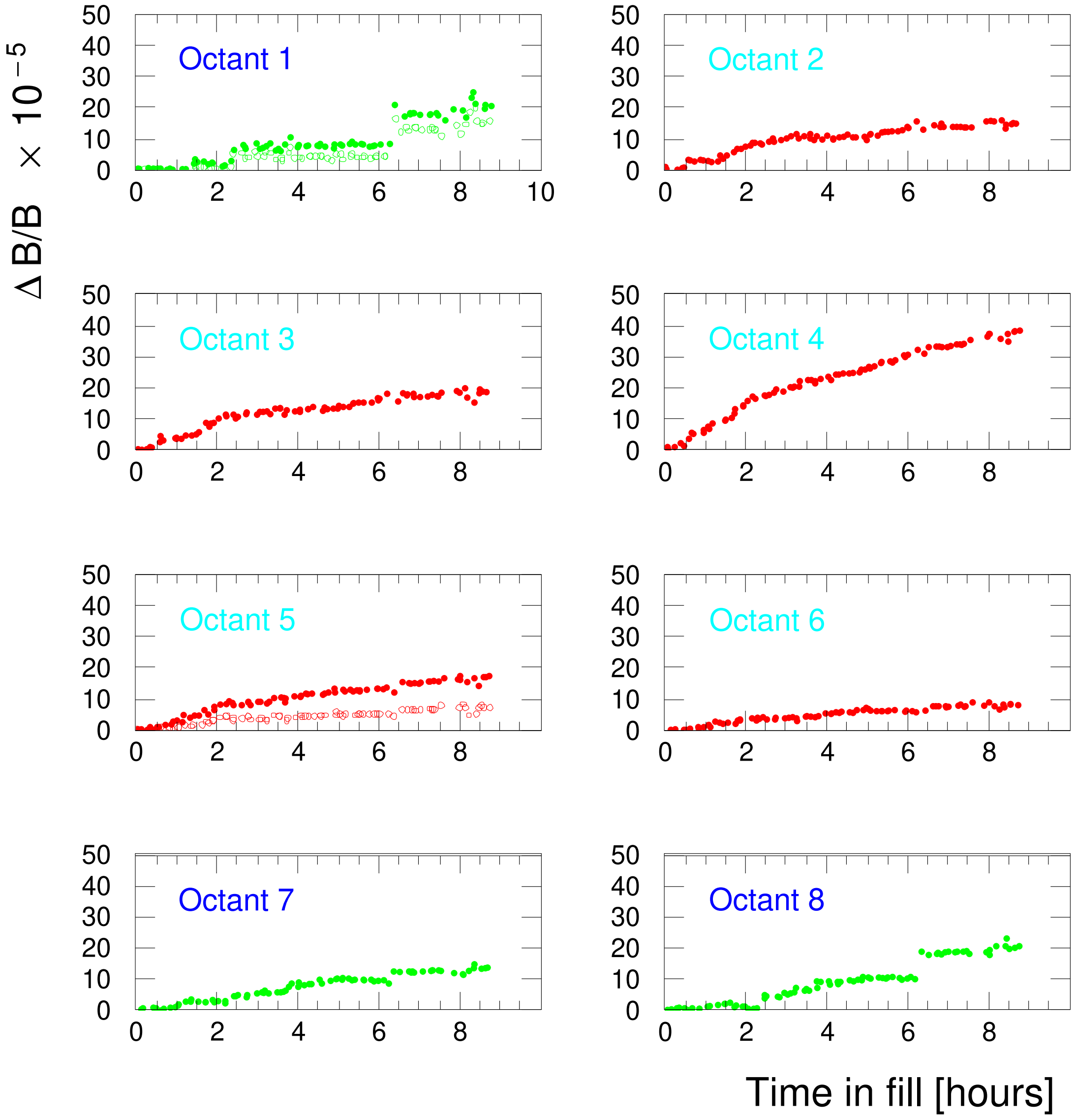
In 1996 LEP dipole, cooling system and section of beampipe set up laboratory (ISR tunnel)



Replayed beampipe current generates same dipole rise as observed in tunnel

NMR data from other octants

As from 1996 at least one dipole in all LEP octants instrumented with NMR (16 probes in all)



Octants 1,7 & 8 similar (jumpy); octants 2,3,4,5 &6 similar (smooth)

NMR48 is representative of ring

But part of the rise comes from temperature...

