LEP1: the Ascent of the Standard Model

Contribution to the celebration of Herwig Schopper's 90th birthday

John Ellis

(King's College London & CERN)

The Historical Context - I

- 1964 – The Englert-Brout-Higgs mechanism
- 1967/8 – Weinberg-Salam model
- 1971/2 – Gauge theories renormalizable
- 1973 - Neutral currents
- 1974 – The November revolution
- 1975 – The τ lepton
- e^+e^- colliders pre-eminent: SPEAR, DORIS, …
- Higher-energy machines under construction: PETRA, PEP

Think big!

- 1975/6 - Burt Richter on sabbatical 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

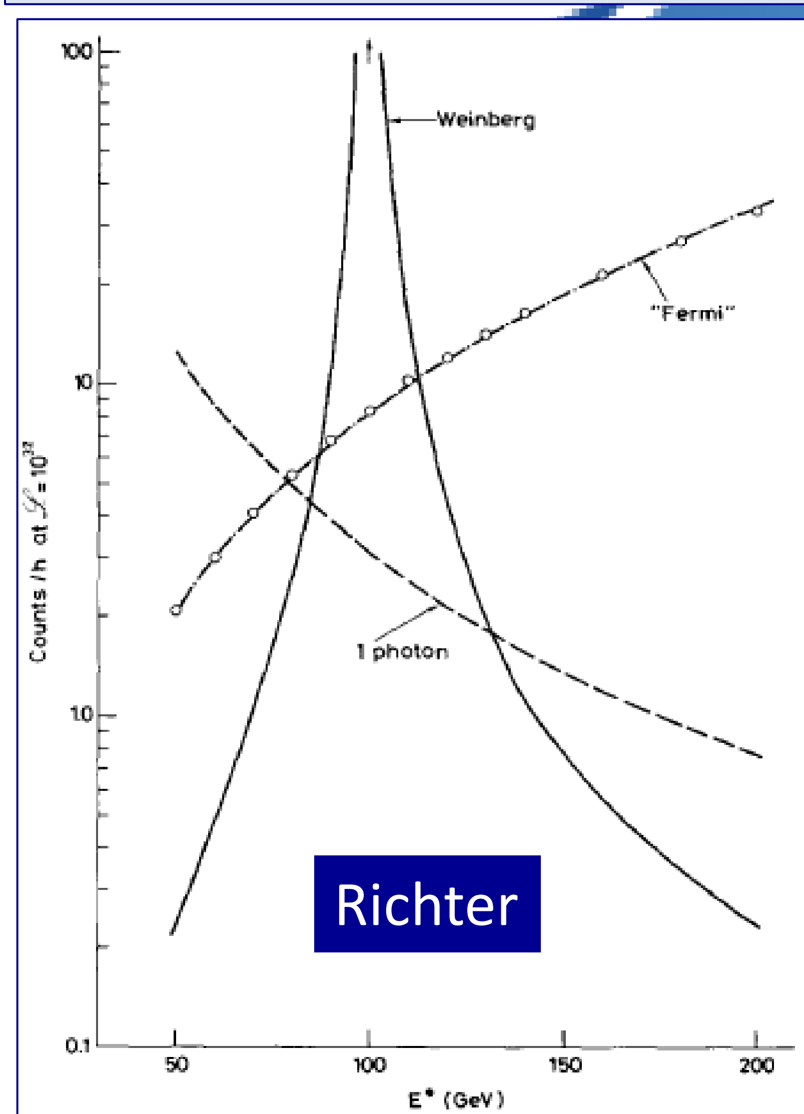
B. RICHTER

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.

The Historical Context - II



- Before the discovery of the W and Z (1983)
- Should in any case be large cross-sections

II- A MACHINE FOR e^+e^- PHYSICS UP TO 200 GeV c.m. ENERGY (LEP)

I - Introduction

The design of a large e^+e^- storage ring is being studied by a small group of machine physicists, the LEP working group (K. Johnsen, Chairman, R. Billinge, P. Bramham, E. Jones, E. Keil, B. Richter (SLAC), W. Schnell) with the technical advice of other people at CERN and elsewhere. The following requirements are imposed on the machine by physics considerations :

- a maximum energy E of 100 GeV,
- a luminosity $L = 10^{32}$ cm^{-2} s^{-1} in each intersection region at 100 GeV, and a good luminosity down to about 40 GeV. The luminosity variation adopted in the design is $L \geq 10^{32}$ cm^{-2} s^{-1} from 50 to 100 GeV and $L \propto E^2$ below 50 GeV.

First LEP machine study 1976

First LEP Study Group

CERN 76-18
8 November 1976

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler*), M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter×),
C. Rubbia, J. Steinberger, B. Wiik†), W. Willis and K. Winter

G E N E V A
1976

*) Visitor from RHEL, Didcot, England.
×) Visitor from SLAC, Stanford, Calif., USA.
†) DESY, Hamburg, Germany.

Page

Page

First LEP Theory Studies

- Highlights:
- Precision Z studies
- W^+W^- production
- Higgs search
- Heavy quarkonia
- Jet studies

III- THEORETICAL REMARKS

J. Ellis, M.K. Gaillard

Contents :

Z Cross-section & Asymmetries

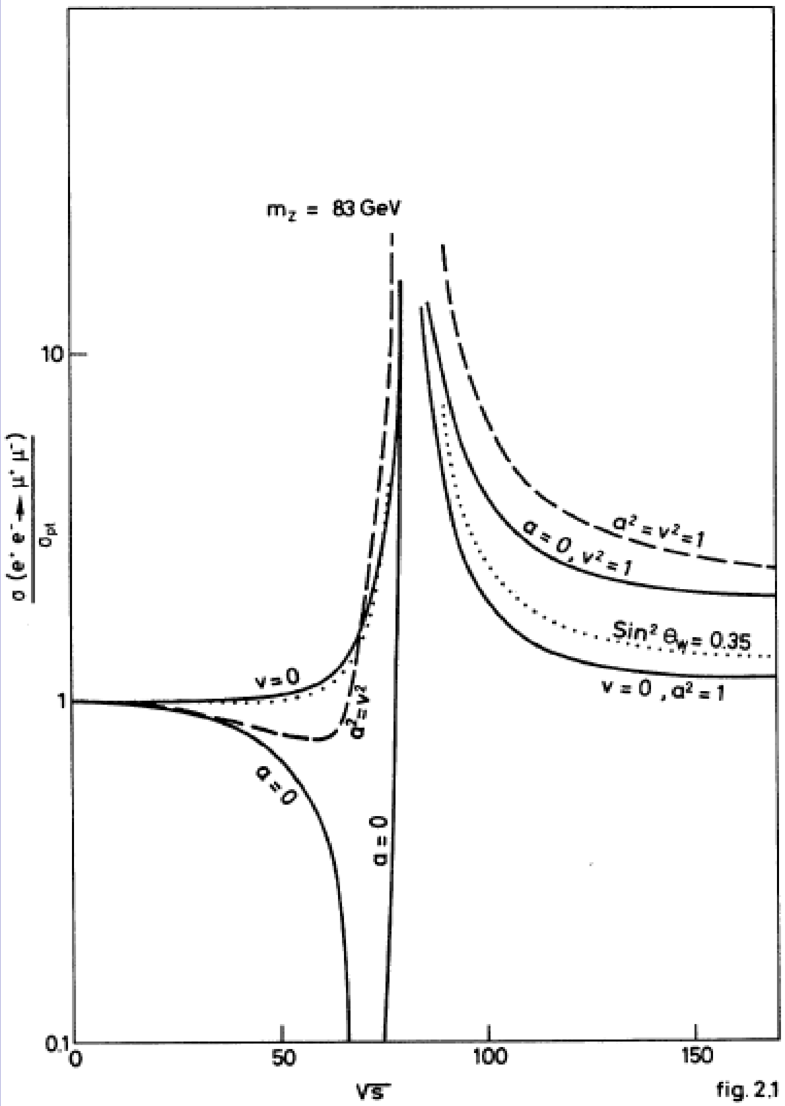


fig. 2.1

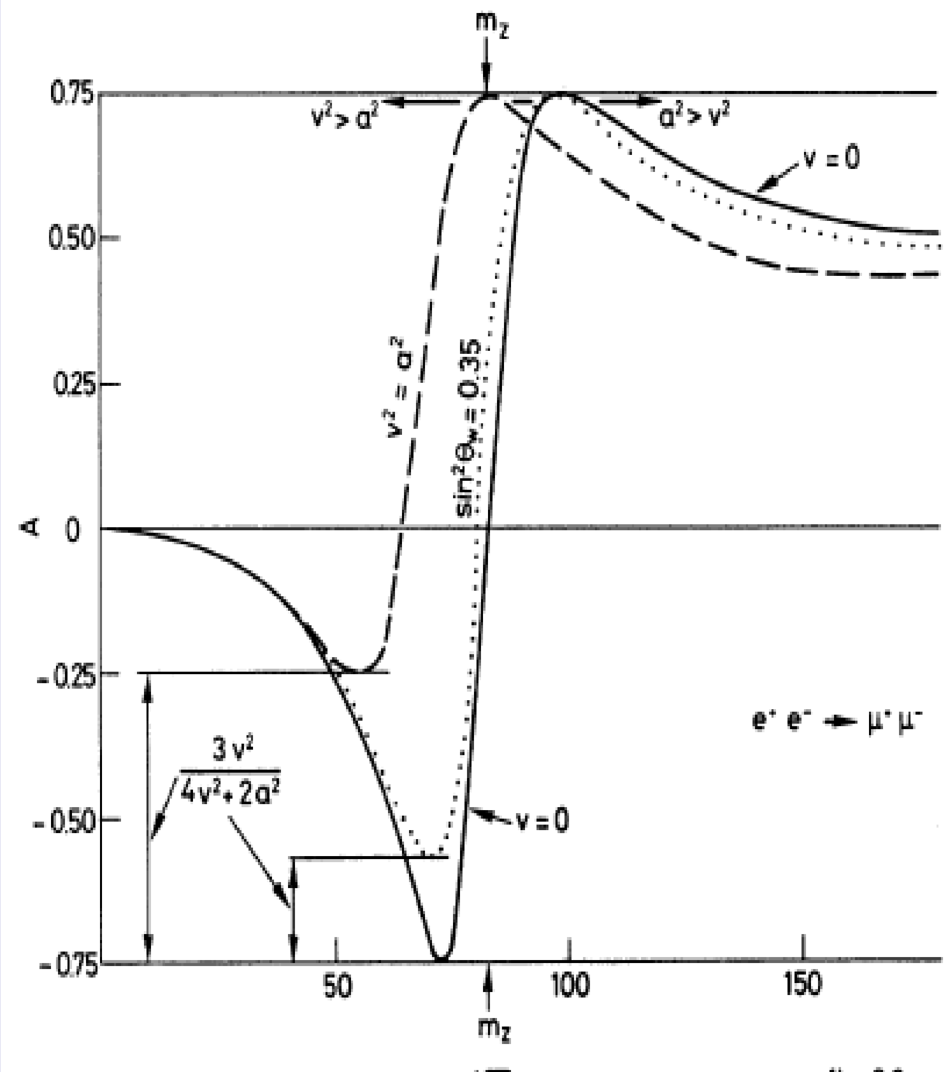
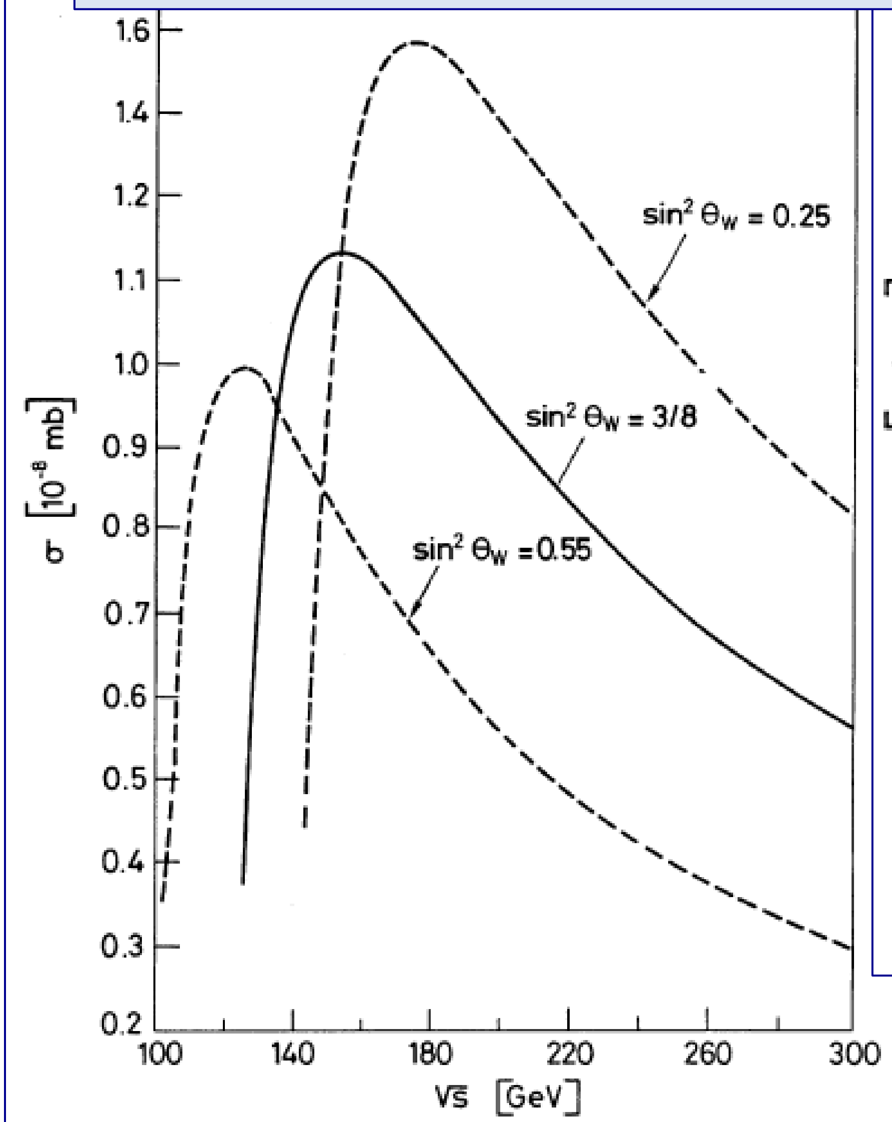
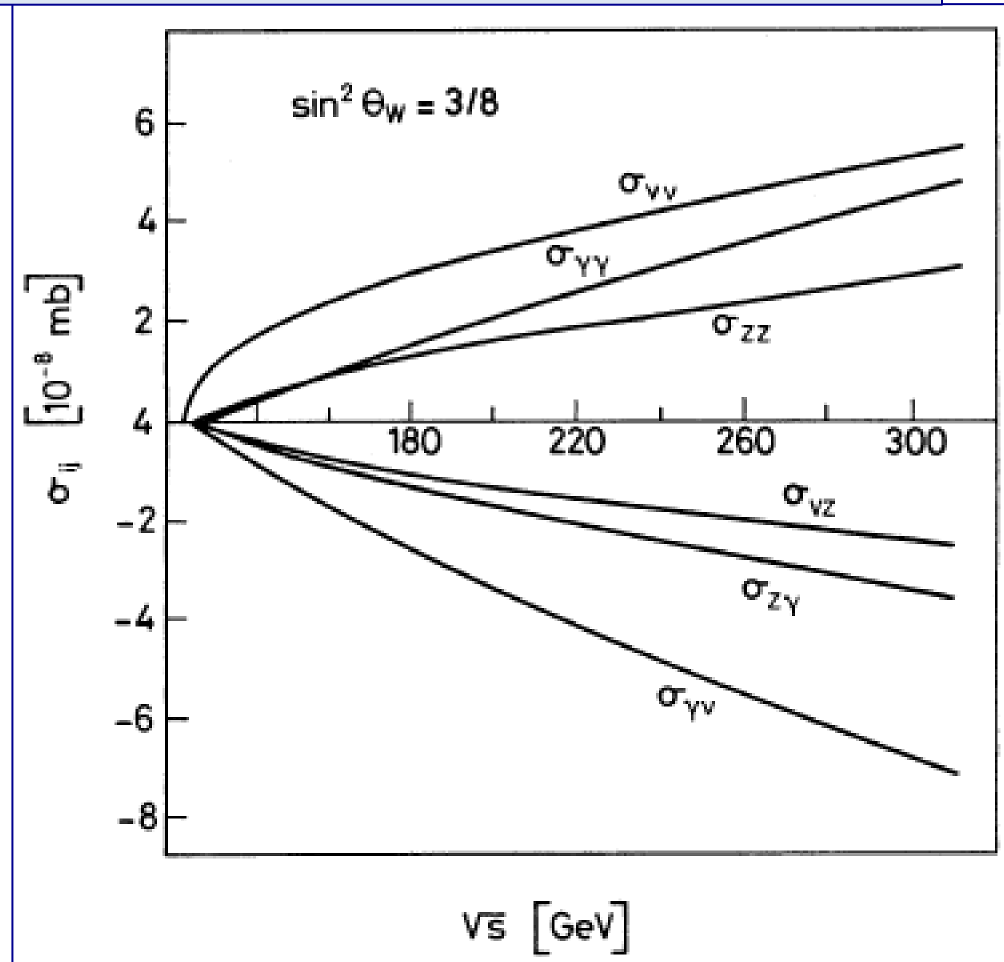


fig. 2.2

W^+W^- Production





Alles, Boyer, Buras

Higgs Production

Z+H: 'Higgsstrahlung' @ LEP 2

Then the Higgs production cross section is maximal for $\sqrt{s} = m_z + \sqrt{2}\, m_H$ and the cross section for fig. 2.10a [13] is

$$\left.\frac{\sigma(Z+H)}{\sigma_{pt}}\right|_{max} = \frac{3}{64}\left(\frac{m_z}{38GeV}\right)^4 \frac{m_z}{2\sqrt{2}m_H}\left(1 + v^2/a^2\right) \simeq \frac{25\ GeV}{m_H} \qquad (2.66)$$

for $\sin^2\theta_w \simeq 0.35$, $m_z \simeq 80$ GeV and $v/a = -0.4$, where v and a are the vector and axial $Z\mu\mu$ couplings and σ_{pt} was defined in (2.5). If $m_H/m_z \simeq 1/10$, the Z contribution to $ee \to \mu\mu$ is about five times greater than the γ contribution, so

$$\left.\frac{\sigma(Z+H)}{\sigma(\mu\mu)_{total}}\right|_{max} \simeq 0.5 \qquad (2.67)$$

for $m_z \simeq 80$ GeV $\simeq 10\, m_H$. Again because of the mass dependence of its couplings, a Higgs mesons of 8 GeV is expected [13] to decay mostly into charmed particles and heavy leptons.

