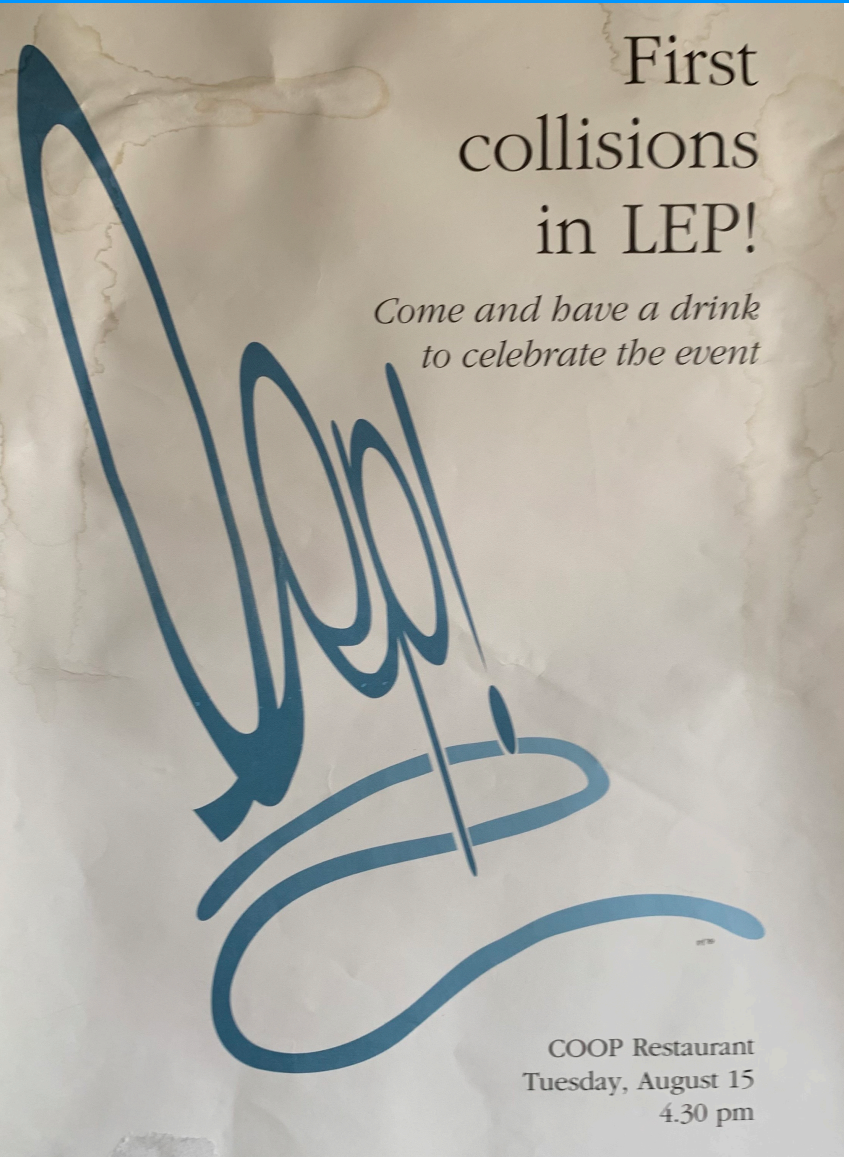
Neutral currents at e+e- colliders



Marie-Hélène SCHUNE
IJCLab
CNRS/IN2P3 – Université Paris-Saclay

- Introduction
- Study of the Z^0 boson
- Use of the Z^0 boson

Some info from G. Wilkinson CERN Symposium
Most of the plots from hep-ex/0509008

Introduction

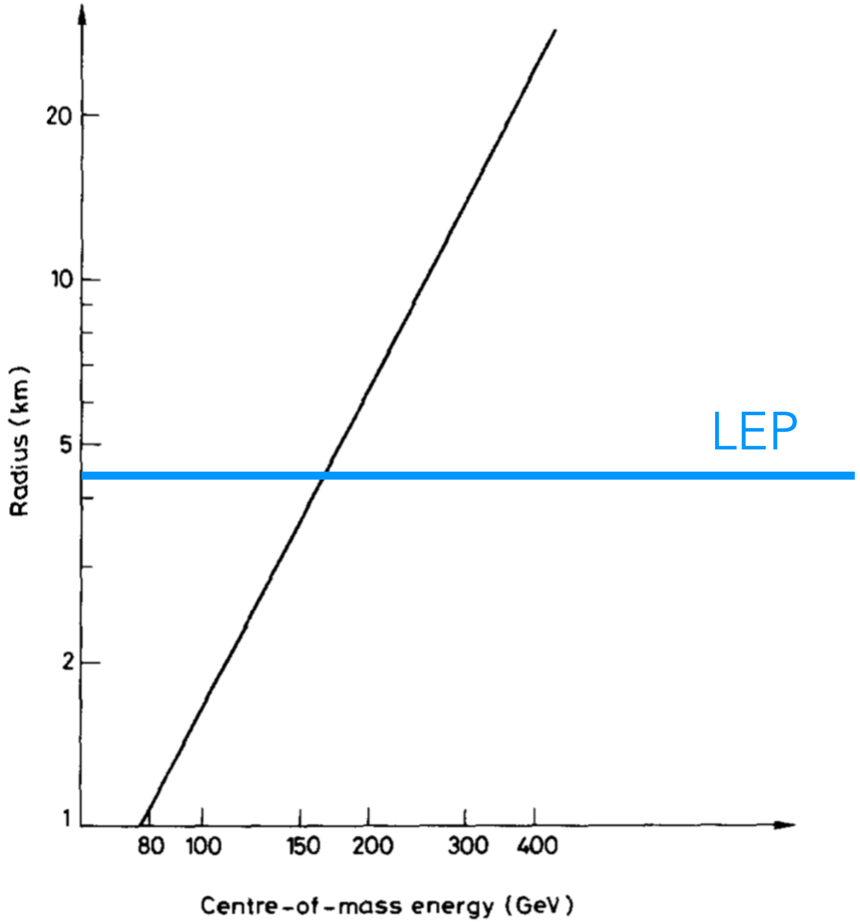
VERY HIGH ENERGY ELECTRON-POSITRON COLLIDING BEAMS FOR THE STUDY OF WEAK INTERACTIONS

B. RICHTER

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

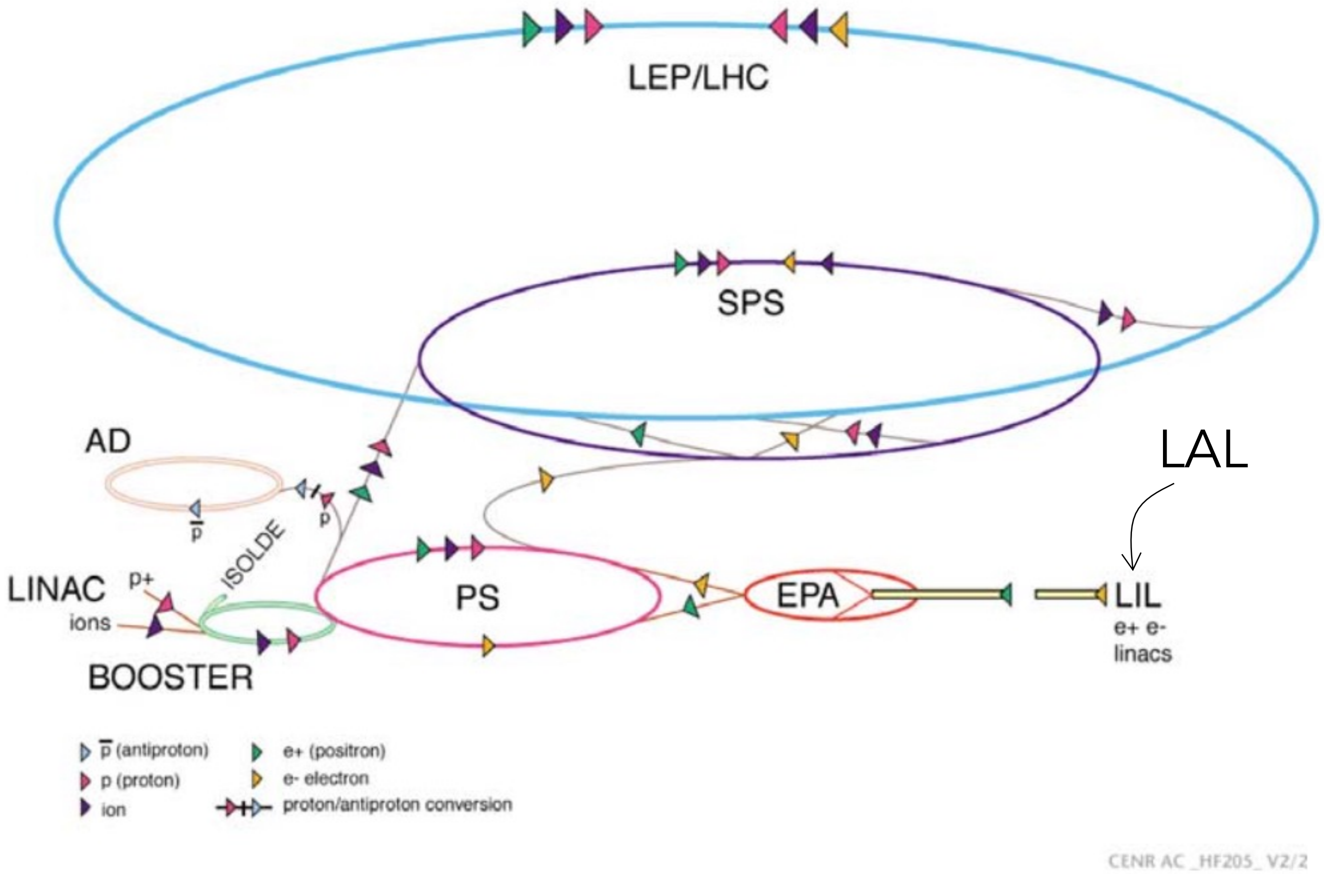
NIM 136 (1976) 47)

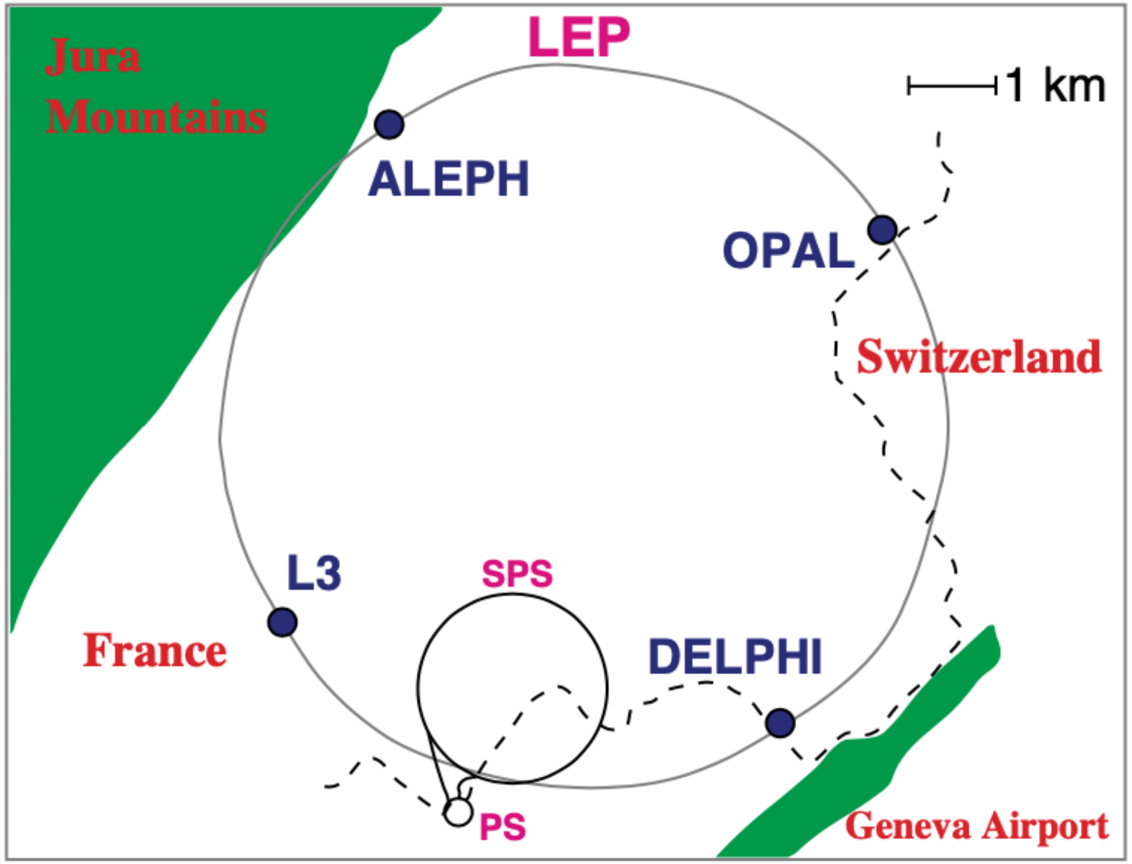
Received 2 April 1976



- Even before direct observation by UA1 and UA2
- Cleanness of e+ e- collider
- But synchrotron radiation (⇒size !)
- Future already foreseen : LHC

