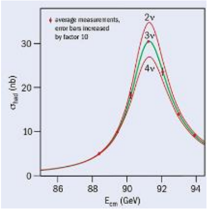
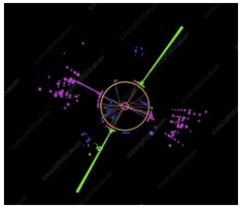
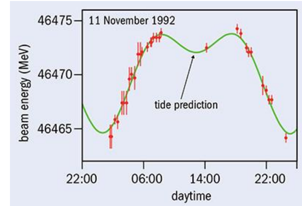
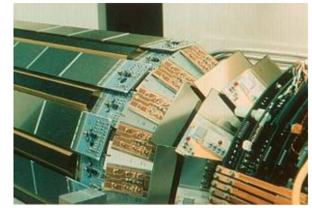
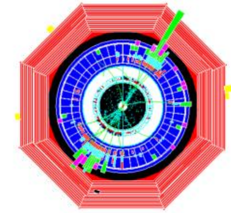


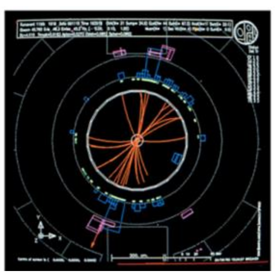
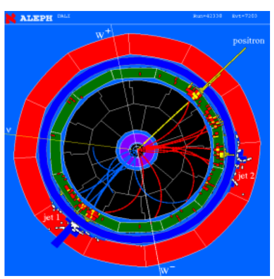


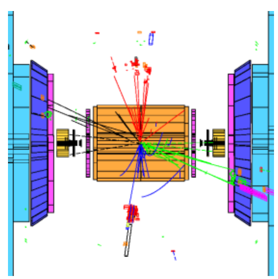
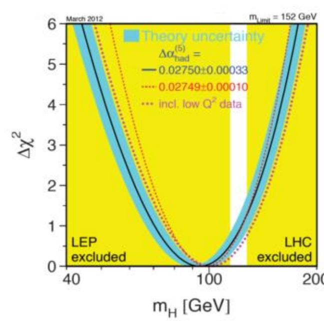


Z and W measurements at LEP and SLC

Electroweak milestones – CERN symposium

Guy Wilkinson
University of Oxford
31/10/23

Overview

Genesis

The Z lineshape and other observables – what they tell us about nature

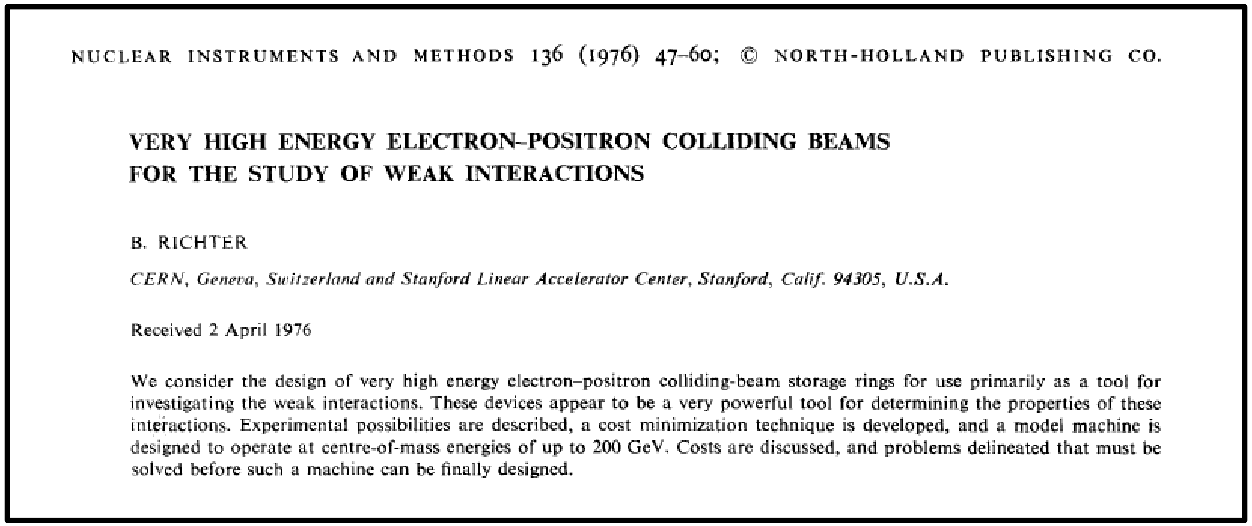
Electroweak physics at LEP2

Beyond electroweak: the Z^0 as a heavy-flavour laboratory

Conclusions

Genesis of the high energy e^+e^- colliders: LEP

Hard to be certain of when the first proposal was advanced for a high-energy e^+e^- collider for precise studies of the Z and W. The leading candidate is NIM 136 (1976) 47, written during Burt Richter's sabbatical year at CERN.



NUCLEAR INSTRUMENTS AND METHODS 136 (1976) 47–60; © NORTH-HOLLAND PUBLISHING CO.

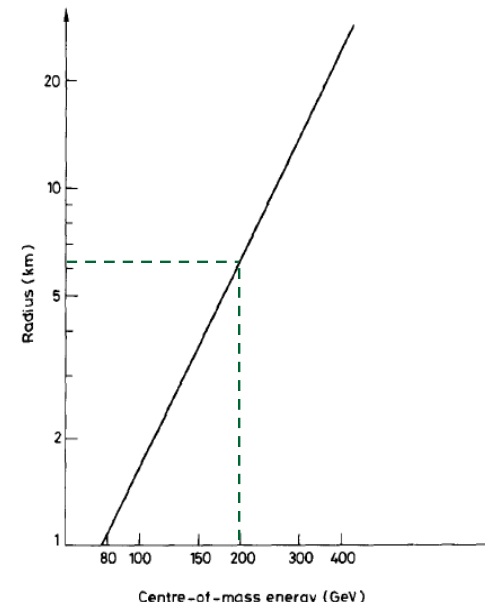
VERY HIGH ENERGY ELECTRON–POSITRON COLLIDING BEAMS FOR THE STUDY OF WEAK INTERACTIONS

B. RICHTER

CERN, Geneva, Switzerland and Stanford Linear Accelerator Center, Stanford, Calif. 94305, U.S.A.

Received 2 April 1976

We consider the design of very high energy electron–positron colliding-beam storage rings for use primarily as a tool for investigating the weak interactions. These devices appear to be a very powerful tool for determining the properties of these interactions. Experimental possibilities are described, a cost minimization technique is developed, and a model machine is designed to operate at centre-of-mass energies of up to 200 GeV. Costs are discussed, and problems delineated that must be solved before such a machine can be finally designed.



Right at the outset, it was clear that such a collider would have to be very large. Soon appreciated that the tunnel could be reused to house a hadron machine.

Genesis of the high energy e^+e^- colliders: SLC

Following discussions at 1978 FNAL workshop, Richter proposed repurposing SLAC's single linac with a `tennis racket' addition to be a collider for Z^0 physics.

[eConf C781015 (1978) 009]

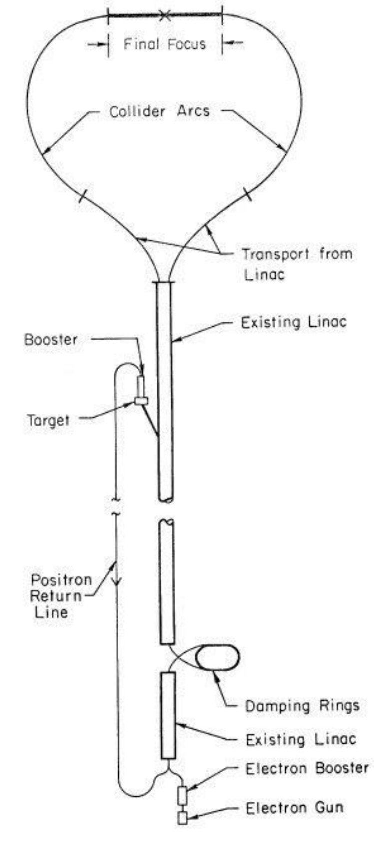
LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND

LINEAR COLLIDING BEAM SYSTEMS AT HIGH ENERGY

J.-E. Augustin[*], N. Dikanski[†], Ya. Derbenev[†], J. Rees[‡],
B. Richter[‡], A. Skrinski[†], M. Tigner[**], and H. Wiedemann[‡]

Introduction

This note is the report of working Group I (J. Rees - Group Leader). We were assisted at times by U. Amaldi and E. Keil of CERN. We concerned ourselves primarily with the technical limitations which might present themselves to those planning a new and higher-energy electron-positron colliding-beam facility in a future era in which, it was presumed, a 70-GeV to 100-GeV LEP-like facility would already exist. In such an era, we reasoned, designers would be striving for center-of-mass energies of at least 700-GeV to 1-TeV. Two different approaches to this goal immediately came to the fore: one, a storage ring based on the principles of PEP, PETRA, and LEP and the other, a system in which a pair of linear accelerators are aimed at one another so that their beams will collide.

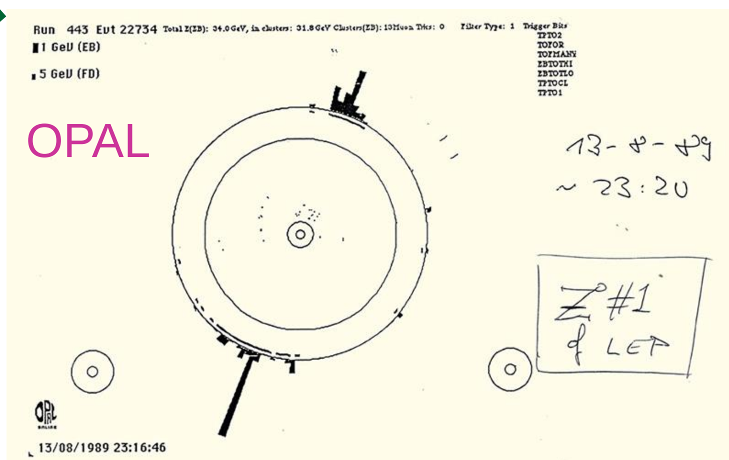


SLC SCHEMATIC

The lightning speed of the past

Astonishingly, first physics results emerged barely a decade after these proposals.

Approval	1981
Tunnel construction begins	1983
LEP installation begins	1987
First octant test	July 1988
First turn	14 July 1989
First collisions and first Z^0s recorded	13 August 1989
First physics run begins	20 September 1989
First results announced, including N_ν	13 October 1989



First Z^0 recorded at SLC in April 1989.

