Precision tests of the Electroweak Standard Model at LEP

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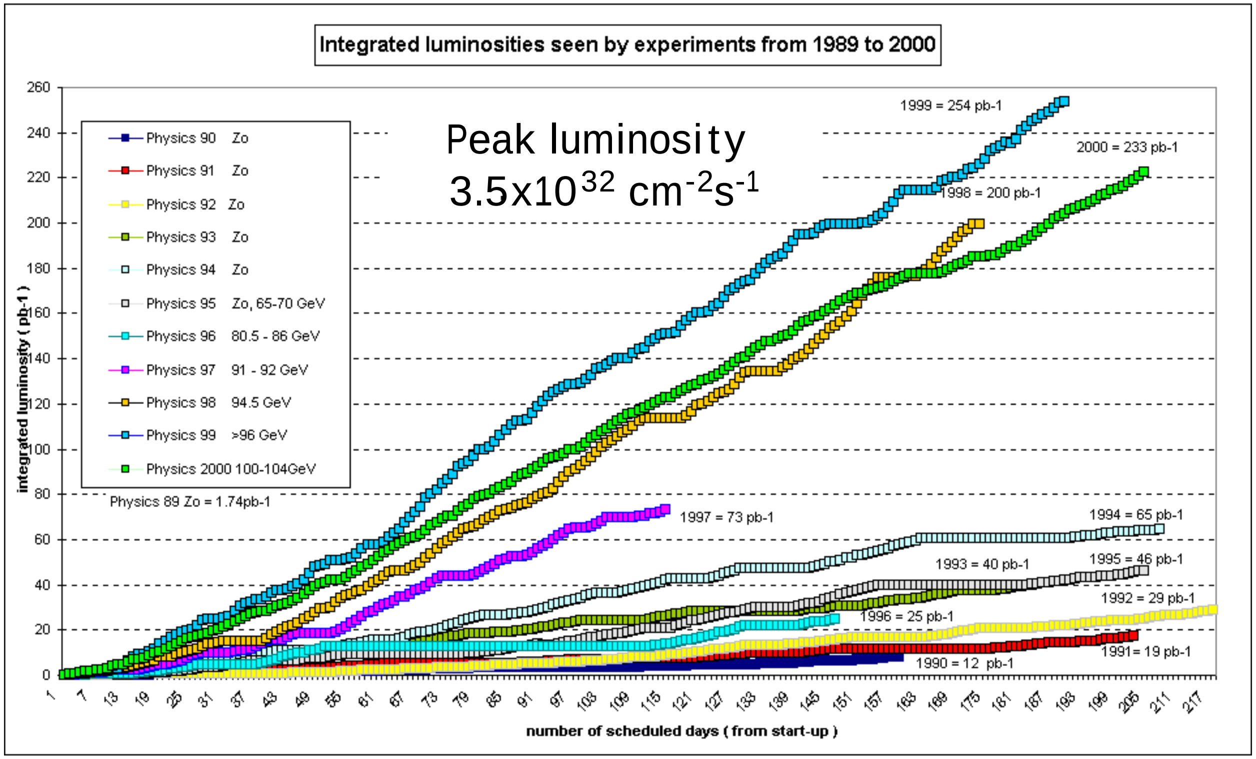
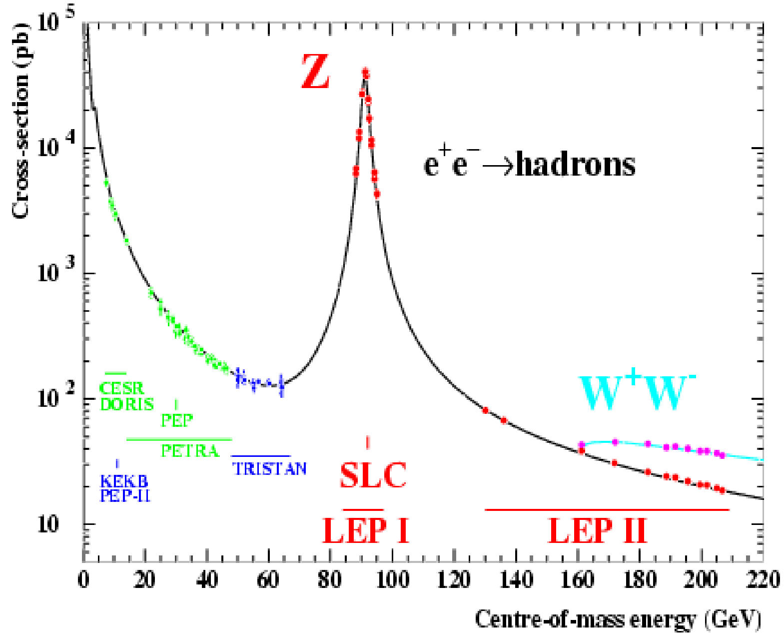
on behalf of the LEP collaborations ALEPH, DELPHI, L3, OPAL
and the LEPEWWG

The LEP data sample



LEP1 : 1989-95	LEP2 : 1995-2000
$\sqrt{s} \sim M_Z$	$\sqrt{s}$ = 161 ... 209 GeV
200 pb^{-1}/exp	700 pb^{-1}/exp
15.5 X 10^6 Z -> qq 1.7 X 10^6 Z -> ll	50K WW

SM measurements at LEP

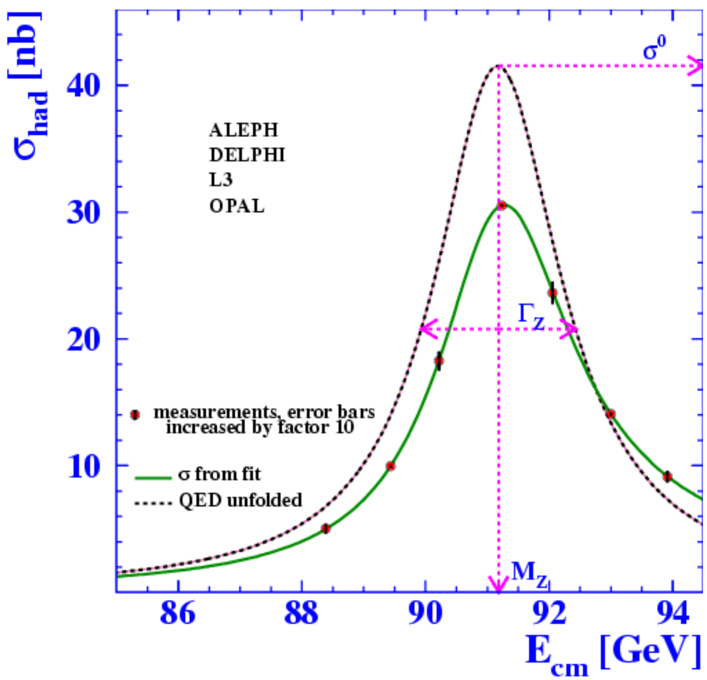


Standard Model Measurements:

- Z lineshape and asymmetries
- Heavy flavours
- LEP2 fermion pair cross-sections and asymmetries
- LEP2 boson production cross-sections
- W boson mass and width

Z lineshape

Set of "pseudo-observables", chosen with minimal experimental correlation, to describe the hadronic and leptonic cross-sections around the Z peak



$$s^{0}_{had} = \frac{12p\Gamma_{ee}\Gamma_{had}}{M_Z^2\Gamma_Z^2}$$

$$R_f = \Gamma_{had} / \Gamma_{ll}$$

The final LEP1 results

Mz = 91.1875 ± 0.0021 GeV

Gz = 2.4952 ± 0.0023 GeV

Excellent experimental precision:

- LEP beam energy from resonant depolarization + corrections => dMz~1.7 MeV dGz~1.2 MeV
- Luminosity measurement error <10^{-3}
- Theory error on Bhabha cross-section for L measurement 0.061%

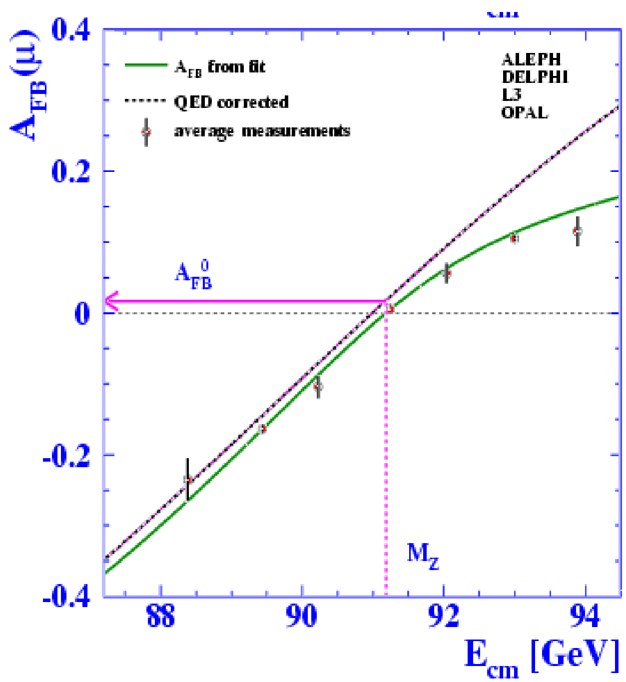
$$\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\Gamma_{ll}$$

