WEAK BOSON PARAMETERS @ LEP

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Contents Overview :

- Introduction
- Z Physics
  - Z resonance parameters
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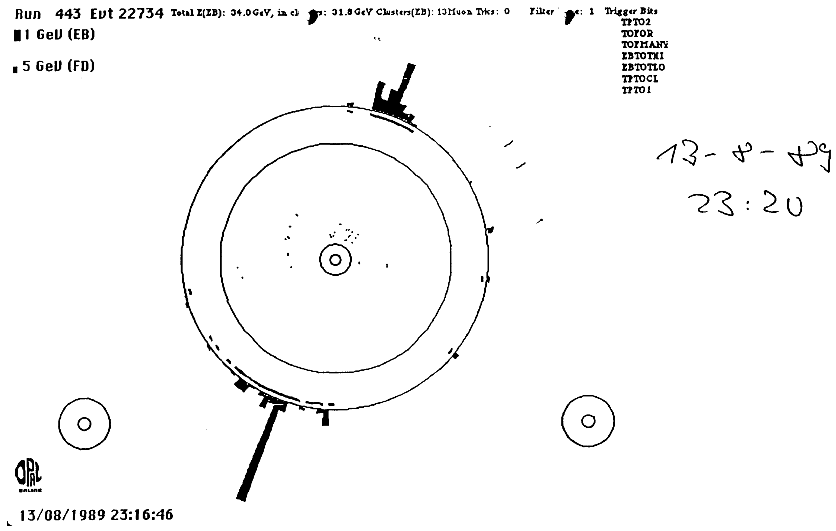
Z Event statistics:

The beginning ...

First event at LEP: August 13th 1989



- 1989 – 1995: $17 \cdot 10^6$ Zs ($15.5 \cdot 10^6\, Z \to q\bar{q}$, $1.7 \cdot 10^6\, Z \to \ell^+\ell^-$)
  recorded for lineshape analyses
  (ALEPH, DELPHI, L3, OPAL)
- 1990– 1991: energy scans with 7 points around the Z peak
- 1992 & 1994 high statistics running on peak
- 1992 last published data
- 1993 & 1995 precision scans at 3 energies
- 1995 report by "Precision calculation WG"
- 1997 LEP Energy calibration finalised
- 1998 / 1999 more theoretical progress
- now, 10 years later

...three analyses final, OPAL close to publication!

W pair event statistics

- 1996 LEP running at W^+W^- threshold
- 1997 E_{cm}=183 GeV, $\int \mathcal{L} = 73\,\mathrm{pb}^{-1}$
- 1998 E_{cm}=189 GeV, $\int \mathcal{L} = 200\,\mathrm{pb}^{-1}$
- 1999 E_{cm}=192 GeV, 196 GeV, 201 GeV, 202 GeV, $\int \mathcal{L} = 250\,\mathrm{pb}^{-1}$
- preparing for run 2000, at highest possible energy

W statistics ∼doubled last year

data taking stopped in November!

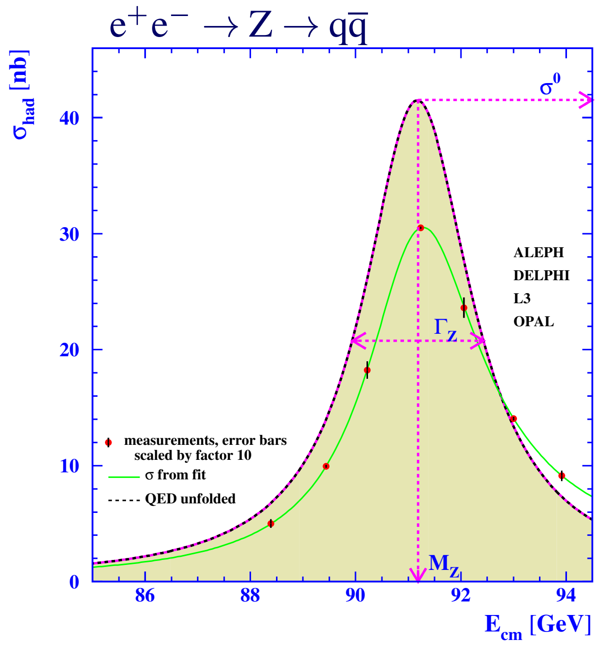
$\Rightarrow$ all LEP II results **very** preliminary

Energy scans around Z peak 1990–1995

total cross sections ...

$e^+e^- \rightarrow$ hadrons
$e^+e^- \rightarrow e^+e^-$
$e^+e^- \rightarrow \mu^+\mu^-$
$e^+e^- \rightarrow \tau^+\tau^-$

... as a function of E_{cm}



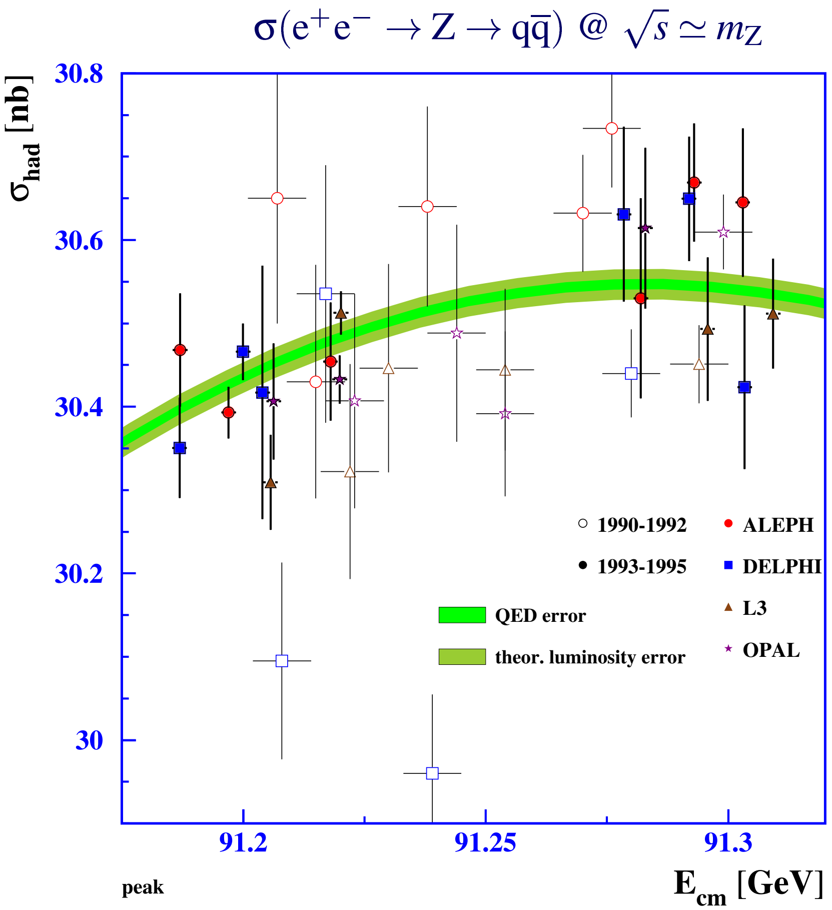
∼30 per channel around 7 “energy points”,

$$\sigma(E_i) = \frac{N^{\mathrm{cand}}_{f\bar{f}}(E_i) - N^{\mathrm{bkg}}_{f\bar{f}}(E_i)}{\varepsilon_{\mathrm{ac}}(E_i)} \frac{1}{\int L\,(E_i)},$$

parameterised in terms of 6 “pseudo-observables”:

- m_Z
- Γ_Z
- $\sigma^o_{\mathrm{had}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\mathrm{had}}}{\Gamma_Z^2}$
- $R_e = \Gamma_{\mathrm{had}} / \Gamma_{ee}$
- $R_\mu = \Gamma_{\mathrm{had}} / \Gamma_{\mu\mu}$
- $R_\tau = \Gamma_{\mathrm{had}} / \Gamma_{\tau\tau}$ $\qquad \Gamma_{ff} \propto \left(g_v^{f\,2} + g_a^{f\,2}\right)$ for f=e, μ, τ

real measurements: 4×27 cross sections



vertical error bars are statistical only
horizontal error bars from beam energy uncertainty fully correlated
theoretical errors (green band) fully correlated
1990-1992 data have larger luminosity errors

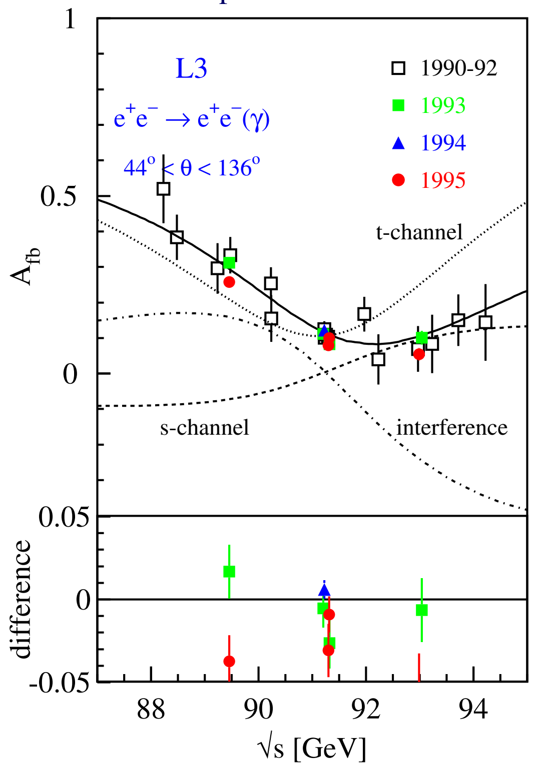
most complicated case: e^+e^-

forward-backward asymmetries

$e^+e^- \to e^+e^-$

$e^+e^- \to \mu^+\mu^-$

$e^+e^- \to \tau^+\tau^-$



$$A_{FB} = \frac{N_{forw} - N_{back}}{N_{tot}} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\sigma_{tot}}$$

3 additional pseudo-observables:

- $A_{FB}^{0,e} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_e$
- $A_{FB}^{0,\mu} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu$
- $A_{FB}^{0,\tau} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_\tau$

$$\mathcal{A}_f = \frac{2\, g_v^f\, g_a^f}{{g_v^f}^2 + {g_a^f}^2}$$

$\sim$200 cross section and asymmetry measurements per experiment described by four sets of only 9 parameters !

What happened last year?

- three experiments final, waiting for OPAL
- QED radiative corrections to $O(\alpha^3)$

  G. Montagna *et al.*, PL **B406** (1997) 243,
  M. Skrzypek, APP **B23** (1992) 135
- reduction in theoretical erron on luminosity by factor 2

  B. Ward et al., ICHEP 98
- results still with version of ZFITTER (6.10 / 6.11)
- cross checks with TOPAZ0 by all experiments

  now also has "model-independent" interface **!**
- improved studies of common uncertainties
- improved calculations of **I**nitial **S**tate **P**air **P**roduction ("ISPP")

  A.B. Arbuzov, hep-ph9907500

will lead to changes of $\sim +0.5\,\mathrm{MeV}$ in m_Z and Γ_Z

Breakdown of errors

Experimental errors:

- event selection, uncertainty ± 0.04–$0.1\,\%$ ($q\bar{q}$) and ± 0.1–$0.7\,\%$ (e, μ, τ)
- integrated luminosity from small-angle Bhabhas, ± 0.033–$0.09\,\%$
- knowledge of beam energy: ± 1.7 MeV on m_Z and ± 1.2 MeV on Γ_Z

  last two correlated among all experiments

Theoretical errors:

all fully correlated among experiments

- small-angle Bhabha cross sections $\pm 0.06\,\%$, OPAL $\pm 0.054\,\%$
- QED $\pm 0.02\,\%$ on σ^o_{had}, $\pm 0.3\,\mathrm{MeV}$ on m_Z, $\pm 0.2\,\mathrm{MeV}$ on Γ_Z

  (dominated by initial state pair production)
- theoretical error on t, s–t correction in Bhabha channel

  R_e : $\pm 0.1\,\%$, $A^{0,e}_{FB}$: $\pm 0.9\,\%$
- uncertainties from "model-independent" parameterisation small

  detailed comparison of TOPAZ0 and ZFITTER
  mSM fits to "realistic observables"

Common errors from energy calibration

Constitute most complicated set of common errors.