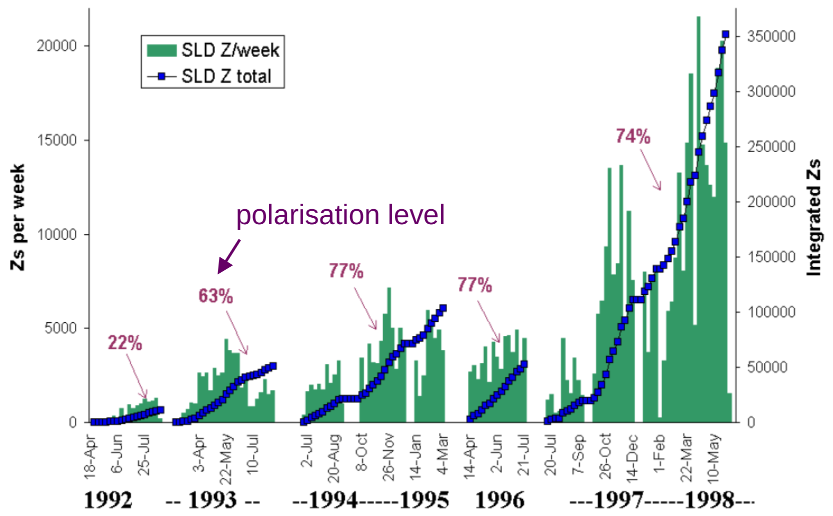
```
Wednesday April 12, 1989
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!                                                                         !
!         ***          FIRST Z DETECTED AT SLC.          ***              !
!                                                                         !
!   A TWO-JET HADRONIC EVENT HAS BEEN IDENTIFIED IN MARK II DATA          !
!   AT A CMS COLLISION ENERGY OF 92.2 GEV.  NINE CHARGED TRACKS           !
!   ARE ASSOCIATED WITH THE EVENT, AND 70 GEV IS ACCOUNTED FOR IN         !
!   THE DETECTOR.                                                         !
!                                                                         !
!   Bhabha update: 1 more Bhabha was seen in the SAM and 4 in the         !
!   mini-SAM last night, for a total this year of 5 in the SAM and        !
!   10 in the mini-SAM.                                                   !
!                                                                         !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

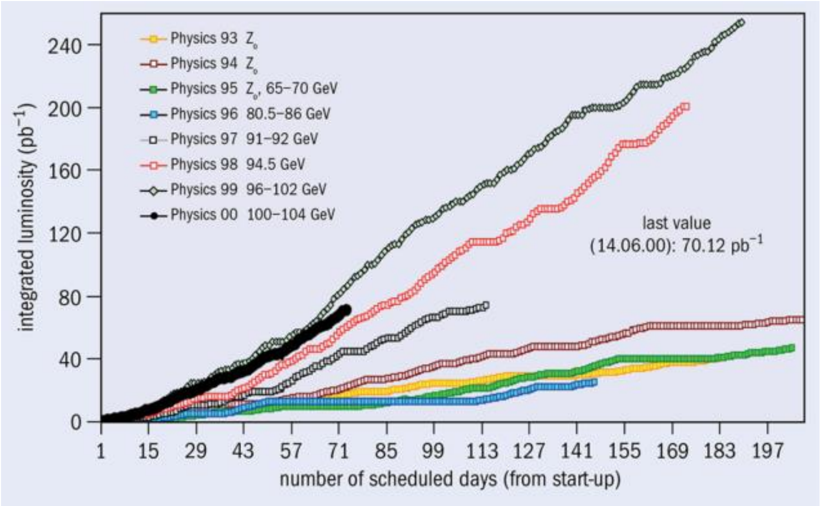
LEP and SLC: performance

LEP operated at the Z resonance from 1989-1995, with two high statistics scans in 1993 and 1995, and then at and above the W^+W^- threshold (161-210 GeV) up until 2000. SLC operated at the Z resonance from 1989 until 1998.

Maximum luminosity achieved at SLC: 3×10^{30} cm^{-2}s^{-1}

Maximum luminosity achieved at LEP1 (LEP2): 34 (100) x 10^{30} cm^{-2} s^{-1}: around 3x design





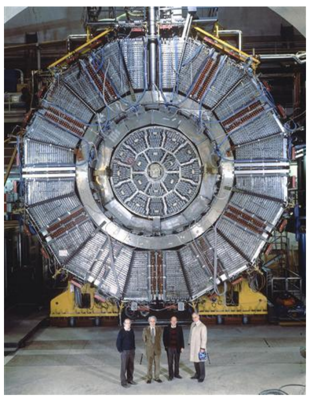
Unique feature: *longitudinal* polarisation – direct access to certain EW parameters

Unique feature: *transverse* polarisation – invaluable for E_b calibration

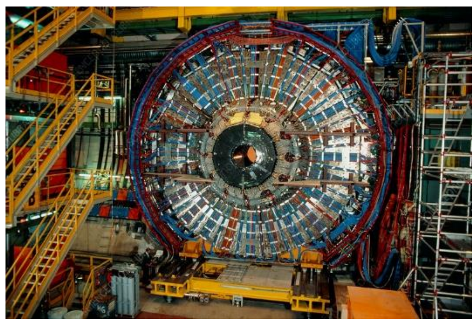
LEP and SLC: dramatis personae

LEP operated at the Z resonance from 1989-1995, with two high statistics scans in 1993 and 1995, and then at and above the W^+W^- threshold (161-210 GeV) up until 2000. SLC operated at the Z resonance from 1989 until 1998.

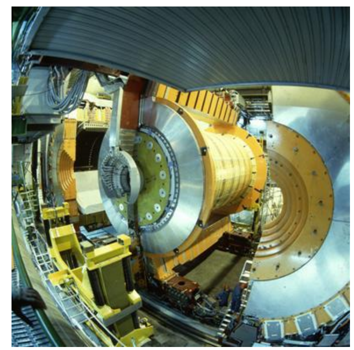
ALEPH
(296 pubs.)



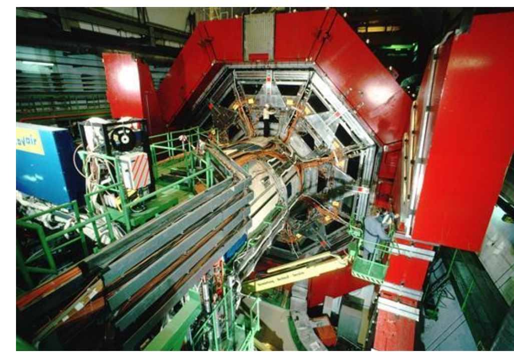
DELPHI
(342 pubs.)



OPAL
(422 pubs.)



L3
(310 pubs.)

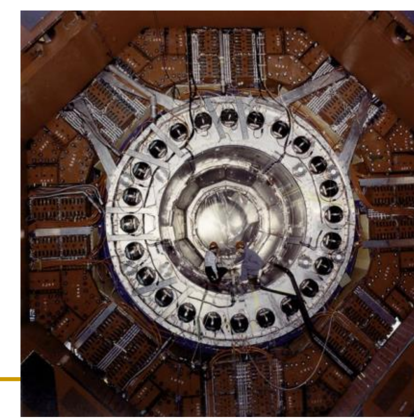


LEP accumulated ~17 million Z^0s and ~40k Ws.

During similar period SLD experiment at SLAC collected ~1 million Z^0s.

(Publication statistics from INSPIRE)

SLD
(72 pubs.)
[replaced Mark II in 1991]



Z metrology: original expectations

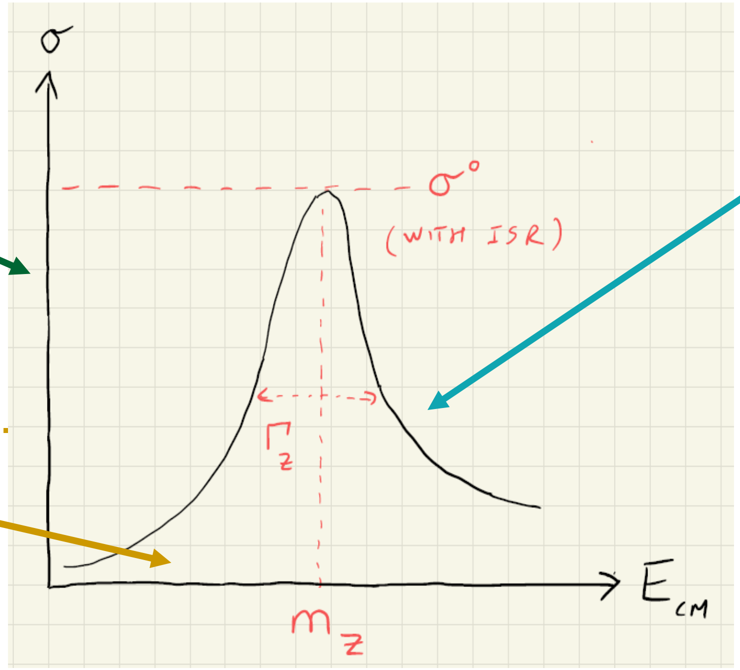
Outlook shortly before LEP turn on: *“The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…”* CERN 86-02 ‘Physics at LEP’, ed. Ellis and Peccei.

Vertical-scale uncertainty dominated by luminosity, largely correlated between experiments.

It was assumed this could be done to ~2%.

Horizontal-scale uncertainty set by knowledge of collision energy, also common between experiments.

It was guessed that ~10 MeV uncertainty *might* be possible.



Also vital Is understanding of shape, in particular effect of QED radiative corrections.

Important, but not discussed further today.

What was achieved

LEP knowledge of line-shape parameters largely derived from two three-point scans in 1993 and 1995, with final precision on mass and width of:

$$\sigma_{M_Z} = 2.1 \text{ MeV}$$

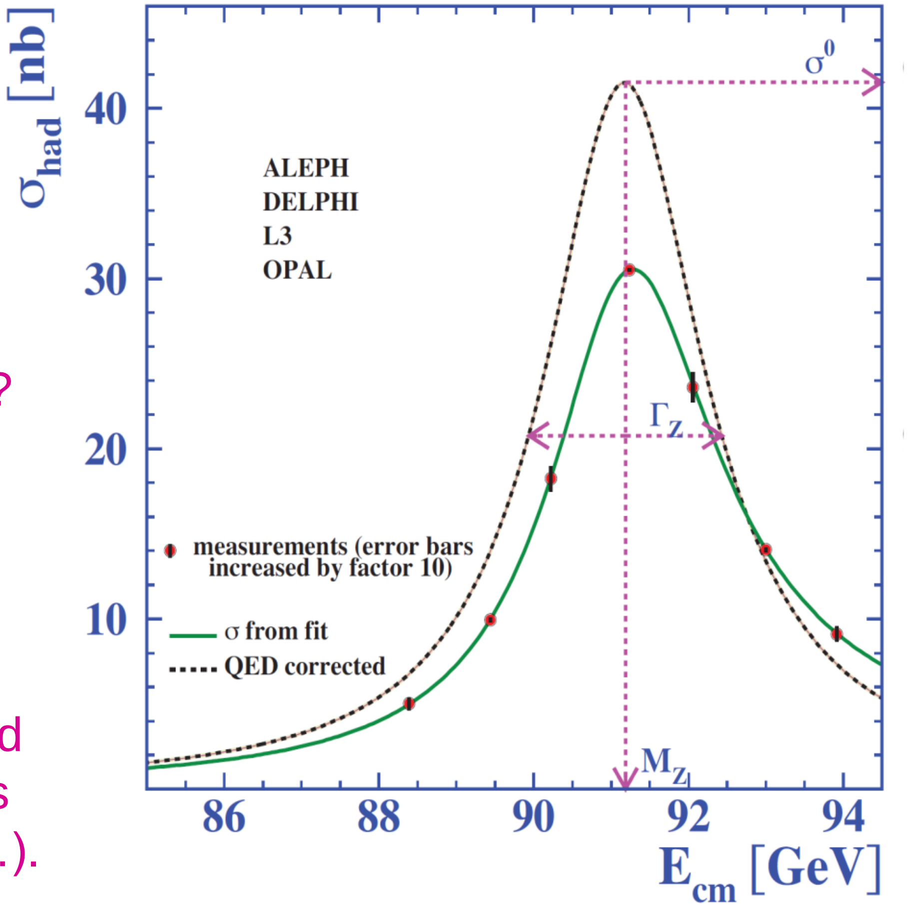
$$\sigma_{\Gamma_Z} = 2.3 \text{ MeV}$$

<<50 MeV !!! How did that happen ?

Another noteworthy output of scans:

$$N_\nu = 2.9840 \pm 0.0082$$

in agreement with the three observed generations of fundamental fermions (although, intriguingly, 2 sigma low…).



