Electroweak Theory:

The Experimental Evidence and Precision Tests PPP-II Lecture 8 (FS 2012)

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1950ies From the messy world of hadrons to weak decays and neutrinos.

1960ies The theoretical and experimental understanding of weak and strong interactions.

1970ies The discovery of neutral current reactions and observations of the γZ interference.

1980ies The discovery of the W and Z bosons
the SM picture before LEP.

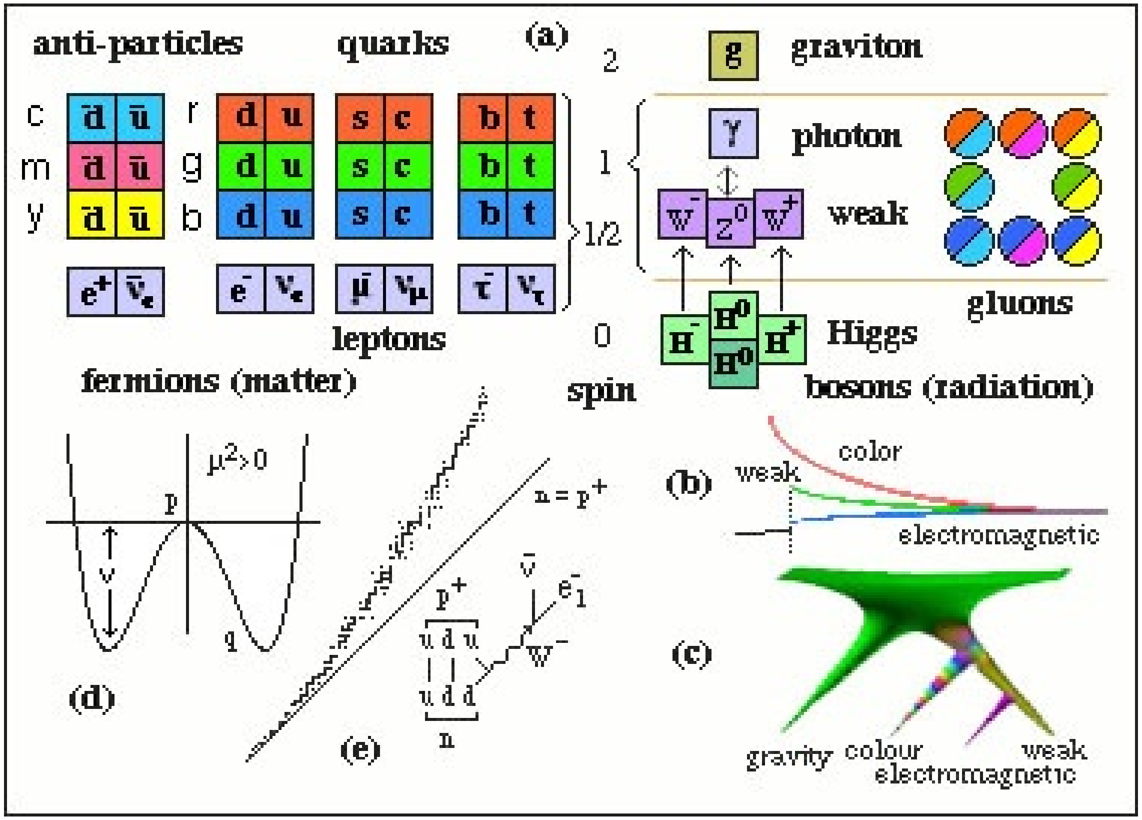
1990ies Electroweak precision physics at LEP I and SLC, LEP II and the Tevatron.

2000ies No Higgs at LEP and towards the LHC.

Introduction: The SM of Particle Physics Today

A “simple” picture of point like particles with no further substructure:

- 3 fermion (spin 1/2) doublets of quarks (fractional charge 2/3, -1/3,) and leptons (integer charge 1, 0).
- Interaction via spin 1 bosons: photon and gluons (massless) and W,Z (massive).
- Masses introduced with the higgs mechanism.



How did we get there? Lets take a time machine back to 1956 and watch the “movie”.

Experimental proofs of the Electro-Weak Theory: a timeline

1956-1962 T.D. Lee and C.N. Yang, paper (1956) about possible parity violation in weak interactions and Discovery of parity violation Wu et al. (Jan. 1957).
The discovery (1956) of the neutrino (F. Reines and C. L. Cowan), helicity of the neutrino (1958, Goldhaber et al.), discovery of two types of neutrinos (1962).

1956-1969 The emerging quark model and the discovery of the Ω^- in 1964. DIS scattering and the quark-parton model of hadrons.

1960-1975 The Glashow-Weinberg-Salam (GWS) Model of unified electro-weak interactions gets formulated and "evidenced" (supported by evidence) in 1973(1972?) with the NC (neutral current) discovery.

The early 1970ies: Discovering the neutral current neutrino reactions (I)

(from D. Haid, October 2003 https://www.desy.de/~haidt/nc30_text.pdf)

- Acceptance of the GWS model only around 1971, when T.Hooft and T. Veltman demonstrated renormalizability:
  "..a viable theory of weak interactions claiming weak neutral currents as crucial ingredient was proposed and experiment was prompted to answer by yes or no whether weak neutral currents existed or not."

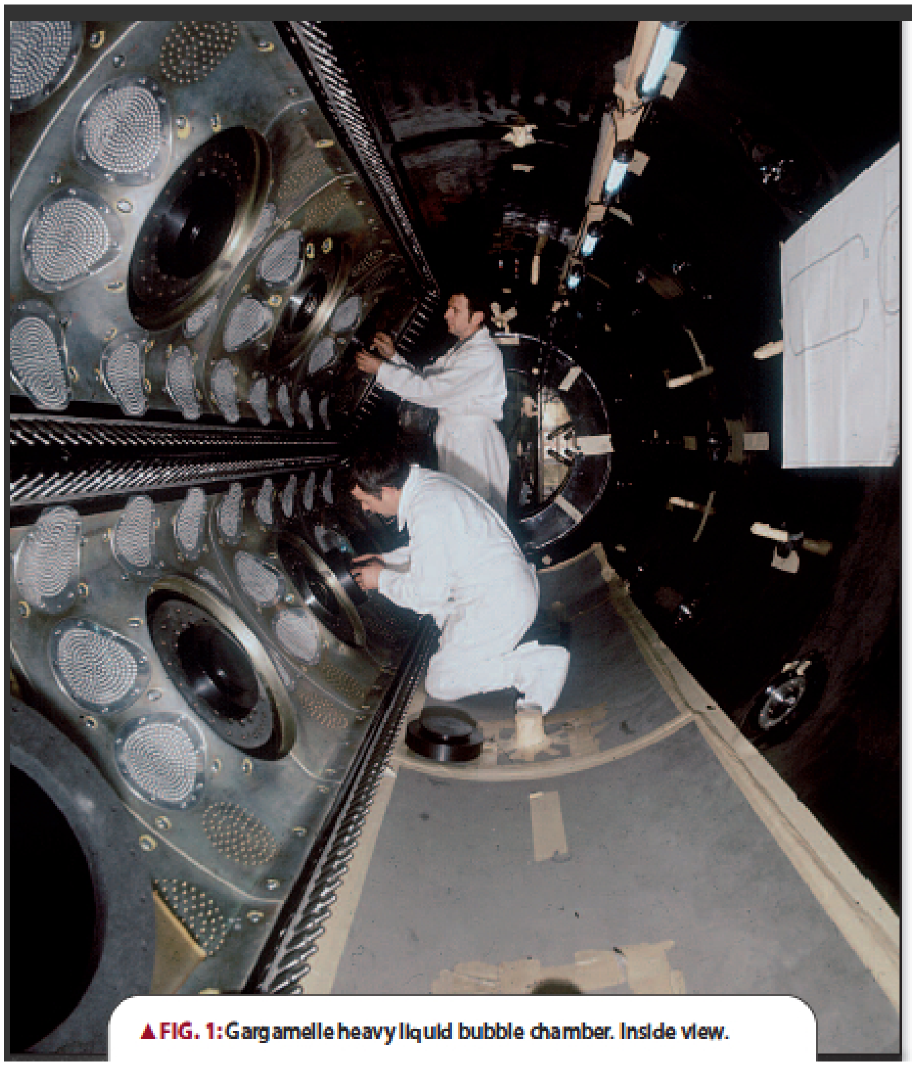
- ".. two neutrino experiments were running, the Gargamelle bubble chamber experiment at CERN and the HPWF counter experiment at NAL (now FNAL). Both were confronted with this challenge without preparation."