$N_n = \Gamma_{inv} / \Gamma_{vv}^{SM} = 2.984 \pm 0.008$

Z pole asymmetries

A_{FB} from fit to polar angle distributions

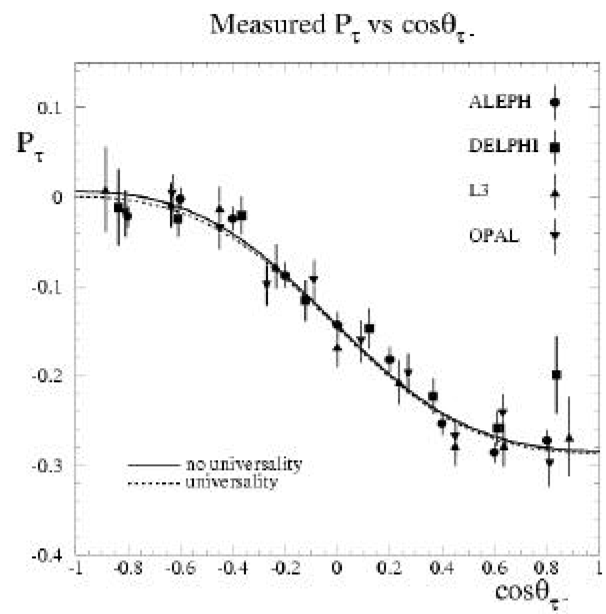
$$\frac{ds}{d\cos J} \propto 1+\cos^2 J + \frac{8}{3} A^f_{FB} \cos J$$



$$A^{0,f}_{FB} = \frac{3}{4} A_e A_f$$

$$A_f = \frac{2 g^f_V g^f_A}{g^{f\,2}_V + g^{f\,2}_A}$$

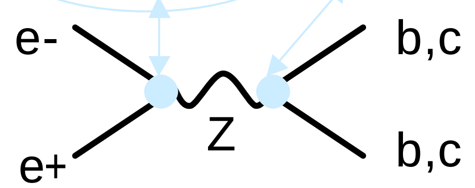
In addition, measure tau polarization

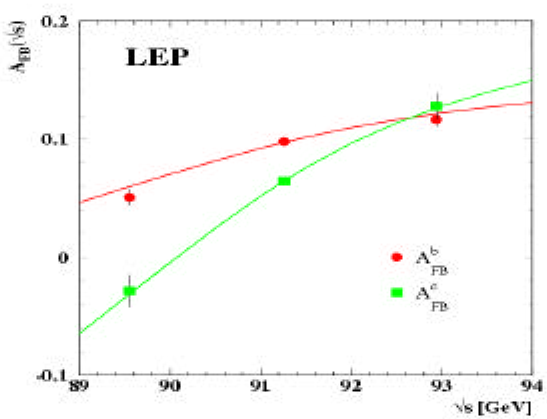


$$A^t_{POL} = A_t$$

Heavy flavours

Measure $A^{0,b}_{FB}$ $A^{0,c}_{FB}$ R^0_b R^0_c





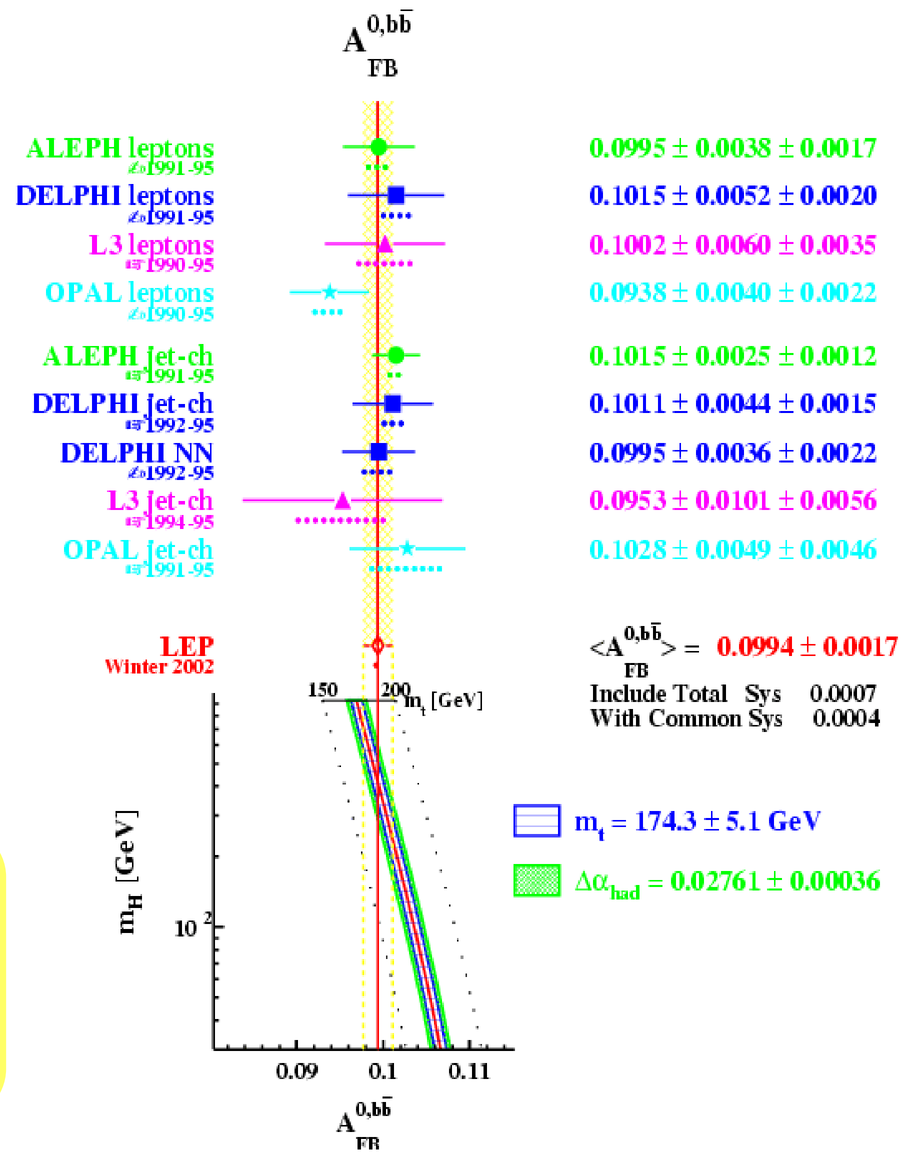
NEW

w.r.t summer 2001:

$A^{0,b}_{FB}$ -1/4s , $A^{0,c}_{FB}$ -2/3s

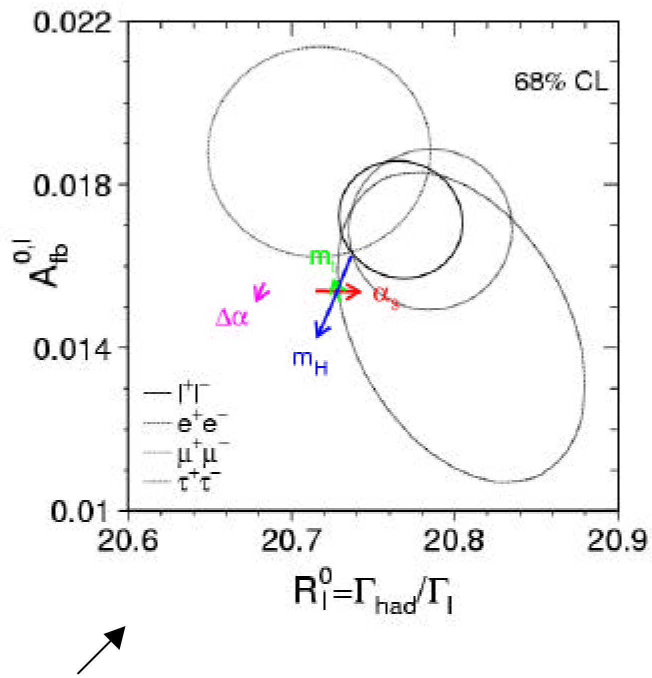
mainly ALEPH updates

(see talk by M.Calvi)