Energy errors at each data point and their correlations must be transformed into errors on fitted pseudo-observables:

- Ansatz: covariance matrix of POs is composed as

$$\mathbf{V} = \mathbf{V}_{\mathrm{Energy}} + \mathbf{V}_{\mathrm{exp.}}$$

- compare fits where energy errors are scaled by factors $f_{\pm} = (1 \pm \varepsilon)$
- solve algebraically for $\mathbf{V}_{\mathrm{Energy}}$

Study performed by all experiments on their own data sets

Validated in full fits to the four sets of (preliminary) hadronic cross sections 1993–1995

Consistent findings

$\Rightarrow$ take average as common errors:

m_Z [GeV]	0.0017^2			
Γ_Z [GeV]	-0.0006^2	0.0012^2		
σ^o_{had} [nb]	-0.0018^2	-0.0027^2	0.011^2	
R_e	0.0017^2	-0.0014^2	0.0073^2	0.013^2

$A^{0,e}_{FB}$	0.0004^2		
$A^{0,\mu}_{FB}$	-0.0003^2	0.0003^2	
$A^{0,\tau}_{FB}$	-0.0003^2	0.0003^2	0.0003^2

Luminosity error

BHLUMI 4.04 used for the small-angle Bhabha cross section
error estimate was recently reduced to $\pm 0.061\ \%$

B.F.L Ward *et al.*, UTHEP-96-501 (1998), to be published in PL **B**

OPAL include the effect of light pairs, error then $\pm$ 0.054 %

G. Montagna *et al.*, PL **B** 559 (1999) 3–16

$\Rightarrow$ common errors:

A, D, L	0.061%
A–O,D–O,L–O	0.054 %

t-channel in Bhabhas

ALIBABA used for **t, s–t** contribution to Bhabha cross section
Theoretical errors evaluated

W. Beenakker, G. Passarino, PL**B425**(1998)

Implications on fitted parameters R_e and $A_{FB}^{0,e}$ studied by experiments. **Findings are consistent.**

$\Rightarrow$ use average:

R_e	0.024^2	
$A_{FB}^{0,e}$	-0.0054^2	0.0014^2

t, s–t correction depends on m_Z
now propagated into fits by all experiments
$\Rightarrow$ correlations of about
$+10\ \%$ between m_Z & R_e
$-10\ \%$ between m_Z & $A_{FB}^{0,e}$

Common errors on Z parameters

QED corrections

Compare 2 different schemes

- O(... $\alpha^2 L^2, \alpha^2 L, \alpha^2 L^0$) calculations

  Berends *et al.*, NP **B297** (1988) 429 and **B304** (1988)

  + exponentiation — E.A. Kuraev, V.S. Fadin, Sov.J.NP**41** (1985)
  + $O(\alpha^3)$ — G. Montagna *et al.*, PL **B406** (1997) 243,
- YFS 2[nd] order inclusive exponentiation scheme

  S. Jadach *et al.* PL**B257**(1991), M. Skrzypek, APP**B23**(1992)

Both schemes implemented in fit programs
Differences of only 0.1 MeV on m_Z & Γ_Z and of 0.01 % on σ^o_{had}

More severe:
fermion pair radiation from the initial state (ISPP)

comparison of the implementation in
ZFITTER and TOPAZ0 with — A.B. Arbuzov, hep-ph9907500
the JSM-approach — S. Jadach, M. Skrzypek, M. Martinez, PL**B280**

leads to error estimates:

± 0.3 MeV	on	m_Z
± 0.2 MeV	on	Γ_Z
$\pm 0.02\ \%$	on	σ^o_{had}

"Parametric" errors

m_Z depends on mSM parameters
dominantly through the γ–Z interference term, which is fixed to the SM value

variation of m_H:

$$\Delta m_Z = +0.23\,\text{MeV per unit change in } \log_{10}(m_H/\text{GeV})$$

variation of $\alpha(m_Z)$:

error of ± 0.05MeV on m_Z

other POs unaffected

The fit programs

Detailed comparison at the level 10^{-4}
of mSM and MI calculations in

TOPAZ0

ZFITTER

Transformation of differences in calculated cross sections
into differences in fitted POs

taken as errors

$\Rightarrow$

± 0.1 MeV	on	m_Z
± 0.1 MeV	on	Γ_Z
± 1 pb	on	σ^o_{had}
± 0.004	on	R_ℓ
± 0.0001	on	$A^{0,\ell}_{FB}$

negligible compared with other errors

Combination Procedure

Combination of $4\times \sim 200$ individual measurements
is too complex a task because of strongly correlated errors.

Average at the level of the nine pseudo-observables
+ correlations & common errors

Cross checks:

- hadrons 1993-1995 by the four experiments treated in one fit

  $\Rightarrow$ **treatment of energy errors sufficiently precise, possible problem with m_Z due to largely different energy errors in 1993 and 1995, solved by next item**
- special fits by each experiment with different Z masses 1990–1992, 1993-1994 and 1995

  $\Rightarrow$ **m_Z ok at the level of 10 % of its combined error**
- mSM fits to cross sections and asymmetries to extract Lagrangian parameters, compare with mSM fit to POs

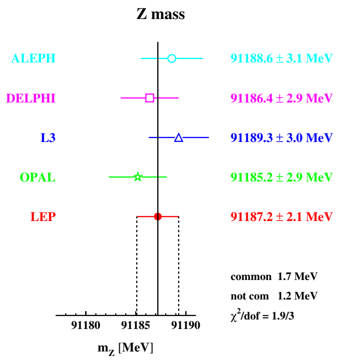
  $\Rightarrow$ **largest effect for m_Z: LEP average changes by $\sim$0.2 MeV or 10 % of error**
- all independent experimental errors scaled by factor 0.5 to simulate a "generic combined LEP experiment"

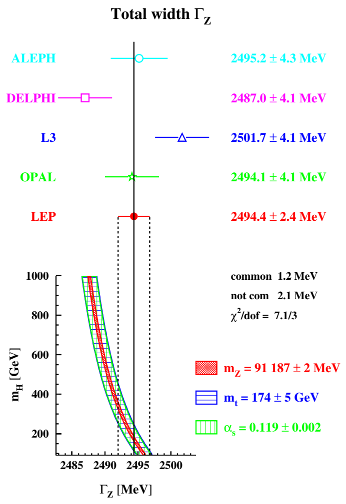
  $\Rightarrow$ **same average for each PO within at most 10 % of the combined error**

Combination of 4 sets of 9 POs ok

Results of combination

based on 9 POs, χ^2/DoF = 33/27 (22 % prob.)



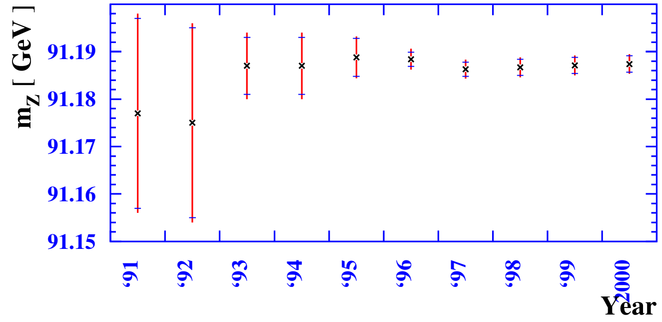


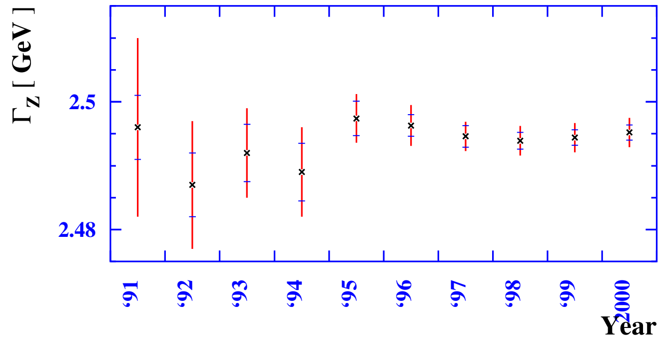
$m_Z = 91.1872 \pm 0.0021$ GeV — will go up ~0.5 MeV

$\Gamma_Z = \ \ 2.4944 \pm 0.0024$ GeV — will go up ~0.5 MeV

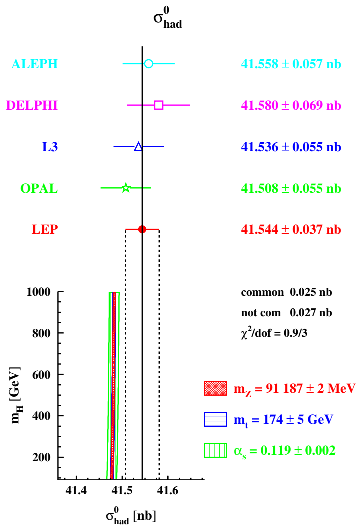
- changes in m_Z and Γ_Z w.r.t. 1998 largely due to $O(\alpha^3)$ QED
- error on m_Z dominated by common energy uncertainty
- theoretical error on m_Z and Γ_Z finally around ± 0.3 MeV

The history of m_Z and Γ_Z measurements at LEP





The hadronic pole cross section

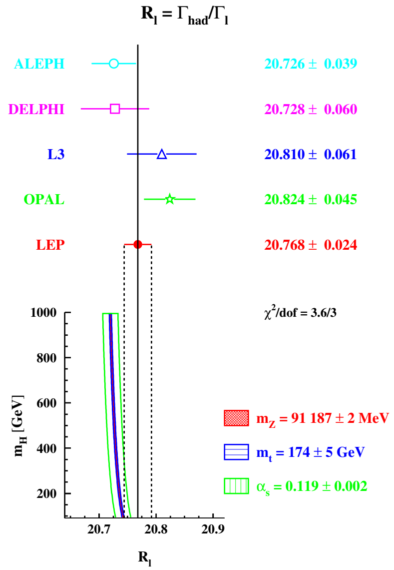


$$\sigma^o_{had} = 41.544 \pm 0.037 \text{ nb}$$

- dominated by common systematic errors:
  - ± 25 pb luminosity theory
  - ± 8 pb QED radiation
  - ± 10 pb energy calibration
- contribution of uncorrelated exp. systematics ($\Delta\mathcal{L}/\mathcal{L}$ & ΔN_{had}): $\sim \pm 20$ pb
- correlation between Γ_Z and σ^o_{had}: 30 %

LS & A_{FB} Results

Lepton cross sections

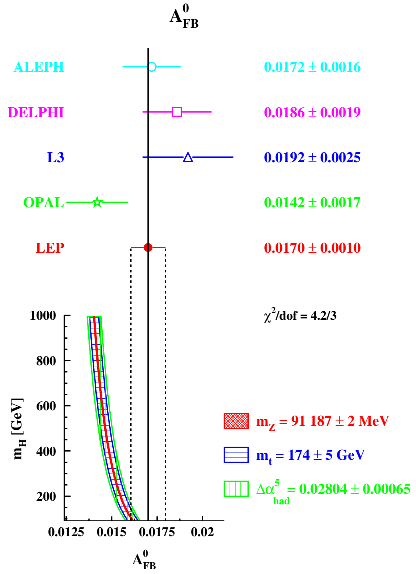


$$R_e = 20.803 \pm 0.049$$
$$R_\mu = 20.786 \pm 0.033$$
$$R_\tau = 20.764 \pm 0.045$$

- common errors on R_e: t-channel of ± 0.022, energy ± 0.013

Günter Quast, CERN & Mainz Loops & Legs 2000

Leptonic forward-backward asymmetries

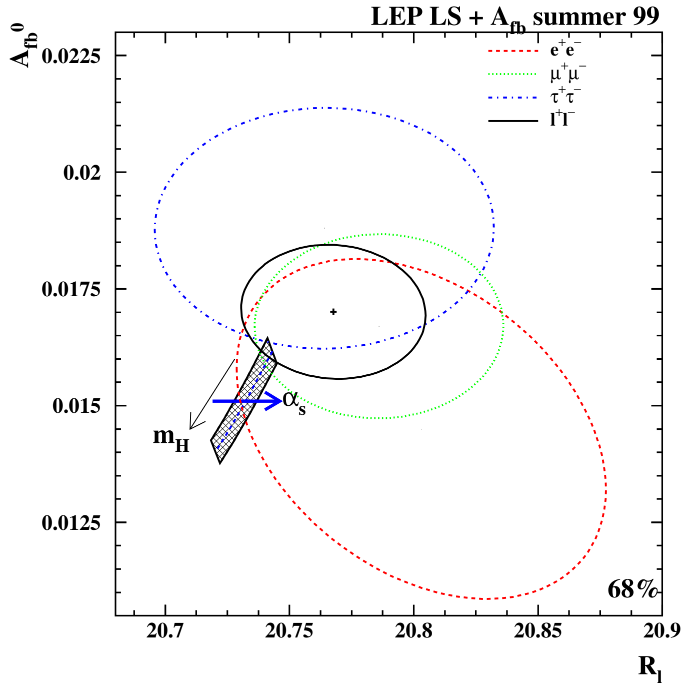


$$A_{FB}^{0,e} = 0.0145 \pm 0.0024$$

$$A_{FB}^{0,\mu} = 0.0167 \quad \pm 0.0013$$

$$A_{FB}^{0,\tau} = 0.0188 \pm 0.0017$$

- common error from t-channel of 0.013 on $A_{FB}^{0,e}$
- correlation between R_e and $A_{FB}^{0,e}$: 35 %