- "The searches for neutral currents in the previous neutrino experiments resulted in discouraging upper limits and were interpreted in a way, that the community believed in their nonexistence and the experimentalists turned to the investigation of the copiously existing questions in the just opened field of accelerator neutrino physics."

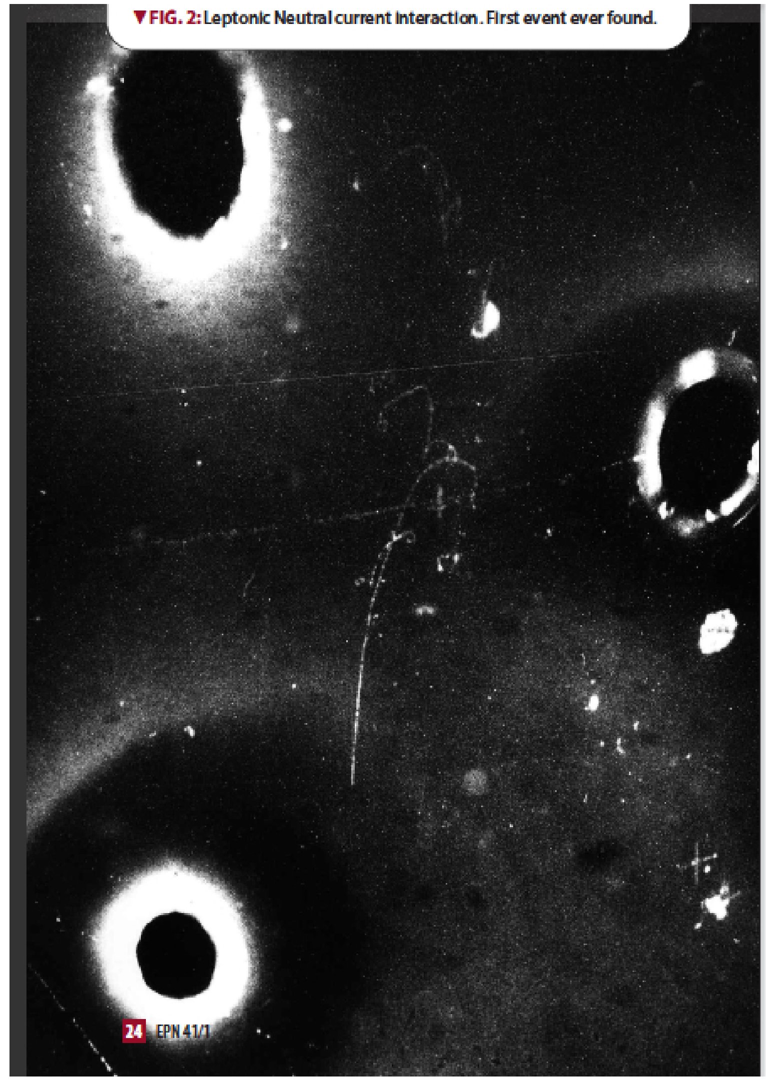
- "During the two-day meeting in November 1968 at Milan, where the Gargamelle collaboration discussed the future neutrino program, the word neutral current was not even pronounced and ironically, as seen from today, the search for neutral currents was solely an also-ran low in the priority list."

The early 1970ies: Discovering the neutral current neutrino reactions (II)

inside Gargamelle and "first" NC event in Gargamelle



▲FIG. 1: Gargamelle heavy liquid bubble chamber. Inside view.



▼FIG. 2: Leptonic Neutral current interaction. First event ever found.

The early 1970ies: Discovering the neutral current neutrino reactions (III)

The "first" NC event in Gargamelle: a leptonic $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$ scattering event

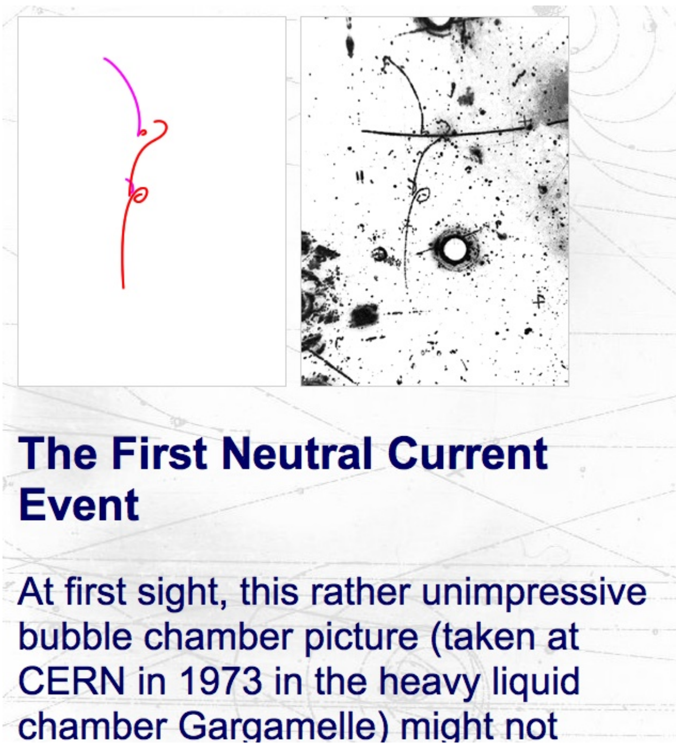


Table 1

Number of single e^- events of $E_e > 300$ MeV, $\theta_e < 5°$

	Flux neutrinos/m^2	Weinberg predictions Mini-mum	Weinberg predictions Maxi-mum	Background	Observed
ν	1.8×10^{15}	0.6	6.0	0.3 ± 0.2	0
$\bar{\nu}$	1.2×10^{15}	0.4	8.0	0.03 ± 0.02	1

The early 1970ies: Discovering the neutral current neutrino reactions (IV)

The discovery of hadronic NC events (Gargamelle): $\nu p \to \nu X$ scattering

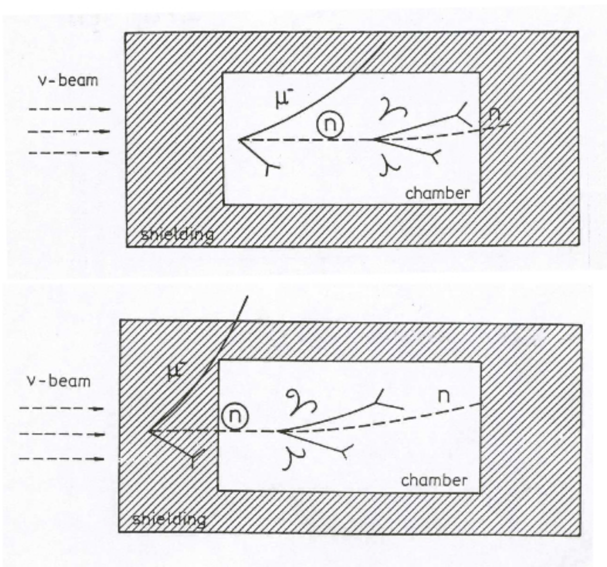


Fig. 5. Two topologies of a neutron cascade. Above : associated event, below : background event.