Imbedded in the CERN accelerators structure

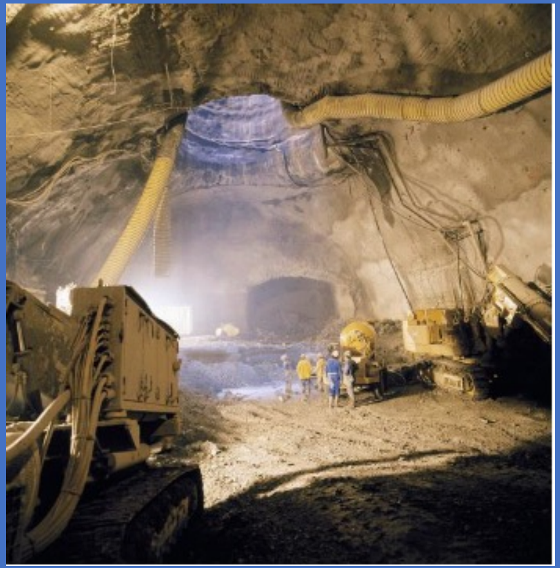




The tunnel

- 1981 Approval
- 1983 Start of civil engineering
- 1988 tunnel done

under the Jura mountains

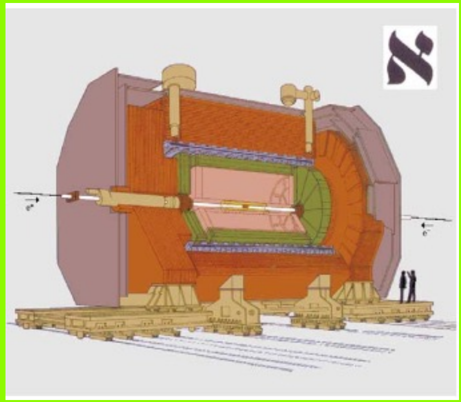


08 February 1988

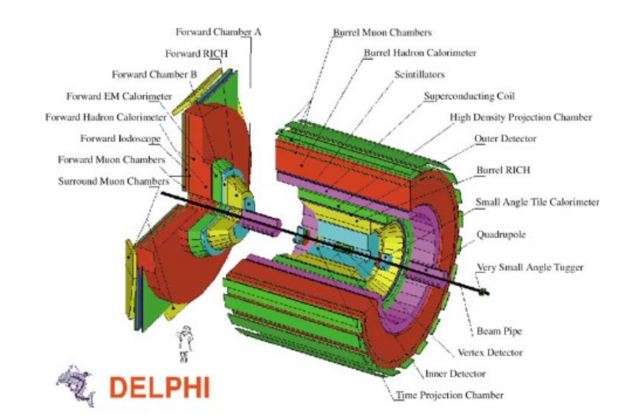
Four detectors

LAL (IJCLab) and CEA

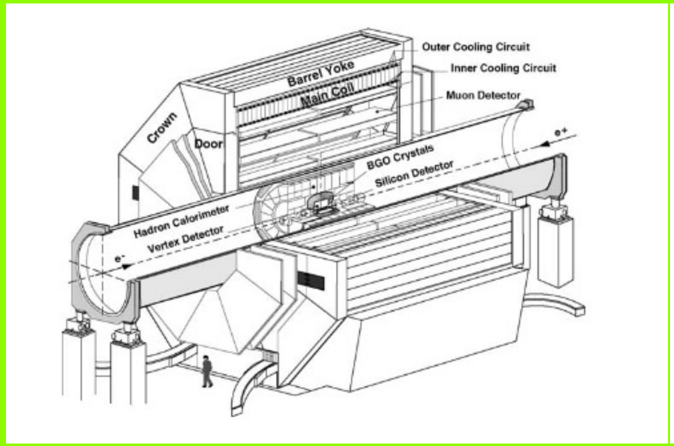
ALEPH



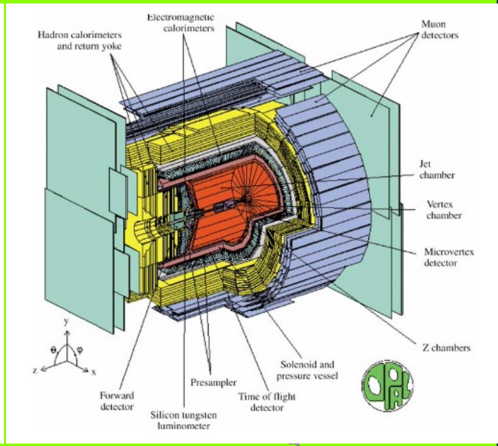
DELPHI



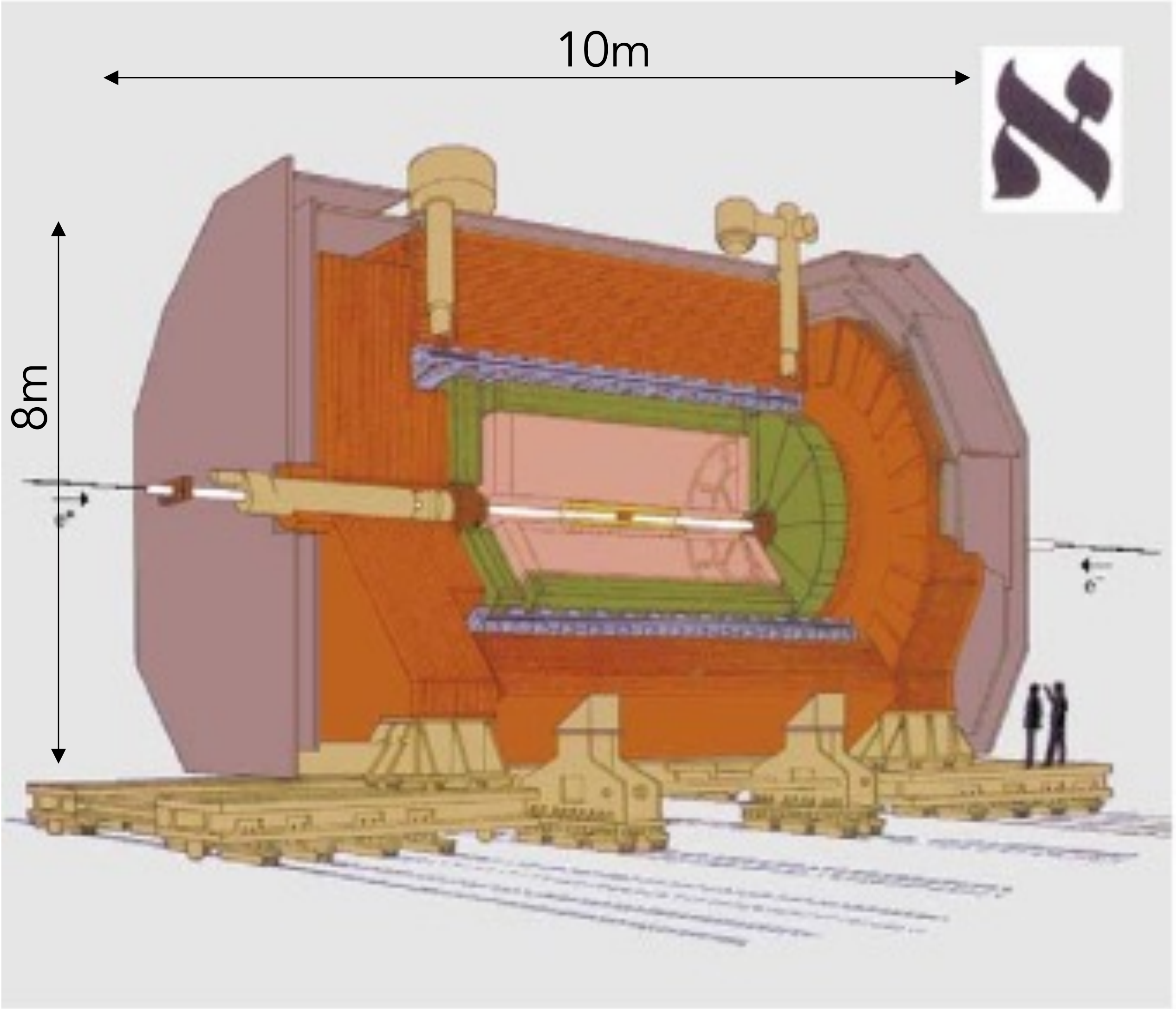
L3



OPAL



4 experiments: 4 different choice but some similarities



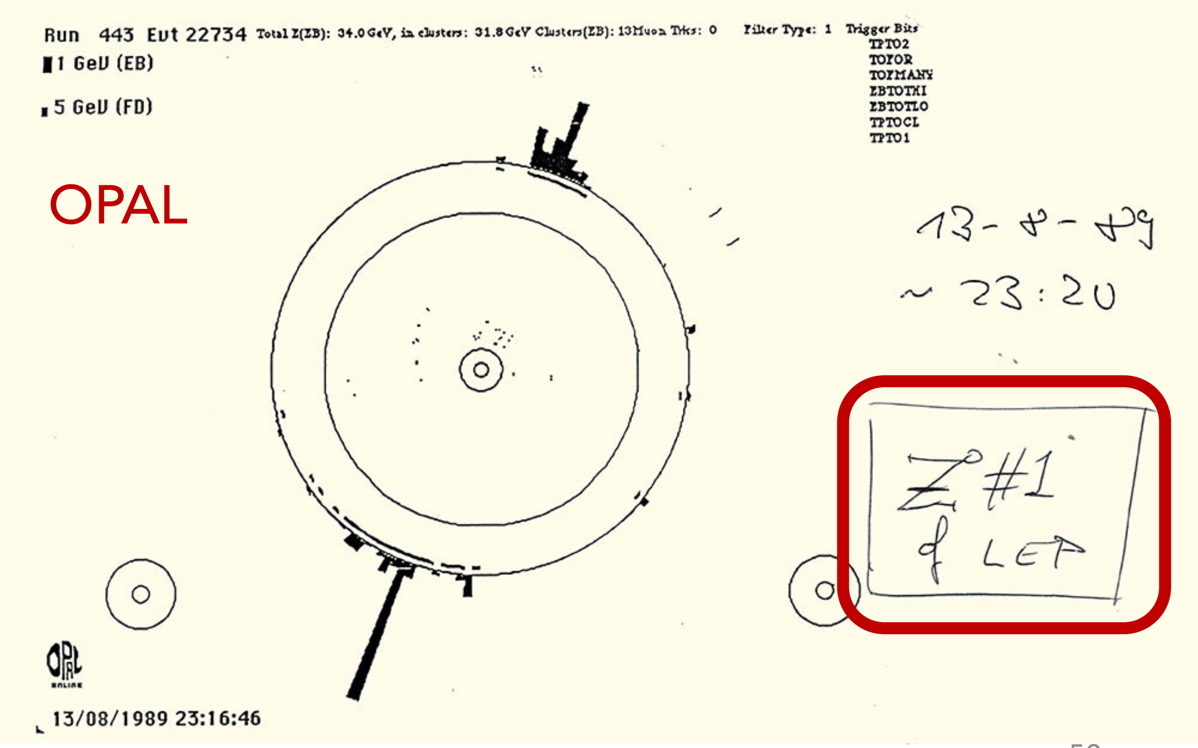
- Onion shape and 4π
- General purpose detector
- Tracking measurements with as little material as possible (TPC)
- PID (dE/dx, Cerenkov)
- Calorimeters (different choices)
- Muon chambers
- Luminometers
- Si vertex detectors (close to beam pipe). ALEPH and DELPHI from the beginning (LoI)

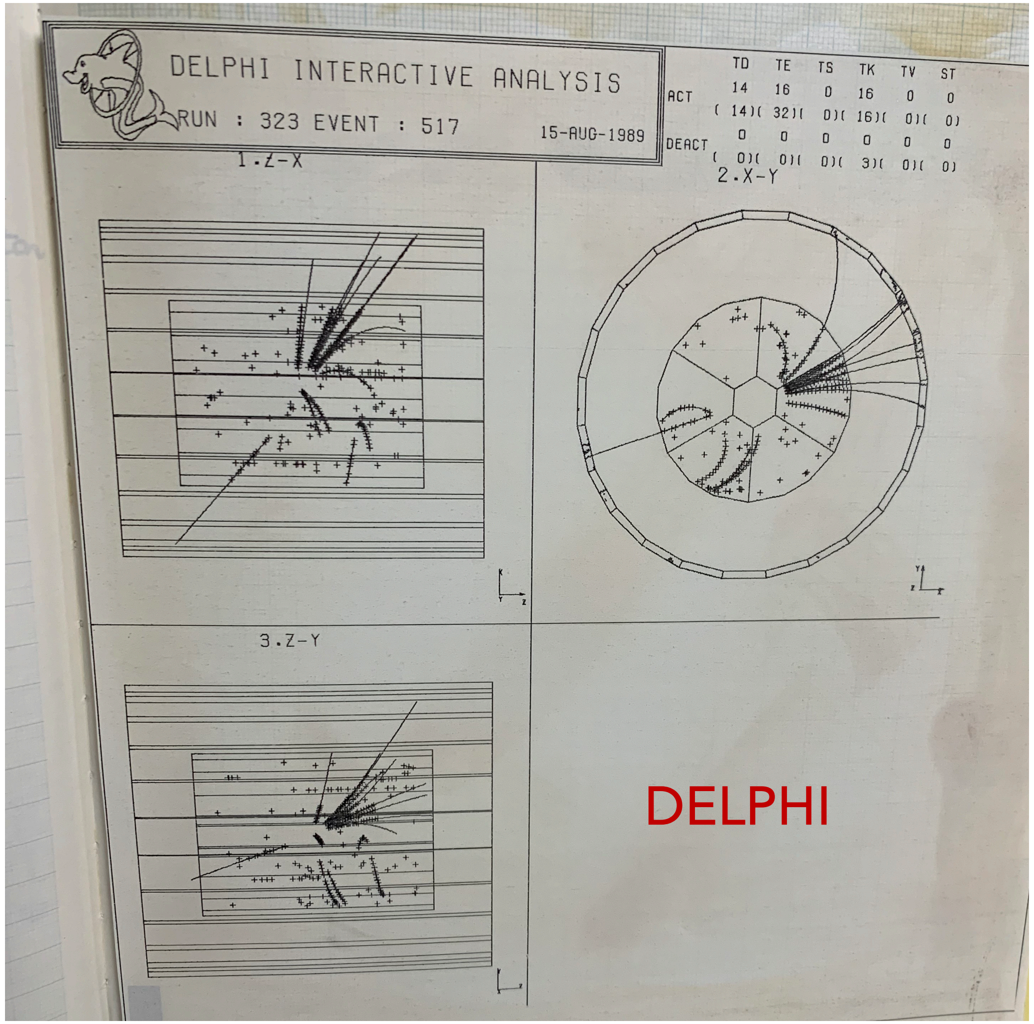
- Start: 4 bunches against 4 bunches (!)
- 1992 : 8 x 8
- 1995 12 x 12

- ~ 400 physicists/experiment

The (heroic) start

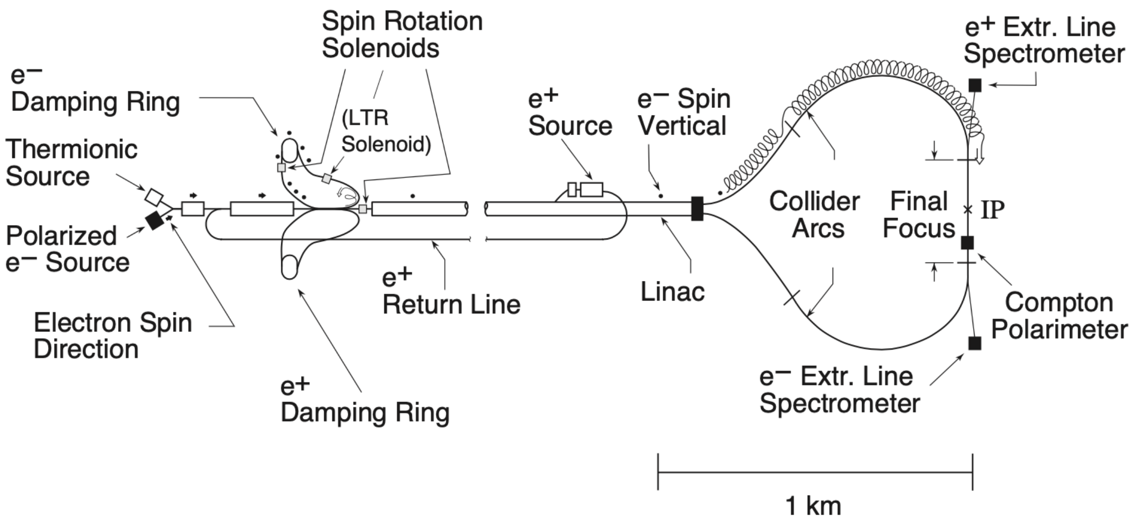
- 14^{th} July 1989 First beam turn
- 13^{th} Aug 1989 First Z^0s (4 exp)
- 20^{th} Sept First physics run
- 13^{th} Oct 1989 First results

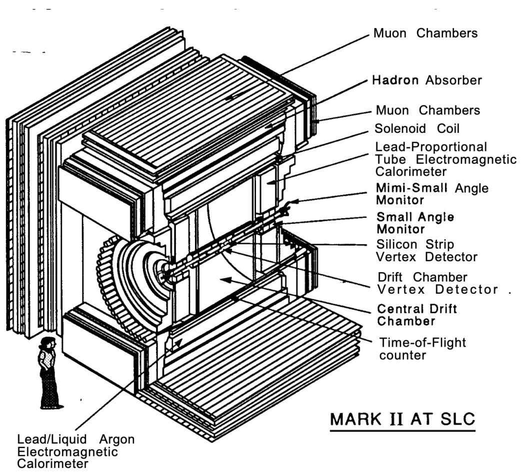


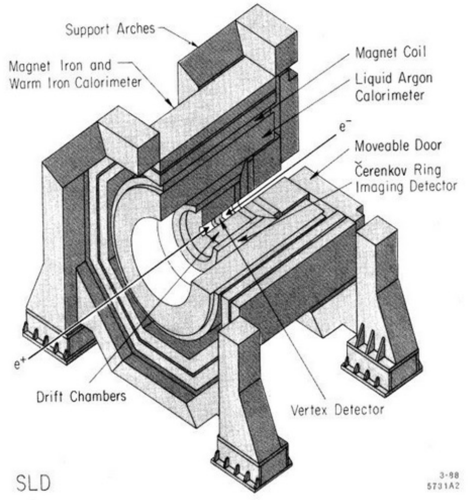


My own logbook

During the same period at SLAC







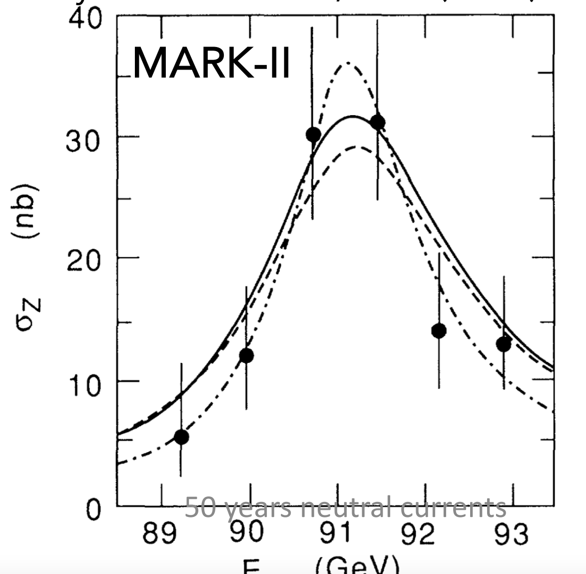
Cut-away view of the SLD with one endcap removed.

