LEP ECAL remembered – lessons for the future ?

Guy Wilkinson
University of Oxford
FCC-ee EPOL, CERN, Sep 2022

(a minor update of talk first given in 2016 FCC EPOL workshop)

In memoriam
Bernd Dehning 1957-2017

Deeply missed, he made an enormous contribution to both LEP1 and LEP2 ECAL studies.

All material can be found here, and references therein

Eur. Phys. J. C6 (1999) 187

EUROPEAN ORGANIZATION FOR PARTICLE PHYSICS

CERN–EP/98–40
CERN–SL/98–12
March 11, 1998

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

The LEP Energy Working Group

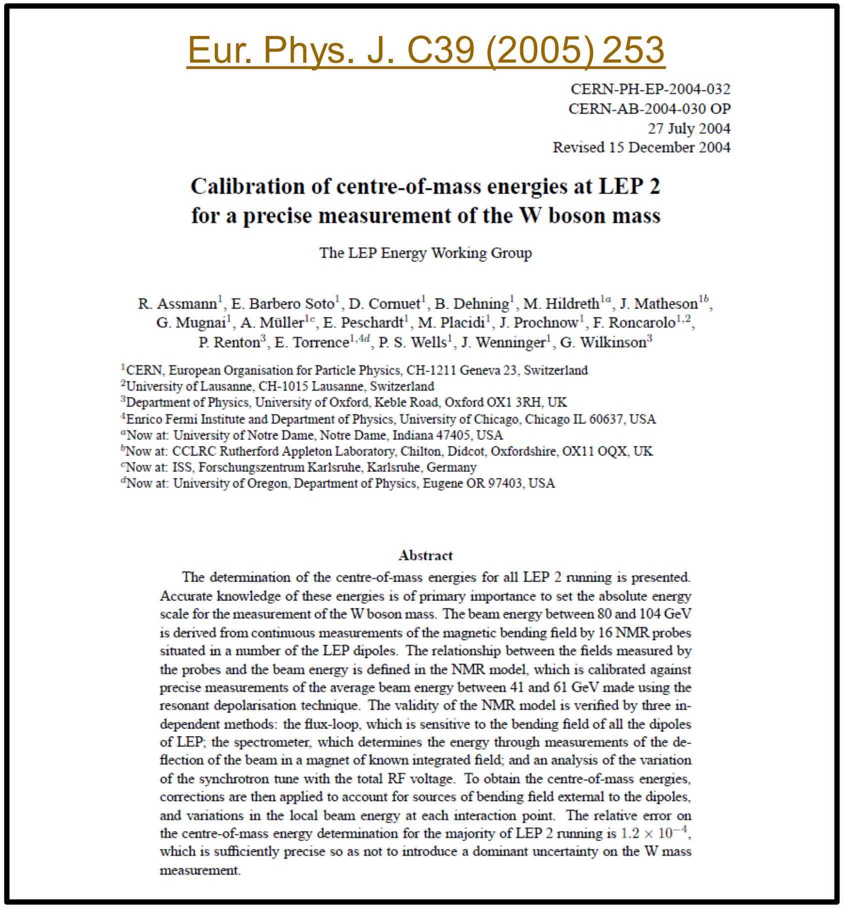
R. Assmann1), M. Böge1,a), R. Billen1), A. Blondel2), E. Bravin1), P. Bright-Thomas1,b), T. Camporesi1), B. Dehning1), A. Drees3), G. Duckeck4), J. Gascon5), M. Geitz1,c), B. Goddard1), C.M. Hawkes6), K. Henrichsen1), M.D. Hildreth1), A. Hofmann1), R. Jacobsen1,d), M. Koratzinos1), M. Lamont1), E. Lancon7), A. Lucotte8), J. Mnich1), G. Mugnai1), E. Peschardt1), M. Placidi1), P. Puzo1,e), G. Quast9), P. Renton10), L. Rolandi1), H. Wachsmuth1), P.S. Wells1), J. Wenninger1), G. Wilkinson1,10), T. Wyatt11), J. Yamartino12,f), K. Yip10,g)

Abstract

The determination of the centre-of-mass energies from the LEP1 data for 1993, 1994 and 1995 is presented. Accurate knowledge of these energies is crucial in the measurement of the Z resonance parameters. The improved understanding of the LEP energy behaviour accumulated during the 1995 energy scan is detailed, while the 1993 and 1994 measurements are revised. For 1993 these supersede the previously published values. Additional instrumentation has allowed the detection of an unexpectedly large energy rise during physics fills. This new effect is accommodated in the modelling of the beam-energy in 1995 and propagated to the 1993 and 1994 energies. New results are reported on the magnet temperature behaviour which constitutes one of the major corrections to the average LEP energy.

The 1995 energy scan took place in conditions very different from the previous years. In particular the interaction-point specific corrections to the centre-of-mass energy in 1995 are more complicated than previously: these arise from the modified radiofrequency-system configuration and from opposite-sign vertical dispersion induced by the bunch-train mode of LEP operation.

Finally an improved evaluation of the LEP centre-of-mass energy spread is presented. This significantly improves the precision on the Z width.



Eur. Phys. J. C39 (2005) 253

CERN-PH-EP-2004-032
CERN-AB-2004-030 OP
27 July 2004
Revised 15 December 2004

Calibration of centre-of-mass energies at LEP 2 for a precise measurement of the W boson mass

The LEP Energy Working Group

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Abstract

The determination of the centre-of-mass energies for all LEP 2 running is presented. Accurate knowledge of these energies is of primary importance to set the absolute energy scale for the measurement of the W boson mass. The beam energy between 80 and 104 GeV is derived from continuous measurements of the magnetic bending field by 16 NMR probes situated in a number of the LEP dipoles. The relationship between the fields measured by the probes and the beam energy is defined in the NMR model, which is calibrated against precise measurements of the average beam energy between 41 and 61 GeV made using the resonant depolarisation technique. The validity of the NMR model is verified by three independent methods: the flux-loop, which is sensitive to the bending field of all the dipoles of LEP; the spectrometer, which determines the energy through measurements of the deflection of the beam in a magnet of known integrated field; and an analysis of the variation of the synchrotron tune with the total RF voltage. To obtain the centre-of-mass energies, corrections are then applied to account for sources of bending field external to the dipoles, and variations in the local beam energy at each interaction point. The relative error on the centre-of-mass energy determination for the majority of LEP 2 running is 1.2×10^{-4}, which is sufficiently precise so as not to introduce a dominant uncertainty on the W mass measurement.

Overview

Goals of energy calibration at LEP

RDP at LEP

The LEP energy model, and its application to the LEP1 m_Z and Γ_Z measurement campaigns

Energy calibration at LEP2 – living without RDP

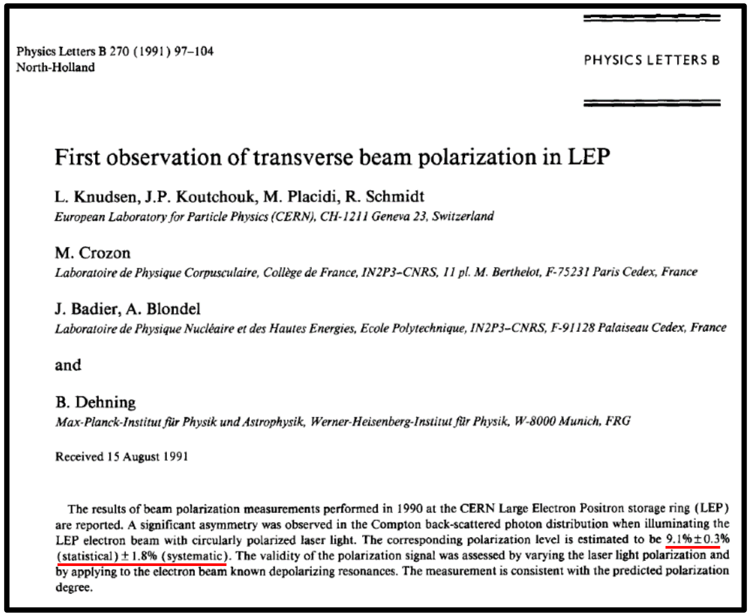
Summary and (maybe) some lessons for the FCC-ee

m_Z – from low goals to lofty ambitions

In mid 1980s goals for measuring the Z mass at LEP were modest.

Outlook shortly before LEP turn on: *“The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…”* CERN 86-02 ‘Physics at LEP’, ed. Ellis and Peccei.

When it became apparent in 1990 that resonant depolarisation measurements could be performed [PLB 270 (1991) 97] then the goals became more ambitious.



Physics Letters B 270 (1991) 97–104
North-Holland

PHYSICS LETTERS B

First observation of transverse beam polarization in LEP

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J. Badier, A. Blondel
Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN2P3–CNRS, F-91128 Palaiseau Cedex, France

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Received 15 August 1991

The results of beam polarization measurements performed in 1990 at the CERN Large Electron Positron storage ring (LEP) are reported. A significant asymmetry was observed in the Compton back-scattered photon distribution when illuminating the LEP electron beam with circularly polarized laser light. The corresponding polarization level is estimated to be 9.1% ± 0.3% (statistical) ± 1.8% (systematic). The validity of the polarization signal was assessed by varying the laser light polarization and by applying to the electron beam known depolarizing resonances. The measurement is consistent with the predicted polarization degree.

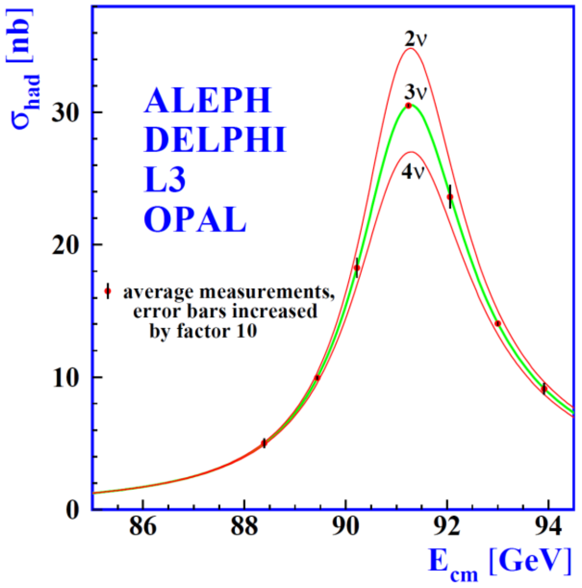
Goals of E_{CM} calibration at LEP

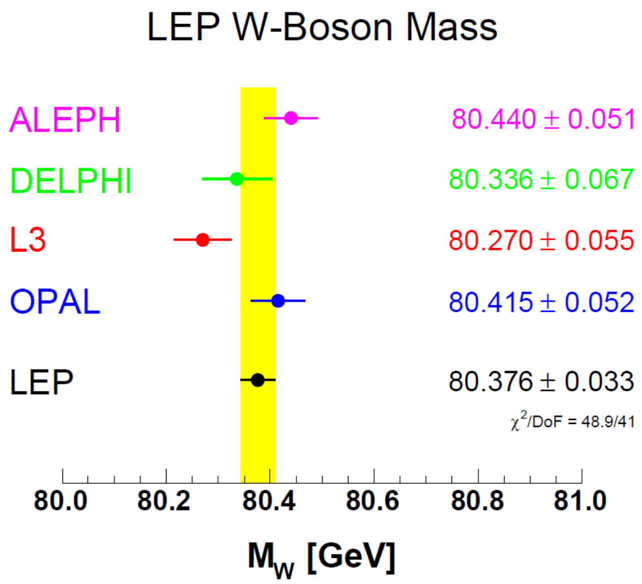
Knowledge of the beam (and collision) energy, a critical common uncertainty for the most important legacy measurements of both LEP1 and LEP2

LEP1: m_Z and Γ_Z
Goal ~1 MeV (~10^{-5}) on $\sigma_{E_{CM}}$

LEP2: m_W
Goal 1-2 x 10^{-4} on E_{CM}

[Phys. Rep. 427 (2006) 257]





[Phys. Rep. 532 (2013) 119]

Key data sets: 3 point scans in 1993 & 1995 (+ peak run in 1994)