	ν-exposure	$\overline{\nu}$-exposure
# NC	102	64
# CC	428	148

Table 1. The NC and CC events samples in the ν and $\overline{\nu}$ films.

The early 1970ies: Discovering the neutral current neutrino reactions (V)

First $\sin^2\theta_W$ results: Ratio of NC/CC events with ν and $\bar{\nu}$ scattering.
Compare with today's $\sin^2\theta_W \approx 0.23$

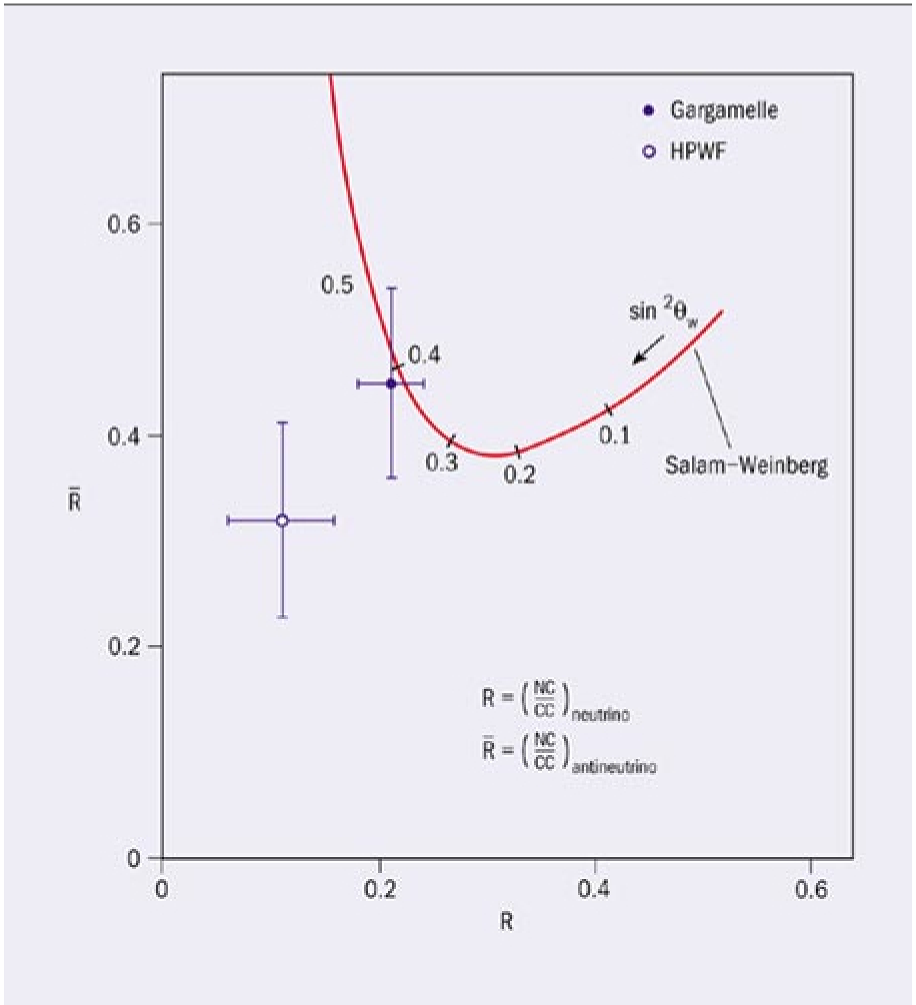


Fig. 4: values of NC:CC ratios from the Gargamelle and HPWF experiments, as compared with the predictions of the Weinberg-Salam model.

The late 1978: parity violation effects in polarized eD scattering

"The predicted asymmetries depend on the kinematic variable y as well as on the weak isospin assignments and on $\sin^2\theta_W$, the Weinberg angle. Figure 4 compares our result for two SU(2) x U(l) models. The simplest model (W-S) is in good agreement with our measurement for $\sin^2\theta_W = 0.20 + 0.03$ which is consistent with the values obtained in neutrino experiments."

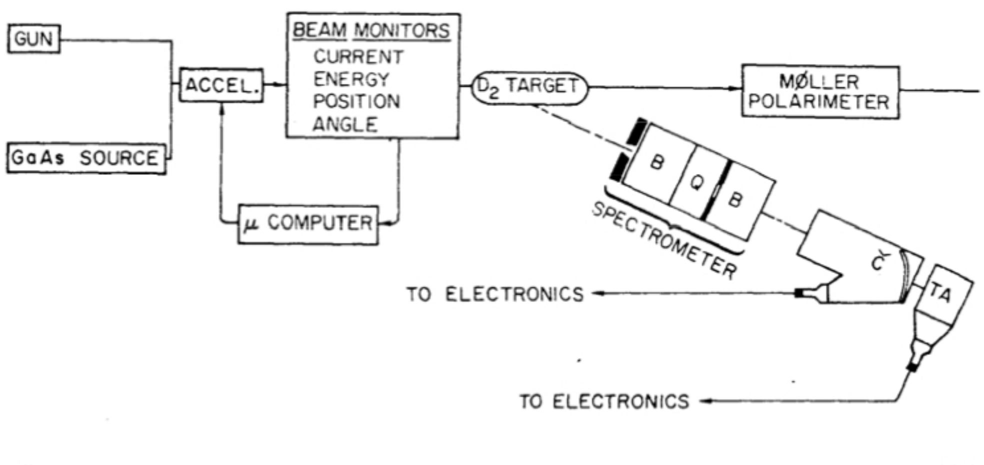


Fig. 1

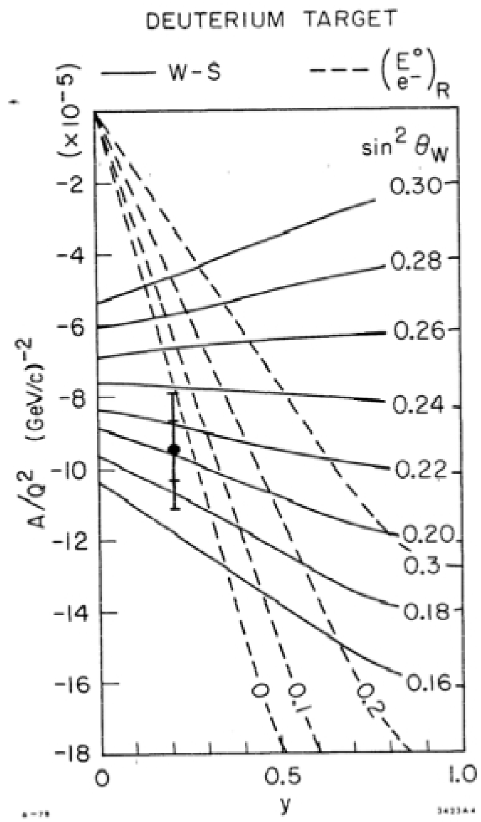


Fig. 4

http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-2148.pdf

The early 1980ies: observations of the γZ interference

Neutral Current interference effects: Forward-Backward charge asymmetries in the reaction $e^+e^- \to \mu^+\mu^-$: Towards the discovery of the W and Z bosons.