Presumably the most reasonable signal is

$$e^+e^- \to \underset{\llcorner l^+l^-}{Z} + \underset{\llcorner hadrons}{H} \qquad (2.68)$$

If the Z leptonic branching ratio is O (5) percent, this will be a few percent of the $\mu\mu$ signal at the optimal energy.

At higher energies the cross section is

$$\frac{\sigma(Z+H)}{\sigma_{QED}(\mu\mu)} = \frac{3}{64}\left(\frac{m_z}{38}\right)^4 \frac{m_z^2}{s-m_z^2}\left(1 + v^2/a^2\right) \simeq 0.2 \qquad (2.69)$$

for $\sqrt{s} \simeq 200$ GeV, $m_z = 80$ GeV.

Below threshold for Z+H production the Higgs can be made via bremsstrahlung from a virtual Z, for example

$$e^+e^- \to H + \mu\mu \qquad (2.70)$$

Z decay @ LEP 1

as illustrated in fig. 2.10b.

$$\frac{\sigma(H\mu\mu)}{\sigma(e^+e^- \to Z^0 \to \mu^+\mu^-)} \simeq \frac{\alpha}{4\pi}\left(\frac{m_z}{38GeV}\right)^2 \frac{m_z^2}{s} \left\{\frac{(2m_z^2 - s)}{s}\ln\left(\frac{m_z^2}{m_z^2 - s'}\right) - \left(\frac{m_z^2 - s}{m_z^2 - s'}\right) - 1\right\}, \qquad (2.71)$$

$$\sqrt{s'} = \sqrt{s} - m_H .$$

At resonance this becomes

$$\left.\frac{\sigma(H\mu\mu)}{\sigma(e^+e^- \to Z^0 \to \mu^+\mu^-)}\right|_{peak} \simeq \frac{\alpha}{4\pi}\left(\frac{m_z}{38GeV}\right)^2 \left\{\ln\left(\frac{m_z}{2m_H}\right) - 1\right\} \simeq 1.5\text{x}10^{-3} \qquad (2.72)$$

for $m_z \simeq 80GeV \simeq 10m_H$. The total fraction of Higgs production at resonance should be similar :

$$\frac{\Gamma(Z \to H + \text{anything})}{\Gamma(Z \to \text{anything})} \simeq \frac{\Gamma(Z \to H\mu\mu)}{\Gamma(Z \to \mu\mu)} \simeq 10^{-3} \qquad (2.73)$$

but presumably the $H\mu\mu$ channel is the most accessible experimentally. If the $Z^0 \to \mu^+\mu^-$ branching ratio is O(10%) we get

$$\left.\frac{\sigma(e^+e^- \to H\mu^+\mu^-)}{\sigma(e^+e^- \to Z^0 \to \text{all})}\right|_{peak} \simeq O(10^{-4}). \qquad (2.74)$$

Below the resonance, $m_H \ll s \ll m_z^2$, the cross section becomes

$$\frac{(e^+e^- \to H\mu^+\mu^-)}{\sigma_{pt}} \simeq \frac{\alpha}{24\pi}\frac{1}{(16)^2}\frac{s^3}{(38GeV)^6} . \qquad (2.75)$$

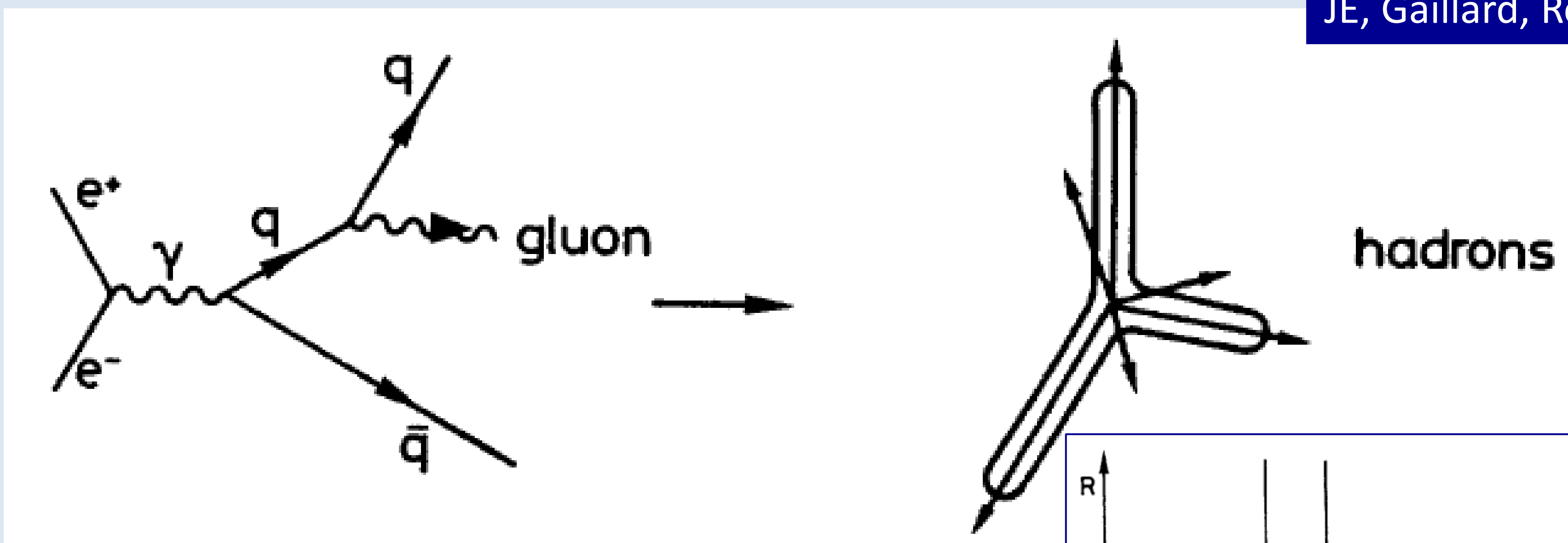
For models beyond the minimal Weinberg-Salam one, predictions may vary, but one might expect that because of the Higgs role in providing masses a correlation between mass and coupling may persist, at least for some of the Higgs scalars. There may also be charged Higgs scalars which would be produced electromagnetically (fig. 2.11) ; they might also identify themselves through a violation of μ-e universality

'Bjorken' process

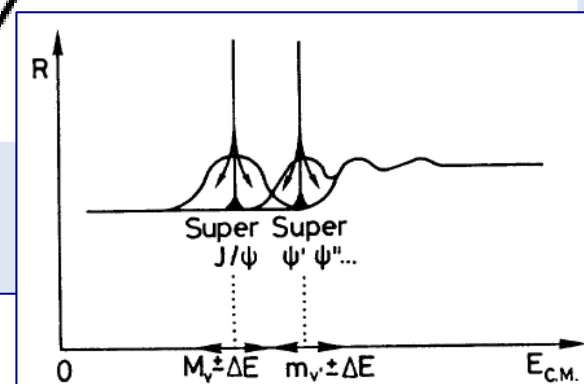
Strong Interactions: Jets & Onia

- Gluon not yet discovered (1979)
- Search for gluon bremsstrahlung

JE, Gaillard, Ross



- Toponia in LEP energy range?



Les Houches Summer Study 1978

CERN 79-01
Volume 1
14 February 1979

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PROCEEDINGS OF THE LEP SUMMER STUDY

Les Houches and CERN
10-22 September 1978

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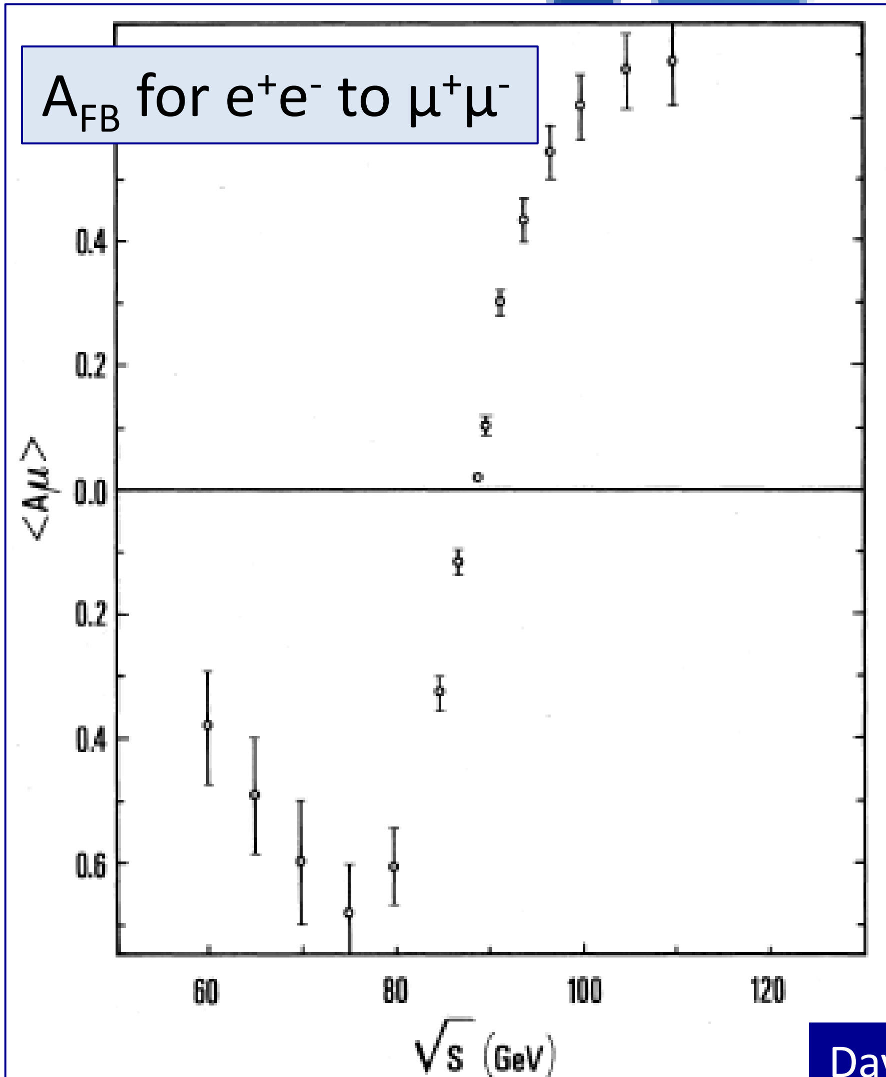
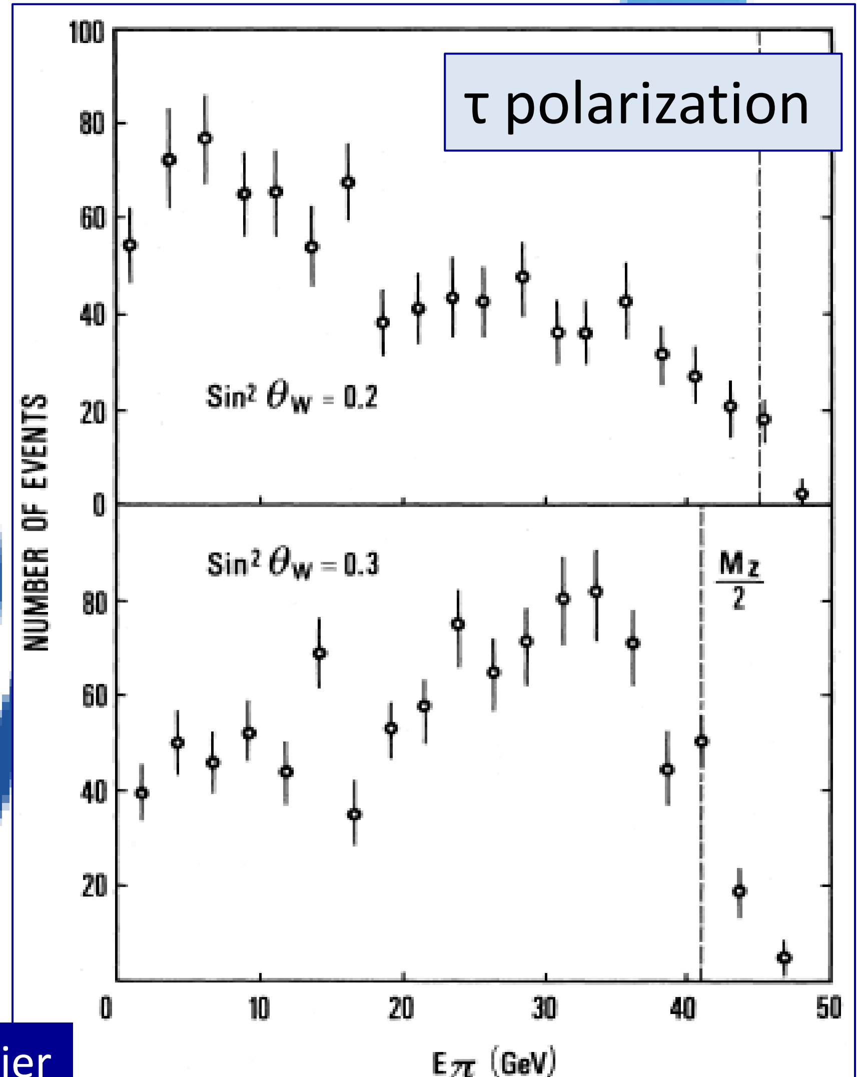
Debating Zedology and the Higgs sector