Luminosity measurement

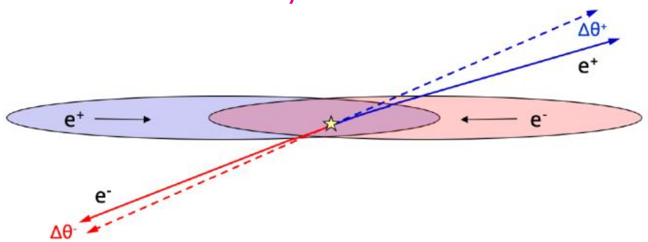
Lumi measured in QED-dominated low-angle $e^+e^- \rightarrow e^+e^-$.

LEP was expected to measure lumi to ~2%, but in fact did better than 0.1% !

Two ingredients: Enormous theoretical work, resulting in a LEP-wide correlated error of 0.06% + Precision luminometers, with 5 μm tolerances & excellent understanding of acceptance — *e.g.* OPAL achieved ~3 x 10^{-4}

There is an amusing epilogue. Reviews of the luminosity determination with the FCC-ee in mind has discovered an overlooked source of bias,

beam-beam effects modifying acceptance
[Voutsinas *et al.*, PLB 800 (2020) 135078]



plus updates to the LEP-era calculations with current knowledge [Janot & Jadach, PLB 803 (2020) 135319].

$$N_\nu = 2.9840 \pm 0.0082 \Rightarrow N_\nu = 2.9963 \pm 0.0074$$

"The 20-years-old 2σ tension… is gone" !

God's gift to synchrotrons: resonant depolarisation (RDP)

Transverse polarisation builds up naturally in a synchrotron.

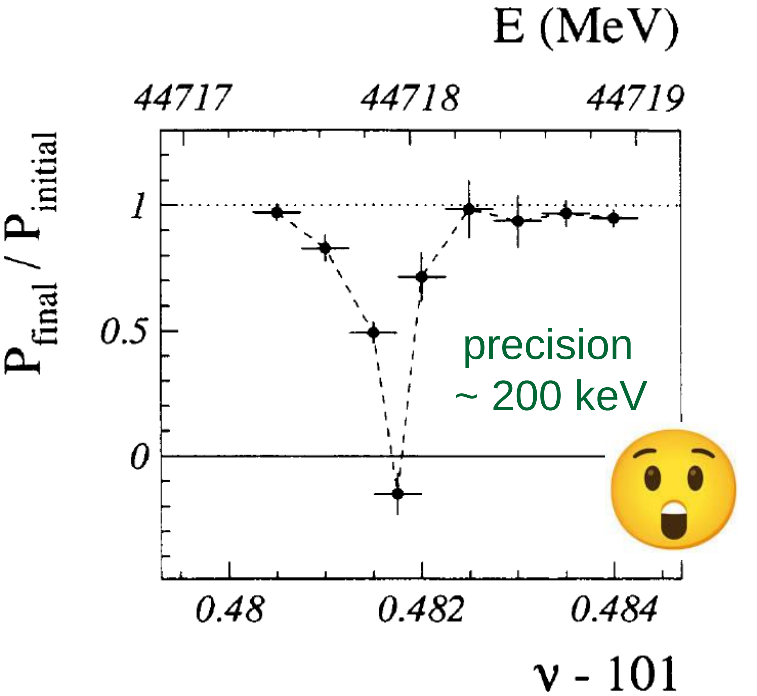
Spin tune v_s = precession frequency of electrons, normalised by revolution frequency, and is directly proportional to beam energy

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

Monitor polarisation levels through reverse Compton scattering.

Kick beam with oscillating field, and vary frequency until it is in phase with spin tune, when depolarisation occurs → spin tune, and hence beam energy, determined !

As always, the devil is in the detail.
This was not a day-1 procedure.



The long road to a precise E_{CM} determination at LEP

1990: polarisation established.
Initially 9%. In time, 60% achieved.

[PLB 270 (1991) 97]

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

First observation of transverse beam polarization in LEP

L. Knudsen, J.P. Koutchouk, M. Placidi, R. Schmidt
European Laboratory for Particle Physics (CERN), CH-1211 Geneva 23, Switzerland

M. Crozon
Laboratoire de Physique Corpusculaire, Collège de France, IN2P3–CNRS, 11 pl. M. Berthelot, F-75231 Paris Cedex, France

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

and

B. Dehning
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, W-8000 Munich, FRG

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.

1991: RDP performed for first time.

Physics Letters B 284 (1992) 431–439
North-Holland
PHYSICS LETTERS B

Measurement of LEP beam energy by resonant spin depolarization

LEP Polarization Collaboration

L. Arnaudon, L. Knudsen, J.P. Koutchouk, R. Olsen, M. Placidi, R. Schmidt
European Laboratory for Particle Physics (CERN), CH-1211 Geneva 23, Switzerland

M. Crozon
Laboratoire de Physique Corpusculaire, Collège de France, IN²P³–CNRS, F-75231 Paris Cedex, France

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

R. Aßmann and B. Dehning
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, W-8000 Munich, FRG

Received 8 April 1992

A transverse beam polarization of around 10% reproducibly observed in LEP in 1991. Resonant spin depolarization was performed at four occasions, from September 16 to November 11, providing measurements of the beam energy with a precision of $\pm 1.5\times 10^{-5}$. Several cross-checks were performed to ascertain that the observed resonance corresponds to the fundamental spin precession frequency. The variability of the results, $\pm 6\times 10^{-5}$, is consistent with the expected stability and reproducibility of the machine.

[PLB 284 (1992) 431]

1995: second major Z scan...
and earlier results revised.

1993: first major Z scan.