Conventional understanding $\rightarrow$ temperature contribution to dipole rise in '95 $\lesssim 20\%$

Magnet studies with laboratory magnet indicate temperature behaviour more complicated than hitherto thought

Describe in empirical model with 5 coefficients!

But during LEP running can be well approximated with 2 coefficients, $C_T^{\rm rise}$ and $C_T^{\rm fall}$

$$\frac{1}{B_0}\frac{dB}{dT} = \begin{cases} C_T^{\rm rise} \text{ if } dT/dt > 0 \\ C_T^{\rm fall} \text{ if } dT/dt < 0 \end{cases}$$

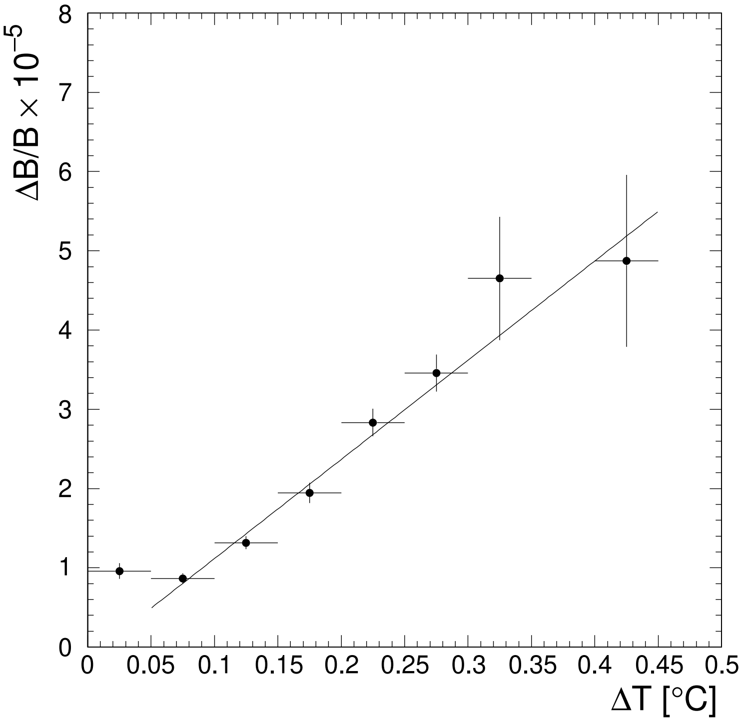
Implies $\sim 50\%$ of dipole rise in '95 comes from temperature

Also, temperature and train induced rises are NOT independent

Measuring $C_T^{\rm rise}$

Measure from 16 NMRs during '96 run (large temperature excursions)

Perform both for ring (assume 16 NMRs are a representative sample) and for NMR48



Results consistent with alternative methods $\rightarrow$

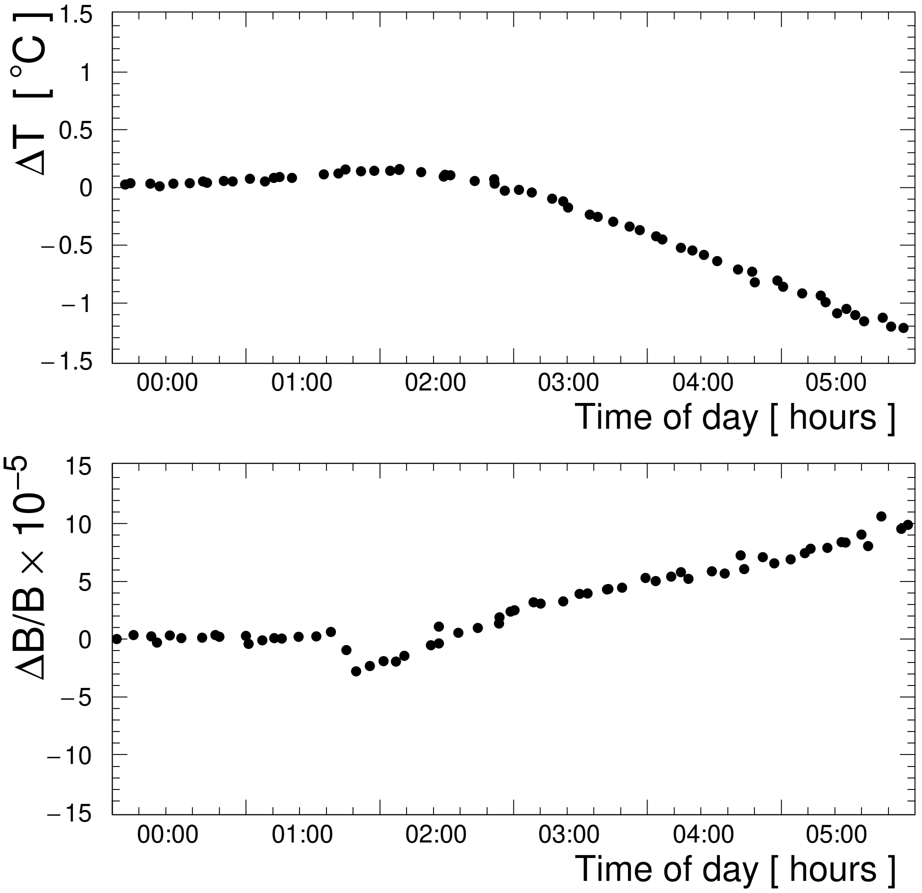
$$C_T^{\rm rise} = 10 \times 10^{-5} \,/^\circ C \quad \begin{array}{l} \pm 30\% \text{ (ring)} \\ \\ \pm 60\% \text{ (NMR48)} \end{array}$$