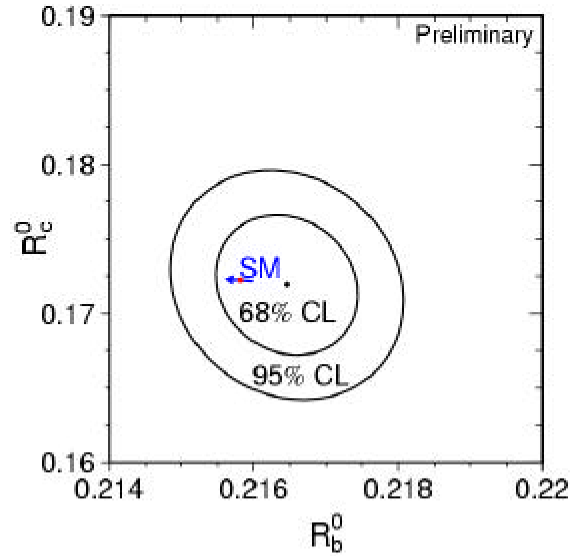


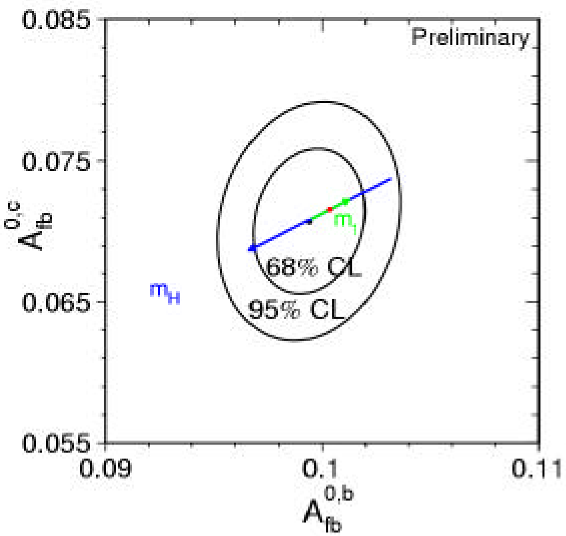
Measurements vs SM predictions (1)

(1) pseudo-observables:



test of lepton universality

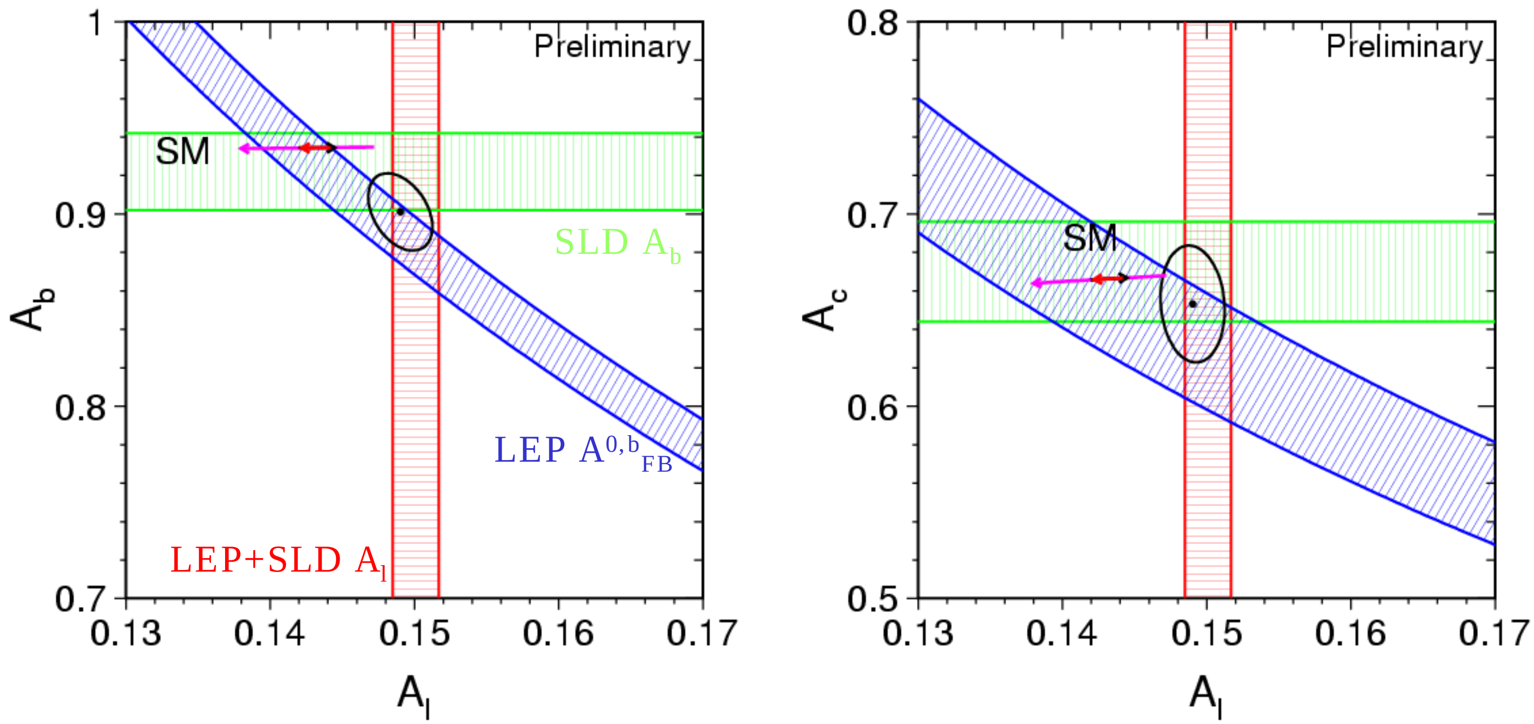


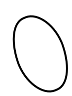


(2) A_f coupling parameters derived from asymmetries

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

$$A_{pol}^{t} = A_t$$



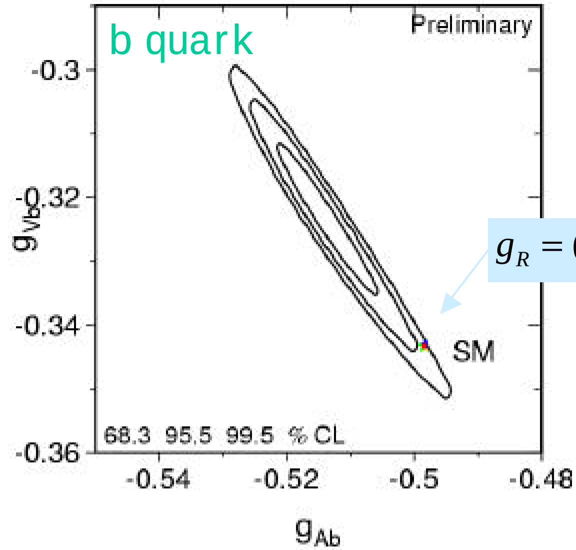
combined in plot with SLD results:  = 68% c.l.

Measurements vs SM predictions (3)

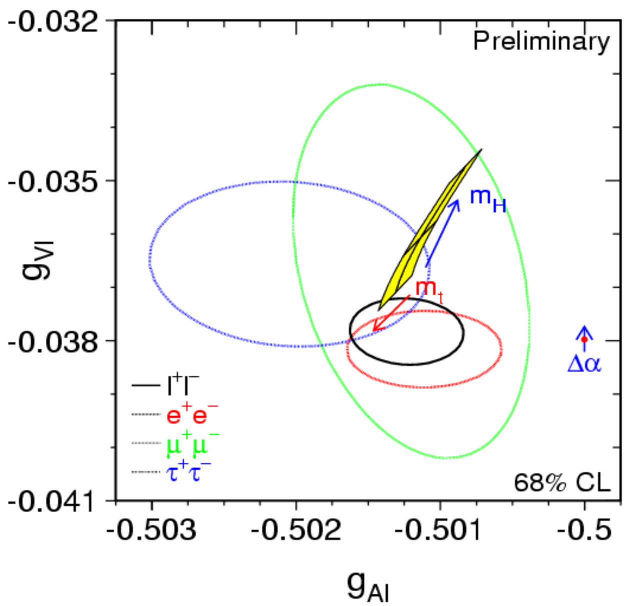
(3) g_V,g_A effective couplings derived from asymmetries and widths

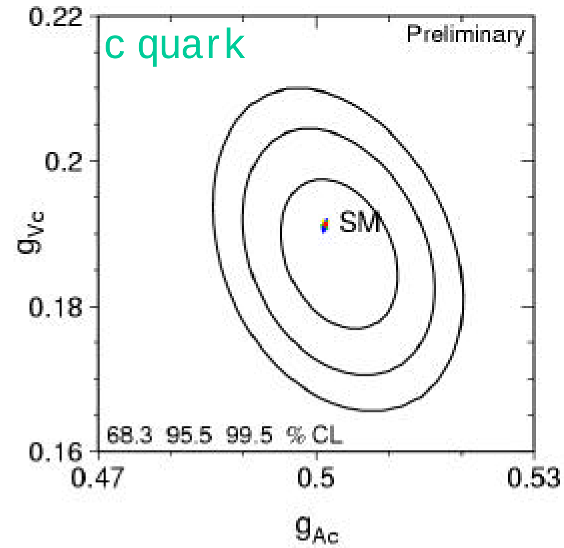
$$A_f = \frac{2 g_V^f g_A^f}{g_V^{f\,2} + g_A^{f\,2}}$$

$$\Gamma_{ff} = \frac{G_F N_C M_Z^3}{24p\sqrt{2}}\left(g_V^{f\,2} + g_A^{f\,2}\right)$$