[ZPC 66 (1995) 567]

Z. Phys. C 66, 567–582 (1995)
ZEITSCHRIFT FÜR PHYSIK C

The energy calibration of LEP in the 1993 scan

The working group on LEP energy

R. Assmann[1,*], A. Beuret[2], A. Blondel[3], J. Billan[2], R. Billen[2], G.J. Bobbink[4], F. Bordry[2], H. Burkhardt[2], B. Dehning[2], A. Drees[5], J. Gascon[6], P. Grosse-Wiesmann[2], H. Grote[2], C.M. Hawkes[2], K. Henrichsen[2], A. Hofmann[2], R. Jacobsen[2,**], M. Jonker[2], M. Koratzinos[7], J.P. Koutchouk[2], J. Miles[2], S. Myers[2], E. Peschardt[2], M. Placidi[2], D. Plane[2], G. Quast[8], P. Renton[9], L. Rolandi[2], R. Schmidt[2], D. Strom[10], R. Veenhof[2,***], M. Vadon[2], H. Wachsmuth[2], J. Wenninger[2], T. Wyatt[11]

[1] Max-Plank-Institut für Pysik, Werner-Heisenberg-Institut, D-80805 München, Germany
[2] European Laboratory for Particle Physics (CERN), CH-1211 Geneva 23, Switzerland
[3] Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN²P³-CRNS, F-91128 Palaiseau Cedex, France
[4] National Institute for High Energy Physics, NIKHEF, NL-1009 DB Amsterdam, The Netherlands
[5] Fachbereich Physik, Univeristy of Wuppertal, Postfach 100 127, D-42097, Wuppertal, Germany
[6] Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Quebec, H3C3J7, Canada
[7] Physics Department, University of Oslo, Blindern, N-1000 Oslo 3, Norway
[8] Institut für Physik, Universität Mainz, D-55099 Mainz, Germany
[9] Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
[10] University of Oregon, Dept. of Physics, Eugene, Oregon 97403, USA
[11] Departement of Physics, Schuster Laboratory, The University, Manchester, M139PL, UK

Received: 6 February 1995

Abstract. This report summarizes the procedure for providing the absolute energy calibration of the LEP beams during the energy scan in 1993. The average beam energy around the LEP ring was measured in 25 calibrations with the resonant depolarization technique. The time variation of this average beam energy is well described by a model of the accelerator based on monitored quantities. The absolute calibration of the centre of mass energies of the off-peak points is determined with a precision of 2 parts in 10^5 resulting in a systematic error on the Z-mass of about 1.4 MeV and on the Z-width of about 1.5 MeV.

Eur. Phys. J. C 6, 187–223 (1999)
DOI 10.1007/s100529801030
THE EUROPEAN PHYSICAL JOURNAL C

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

The LEP Energy Working Group

R. Assmann[1], M. Böge[1,a], R. Billen[1], A. Blondel[2], E. Bravin[1], P. Bright-Thomas[1,b], T. Camporesi[1], B. Dehning[1], A. Drees[3], G. Duckeck[4], J. Gascon[5], M. Geitz[1,c], B. Goddard[1], C.M. Hawkes[6], K. Henrichsen[1], M.D. Hildreth[1], A. Hofmann[1], R. Jacobsen[1,d], M. Koratzinos[1], M. Lamont[1], E. Lancon[7], A. Lucotte[8], J. Mnich[1], G. Mugnai[1], E. Peschardt[1], M. Placidi[1], P. Puzo[1,e], G. Quast[9], P. Renton[10], L. Rolandi[1], H. Wachsmuth[1], P.S. Wells[1], J. Wenninger[1], G. Wilkinson[1,10], T. Wyatt[11], J. Yamartino[12,f], K. Yip[10,g]

[1] European Laboratory for Particle Physics (CERN), CH-1211 Geneva 23, Switzerland
[2] Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN²P³-CRNS, F-91128 Palaiseau Cedex, France
[3] Fachbereich Physik, University of Wuppertal, Postfach 100 127, D-42097, Wuppertal, Germany
[4] L.M. Universität, München, D-85748 Garching, Germany
[5] Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Quebec, H3C 3J7, Canada
[6] Cavendish Laboratory, Cambridge, CB3 0HE, UK
[7] CEA, DAPNIA/Service de Physique des Particules, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France