(1° T rise $\rightarrow \sim 5$ MeV E_b rise)

Measuring C_T^{fall}

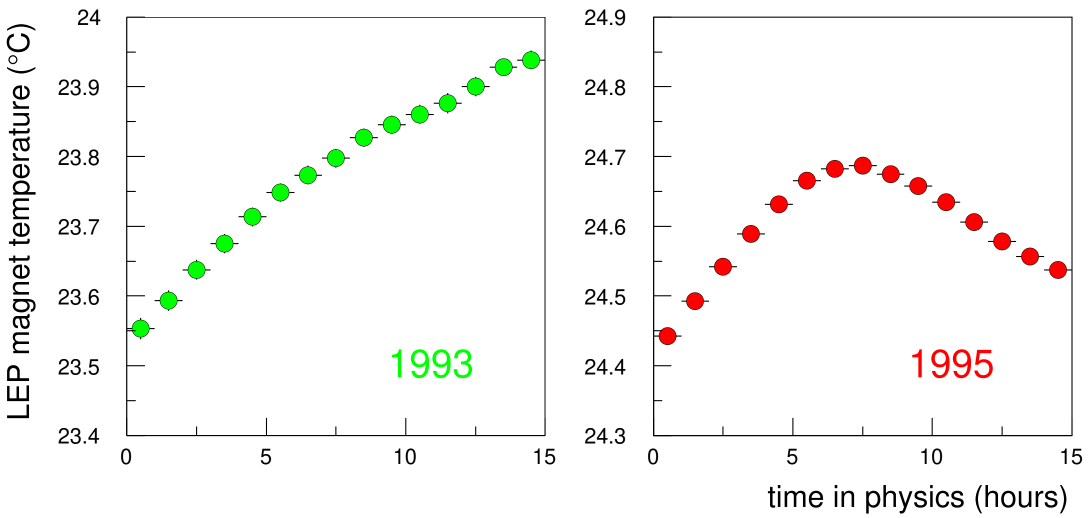
Measure in lab and in LEP during dedicated experiment

Find to be negative, ie. field rises as temperature falls!



$C_T^{\mathrm{fall}} = -5.0 \times 10^{-5} /^\circ C, \pm 50\%$ (1° T fall $\rightarrow \sim 2$ MeV E_b rise)

Important discovery! Especially when comparing '93 and '95



Modelling the dipole rise

How is dipole rise include in the energy model?