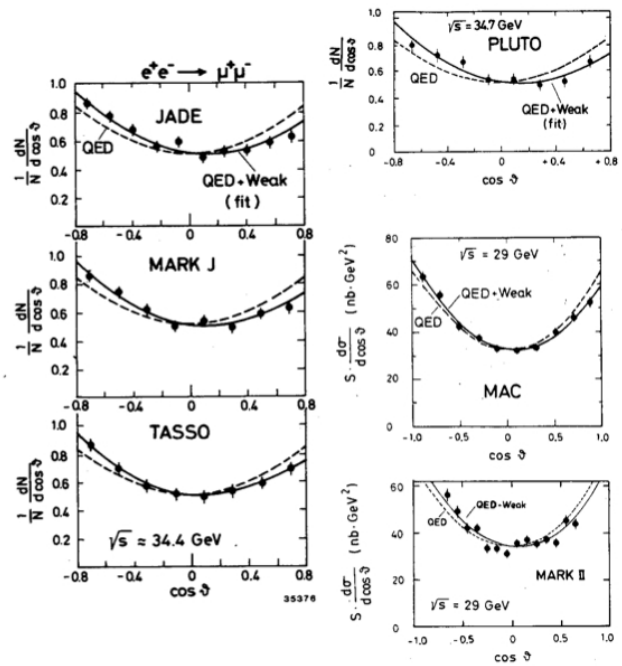


Fig. 5 Measurements of the angular distribution of $e^+e^- \to \mu^+\mu^-$ compared to the prediction of QED (dashed line) and to a fit including the weak interaction (solid line).

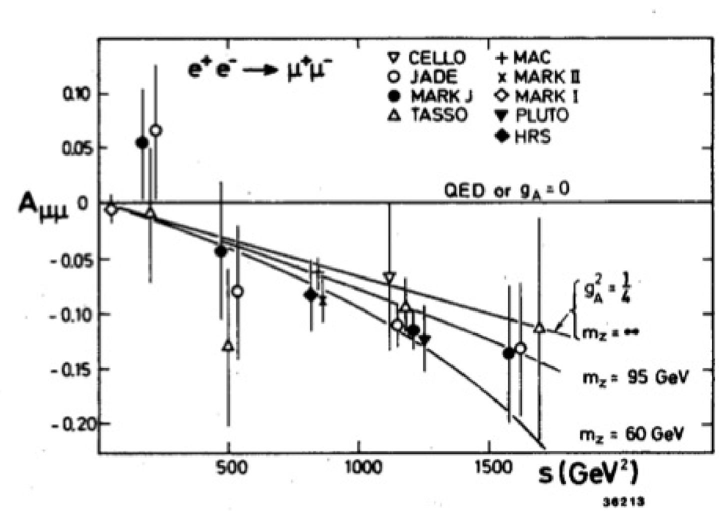


Fig. 6 Measurements of the forward-backward asymmetry of the reaction $e^+e^- \to \mu^+\mu^-$ as a function of the c.m. energy squared. The data are compared to the predictions of an electroweak interference with $g_A^2 = 1/4$ and different masses of the Z^0-boson. Since the measurements are corrected for radiative effects, pure QED or an electroweak theory with $g_A = 0$ predicts no asymmetry.

1982/83: Discovery of the W and Z bosons (I)

After the discovery of the weak neutral currents and around the year 1973:
How to discover W, Z bosons with a mass of about 100 GeV?
One needs a super high energy collider and as quickly(why?) as possible!

- $e^+e^- \rightarrow Z \rightarrow f_i\bar{f}_i$ and $e^+e^- \rightarrow W^+W^-$ with $\sqrt{s} = 100 - 200$ GeV
  The "LEP" machine, yes but could be ready at best only in the 90ies!

- High luminosity and energy $pp \rightarrow W^\pm(Z^0) \rightarrow \ell\nu(\ell\ell)$
  The 400 GeV Brookhaven Isabelle pp collider (3.8 km ring) with superconducting magnets (Design started in 1973 without knowing how to make the magnets.. never terminated!) `http://en.wikipedia.org/wiki/ISABELLE`.

- High energy $p\bar{p} \rightarrow W^\pm(Z^0) \rightarrow \ell\nu(\ell\ell)$
  A 540-630 GeV $p\bar{p}$ collider in the 6.8 km SPS CERN tunnel with normal conducting magnets. To start data taking in 1981..
  A 2 TeV $p\bar{p}$ collider in the 6.3 km TEVATRON Fermilab tunnel with superconducting magnets.
  To start around 1986 ..

1982/83: Discovery of the W and Z bosons (II)

For people in particle physics: 1983 was a really exciting year!

D. Denegri / Physics Reports 403–404 (2004) 107–145 117

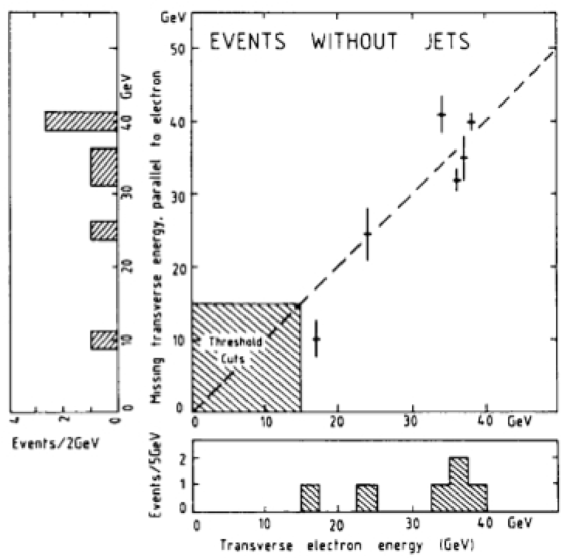


Fig. 8. Missing transverse energy versus electron transverse energy for the first W events in UA1, the threshold cuts are indicated [15].

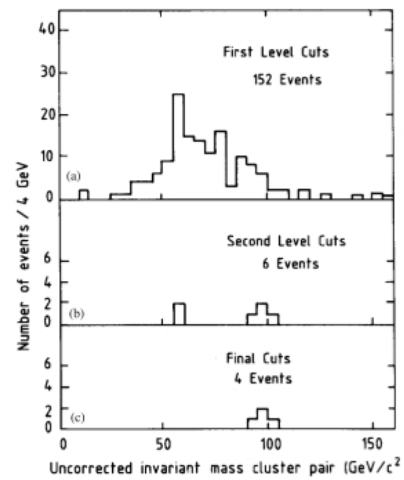


Fig. 14. Invariant mass distributions for two electromagnetic clusters in UA1, (a) with $E_t > 25$ GeV, (b) requiring in addition an isolated track with $p_t > 7$ GeV pointing to the cluster and a small (< 0.8 GeV) energy deposition in the hadron calorimeter behind the cluster, and (c) the second cluster has an associated isolated track [20,11].

For a historical review see: http://cern-discoveries.web.cern.ch/cern-discoveries/Courier/HeavyLight/Heavylight.html and http://cerncourier.com/cws/article/cern/29053.

Around 1985: W and Z boson signal established

After the discoveries, more accurate mass and cross section determinations

A (very) old saying was:
1 event = discovery; 2 events = cross section and 3 events = spin.

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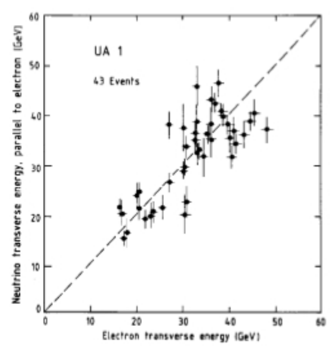


Fig. 12. Electron versus neutrino transverse momentum distributions for the W → eν samples collected by UA1 in runs of 1982/83, after fiducial volume cuts [17,11].