Data at E_{CM} = 161-207 GeV, 1996-2000

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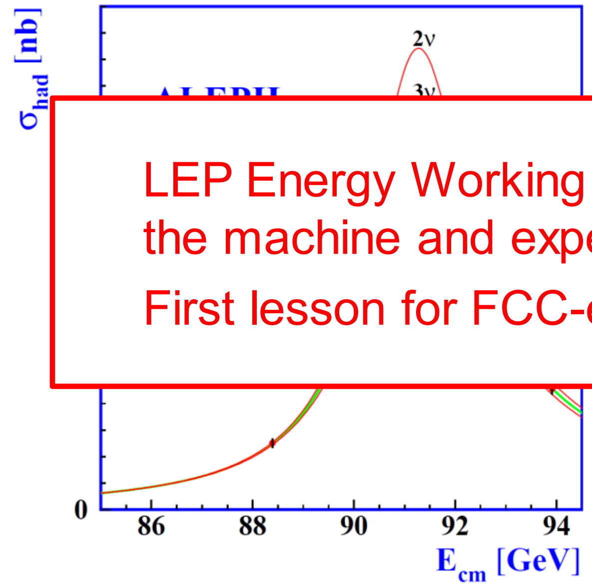
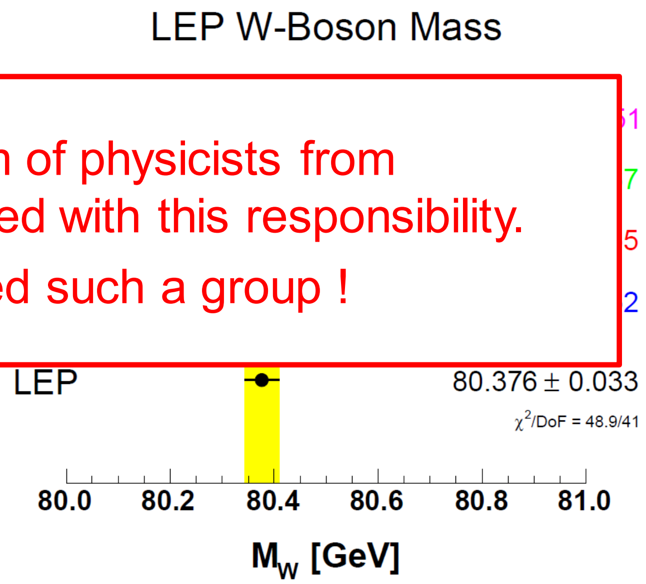




[Phys. Rep. 532 (2013) 119]

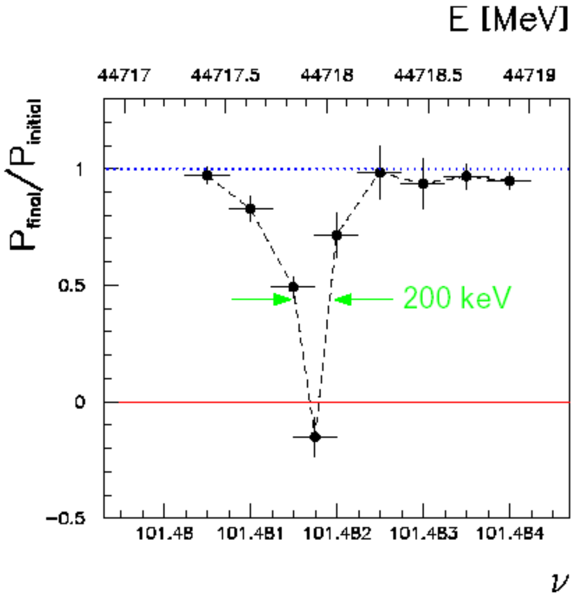
LEP Energy Working Group: a team of physicists from the machine and experiments, tasked with this responsibility.

First lesson for FCC-ee: we will need such a group !

Key data sets: 3 point scans in 1993 & 1995 (+ peak run in 1994)

Data at E_{CM} = 161-207 GeV, 1996-2000

E_b calibration: resonant depolarisation (RDP)



Method of attack:

- Wait for transverse polarisation to build up.
- Precession frequency, ν_s , directly proportional to E_b :

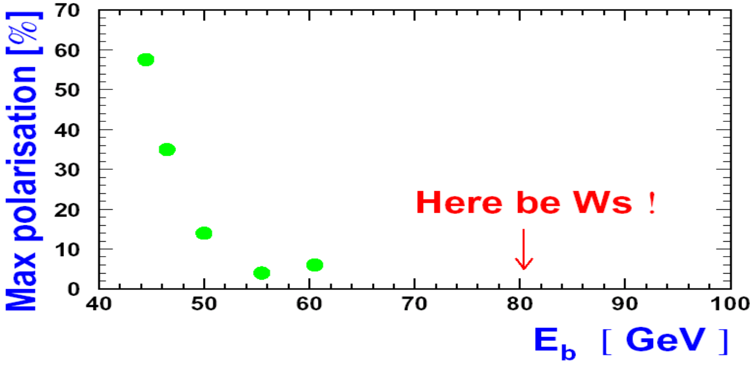
$$E_b = 2\,\nu_s\,m_e\,c^2\,/\,(g_e - 2).$$

- Monitor polarisation (with Compton-scattered laser light) whilst exciting beam with transverse oscillating B field.

Ultra precise (10^{-6}), however, two problems (at least at LEP):

- Not compatible with physics operation.

  Required dedicated measurements *i.e.* selected sampling out of physics collisions, typically at end of fill.



- Polarisation never obtained above ~60 GeV, *i.e.* cannot be *directly* used for m_W measurement.

Selected RDP sampling is not enough !

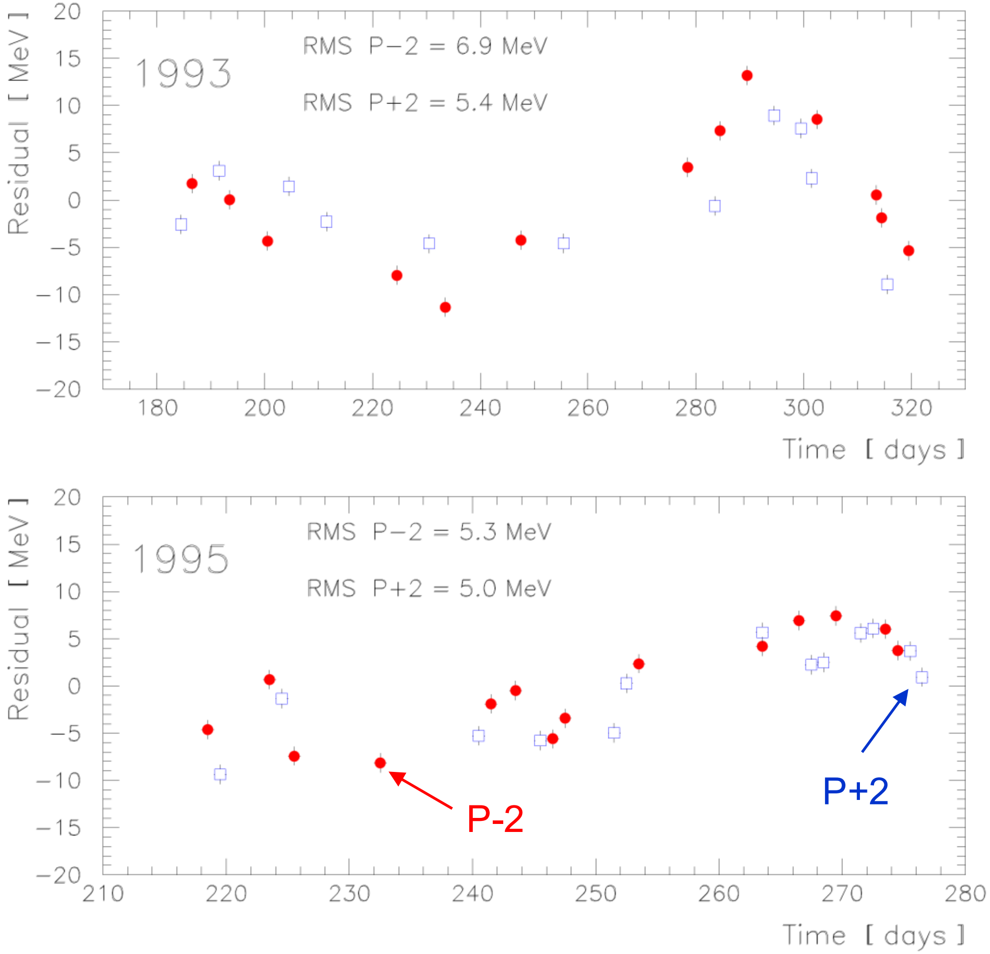
Distribution of E_b from RDP shows significant scatter and strong suggestion of time evolution.

Need model to reduce this scatter, to track time evolution between fills (not all were calibrated) and within fill (RDP took place at end).

Many ingredients in this model. Here we will review the most important. Final (still imperfect) understanding took many years to arrive at, and long periods of dedicated machine time !

Lesson for FCC-ee: calibrate often and during physics operation.

E_b residuals w.r.t. mean vs time



Circumference changes

α = momentum compaction factor

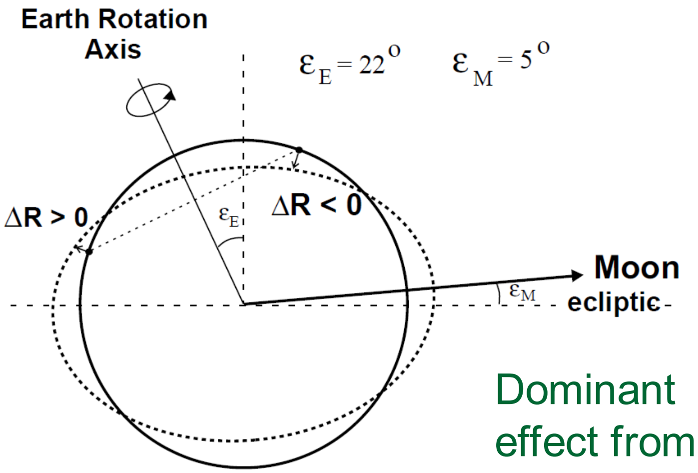
Energy changes can be induced by changes in the ring circumference, as this will lead the beam to sample different fields in the quadrupoles.

$$\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta C}{C}$$

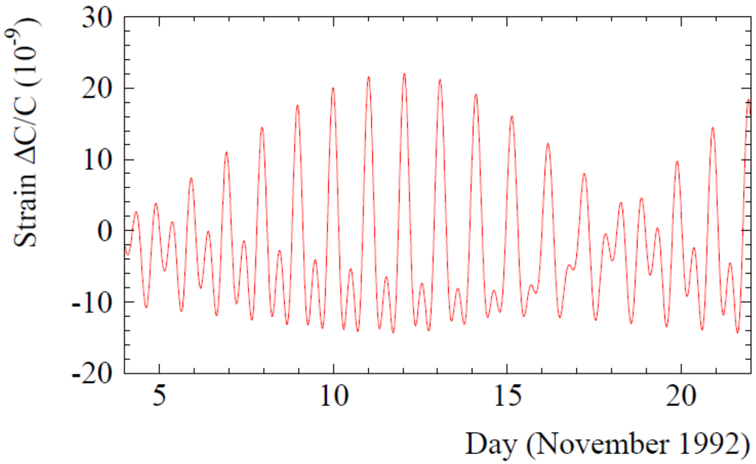
At LEP 1/α ~ 5000 → even $\Delta C/C \sim 10^{-9}$ (~0.1mm) changes give noticeable effects.

!! At FCC 1/α is order-of-magnitude larger. Effects will grow to $\Delta E_b \sim 100$ MeV !!

What though can affect the ring size ?
In the early days of RDP (1991) short-term energy changes were observed, & it was suggested that the origin might be 'earth tides'.



Precise modelling !