MARK-II and later SLD (from 1991)

First Z^0 hadronic decay: April 11th 1989

(low luminosity : $3\ 10^{27}\ cm^{-2}\ s^{-1}$)

Phys. Rev. Lett. 63, 724 (1989)

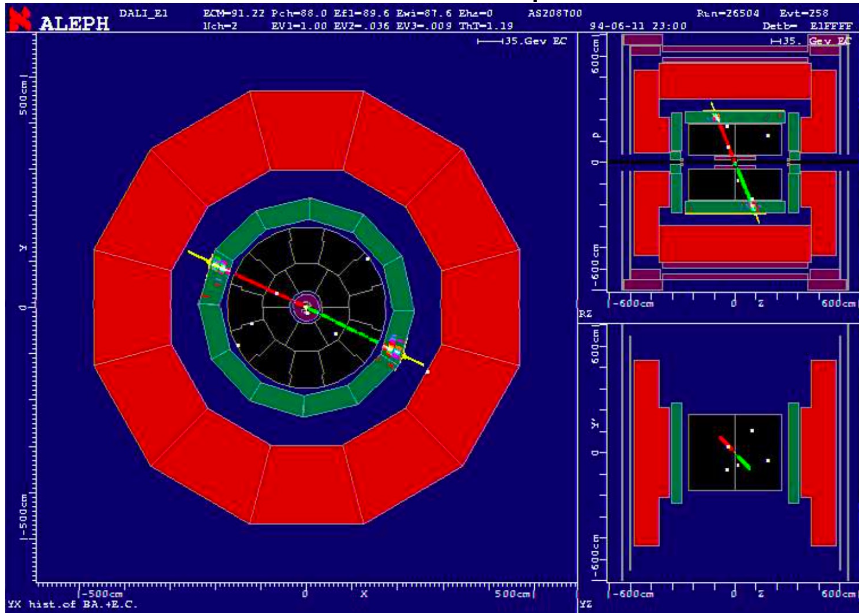


$\mu\mu$, $\tau\tau$, $q\bar{q}$

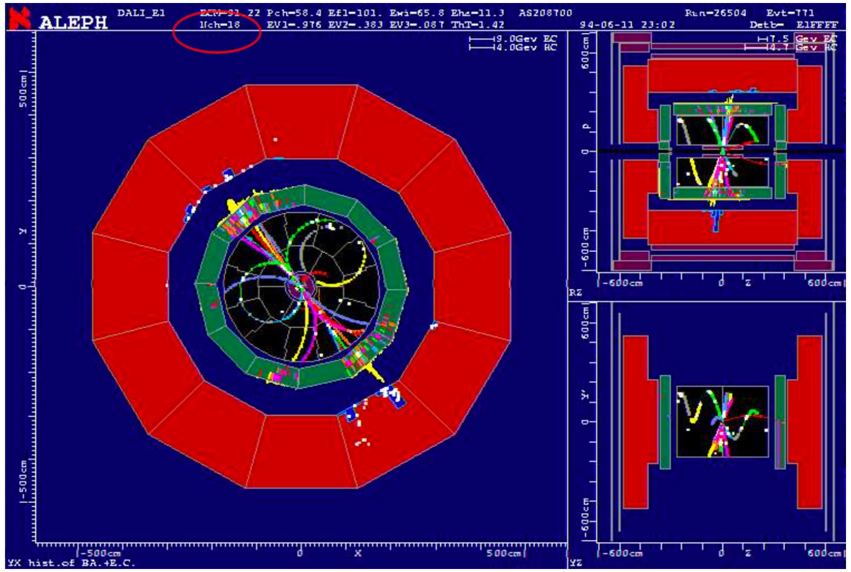
106 Z^0 decays

Study of the Z^0 boson

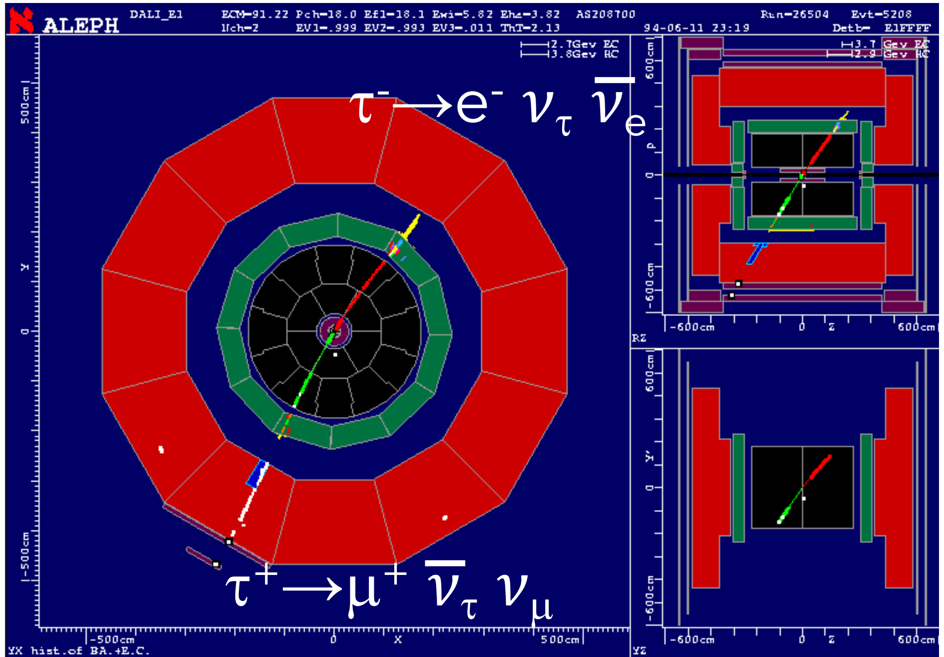
$Z^0 \rightarrow ee$ (large polar angle)



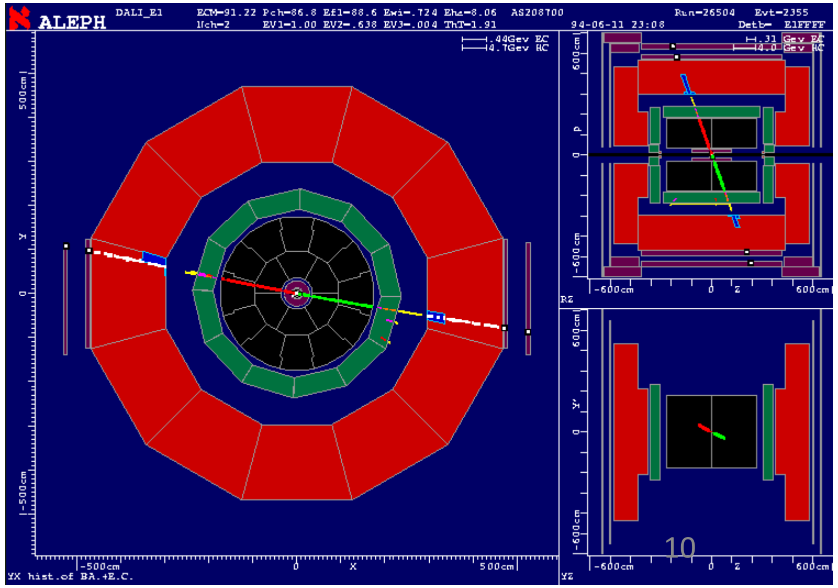
$Z^0 \rightarrow qq$



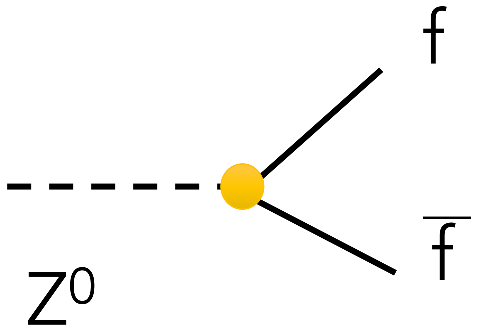
$Z^0 \rightarrow \tau\tau$



$Z^0 \rightarrow \mu\mu$



SM: Tree level



$$G_F = \frac{\pi\alpha}{\sqrt{2} m_W^2 \sin^2\theta_W^{\text{tree}}}$$

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W^{\text{tree}}}$$ =1 in the SM (Higgs doublet)

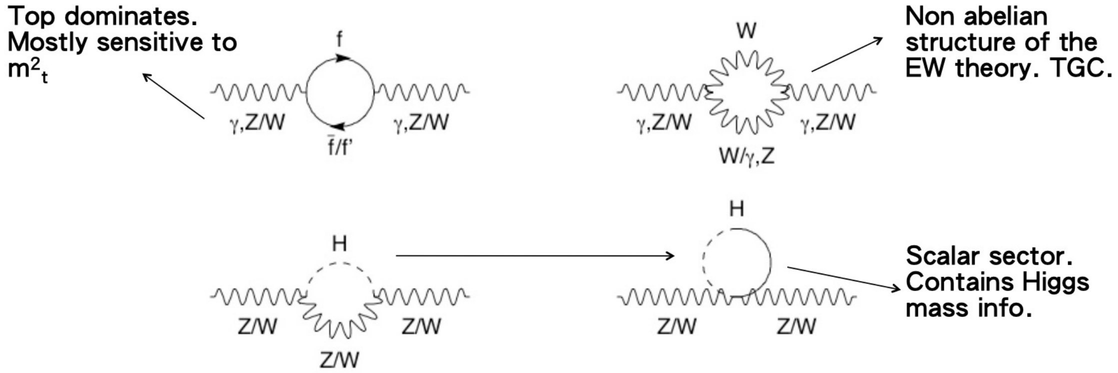
Z^0 couplings to fermions depends on their charge and weak isospin

Family			T	T_3	Q
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	1/2	+1/2 −1/2	0 −1
ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	0	0	0
e_R	μ_R	τ_R	0	0	−1
$\begin{pmatrix}u\\ d\end{pmatrix}_L$	$\begin{pmatrix}c\\ s\end{pmatrix}_L$	$\begin{pmatrix}t\\ b\end{pmatrix}_L$	1/2	+1/2 −1/2	+2/3 −1/3
u_R	c_R	t_R	0	0	+2/3
d_R	s_R	b_R	0	0	−1/3

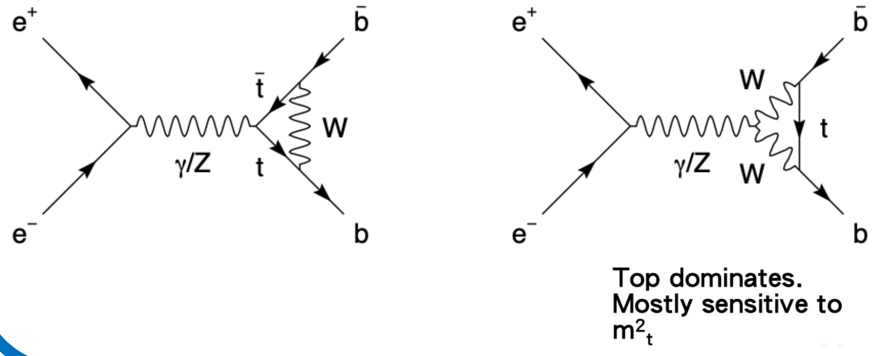
$$g_V^{\text{tree}} \equiv g_L^{\text{tree}} + g_R^{\text{tree}} = \sqrt{\rho_0}\,(T_3^f - 2Q_f \sin^2\theta_W^{\text{tree}})$$
$$g_A^{\text{tree}} \equiv g_L^{\text{tree}} - g_R^{\text{tree}} = \sqrt{\rho_0}\,T_3^f\,.$$

SM: radiative corrections

propagator corrections (self energy)



vertex corrections



$$\sin^2\theta_{\text{eff}}^f = \kappa_f \sin^2\theta_W$$

$$g_V^f = \sqrt{\rho_f}\left(T_3^f - 2Q_f\sin^2\theta_{\text{eff}}^f\right)$$

$$g_A^f = \sqrt{\rho_f}\,T_3^f$$

$$\rho_f = 1 + \Delta\rho_{se} + \Delta\rho_f$$

$$\kappa_f = 1 + \Delta\kappa_{se} + \Delta\kappa_f$$

propagator corrections: all observables, suppressed in ratio of widths eg $\sigma^0_{\text{had}} = \dfrac{12\pi\Gamma_{e^+e^-}\Gamma_{\text{had}}}{m_Z^2\Gamma_Z^2}$

vertex corrections: mostly $R_b = \dfrac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to \text{had})}$

The Z line shape

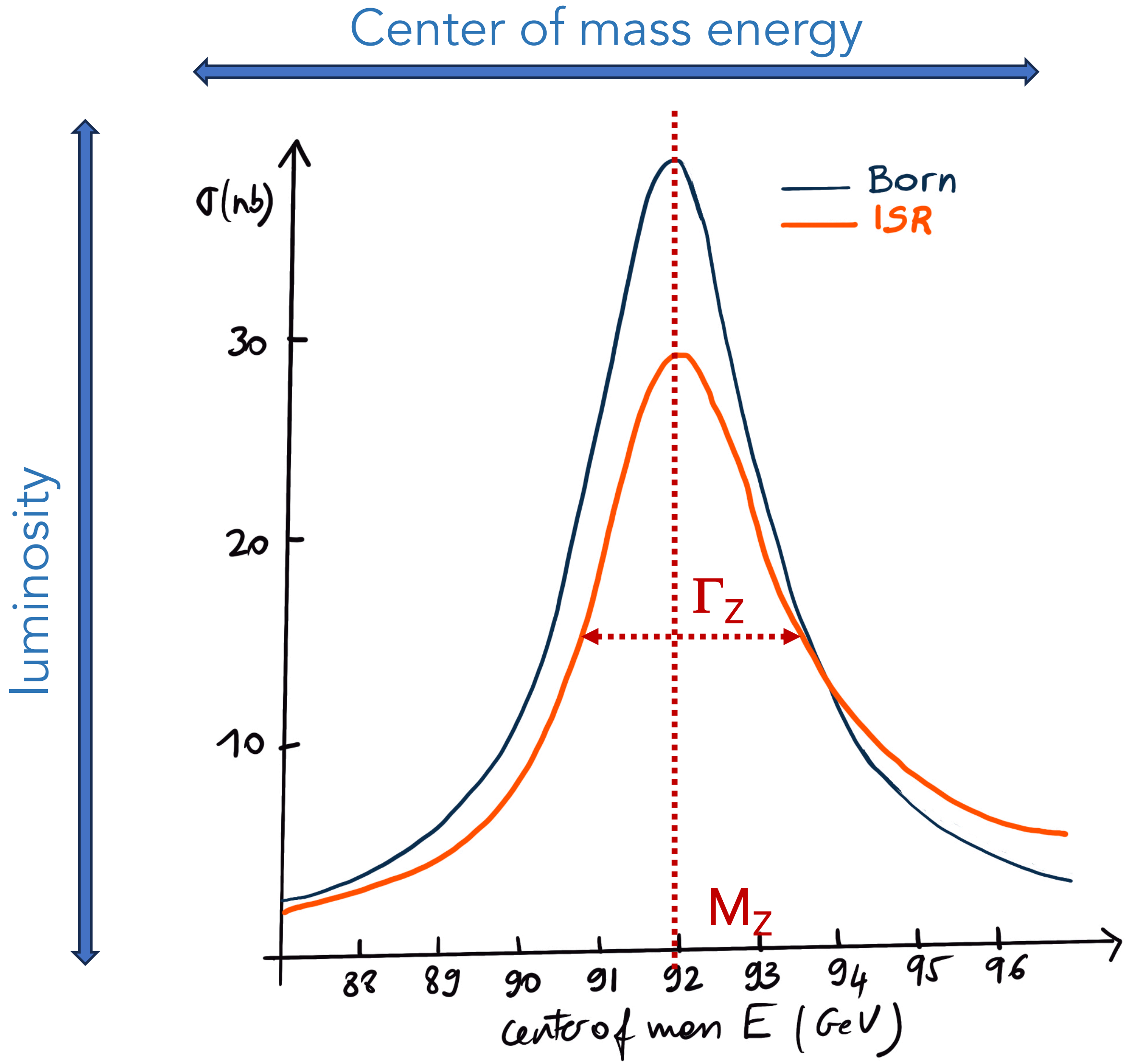
$$\sigma = \frac{N_{\rm sel} - N_{\rm bg}}{\epsilon_{\rm sel}\mathcal{L}}$$

$$\sigma_f = \frac{12\pi(\hbar c)^2}{M_Z^2}\frac{s\Gamma_e\Gamma_f}{(s - M_Z^2)^2 + s^2\frac{\Gamma_Z^2}{M_Z^2}}$$

SM

- BR($Z^0 \rightarrow qq$) ~ 70%
- BR($Z^0 \rightarrow \ell\ell$) ~ 3% ℓ=e, μ or τ
- BR($Z^0 \rightarrow \nu\nu$)~ 20% (N_ν= 3)

Importance of the hadronic channel



What do we extract as information ?