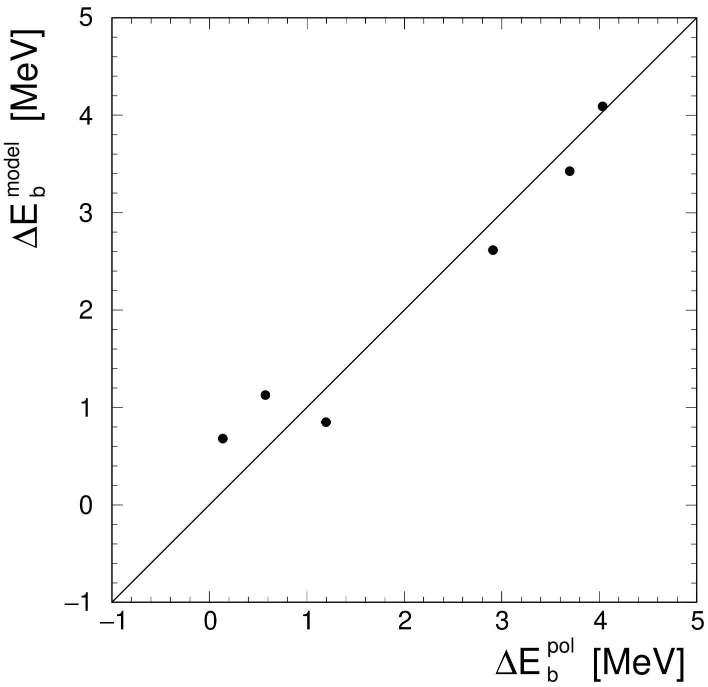
- Assume NMR48 field 'train rise' is representative of ring energy rise
- Histogram ensemble of NMR48 data in bins of $t_{\rm day}$ and $t_{\rm fill}$, after subtraction of local temperature effects $\rightarrow \Delta E^{\rm train}$
- In model apply this train rise together with 'global ring temperature rise', $\Delta E^{\rm T}$

$$\Delta E^{\rm ring}(t_{\rm day}, t_{\rm fill}, T) \;=\; \Delta E^{\rm train}(t_{\rm day}, t_{\rm fill}) + \Delta E^{\rm T}(T, dT/dt)$$

This assumes the train and temperature induced rises are independent, ie. ignores the 'interference' term

How well can we trust dipole rise modelling?

Compare with multiple depolarisation fills ($\Delta m_{\rm Z}$)



Comparison good!

$$\Delta E_b^{\rm model} - \Delta E_b^{\rm pol} = 0.0 \text{ MeV, rms of } 0.4 \text{ MeV}$$

In fact too good! Perform 'Monte Carlos' on data to get more realistic rms (1.2 MeV)

Variation of temperature coefficients ($\Delta m_{\rm Z}$, $\Delta \Gamma_{\rm Z}$)

Vary both c_T for NMR48 ($+$ remake model) and ring

How well can we trust dipole rise modelling? (ctd)

Compare with other models ($\Delta\Gamma_Z$):

- Deterministic approach
  From knowledge gained with laboratory dipole

  typical current patterns
  $\rightarrow$ rise
  octant temperature profiles

  This includes 'train-temperature interference' term

- Other treatments of NMR48 data
  eg. separate use of P-2 and P+2 subsets (important for Γ_Z)

Possibility of double counting $\rightarrow$ conservative

Rise uncertainty contributes for '95:

$$\Delta\Gamma_Z \approx 0.7\,\mathrm{MeV},\ \Delta m_Z \approx 1.2\,\mathrm{MeV}$$

But what of ‘93 ?

No choice but to use model derived from ‘95 data

Worries:

- Were parasitic currents the same in ‘93?
- Is model still valid in presence of different temperature profile?

However:

- There *were* MDs in ‘93 with multiple depolarisation measurements. Confirm rise, albeit with limited precision ($\sim 100\%$)
- Comparision with deterministic model allows ‘train temperature interference’ to be tested

Rise uncertainty contributes for ‘93:

$$\Delta\Gamma_Z \approx 1.1\,\mathrm{MeV},\ \Delta m_Z \approx 2.7\,\mathrm{MeV}$$

($\sim 60\%$ correlation with ‘95)

Calibration vs physics

Must correct for any differences of LEP between physics running and during calibration

Trivial example: tides, Pathological example: dipole rise

Is there anything systematically different in LEP settings between physics and calibration which could affect E_b?

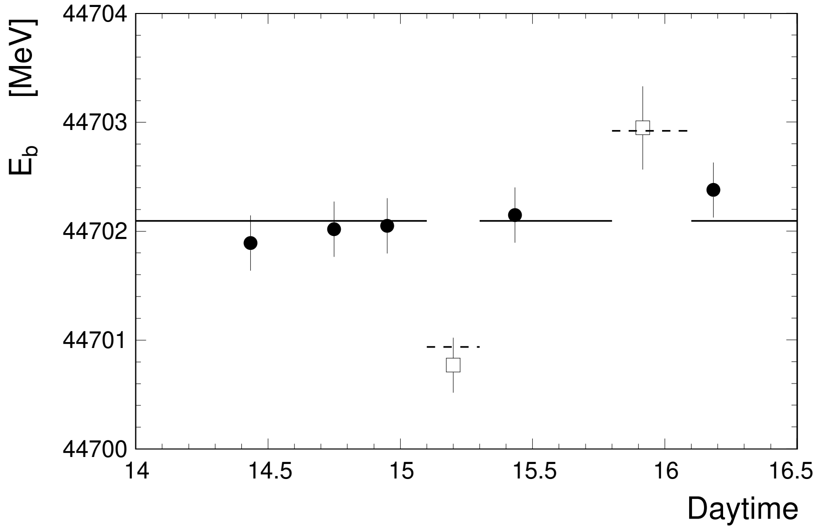
Horizontal-correctors - small magnets used to modify orbit