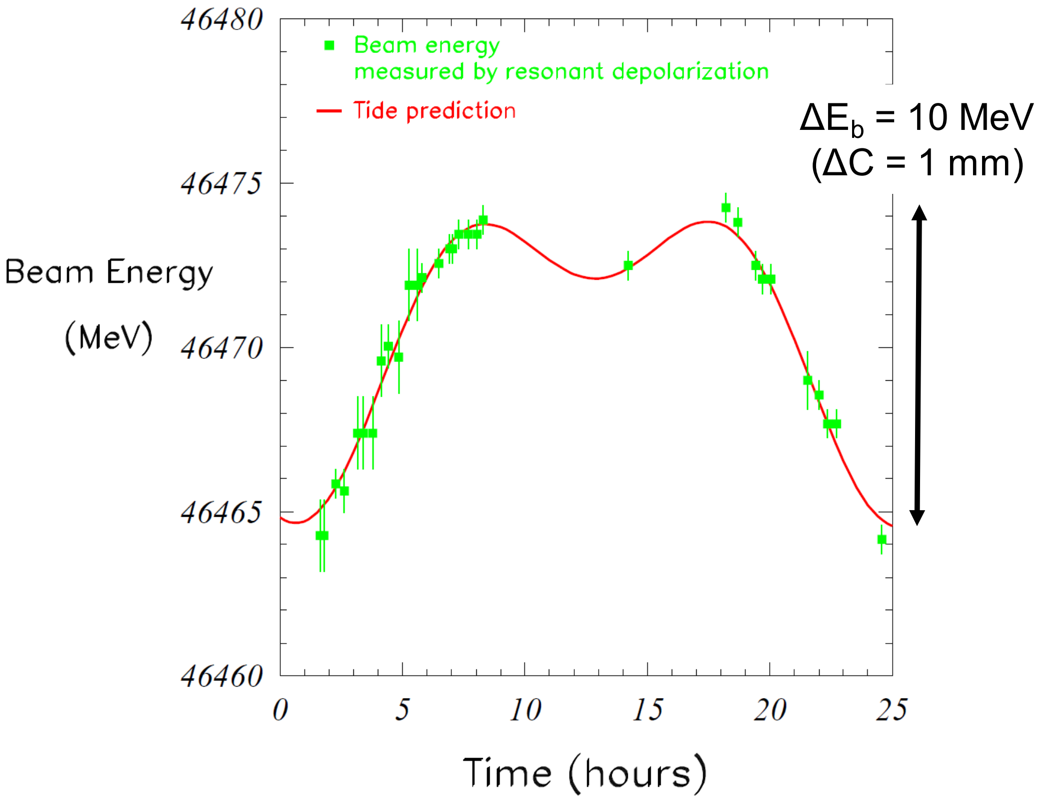


Dominant effect from moon.

$$\Delta R \sim \frac{M}{2d^3}(3cos^2\theta - 1)$$

The tide experiment

Importance & understanding of tide effects demonstrated in dedicated RDP experiment of autumn 1992.



ΔE_b = 10 MeV

(ΔC = 1 mm)

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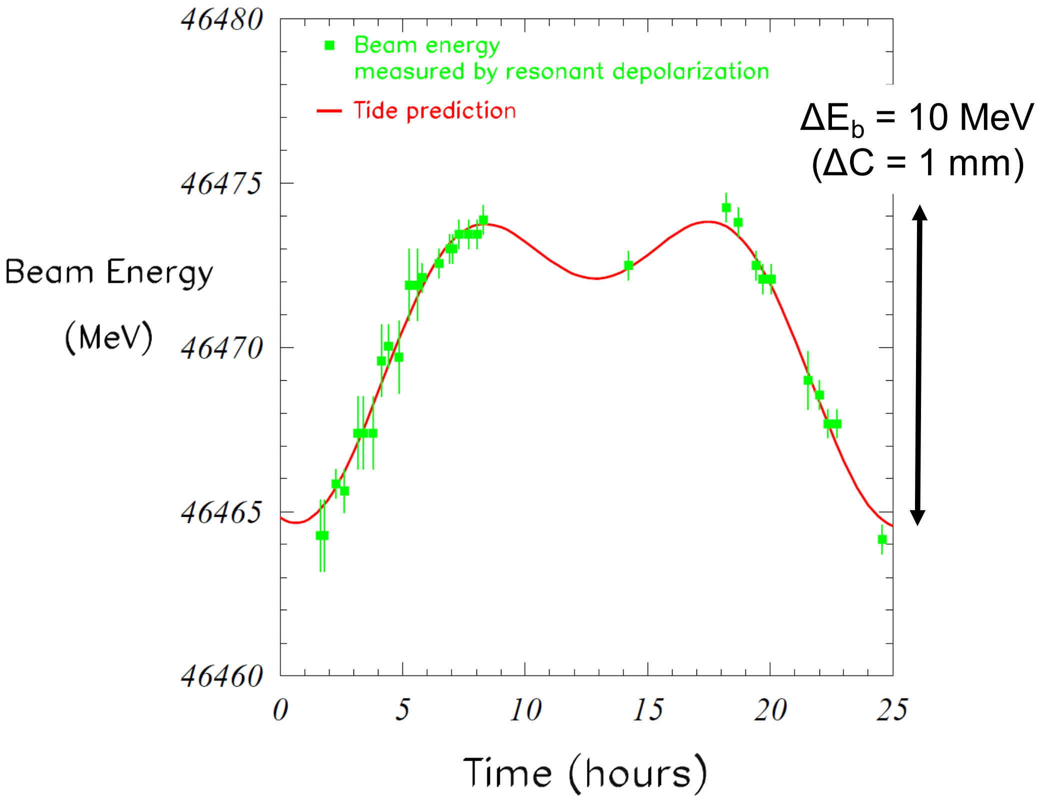
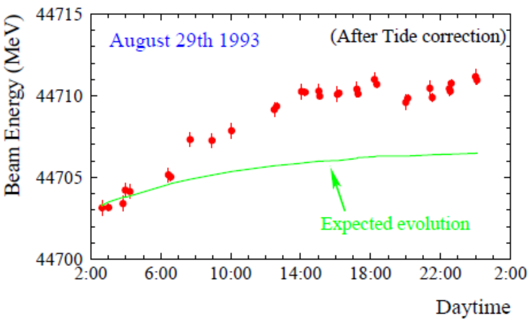


ΔE_b = 10 MeV
(ΔC = 1 mm)

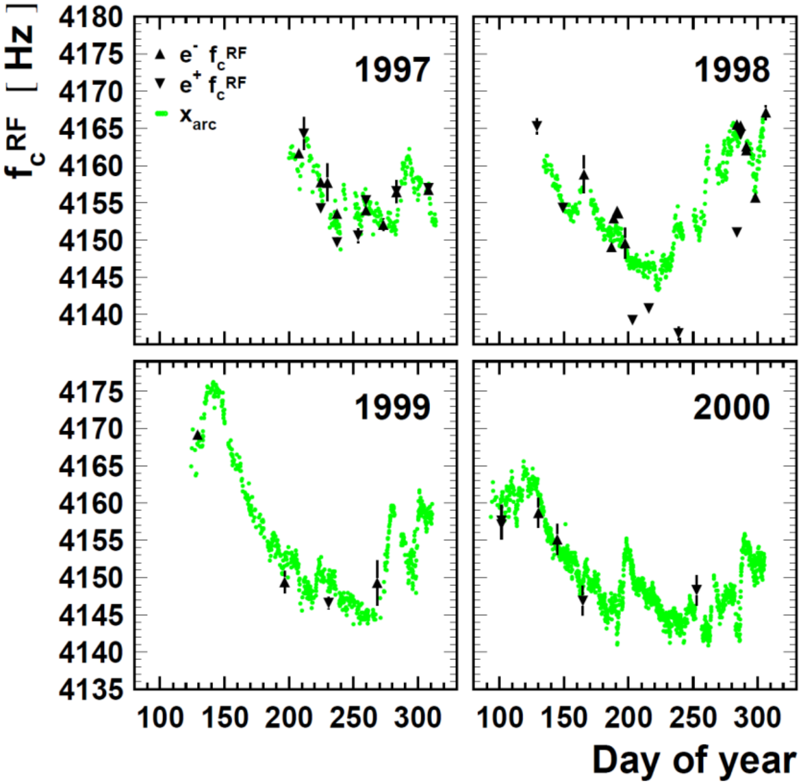
Note that these measurements were taken when the fill was already many hours long.



Otherwise the agreement would have been worse (benefit of hindsight). Discrepancy seen in a later experiment, but not understood for two more years…

Longer-term effects

On top of the tide-effect, there is a slower evolution in the ring circumference which can be tracked by average beam position measured by BPMs, and then checked from time-to-time with 'central frequency measurements'.



'Central frequency' as deduced from BPM data (x_{arc}) and from dedicated measurements during LEP2 era (again, corresponds to ΔC of a few mm).

Can be modelled with good precision.

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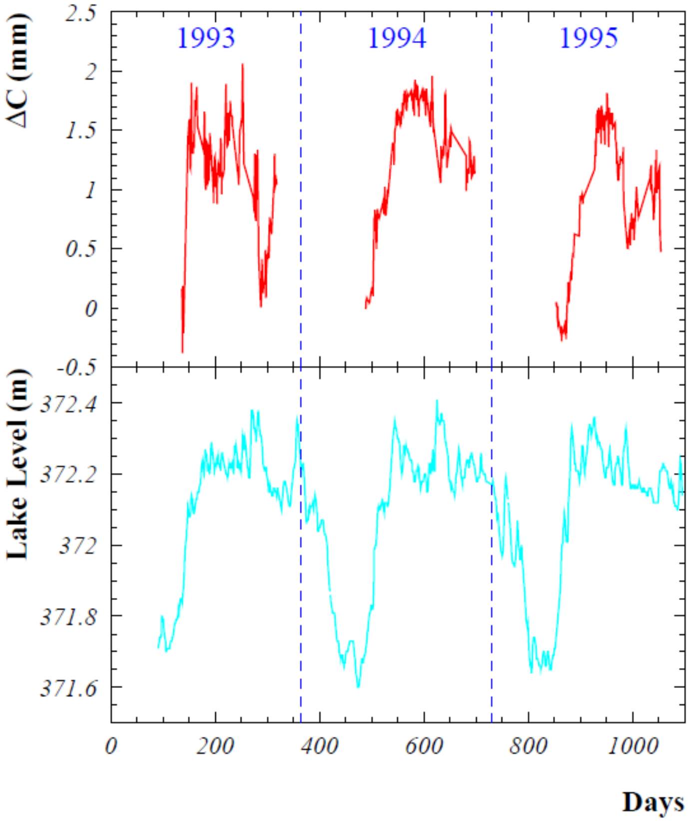


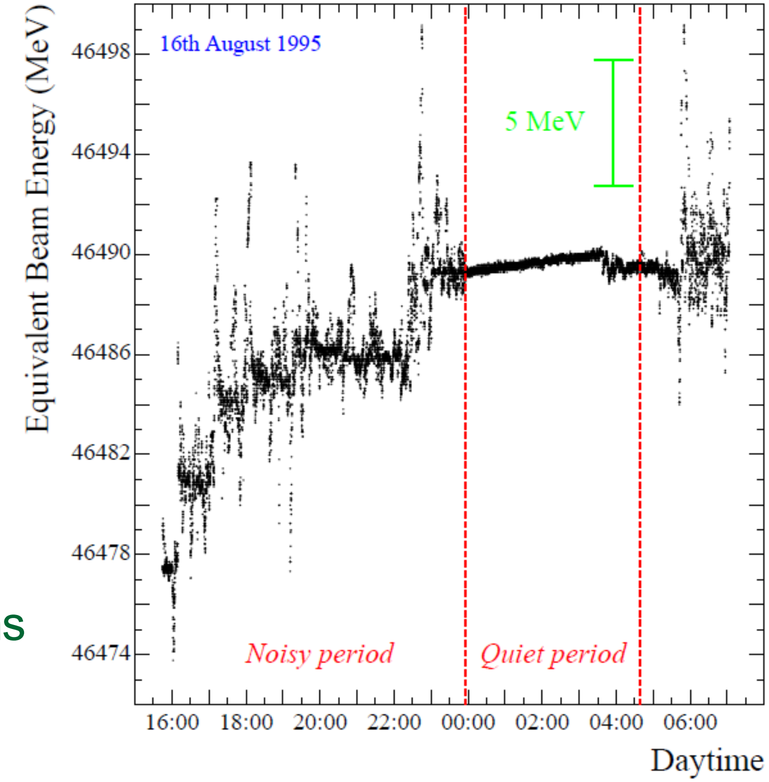
Likely cause – ground stress caused by annual modulation in water table and level of Lac Leman.

Back to that odd experiment…

Recall that single RDP experiment, where the E_b change could not be explained by the tides, nor the then (simple) model of dipole temperature-dependence.

During 1995 NMR probes were inserted in two dipoles in tunnel (several more added during 1996). Revealing !

- Noise and B-rise dependent on time of day (quiet during night) & fill duration (reducing with time).
- Size of effect dependent on position around ring.
- If interpreted as an energy rise, it meant that all previous end-of-fill RDP calibrations had overestimated mean energy of fill (and hence m_Z) by 5 MeV.



- Indeed, dedicated RDP measurements confirmed this a real effect on E_b !