Note: R_τ expected to be 0.23 % larger due to mass effects

Measurements consistent with lepton universality

$$R_\ell = 20.768 \pm 0.024\,, \qquad A_{FB}^{0,\ell} = 0.01701 \pm 0.00095$$

- theory error on R_ℓ and $A_{FB}^{0,\ell}$ $\sim \pm 10\,\%$ of total error

α_s from R_ℓ: $0.1229 \pm 0.0036_{\mathrm{exp.}}$

α_s from $\sigma^o_{\mathrm{lept}} = \sigma^o_{\mathrm{had}} / R_\ell$: $0.1186 \pm 0.0030_{\mathrm{exp.}}$ for $m_H = 100$ GeV

Weak mixing angle from $A_{FB}^{0,\ell}$: $\sin^2\theta^{\mathrm{lept}}_{eff} = 0.23107 \pm 0.00053$

Some derived quantities

	without	with
	lepton universality	
Γ_{had} [MeV]	1745.3±2.7	1743.9±2.0
Γ_{inv} [MeV]	497.2±2.5	498.8±1.5
$\Gamma_{inv}/\Gamma_{\ell\ell}$	-	5.941±0.016
$\Gamma_{\ell\ell}$ [MeV]	-	83.959±0.089
Γ_{ee} [MeV]	83.90 ±0.12	-
$\Gamma_{\mu\mu}$ [MeV]	83.96 ±0.18	-
$\Gamma_{\tau\tau}$ [MeV]	84.05 ±0.22	-

Number of neutrino generations

with $\left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = 1.9912^{+0.0012}_{-0.0003}$ for $m_H = 150^{+900}_{-60}$ GeV

$\Rightarrow$ $$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\ell\ell}} \Big/ \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = 2.9835 \pm 0.0083$$

- 2 σ below 3 !

Limit on invisible width not from neutrinos

with $(\Gamma_{inv})_{SM} = 501.7^{+0.1}_{-0.9}$ MeV

$\Rightarrow$ $$\Gamma^x_{inv} = -2.9^{+1.7}_{-1.5}\,\text{MeV}$$

$$\Delta\Gamma^x_{inv} < 2.0\,\text{MeV @ 95\% CL}$$

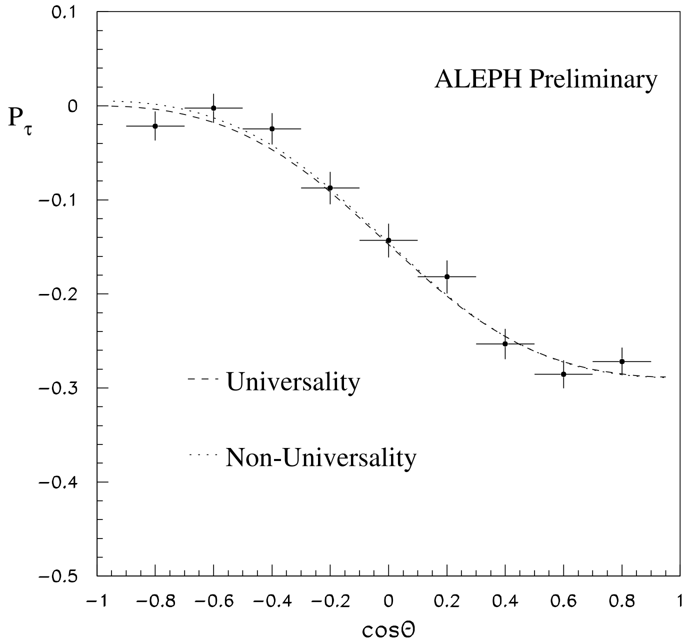
conservatively, limit was derived allowing only positive values of $\Delta\Gamma^x_{inv}$.

τ Polarisation

in $e^+e^- \to \tau^+\tau^-$ spin in final state measurable
if validity of V-A in τ decay assumed

angular dependence of τ polarisation:

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$



also: average τ polarisation $\langle\mathcal{P}_\tau\rangle$ and
forward-backward asymmetry of τ polarisation $A^{\mathcal{P}_\tau}_{fb}$

$\Rightarrow$ $\mathcal{A}_\tau$ and $\mathcal{A}_e$
as observables

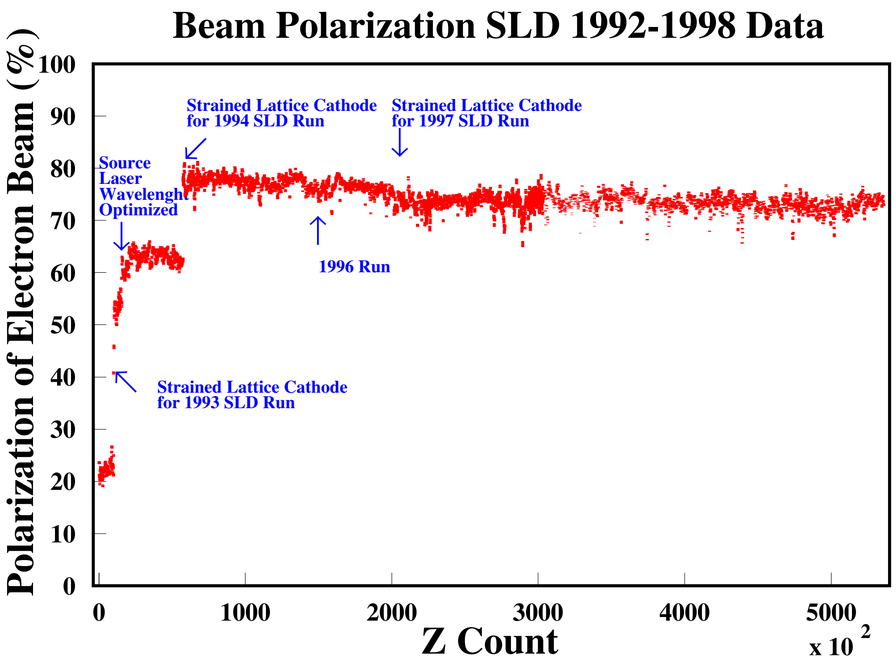
Measurements at SLC

Measurements with polarised e^- colliding with unpolarised e^+;

analogous to LEP:

σ and A_{FB} separately for right- and left-handed polarised e^-

sensitive to polarisation level $\mathcal{P}_e$!



$$A_{LR} = \frac{1}{\mathcal{P}_e} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto \mathcal{A}_e \quad A_{fb,LR} = \frac{1}{\mathcal{P}_e} (A_{fb,L} - A_{fb,R}) \propto \mathcal{A}_f$$

Observables: $\mathcal{A}_f$ for f=e, μ, τ, c ,b

also: $R_b = \Gamma_{b\bar{b}} / \Gamma_{had}$

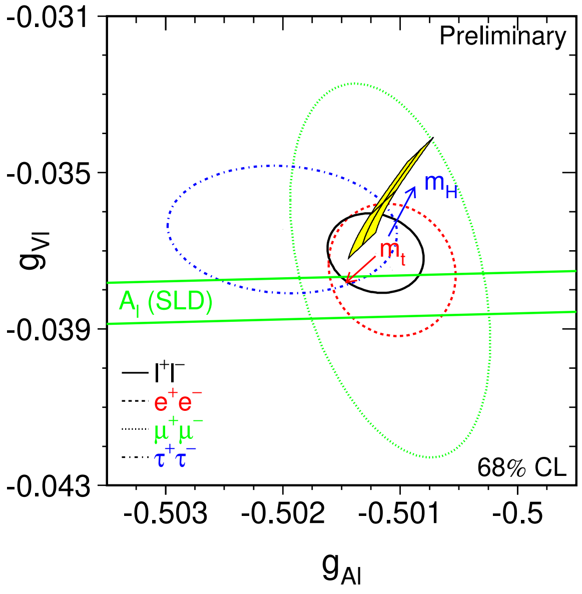
thanks to good vertex detector and small IP

Lepton couplings

include τ polarisation results

LEP average: $\mathcal{A}_\tau = 0.1425 \pm 0.0044$

$\mathcal{A}_e = 0.1483 \pm 0.0051$



ratios of couplings

LEP only

$g^v_\mu / g^v_e = 0.998 \pm 0.099$
$g^v_\tau / g^v_e = 0.972 \pm 0.042$
$g^a_\mu / g^a_e = 1.0000 \pm 0.0014$
$g^a_\tau / g^a_e = 1.0019 \pm 0.0015$

LEP + SLC

$g^v_\mu / g^v_e = 0.955 \pm 0.063$
$g^v_\tau / g^v_e = 0.954 \pm 0.030$
$g^a_\mu / g^a_e = 1.0002 \pm 0.0013$
$g^a_\tau / g^a_e = 1.0019 \pm 0.0015$

Note: SLD and LEP consistent !

lepton universality $\surd$

Heavy Flavour Physics

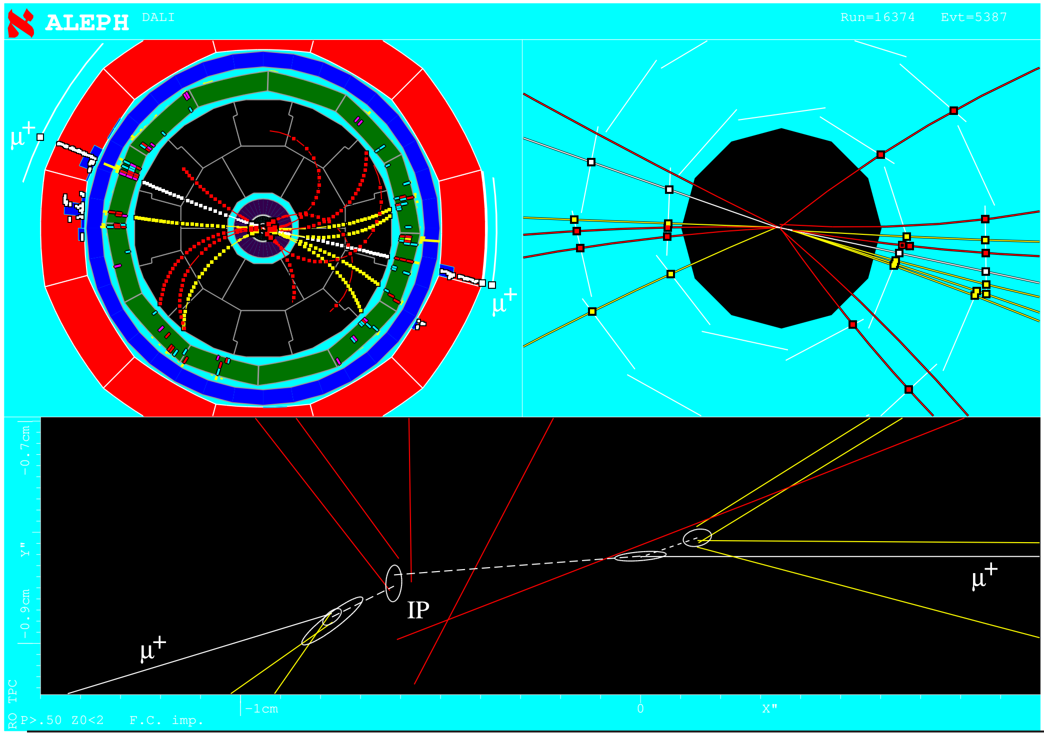
b-quarks are
- long-lived ($\mathcal{O}$(mm) flight distance)
- heavy
- decay in cascades

can be well identified in detectors

electroweak observables

$$R_\mathrm{b} = \frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_\mathrm{had}} \quad \Rightarrow \quad \rho_\mathrm{b}$$

$$A_\mathrm{FB}^{0,\mathrm{b}} \quad \Rightarrow \quad \sin^2\theta_{eff}^{\mathrm{lept}}$$



Complicated combination procedure,
depends on many properties of heavy hadrons

EW parameters extracted from 18-parameter fit:

R_b	=	0.21643 ± 0.00073
R_c	=	0.1674 ± 0.0038
$A_\mathrm{FB}^{\mathrm{b\bar{b}}}(-2)$	=	0.0570 ± 0.0078
$A_\mathrm{FB}^{\mathrm{c\bar{c}}}(-2)$	=	-0.037 ± 0.017
$A_\mathrm{FB}^{\mathrm{b\bar{b}}}(\mathrm{pk})$	=	0.0968 ± 0.0021
$A_\mathrm{FB}^{\mathrm{c\bar{c}}}(\mathrm{pk})$	=	0.0628 ± 0.0038
$A_\mathrm{FB}^{\mathrm{b\bar{b}}}(+2)$	=	0.1130 ± 0.0069
$A_\mathrm{FB}^{\mathrm{c\bar{c}}}(+2)$	=	0.138 ± 0.015
$\mathcal{A}_\mathrm{b}$	=	0.911 ± 0.025
$\mathcal{A}_\mathrm{c}$	=	0.630 ± 0.026
$\mathrm{BR}(\mathrm{b} \to \ell)$	=	0.1062 ± 0.0017
$\mathrm{BR}(\mathrm{b} \to \mathrm{c} \to \bar{\ell})$	=	0.0807 ± 0.0025
$\mathrm{BR}(\mathrm{c} \to \ell)$	=	0.0985 ± 0.0032
$\bar{\chi}$	=	0.1186 ± 0.0043
$f(\mathrm{D}^+)$	=	0.239 ± 0.016
$f(\mathrm{D_s})$	=	0.117 ± 0.025
$f(\mathrm{c_{baryon}})$	=	0.084 ± 0.023
$\mathrm{P}(\mathrm{c} \to \mathrm{D}^{*+}) \times \mathrm{BR}(\mathrm{D}^{*+} \to \pi^+\mathrm{D}^0)$	=	0.1653 ± 0.0053

χ^2/d.o.f. of $54/(96-18)$

Use in fits to LEP only [and LEP+SLC] data:

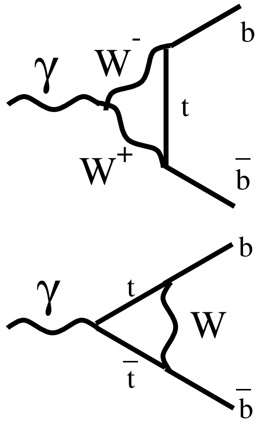
R_b, R_c, $A_\mathrm{FB}^{0,\mathrm{b}}$, $A_\mathrm{FB}^{0,\mathrm{c}}$ [,$\mathcal{A}_\mathrm{b}$, $\mathcal{A}_\mathrm{c}$]

	R_b (10^{-3})	R_c (10^{-3})	$A_{FB}^{0,b}$ (10^{-3})	$A_{FB}^{0,c}$ (10^{-3})	$\mathcal{A}_b$ (10^{-2})	$\mathcal{A}_c$ (10^{-2})
statistics	0.46	2.6	1.8	3.2	1.8	2.0
internal systematics	0.32	2.3	0.8	1.5	1.7	1.6
QCD effects	0.21	0.2	0.2	0.1	0.5	0.2
BR(D $\rightarrow$ neut.)	0.17	0.1	0	0	0	0
D decay multiplicity	0.10	0.3	0	0	0	0
BR($D^+ \rightarrow K^-\pi^+\pi^+$)	0.11	0.4	0.1	0	0	0
BR($D_s \rightarrow \phi\pi^+$)	0.03	0.9	0.1	0	0	0
BR($\Lambda_c \rightarrow p K^-\pi^+$)	0.06	0.8	0	0.1	0	0
D lifetimes	0.07	0.2	0	0.1	0	0
gluon splitting	0.28	0.7	0	0.2	0.1	0.1
c fragmentation	0.08	0.4	0.1	0.1	0.1	0.1
light quarks	0.08	0.3	0.5	0.1	0	0
total	0.73	3.8	2.0	3.7	2.5	2.6

Dominant errors on HvFl. parameters

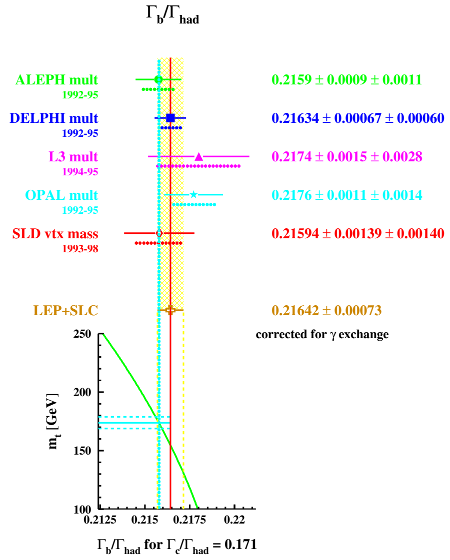
Overview of measurements with b quarks

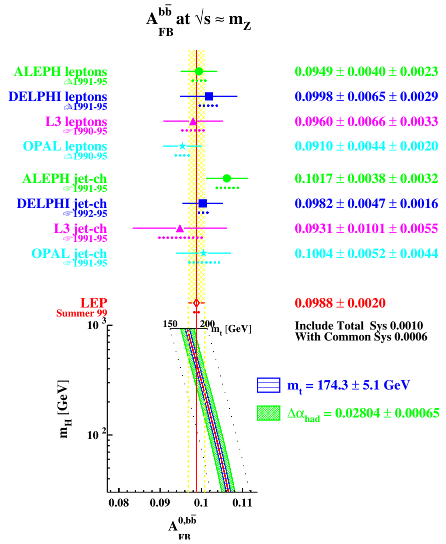
special top dependence:



$\Rightarrow$

$$\rho^b_{eff} = \rho_{eff}(1+\delta_b)$$
$$\sin^2\theta^b_{eff} = \sin^2\theta_{eff}(1-\tfrac{1}{2}\delta_b)$$





almost no dependence on Higgs!

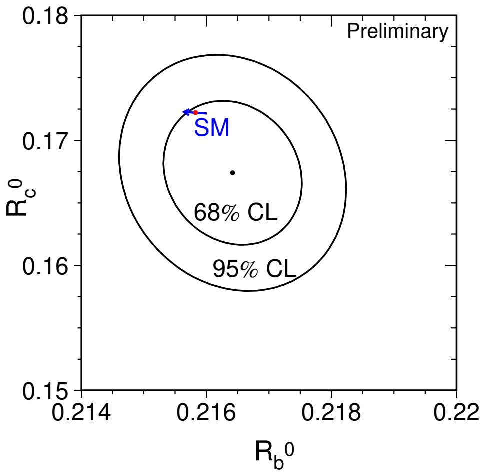
most precise $\sin^2\theta^{lept}_{eff}$ at LEP!

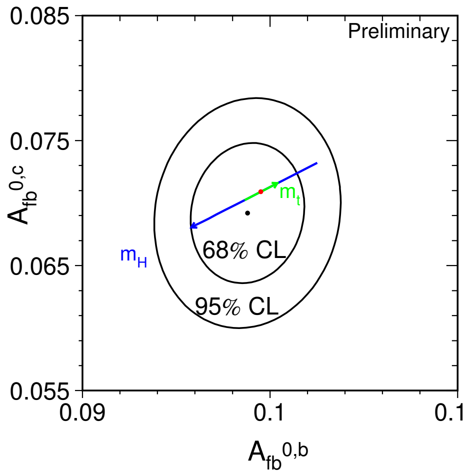
all data up to 1995 analysed   some results not yet final

correlations are important

Rb and Rc: $-17\,\%$

$A_{FB}^{0,b}$ and $A_{FB}^{0,c}$: $+13\,\%$ $\Rightarrow$ contour plots





LEP:

$R_b = 0.21642 \pm 0.00075$, $R_c = 0.1675 \pm 0.0048$,

$A_{FB}^{0,b} = 0.0988 \pm 0.0020$, $A_{FB}^{0,c} = 0.0689 \pm 0.0037$,

LEP + SLD combination:

$R_b = 0.21642 \pm 0.00073$, $R_c = 0.1674 \pm 0.0038$,

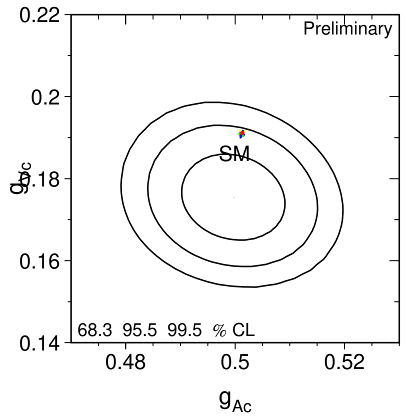
$A_{FB}^{0,b} = 0.0988 \pm 0.0020$, $A_{FB}^{0,c} = 0.0692 \pm 0.0037$,

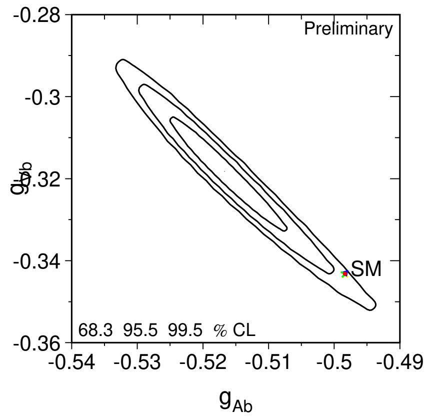
$\mathcal{A}_b = 0.911 \pm 0.025$, $\mathcal{A}_c = 0.630 \pm 0.026$.

+ correlations

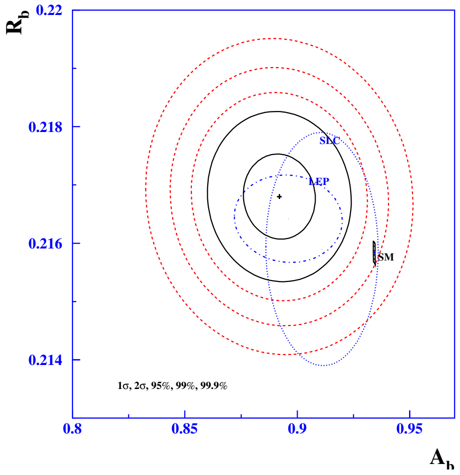
Is there a problem?

Couplings in b sector deviate from Standard Modell!



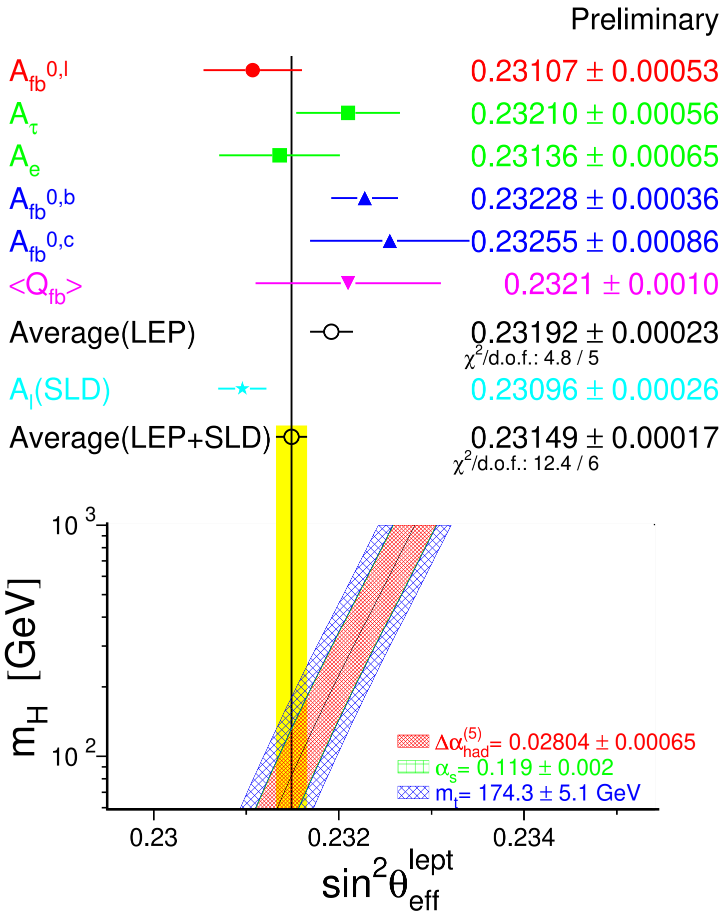


$\mathcal{A}_b$	$\mathcal{A}_c$
LEP ($\mathcal{A}_\ell = 0.1471 \pm 0.0026$)	
0.896 ± 0.024	0.625 ± 0.035
SLD direct	
0.911 ± 0.025	0.630 ± 0.026
LEP+SLD ($\mathcal{A}_\ell = 0.1497 \pm 0.0016$)	
0.892 ± 0.016	0.625 ± 0.021
SM	
$0.9345^{+0.0002}_{-0.0006}$	$0.667^{+0.001}_{-0.004}$



Combination of three small problems: $\mathcal{A}_b$ by SLD, $A_{FB}^{0,b}$ from LEP and $\mathcal{A}_\ell$ by LEP/SLD result in 3-sigma effect on $\mathcal{A}_b$!