- Z^0 mass: one of the SM parameter
- Z^0 width: sensitive to radiative corrections (top mass, Higgs mass (log))

- Peak cross section : sensitive to the number of light neutrinos

$$\sigma_f = \frac{12\pi(\hbar c)^2}{\mathrm{M_Z^2}} \frac{s\Gamma_e\Gamma_f}{(s-\mathrm{M_Z^2})^2 + s^2\frac{\Gamma_Z^2}{\mathrm{M_Z^2}}}$$

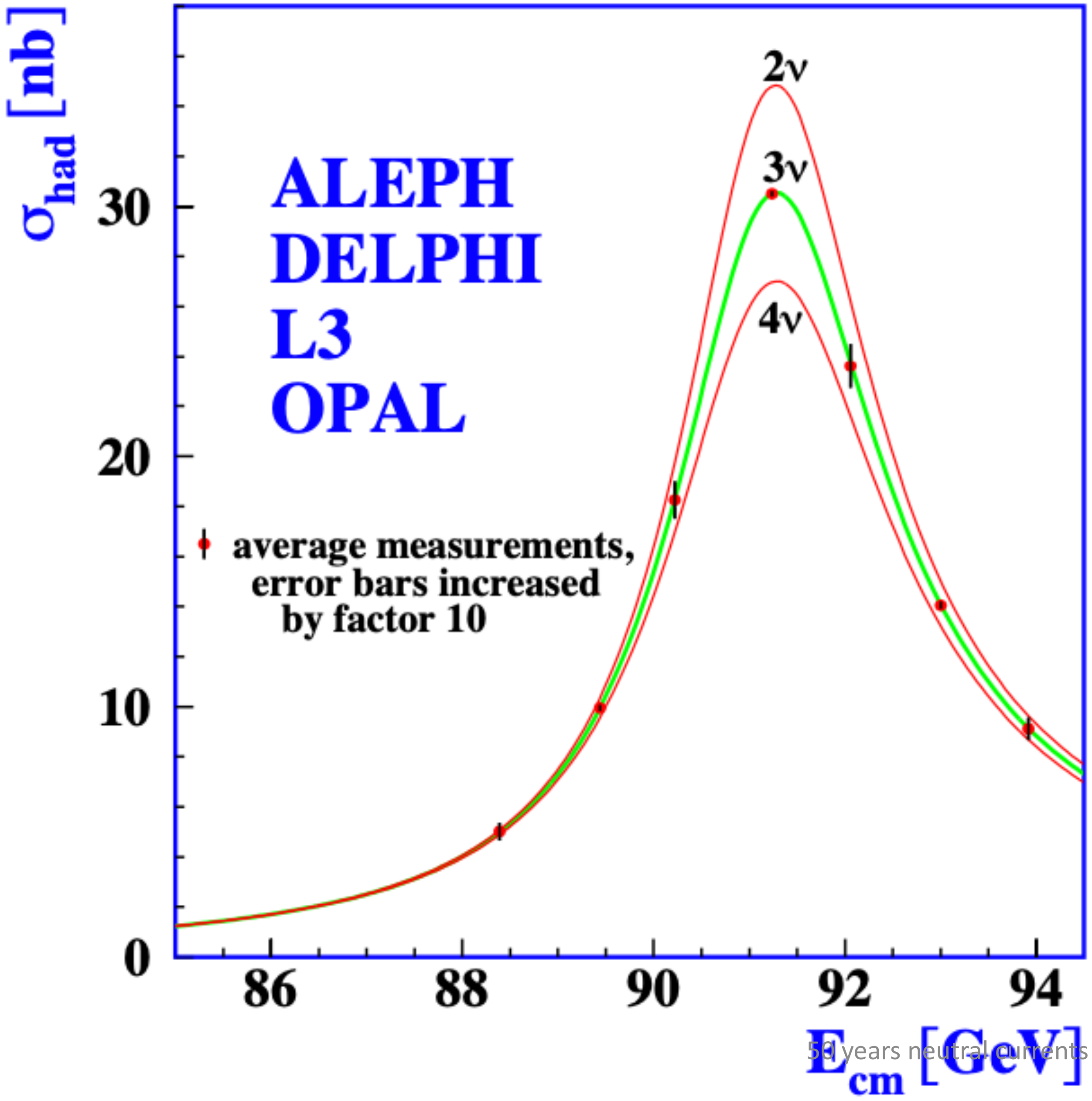
$$\Gamma_Z = 3\Gamma_\ell + \Gamma_{had} + N_\nu\Gamma_\nu$$

- test of lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$?

SM

BR($Z^0 \rightarrow qq$) ~ 70%
BR($Z^0 \rightarrow \ell\ell$) ~ 3% ℓ=e, μ or τ
BR($Z^0 \rightarrow \nu\nu$)~ 20% (N_ν= 3)

~4 10^6 Z^0/experiment , (1990-1995), many challenges: final(*) results in 2005



$$m_Z = 91.1875 \pm 0.0021 \text{ GeV} \qquad 2\ 10^{-5}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV} \qquad 9\ 10^{-4}$$

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

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

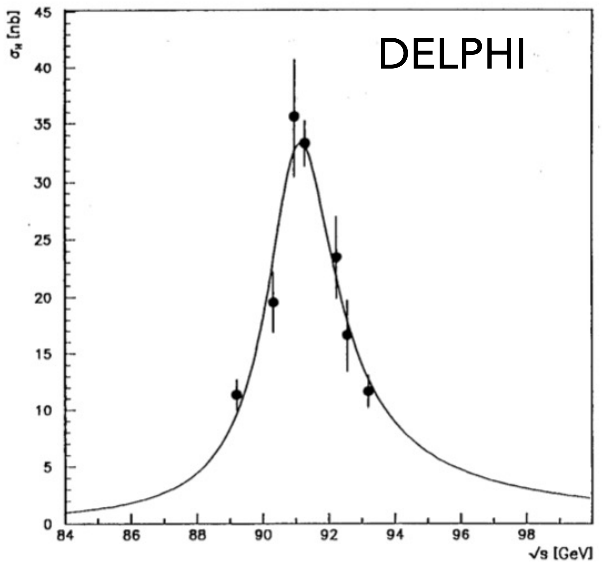
-0.23% to be applied to take into account τ mass

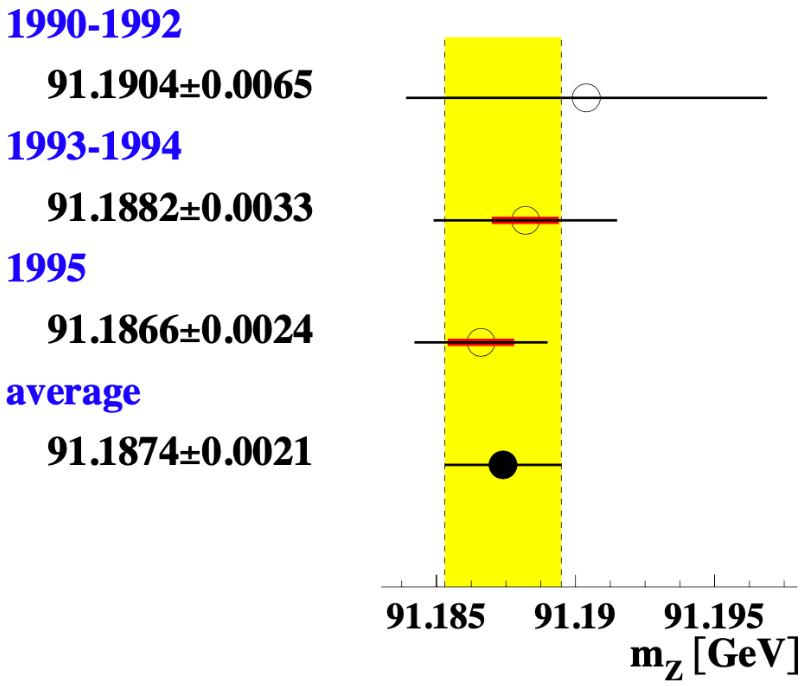
(*) but full width (2019)

A. Blondel (CR Academie des Sciences)

Table 1. First results from LEP and SLC on the Z mass and the number of light neutrino species, as published around 12 October 1989 (in order of submission to the journal).

Experiment	Hadronic Zs	Z mass (GeV·c^{-2})	N_ν
MARKII	450	91.14 ± 0.12	2.8 ± 0.60
L3	2538	91.13 ± 0.06	3.42 ± 0.48
ALEPH	3112	91.17 ± 0.05	3.27 ± 0.30
OPAL	4350	91.01 ± 0.05	3.10 ± 0.40
DELPHI	1066	91.06 ± 0.05	2.4 ± 0.64
Average		91.10 ± 0.05	3.12 ± 0.19





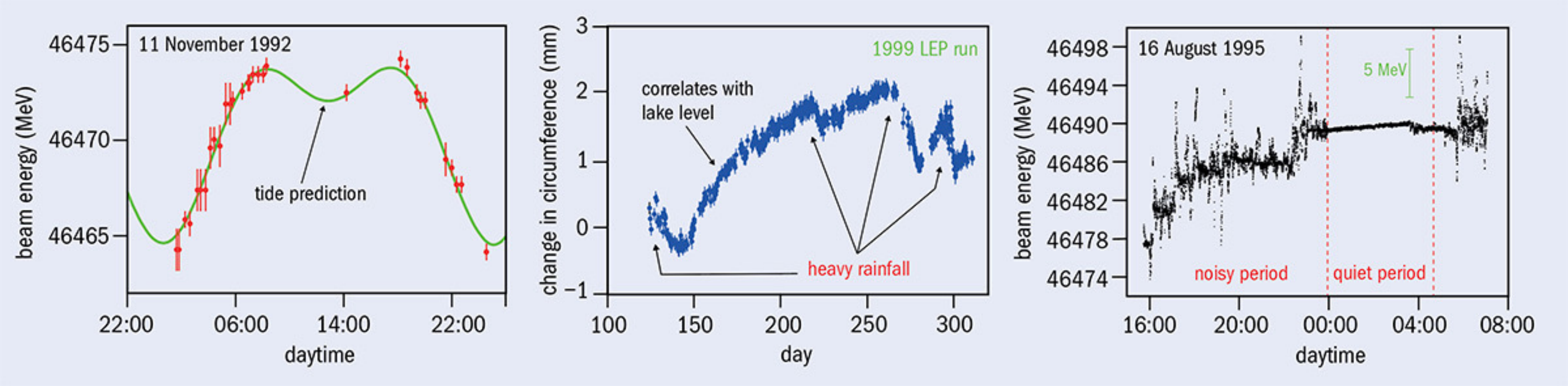
https://doi.org/10.1016/0370-2693(89)90706-5

Challenges in the energy calibration

Most sensitive parameter: M_Z
Strategies in the energy scan developed (energy changed at each fill)
Resonant depolarization technique (end of fill)
NRM probes

Change in the orbit length

Rise of dipole field due to electric perturbations due to TGV passing

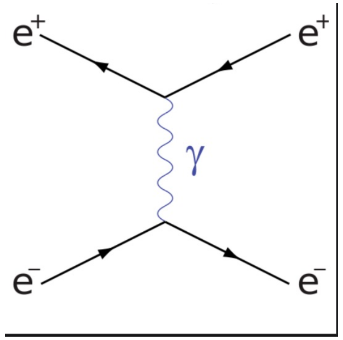


change in circonference :
1mm ⇒ 10 MeV

$\Delta M_Z = 1.7$ MeV

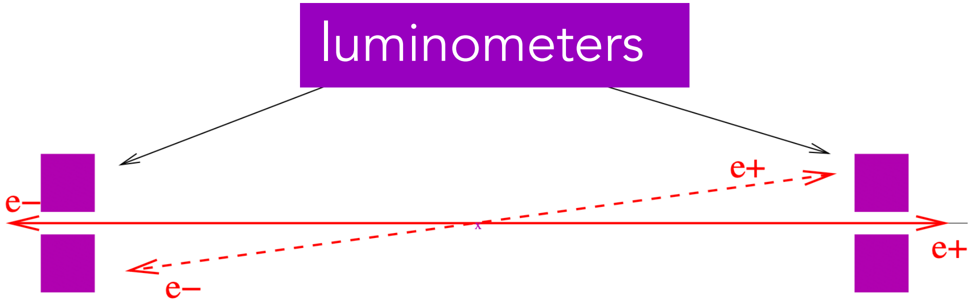
Challenges in the luminosity determination

Bhabha scattering $e^+e^- \to e^+e^-$

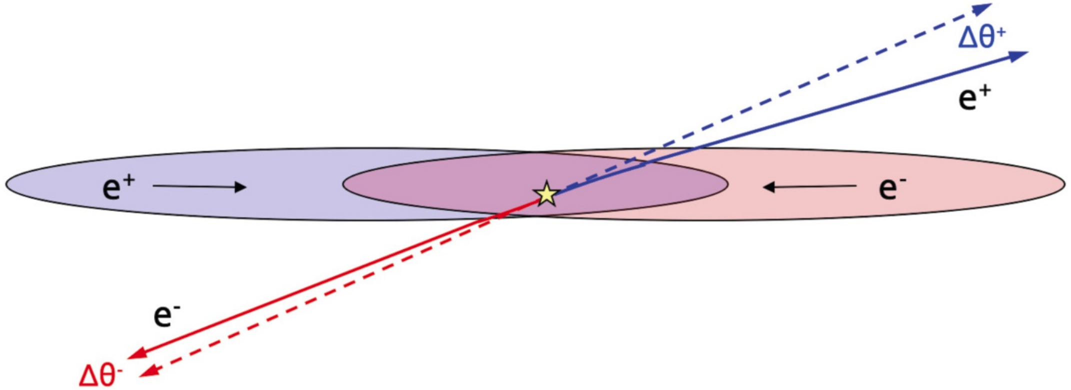


Theoretical computation + precision luminometers (~ 5 μm tolerance)

Accuracy 5 10^{-4}



In 2019 !



Beam-beam effect

underestimation of the integrated luminosity by -0.1 %

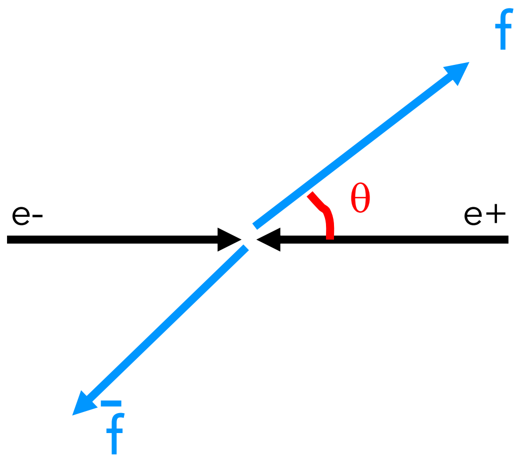
Physics Letters B 800 (2020) 135068

$N_\nu = 2.9840 \pm 0.0082$ → $N_\nu = 2.9919 \pm 0.0081$

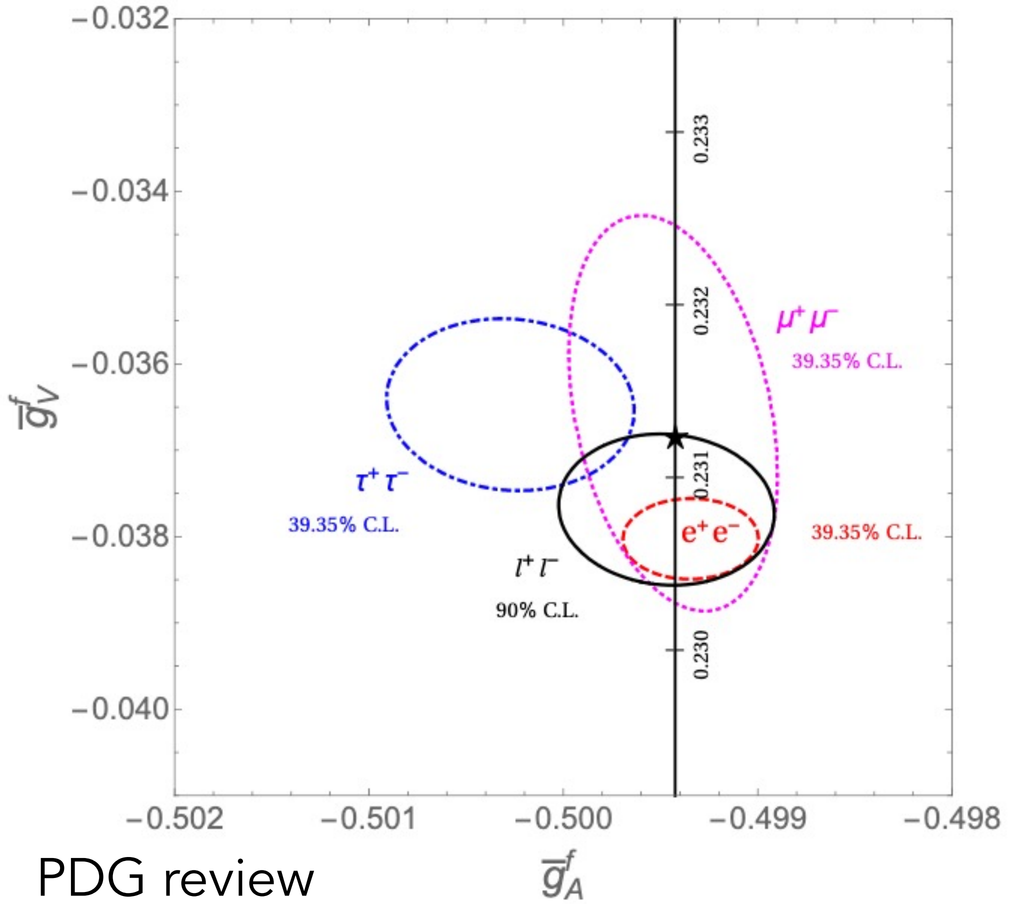
An overall test of the Standard Model: couplings