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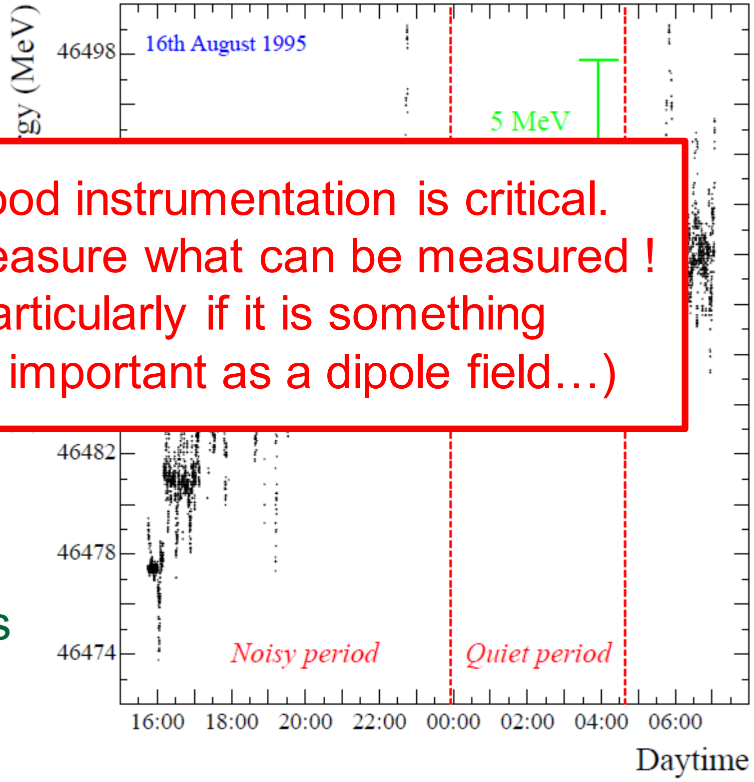
Good instrumentation is critical. Measure what can be measured ! (particularly if it is something as important as a dipole field…)



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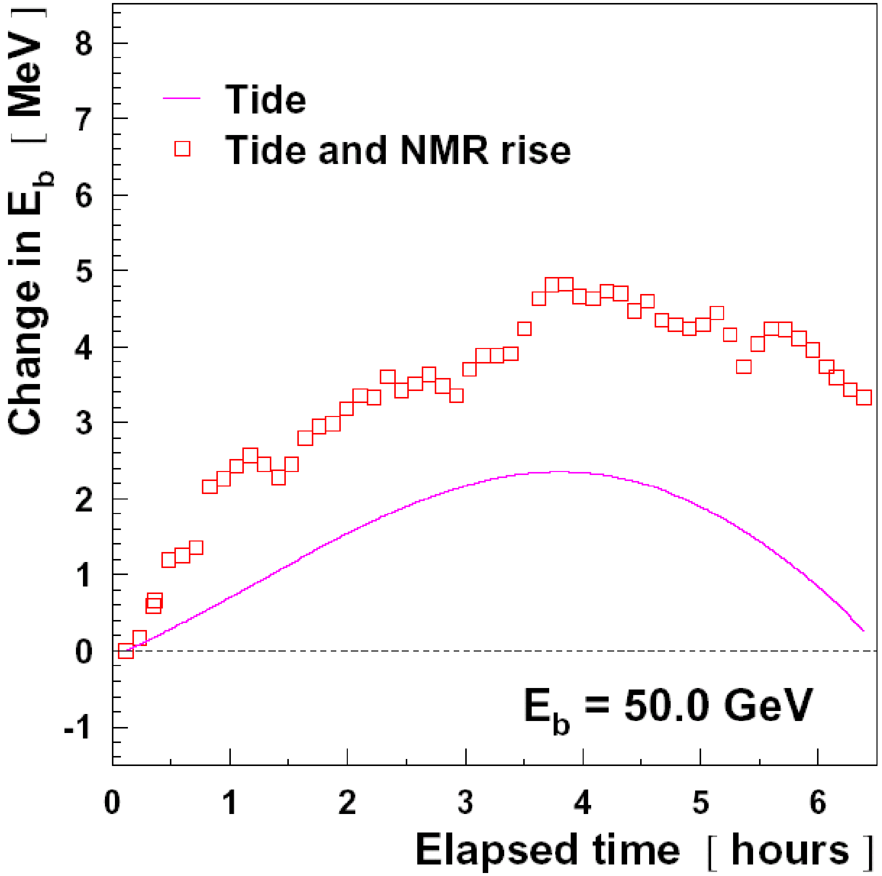
Validating the field rise with RDP

Modelling of energy rise by (selected) NMR sampling of B-field is excellent !



(Experiment from 1999)

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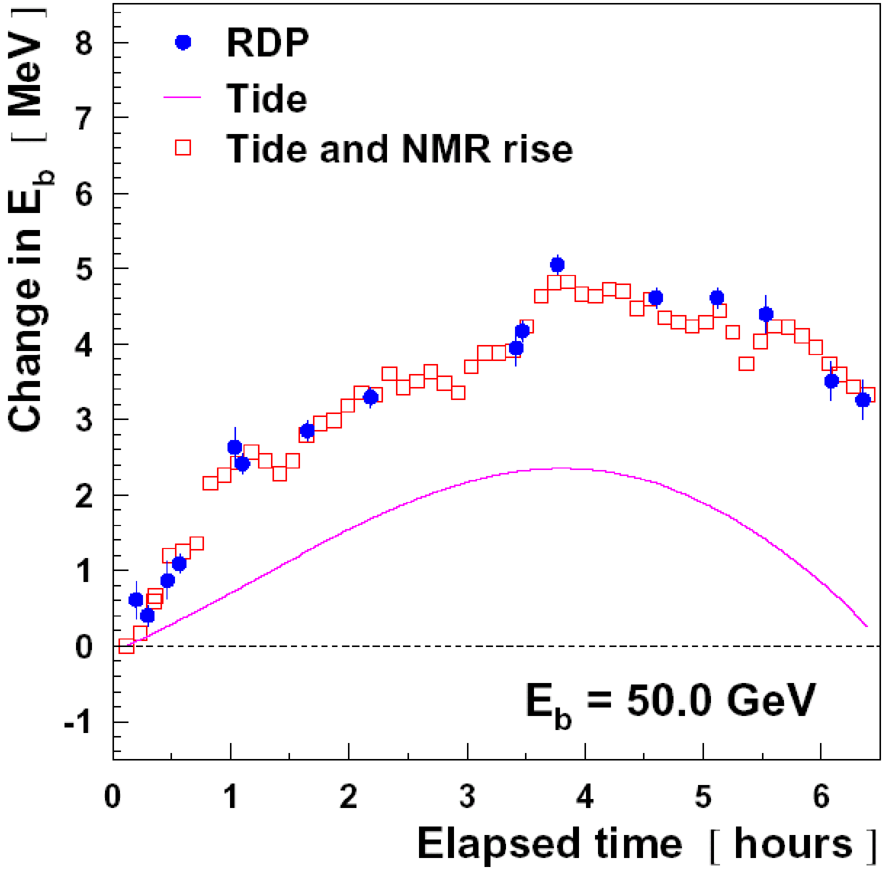
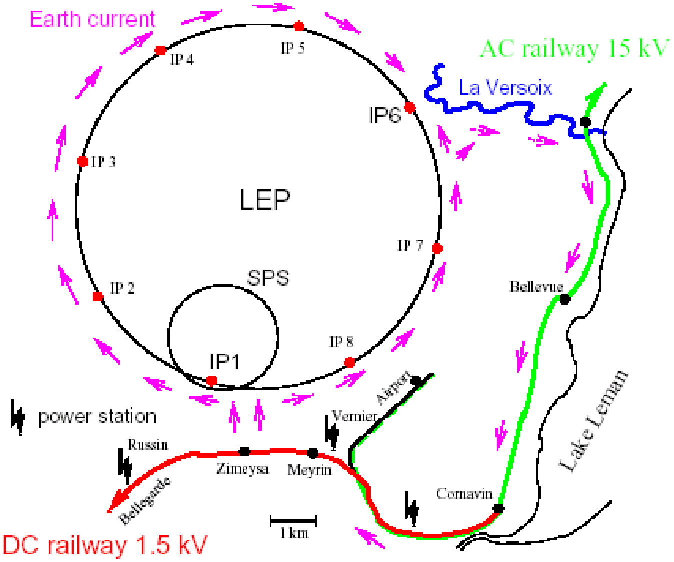
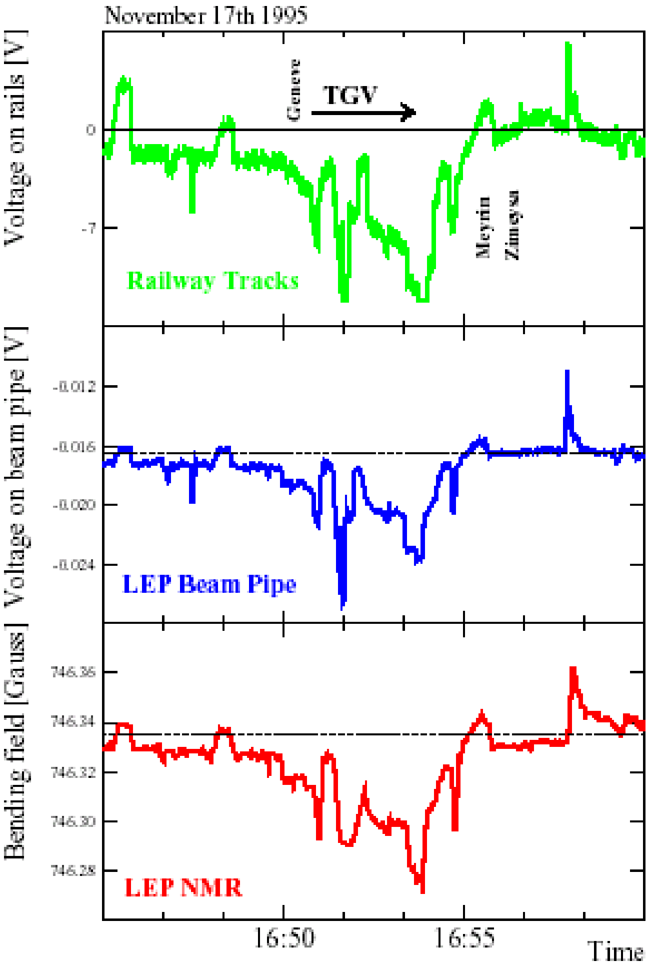


(Experiment from 1999)

The TGV effect

Explanation: magnets being ‘tickled’ by vagabound currents from (daytime) trains leaking onto the vacuum pipe.





Significant effect on magnets not yet at the top of their hysteresis curve.
(Also found that temperature effects are more complicated than originally thought.)

Getting the local E_b – the RF sawtooth

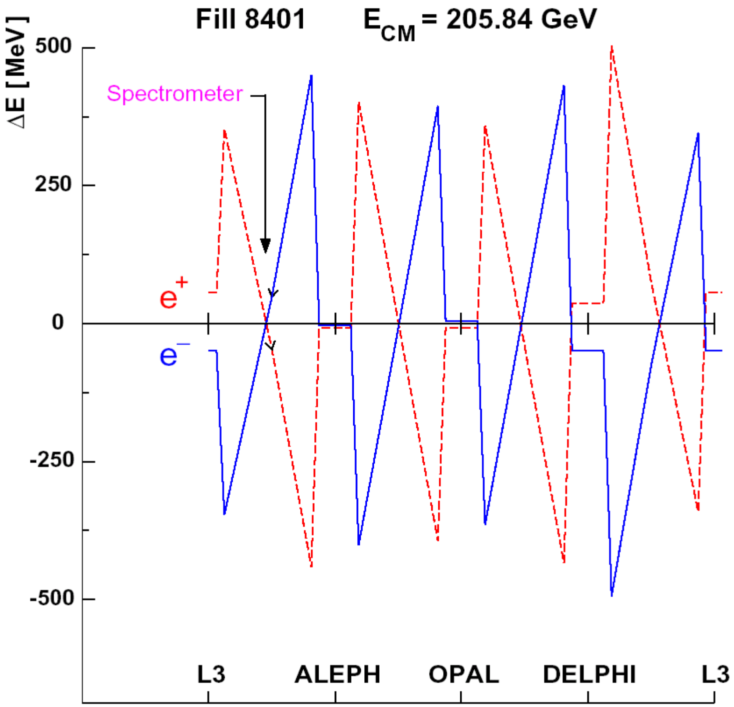
RDP, and the beam-energy model, gives the mean energy.