[8] LAPP, Chemin de Bellevue BP909, F-74019 Annecy-Le-Vieux Cedex, France
[9] Institut für Physik, Universität Mainz, D-55099 Mainz, Germany
[10] Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
[11] Department of Physics, Schuster Laboratory, The University Manchester, M13 9PL, UK
[12] Department of Physics, University of Wisconsin, Madison, WI 53706, USA

Received: 25 March 1998 / Revised version: 3 August 1998 / Published online: 29 October 1998

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.

[EPJC 6 (1999) 187]

The long road to a precise E_{CM} determination at LEP

1990: polarisation established.
Initially 9%. In time, 60% achieved.

1991: RDP performed for first time.

[PLB 270 (1991) 97]

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

First observation of transverse beam polarization in LEP

[PLB 284 (1992) 431]

Physics Letters B 284 (1992) 431–439
North-Holland
PHYSICS LETTERS B

Measurement of LEP beam energy by resonant spin depolarization

Note that precise RDP measurements alone were not sufficient to calibrate LEP collision energy.

- RDP never performed continuously, only with single beams at end (or start) of fills.
- Measurements showed that same machine settings do not give same energy !
- Ergo, E_b evolves between measurements. This evolution had to be understood, and modelled.
- Non trivialities also, in going from E_b to E_{CM}.

199

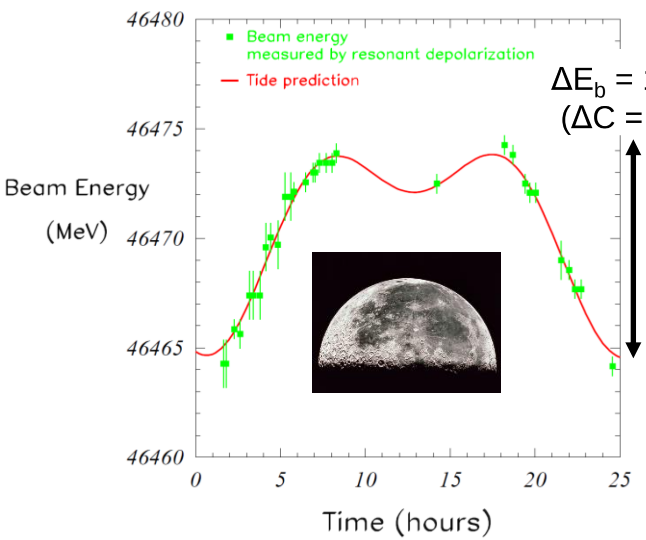
scan...
vised.

[ZPC 66 (1995) 567]

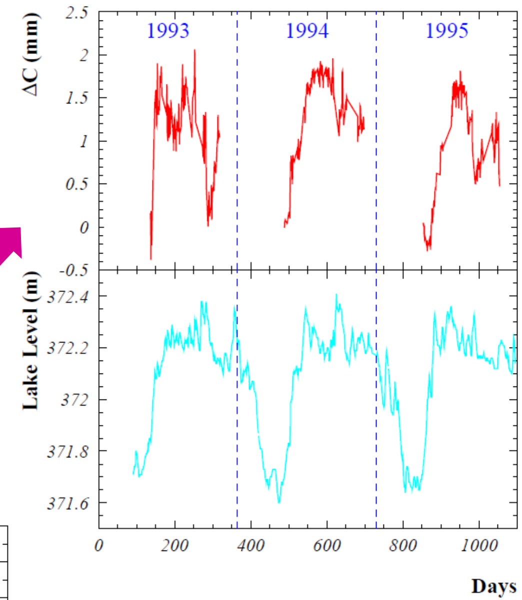
[EPJC 6 (1999) 187]

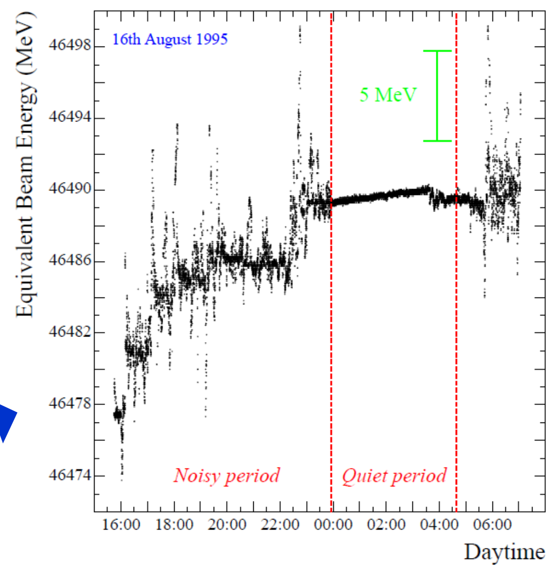
Some mechanisms of E_b variation

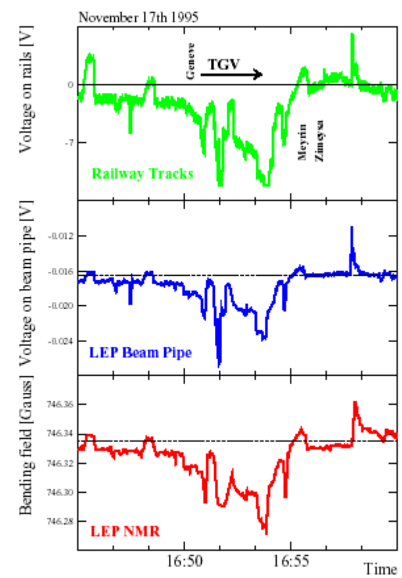
Short- (tide) and long- (lake) term ring distortions.



ΔE_b = 10 MeV
(ΔC = 1 mm)







Rise of dipole fields due to stimulation from returning current from TGV (a dangerous source of bias, because most RDP measurements performed at the *end* of fills).

Z metrology: lessons for next time

Plan ahead

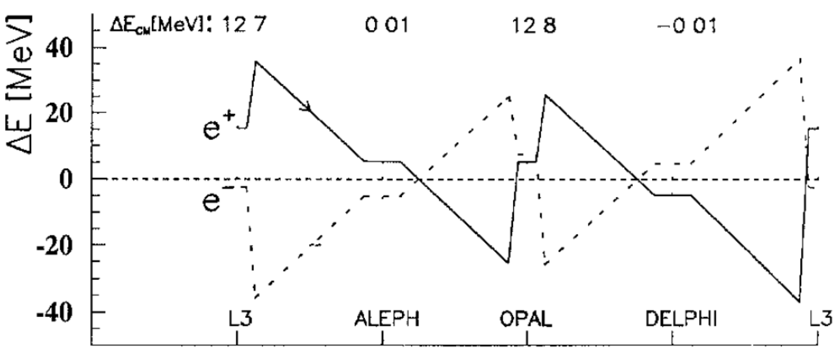
Ensure critical items such as E_{CM} calibration are central elements of project from the very beginning. The LEP Z-scan experience was an exhilarating seat-of-the-pants ride that was successful… but only just !

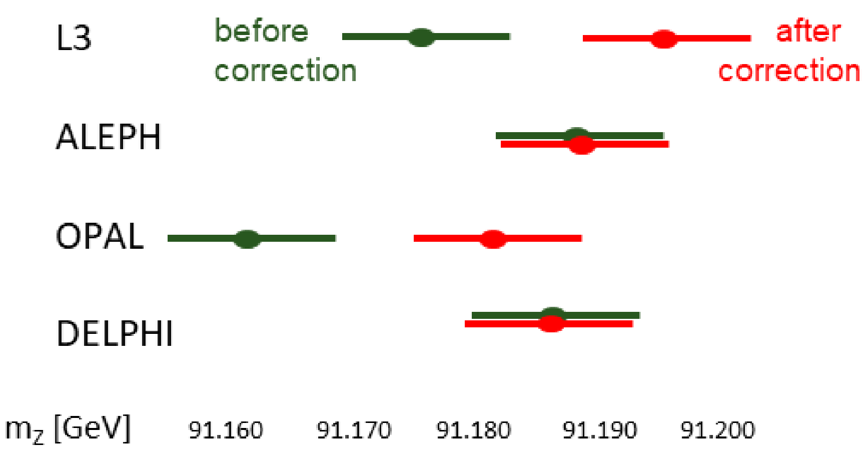
Repeat

e.g. TGV effect only discovered in final scan. Without this, m_Z would be wrong.

Have the right number of experiments

e.g. consequence of `RF sawtooth' (synchrotron loss + RF boost) only appreciated after considering ensemble of results on m_Z (1991 scan PLB 307 (1993) 187).

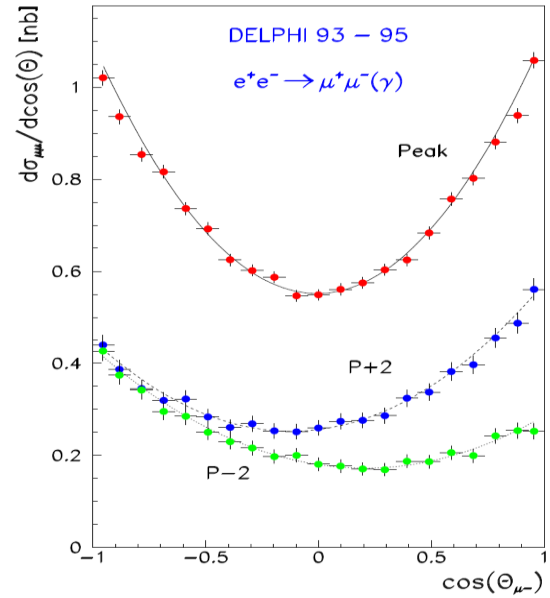




Beyond the lineshape

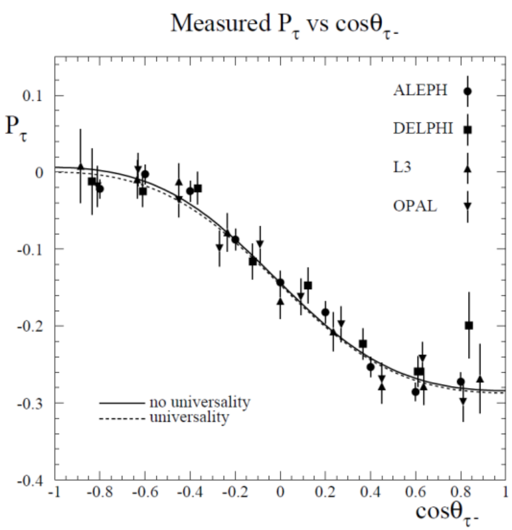
Forward-backward asymmetries
(and at SLD L-R asymmetries)

Many other observables measurable at the Z^0, providing access to the vector and axial fermion couplings, and $\sin^2\theta_{eff}$.



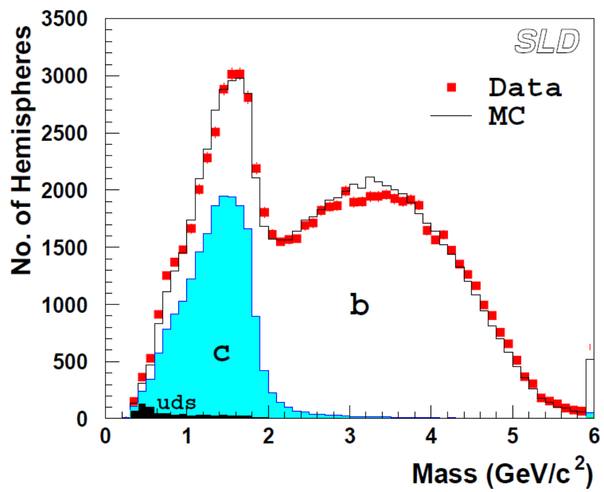
Together, these allowed for a rigorous test of the Standard Model description of nature, and sensitivity to (then) undiscovered particles through radiative corrections.

Tau polarisation measurements



Partial-width ratios involving heavy flavours

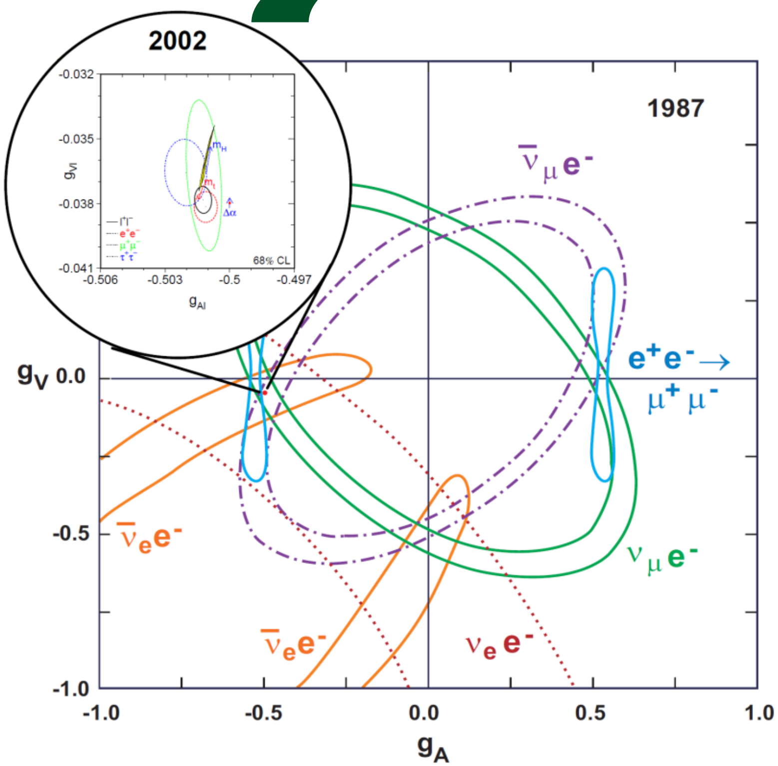
e.g. $R_b=\Gamma_{bbbar}/\Gamma_{had}$

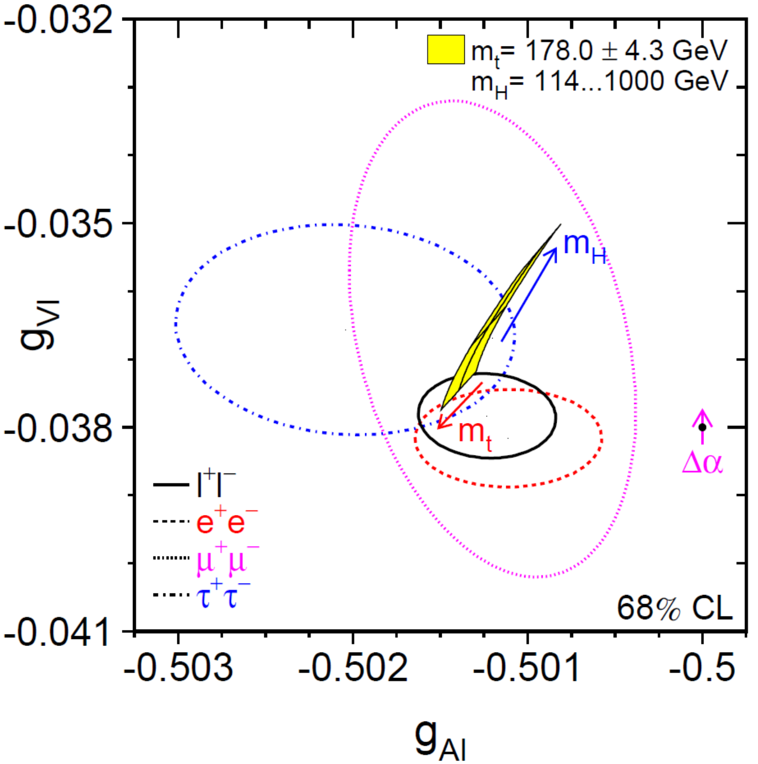


The achievements of LEP & SLD

Dramatic improvements in the knowledge of the vector & axial couplings.

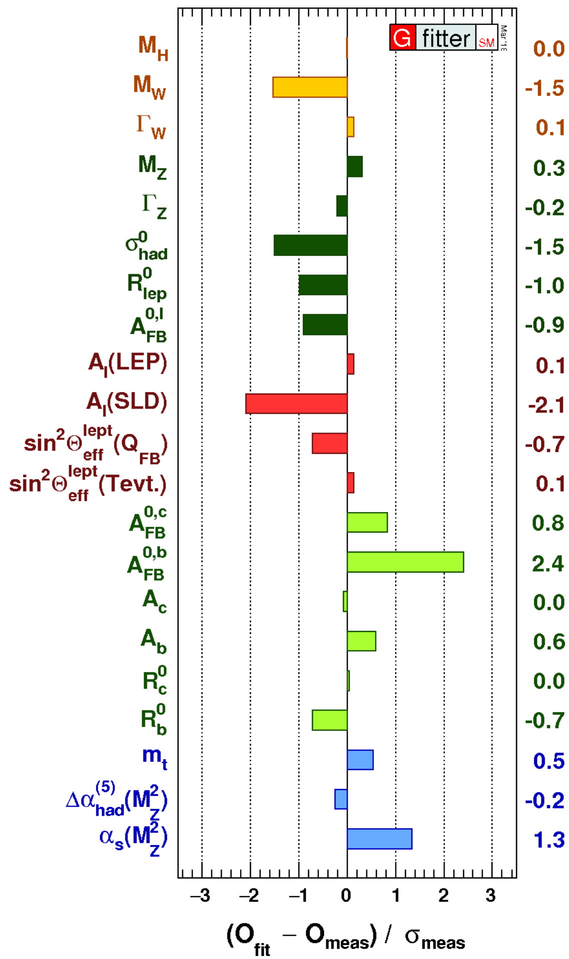
magnified by
a factor 65



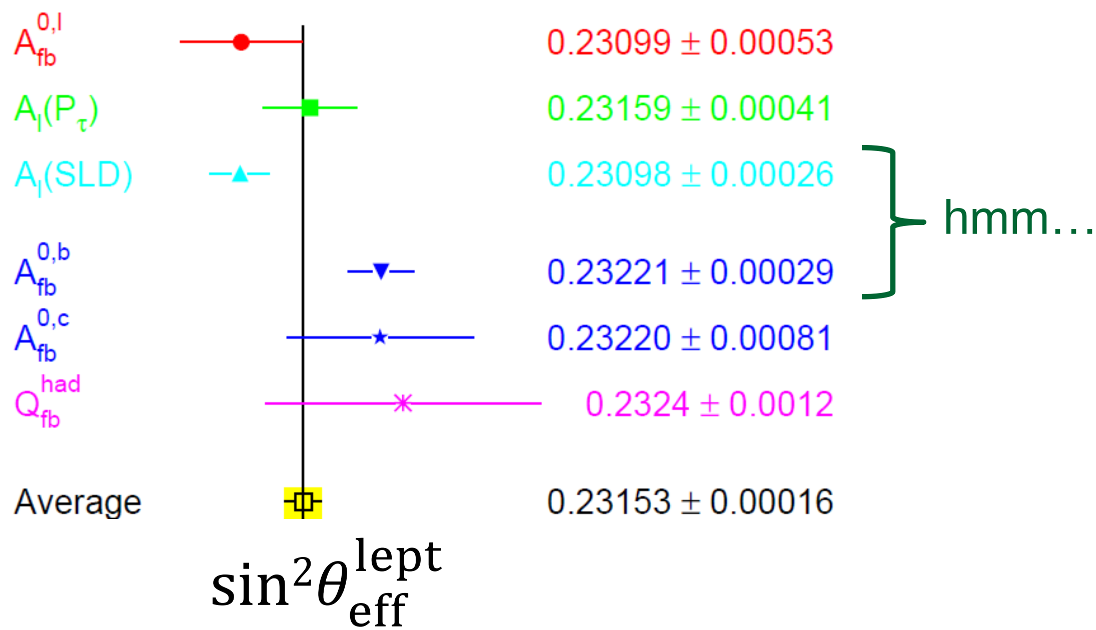


The achievements of LEP & SLD

Excellent self-consistency within Standard Model interpretation...