Z^0 partial widths : $|g_V^f|^2 + |g_V^f|^2$

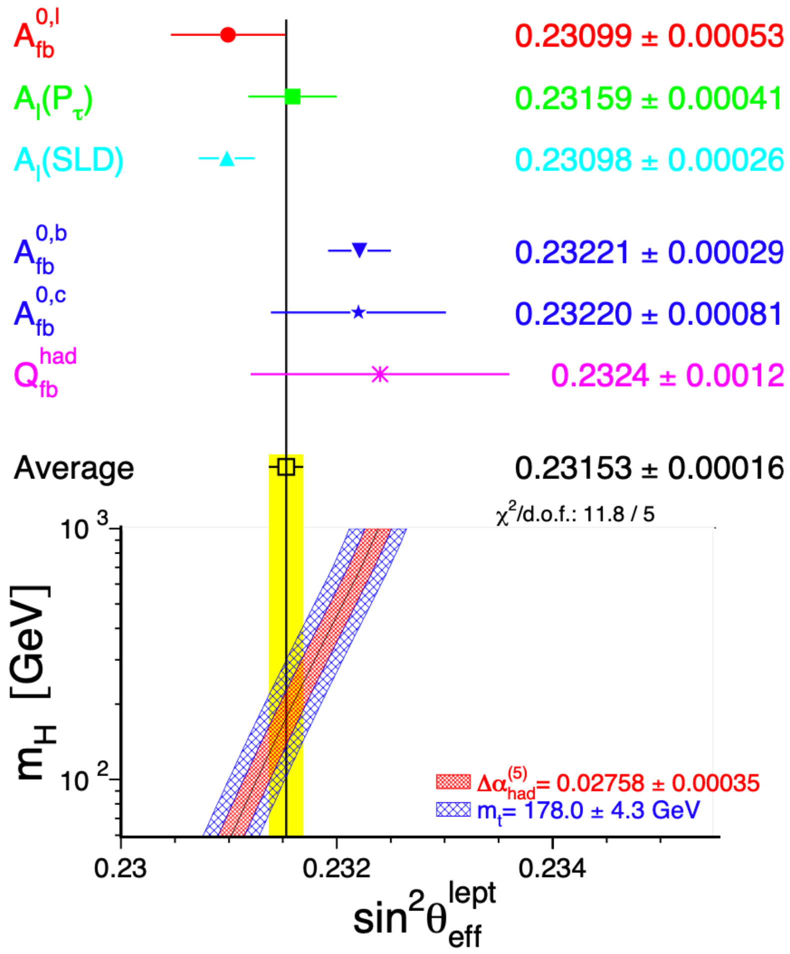
Asymmetries: g_V^f / g_A^f and $\sin^2 \theta_{\mathrm{eff}}^f$



FB asymmetries, τ polarisation
SLC initial state polarisation

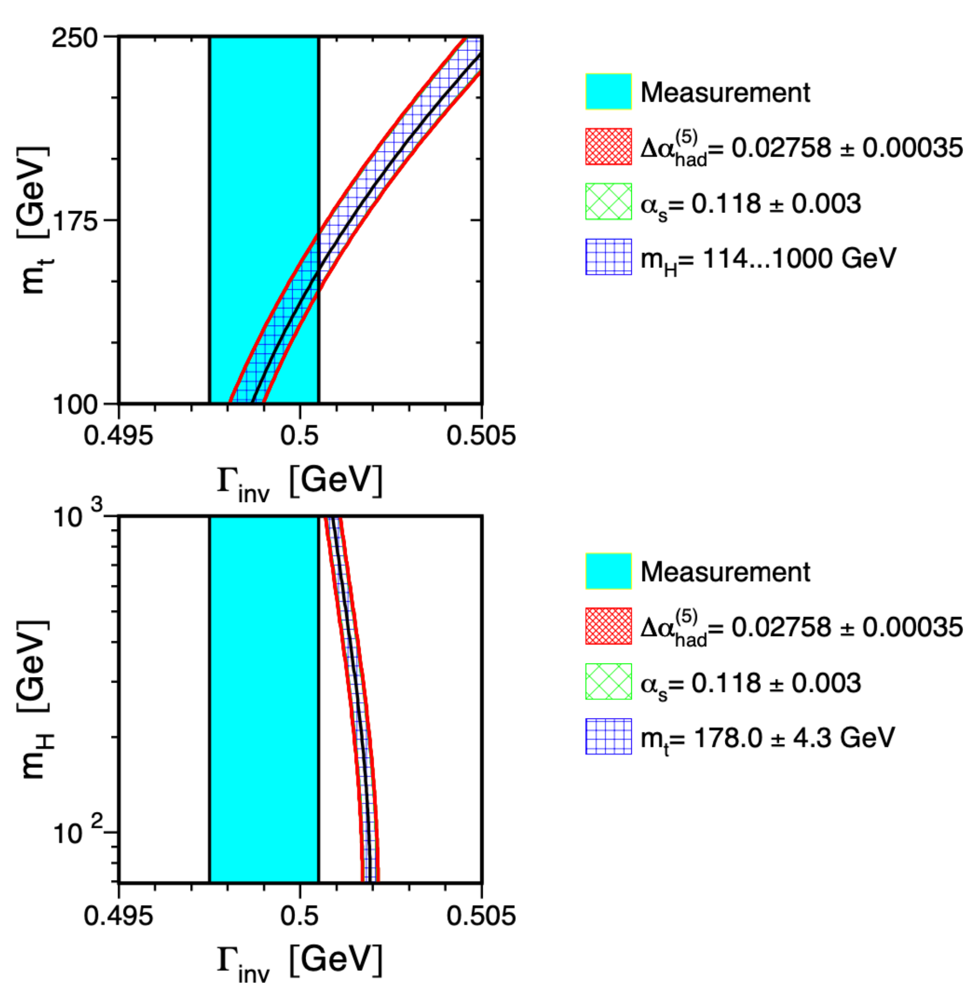


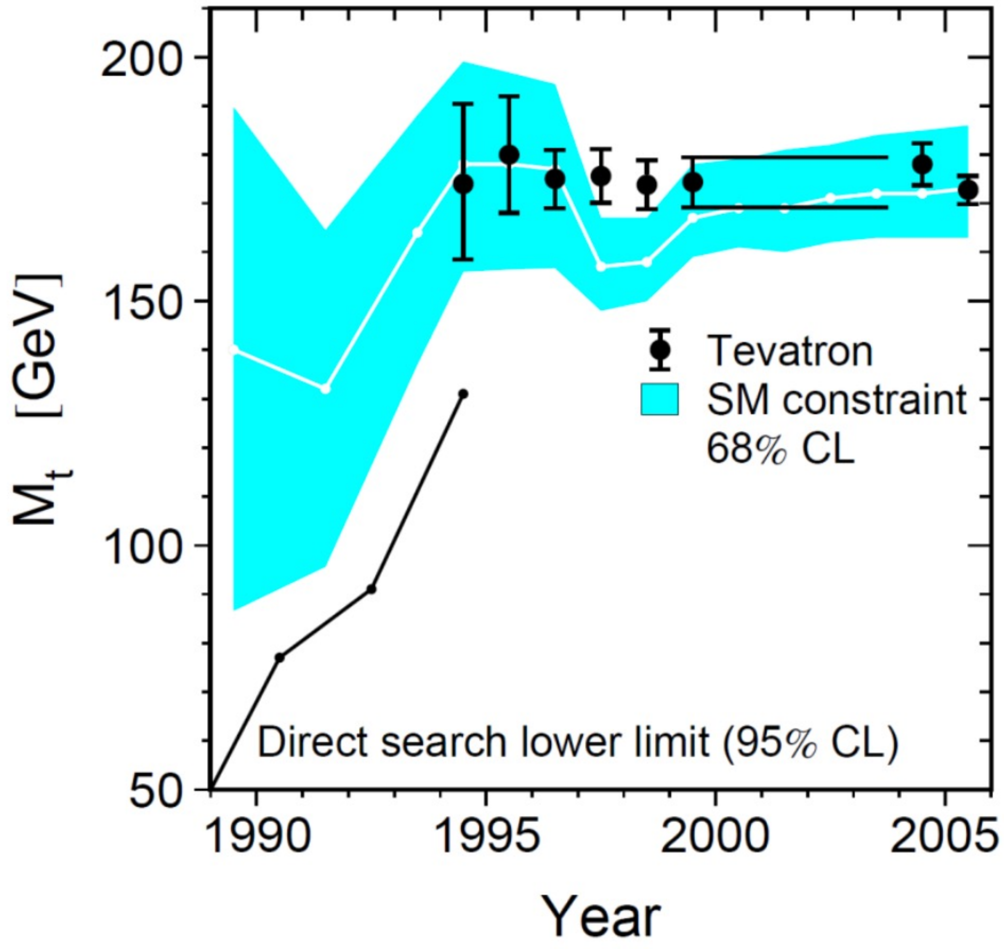
PDG review



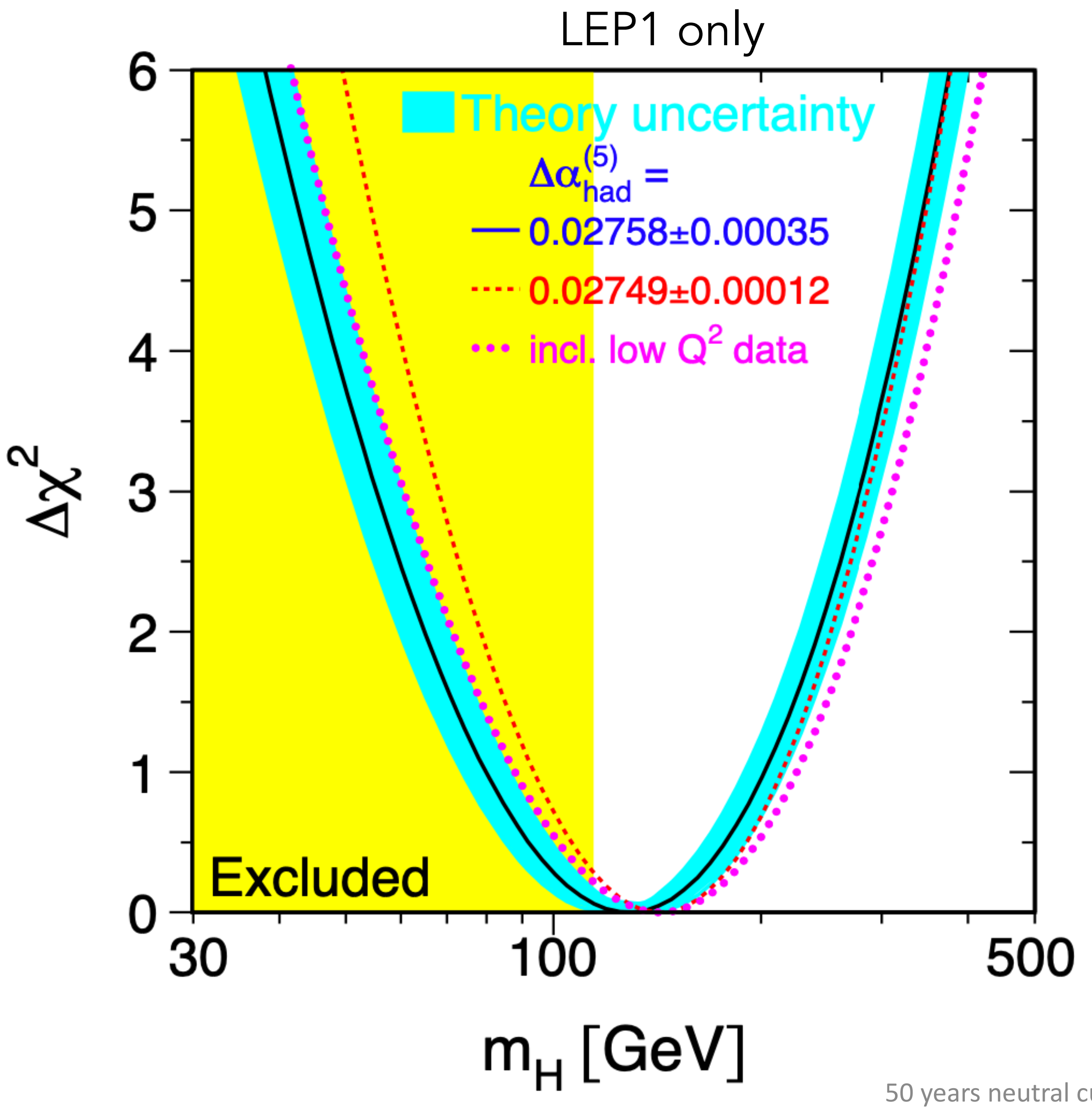
Predictions

Electroweak corrections in the prediction of observables: depends on m^2_{top} and $\ln(m_{Higgs})$





2005



2005:

m_H < 285 GeV/c^2 @95 %CL LEP1 only

m_H < 152 GeV/c^2 @95 %CL LEP1+ LEP2

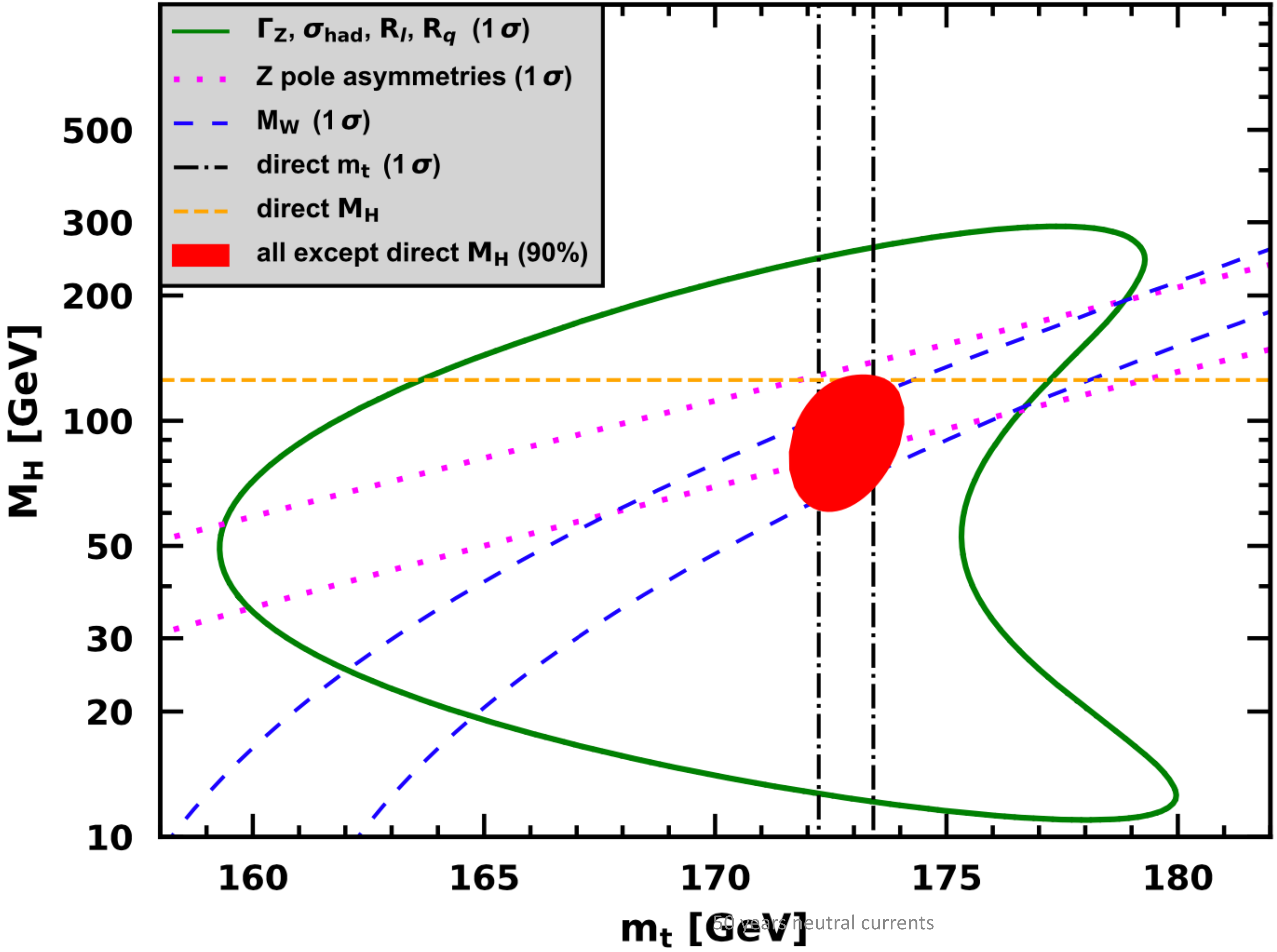
2012:

discovery of a light Higgs boson

2023

$$m_H = 125.25 \pm 0.17 \ \mathrm{GeV}/c^2$$

PDG



1σ

PDG review

Nobel 1999 prize to M. Veltman and G. 't Hooft


Martinus Veltman


Gerardus 't Hooft

The theory's predictions verified

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.