Anticipating LEP 1 Measurements

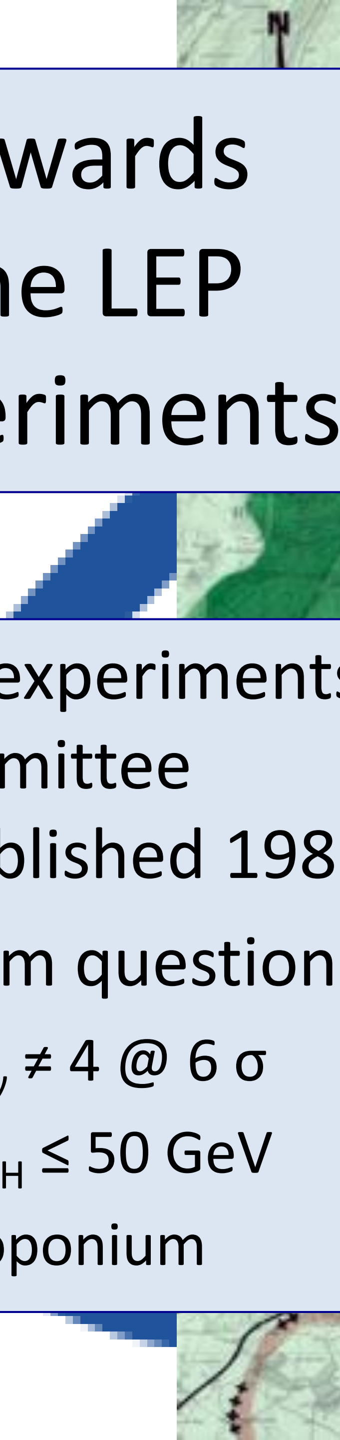


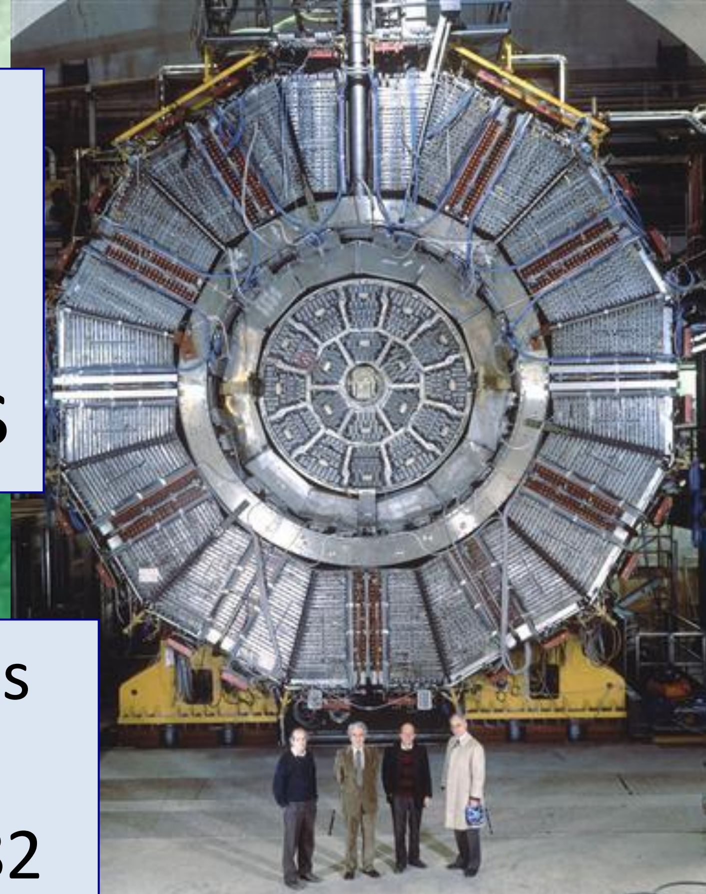


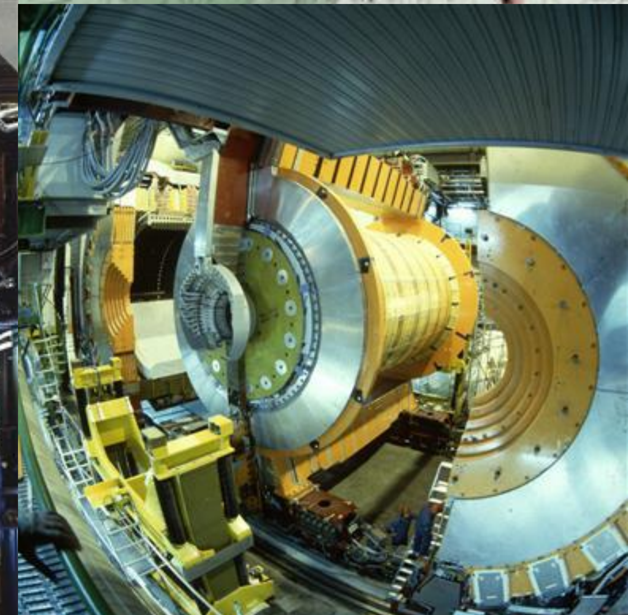
Davier

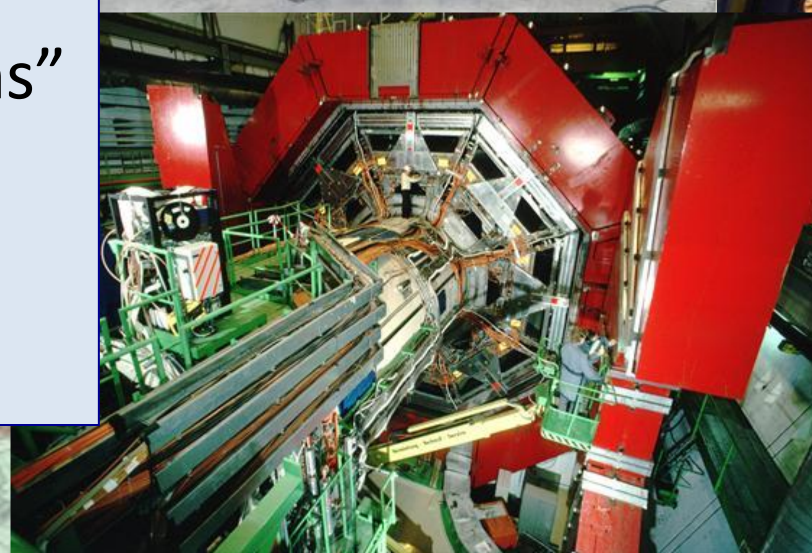
Towards the LEP Experiments

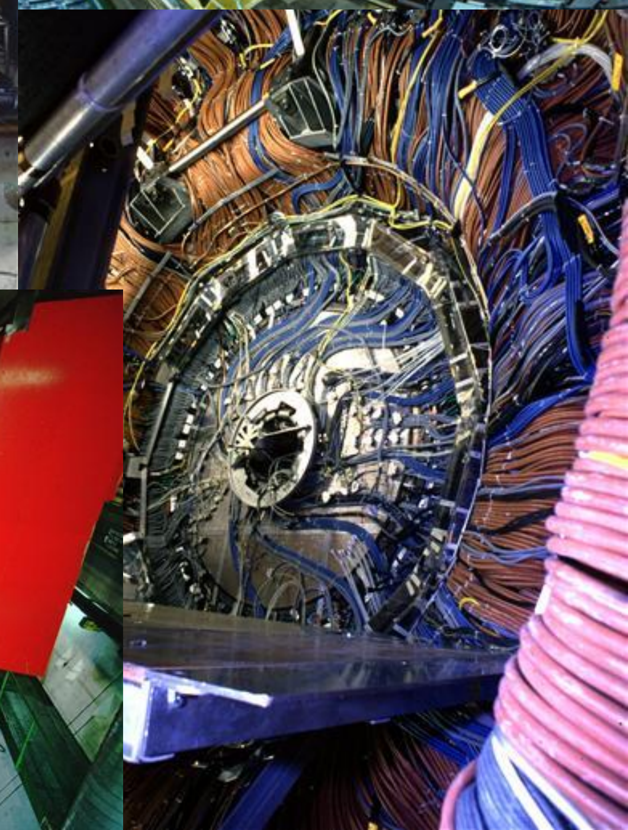
- LEP experiments committee established 1982
- “Exam questions”
  - $N_\nu \neq 4$ @ 6 σ
  - $m_H \leq 50$ GeV
  - Toponium



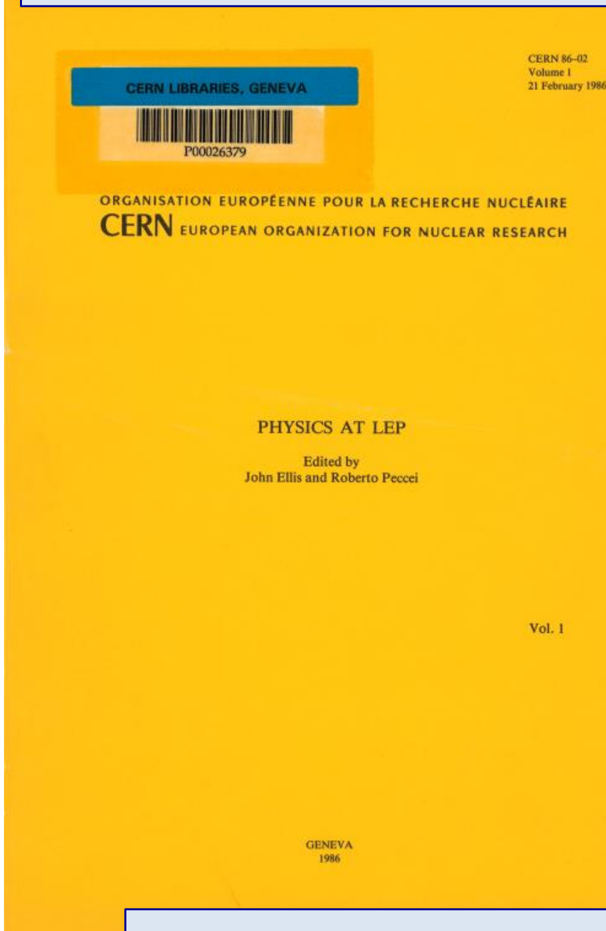








The Yellow Report Road



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Volume 1
21 February 1986

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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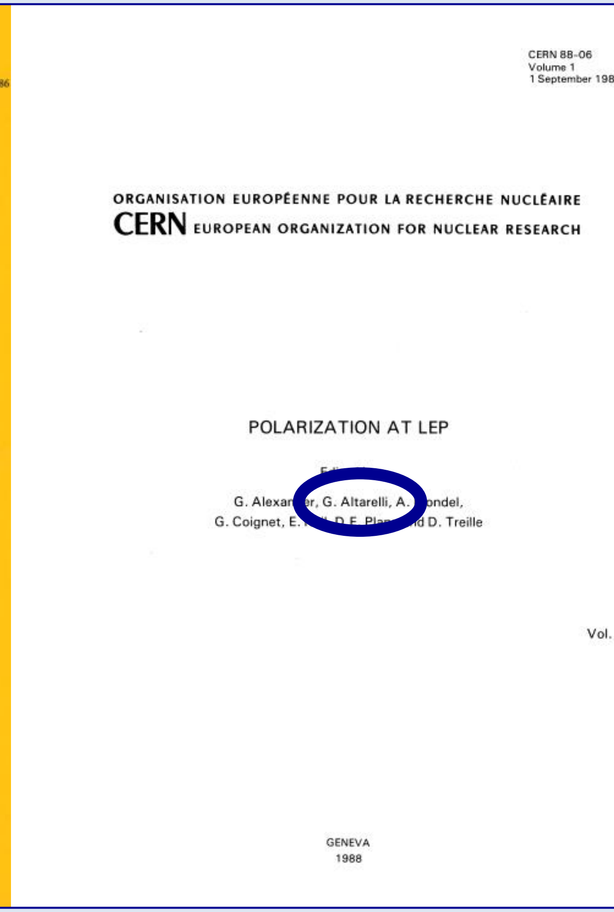
PHYSICS AT LEP

Edited by
John Ellis and Roberto Peccei

Vol. 1

GENEVA
1986



CERN 88-06
Volume 1
1 September 1988

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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

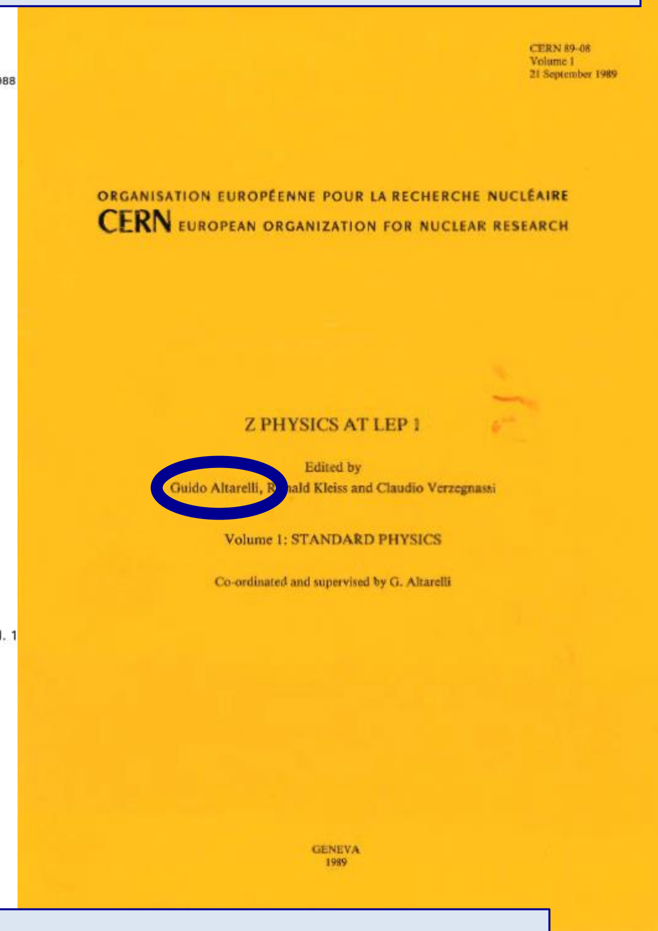
POLARIZATION AT LEP

[illegible]

G. Alexan[illegible]er, G. Altarelli, A. [illegible]ondel,
G. Coignet, E. [illegible] [illegible]d D. Treille

Vol. 1

GENEVA
1988



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Volume 1
21 September 1989

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Z PHYSICS AT LEP 1

Edited by
Guido Altarelli, R[illegible]nald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

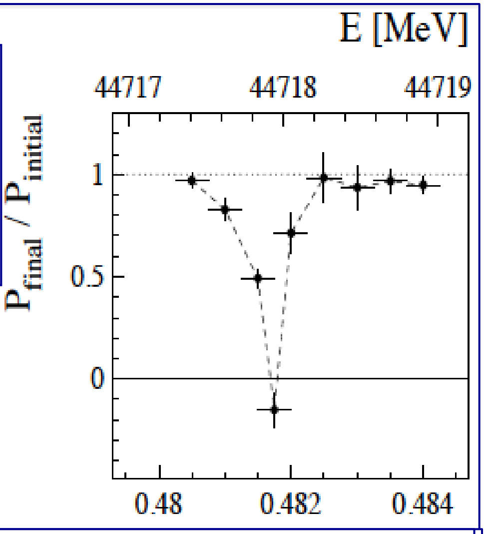
Co-ordinated and supervised by G. Altarelli

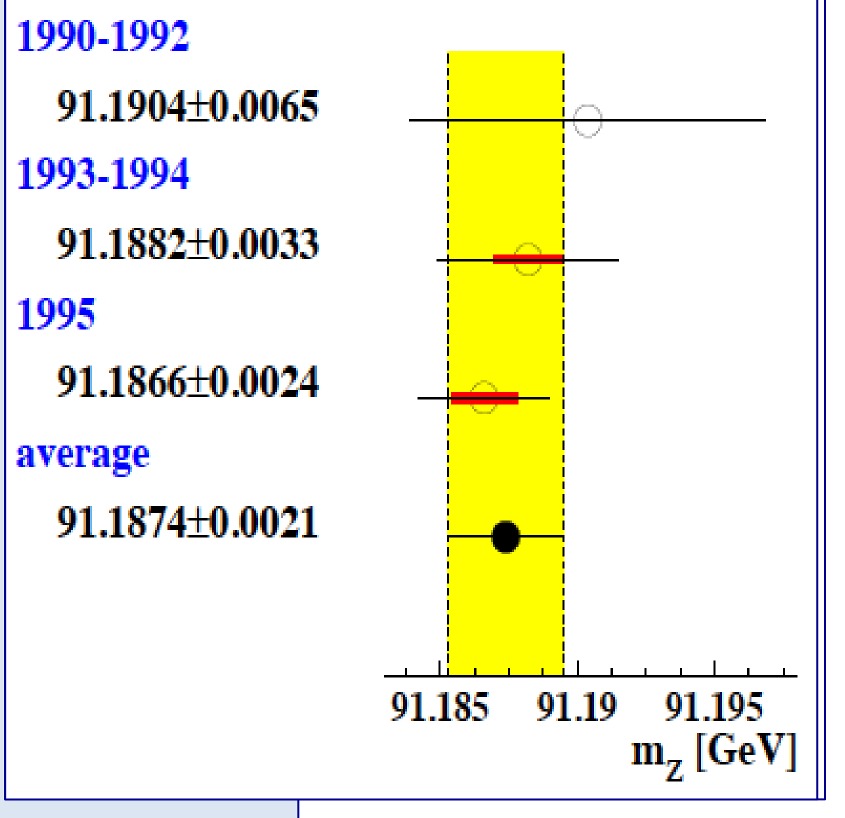
GENEVA
1989

Theorists + experimentalists + accelerator physicists working together to study physics opportunities

Measuring the Z Mass

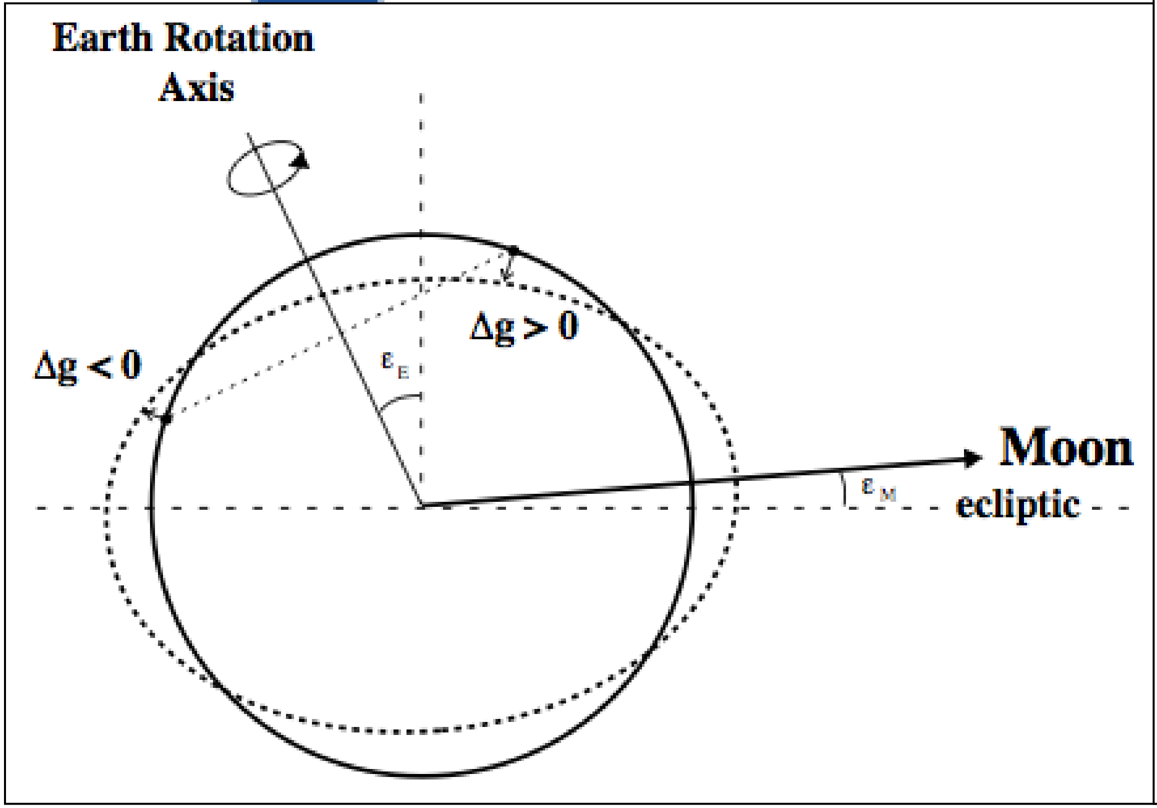
- Needed to measure beam energy at LEP using resonant depolarization
- Affected by
  - Magnet temperature
  - Terrestrial tides
  - Water (rain, Lake Geneva)
  - Trains
- Final error ± 2 MeV