However we are interested in the local beam energy at the IPs.

Need to account for the 'RF sawtooth' – the synchrotron energy loss and RF-system replenishment around ring.

Modelling sensitive to things such as rate of tripping (gives asymmetries – logging important!), phasing, misalignments *etc*.

This is the LEP2 sawtooth. At LEP1 there were two sets of RF stations and the amplitude of the sawtooth was ~30 MeV.



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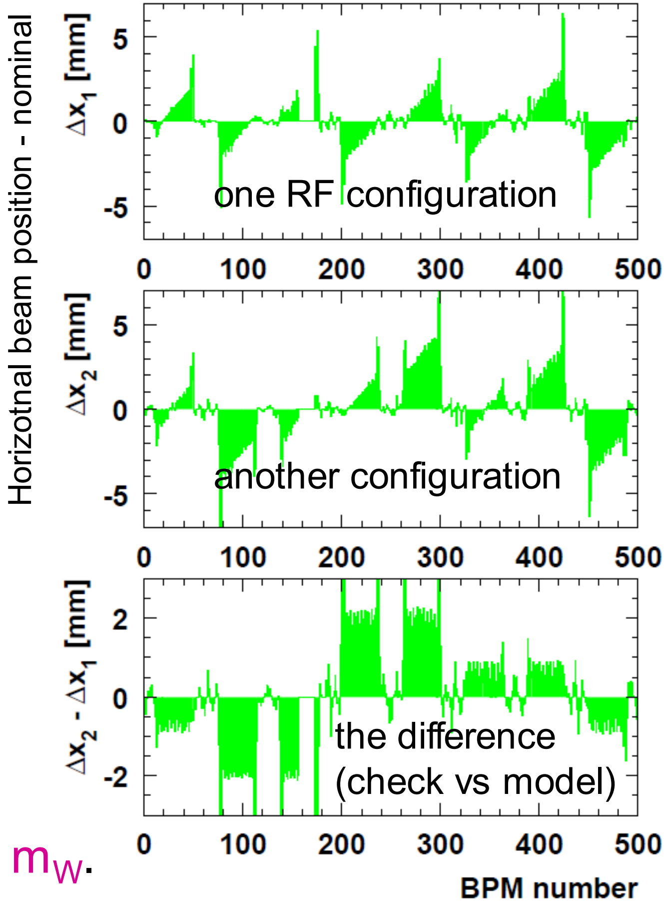
Modelling sensitive to things such as rate of tripping (gives asymmetries – logging important!), phasing, misalignments *etc*.

Anti-correlation between e^+ and e^-, and averaging over the four IPs helps in diluting uncertainty. Contributes ~0.4 MeV in m_Z and 0.2 MeV in Γ_Z, and around 4 MeV on m_W.

Powerful constraints on sawtooth model come from measured synchrotron tune and beam position in arcs.



Discovery of RF sawtooth systematic

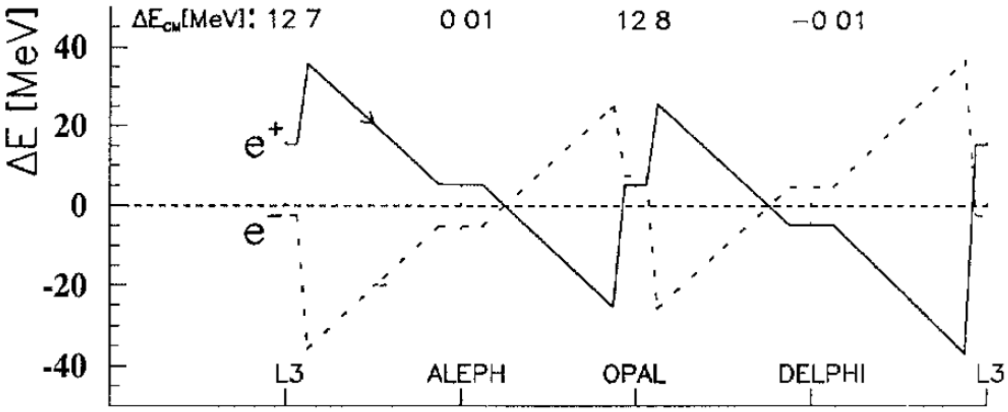
With only two experiments, important systematic effects risk being overlooked.

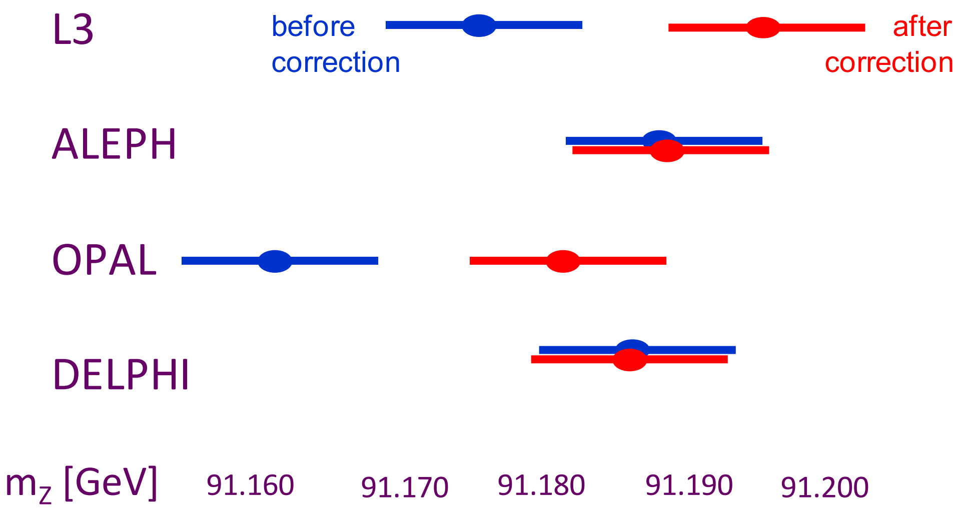
At LEP, it was inspection of 1991 individual m_Z results from each experiment that led to appreciation of effect of `RF sawtooth'

[PLB 307 (1993) 187]

On a ring containing only L3 & OPAL (or ALEPH & DELPHI) this would have been much harder to spot.

Lesson for the project: have 4 IPs !
lesson for EPOL: pay attention
to experimental constraints !

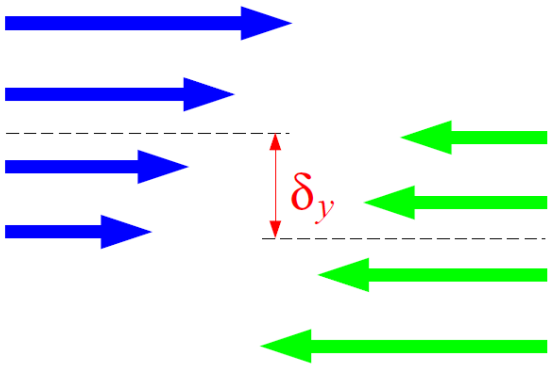




Dispersion effects

Even with perfect knowledge of E_b at interaction point, there are other issues to consider when calculating E_{CM}. For example opposite sign vertical dispersion…

Opposite sign vertical dispersion induced by 1995 bunch train operation, when coupled with collision offset, can lead to significant E_{CM} bias !



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

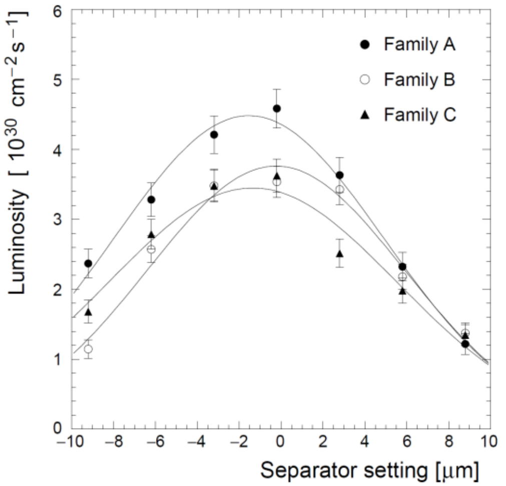
σ_{E_b}= Energy spread

ΔE^*_b= Difference in dispersion between e^+ and e^-

e.g. if $\Delta D^*_y \sim 2$ mm and δy=1 μm

→ ΔE_{CM} = 2 MeV.

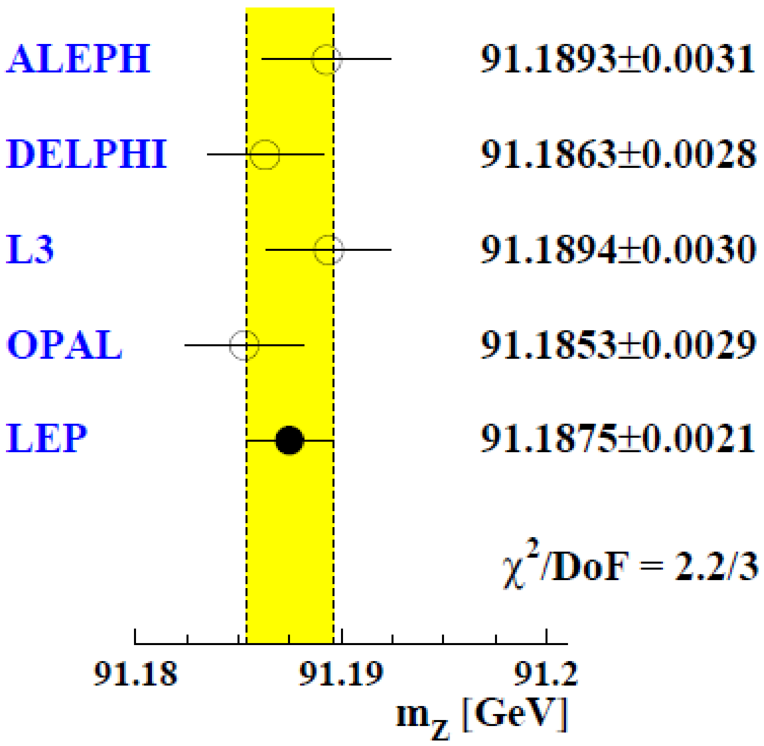
Biases suppressed by routine separator scans to optimise luminosity. This minimises offset averaged over bunches in train.

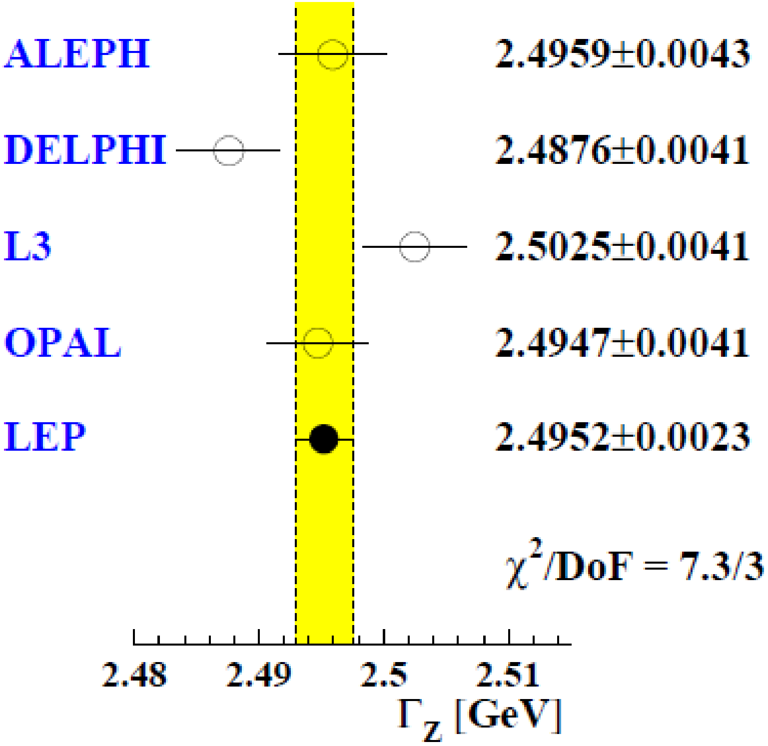


→ residual uncertainty on E_{CM} = 0.3 MeV.