Summary of asymmetry-type measurements
- effective weak mixing angle



worst disagreement: the two most precise measurements, A_{LR} from SLD and $A_{FB}^{0,b}$ from LEP, disagree by about 3 σ

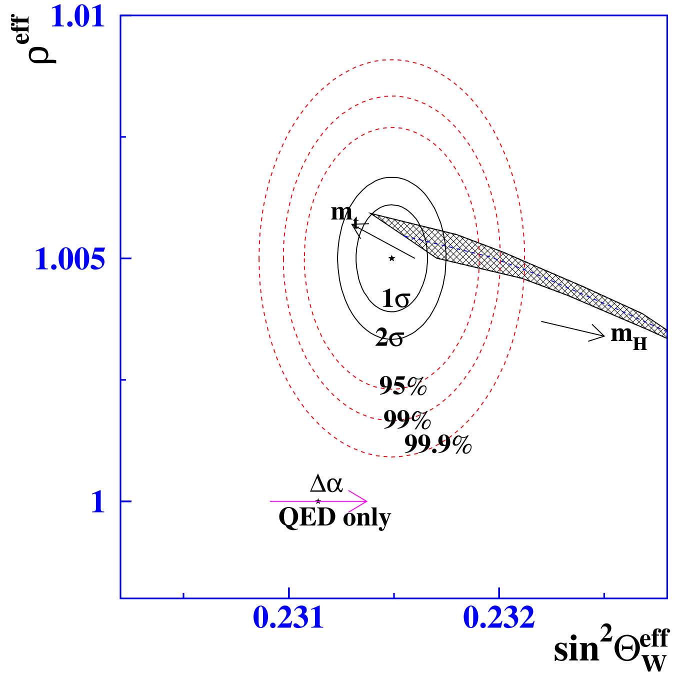
overall χ^2 of the average is 12 for 6 DoF, χ^2-prob. 6 %

Most results final, we'll have to live with it!

look at ρ_{eff}^{lept} vs. $\sin^2\theta_{eff}^{lept}$

$$\Gamma_{\ell\ell} \propto \rho = \frac{1}{1-\Delta\rho}$$

$$\rho_{eff}^{lept} = 1.0050 \pm 0.0011$$

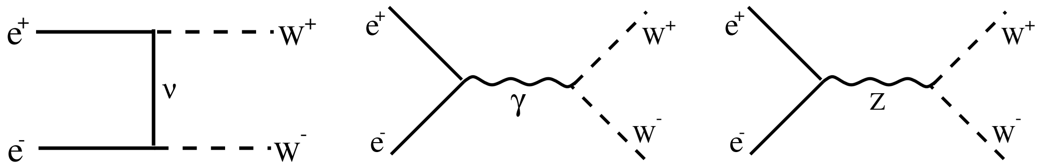


pure QED corrected point ("*" on plot) given by

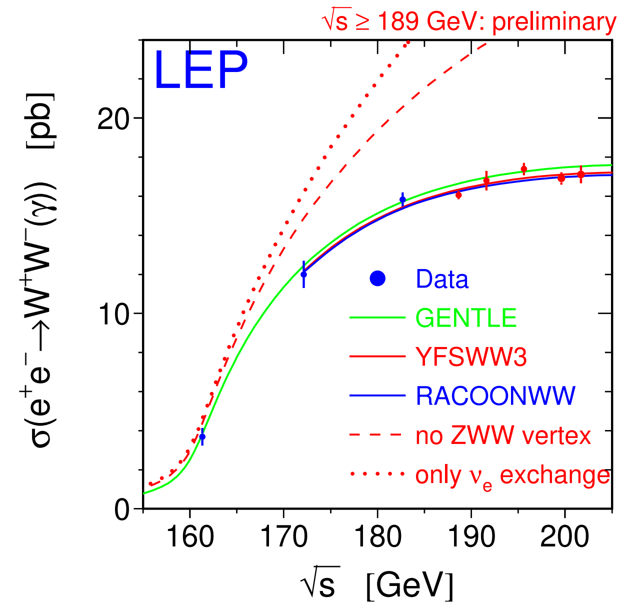
$$(\sin^2\theta_W)^0\,(\cos^2\theta_W)^0 = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2}$$

- presence of genuine electroweak corrections with >99.9 % CL (mainly due to $\Delta\rho$) !

WW cross section contributing diagrams:



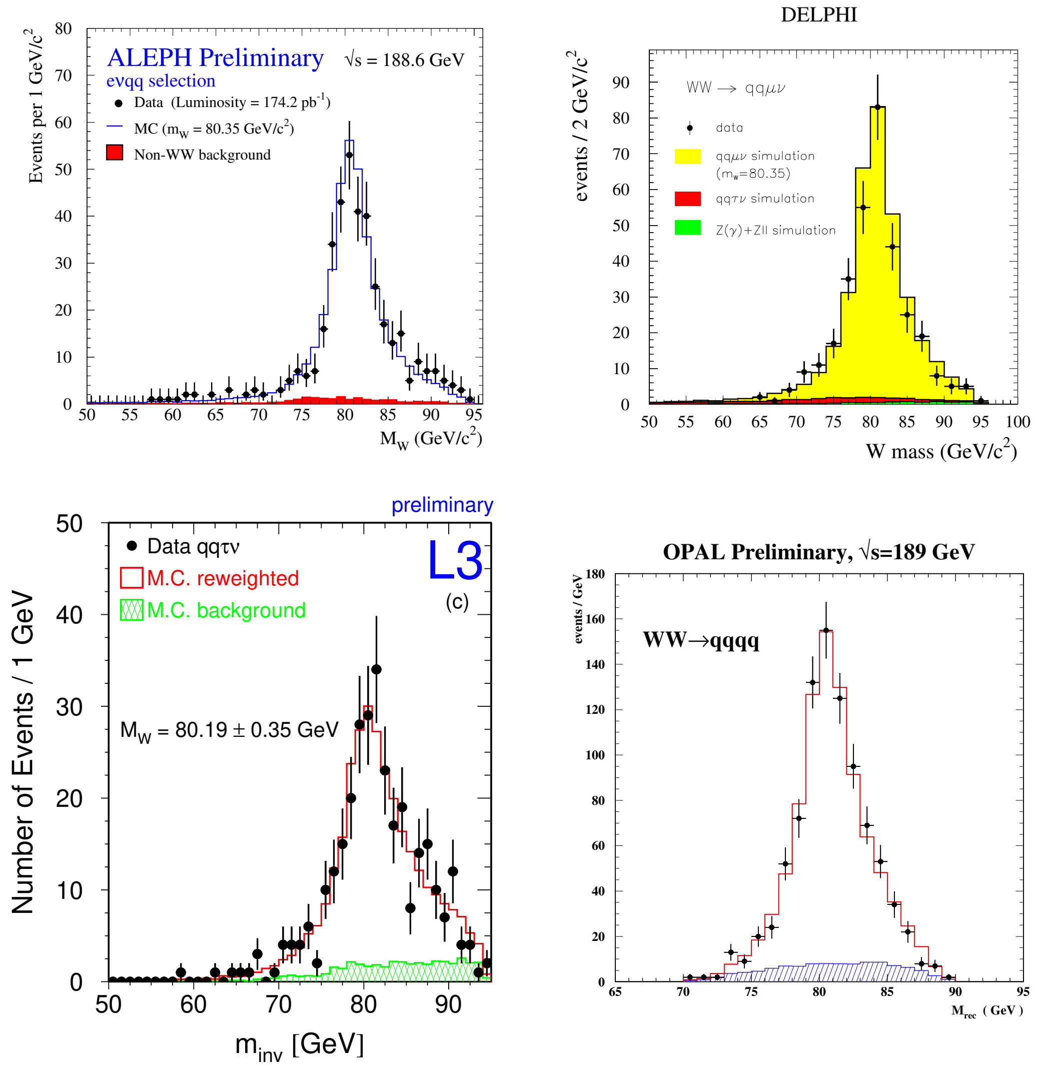
including 1999 data(**very prel.**)



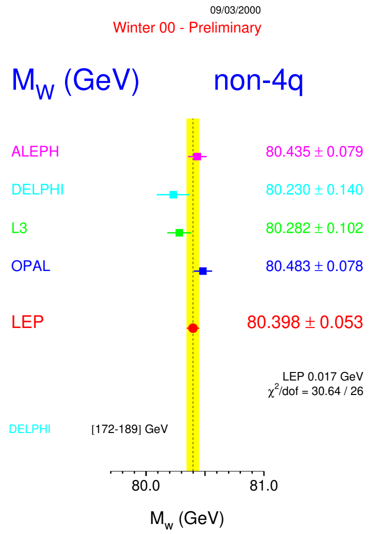
- SM branching fractions of $W^{\pm}$ assumed
- QED component of error ($\sim \pm 0.010$ pb) taken as fully correlated
- calculations:
  - Gentle: D. Bardin *et al.*, Comp. Phys. Comm. **104** (1997) 161
  - YFSWW3: Monte Carlo, S. Jadach *et al.*, CERN-TH-99-222
  - RacoonWW: Monte Carlo, A. Denner *et al.*, hep-ph/9912261

W boson mass

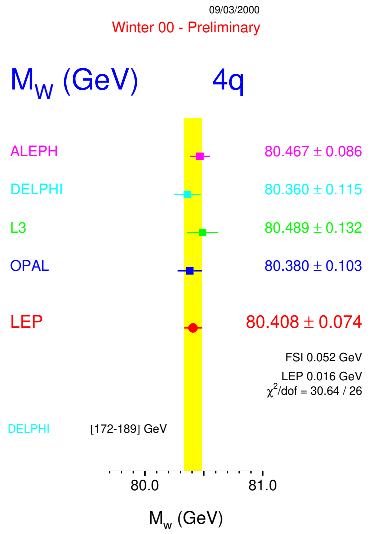
Measuremnts at 189 GeV



W mass averages



common errors: ± 31 MeV± 17 MeV$_{energy}$



common errors: ± 31 MeV± 52 MeV$_{FSI}$$\pm 16$ MeV$_{energy}$

correlated errors:

- ISR and fragmentation errors (± 31 MeV) among all measurements
- LEP beam energy uncertainty (± 17 MeV on m_{W}) among all measurements
- **F**inal **S**tate **I**nteractions ("FSI") [Bose-Einstein & Color Reconnection] (± 52 MeV) among $\mathrm{q\bar{q}q\bar{q}}$ measurements

important cross check on FSI:

$$m_{\mathrm{W}}{}^{4q} - m_{\mathrm{W}}{}^{\mathrm{non}-4q} = 35 \pm 55\,\mathrm{MeV}$$ FSI appears to be really small

average from direct reconstruction: $m_{\mathrm{W}} = 80.401 \pm 0.049$ GeV

combine with σ_{WW} from threshold: $m_{\mathrm{W}} = 80.40 \pm 0.22$ GeV

$\Rightarrow$ LEP combined: $m_{\mathrm{W}} = 80.401 \pm 0.048$ GeV

W mass - non-LEP

W mass from CDF/D0: $m_{\mathrm{W}\,\mathrm{p\bar{p}}} = 80.448 \pm 0.062$ GeV

$\Rightarrow$ world average: $m_{\mathrm{W}} = 80.419 \pm 0.038$ GeV

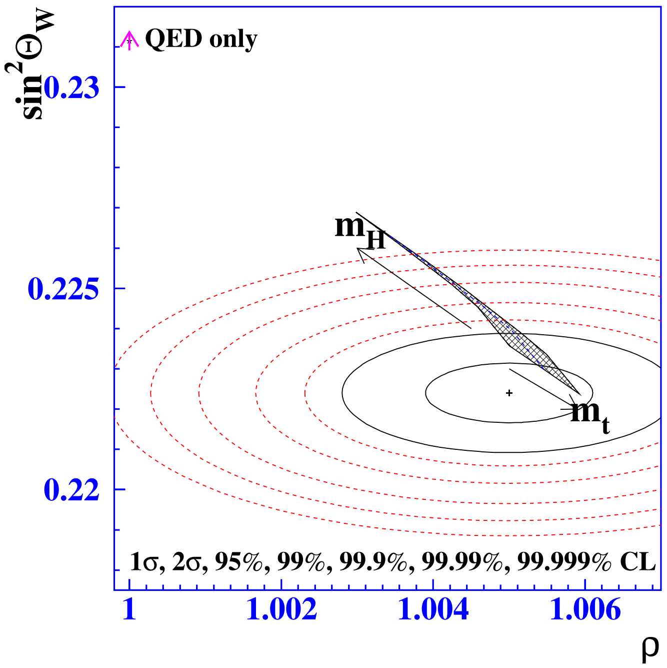
Now dominated by LEP measurements!