Betatron tunes different in physics and in calibration $\rightarrow$ in general different corrector settings applied

Horizonal correctors

Can horizonal correctors influence E_b ?

Yes! Demonstrated by MD experiment in ‘95



Effects large: changes Γ_Z by ~ 1 MeV in ‘95

Well described by theory: coherent addition of fields changes path length and thereby position in quadrupoles

Error set by comparison with other plausible theories of corrector behaviour

This contributes errors of (‘93 & ‘95 combined):

$$\Delta\Gamma_Z \approx 0.2\,\mathrm{MeV},\ \Delta m_Z \approx 0.1\,\mathrm{MeV}$$

Errors from E_b

Summary of errors on m_Z and Γ_Z from uncertainty in E_b:

Uncertainty	'93		'95		Combined	
	Δm_Z	$\Delta\Gamma_Z$	Δm_Z	$\Delta\Gamma_Z$	Δm_Z	$\Delta\Gamma_Z$
RD measurement	0.4	0.5	0.4	0.5	0.4	0.5
Fill-to-fill scatter	1.0	1.4	0.5	0.7	0.5	0.8
Dipole rise	2.7	1.1	1.2	0.7	1.7	0.7
Calibration vs physics	0.3	0.4	0.2	0.2	0.2	0.2
Total	2.9	1.8	1.3	1.1	1.9	1.1

(All numbers in MeV)

Dominant error on m_Z comes from dipole rise

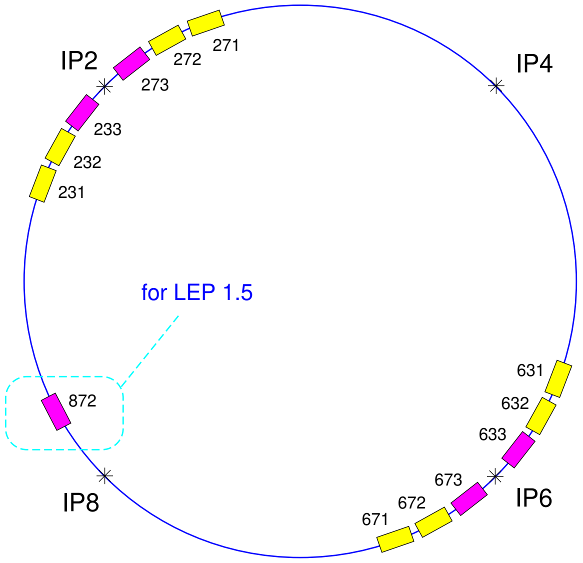
Errors on Γ_Z equally shared; fill-to-fill is largest contribution

(Illustration only! Correct treatment requires error matrix formalism)

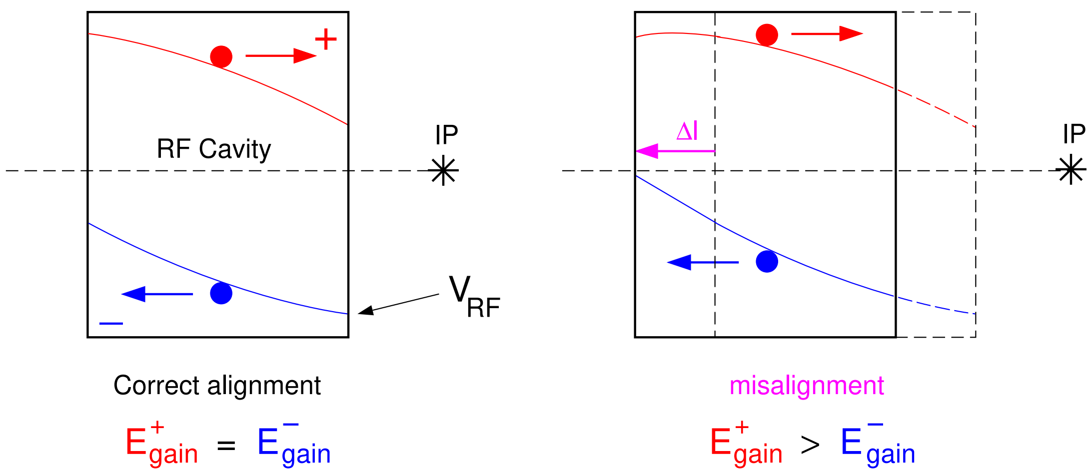
RF corrections

RF acceleration compensates for synchrotron loss (~ 125 MeV per turn)

'93 scan Cu cavities; '95 scan Cu + SC cavities



Why RF corrections?