$g_R = (g_A - g_V)/2$



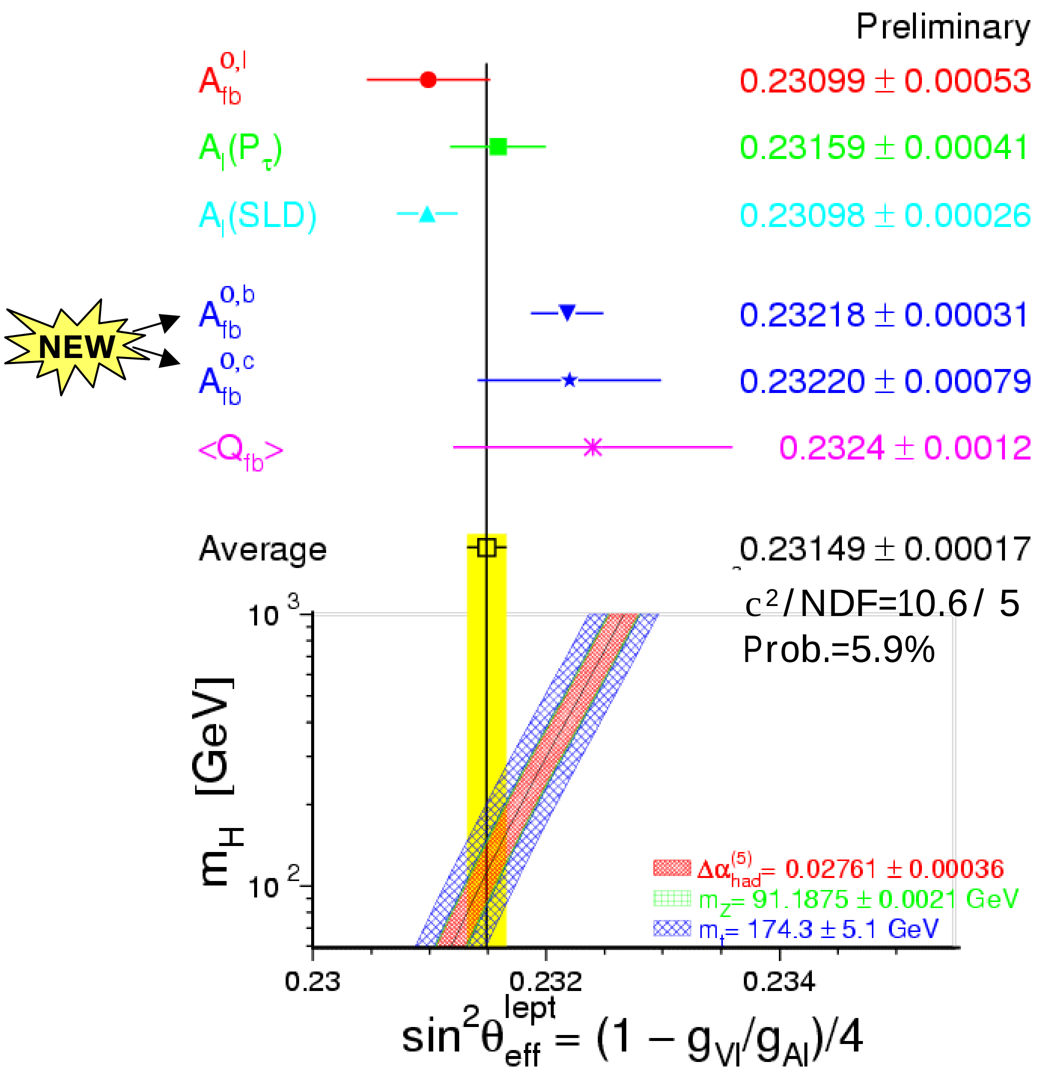


combined in plots with SLD results

Effective weak mixing angle

Asymmetry parameters measure $\sin^2\theta_{eff}^{lept}$

$g_V = T^3_f - 2Q_f \sin^2\theta_W$
$g_A = T^3_f$



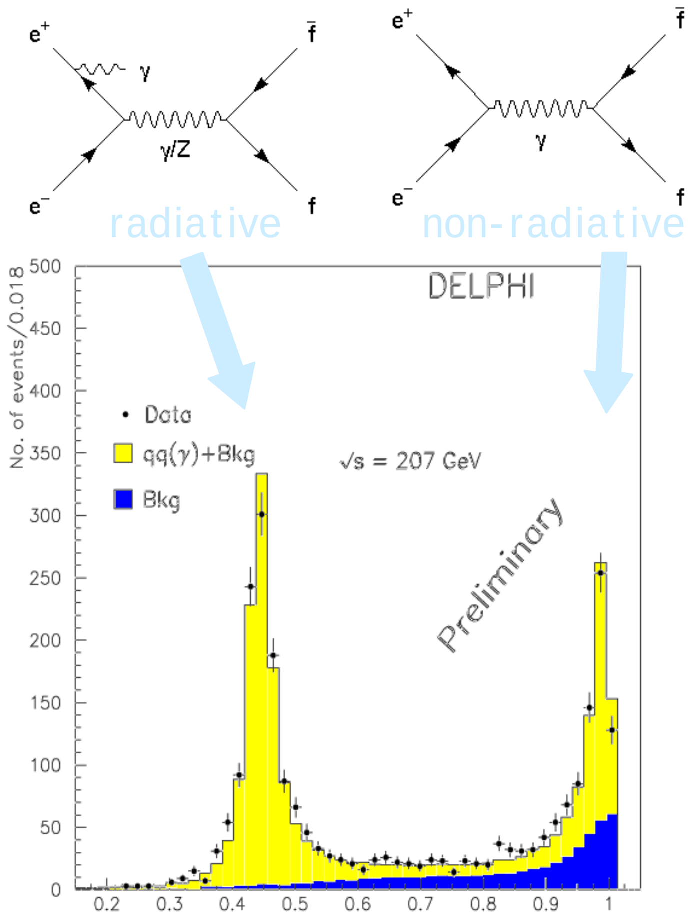
Leptons: 0.23113 ± 0.00021
χ^2/NDF=1.64/2 Prob.=44%

Hadrons: 0.23220 ± 0.00029
χ^2/NDF=0.031/2 Prob.=98.5%

Difference 3.0 σ

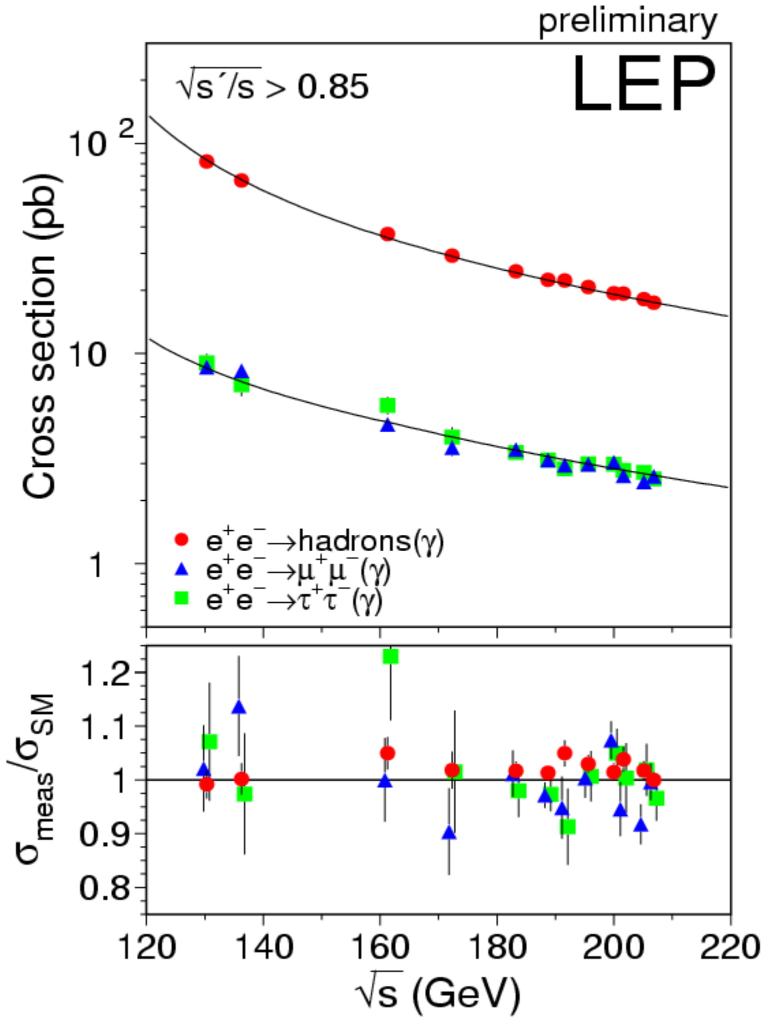
($\downarrow$0.3 σ w.r.t summer 2001)
now solely driven by
A_l(SLD) and $A^{0,b}_{FB}$