The real proof for genuine ew corrections ...

$$\sin^2\theta_W = 1 - m_W^2/m_Z^2 \quad \text{vs.} \quad \Delta\rho$$

$$\sin^2\theta_W = 0.22224 \pm 0.000074$$

$$\Delta\rho = 0.0050 \pm 0.000011$$



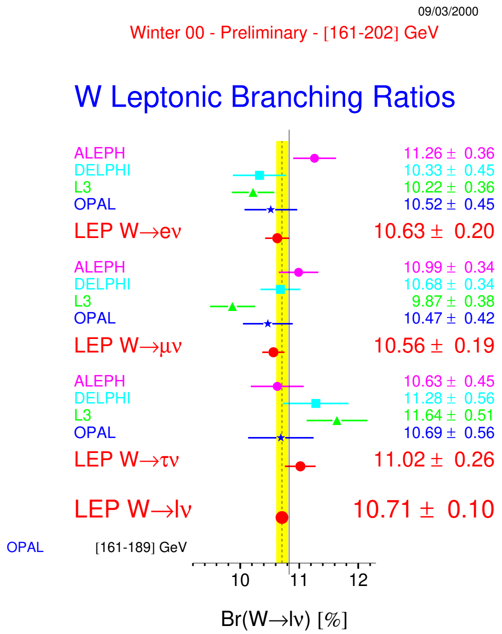
pure QED corrected point ("*" on plot) given by

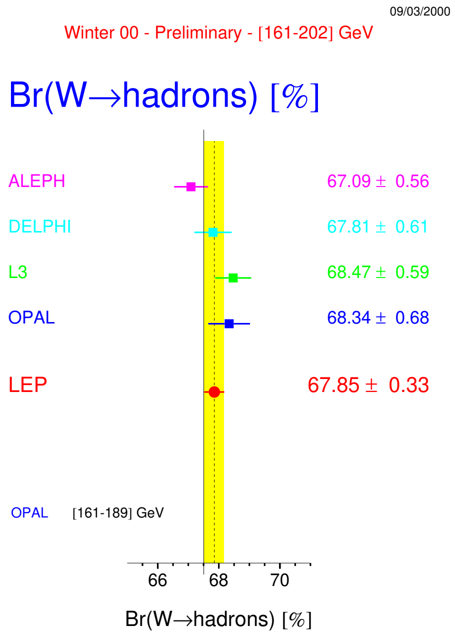
$$(\sin^2\theta_W)^0\,(\cos^2\theta_W)^0 = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2}$$

and $\Delta\rho = 1$

- need genuine electroweak corrections at $>> 99.999\,\%$ *CL*! $\surd$

W branching fractions





$$\text{Br}(W \to \text{leptons}) = 3\times(10.71\pm0.10\,\%)$$

$$\text{Br}(W \to \text{hadrons}) = 67.85\pm0.33\,\%$$

From this, can derive least-well known CKM element V_{cs}:

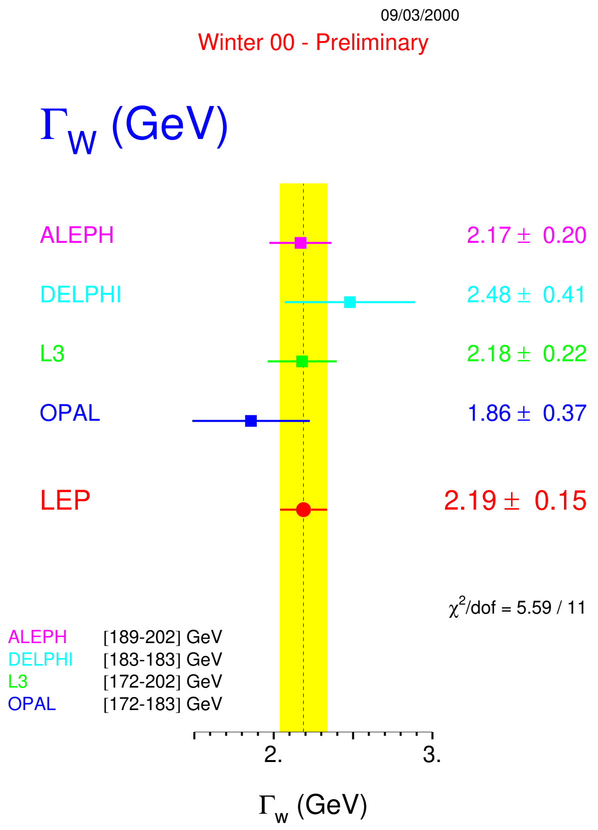
$$\frac{\text{Br(hadrons)}}{\text{Br(leptons)}} = \sum |V_{ij}|^2 \left(1 + \frac{\alpha_s(m_W)}{\pi}\right)$$

solve for $|V_{cs}| = 0.993 \pm 0.016$

not assuming unitarity here !

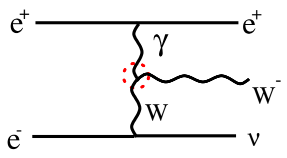
error dominated by statistics (± 0.012)

W Width



averaging analogous to m_W

Single W production



Cross section definition:

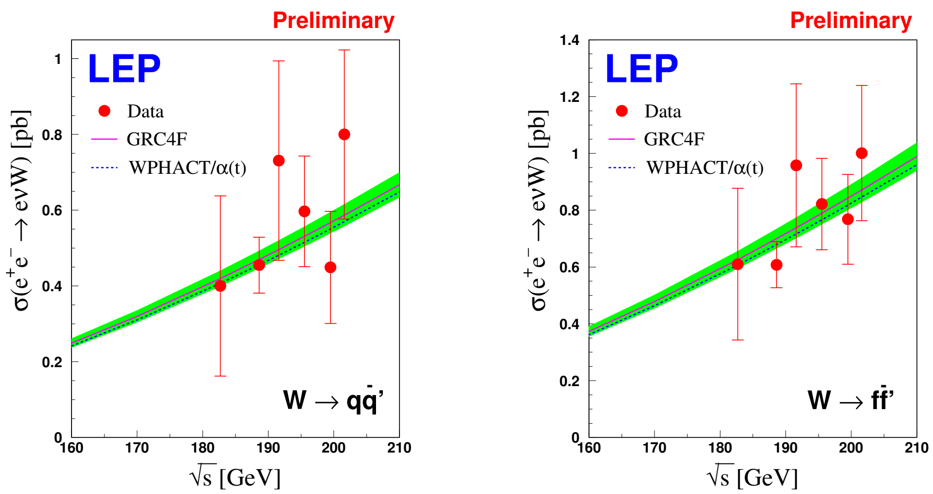
t-channel contribution

to $e\nu W$ final states

common cuts:

- $m_{q\bar{q}} > 45\,\text{GeV}$
- $E_{\ell^+} > 20\,\text{GeV}$ for $\ell = \mu, \tau$
- $|\cos\theta_{e^-}| > 0.95$, $|\cos\theta_{e^+}| < 0.95$, $E_{e^+} > 20\,GeV$ for $e\nu e\nu$ final states

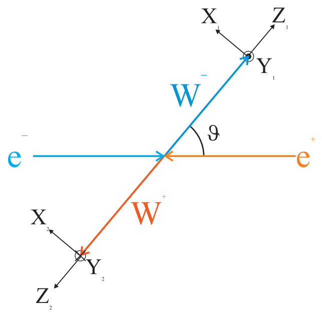
combination assumes uncorrelated systematics and **expected** statistical errors

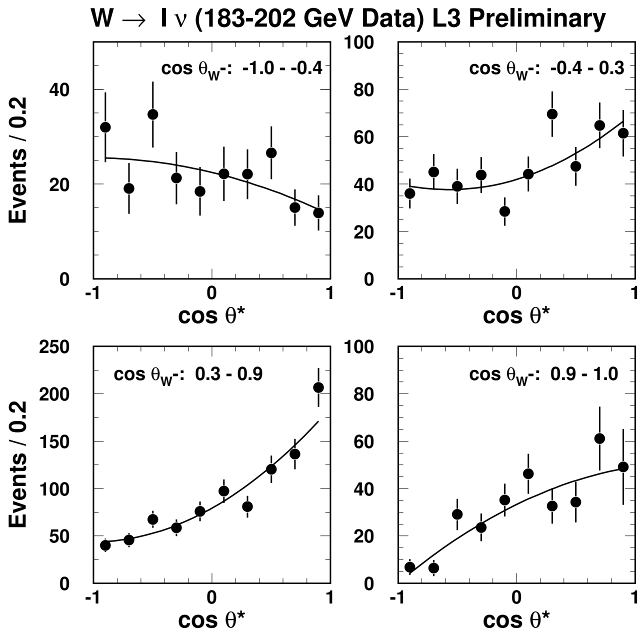


theoretical error band accounts for uncertainty of sacle for α_{em} and for ISR effects

Anomalous couplings

- W^- production angle ϑ and
  $W^\pm$ polarization from W decy fermion angles $\theta^*_{f(\bar{f})}$, $\phi^*_{f(\bar{f})}$

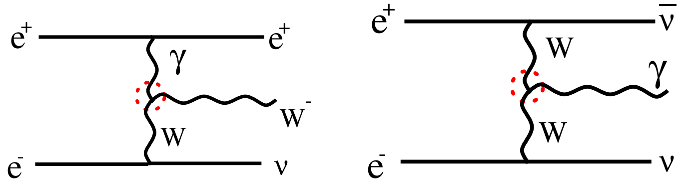




Shows W helicity vs. scattering angle w.r.t. beam direction
FIT: fractions of (+1,-1,0) helicity states, consistent with SM

Anomalous couplings (2)

- Single $W(+e\nu)$ and $\gamma(+\nu\bar{\nu})$ sensitive to γWW vertex



(there are also a number of background processes!)

C & P-conserving anomalous couplings parameterised in terms of

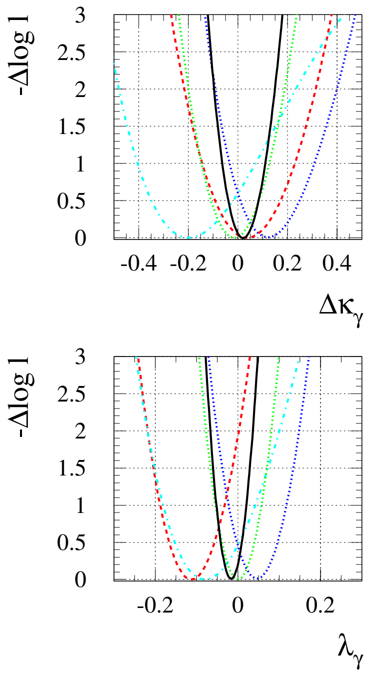
$$\Delta g_1^Z = g_1^Z - 1$$
$$\Delta\kappa_\gamma = \kappa_\gamma - 1$$
$$\lambda_\gamma$$

with the SU(2)×SU(1) gauge constraints

$$\lambda_Z = \lambda_\gamma \qquad \Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$$

LEP average anomalous couplings

ALEPH + DELPHI + L3 + OPAL



$\Delta\kappa_\gamma = 0.021\,^{+0.063}_{-0.059}$

$\Delta g_1^Z = -0.024\,^{+0.024}_{-0.024}$

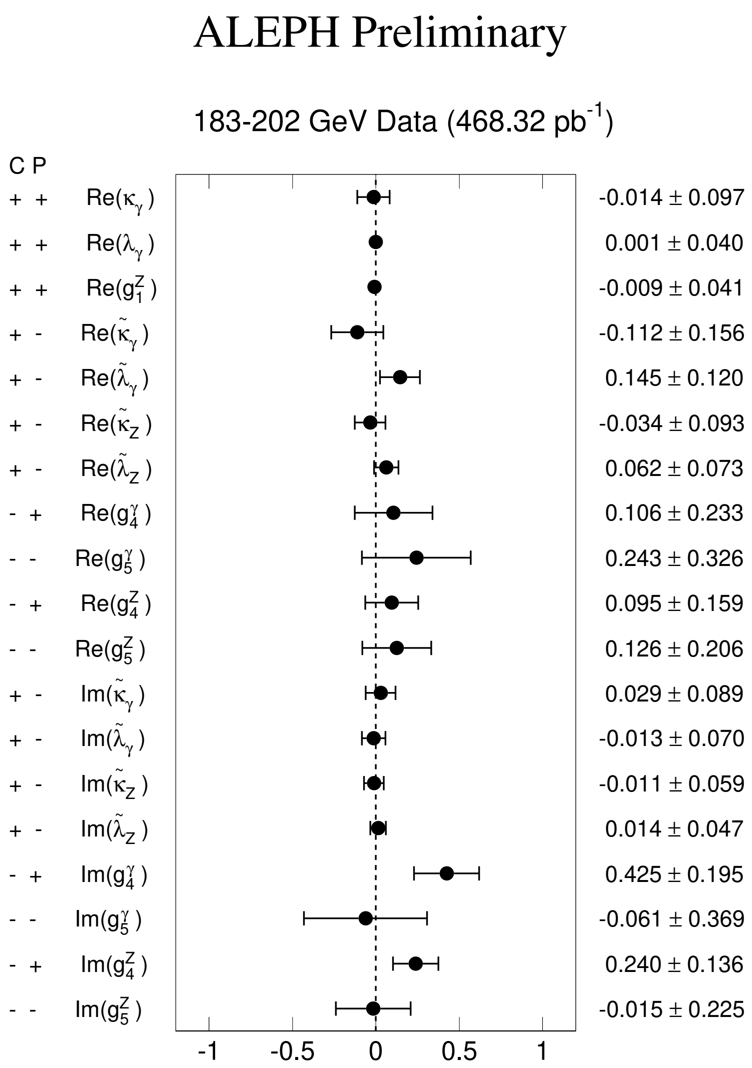
$\lambda_\gamma = -0.016\,^{+0.026}_{-0.026}$