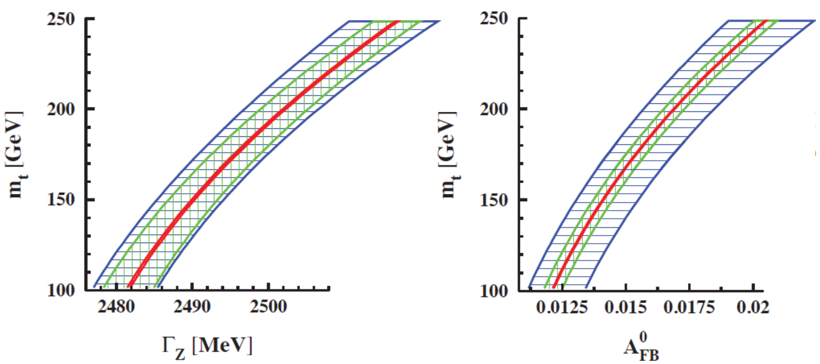


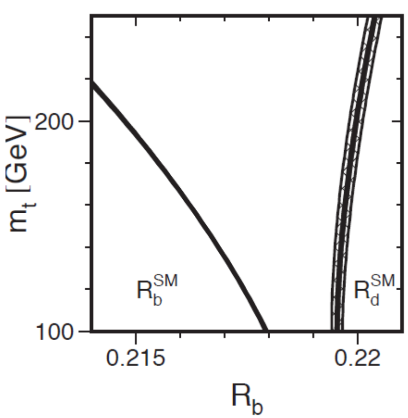
…though (inevitably!) not perfect.

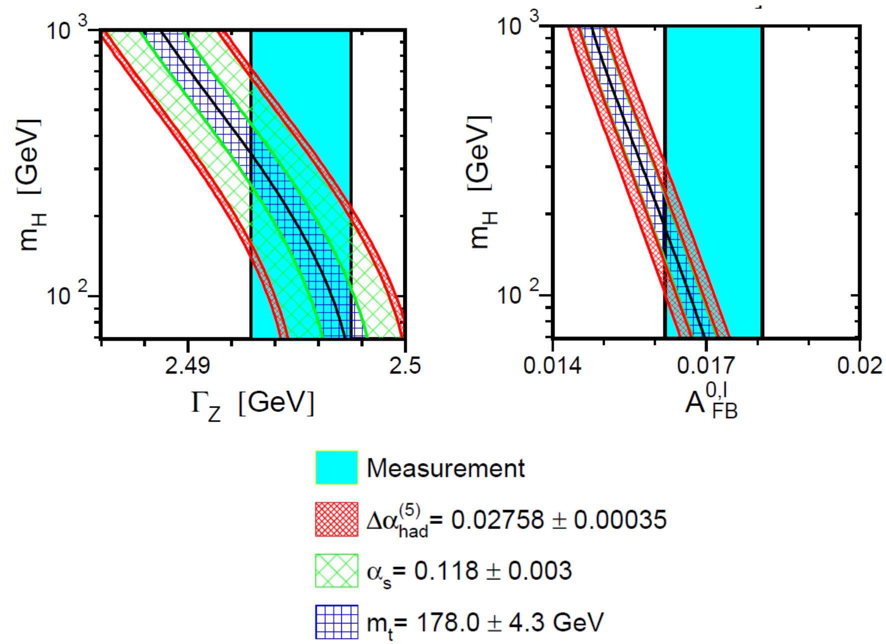


Pointing the way to the top and the Higgs

Electroweak corrections present in the EW observables have a quadratic dependence on the top mass, and a logarithmic dependence on the Higgs.







Pointing the way to the top and the Higgs

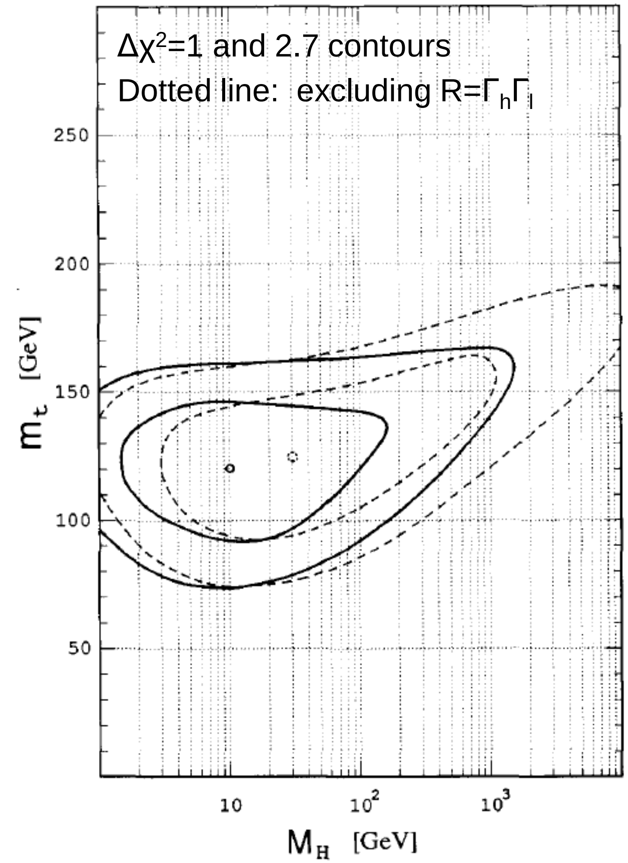
Electroweak corrections present in the EW observables have a quadratic dependence on the top mass, and a logarithmic dependence on the Higgs.

This fact had been known for many years (*e.g.* Veltmann, Nucl. Phys. B123 (1977) 89, Acta Phys. Polon. B8 (1977) 475), but no serious attempt to estimate the reach of LEP/SLC observables, no doubt influenced by conservative expectations.

With early LEP data, first attempts were made to perform this analysis with data *e.g*. Ellis, Fogli and Lisi PLB 274 (1992) 456.

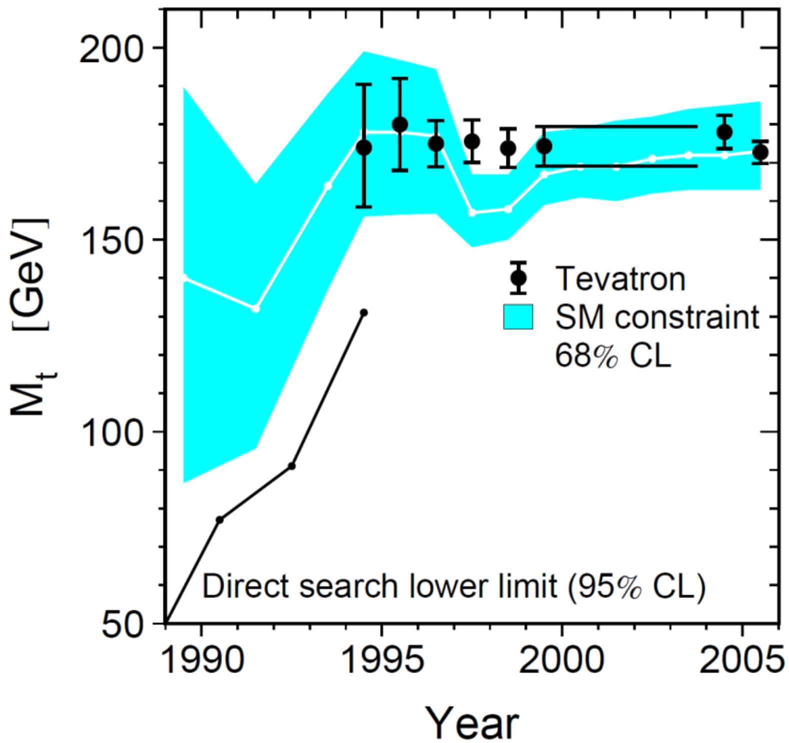
$$m_t = 120^{+27}_{-28}\ \mathrm{GeV}$$

$$0.5 < M_H < 800\ \mathrm{GeV}, \quad 90\%\ \mathrm{CL}$$



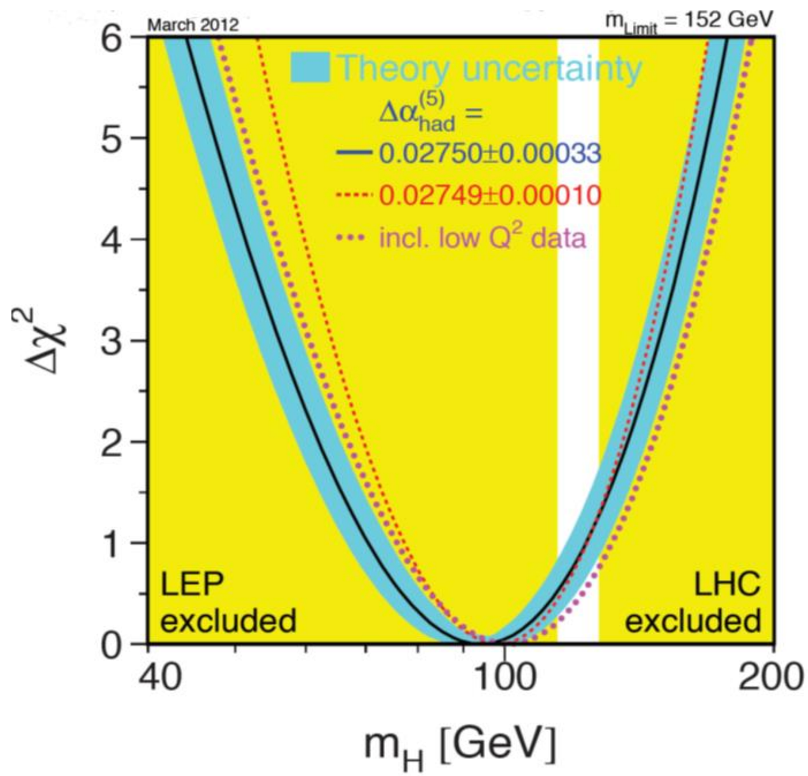
Pointing the way to the top and the Higgs

Electroweak corrections present in the EW observables have a quadratic dependence on the top mass, and a logarithmic dependence on the Higgs.



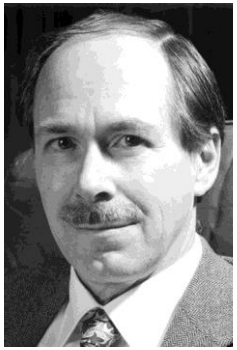
LEP & SLD Z data 'measured' top mass well before discovery.

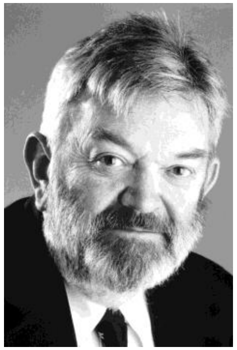
(including LEP2 inputs)



LEP data and SM require something Higgs-like and within LHC reach !

Nobel Prize 1999





Award to t'Hooft and Veltman made possible by the impressive agreement between measurements at LEP and the predictions of the re-normalised EW theory, in particular the mass of the top quark.

As described above, the theory of the electro-weak force predicted the existence of the new W and Z particles right from the start. But it was only through 't Hooft's and Veltman's work that more precise prediction of physical quantities involving properties of W and Z could start. Large quantities of W and Z have recently been produced under controlled conditions at the LEP accelerator at CERN. Comparisons between measurements and calculations have all the time showed great agreement, thus supporting the theory's predictions.

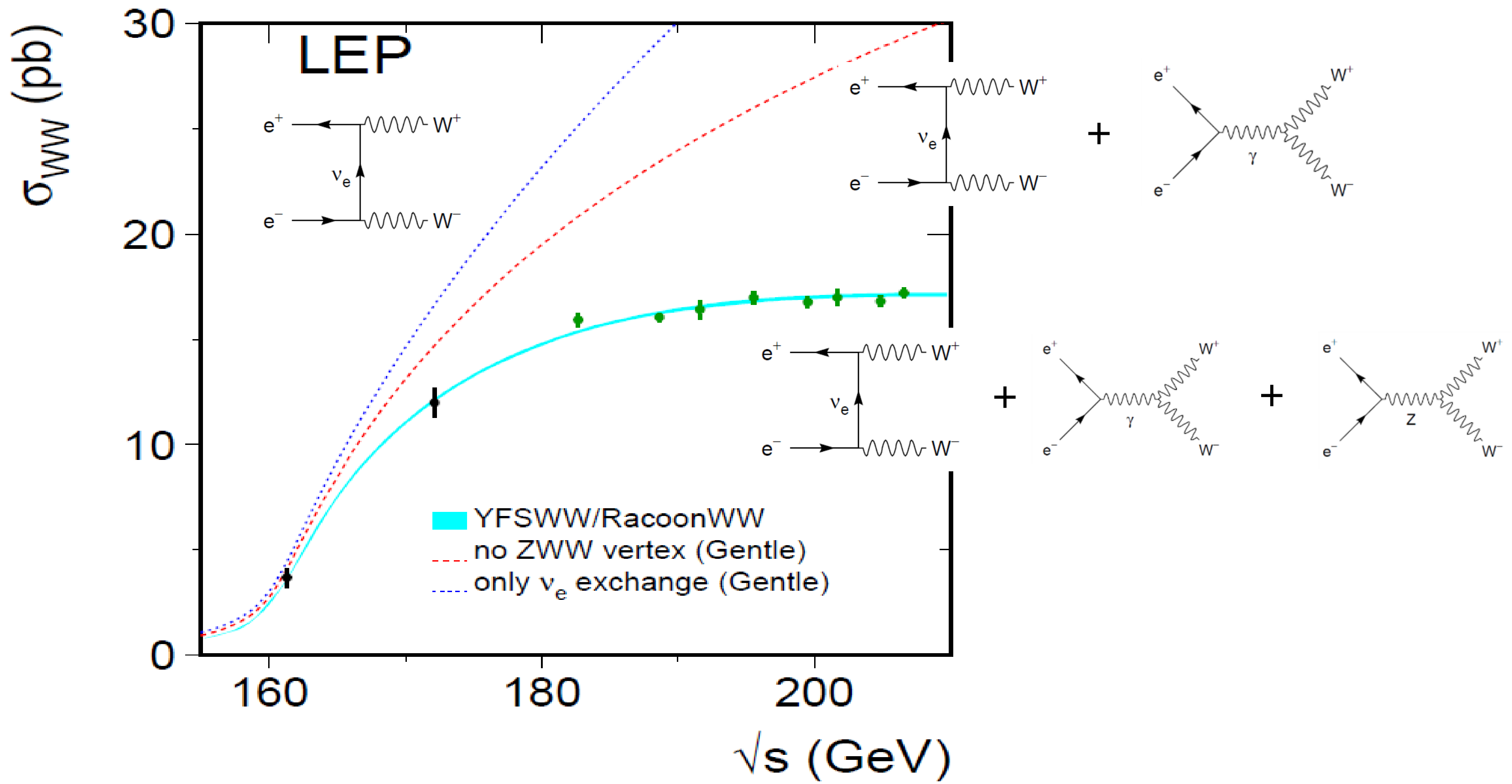
One particular quantity obtained with 't Hooft's and Veltman's calculation method based on CERN results is the mass of the *top quark*, the heavier of the two quarks included in the third family in the model. This quark was observed directly for the first time in 1995 at the Fermilab in the USA, but its mass had been predicted several years earlier. Here too, agreement between experiment and theory was satisfactory.

[from Nobel Prize press release]

The discovery of a \`light' Higgs in 2012 is another legacy triumph of LEP/SLC data.

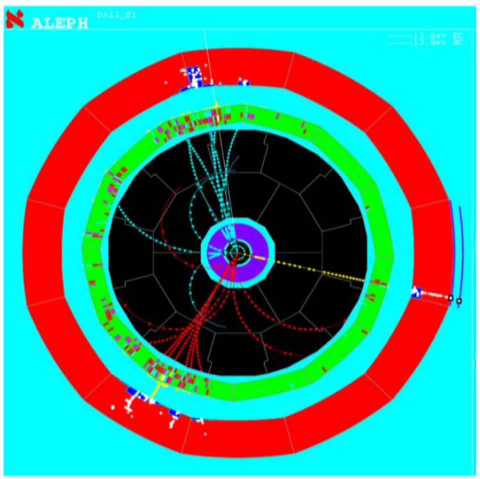
Electroweak physics at LEP2

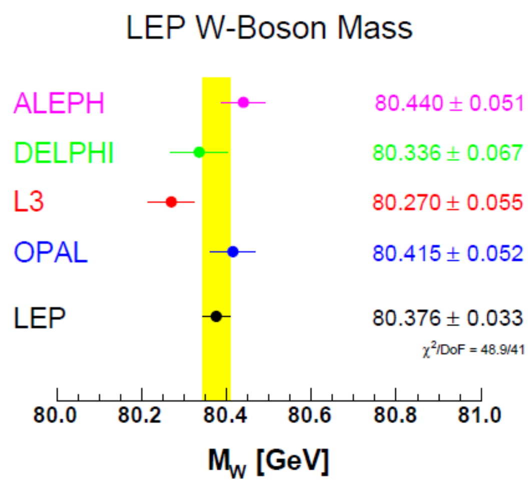
LEP operation at and above W^+W^- threshold during 1996-2000 made many new heavy-boson EW observables accessible, such as W branching fractions, triple gauge boson couplings and W^+W^- cross section….

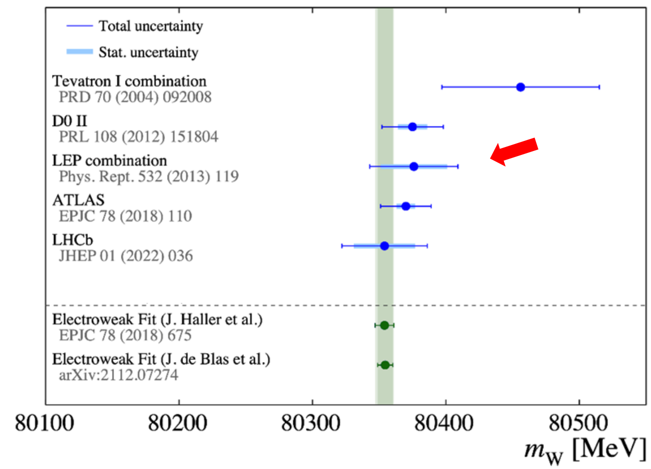


W mass at LEP2

W-mass measurement performed through full reconstruction* of events with E_{CM} constraint, with main challenges being role of hadronisation, colour reconnection effects and Bose-Einstein correlations in hadronic events, and knowledge of E_{CM} (no RDP possible, for LEP at least, at these energies – see EPJC 39 (2005) 253).