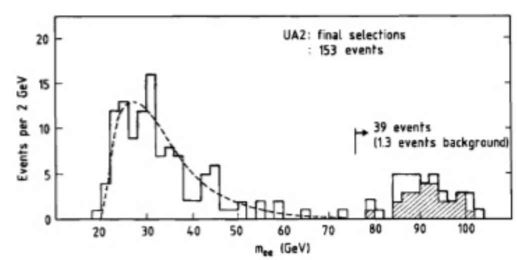


Fig. 27. The m_{ee} distribution with two identified electrons, at least one satisfying track criteria, the QCD background is indicated; the hatched events are used in the Z mass determination [29].

The Standard Model before and after LEP (Particle Data Group)

1988:

$M_Z = 92.4\pm$ 1.8 GeV, $M_W = 81.0 \pm 1.3$ GeV

Number of light neutrinos $<$ 15-20 (indirect $<$ 6)

$\sin^2_W(eff) = 0.229 \pm 0.007$

2010:

$M_Z = 91.1876\pm$ 0.0021 GeV, $M_W = 80.398 \pm 0.025$ GeV

Number of light neutrinos (direct) 2.985 ± 0.009

$\sin^2_W(eff) = 0.23119 \pm 0.00014$

1989-2000: From a spectacular start of LEP to precisison tests of the SM

The Large Electron Positron Collider (LEP) at CERN: Design approved in 1982, construction started in 1983 planned first beam 1.1.1989, first beam and collisions summer 1989, last collisions November 2000 at 206 GeV.

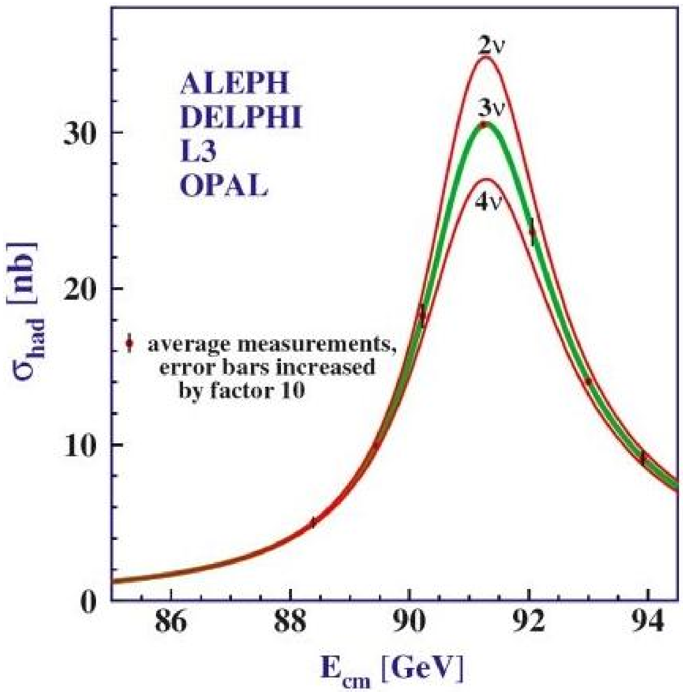
1989 Results (two weeks of data taking) $\Delta M_Z \approx 20 MeV$ ($\pm$ 1.8 GeV in 1988) and $\pm$ 200 MeV (from SLAC and CDF just before LEP)
At the end of 1989, 20-30 000 Z decays recorded by each LEP experiments.
3$\pm$ 0.2 Neutrinos and strong limits on physics beyond the SM.

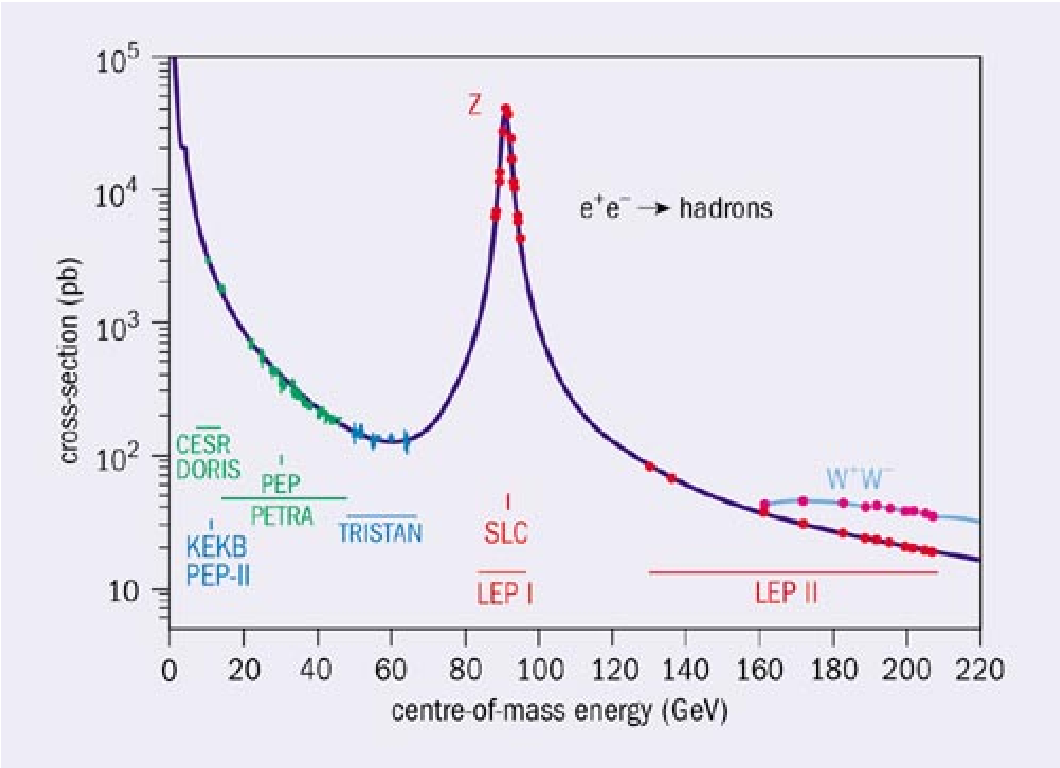
1995 About 5 Million recorded and analyzed Z decays per Experiment.
$M_Z = 91.1876\pm$ 0.0021 GeV, Zahl der (leichten) Neutrinos direkt
2.985 ± 0.009 und $\sin^2_W(eff) = 0.23119 \pm 0.00014$

2000 About 10 k W^-W^+ events recorded and analyzed by each LEP experiment.
$M_W = 80.398 \pm 0.025$ GeV (including Tevatron results) and still no sign of the Higgs or physics beyond the SM.