Use of the Z^0 boson

b-physics

In total ~ 16 millions Z^0 were produced

$$Z^0 \rightarrow b\bar{b} \sim 15\%$$

~ 1.2 millions b-hadrons produced per experiment

Total at LEP

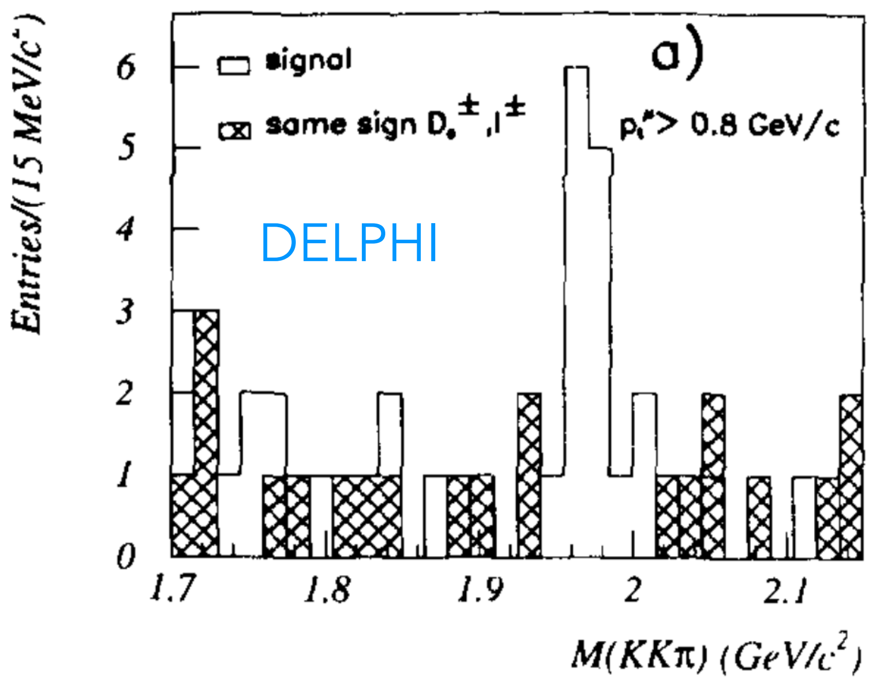
B_u	B_d	B_s	Λ_b
1.9 10^6	1.9 10^6	0.48 10^6	0.48 10^6

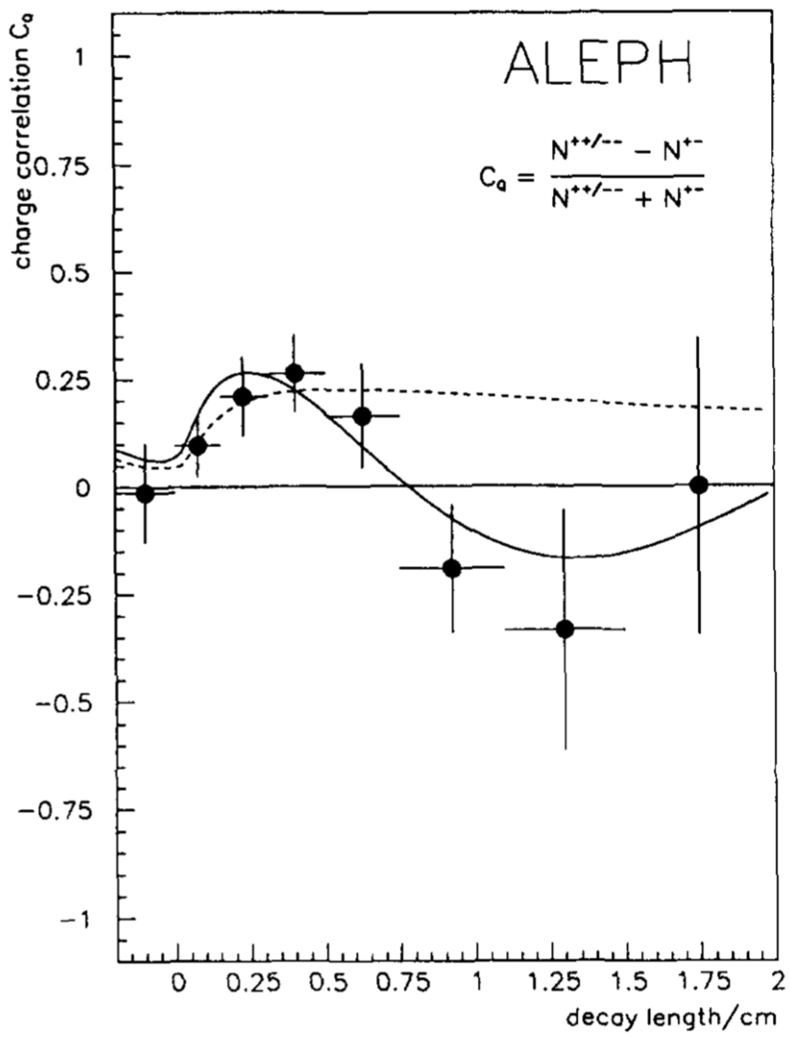
$B_s \to D_s \ell \nu$

Observation of the time-dependence of $B^0 \bar{B}^0$ mixing

PLB 313 (1993) 498

Evidence for Bs production in Z decays





https://doi.org/10.1016/0370-2693(92)91385-M

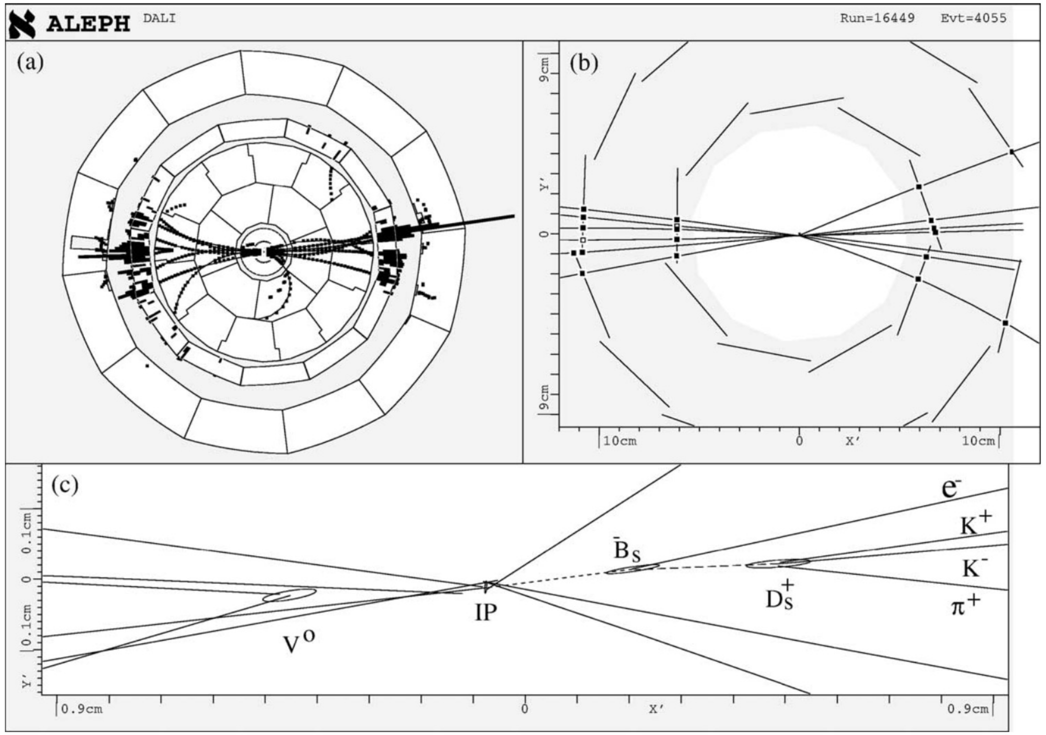
1990 -1991 data

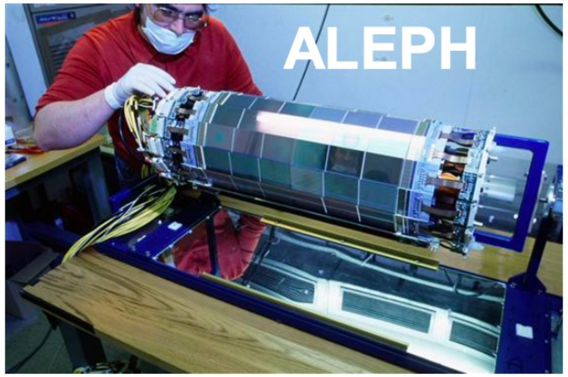
Was only possible given the innovative Si detectors

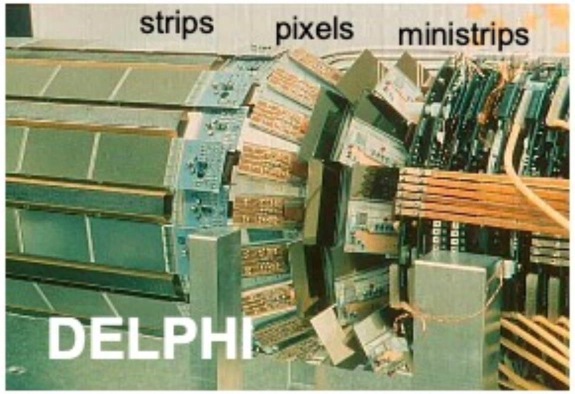
A few mm between the Interaction point and the b-hadron vertex

1990 : ALEPH and DELPHI

1993 : all 4 experiments, Be beampipe with smaller radius (~ 5 cm)



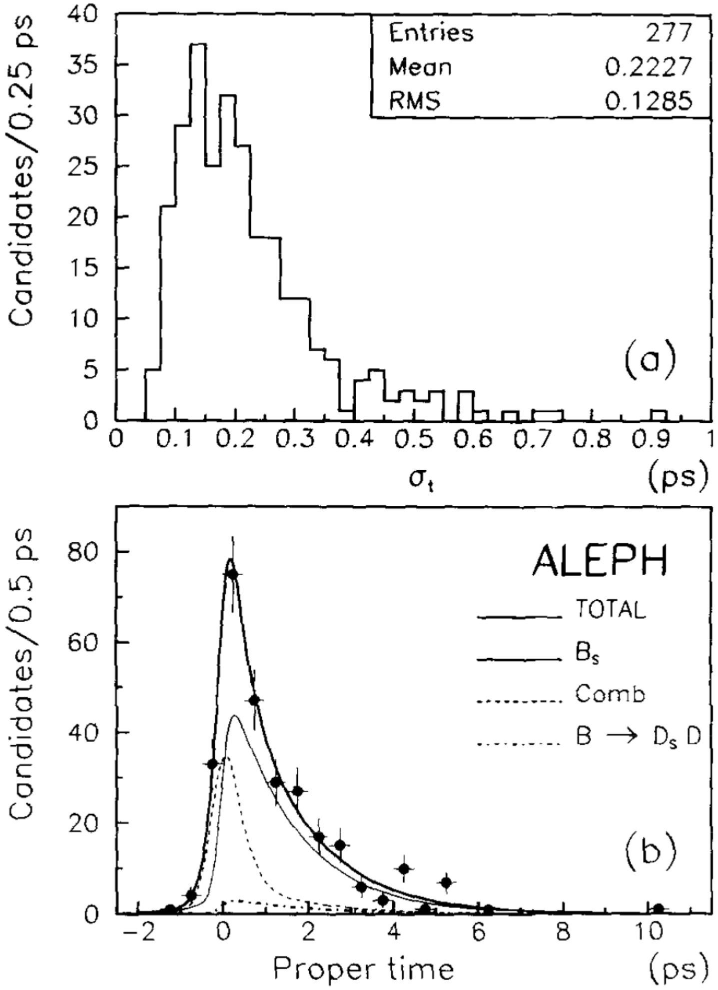




50 years neutral currents

$B_s \rightarrow D_s \ell\nu$

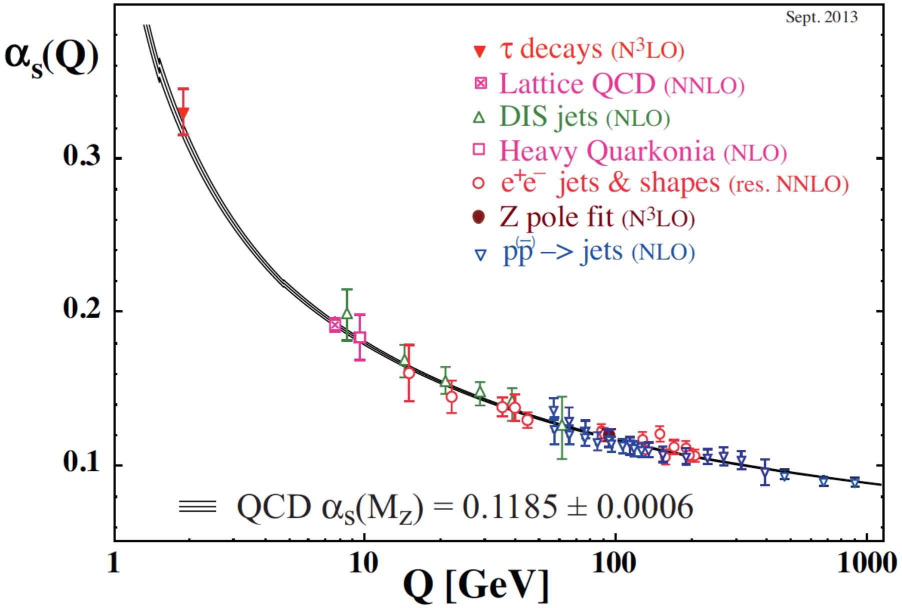
Physics Letters B 377 (1996) 205–221



$$\tau = 1.54^{+0.14}_{-0.13} \pm 0.04 \text{ ps}$$

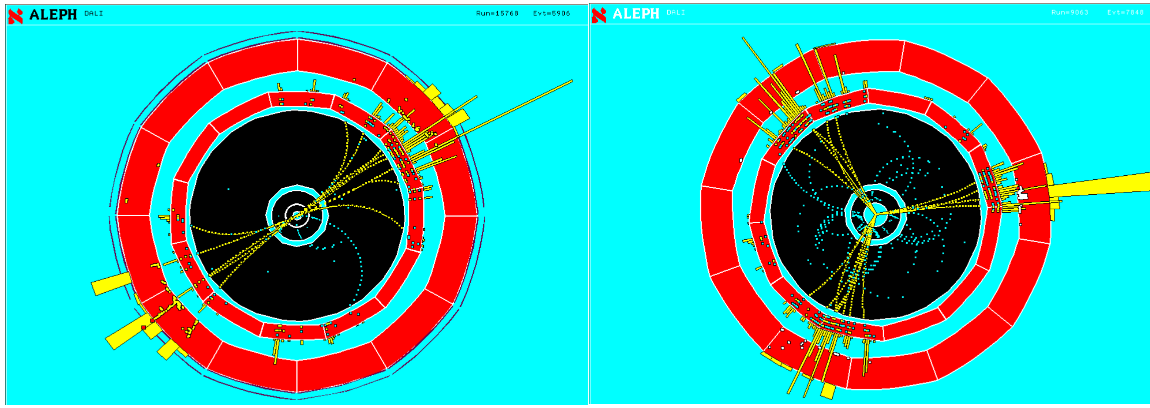
$\Delta m_s > 6.6 \text{ ps}^{-1}$ Full LEP1 data

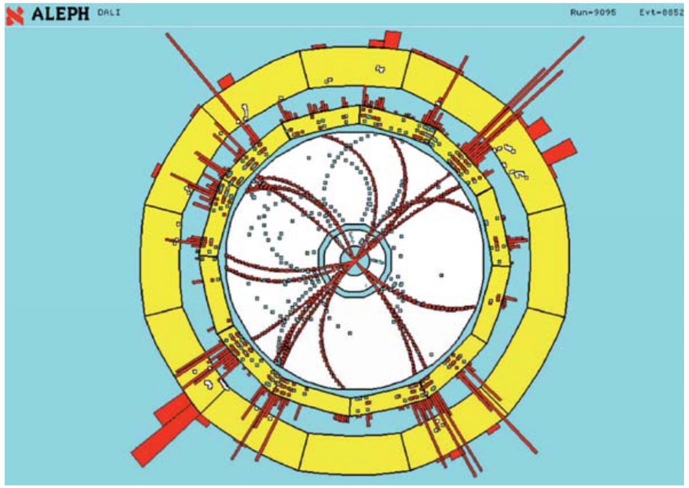
QCD



0.5 % precision !