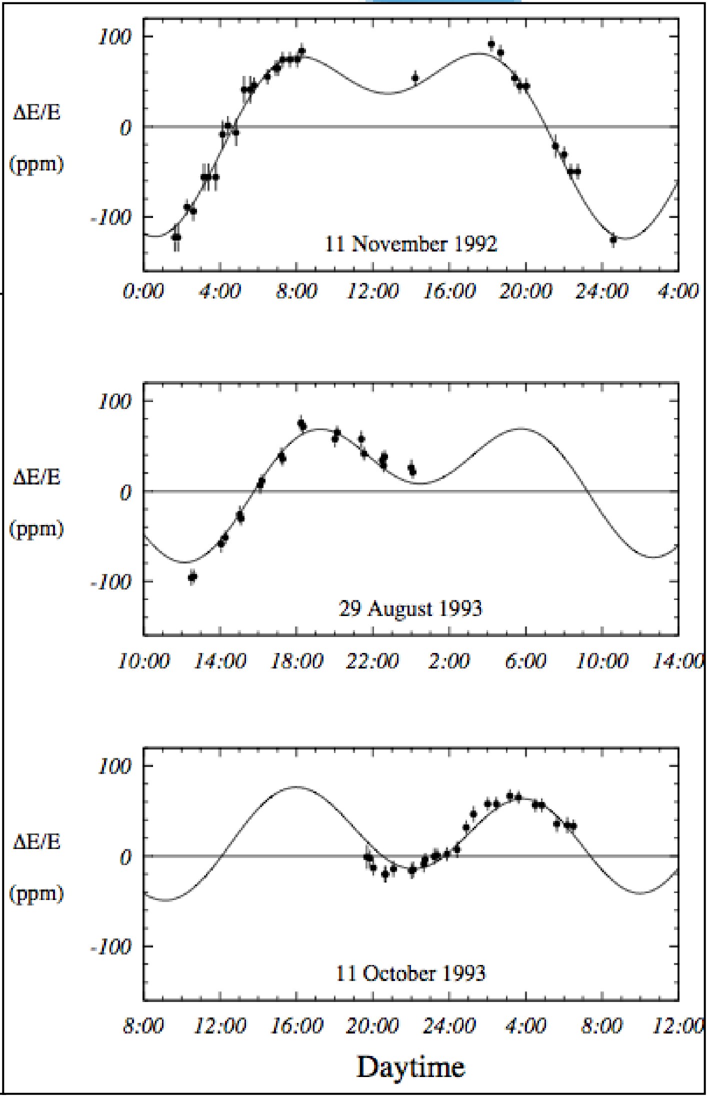




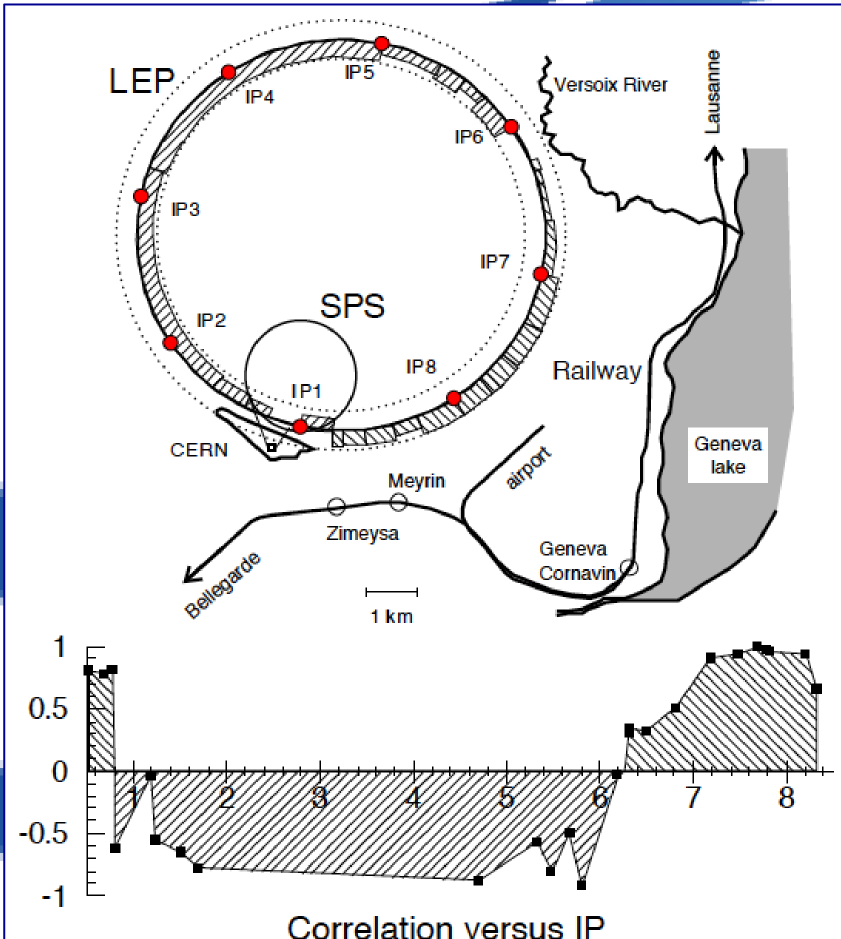
Terrestrial Tides

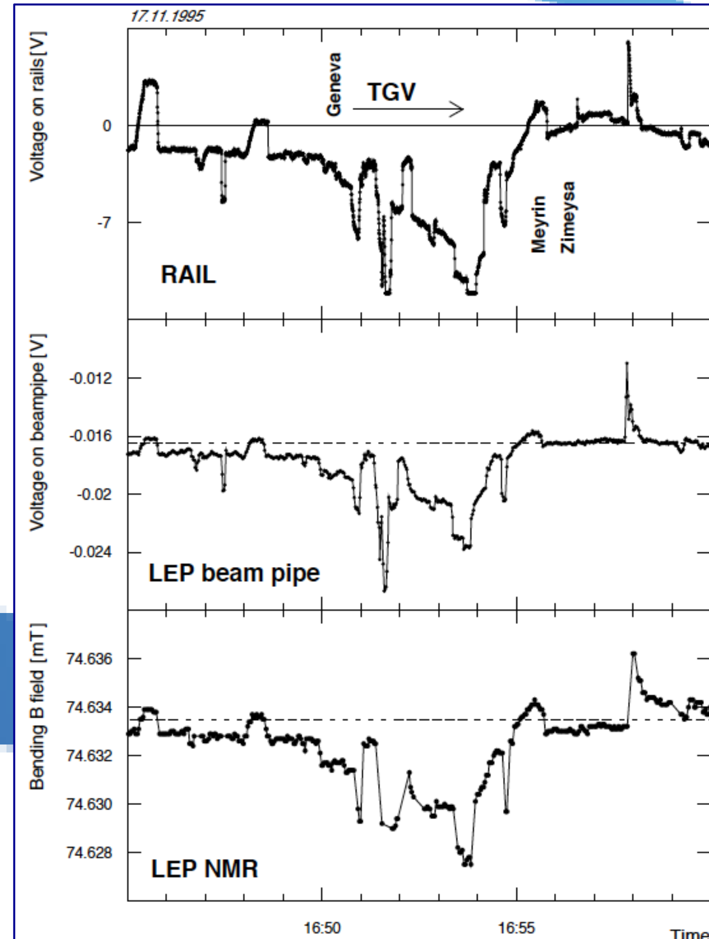
Affect circumference of ring change beam energy





Trains: Currents through Magnets





Effect on magnetic field: ΔE several MeV

Combination of EW Measurements

Unprecedented combined effort, together with SLD

Available online at www.sciencedirect.com
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Physics Reports 427 (2006) 257–454
PHYSICS REPORTS
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Precision electroweak measurements on the Z resonance☆,☆☆

The ALEPH Collaboration
The DELPHI Collaboration
The L3 Collaboration
The OPAL Collaboration
The SLD Collaboration
The LEP Electroweak Working Group
The SLD Electroweak and Heavy Flavour Groups

Accepted 13 December 2005
Available online 3 March 2006
editor: J.A. Bagger

Abstract

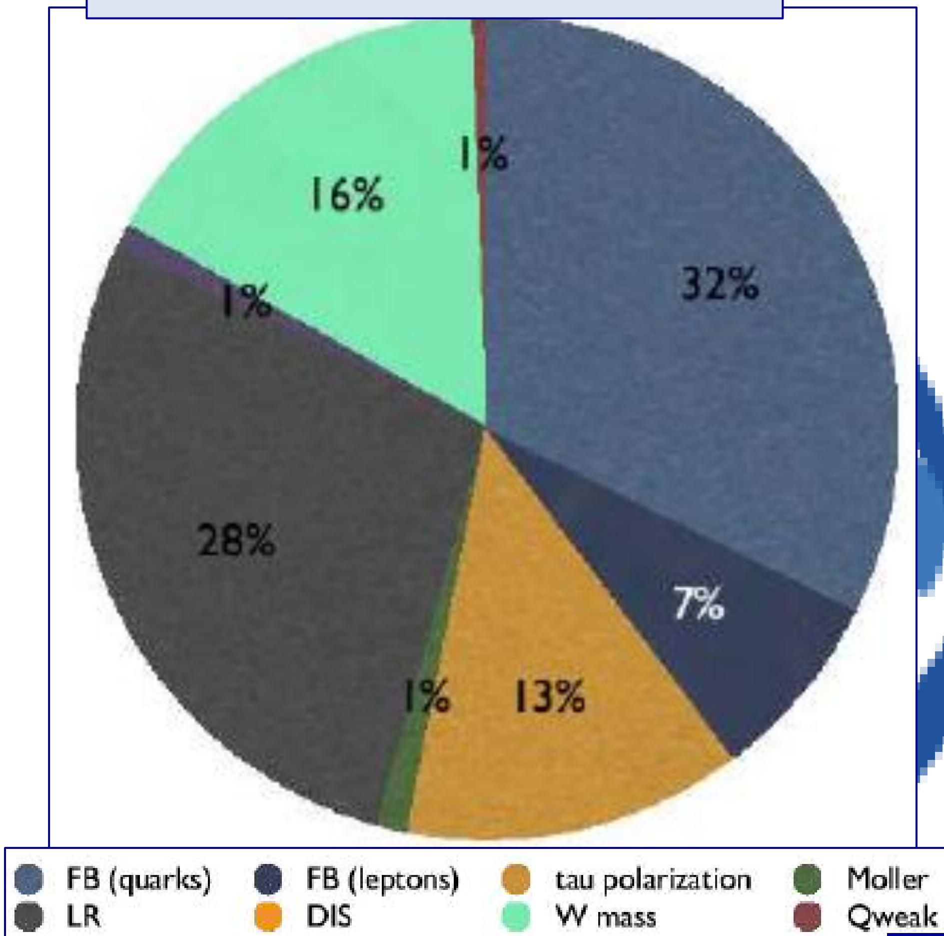
We report on the final electroweak measurements performed with data taken at the Z resonance by the experiments operating at the electron–positron colliders SLC and LEP. The data consist of 17 million Z decays accumulated by the ALEPH, DELPHI, L3 and OPAL experiments at LEP, and 600 thousand Z decays by the SLD experiment using a polarised beam at SLC. The measurements include cross-sections, forward–backward asymmetries and polarised asymmetries. The mass and width of the Z boson, m_Z and Γ_Z, and its couplings to fermions, for example the ρ parameter and the effective electroweak mixing angle for leptons, are precisely measured:

$$m_Z = 91.1875 \pm 0.0021\,\text{GeV},$$
$$\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV},$$
$$\rho_\ell = 1.0050 \pm 0.0010,$$
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23153 \pm 0.00016.$$

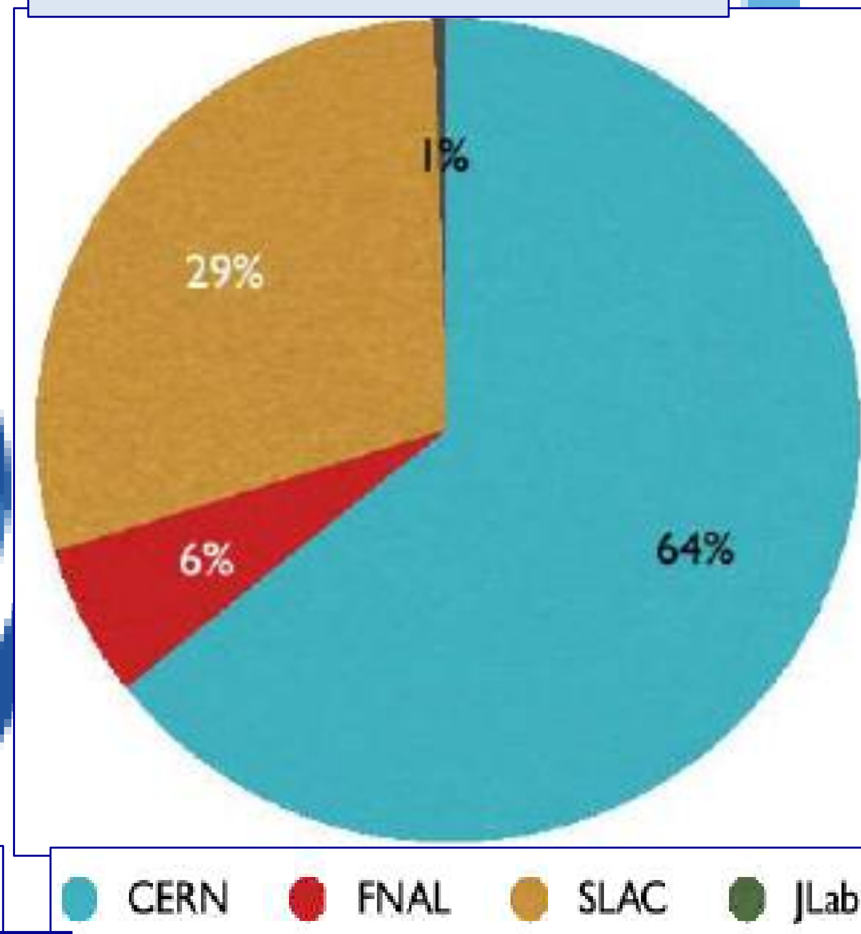
The number of light neutrino species is determined to be 2.9840 ± 0.0082, in agreement with the three observed generations of fundamental fermions.