More info and further links at http://cerncourier.com/cws/article/cern/29076

The most(?) important LEP results in 2 plots!





many many more plots and links for example here `http://www.roma1.infn.it/people/dionisi/docs_specialistica/pippa_1.pdf` and here `http://arxiv.org/pdf/hep-ex/0110077v1.pdf`

1990-95: precision measurements at LEP and the number of light neutrinos

"The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{SM} = 1.991 \pm 0.001$, is used instead of $(\Gamma_\nu)_{SM}$ to determine the number of light neutrino types:

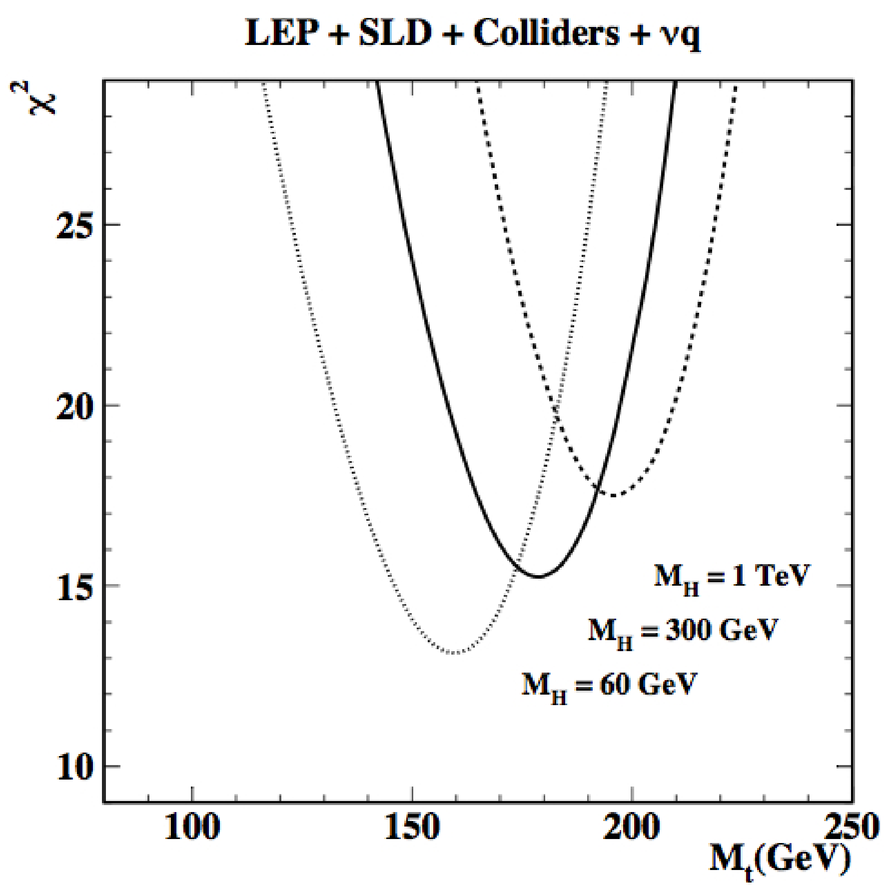
$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\ell} \times \left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}$$

The combined result from the four LEP experiments is $N_\nu = 2.984 \pm 0.008$.

Source and more details see: http://pdg.lbl.gov/2000/s007.pdf

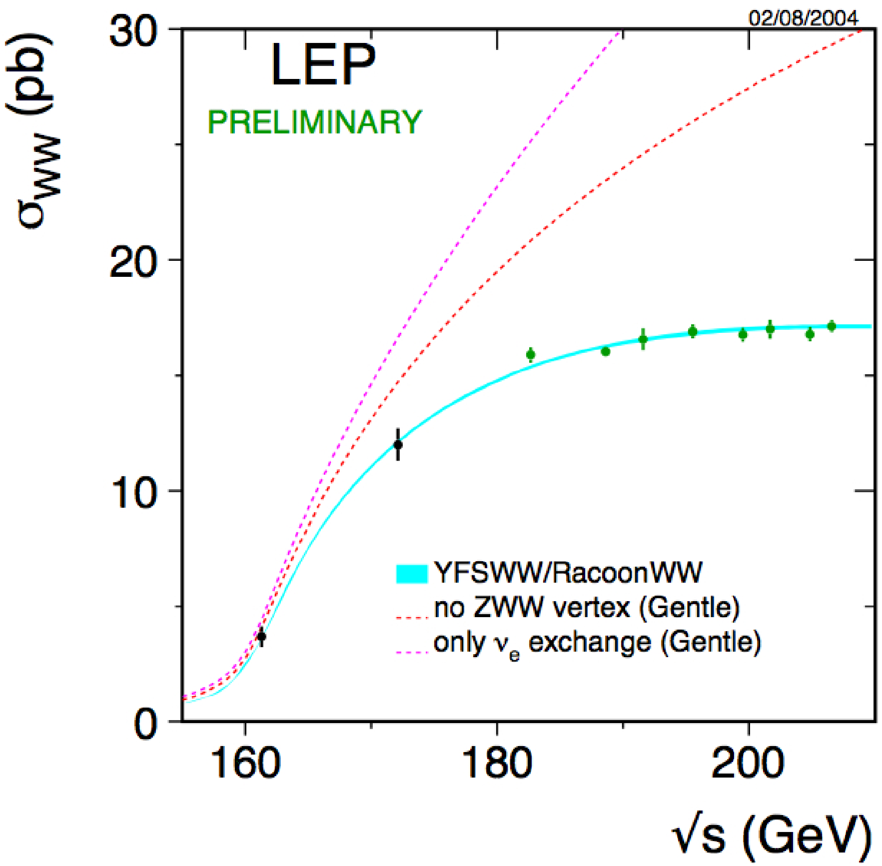
1990-95: precision measurements at LEP and the top quark

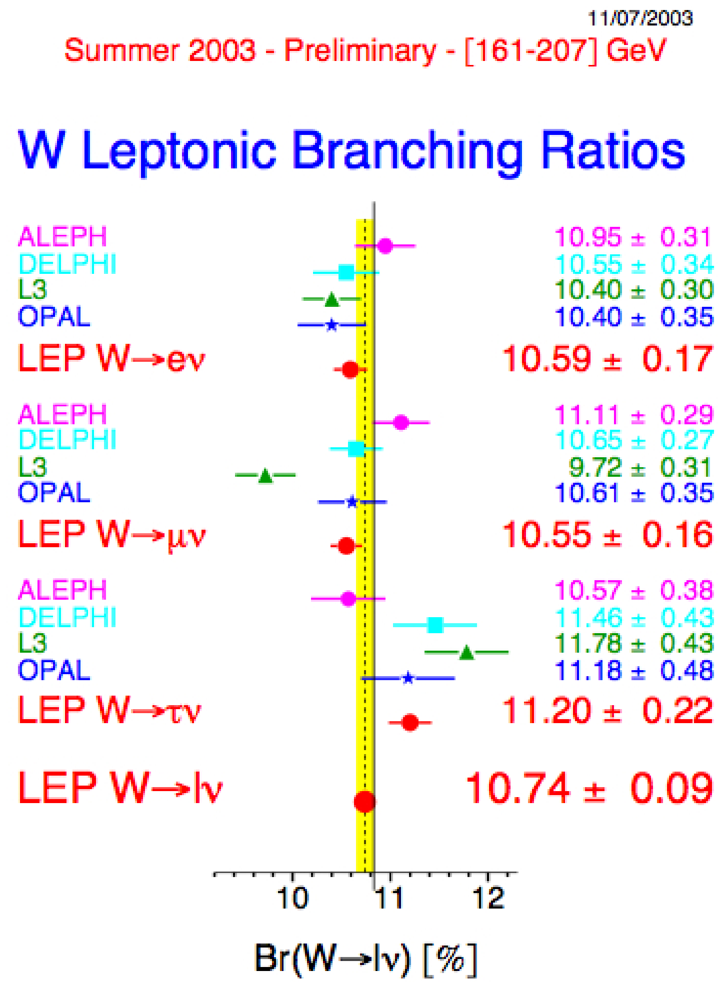
Did the LEP experiments discover the top quark before CDF/D0(1994)?
Not really (my view), other LEP people might "disagree" with me.
1994/95: with $M_H = 300$ GeV $\rightarrow$
M_{top} was constrained within the SM to about 180$\pm$ 10 GeV.