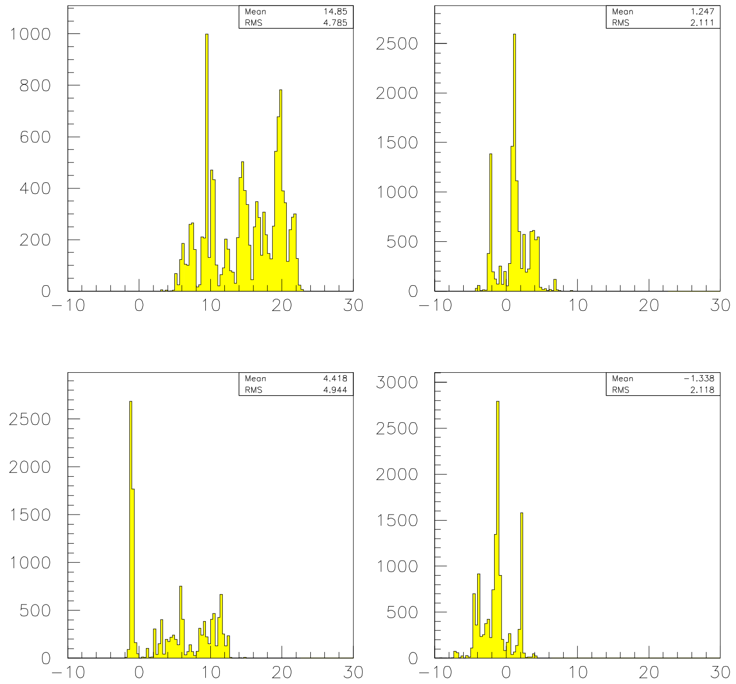
f_{RF} for Cu $\rightarrow$ misalignment of 25 cm $\rightarrow$ $\Delta E_{\rm cm} \sim 20\,\mathrm{MeV}$!

RF corrections (ctd)

RF modelling more difficult in '95 than '93:

- Unstable system, due to commissioning of SC
- Unused cavities, with which beams interact
- Modelling of bunch trains

Calculated $E_{\rm cm}$ shifts in '95:

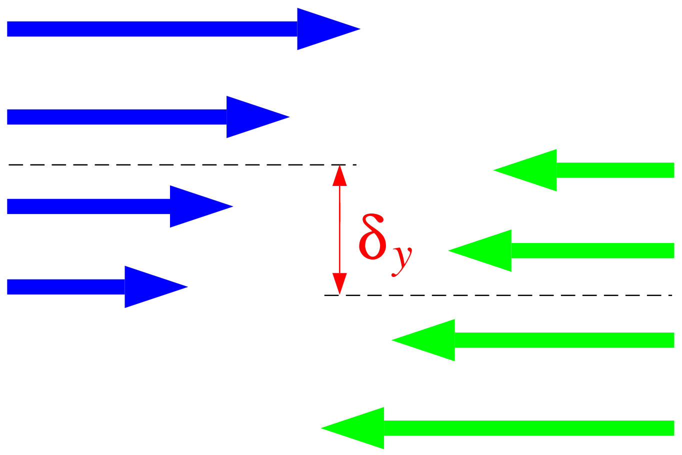


Contributing uncertainties of (in MeV):

	$\Delta m_{\rm Z}$	$\Delta\Gamma_{\rm Z}$
'93	0.4	0.1
'95	0.5	0.4
Combined	0.4	0.2

Dispersion effects

'Bumps' required for bunch train operation in '95 $\rightarrow$ opposite sign vertical dispersion (OSVD)



OSVD ($e^+ - e^- = \Delta D_y^\star$) and vertical offset ($\delta y$) $\rightarrow$ energy shift, $\Delta E_{\rm cm}$

$$\Delta E_{\rm cm} = \frac{-1}{2} \frac{\delta y}{\sigma_y^2} \frac{\sigma_{E_b}^2}{E_b} \Delta D_y^\star \tag{1}$$

(where σ_y is vertical beam size $\sim 5\,\mu{\rm m}$, σ_{E_b} is beam spread)

If $\Delta D_y^\star \sim 2\,{\rm mm}$, $\delta y = 1\,\mu{\rm m}$ then $\Delta E_{\rm cm} \sim 2\,{\rm MeV}$!