Preliminary

All consistent with zero. **Nothing beyond SM!**

Note: Excludes Kaluza/Klein-type theories (5-dim spacetime), which would require $\Delta\kappa_\gamma = -3$ (L. Maiani and P.M. Zerwas in memo to LEP EWWG)

Scanning for more exotic couplings



One-parameter fits, setting all others to SM values

Anomalous $W^+W^-\gamma\gamma$ or $W^+W^-Z\gamma$ couplings

SM contribution from quartic couplings negligible at LEP

anomalous quartic couplings become acessible through

- $W^+W^-\gamma$,
- $(\nu\bar{\nu})\gamma\gamma$ and
- $Z\gamma\gamma$ final states.

final state	a_0/Λ^2	a_c/Λ^2	exp.
$W^+W^-\gamma$	[-0.070, 0.070]	[-0.13, 0.19]	OPAL@189 GeV
	[-0.042, 0.045]	[-0.072, 0.148]	L3@183&189,GeV
$(\nu\bar{\nu})\gamma\gamma$	[-0.086, 0.085]	[-0.23, 0.23]	L3@183&189,GeV
$Z\gamma\gamma$	[-0.009, 0.008]	[-0.007, 0.013]	L3@183&189,GeV

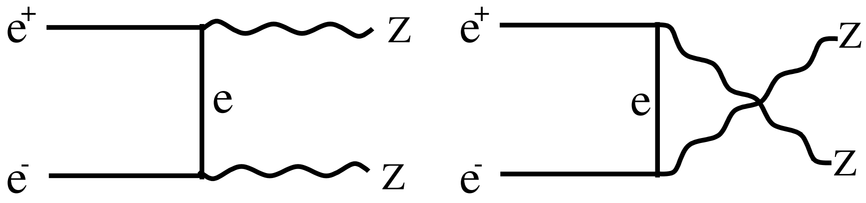
95 % CL limits in GeV^{-2}

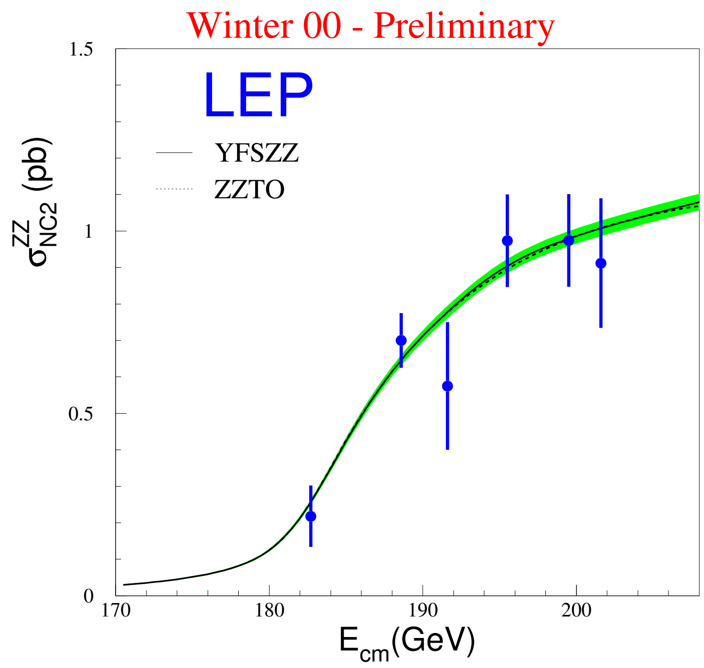
parameters as in G. Bélanger, F. Boudjema, PL**B**288 (1992) 201

Indirect limits from precise LEP I and SLC data more stringent!

Since 1998 production of ZZ events kinematically possible

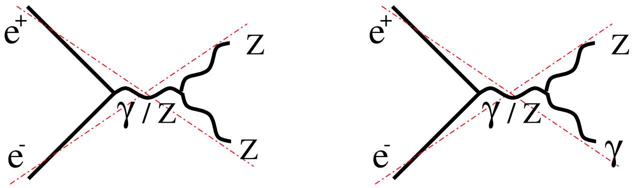
contributing diagrams:





Anomalous ZZ couplings

forbidden (at tree level):



ZZ final state | Zγ final state

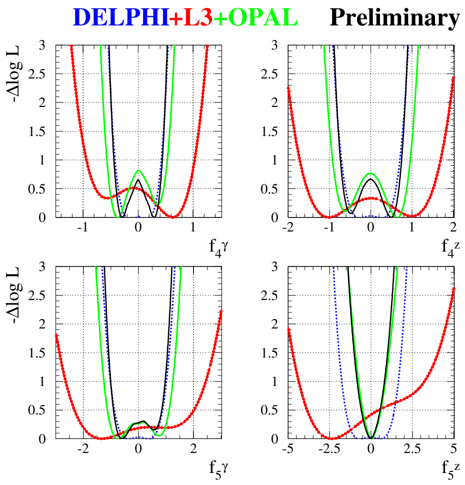
anomalous vertices parameterised by

$f_4^\gamma,\ f_4^Z$	P violating	$h_1^\gamma,\ h_2^\gamma,\ h_1^Z,\ h_2^Z$	CP violating
$f_5^\gamma,\ f_5^Z$	$\cancel{C}$, $\cancel{P}$, CP conserving	$h_3^\gamma,\ h_4^\gamma,\ h_3^Z,\ h_4^Z$	CP conserving

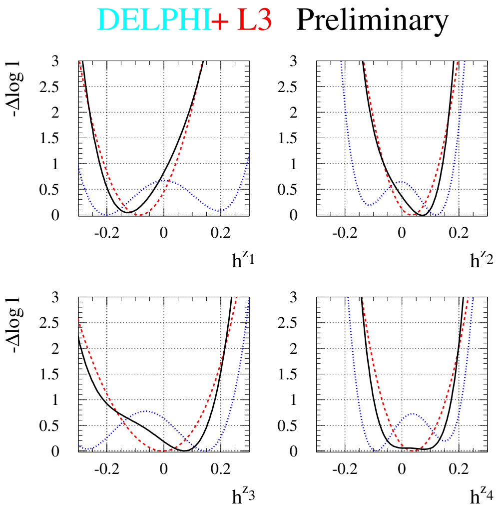
Analyses very preliminary and some experiments missing!

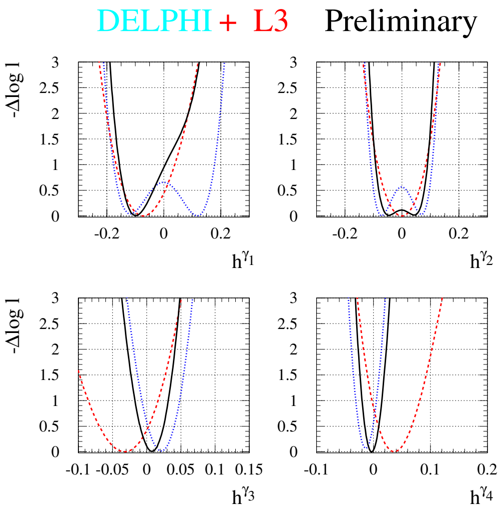
Limits on Anomalous ZZ couplings

ZZ final state



Zγ final state



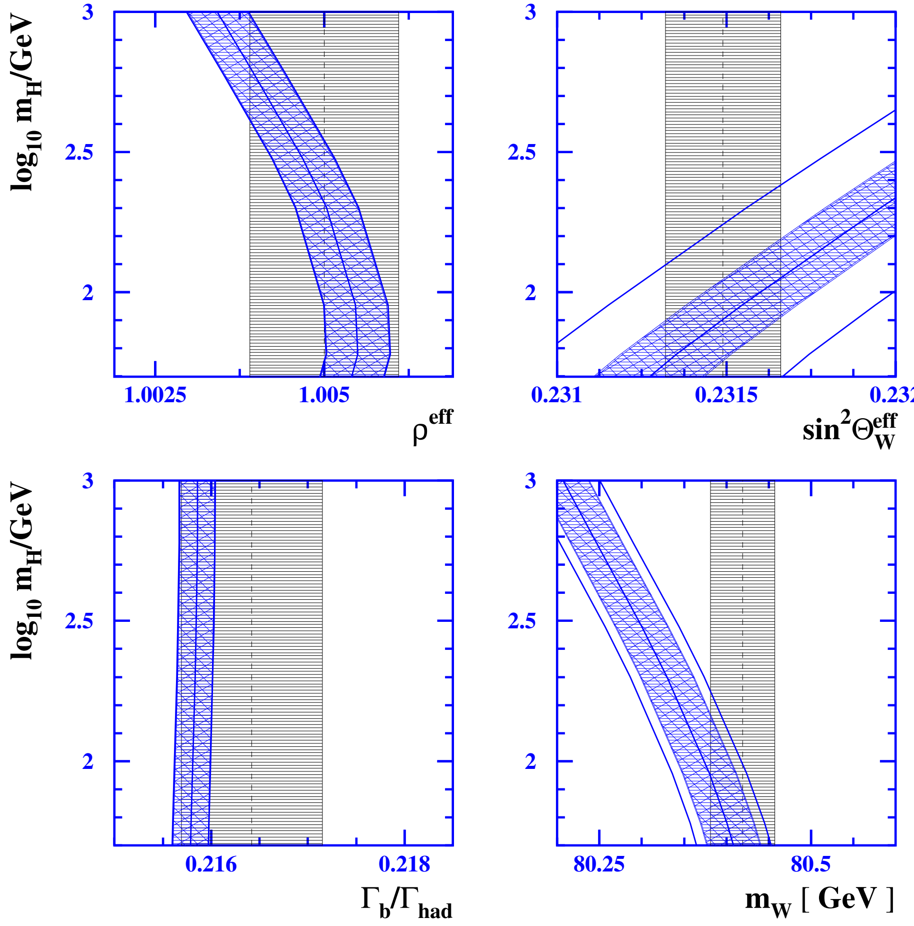


all consistent with 0 $\surd$

Comparison with Standard Model

Measurements determine four types of radiative corrections:

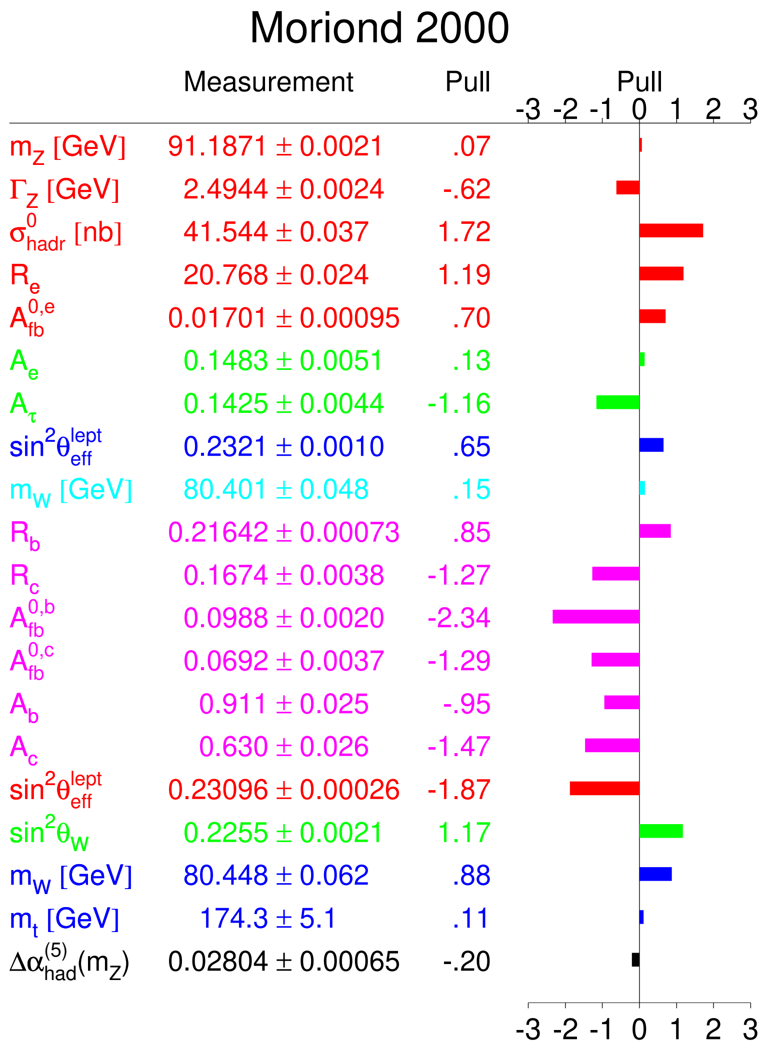
ρ_{eff}^{lept}	$\Gamma_{\ell\ell}$ (Γ_{inv})	LEP
$\sin^2\theta_{eff}^{lept}$	A_{FB}, A_{LR}, τ-Pol.	LEP, SLD
ρ_b	$R_b = \Gamma_{b\bar{b}} / \Gamma_{had}$	LEP, SLD
m_W	σ_{WW} a. dir. reconstruction	LEP, CDF, D0



dark hatched: m_t dependence, for $m_t = 174 \pm 5$ GeV
light area: $\alpha(m_Z)$ dependence for $1/\alpha(m_Z) = 128.886 \pm 0.090$

no α_s dependence in these observables

Overview of precision measurements vs. SM



$p_\chi = 9\ \%$

(Pull is from full SM fit, see later)

Strong coupling constant

Information on α_s from R_ℓ, Γ_Z and σ^o_{had} (+ correlations!)