1996-2000: W measurements at LEP 2 (I)

WW cross section measurements confirm another SM prediction and the W decays branching ratios





source LEP electroweak physics working group `http://lepewwg.web.cern.ch/LEPEWWG/`

1996-2000: W measurements at LEP 2 (II)

A biased selection: "my" W_{long} result (the long distant cousin(?) of the Higgs):

"Direct Observation of Longitudinally Polarised $W^{\pm}$ Bosons"

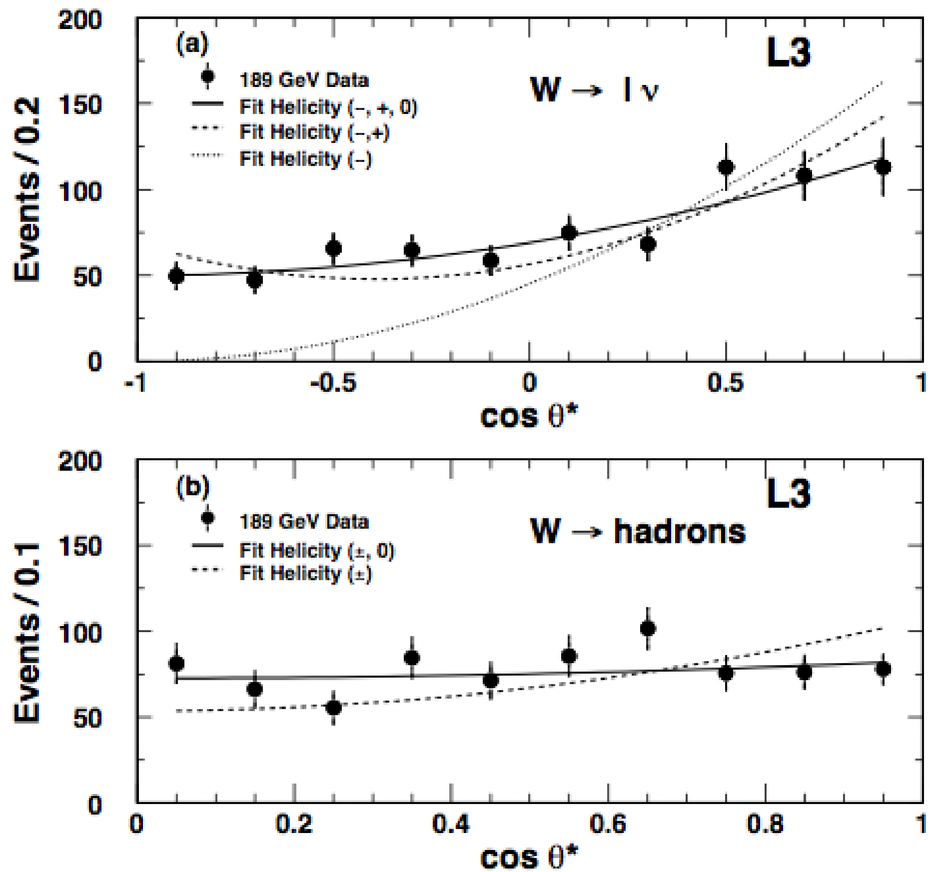


Figure 2: Efficiency– and background–corrected $\cos\theta^*$ distributions for (a) leptonic W decays and (b) for hadronic W decays at $\sqrt{s} = 189$ GeV. The fit results for the different W helicity hypotheses are also shown.

the L3 paper `http://arxiv.org/pdf/hep-ex/0001016.pdf`

1996-2000: Higgs search at LEP (I)

A few times some "interesting" excess events were reported during 10 years of LEP physics and at different CM-energies, masses and signatures but:
at the end of LEP in fall of the year 2000 lots of CERN people got into a terrible excited mind state!

Ale de Angelis, SISSA/ICTP Sept 2000

A selection of titles...

- Le Temps: "On a peut-être vu l'ombre du Higgs"
- BBC News: "Scientists close in on elusive particle"
- La Stampa: "Svelata la particella di Dio"
- El Pais: "El CERN logra posibles indicios de la partícula más buscada"
- New York Times: "Swiss Physicists Face Decision in Race for Atomic Particle"
- Bild der Wissenschaft: "Higgs Boson entdeckt"
- Gazeta Wyborcza: "Czastka Higgsa zlapana?"
- The Sunday Times: "Scientists find 'God's particle'"
- Le Monde: "Le boson de Higgs perturbe les projets des chercheurs du CERN"
- Der Spiegel: "Entdeckten Forscher das "Teilchen Gottes"?"
- Le Figaro: "Le Boson de Higgs en ligne de mire"
- San Francisco Chronicle: "The Search for The Higgs Boson"
- Liberation: "Le Cern est en passe de détecter le mystérieux boson de Higgs."
- Süddeutsche Zeitung: "Das Teilchen Gottes"
- Tagesspiegel: "Ein Higgs im Cocktail"
- The Dallas Morning News: "Hints of elusive particle may be massive find"

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Source http://www.fisica.uniud.it/~deangeli/test/Higgs.PDF

1996-2000: Higgs search at LEP (II)

Something was seen by some physicist from ALEPH..

Ale de Angelis, SISSA/ICTP Sept 2000

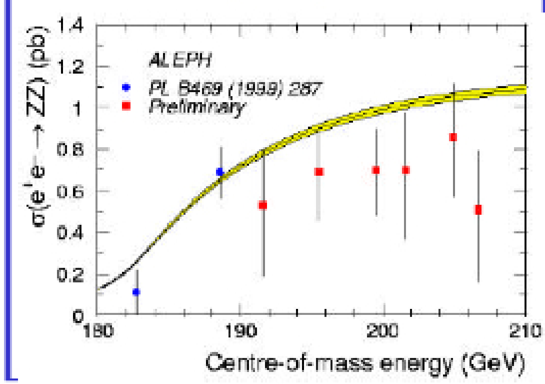
ALEPH: conclusions

- at $s/b \geq 2$ and $m_{rec} > 109$ GeV, ALEPH observes 3 candidates, 0.3 bkg evts expected (signal $\approx$ 0.6 evts, m_H =114 GeV)

- 3.5σ - 3.9σ from Standard Model background compatible with SM Higgs ~ 114 GeV but cross section 1σ - 2.5σ too high

Exciting, but small number of events and not background free!

Caveat: σ(ZZ) 2σ low...



Source http://www.fisica.uniud.it/~deangeli/test/Higgs.PDF

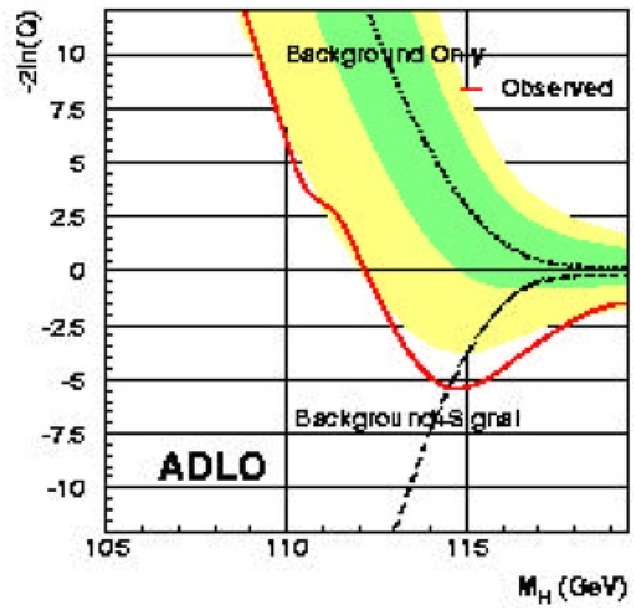
1996-2000: Higgs search at LEP (III)

After September 2000, the following weeks showed some alternating "things" from the other experiments.