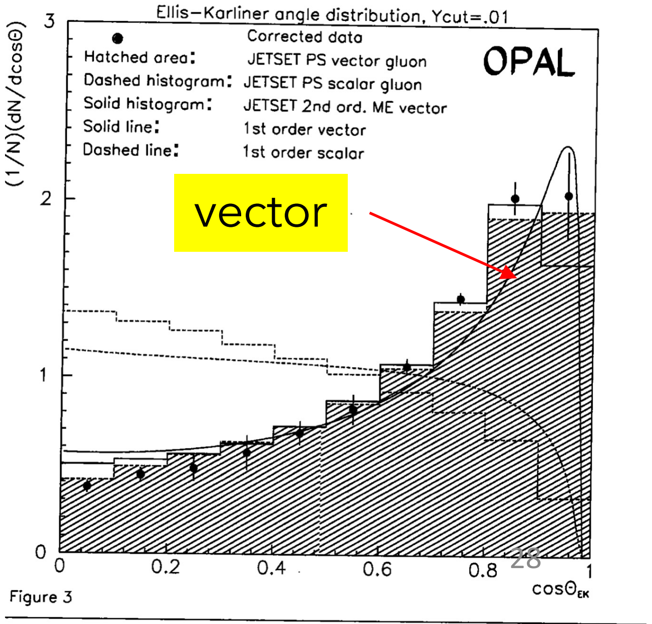
ALEPH





4-jets events
⇒ Observation of gluon self-coupling

gluon spin measurement



Summary

August 1989 : 1 Z^0/day

End of 1995 :1000 Z^0 /h

```
  2D Num 12  dax_day         total entries       6697
        x          y                               8 I        82 I        28
  beg.  -1.00E-01 -1.00E-01              ---------------------------------
  step   1.00E-02  1.25E-02                       97 I      6321 I       100
  end    1.00E-01  1.00E-01              ---------------------------------
  bins    20        16                             0 I        53 I         8
center:  -1.500E-02   6.250E-03
Regression:    y= 7.759E-03+( 5.477E-03)*x
               x=-1.417E+00+( 1.826E+02)*y

               bin y:    1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
              y-proj.:  20   23   22   34   65   50  150  651 3814 1007  182   89   94   52   48   20
bin   arg.x    sum.y  -------------------------------------------------------------------------------
 1   -0.095    16.     I  4    .    .    .    4    .    .    .|   4    4    .    .    .    .    .   .I
 2   -0.085    32.     I  .    .    .    .    .    4    .    .|   6    8    4    .    .    2    8   .I
 3   -0.075    54.     I  .    4    .    .    4    .    5   11|   4    1   13    4    4    .    4   .I
 4   -0.065    51.     I  2    .    .    .    7    .    4   13|  12    8    .    1    4    .    .   .I
 5   -0.055    68.     I  2    .    1    .    4    .    7   12|  11   15    4    3    4    4    1   .I
 6   -0.045    98.     I  .    .    1    3    .    .    8   16|  29    9    .    8   16    2    6   .I
 7   -0.035    199.    I  4    .    .    1    4    1    4   27|  92   26   16   16    8    .    .   .I
 8   -0.025    1.92E+03 I 4    .    4    4    8    9   30  174|1255  357   36   12   12    .    5   8I
 9   -0.015    2.70E+03 I .    8    4   16    6    9   48  267|1880  385   51    8    8    4    5   3I
10  -5.00E-03  593.    I  4    3    .    .    8    4   18   63| 346   87   15   12   16   16    .   1I
                       I-------------------------------------------------------------------------------
11   5.00E-03  165.    I  .    .    4    4    .    4    2   20|  49   42   20    4    .   12    4   .I
12    0.015    148.    I  .    .    4    .    .    5    5   11|  64   29    8    4    6    4    8   .I
13    0.025    113.    I  .    .    4    4    8    4   11   19|  31   13    4    8    4    .    3   .I
14    0.035    45.     I  .    .    .    .    .    4    5   10|  11    7    .    .    .    .    4   4I
15    0.045    29.     I  .    .    .    .    .    .    3    4|   4    6    .    .   12    .    .   .I
16    0.055    27.     I  .    .    .    2    4    2    .    .|   4    3    8    1    .    3    .   .I
17    0.065    26.     I  .    4    .    .    .    .    .    4|   4    5    .    8    .    1    .   .I
18    0.075    21.     I  .    .    .    .    4    4    .    .|   4    2    3    .    .    4    .   .I
19    0.085    8.      I  .    .    .    .    .    .    .    .|   4    .    .    .    .    .    .   4I
20    0.095    8.      I  .    4    .    .    4    .    .    .|   .    .    .    .    .    .    .   .I
bin   arg.x    sum.y  -------------------------------------------------------------------------------
              y-proj.:  20   23   22   34   65   50  150  651 3814 1007  182   89   94   52   48   20
               bin y:    1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
```

1988

CERN Program Library Long Writeup Q121

PAW

Physics Analysis Workstation

An Introductory Tutorial

Application Software Group
Computing and Networks Division

CERN Geneva, Switzerland

A last word

J'ai eu la chance de participer au démarrage de LEP en préparation depuis huit ans. C'est dans cette phase exceptionnelle que constitue la recherche fébrile des premières désintégrations hadroniques du Z^0 que j'ai pleinement apprécié les prouesses techniques nécessaires à l'acquisition d'un détecteur si complexe. Même si moins d'un an s'est écoulé depuis ces débuts "héroïques", nous sommes maintenant loin du temps où l'on pouvait distinguer individuellement chaque Z^0 par ses caractéristiques topologiques... En effet, le nombre d'événements acquis cette année devrait dépasser la centaine de milliers et permettre alors, une détermination des paramètres du boson neutre vecteur de l'interaction faible avec des erreurs statistiques réduites d'environ un facteur trois rendant entre autres possible un test encore plus contraint du Modèle Standard.

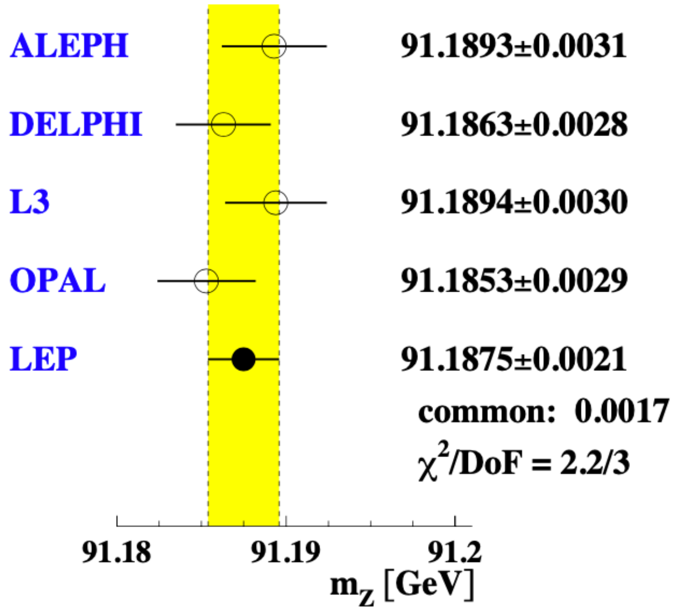
Last paragraph of the concluding remarks of my PhD thesis

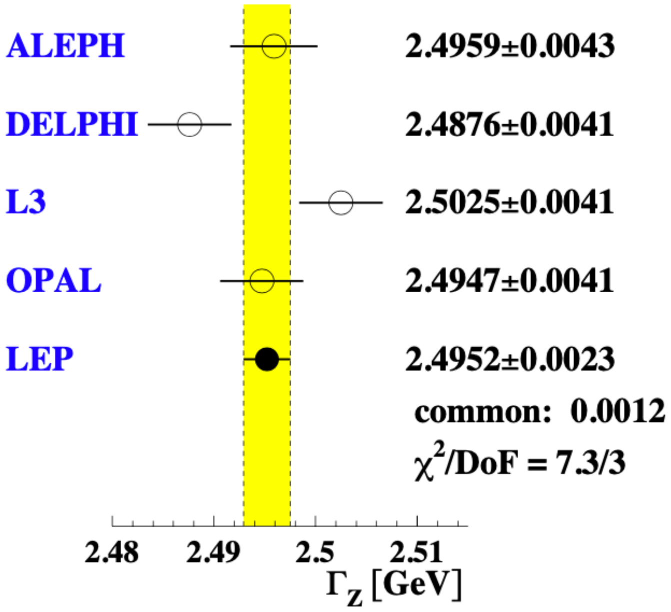
May 1990

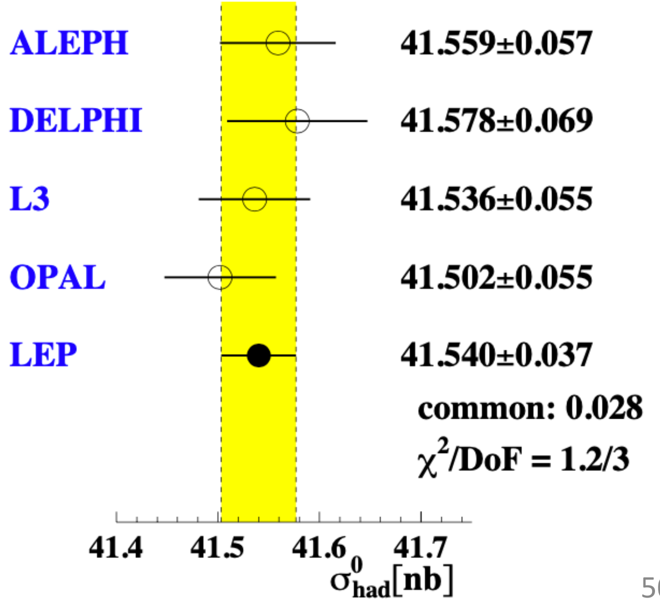
Thank you for your attention

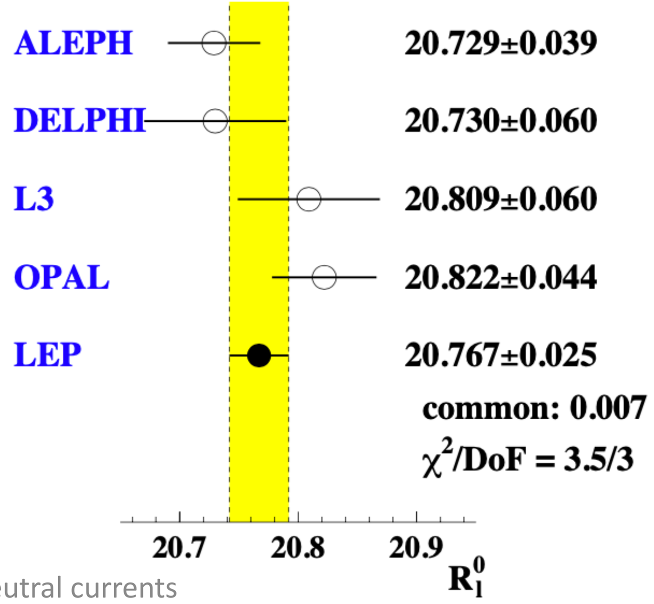
Backup slides

DELPHI solenoid (superconducting magnet)


ALEPH
DELPHI
L3
OPAL
LEP
91.1893±0.0031
91.1863±0.0028
91.1894±0.0030
91.1853±0.0029
91.1875±0.0021
common: 0.0017
χ^2/DoF = 2.2/3
91.18
91.19
91.2
m_Z [GeV]


ALEPH
DELPHI
L3
OPAL
LEP
2.4959±0.0043
2.4876±0.0041
2.5025±0.0041
2.4947±0.0041
2.4952±0.0023
common: 0.0012
χ^2/DoF = 7.3/3
2.48
2.49
2.5
2.51
Γ_Z [GeV]


ALEPH
DELPHI
L3
OPAL
LEP
41.559±0.057
41.578±0.069
41.536±0.055
41.502±0.055
41.540±0.037
common: 0.028
χ^2/DoF = 1.2/3
41.4
41.5
41.6
41.7
σ^0_{had}[nb]


ALEPH
DELPHI
L3
OPAL
LEP
20.729±0.039
20.730±0.060
20.809±0.060
20.822±0.044
20.767±0.025
common: 0.007
χ^2/DoF = 3.5/3
20.7
20.8
20.9
R^0_l

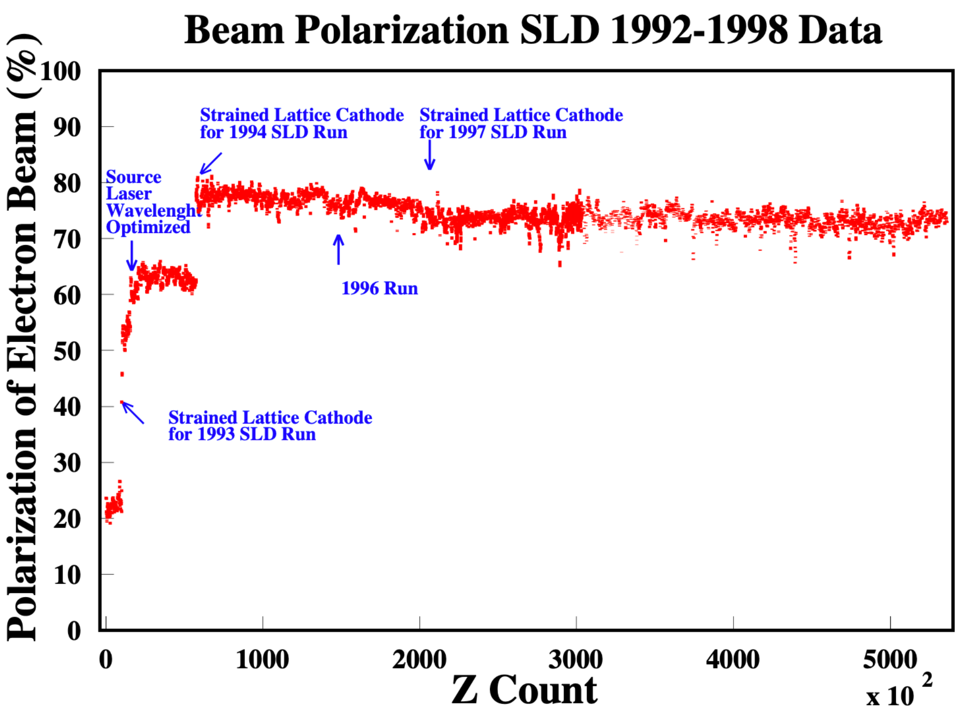
Left-Right asymmetry @ SLC

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{\langle \mathcal{P}_e \rangle}$$

N_L= # of Z^0 produced for left-handed electron bunches
N_R= # of Z^0 produced for right-handed electron bunches
$\langle P_e \rangle$ = electron polarization

Compton-scattering polarimeter installed near the IP:
0.5 % precision on the polarisation measurement