Contributions of EW Measurements

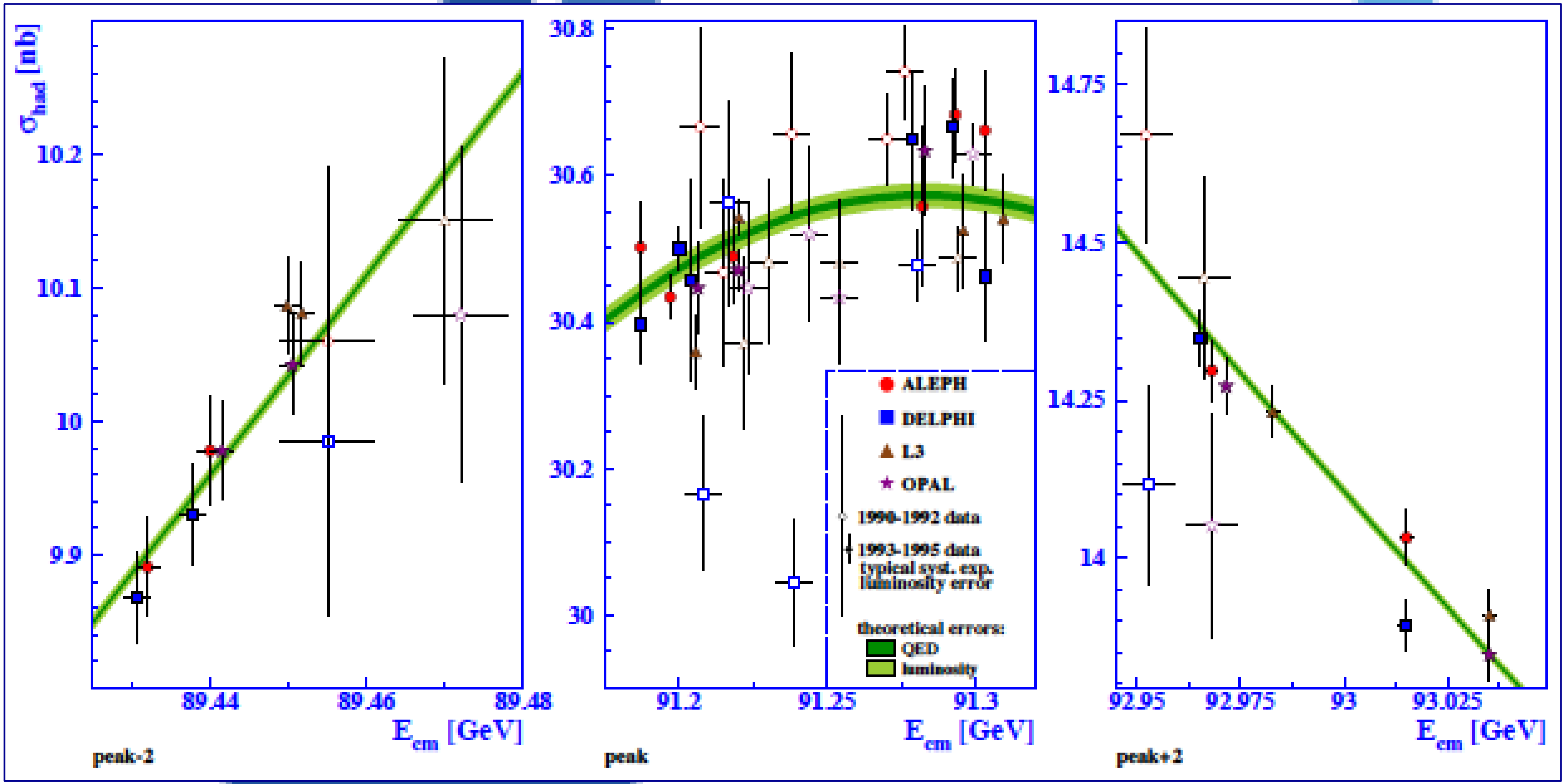
Different observables



Different laboratories

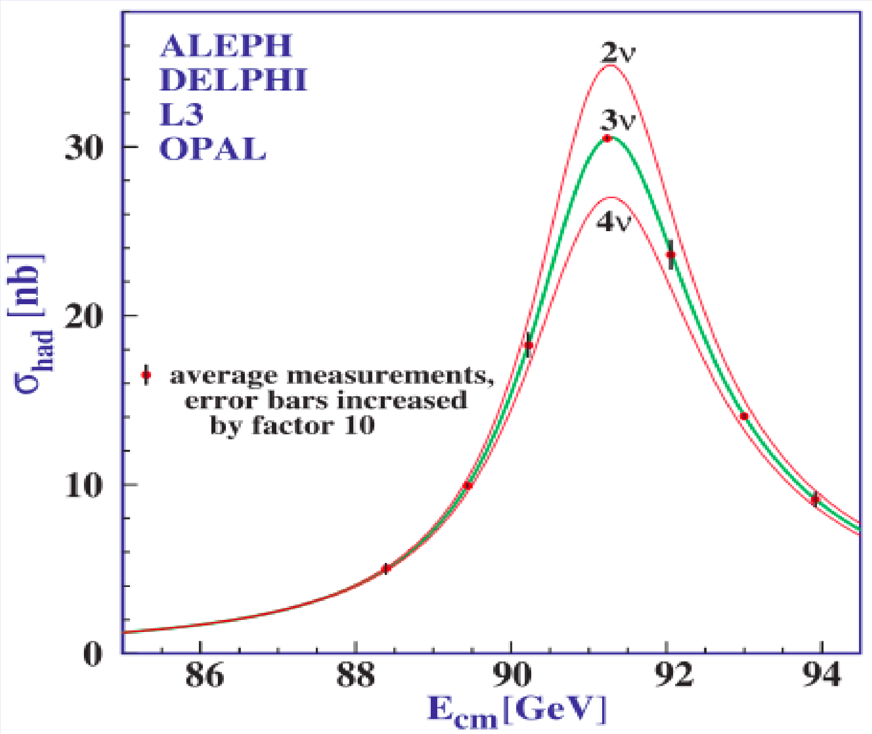


Cross-Sections on/off Z Peak



‘Neutrino’ Counting

- One of the first LEP results: Oct. 1989
- Two techniques: Z peak measurements:
  - $N_\nu = 2.9840 \pm 0.0082$
- Radiative return
  - $N_\nu = 2.92 \pm 0.05$
- Within SM:
  - determines # generations
- Beyond SM:
  - constrains SUSY, …



Electroweak Measurements

- Unanticipated precision
- Unprecedented precision
- Establish validity of SM @ per-mille level
- Insights into BSM

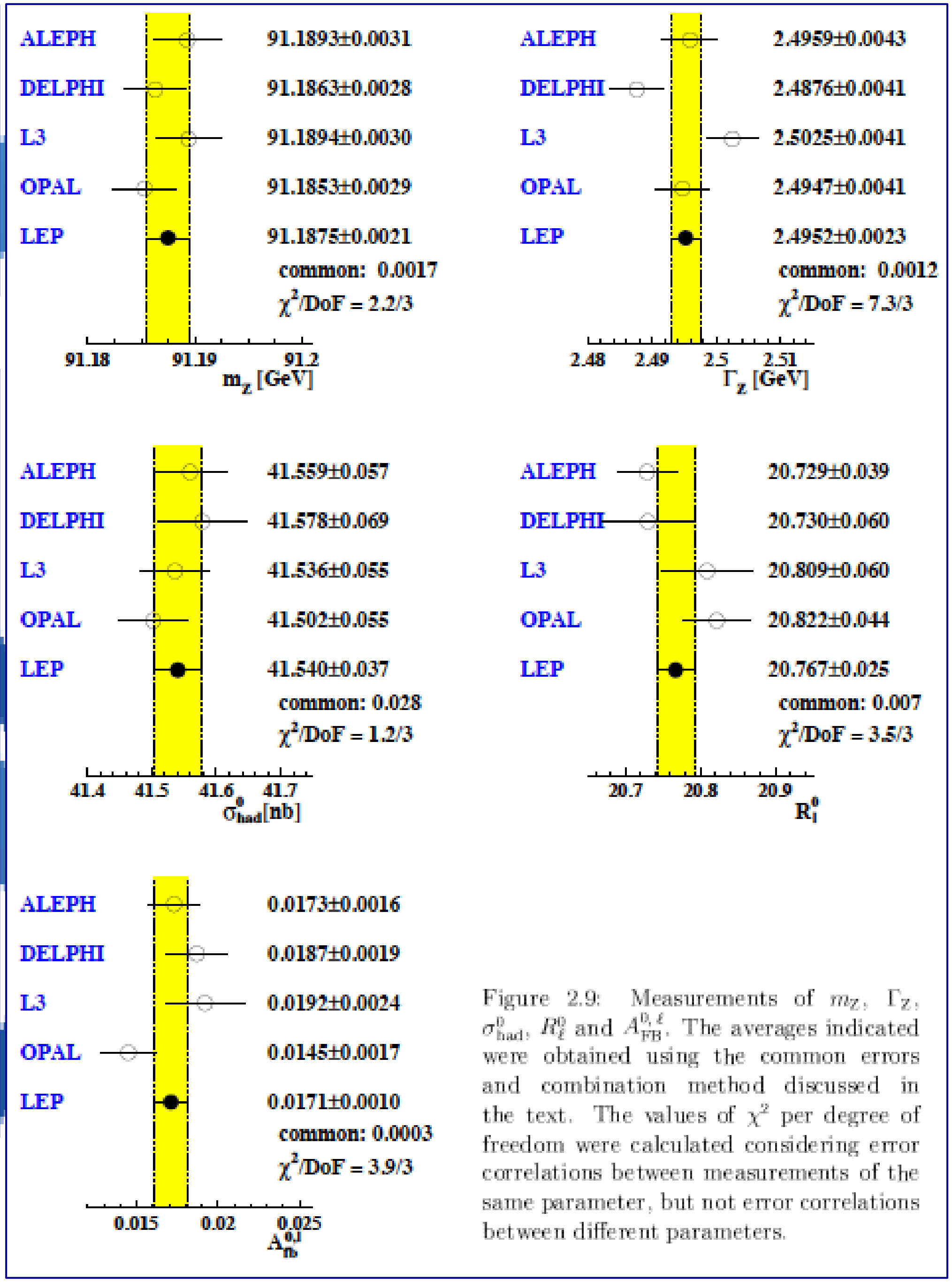
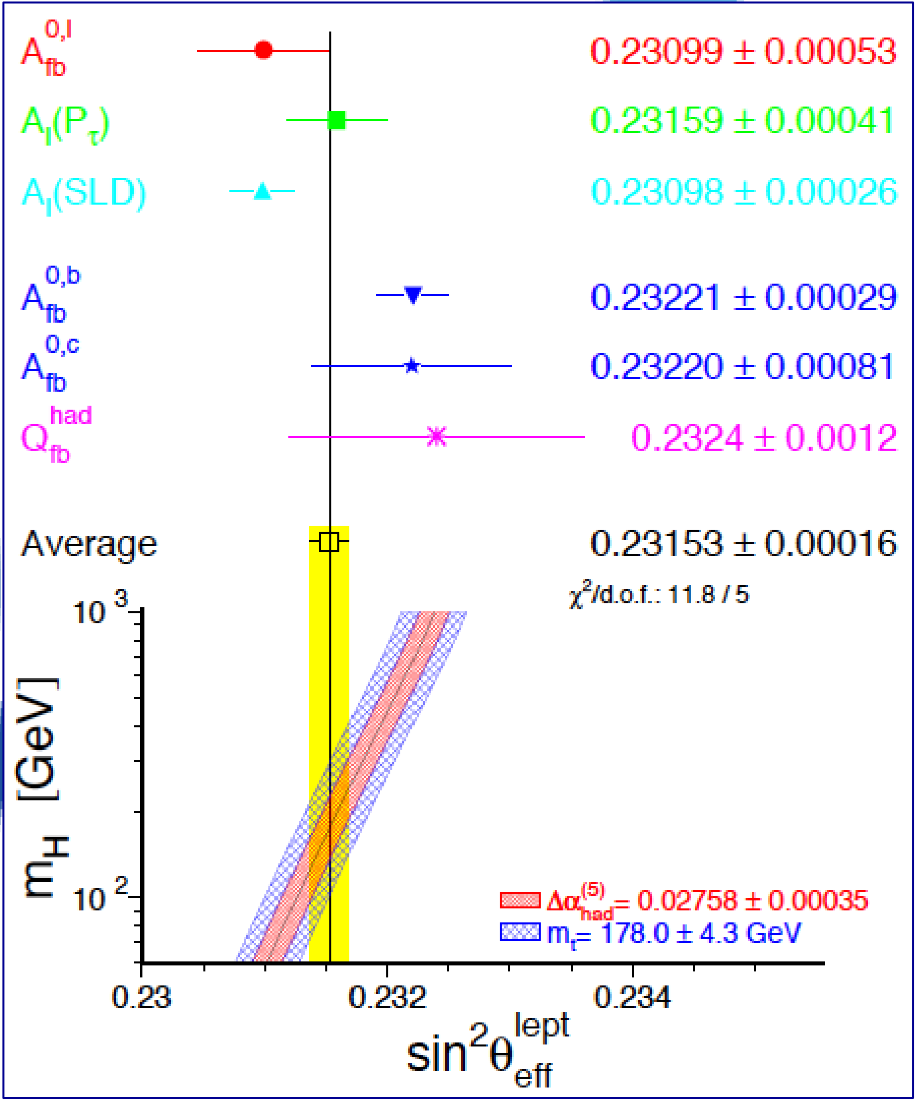


Figure 2.9: Measurements of m_Z, Γ_Z, $\sigma^0_{\rm had}$, R^0_ℓ and $A^{0,\ell}_{\rm FB}$. The averages indicated were obtained using the common errors and combination method discussed in the text. The values of χ^2 per degree of freedom were calculated considering error correlations between measurements of the same parameter, but not error correlations between different parameters.

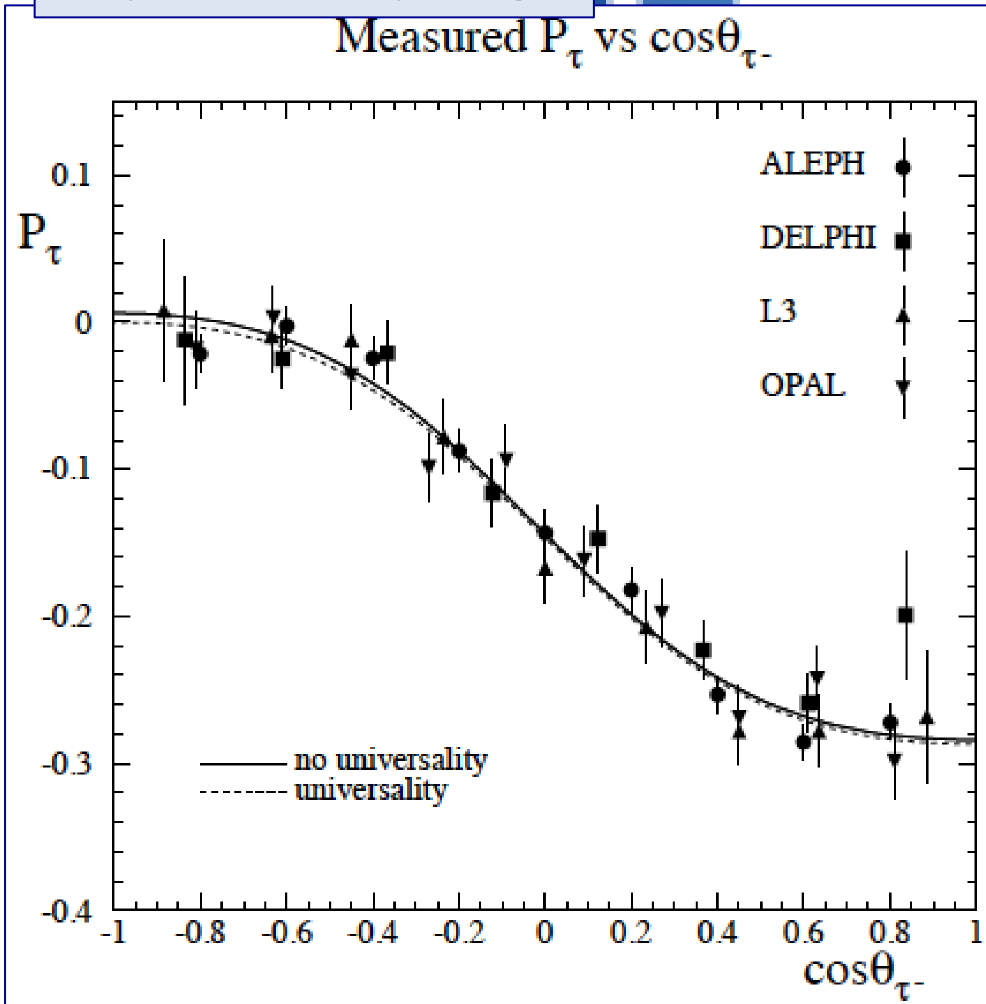
Electroweak Mixing Angle

- Many contributing electroweak measurements
- Tension between two highest-precision measurements
  - A_{FB}^{b}, $A_l(SLD)$
- Important clue for grand unification?