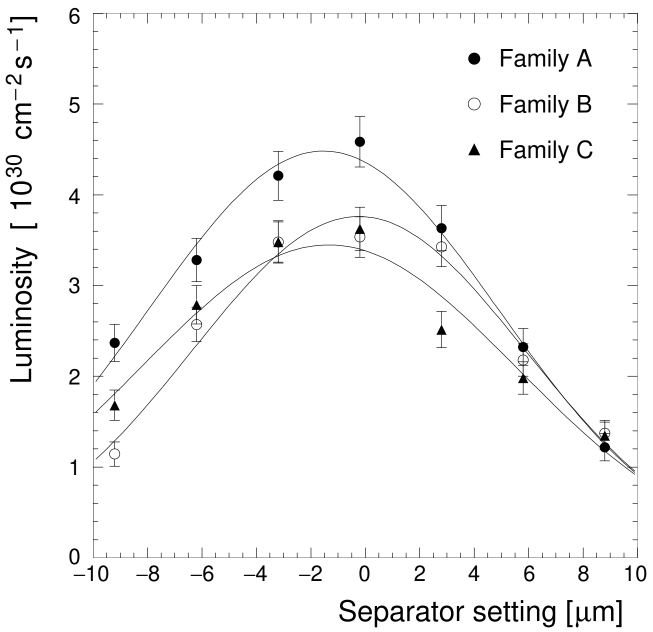
Any small systematic collinson offset very dangerous!

(Problem originally called feasibility of '95 scan into question)

Dispersion effects (ctd)

Cure by separator scans (a.k.a. 'Vernier scans')

Once/twice per fill at each IP move beams vertically across each other and record change in $\mathcal{L}$



From scan can calculate for each IP:

- Optimum position to set beams at & bias prior to scan
- Vertical beam size, σ_y
- $\Delta D_y^\star$, if scans repeated with changed f_{RF} (MDs!)

Result - errors limited to negligible level!

	Δm_Z	$\Delta\Gamma_Z$
'93	0.2	0.1
'95	0.3	0.2
Combined	0.2	0.1

Note contribution from residual OSVD in '93

Errors from $E_{\rm cm}$ corrections

Summary of errors on $m_{\rm Z}$ and $\Gamma_{\rm Z}$ from uncertainty in $E_{\rm cm}$ corrections:

Uncertainty	'93		'95		Combined	
	$\Delta m_{\rm Z}$	$\Delta\Gamma_{\rm Z}$	$\Delta m_{\rm Z}$	$\Delta\Gamma_{\rm Z}$	$\Delta m_{\rm Z}$	$\Delta\Gamma_{\rm Z}$
RF modelling	0.4	0.1	0.5	0.4	0.4	0.2
Dispersion	0.2	0.1	0.3	0.2	0.2	0.1
e^+ vs e^-	0.3	0.2	0.2	0.2	0.2	0.1
Total	0.5	0.3	0.6	0.5	0.4	0.3

(All numbers in MeV)

'e^+ vs e^-' contribution comes from dedicated RD experiments with positron beam

In comparison with errors coming from E_b knowledge, IP corrections contribute small uncertainties. This due to advanced understanding, rather than unimportance of effects!

In total, collision energy uncertainty leads to errors of

$$\Delta\Gamma_{\rm Z} \approx 1.9\,{\rm MeV},\ \Delta m_{\rm Z} \approx 1.2\,{\rm MeV}$$

for data of '93 and '95 scans

Error matrices

All errors shown on m_{Z} and Γ_{Z} for illustration only

Approximate - assume all experiments and both scans contribute with equal weight

Correct approach is to produce error matrices giving uncertainties on 7 energy points of '93, '94, '95 and correlations. 6 matrices have been calculated:

1. Four separate 7×7 matrices for each IP, appropriate for individual experiment's results
2. A 28×28 matrix holding correlations between all IPs, appropriate for global fit of cross-sections of all experiments
3. A 7×7 matrix appropriate for combining the fit results of all 4 experiments