LEP2 fermion pair production

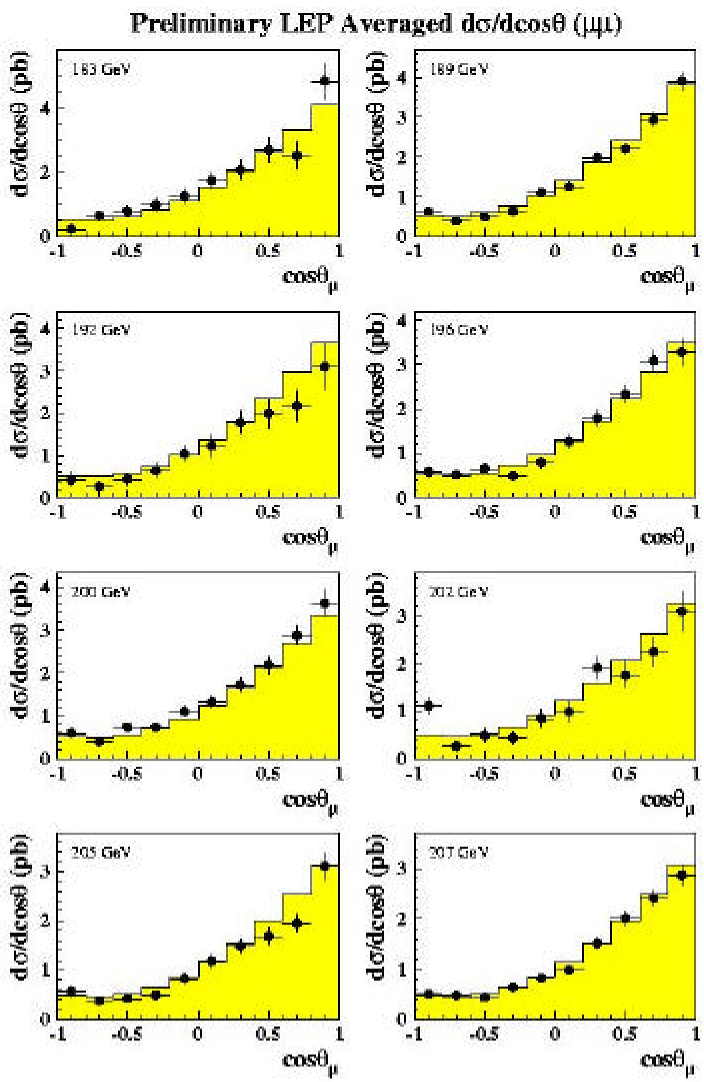


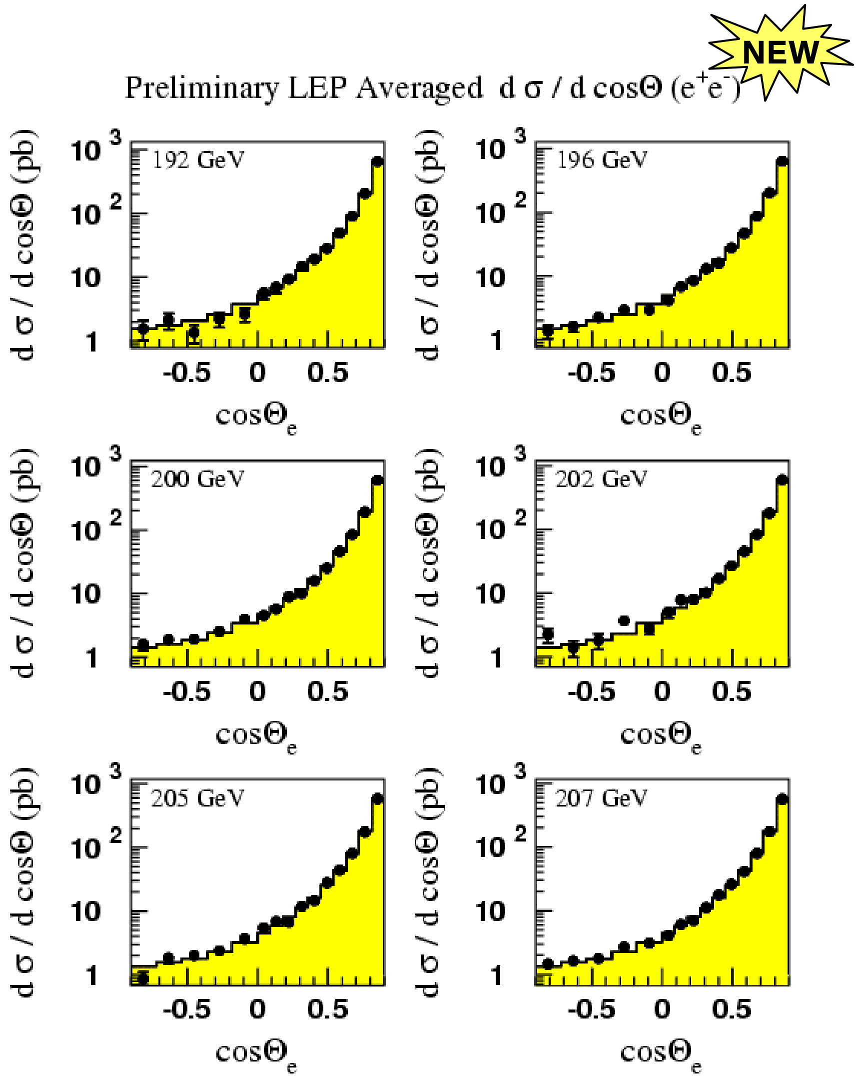
√s'=M(f f)

Cross-section for non-radiative events



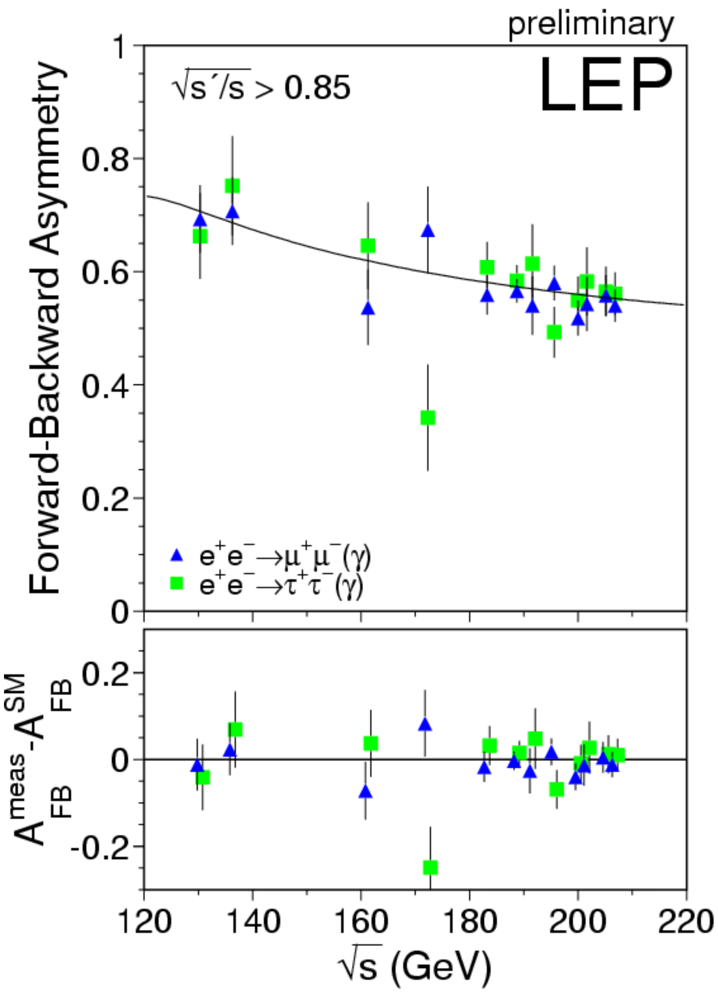
LEP2 fermion pair differential cross-sections