Final LEP1 results

[Phys. Rep. 427 (2006) 257]

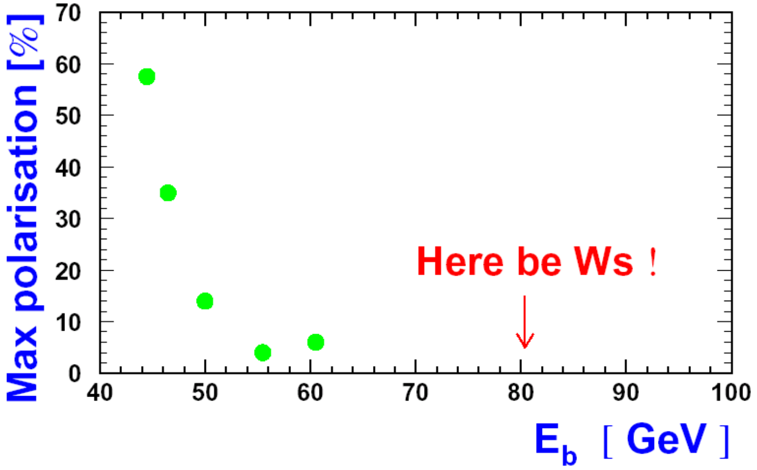




Contribution to uncertainty arising from E_{CM}	0.0017 GeV	0.0012 GeV

E_b calibration for m_W – the 'NMR model'

Recall that at LEP, RDP was not possible at W-production energies. Alternative strategies necessary.



At FCC-ee, we expect polarisation in this regime, but measurements won't be easy, so alternative approaches provide very valuable cross-checks.

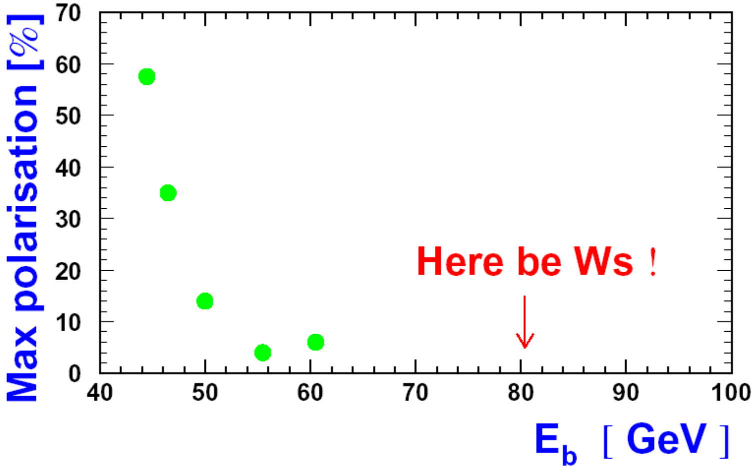
Moreover, these alternative methods will be the baseline when going to higher energies.

So let us review what was done.

E_b calibration for m_W – the ‘NMR model’

Recall that at LEP, RDP was not possible at W-production energies. Alternative strategies necessary.

Adopted approach: take B field readings of 16 NMR probes distributed around ring, and make a linear fit to E_b measurements over the interval in which RDP was possible.

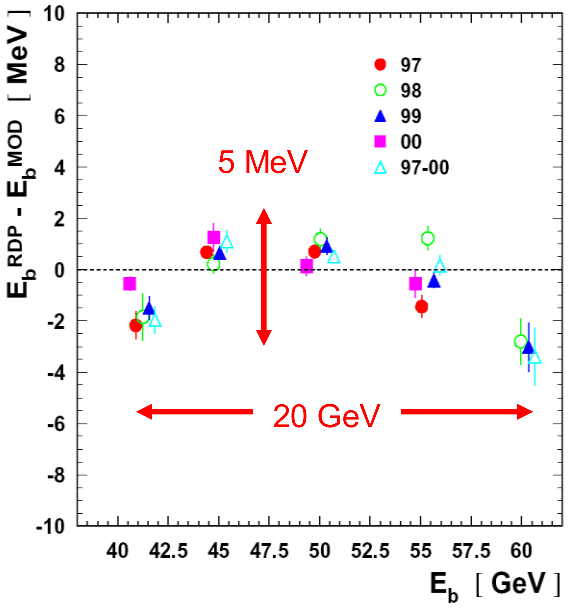


→ predictions of this model at high field sets scale for the W mass measurement

However:

- How representative of the total bending field are these 16 readings (~3200 dipoles in all);
- How linear is the relationship ?

Fit residuals show excellent year-to-year reproducibility, but evidence of (mild) non-linearity.



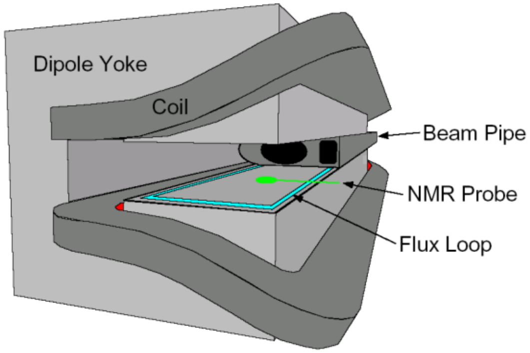
Validating the NMR model at high energy

Three methods used to check the validity of the NMR model in the W^+W^- regime. NB all required machine time, which had to be balanced against Higgs search !

1) The flux loop

Copper loop in each dipole which sampled ~96% of the total LEP bending field.

Does not provide an absolute E_b measurement, but flux-loop cycles allow sampling representability & linearity of NMR model to be checked.

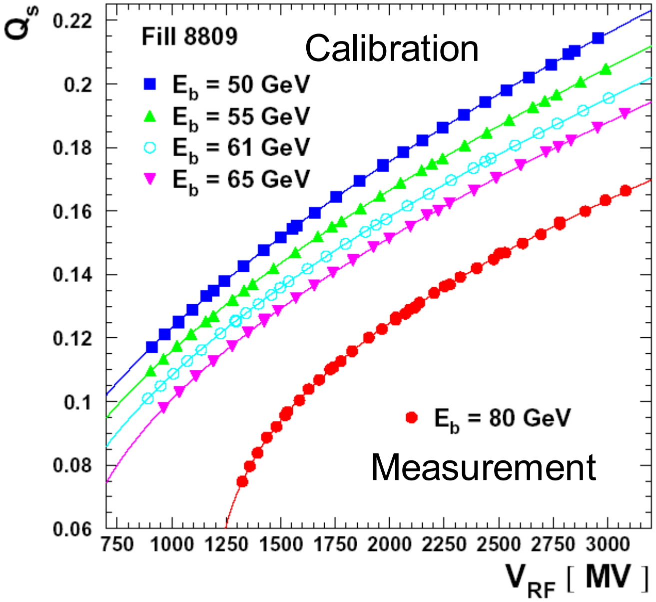


2) Energy loss / synchrotron tune (Q_s) studies

$$Q_s^2 \sim (1/E_b) \sqrt{(e^2 V_{RF}^2 - U_0^2)}$$

U_0 = energy loss / turn – also depends on E_b

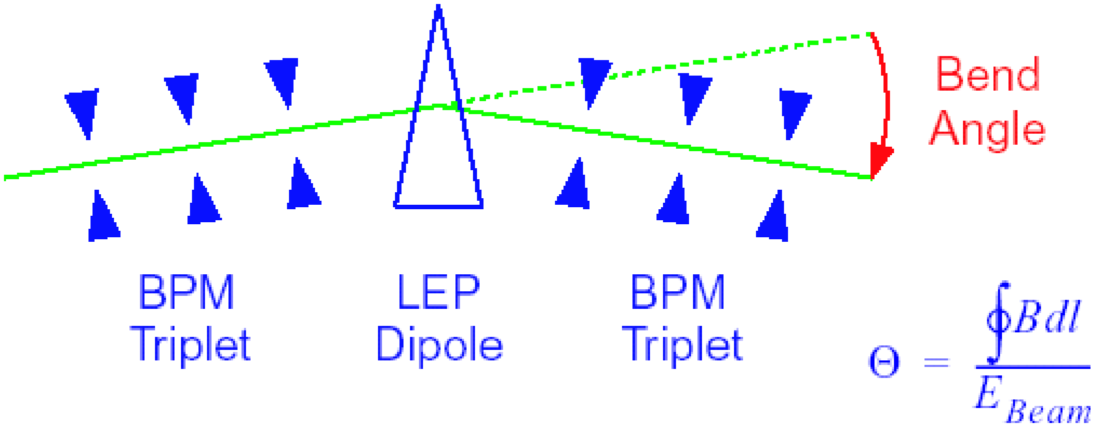
Fit Q_s dependence at low energy, to calibrate RF voltage scale, and then extract E_b at higher energy.



Validating the NMR model at high energy

3) The LEP in-line spectrometer

First proposed in 1997; installed close to IP3 and commissioned in 1999; data taking for E_b measurements in 2000.

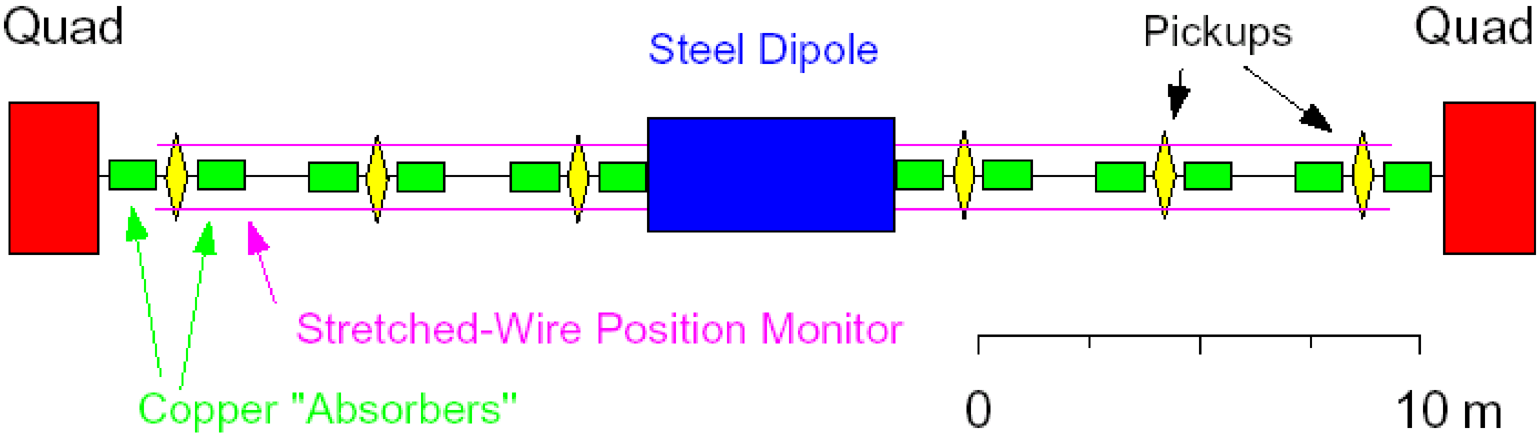


$$\Theta = \frac{\oint B\,dl}{E_{Beam}}$$

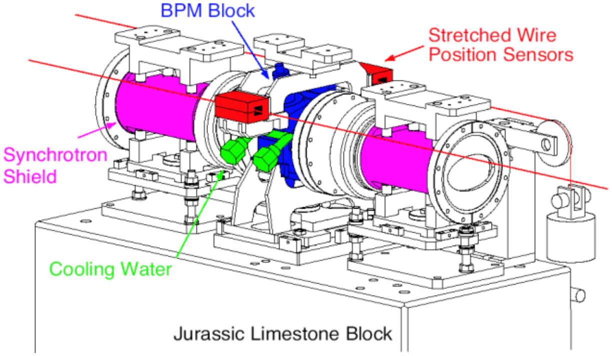
Required precision makes absolute measurement too challenging (impossible?). Rather make relative measurement, in which the change in bend angle and B-field integral is determined when ramping from ~50 GeV up to high energy.

- Since the dipole is ramped with the rest of LEP, the change in bend angle during this procedure only enters as a second order effect (<< mrad).
- Clearly a local measurement – need RF-sawtooth to relate to average E_b.