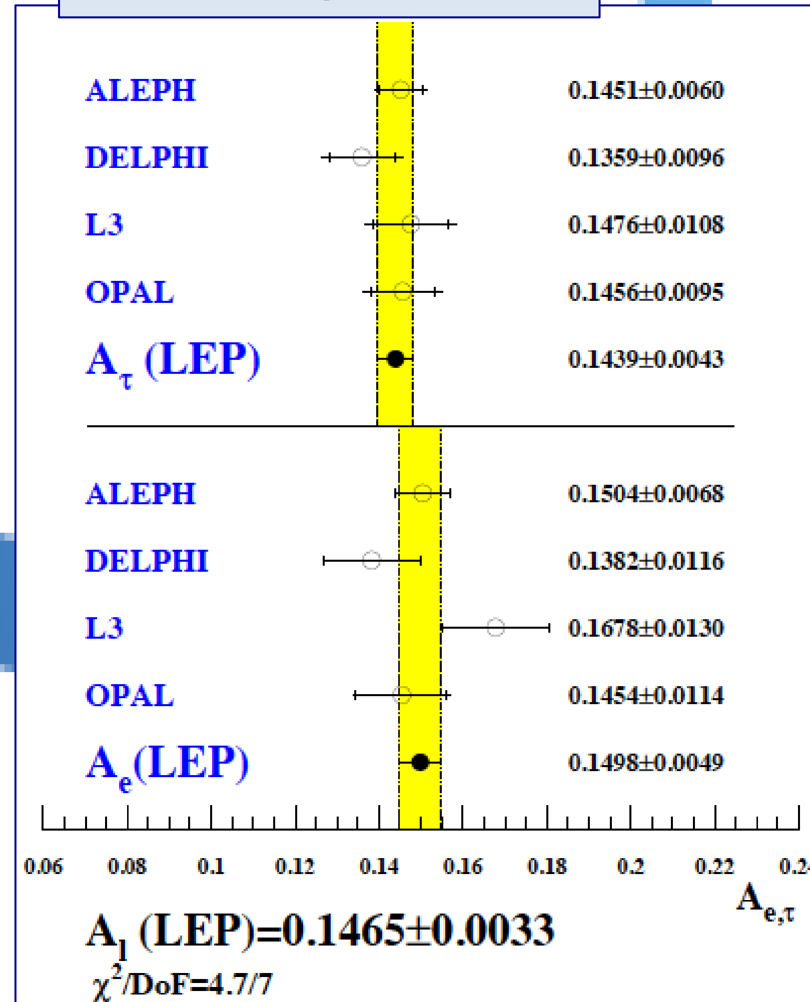


Tau Polarization Measurements

Lepton couplings

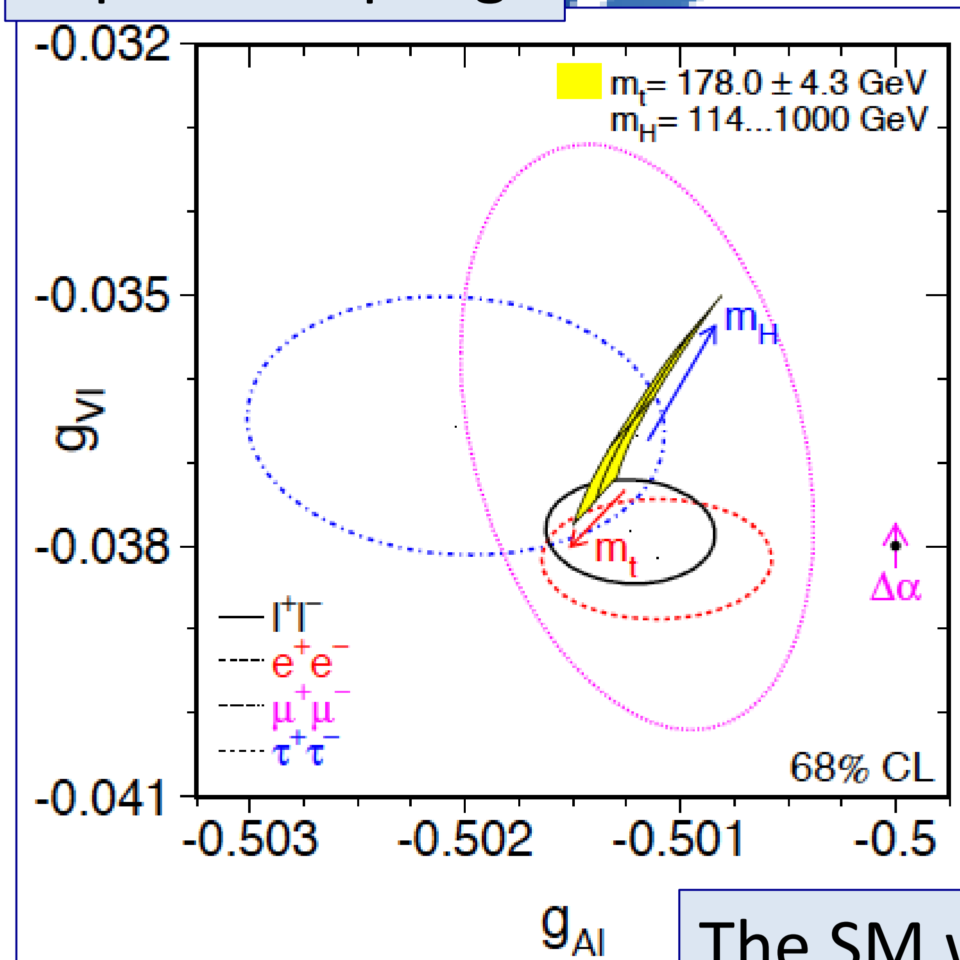


Pulls in global fit

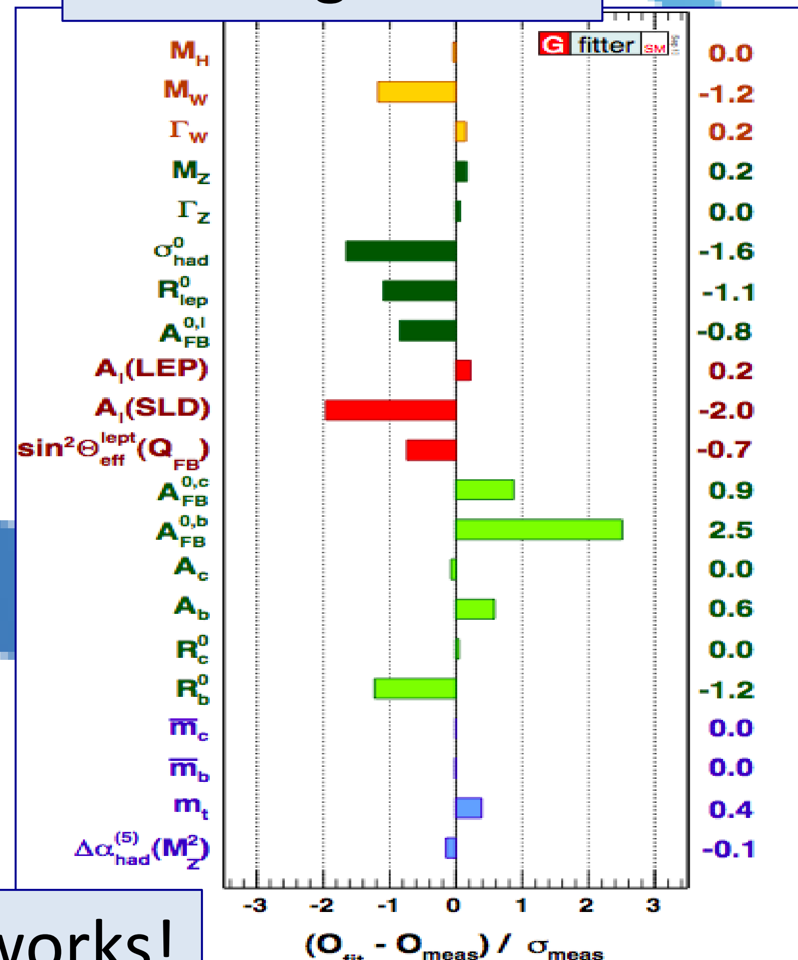


Precision Tests of the Standard Model

Lepton couplings



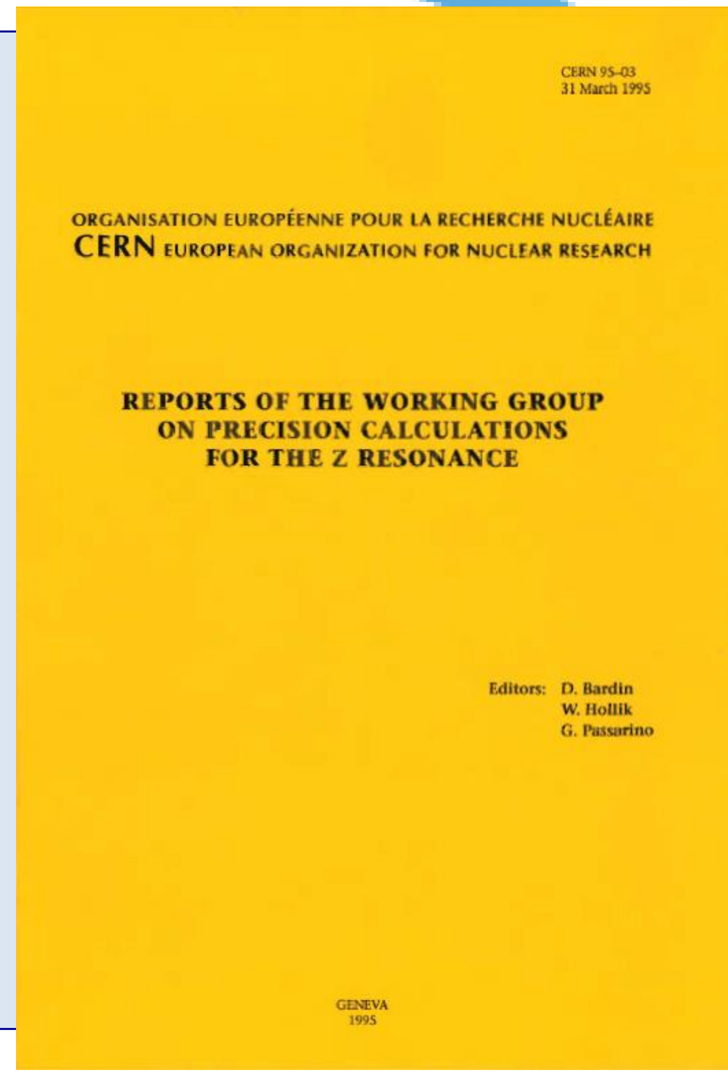
Pulls in global fit



The SM works!

Electroweak Radiative Corrections

- Attainable experimental precision greatly exceeded initial expectations
- Heroic effort by several groups to calculate leading (and most important non-leading radiative corrections
- Combination carried interpretation to unexpected level


CERN 95-03
31 March 1995

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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REPORTS OF THE WORKING GROUP
ON PRECISION CALCULATIONS
FOR THE Z RESONANCE

Editors: D. Bardin
W. Hollik
G. Passarino

GENEVA
1995

Constraints on Top, Higgs Masses

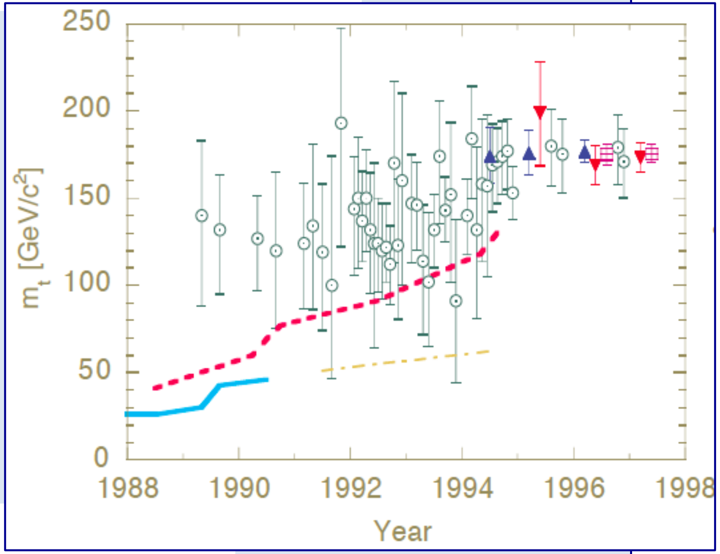
Veltman

- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Quadratic sensitivity to top:

$$\frac{3G_F}{8\pi^2\sqrt{2}} m_t^2$$



- Successful prediction!
- Logarithmic sensitivity to m_H

$$\frac{\sqrt{2}G_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

- (Successful prediction!)

Predicting m_t before LEP

NEUTRAL CURRENTS, M_Z AND m_t

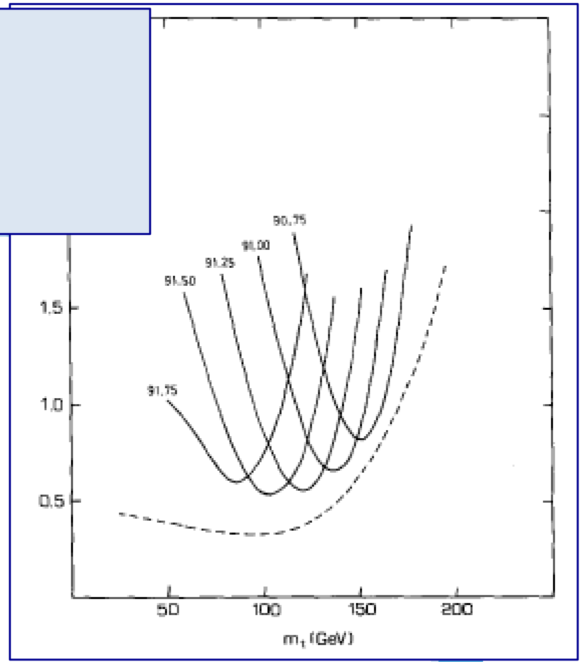
John ELLIS
CERN, CH-1211 Geneva 23, Switzerland

and

G.L. FOGLI
Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
and Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy

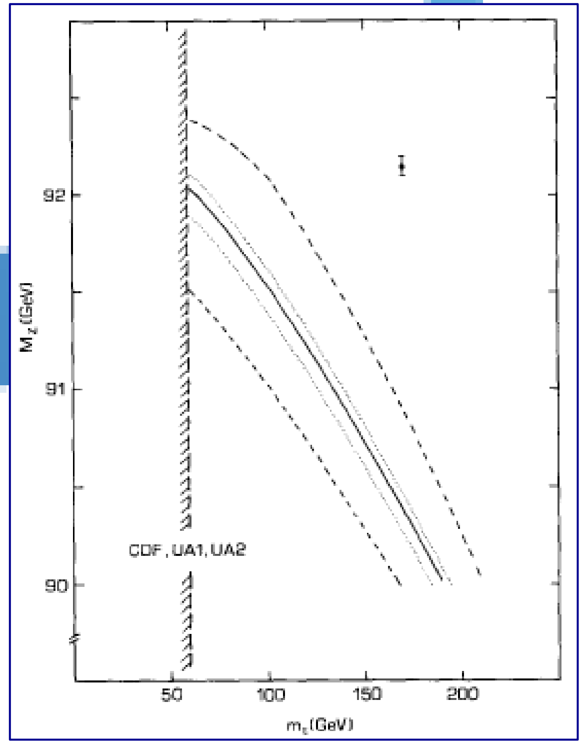
Received 17 July 1989

We summarize and update constraints on m_t from present neutral current data. Soon precision measurements of M_Z will give a tight correlation between $\sin^2\vartheta_W$ and m_t. Combining this information with low-energy neutral current data will pin down $\sin^2\vartheta_W$ and hence fix m_t with an error of $\sim \pm 35$ GeV. The central value of the top quark mass will be $m_t \simeq 95\,\text{GeV} + 66(91.6\,\text{GeV} - M_Z)$.



- An accurate measurement of m_Z would make possible the prediction of m_t

$$m_t \simeq 95\,\text{GeV} + 66(91.6\,\text{GeV} - M_Z)$$



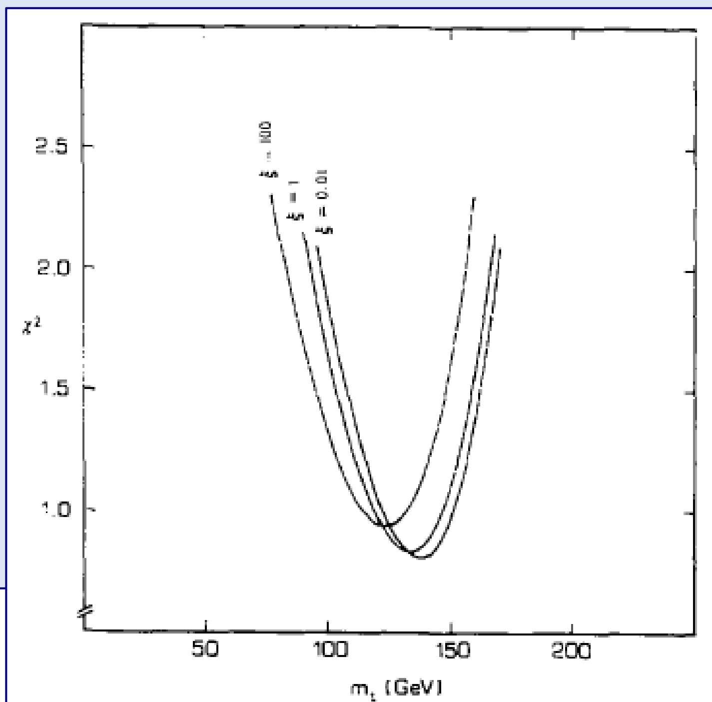
Predicting m_t after the first high-precision measurement of m_Z

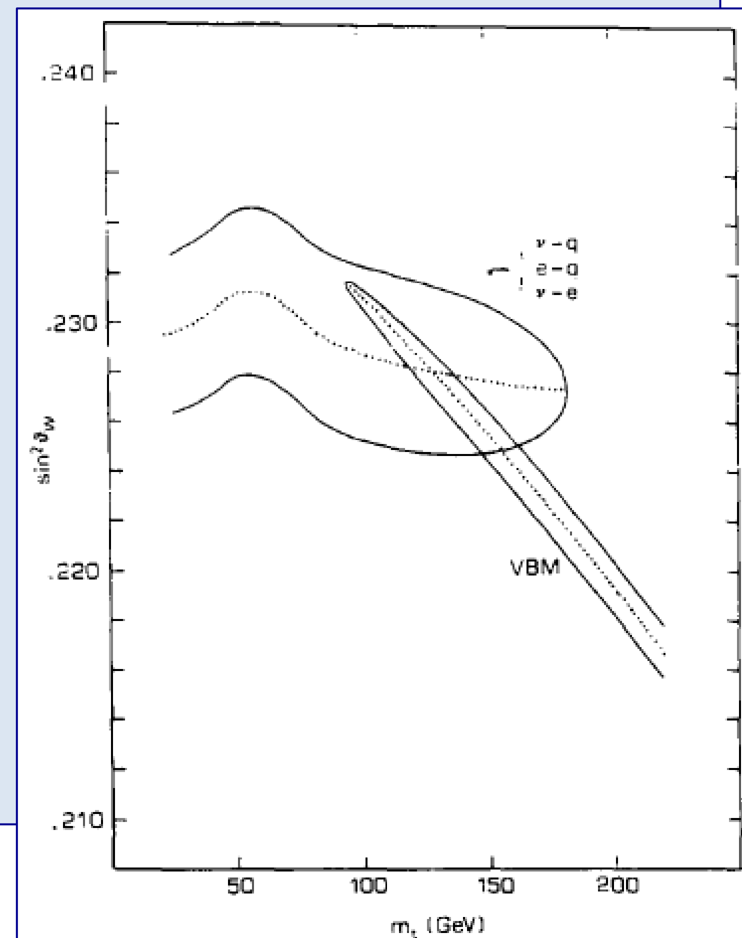
- Combination with low-energy data

JE, Fogli; Langacker; …

$$m_t = 132^{+31}_{-37}\ \text{GeV}$$

- First discussion of m_H

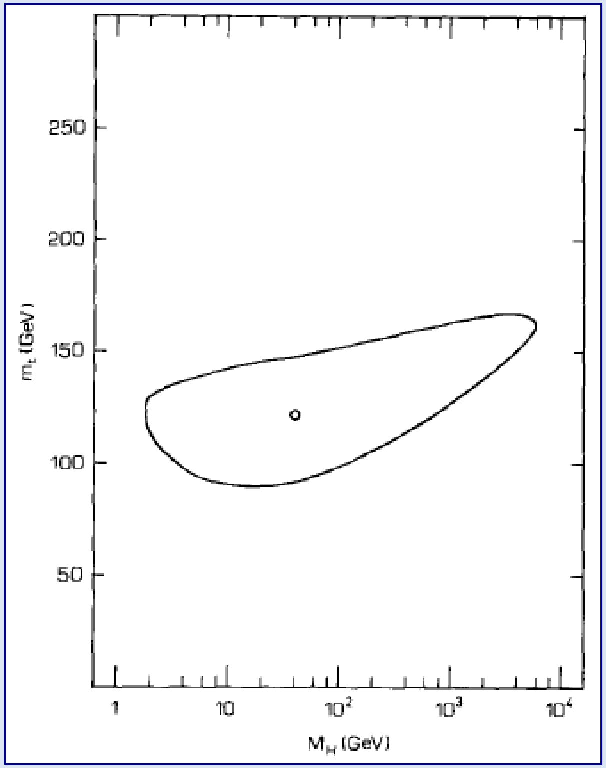


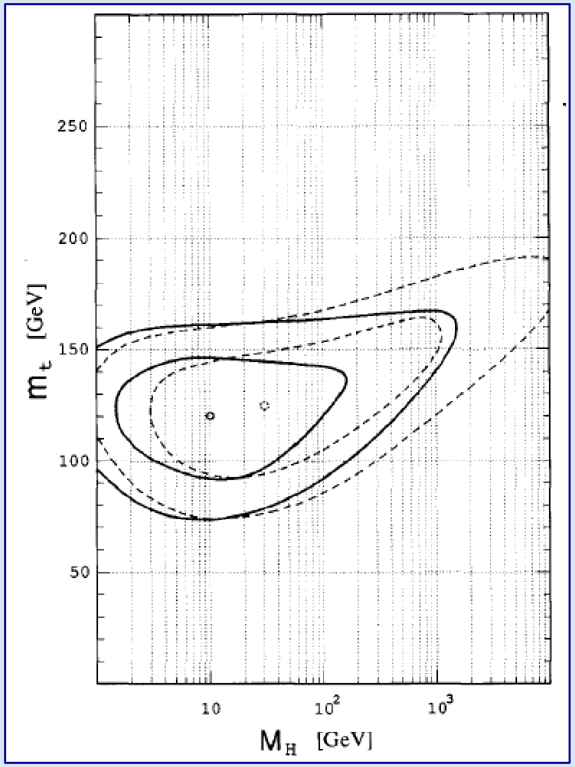


Estimating the Higgs Mass

- First attempts in 1990, 1991:

JE, Fogli, Lisi



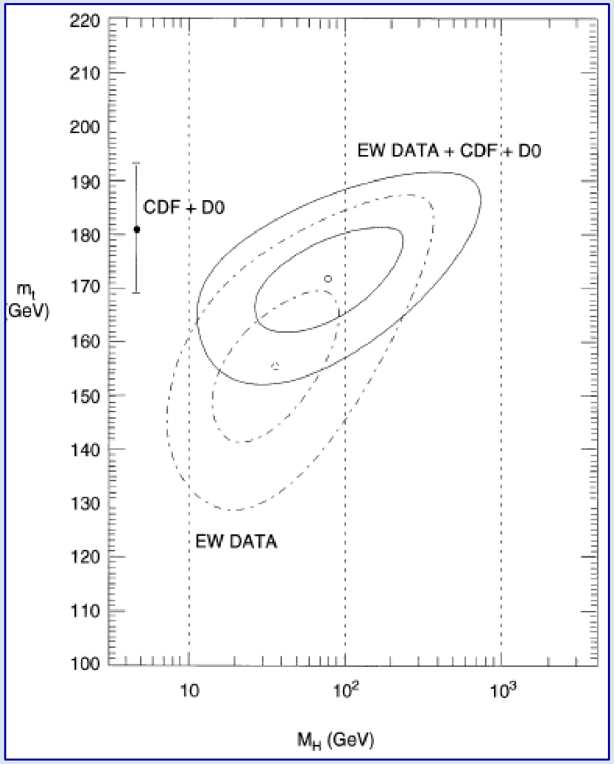


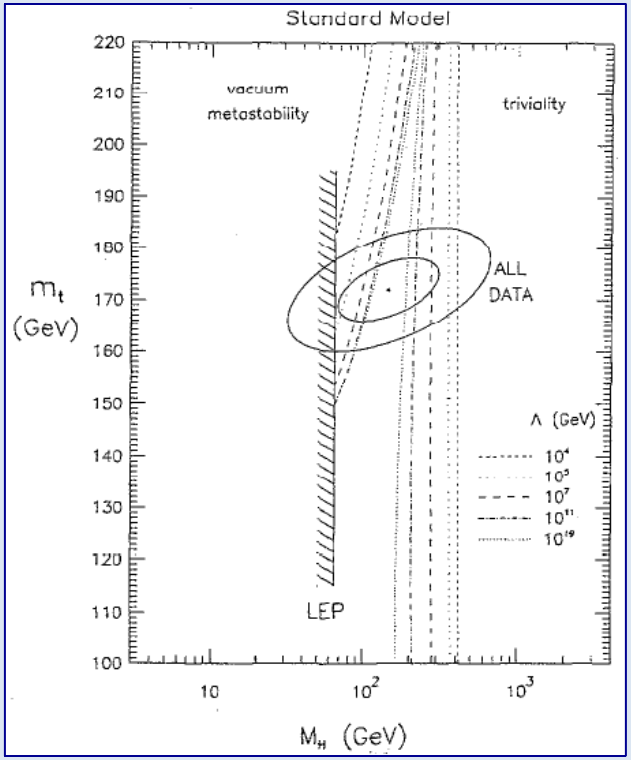
- Uncertainty before the discovery of the top

Estimating the Higgs Mass

- After the top discovery:

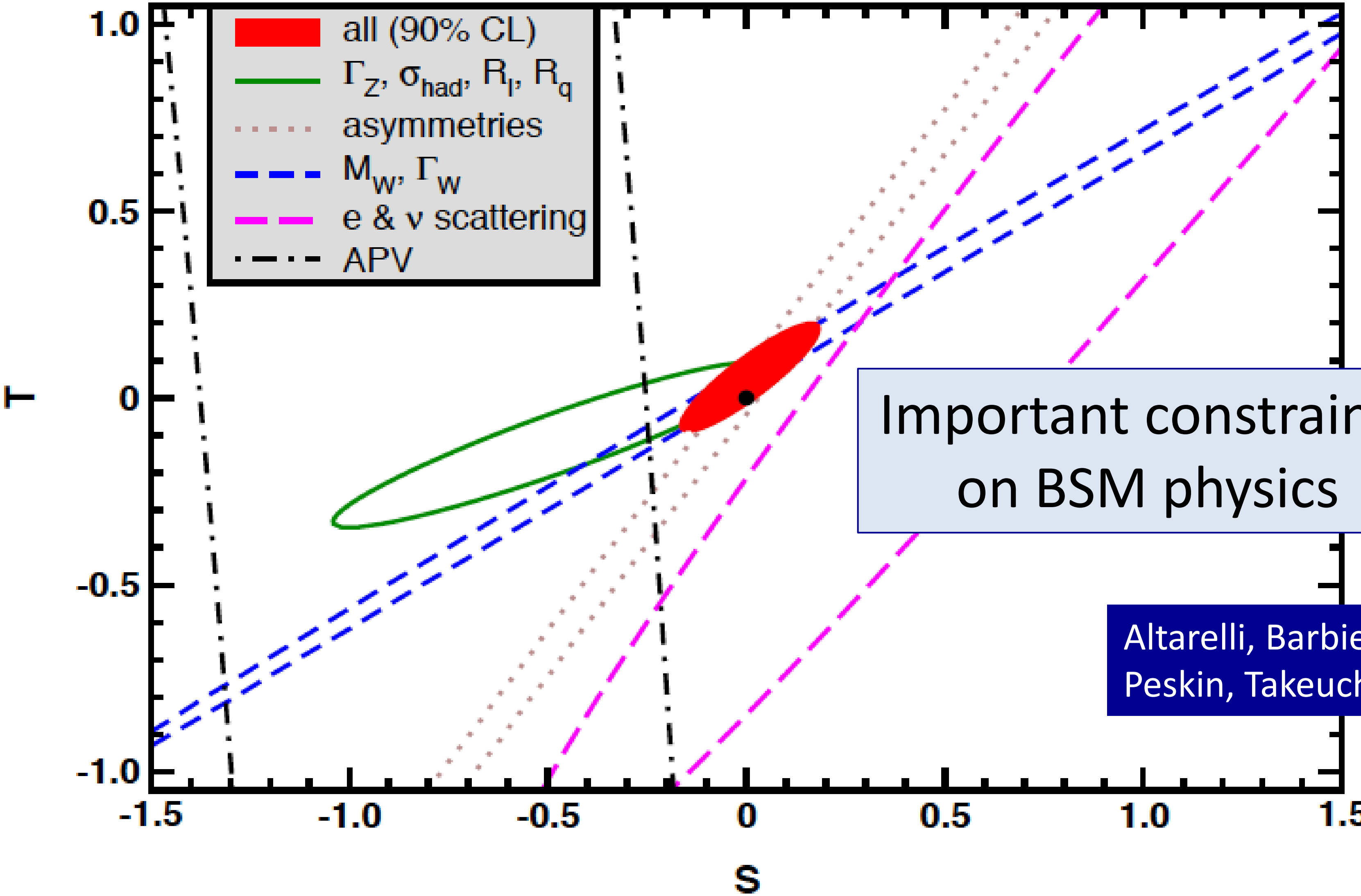
JE, Fogli, Lisi





- Solid indication that the Higgs is 'light'

Model-Independent Analysis

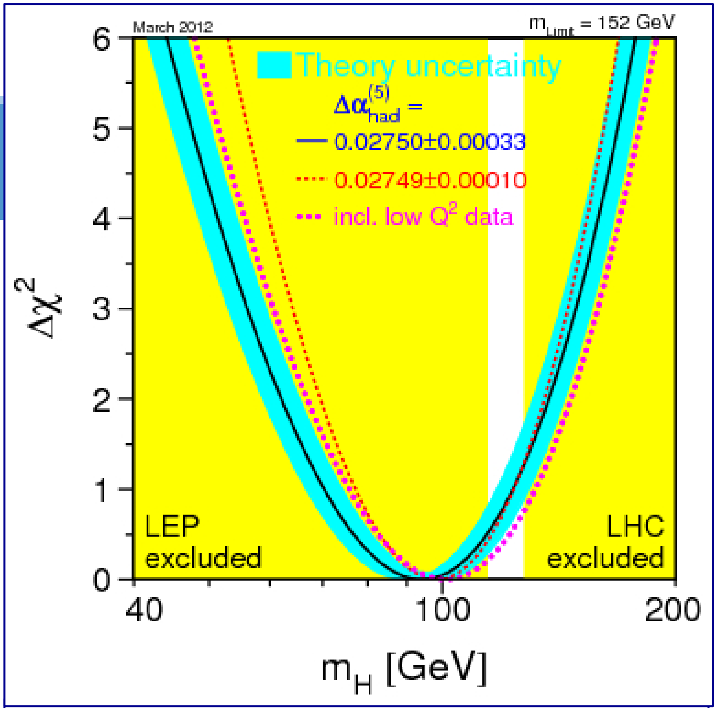


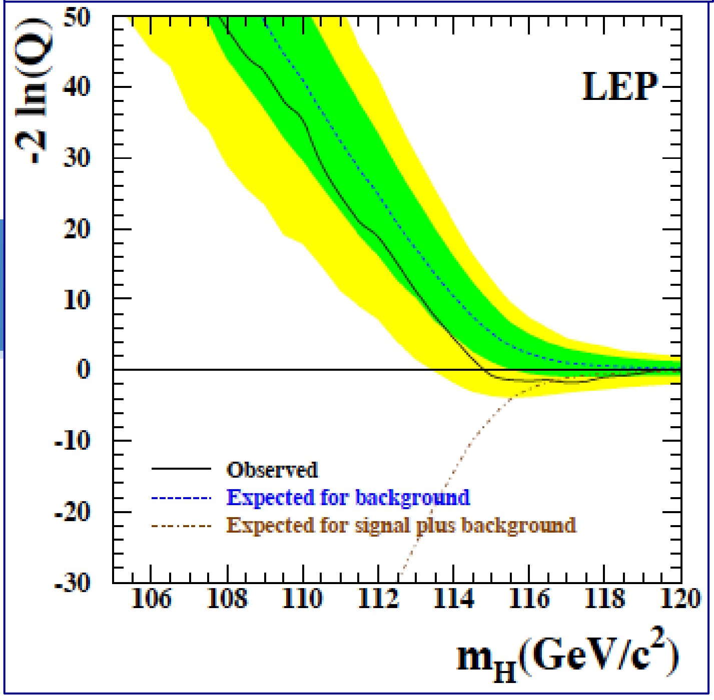
Important constraints on BSM physics

Altarelli, Barbieri; Peskin, Takeuchi

LEP Physics Working Groups

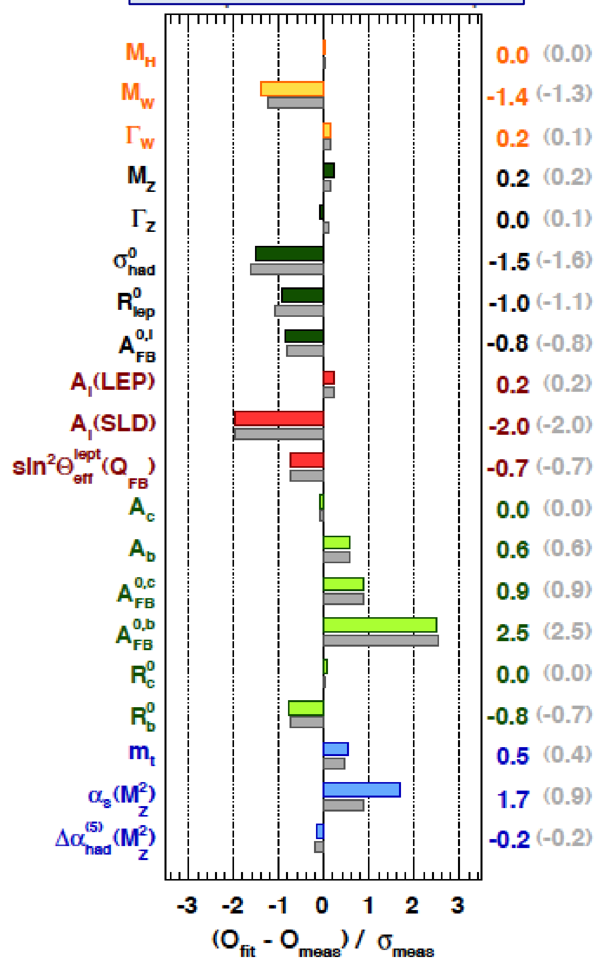
- Uniting collaborations and interested theorists in combining data analyses:
  - Electroweak, Higgs, Supersymmetry, Exotica, QCD/γγ, Heavy flavour, Energy calibration
- Set standards for interpretation of LEP data