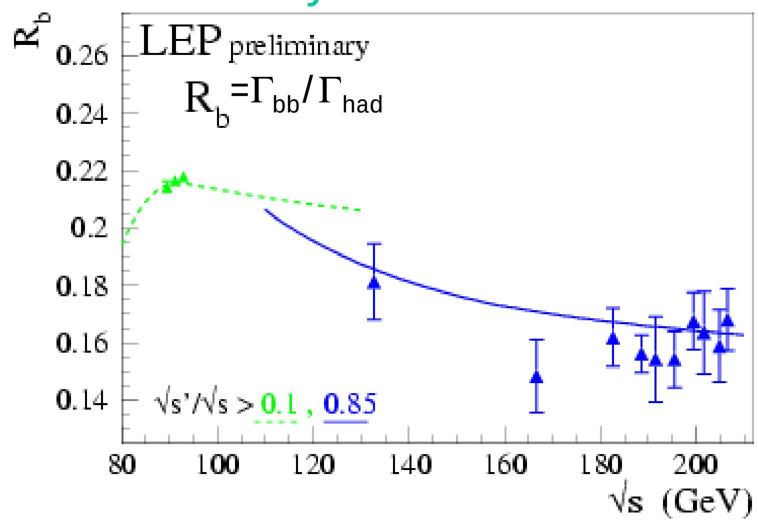


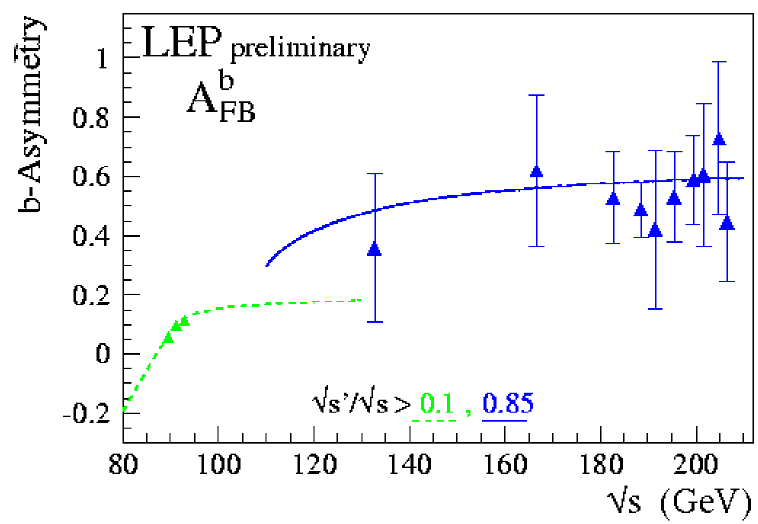
LEP2 fermion pair asymmetries and heavy flavours

Leptonic forward-backward asymmetries



Heavy quark fractions and asymmetries

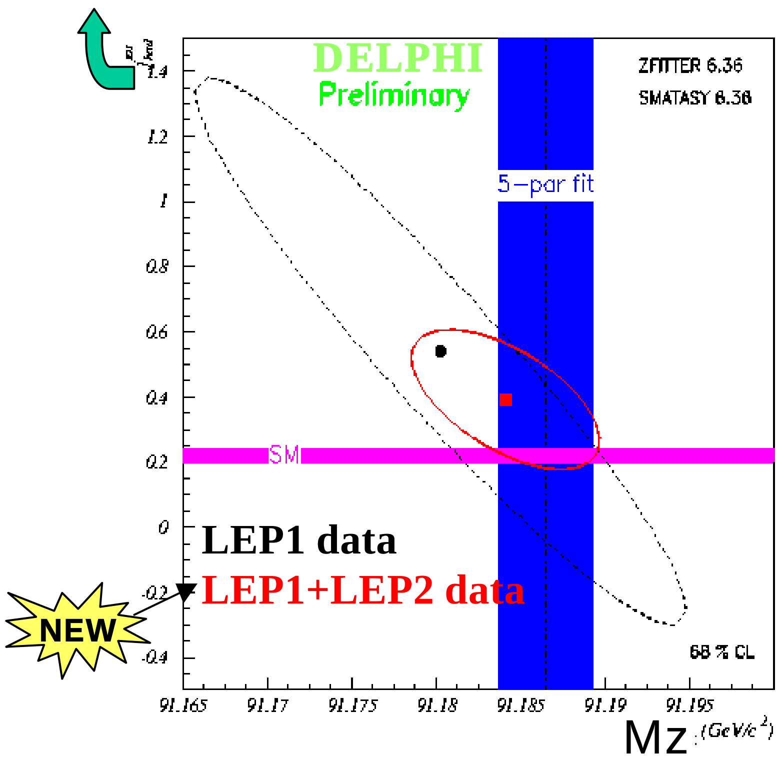




S-matrix fits:

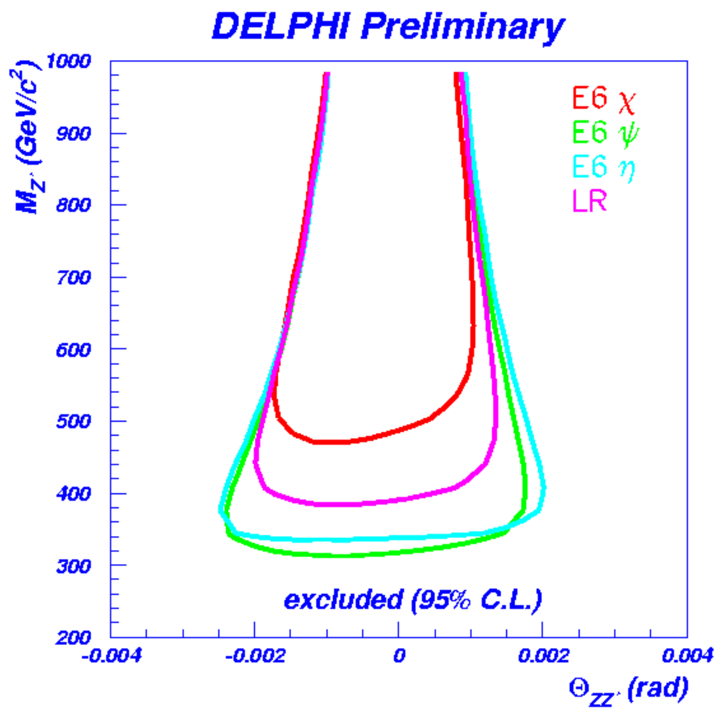
a model independent approach to describe cross-sections and asymmetries in e+e- annihilations

j_{had}^{tot} <-> gZ interference



Constraints on new physics:

Z` bosons



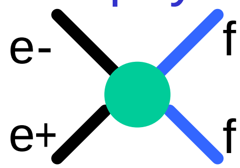
LEP combined (prel.), 95% c.l.

$M_{Z'}$ > 678 463 436 800 GeV

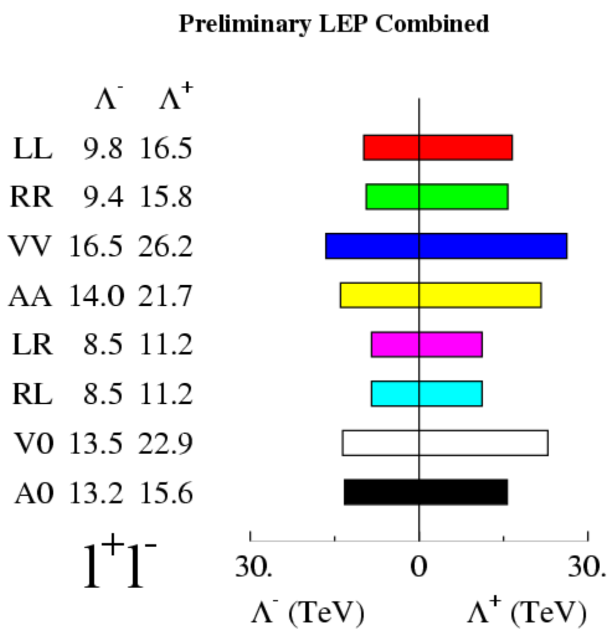
LEP2 difermion data interpretation (2)

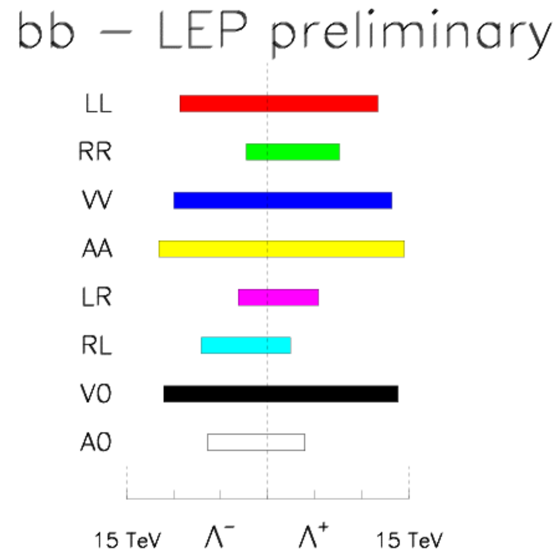
Constraints on new physics:

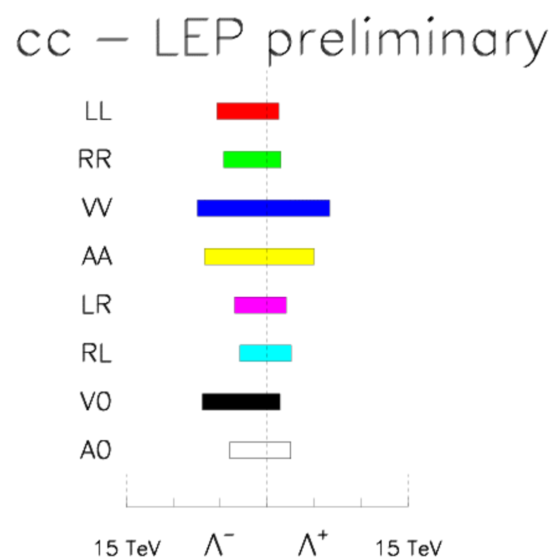
4-f contact interactions



$$L_{eff} = \frac{1}{1+\delta_{ef}} \sum_{i,j=L,R} h_{ij} \frac{g^2}{\Lambda_{ij}^2} \left(\bar{e}_i \gamma^{\mu} e_i\right)\left(\bar{f}_j \gamma_{\mu} f_j\right)$$

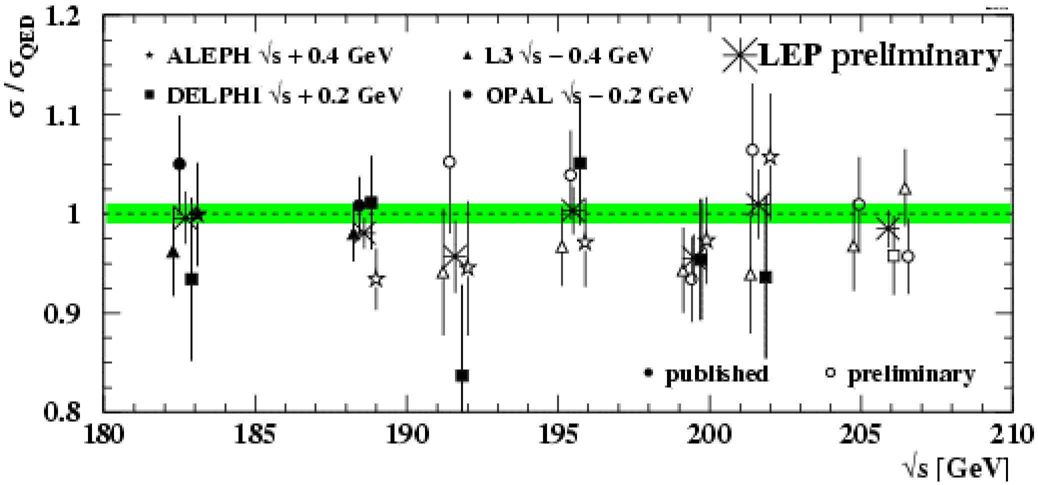




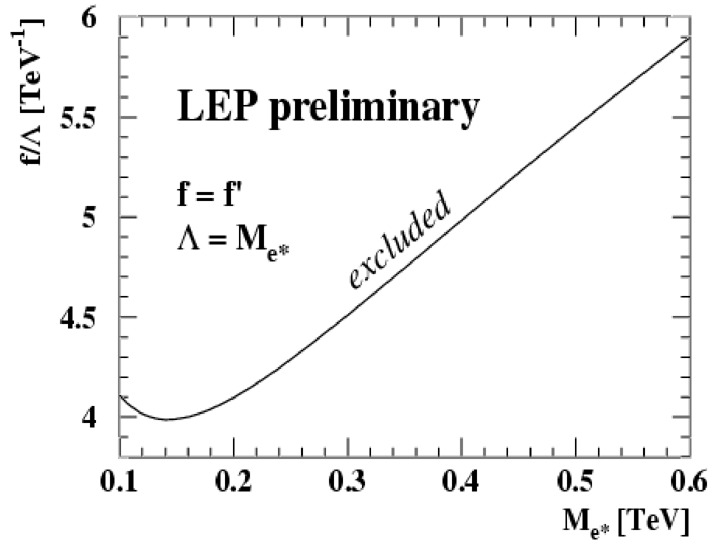


LEP2 photon pair cross section

e+e- -> gg(g) is a clean test of QED



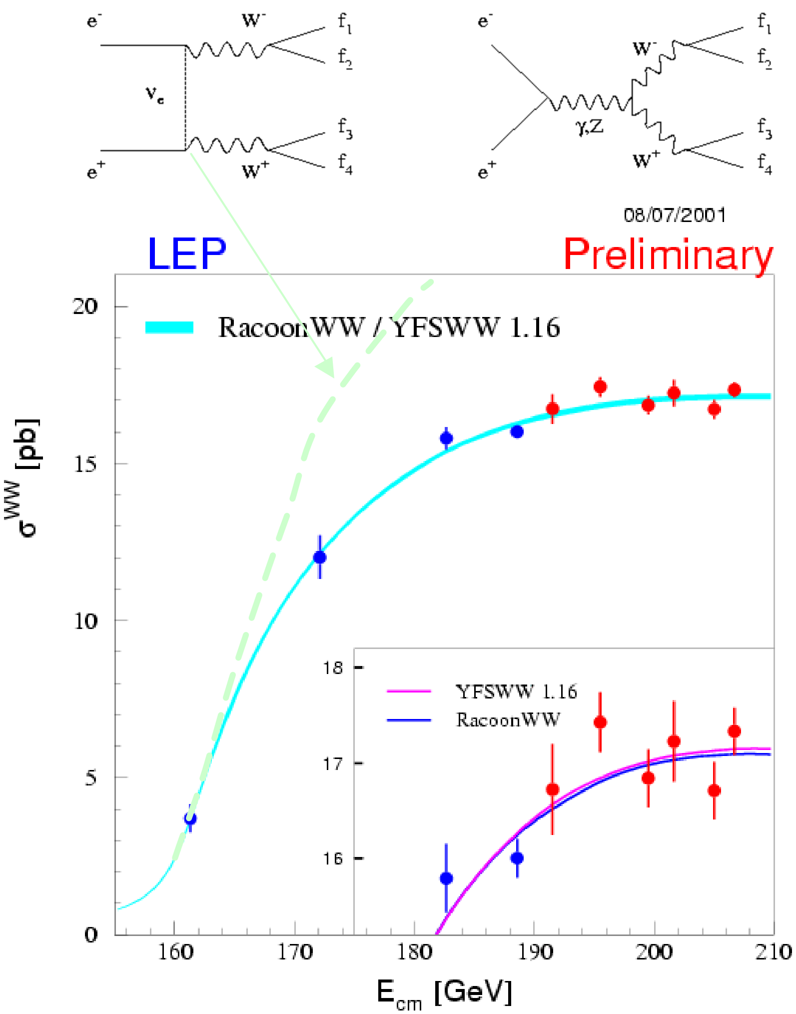
total cross-section and polar angle distributions are measured up to the highest available energy



No deviations from SM expectations => limits on new physics

LEP2 W pair cross sections

e+e- -> W+W-



Theory at tree-level, i.e. existence of Triple Gauge-boson Couplings, was proven since the first LEP2 data.

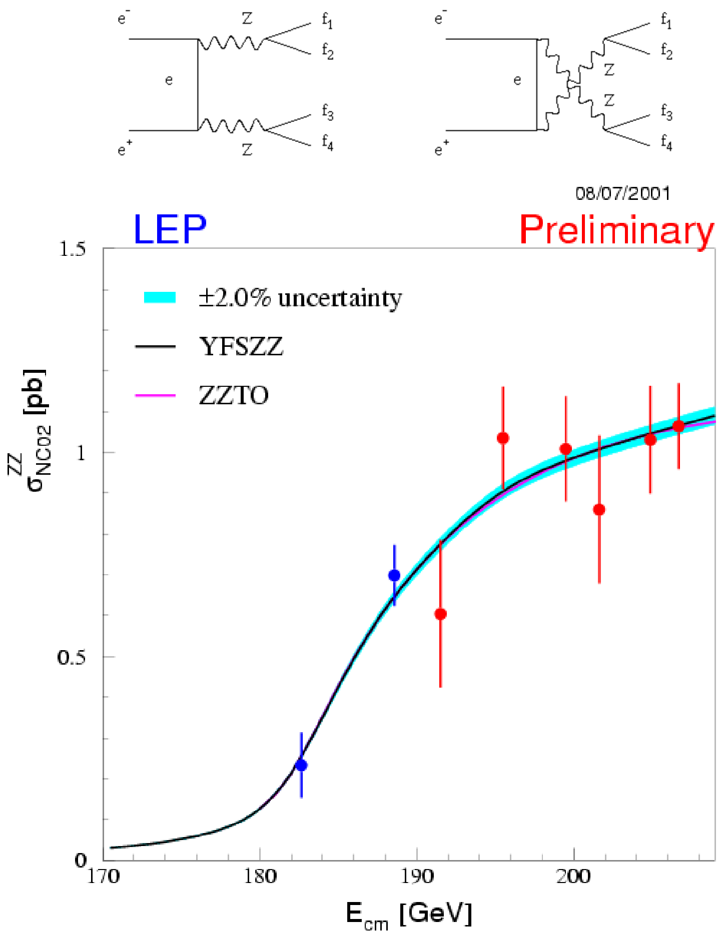
Now theory is tested
at loop level !
Experimental precision is close to theoretical prediction accuracy (0.5%)