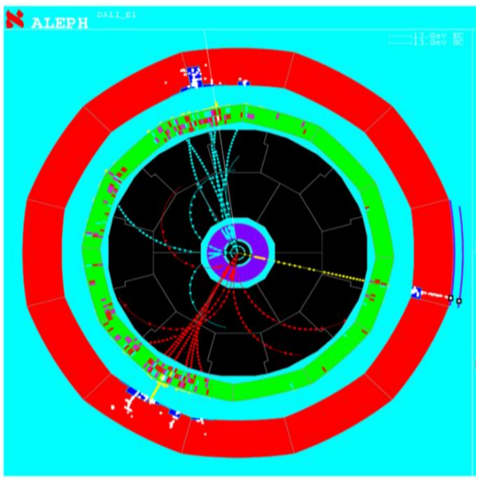


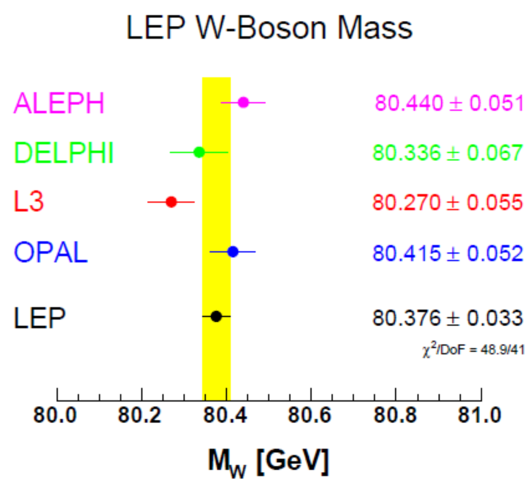
Consistency with previous & future measurements with statistically more sensitive, but systematically more challenging, hadron-collider results very reassuring…

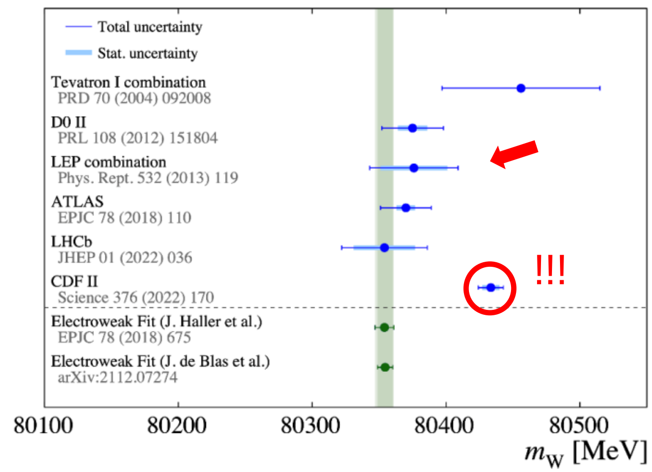
* With some contribution from measurement of cross section at threshold

W mass at LEP2

W-mass measurement performed through full reconstruction* of events with E_{CM} constraint, with main challenges being role of hadronisation, colour reconnection effects and Bose-Einstein correlations in hadronic events, and knowledge of E_{CM} (no RDP possible, for LEP at least, at these energies – see EPJC 39 (2005) 253).







Consistency with previous & future measurements with statistically more sensitive, but systematically more challenging, hadron-collider results very reassuring…

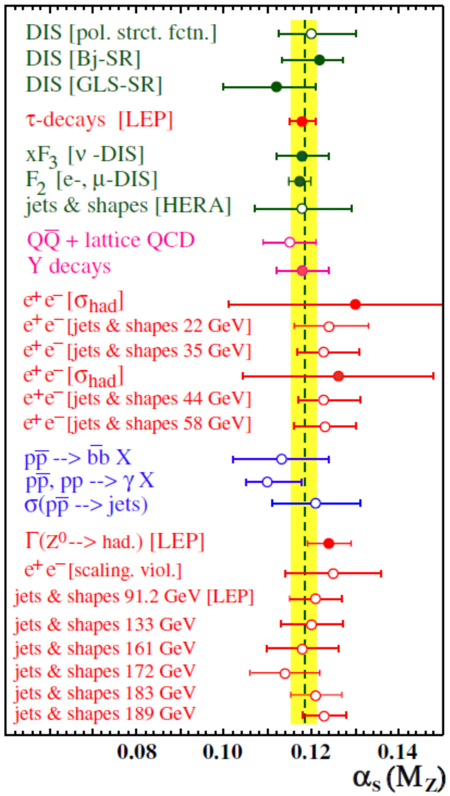
…or so was the case until recently. Resolving this issue may require new measurement with much larger sample at a future e^+e^- machine, *e.g.* FCC-ee.

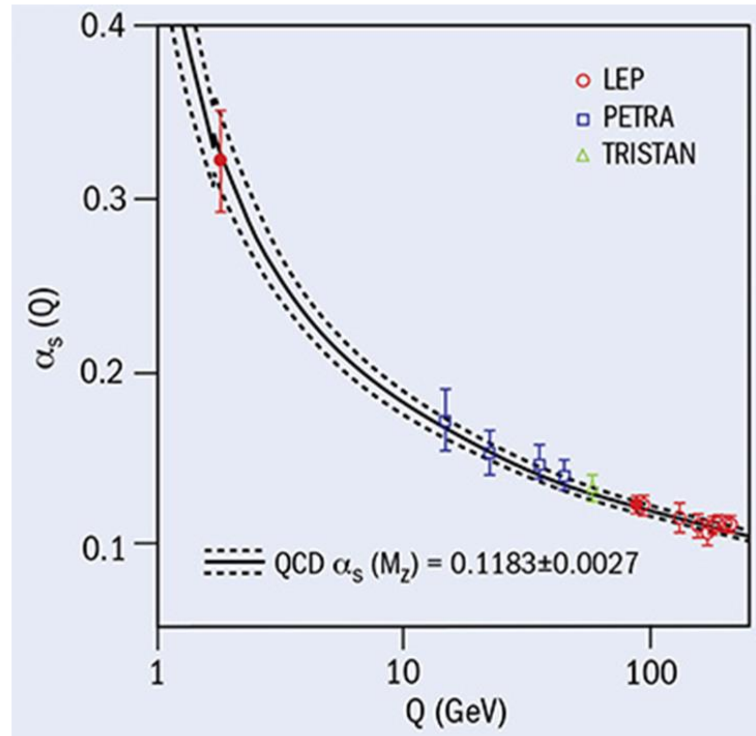
* With some contribution from measurement of cross section at threshold

Beyond electroweak

Much more can be done at a Z factory (and at higher energies) than EW physics alone, *e.g.* QCD studies, including measurements of α_s in a multitude of ways.

[Bethke, JPG 26 (2000) R27]



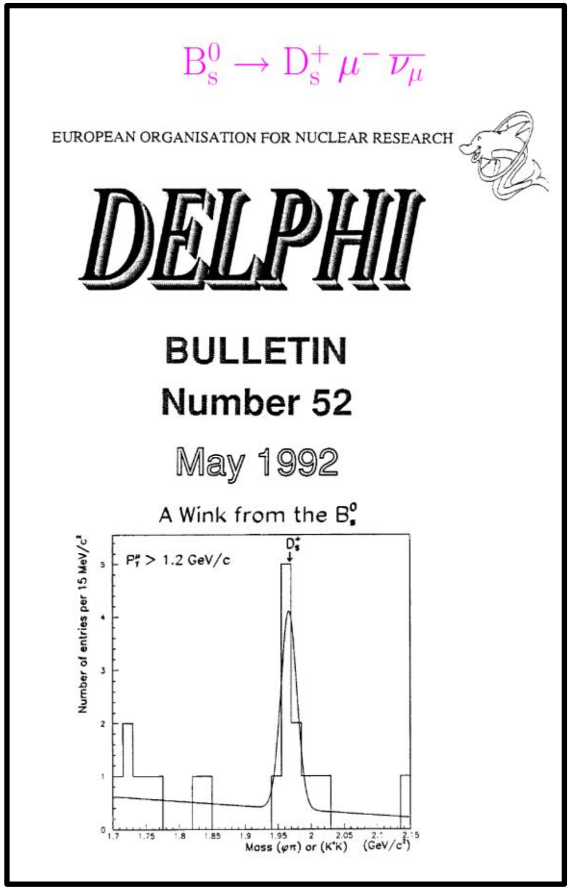


Also heavy-flavour physics: big contributions from LEP/SLD in results & technology.

b physics at the Z pole

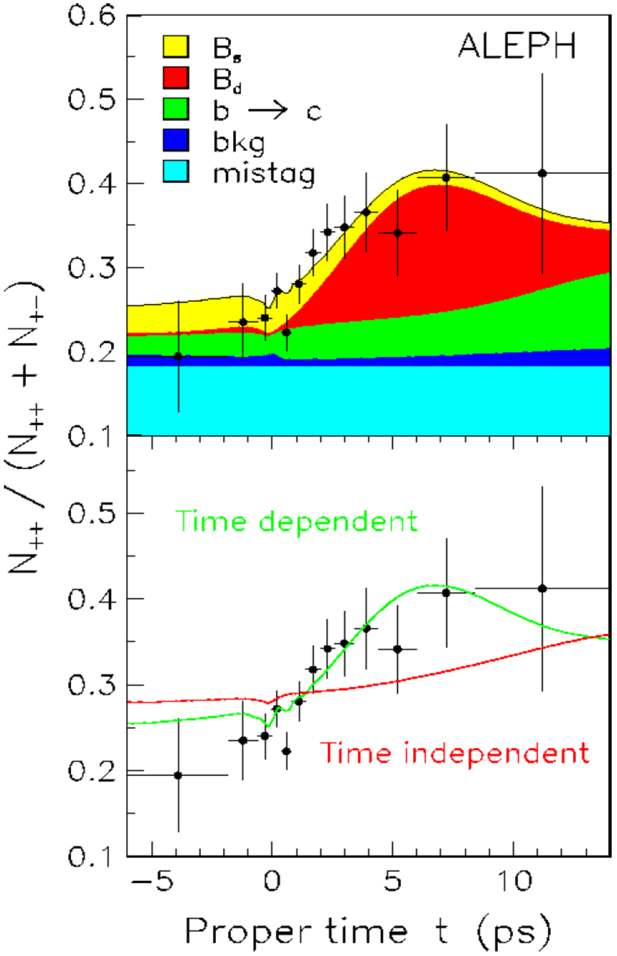
LEP and SLD demonstrated that $e^+e^- \to Z^0$ is an excellent laboratory for b physics.

e.g. first studies in B_s^0 physics



[PLB 289 (1992) 199]

observation of time-dependence of $B^0\overline{B^0}$ oscillations



[PLB 313 (1993) 498]

Silicon vertex detectors at LEP (or how upgrades happened in the pre-LHC era)

1989, ALEPH & DELPHI

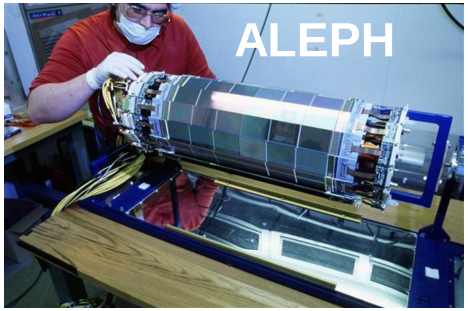
- Install prototype modules.

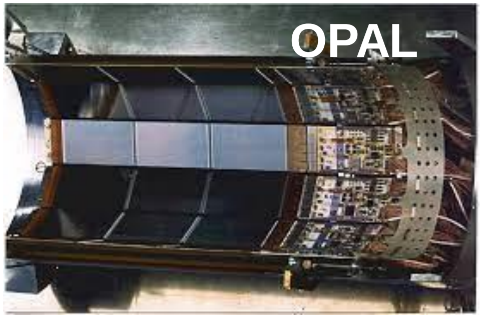
1990, ALEPH & DELPHI

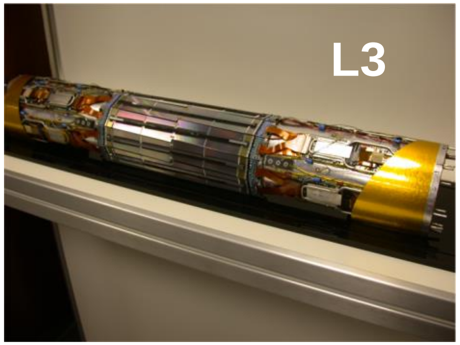
- Install first complete barrels;
- ALEPH read r-z coordinate with 'double-sided' detectors.

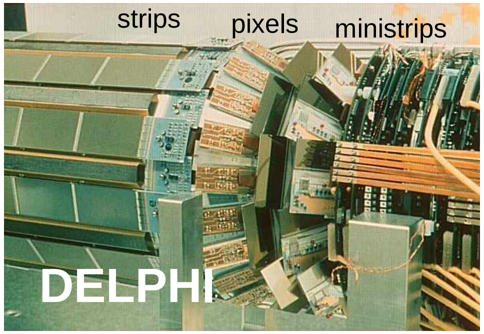
1991, all

- Beampipes modified from Al with r=8 cm to r=5.3 cm Be;
- DELPHI installs three-layer vertex detector;
- OPAL detector installed.









1993, OPAL & L3

- OPAL: r-z readout with back-to-back detectors;
- L3: install two-layer detector.

1994, DELPHI

- Double-sided detectors & `double-metal readout (low X_0).

1995, ALEPH OPAL

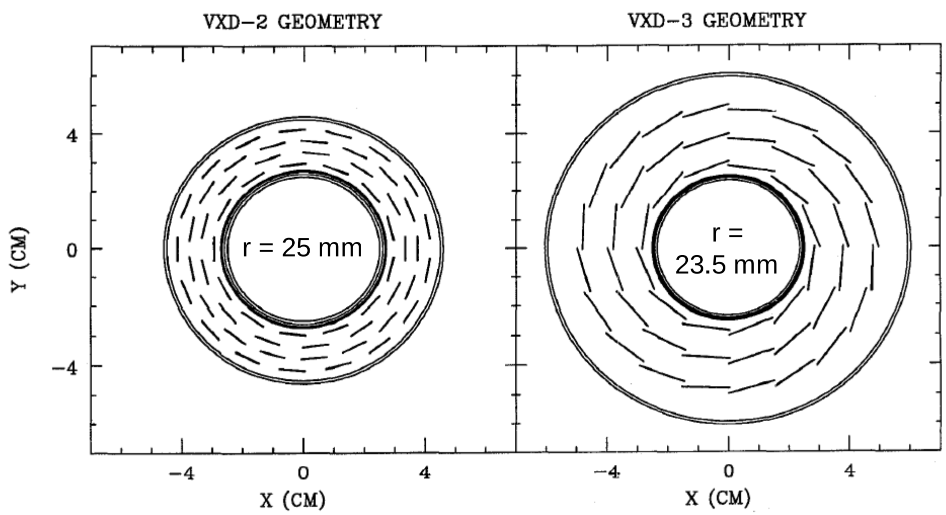
- LEP 2 upgraded detectors.

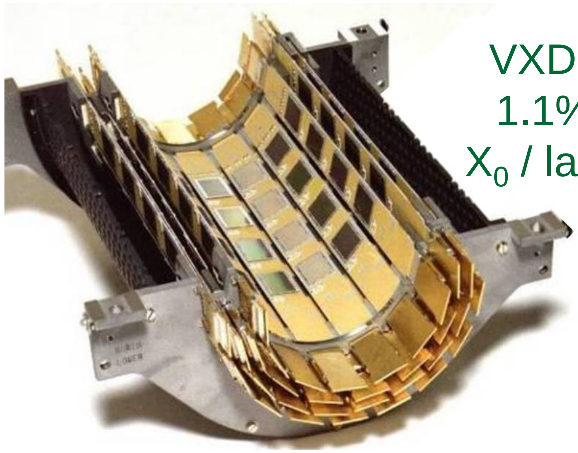
1996, DELPHI

- `LEP 2 Si tracker', with microstrips, ministrips & pixels.

A similar story at SLC/SLD

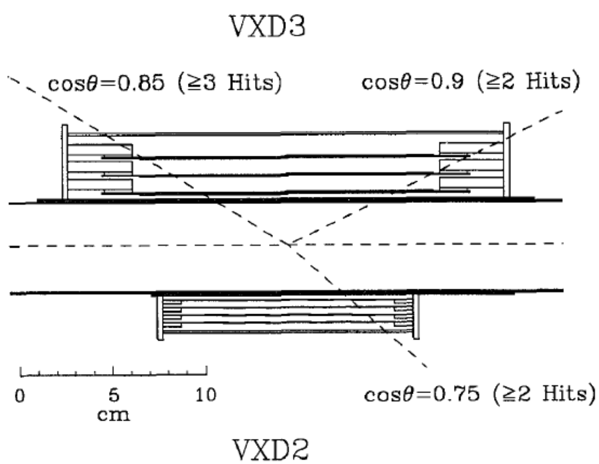
Vertex detector a particular strength of SLD. CCD pixels. Small beampipe.
1996 upgrade from two layer VXD2 (120M pixels) to three layer VXD3 (307M pixels).

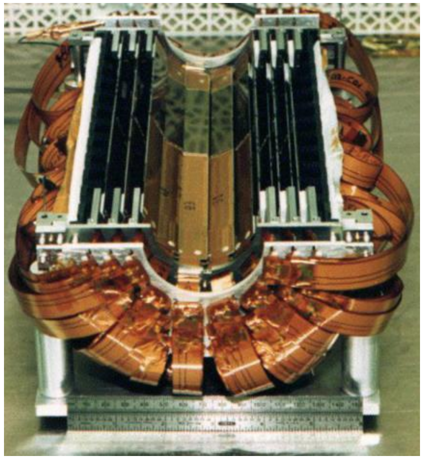




VXD2:
1.1%
X_0 / layer

VXD3:
extended
coverage
in θ



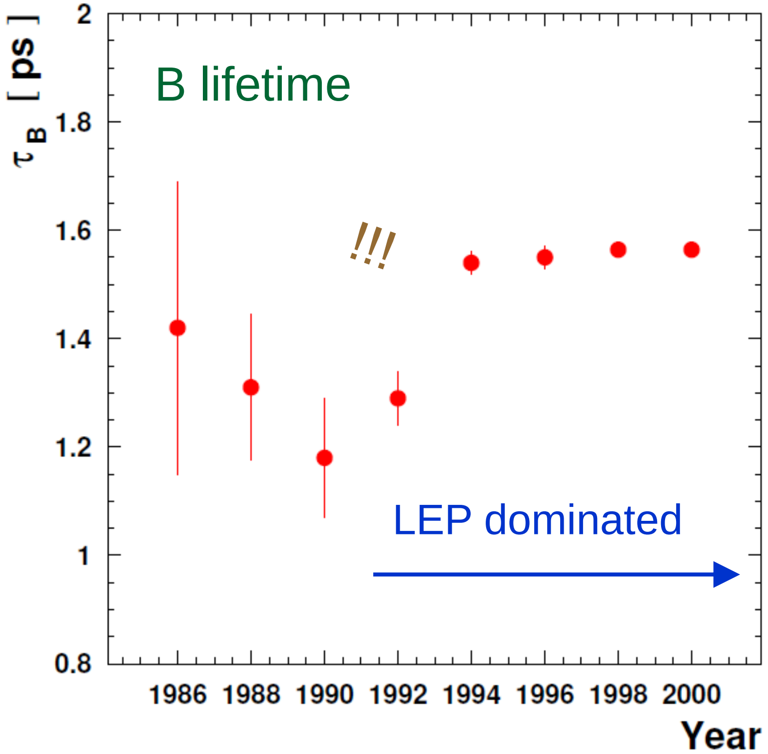


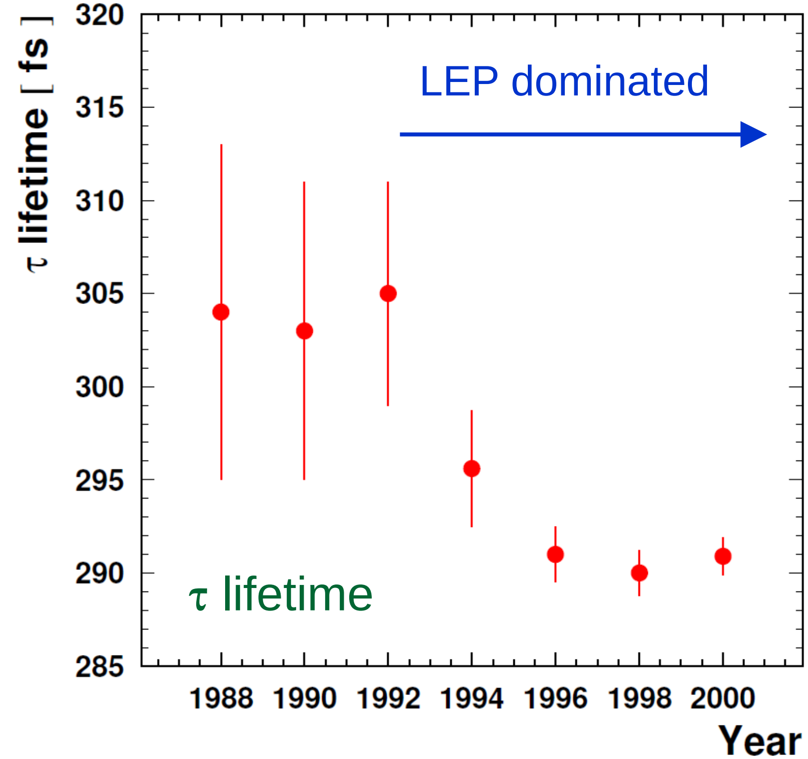
VXD3:
0.4%
X_0 / layer

Upgrade improved asymptotic IP resolution by a factor of two (~20 μm in rz).

Impact of LEP/SLC vertex detectors

Impact of LEP/SLC vertex detectors (& event yields, of course) on flavour physics is evident from surveying evolution of PDG averages for certain benchmark quantities.





Improved precision of the new technology exposes earlier systematic biases.