	93 P–2	**93 P**	**93 P+2**	**94 P**	**95 P–2**	**95 P**	**95 P+2**
93 P–2	11.71	7.60	6.73	5.06	1.66	1.41	1.45
93 P		44.81	6.96	5.67	1.30	1.43	1.33
93 P+2			8.69	4.67	1.51	1.57	1.76
94 P				13.14	1.51	1.68	1.53
95 P–2					3.17	1.53	1.49
95 P						29.08	1.79
95 P+2							2.83

(In principle 2 and 3 should give same answer)

Fits in progress! Expect slightly different errors for m_{Z} & Γ_{Z}

Energy Spread

'95 also saw improved understanding of energy spread, $\sigma_{E_{\rm cm}}$

Energy spread shifts $\Gamma_{\rm Z}$ through changing the cross-section ($\delta\sigma$) at P-2,P+2

$$\delta\sigma = -0.5\,\frac{d^2\sigma}{dE^2}\,\sigma_{E^2_{\rm cm}}$$

Significant! $\Delta\Gamma_{\rm Z} \sim -4\,{\rm MeV}$ for $\sigma_{E_{\rm cm}} \sim 55\,{\rm MeV}$

Scan symmetric around peak $\rightarrow$ negligible effect on $m_{\rm Z}$

Prior to '95 largest single systematic error on $\Gamma_{\rm Z}$ was uncertainty in $\sigma_{E_{\rm cm}}$

$\sim 10\%$ uncertainty in $\sigma_{E_{\rm cm}} \rightarrow \Delta\Gamma_{\rm Z} \sim 1\,{\rm MeV}$

Energy Spread (ctd)

Experimentally can determine $\sigma_{E_{\rm cm}}$ from measuring longitudinal size of interaction region, σ_z

$$\sigma_{E_b} = \frac{\sqrt{2} E_b}{\alpha R_{\rm LEP}} Q_s^{\rm inc} \sigma_z$$

(σ_{E_b} is *beam* energy spread, $R_{\rm LEP}$ is LEP radius, α is momentum compaction factor)

Note $Q_s^{\rm inc}$:

- $Q_s^{\rm coh}$ - coherent synchrotron tune
  Number of longitudinal oscillations of full bunches per turn. Measured in normal operation by RF system
- $Q_s^{\rm inc}$ - incoherent synchrotron tune
  Number of longitudinal oscillations of individual beam particles per turn. Not measured

Must calculate $Q_s^{\rm inc}$ from knowledge of $Q_s^{\rm coh}$, but relationship between two badly known

$Q_s^{\rm inc}$ measured directly during '95 RD MD from synchrotron side-bands of depolarising resonance, and then compared with values of $Q_s^{\rm coh}$ $\rightarrow$ more reliable knowledge of σ_{E_b}

Improved theoretical calculations of σ_{E_b} agreed with measurement within 2%

This knowledge can be applied retrospectively to '93 (and '94)

Energy Spread (ctd)

Must go from σ_{E_b} to $\sigma_{E_{\rm cm}}$

	$\sigma_{\rm E_{CM}}$ in MeV					
	1993	1994	1995			
			IP2	IP4	IP6	IP8
P$-$2	54.6		55.0	55.7	55.7	55.7
P	55.4	54.9	55.6	56.2	56.2	56.3
P$+$2	55.6		56.0	56.6	56.7	56.7

Note that for '95, dispersion effects must be considered (hence IP dependence)

Associated error is 1.1 MeV for '93, '94 and 1.3 MeV in '95

$$\rightarrow \Delta\Gamma_{\rm Z} \approx 0.2 \text{ MeV}$$

an almost five-fold improvement on previously

Summary

LEP energy determined with precision necessary for m_{Z}, Γ_{Z} measurements:

- Dominant error on m_{Z} from dipole rise
- For Γ_{Z} errors shared between contributions

Gives from LEP E_{CM} $\Delta\Gamma_{\mathrm{Z}} \approx 1.9\,\mathrm{MeV}, \Delta m_{\mathrm{Z}} \approx 1.2\,\mathrm{MeV}$
(but final errors must await full fit)

1995 scan vital in understanding 1993

Energy spread now a negligible error on Γ_{Z}

All lessons valuable for m_{W} at LEP 2

- Rise in fill now monitored by 16 NMRs
- Need to understand physics-calibration (different optics!)
- Whenever possible measure ! (spectrometer to test extrapolation method)