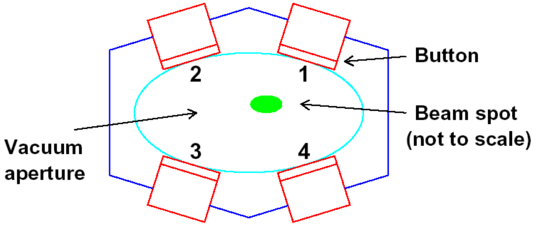
The LEP spectrometer



Shielding & position monitoring system



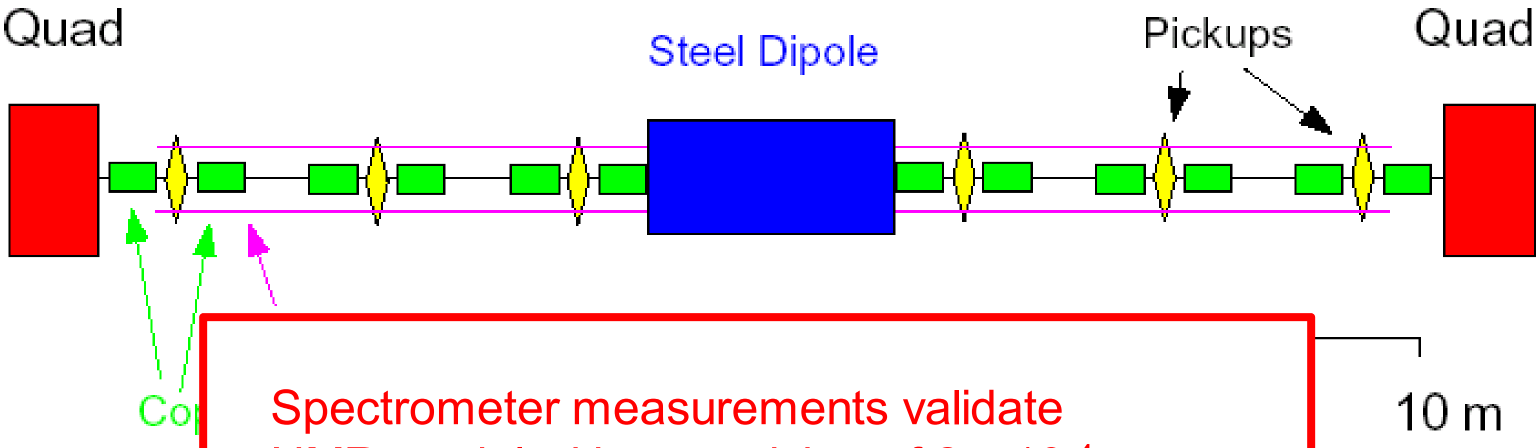
Standard LEP BPMs with customised electronics



Micron precision achieved, but controlling relative stability in ramping to high energy challenging.

Dipole being mapped in lab

The LEP spectrometer



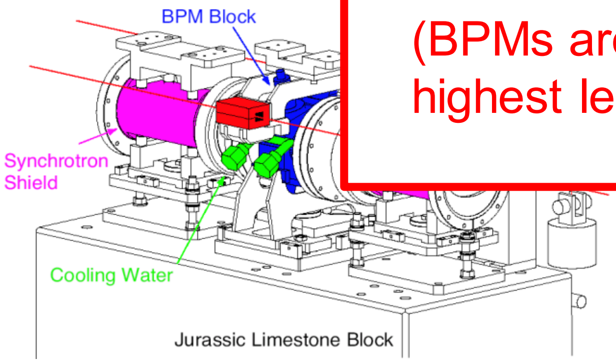
Shielding &
monitoring s

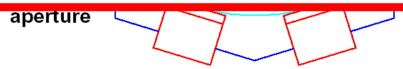
Spectrometer measurements validate NMR model with a precision of 2 x 10^{-4}.

Dominant uncertainty from stability of BPM response – without this 1 x 10^{-4} achievable.

(BPMs are important ! Let us insist on the highest level of BPM performance for FCC-ee.)

Dipole being mapped in lab

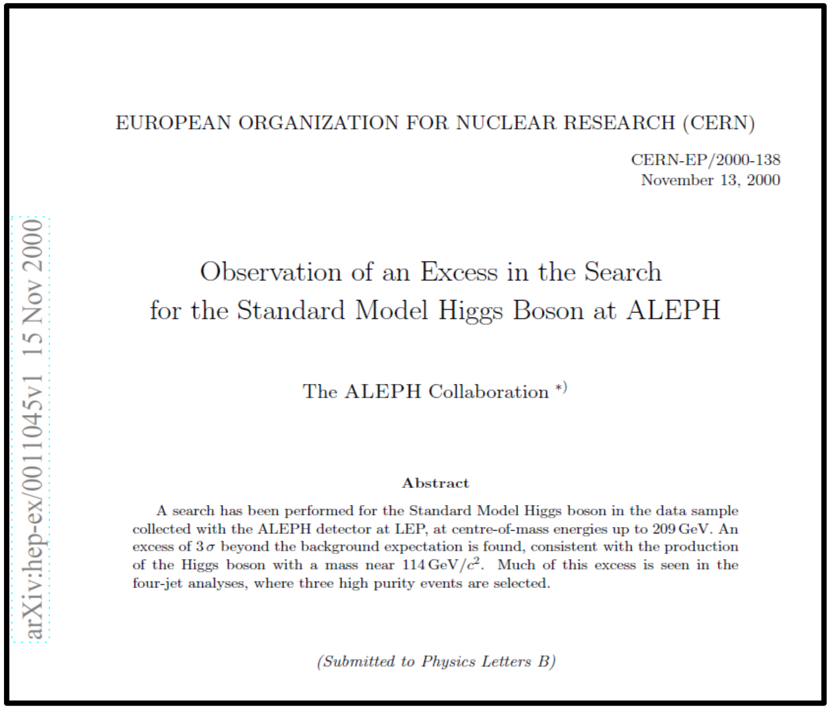




Micron precision achieved, but controlling relative stability in ramping to high energy challenging.

Distractions

Strong competition for time between ECAL and physics operation in final period of LEP 2 operation. (Quiz question: guess who was LEP Physics Coordinator at this time ?)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP/2000-138
November 13, 2000

arXiv:hep-ex/0011045v1 15 Nov 2000

Observation of an Excess in the Search
for the Standard Model Higgs Boson at ALEPH

The ALEPH Collaboration *)

Abstract

A search has been performed for the Standard Model Higgs boson in the data sample collected with the ALEPH detector at LEP, at centre-of-mass energies up to 209 GeV. An excess of 3σ beyond the background expectation is found, consistent with the production of the Higgs boson with a mass near 114 GeV/c^2. Much of this excess is seen in the four-jet analyses, where three high purity events are selected.

(Submitted to Physics Letters B)

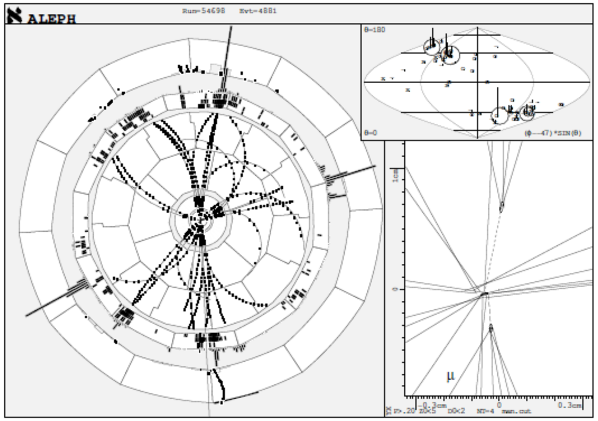


Figure 13: Four-jet Higgs boson candidate (c) with a reconstructed Higgs boson mass of 114.3 GeV/c^2. The two Higgs boson jets are well b tagged.

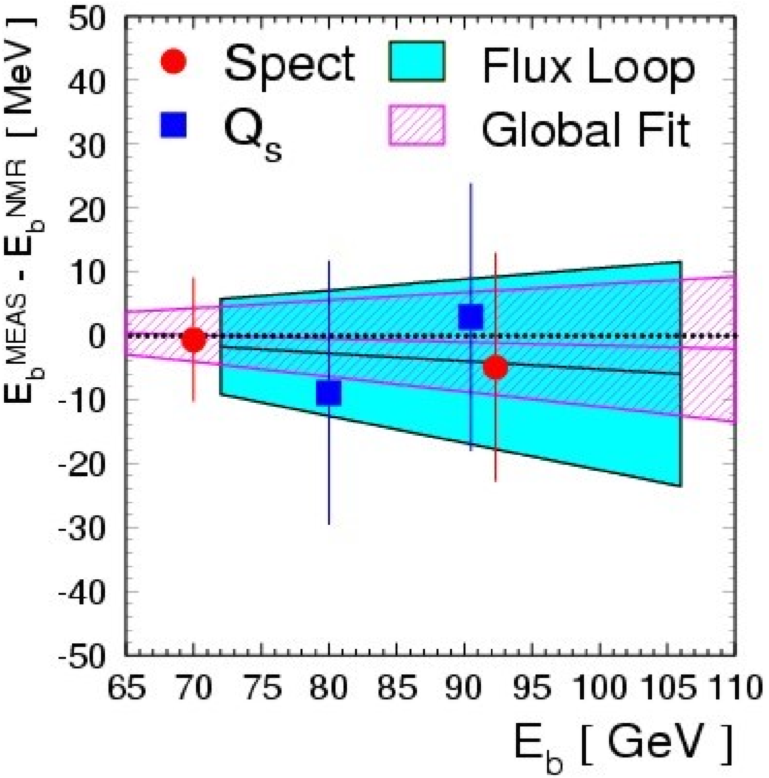
Citations per year

‘sic transit gloria mundi’

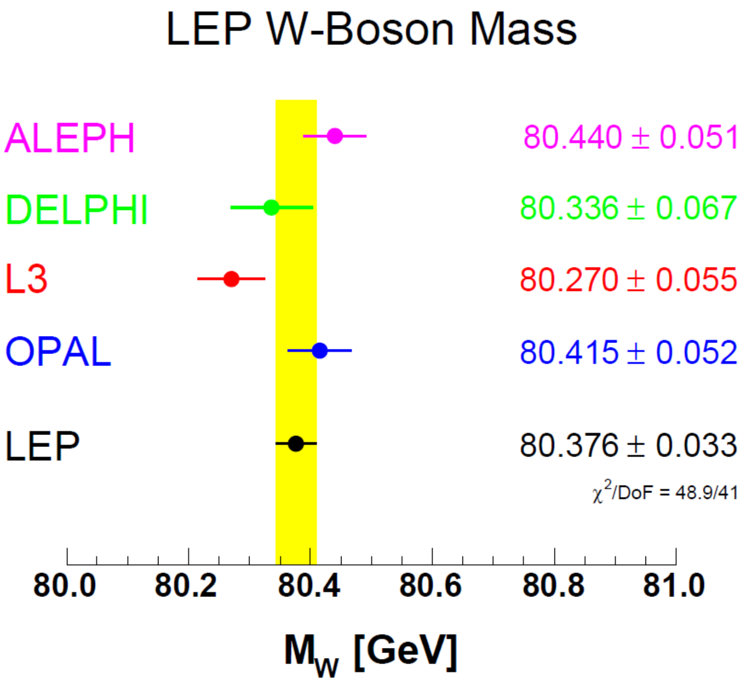
Lesson: keep your eye on what endures !