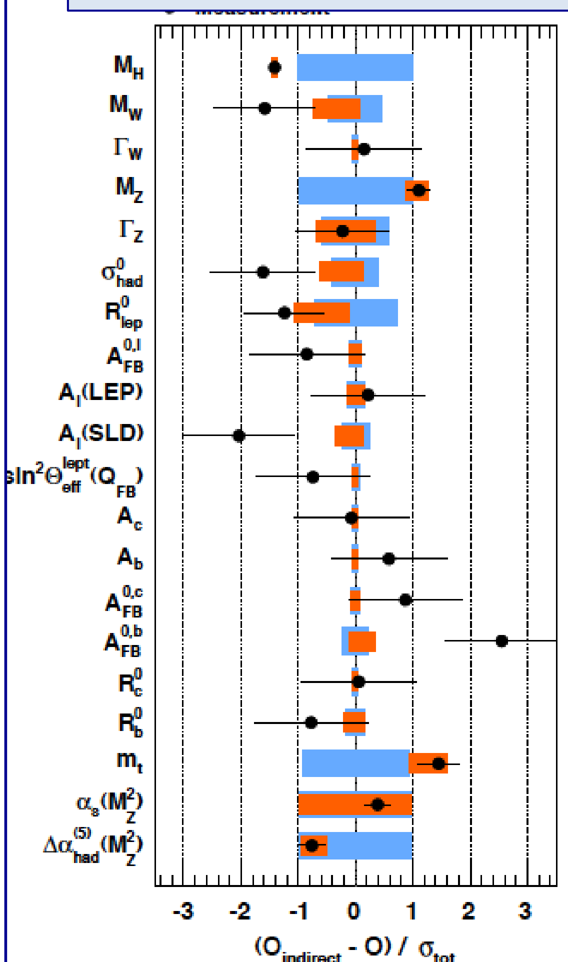


The LEP 1 legacy: Precision EW

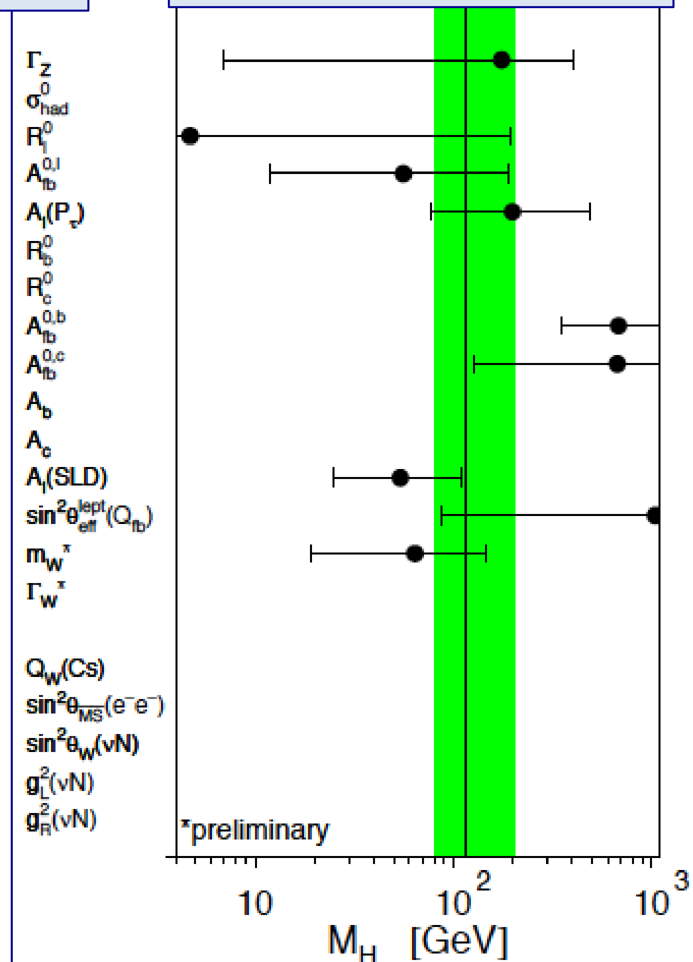
Pulls in SM fit



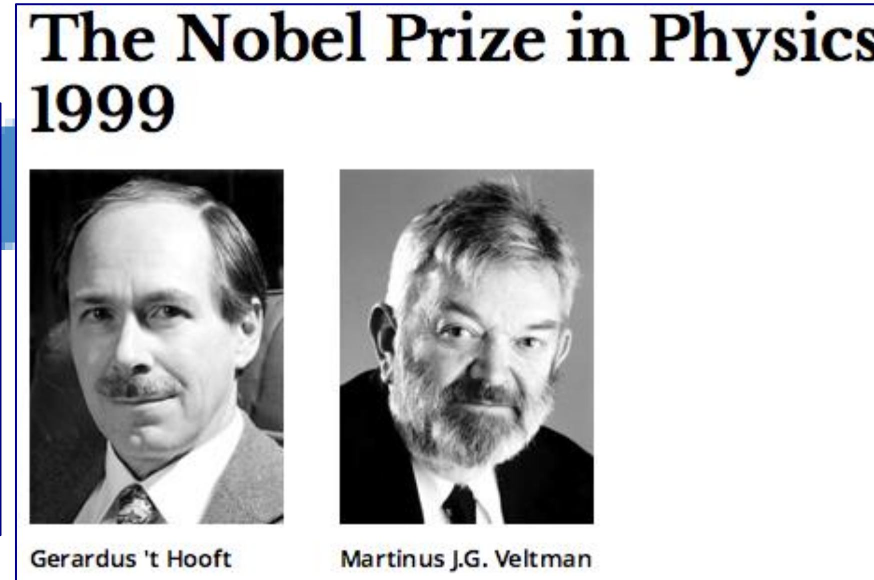
Fit vs measurements



H mass sensitivity

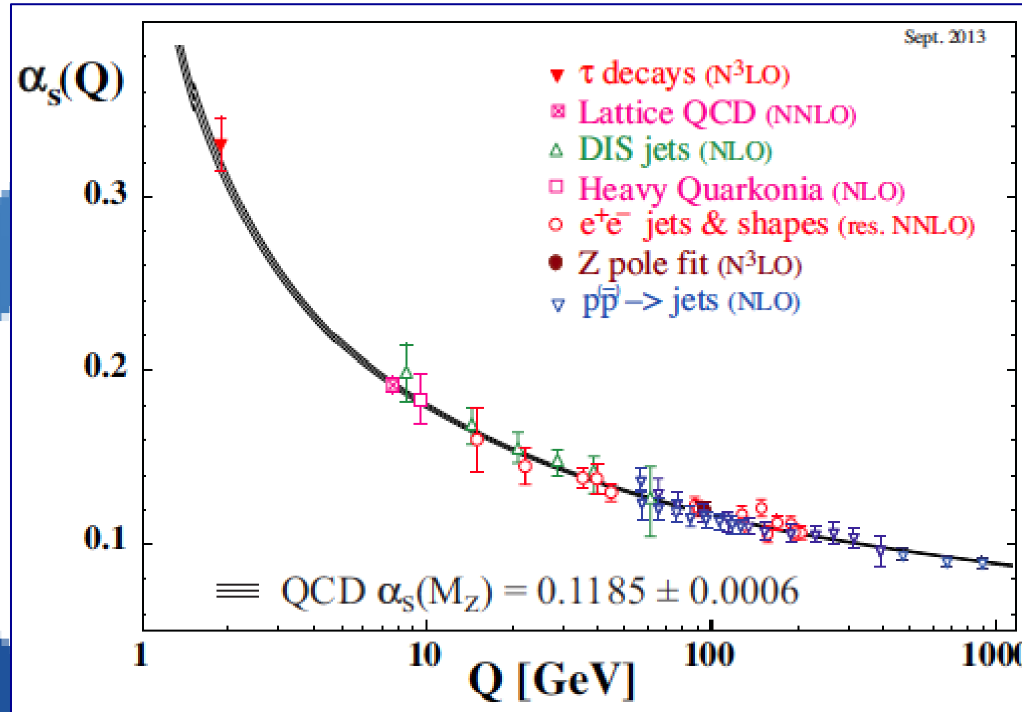


The LEP 1 Legacy: 1999 Nobel Prize



- The contributions of 't Hooft and Veltman … made it possible to compute quantum corrections to many processes and compare the results with experimental observations or to make predictions. ***For example, the mass of the top quark could be predicted, using high precision data from the accelerator LEP (Large Electron Positron) at the Laboratory CERN, Switzerland, several years before it was discovered, in 1995 at the Fermi National Laboratory in USA. …Similarly, comparison of theoretical values of quantum corrections involving the Higgs Boson with precision measurements at LEP gives information on the mass of this as yet undiscovered particle.*** *By Professor Cecilia Jarlskog Member of the Nobel Committee for Physics*

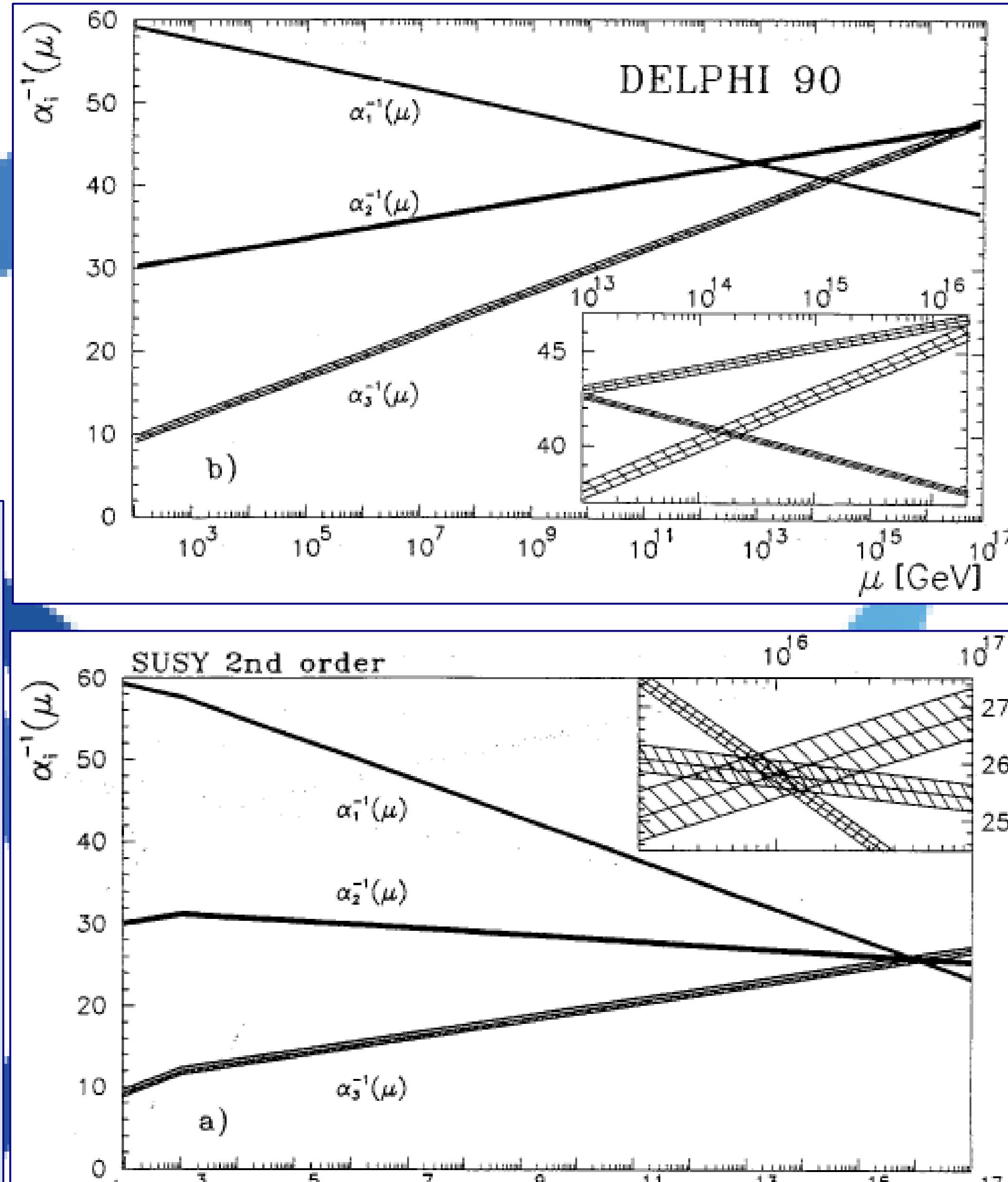
The LEP 1 Legacy: QCD



- Determination of α_s
- Important contributions to global average from LEP 1 measurements: σ_{peak}, jets, τ decay
- $\alpha_s(m_Z) = 0.1185 \pm 0.0006$
- Also 3-g coupling: $C_A = 2.89 \pm 0.21$

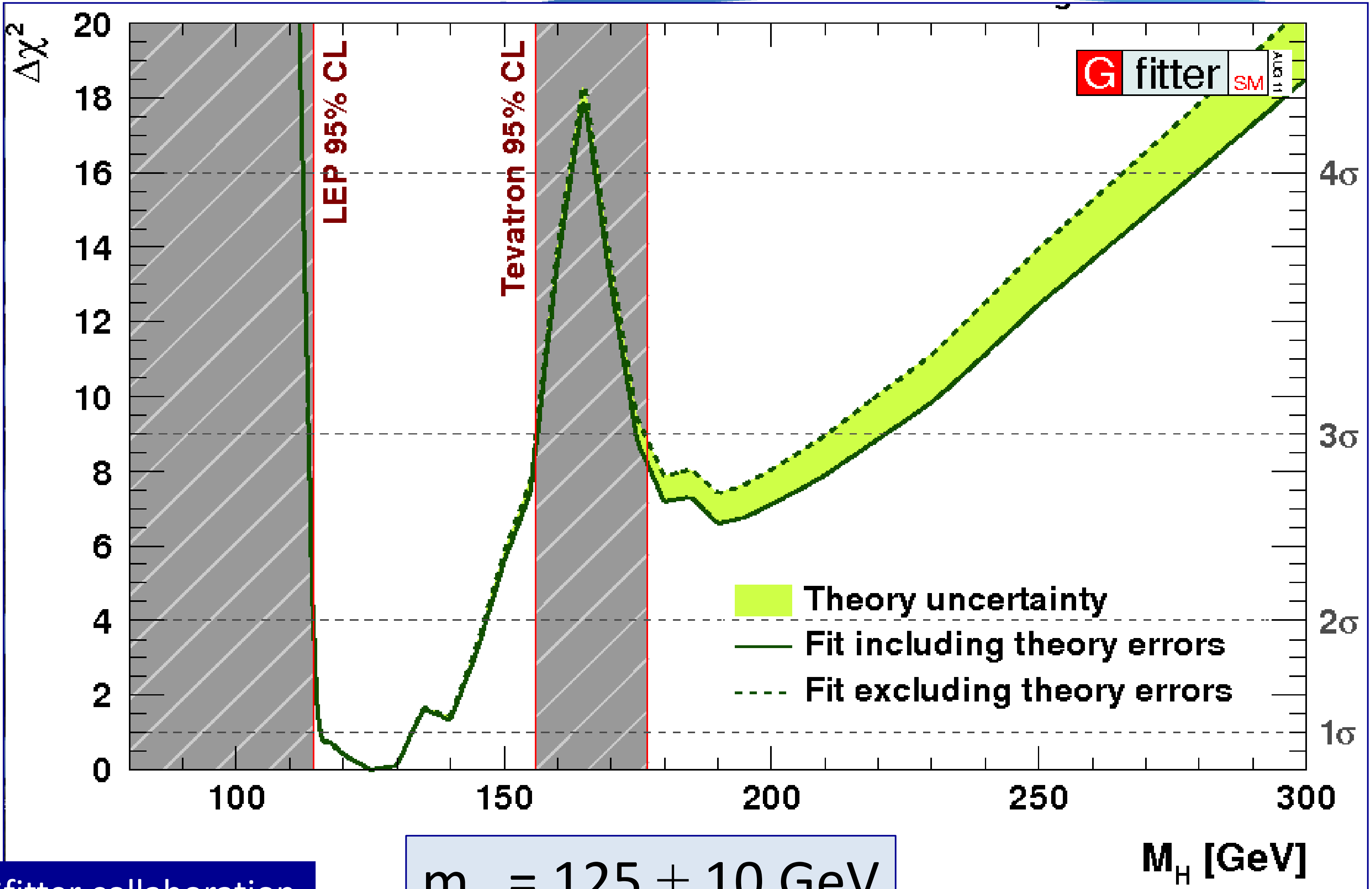
The LEP 1 Legacy: SUSY GUTs?

- Precision EW and QCD measurements test GUTs
- Ordinary GUTs fail
- Data consistent with SUSY GUTs
- But no SUSY!



Amaldi, De Boer, Fürstenau

The LEP (& Tevatron) Legacy: m_H

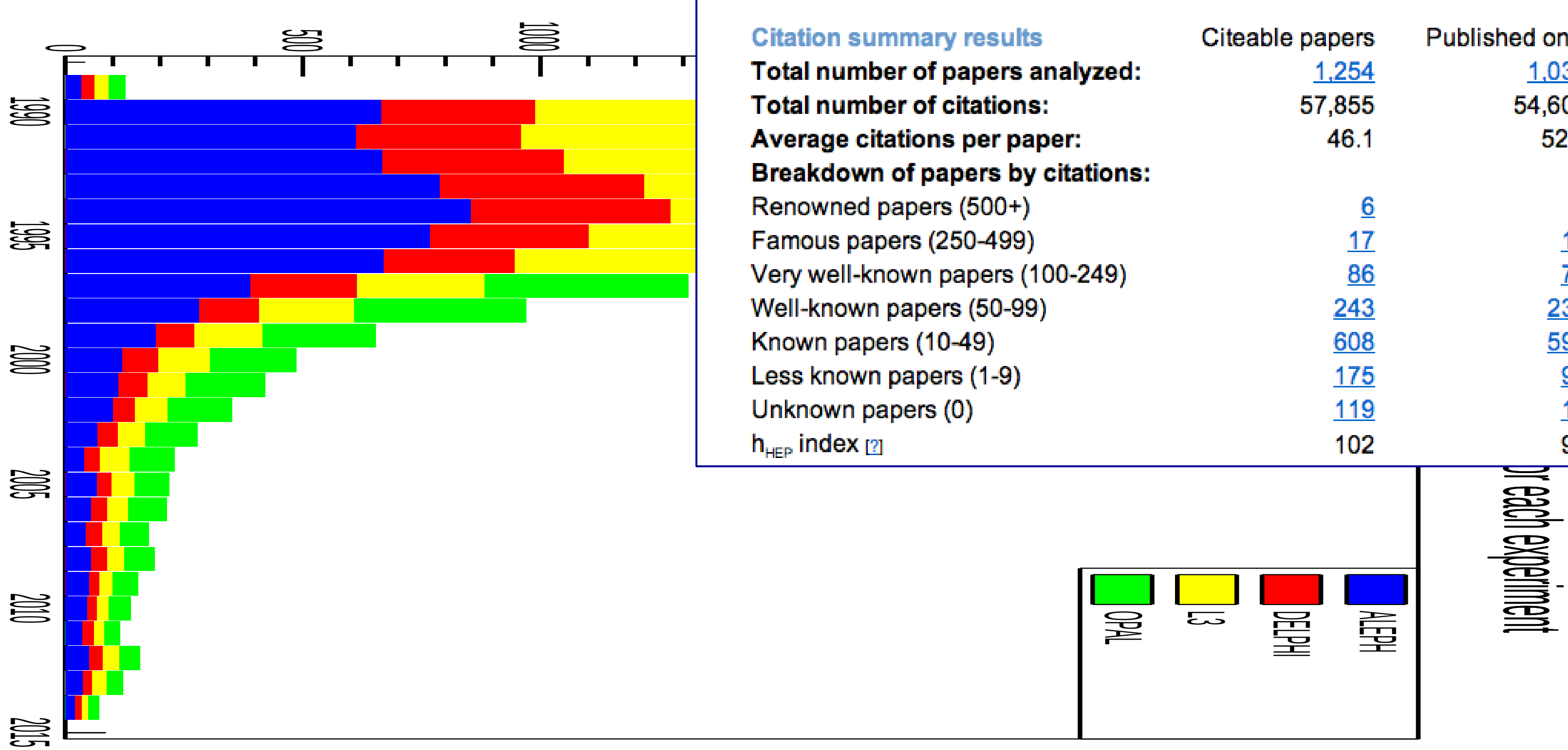


Gfitter collaboration

$m_H = 125 \pm 10$ GeV

The LEP 1 Legacy:
1944 papers, 57855 Citations

- From Inspire records



Citations summary

Generated on 2014-09-08

1944 papers found, 1254 of them citeable (published or arXiv)

Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	1,254	1,036
Total number of citations:	57,855	54,605
Average citations per paper:	46.1	52.7
Breakdown of papers by citations:		
Renowned papers (500+)	6	6
Famous papers (250-499)	17	15
Very well-known papers (100-249)	86	75
Well-known papers (50-99)	243	238
Known papers (10-49)	608	599
Less known papers (1-9)	175	93
Unknown papers (0)	119	10
h_{HEP} index [?]	102	98

The LEP Legacy

- Establishment of the Standard Model
- Hints/constraints on BSM physics
- Collaborations of hundreds of physicists can work
- Collaborations can work with each other
- Theorists, experimenters and accelerator physicists can work together
- Groundwork laid for the LHC

Happy Birthday!