In 1998 : total 0.5 10^6 Z^0 recorded



Asymmetries and τ polarisation

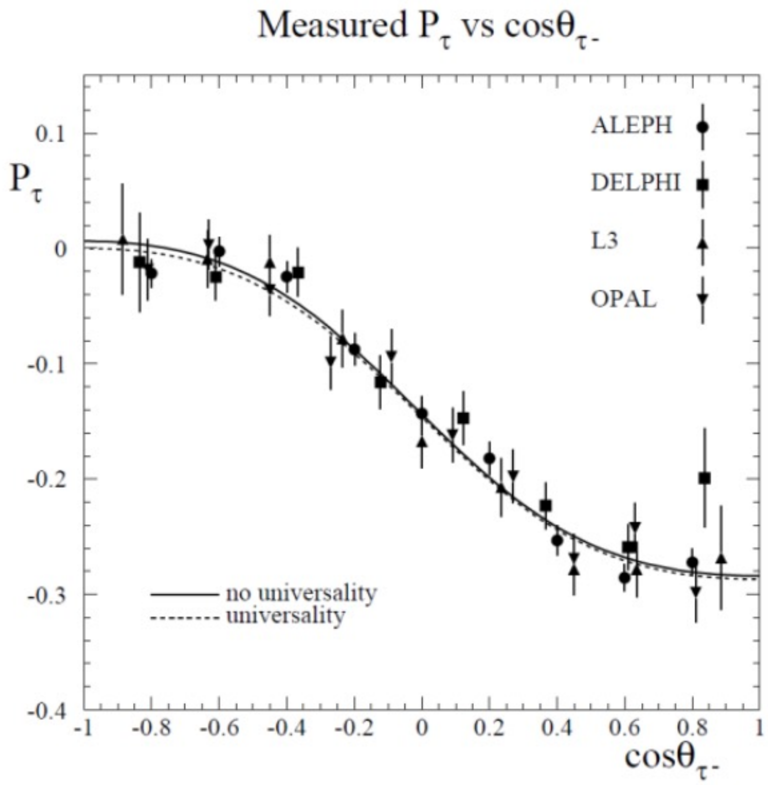
$$A_{\rm FB}^{0,\,\rm f} = \frac{3}{4}\mathcal{A}_{\rm e}\mathcal{A}_{\rm f}$$

$$A_{\rm LR}^{0} = \mathcal{A}_{\rm e}$$

$$A_{\rm LRFB}^{0} = \frac{3}{4}\mathcal{A}_{\rm f}$$

$$\langle \mathcal{P}_\tau^0 \rangle = -\mathcal{A}_\tau$$

$$A_{\rm FB}^{\rm pol,0} = -\frac{3}{4}\mathcal{A}_{\rm e}\,.$$



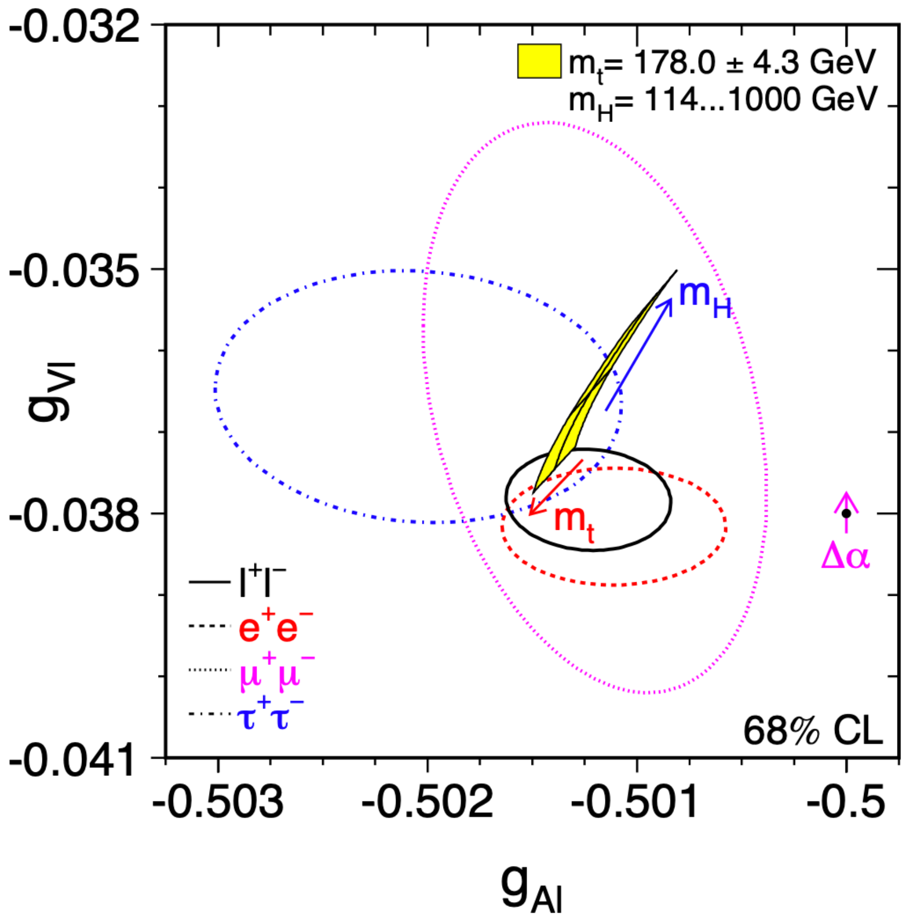
$$\frac{{\rm d}\sigma_{\rm f\bar{f}}}{{\rm d}\cos\theta} = \frac{3}{8}\sigma_{\rm f\bar{f}}^{\rm tot}\left[(1-\mathcal{P}_{\rm e}\mathcal{A}_{\rm e})(1+\cos^2\theta) + 2(\mathcal{A}_{\rm e}-\mathcal{P}_{\rm e})\mathcal{A}_{\rm f}\cos\theta\right]\,.$$

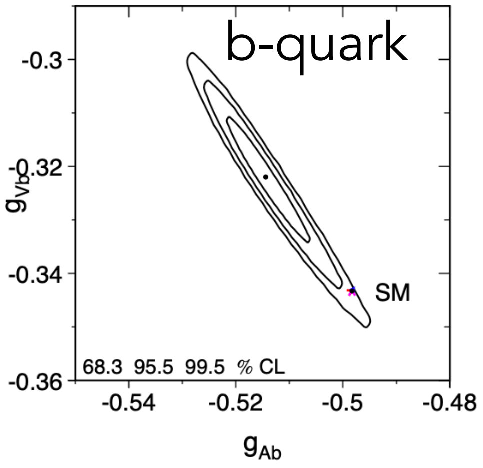
An overall test of the Standard Model: couplings

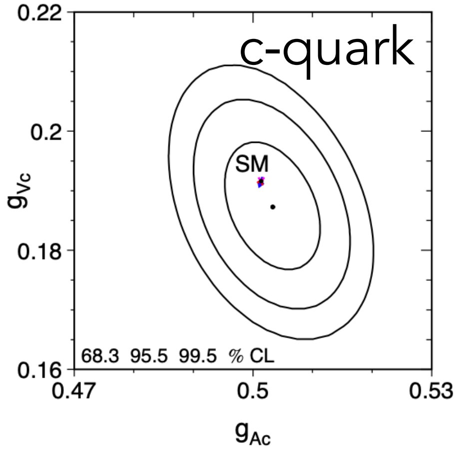
Z^0 partial widths : $|g_V^f|^2 + |g_V^f|^2$

Asymmetries: g_V^f / g_A^f and $\sin^2 \theta_{\text{eff}}^f$

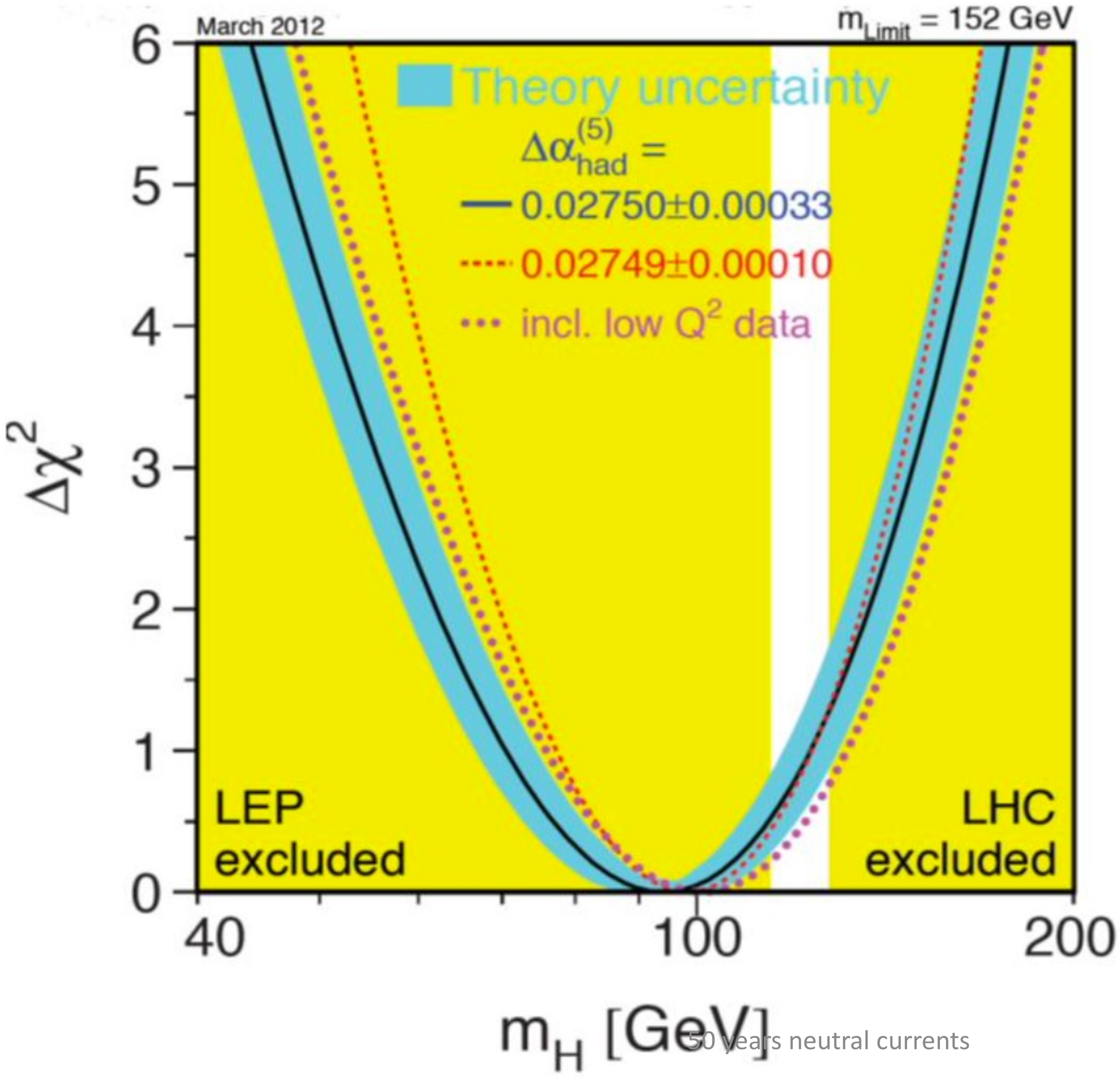
FB asymmetries, τ polarisation, at SLC initial state polarisation



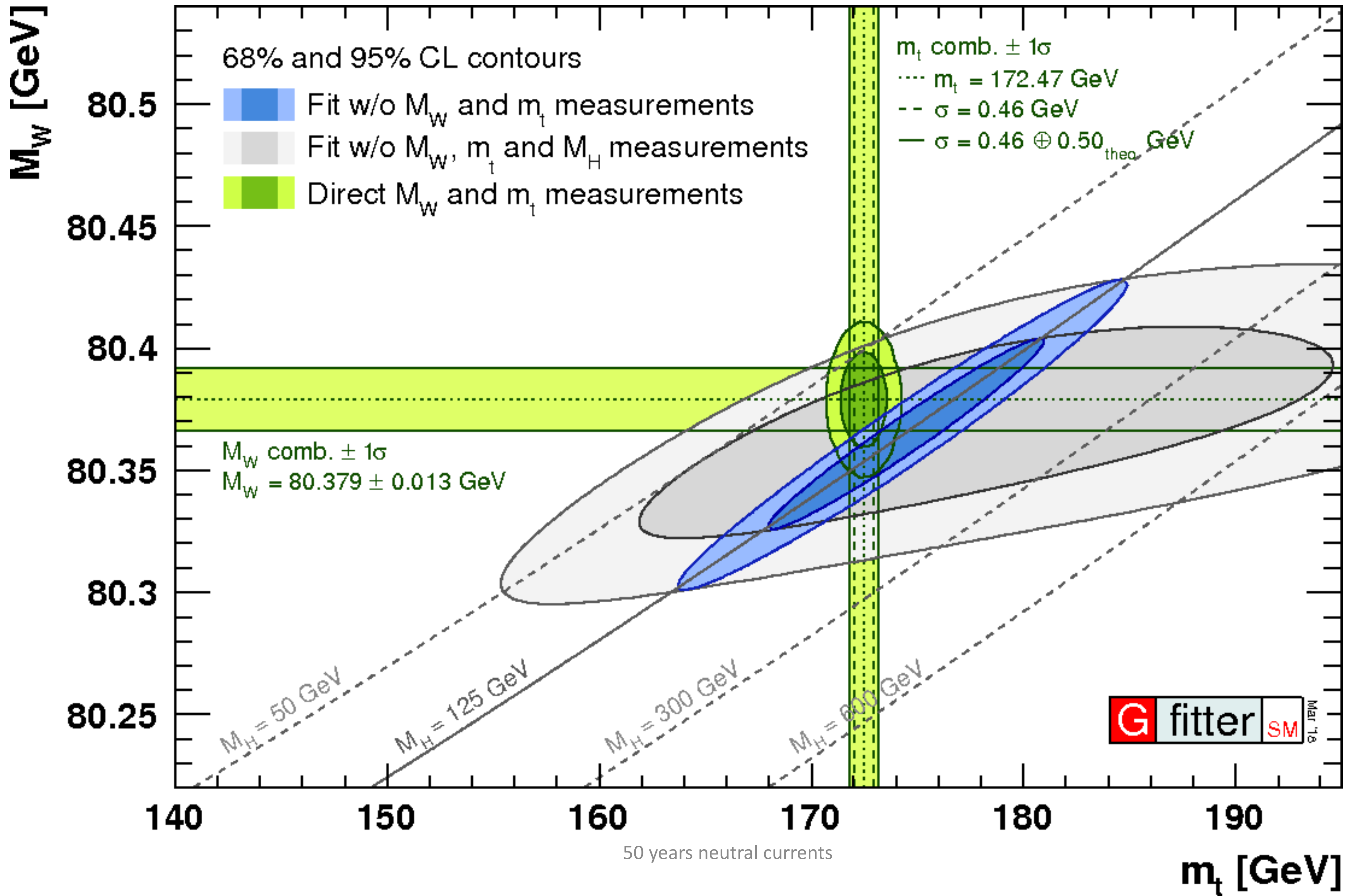




(including LEP2 inputs)

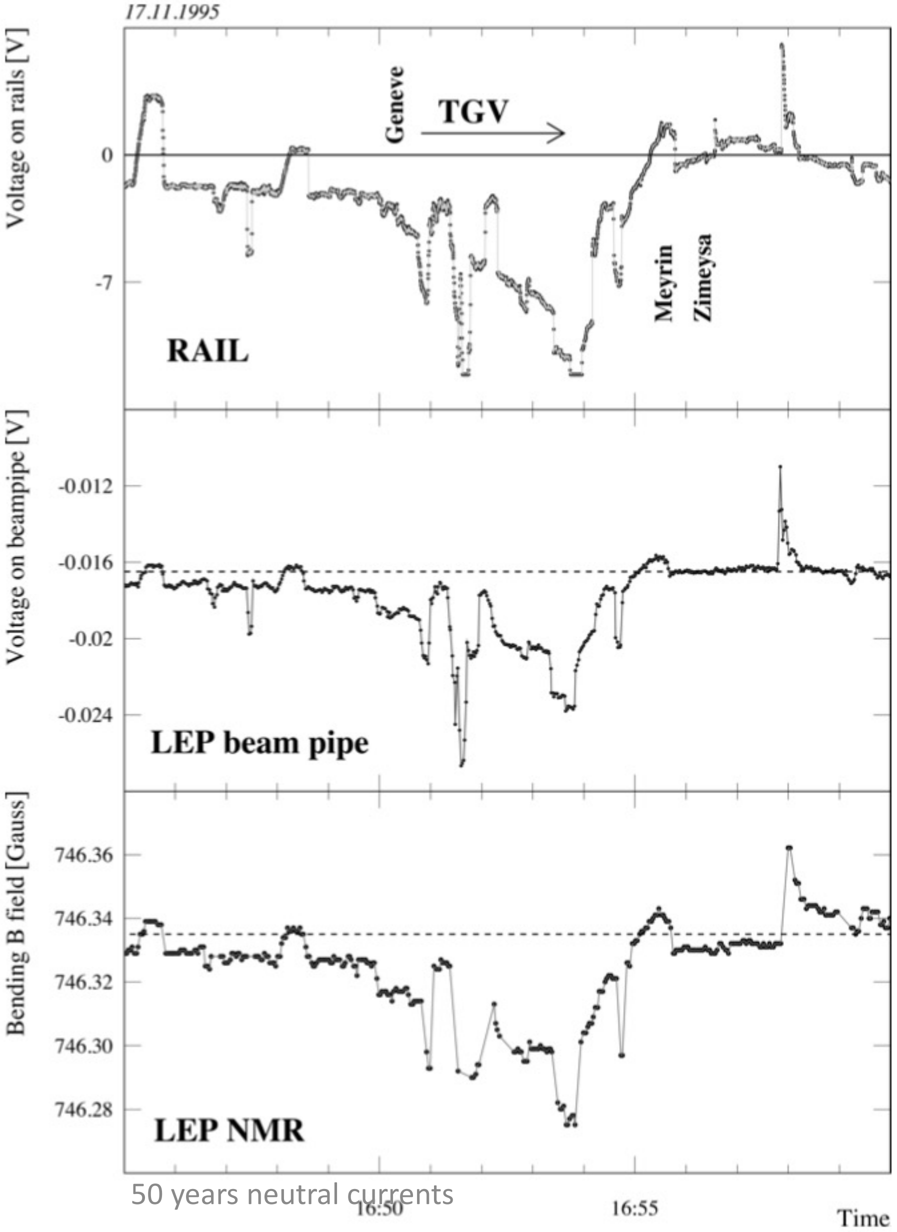


$m_H < 152$ GeV @ 95%CL



68% and 95% CL contours
Fit w/o M_W and m_t measurements
Fit w/o M_W, m_t and M_H measurements
Direct M_W and m_t measurements
m_t comb. ± 1σ
m_t = 172.47 GeV
σ = 0.46 GeV
σ = 0.46 ⊕ 0.50$_{theo}$ GeV
M_W comb. ± 1σ
M_W = 80.379 ± 0.013 GeV
M_H = 50 GeV
M_H = 125 GeV
M_H = 300 GeV
M_H = 600 GeV
G fitter SM
Mar '18
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190

Effect of the TGV on beams energy



Non-abelian structure of QCD