α_s from R_ℓ only

$\alpha_s = 0.123 \pm 0.004 \left(^{+0.003}_{-0.000}\right)_{m_{\text{H}}}$

α_s from σ^o_{lept}

$\alpha_s = 0.119 \pm 0.003 \left(^{+0.003}_{-0.000}\right)_{m_{\text{H}}}$

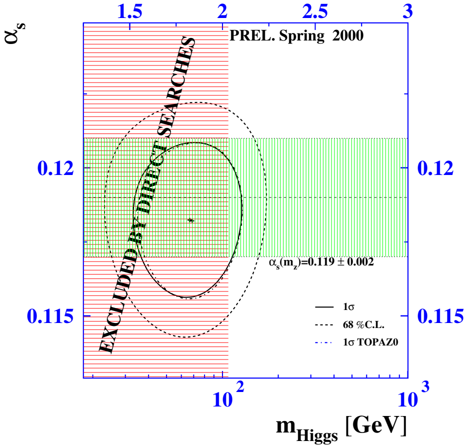
for $m_{\text{H}} = 100^{+900}_{-0}$ GeV

α_s from full mSM fit

$\alpha_s = 0.1182 \pm 0.0026$

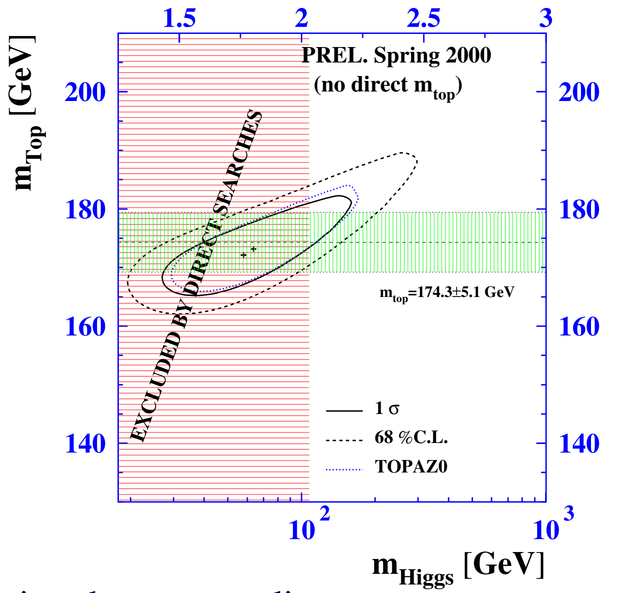
note that a syst. QCD error of $\sim$0.002 still has to be added

this value agrees well with present world average from PDG! $\surd$



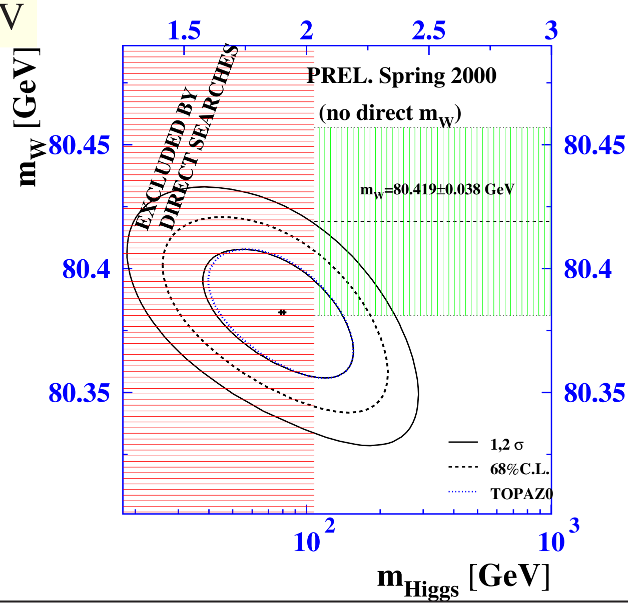
Indirect m_t - use **all** precision data except direct m_t

$m_t = 172^{+10}_{-7}$ GeV



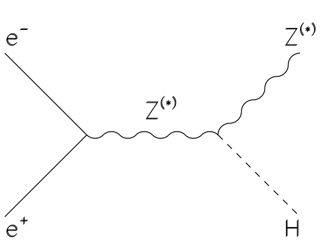
Indirect m_W - use all precision data except direct m_W

$m_W = 80.383 \pm 0.026$ GeV

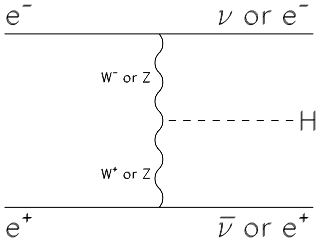


Direct search for the Higgs boson

Mechanism for Higgs production at LEP:



Higgs "Bremsstrahlung"
LEP I a. LEP II



"Fusion" - contributes at LEP II

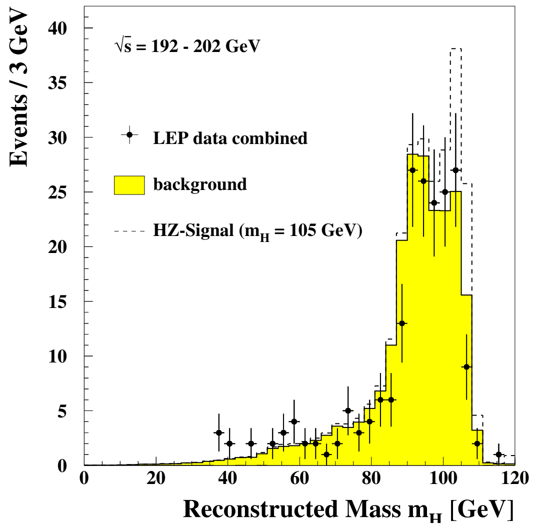
Higgs decays predominantly into heaviest kinematically possibe particles - $b\bar{b}$ and $\tau^+\tau^-$ at LEP energies

LEP experiments look for all possible signatures

$b\bar{b}q\bar{q}$	($\sim$ 64 %)
$H\nu\bar{\nu}$	($\sim$ 20 %)
$H\ell^+\ell^-$ (i.e. e^+e^-, $\mu^+\mu^-$)	($\sim$ 7 %)
$H\tau^+\tau^-$, $\tau^+\tau^-q\bar{q}$	($\sim$ 9 %)

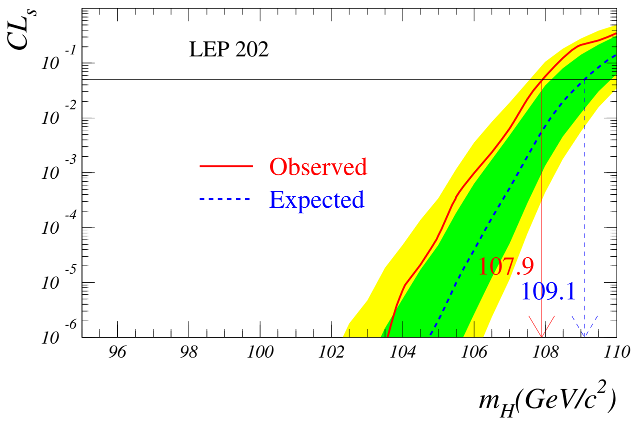
Results from direct searches for the Higgs boson

Higgs candidates observed at LEP ...



... is irreducible background from ZZ but no signal!

Limit:



$$m_{\rm H} > 108\,{\rm GeV}\ @\ 95\,\%\,{\rm CL}$$

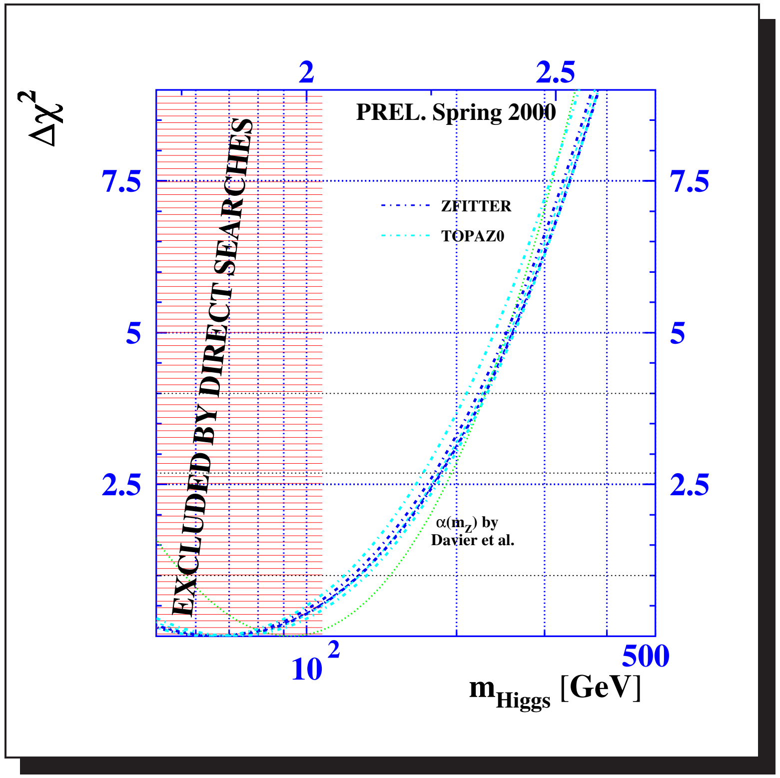
Tables from SM fits

Fit with ZFITTER 6.23 (TOPAZ0 4.4)	$\chi^2/N_{df} = 22.7/15$, **p=9.0%**
m_t [GeV]	173.7 ± 4.4
	(174.0 ± 4.4)
m_H [GeV]	$66\ ^{+60}_{-33}$
	$(68\ ^{+59}_{-33})$
α_s	0.1182 ± 0.0026
	(0.1882 ± 0.0026)
derived:	
$\sin^2\theta^{lept}_{eff}$	0.23145 ± 0.00016
m_W [GeV]	80.394 ± 0.021

LEP only

fit with ZFITTER 6.23	$\chi^2/N_{df} = 11.6/9$, prob.=24%
m_t [GeV]	$176\ ^{+14}_{-11}$
m_H [GeV]	$147\ ^{+300}_{-92}$
α_s	0.1196 ± 0.0029
derived:	
$\sin^2\theta^{lept}_{eff}$	0.23178 ± 0.00021
m_W [GeV]	80.363 ± 0.030

Higgs mass limit



limit on Higgs mass:

take 1.64 σ from minimum of most pessimistic blue curve ⇒

$$m_H < 188\,\text{GeV @ 95\% C.L.}$$

in a Bayesian approach, taking into account direct exclusion limit ⇒

$$m_H < 280\,\text{GeV @ 95\% C.L.}$$

Make your own choice, the plot contains all information!

Resumé:

- High-precision measurements at LEP I approaching finalisation

  LEP II on the way to true precision physics

- preliminary results of data at $\geq$192 GeVavailable
- Standard Modell experimentally in good shape
- Higgs boson remains the ultimate test of the theory
  - EW corrections let us expect $m_{\mathrm{H}} = 66\ ^{+60}_{-33} \pm 6$ GeV
  - direct seach at LEP: $m_{\mathrm{H}} > 108$ GeV @ 95 % C.L.

  this becomes exciting!

- a new run at >200 GeVahead of us - main goal: **Higgs hunt**

  also hope to increase total LEP II statistics by ~30 % !

$\boxed{\text{2000 is the last year of LEP running } \dagger}$

but still important results expected for several years to come!