Vertex detectors - the *most* important legacy of LEP/SLC to flavour physics !

Conclusions

The LEP programme exceeded expectations in characterising the nature of the Z and W bosons, and demonstrating the validity of the Standard Model, with exquisite sensitivity to higher-order corrections.

The results of the LEP experiments, together with those of SLD, remain benchmarks for many of the most important measurements in EW physics.

The achievements in QCD and heavy-flavour physics are no less impressive. The rapid advances in Si vertex-detector technology are particularly noteworthy.

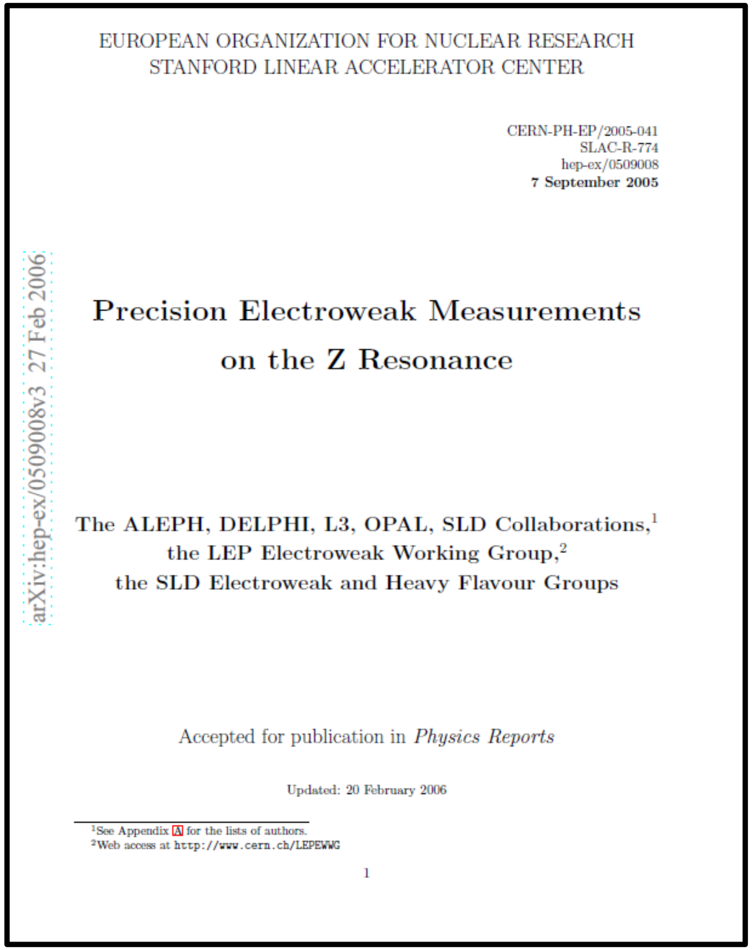
Everything was done well, but we have learned how to do still better. There would be much benefit in revisiting programme at a future, very high luminosity machine (see talk of Rebeca Gonzalez Suarez) !

[Many thanks to John Ellis for fruitful discussions while preparing this talk !]

Backups

The LEP and SLD EW legacy

[Phys. Rept. 427 (2006) 257]



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
STANFORD LINEAR ACCELERATOR CENTER

CERN-PH-EP/2005-041
SLAC-R-774
hep-ex/0509008
7 September 2005

arXiv:hep-ex/0509008v3 27 Feb 2006

Precision Electroweak Measurements on the Z Resonance

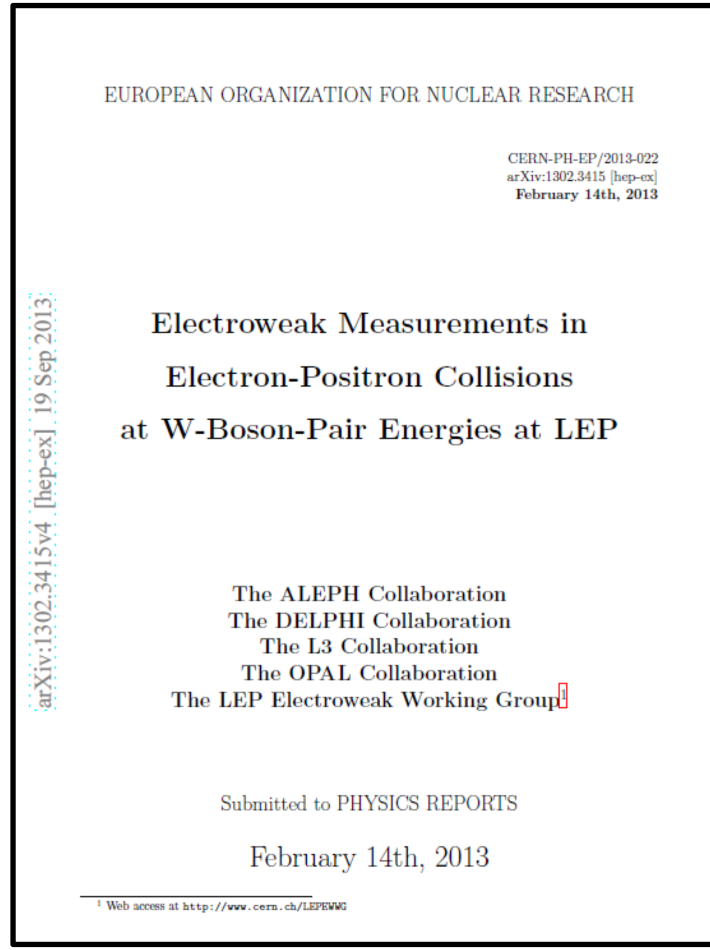
The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1]
the LEP Electroweak Working Group,[2]
the SLD Electroweak and Heavy Flavour Groups

Accepted for publication in *Physics Reports*

Updated: 20 February 2006

[1] See Appendix A for the lists of authors.
[2] Web access at http://www.cern.ch/LEPEWWG

1



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PH-EP/2013-022
arXiv:1302.3415 [hep-ex]
February 14th, 2013

arXiv:1302.3415v4 [hep-ex] 19 Sep 2013

Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP

The ALEPH Collaboration
The DELPHI Collaboration
The L3 Collaboration
The OPAL Collaboration
The LEP Electroweak Working Group[1]

Submitted to PHYSICS REPORTS

February 14th, 2013

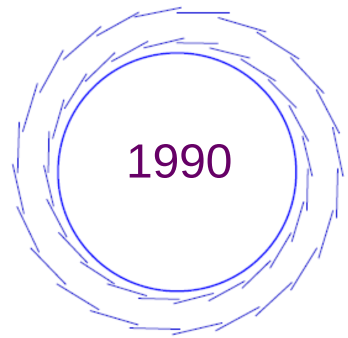
[1] Web access at http://www.cern.ch/LEPEWWG

[Phys. Rept. 532 (2013) 119]

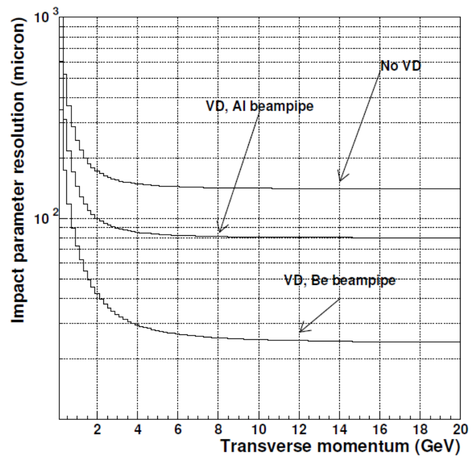
Silicon vertex detectors at LEP (or how upgrades happened in the pre-LHC era)

1989, ALEPH & DELPHI
- Install prototype modules.

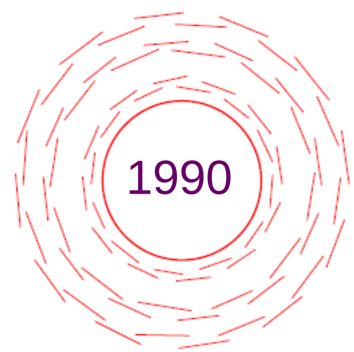
1990, ALEPH & DELPHI
- Install first complete barrels;
- ALEPH read r-z coordinate with ‘double-sided’ detectors.



DELPHI



1991, all
- Beampipes modified from Al with r=8 cm to r=5.3 cm Be;
- DELPHI installs three-layer vertex detector;
- OPAL detector installed.



1993, OPAL & L3
- OPAL: r-z readout with back-to-back detectors;
- L3: install two-layer detector.

1994, DELPHI
- Double-sided detectors & `double-metal readout (low X_0).

1995, ALEPH OPAL
- LEP 2 upgraded detectors.

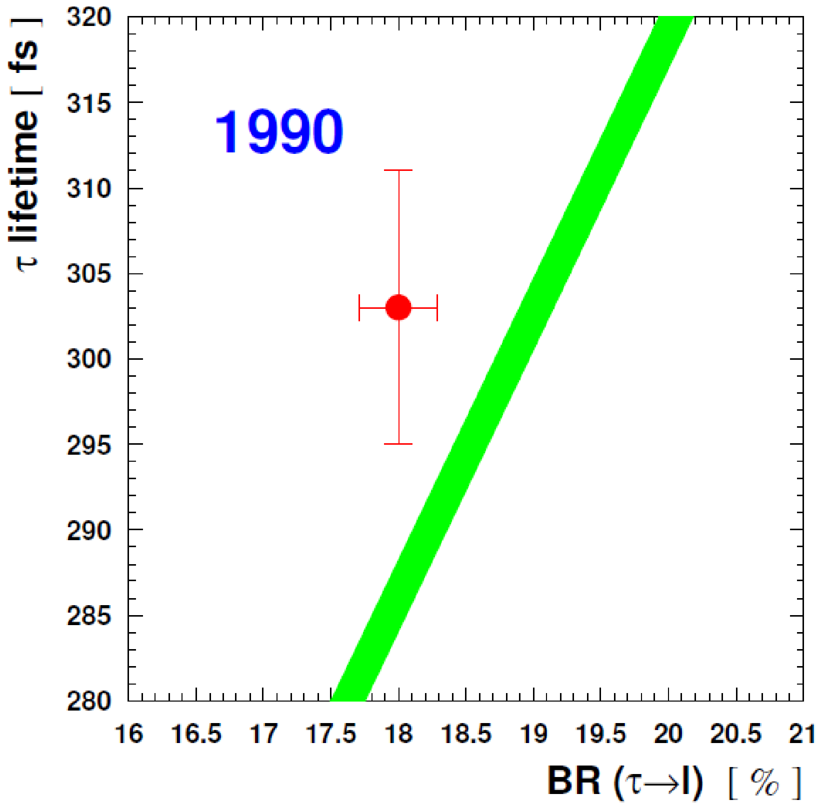
1996, DELPHI
- `LEP 2 Si tracker’, with microstrips, ministrips & pixels.

Tau physics at the Z pole

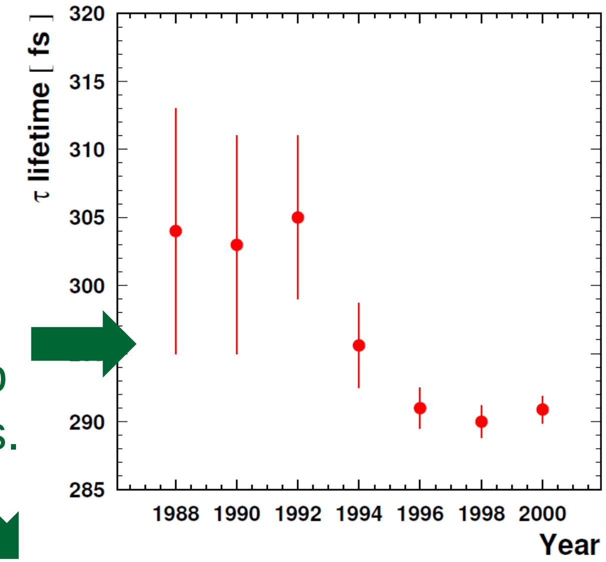
$e^+e^- \rightarrow Z^0$ is an excellent laboratory for tau physics.

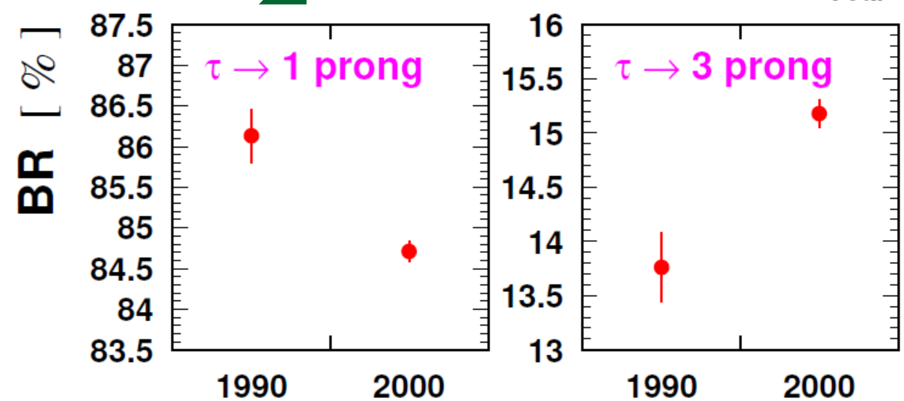
e.g. tau lifetime vs. BR measurement

Before LEP – a significant problem….



Impact of LEP on lifetime and branching ratio measurements.



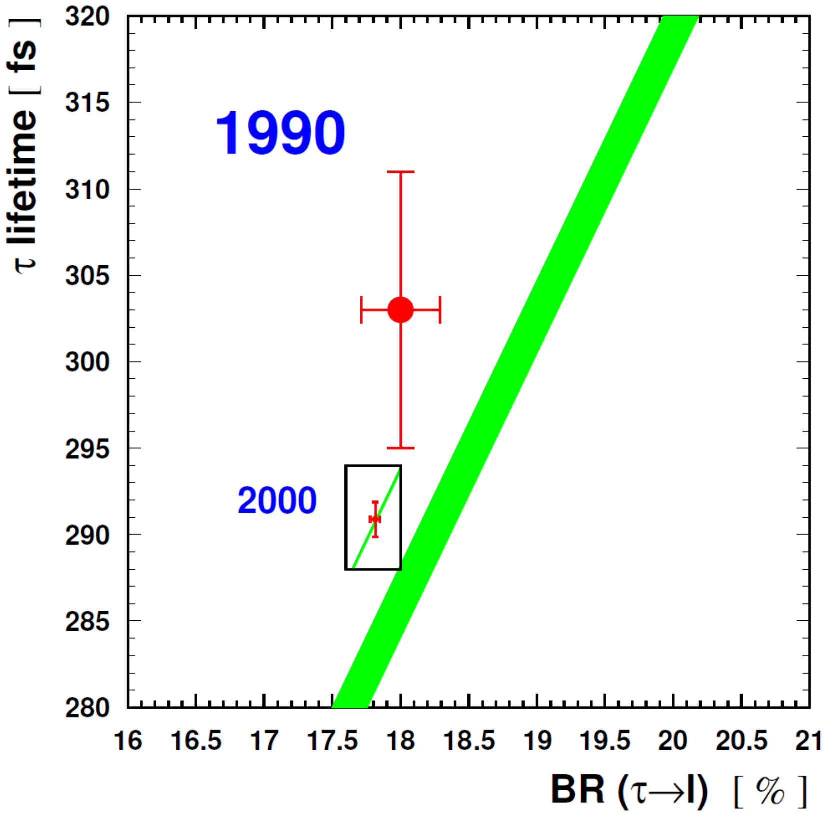


Tau physics at the Z pole

$e^+e^- \rightarrow Z^0$ is an excellent laboratory for tau physics.

e.g. tau lifetime vs. BR measurement

Before LEP – a significant problem….



…but precision brings clarity.

(note also the dramatic change in the prediction from BES m_τ measurement)