LEP2 results

Three methods give consistent results and validate NMR model



Offset to NMR model
at 100 GeV -2 +/- 10 MeV

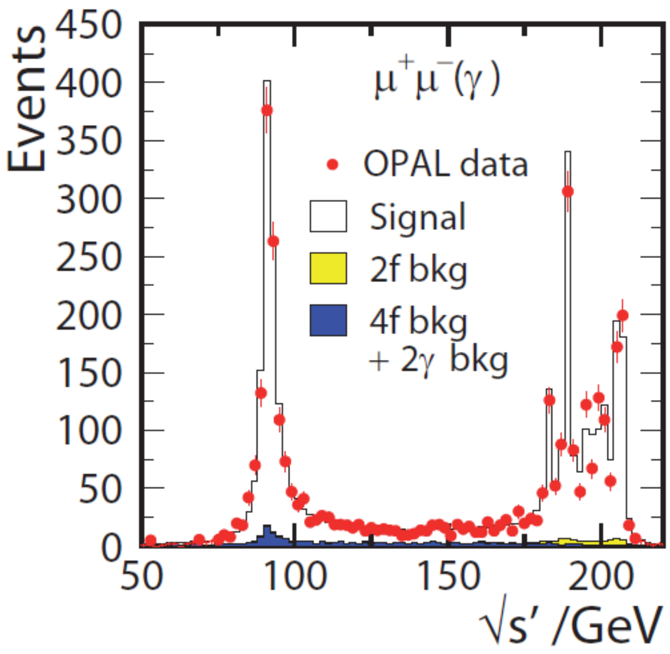


Common uncertainty from E_{CM} 0.009 GeV

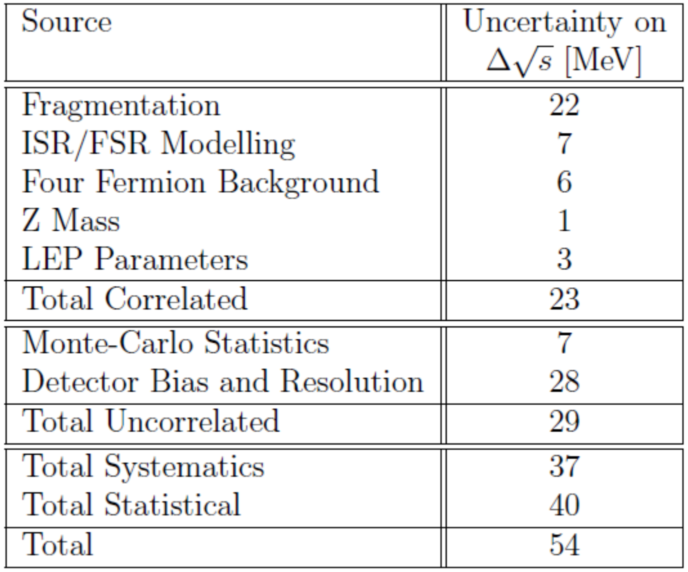
Best precision now comes from Tevatron, but compatibility is excellent !

Experimental cross checks

Cross-checks of energy scale came from experiments, through measurement of position of Z mass in radiative return events [Physics Reports 533 (2013) 119].



All experiments



Source	Uncertainty on $\Delta\sqrt{s}$ [MeV]
Fragmentation	22
ISR/FSR Modelling	7
Four Fermion Background	6
Z Mass	1
LEP Parameters	3
Total Correlated	23
Monte-Carlo Statistics	7
Detector Bias and Resolution	28
Total Uncorrelated	29
Total Systematics	37
Total Statistical	40
Total	54

All experiments $\Delta\sqrt{s} = -54 \pm 54$ MeV

Summary and lessons for the future

LEP energy calibration was a great success, and all goals were met.

But it took many years to achieve sufficient understanding,
a great deal of effort, and much dedicated machine time
(>50 full days from 1993 onwards…).

At FCC-ee, continuous RDP during physics operation, and polarisation in the W^+W^- regime (if achieved) will ameliorate many problems that LEP faced.

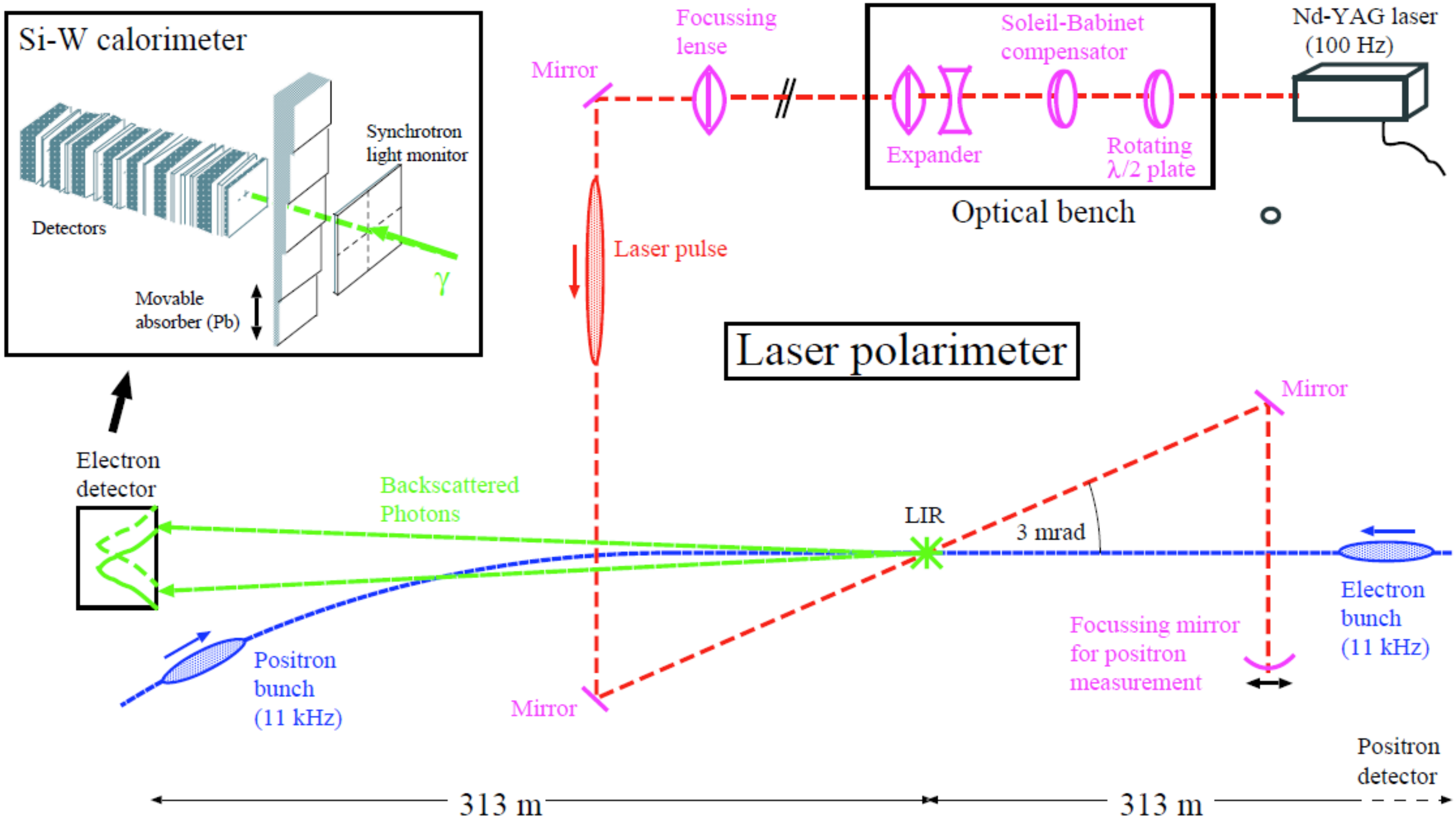
But problems will remain (*e.g.* determining local E_b at the IPs), and the scale of some of the effects will for sure lead to residual uncertainties.

High quality instrumentation, plus mundane tasks such as continuous logging, are essential for making sense of energy variation.

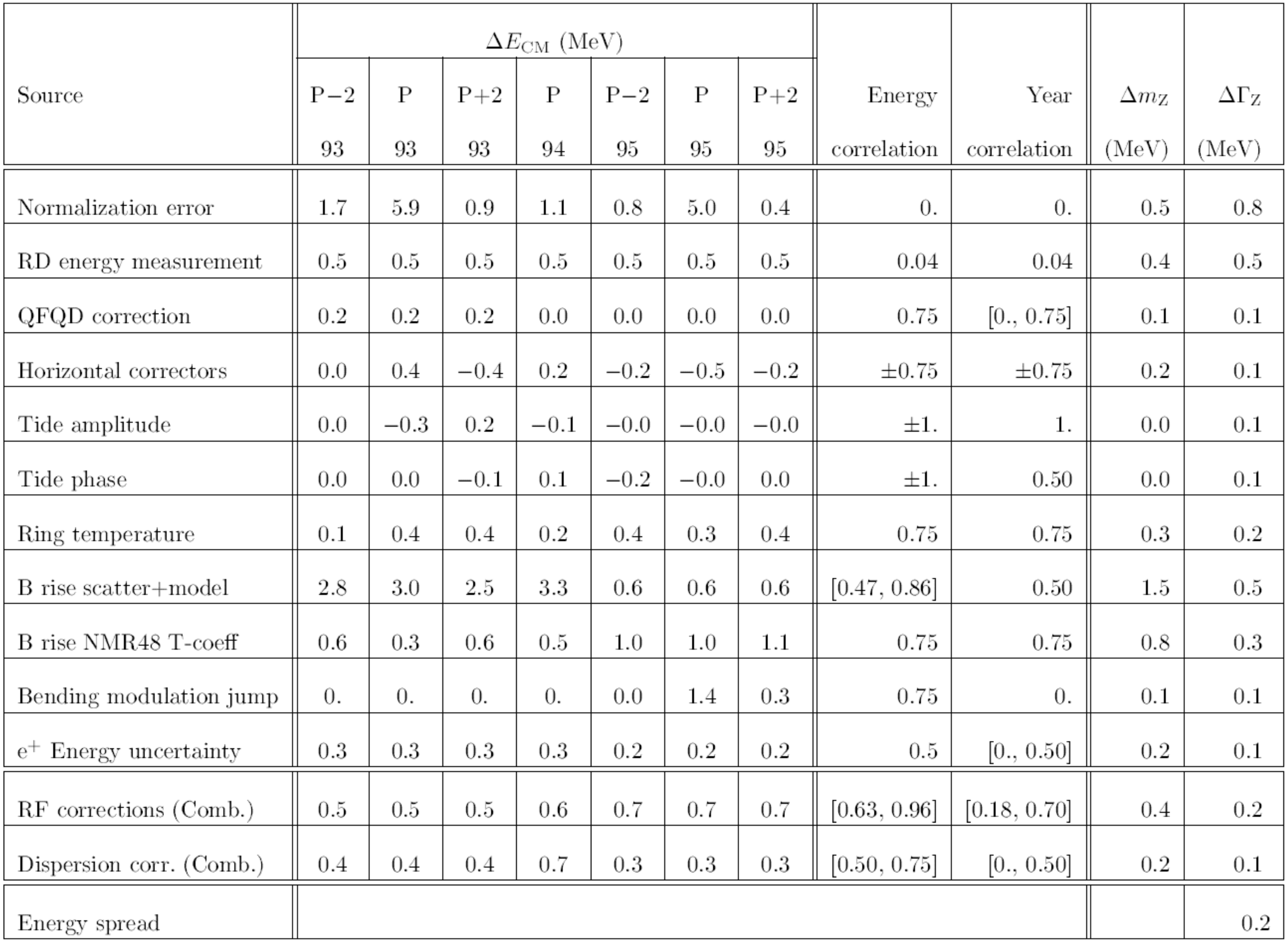
Surprises are inevitable !

Backups

LEP polarimeter



LEP1 energy uncertainty budget



Source	ΔE_{CM} (MeV)							Energy correlation	Year correlation	Δm_{Z} (MeV)	$\Delta\Gamma_{\mathrm{Z}}$ (MeV)
	P−2 93	P 93	P+2 93	P 94	P−2 95	P 95	P+2 95				
Normalization error	1.7	5.9	0.9	1.1	0.8	5.0	0.4	0.	0.	0.5	0.8
RD energy measurement	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.04	0.04	0.4	0.5
QFQD correction	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.75	[0., 0.75]	0.1	0.1
Horizontal correctors	0.0	0.4	−0.4	0.2	−0.2	−0.5	−0.2	±0.75	±0.75	0.2	0.1
Tide amplitude	0.0	−0.3	0.2	−0.1	−0.0	−0.0	−0.0	±1.	1.	0.0	0.1
Tide phase	0.0	0.0	−0.1	0.1	−0.2	−0.0	0.0	±1.	0.50	0.0	0.1
Ring temperature	0.1	0.4	0.4	0.2	0.4	0.3	0.4	0.75	0.75	0.3	0.2
B rise scatter+model	2.8	3.0	2.5	3.3	0.6	0.6	0.6	[0.47, 0.86]	0.50	1.5	0.5
B rise NMR48 T-coeff	0.6	0.3	0.6	0.5	1.0	1.0	1.1	0.75	0.75	0.8	0.3
Bending modulation jump	0.	0.	0.	0.	0.0	1.4	0.3	0.75	0.	0.1	0.1
e^+ Energy uncertainty	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.5	[0., 0.50]	0.2	0.1
RF corrections (Comb.)	0.5	0.5	0.5	0.6	0.7	0.7	0.7	[0.63, 0.96]	[0.18, 0.70]	0.4	0.2
Dispersion corr. (Comb.)	0.4	0.4	0.4	0.7	0.3	0.3	0.3	[0.50, 0.75]	[0., 0.50]	0.2	0.1
Energy spread											0.2