Ale de Angelis, SISSA/ICTP Sept 2000

Combined SM result (as of Sept 5)

- Mimimum m_H = 114.9 GeV (2.6 σ), cross section ~OK



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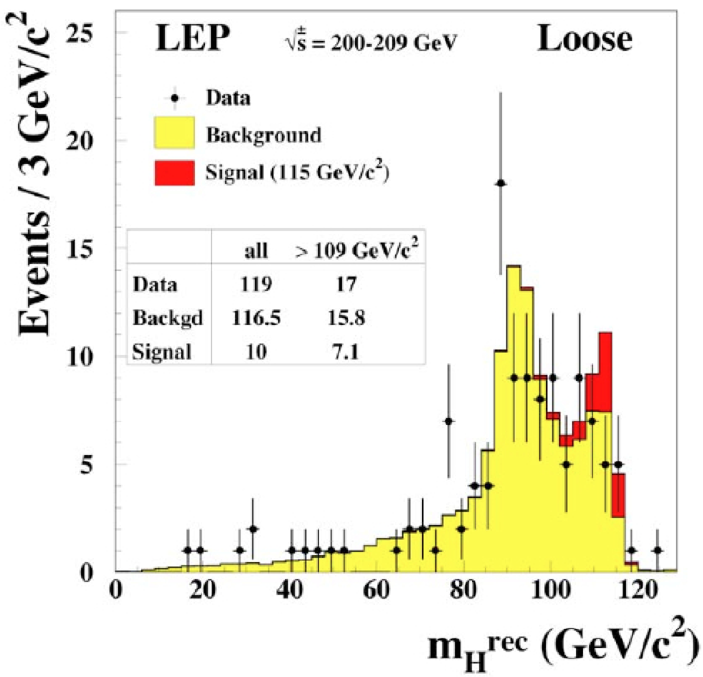
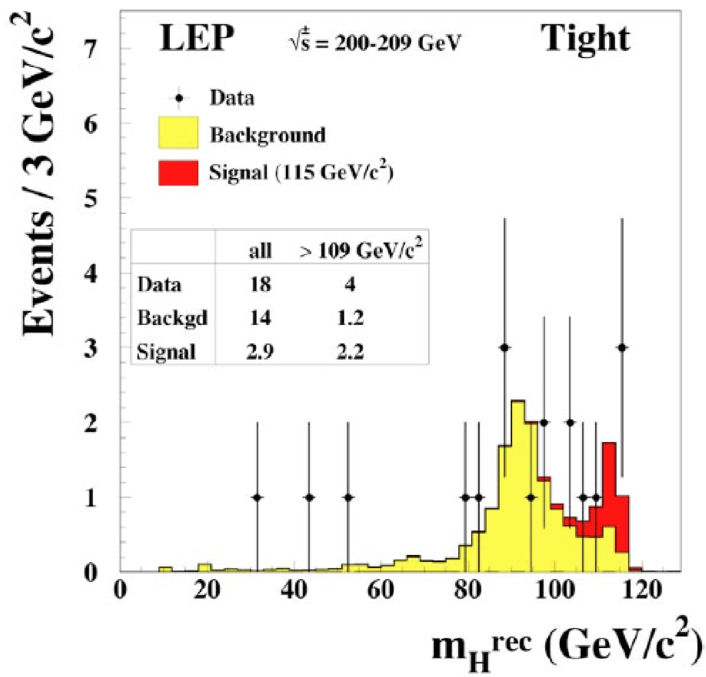
Source http://www.fisica.uniud.it/~deangeli/test/Higgs.PDF

1996-2000: Higgs search at LEP (IV)

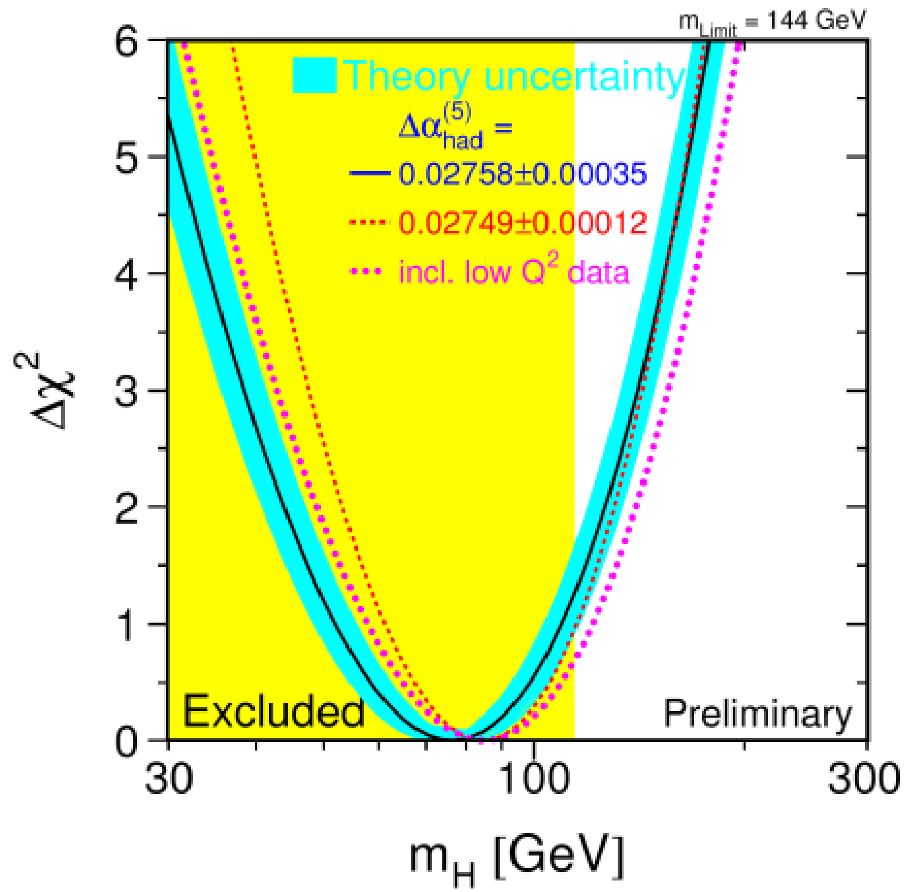
With the end of LEP in Nov. 2000 and in a crazy seminar, a revolting “crowd” tried to force the CERN management to extend the LEP program and delay the LHC start at least to the year 2007. They failed!
Half a year later and after better calibration and analysis improvements the “excess” had almost totally disappeared!





1990-2000: electroweak precision measurements and the Higgs mass

What most likely will remain "forever": the LEP/SLC/Tevatron electroweak precision results and their indirect Higgs constraints!



A “2009 like Summary” (from 2009 $\rightarrow$ today (wait for my May 2012 lectures about the “LHC”)

$M_W = 80.399 \pm 0.025$ GeV and $M_{top} = 173.3 \pm 1.1$ GeV

Fitted	M_{Z} [GeV]	91.1875 ± 0.0021
	Γ_{Z} [GeV]	2.4952 ± 0.0023
	σ^0_{h} [nb]	41.540 ± 0.037
	R^0_ℓ	20.767 ± 0.025
	$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010
Derived	Γ_{inv} [MeV]	499.0 ± 1.5
	Γ_{had} [MeV]	1744.4 ± 2.0
	$\Gamma_{\ell\ell}$ [MeV]	83.984 ± 0.086
	N_ν	2.984 ± 0.008

$M_{H(SM)} >\geq 114.4$ GeV (from LEP direct searches) and
from fits (somewhat bad) to electroweak precision data $M_{H(SM)} \leq 180$ GeV