TGCs are measured directly from angular distributions in WW events

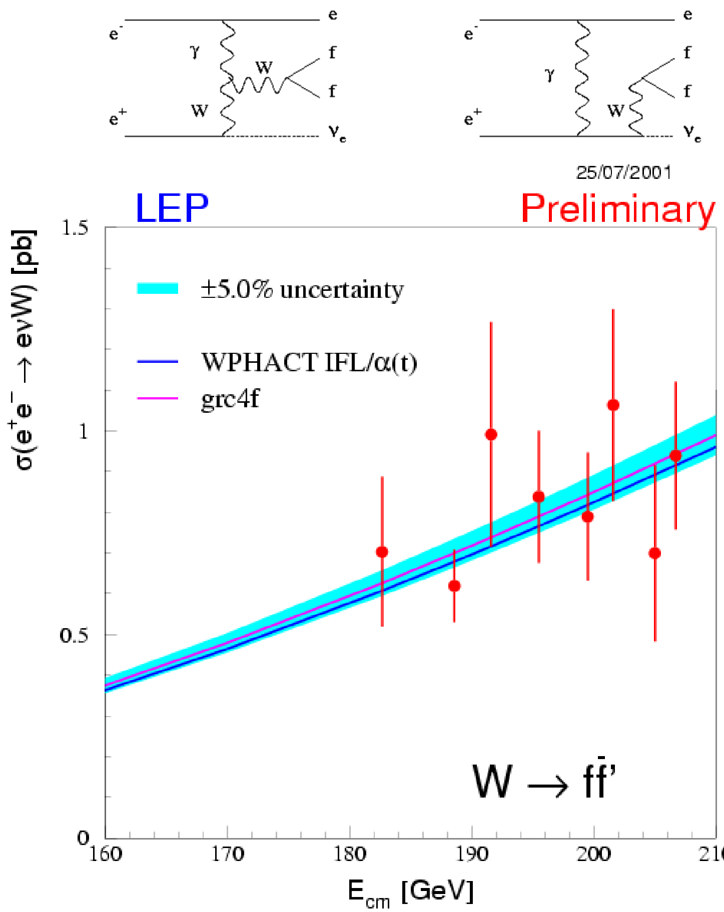
(see talk by A.Straessner for all details)

LEP2 ZZ and single-boson cross sections

e+e- -> ZZ



e+e- -> Wen



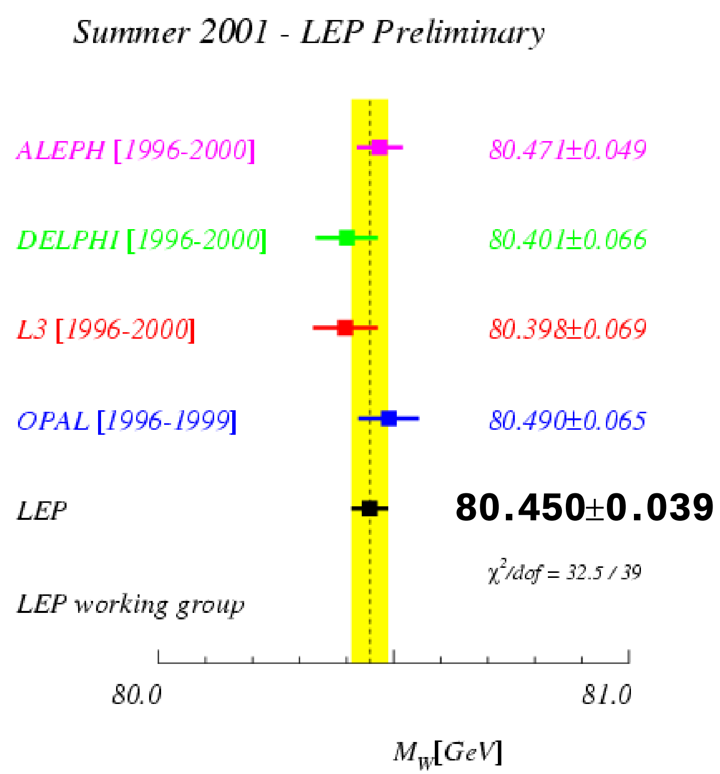
Precision limited by statistics

LEP2: W boson mass and width

(see talk by A.Straessner for all details)

LEP2 currently provides the most precise direct measurement of the W boson mass

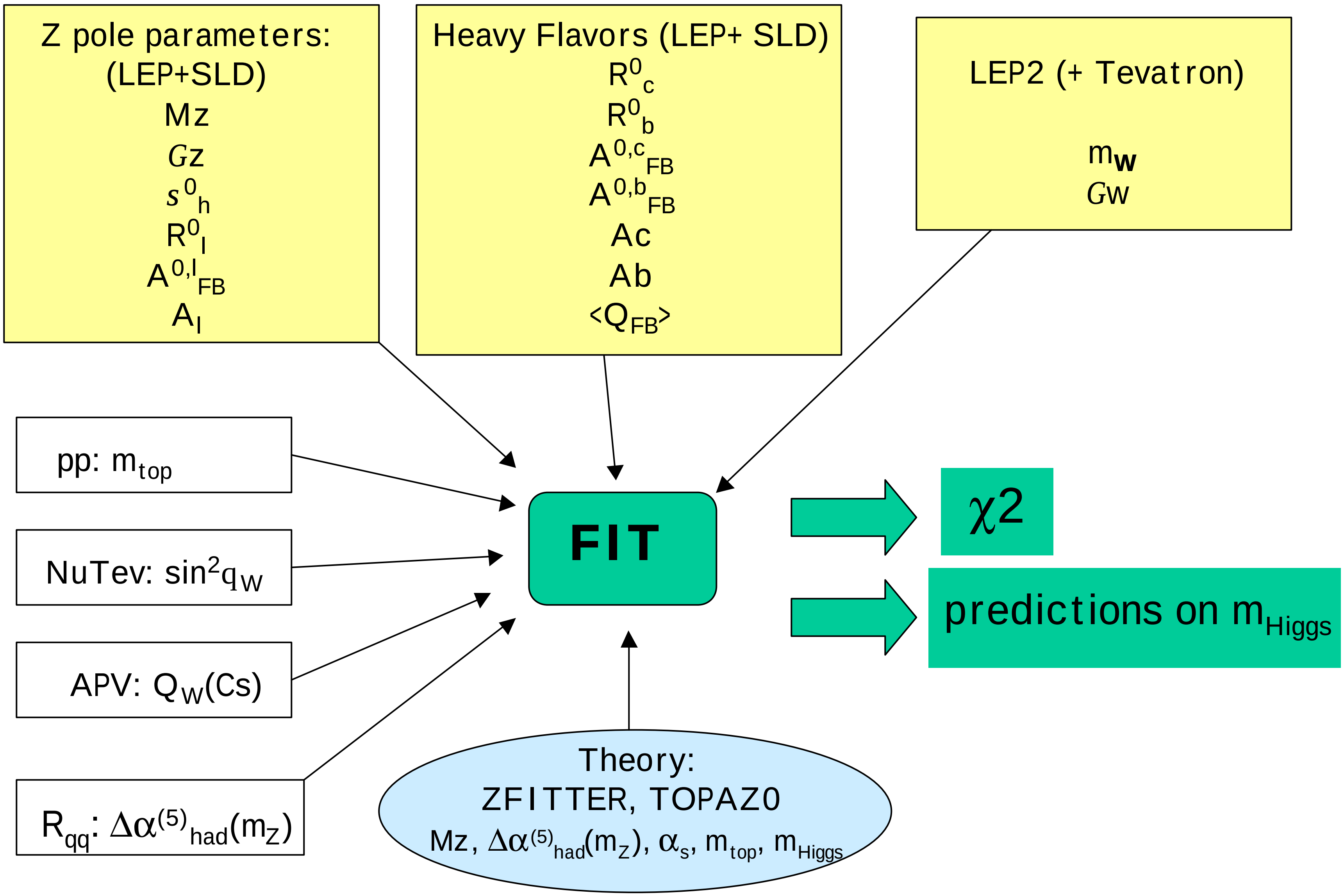
δm_W(stat) = 26 MeV
δm_W(syst) = 30 MeV



➢ Aim for 30-35 MeV final precision, with ongoing efforts on common systematics (Colour Reconnections, LEP beam energy)

We also measure the W width: Γ_W = 2.150 ± 0.091 GeV

Global electroweak fit



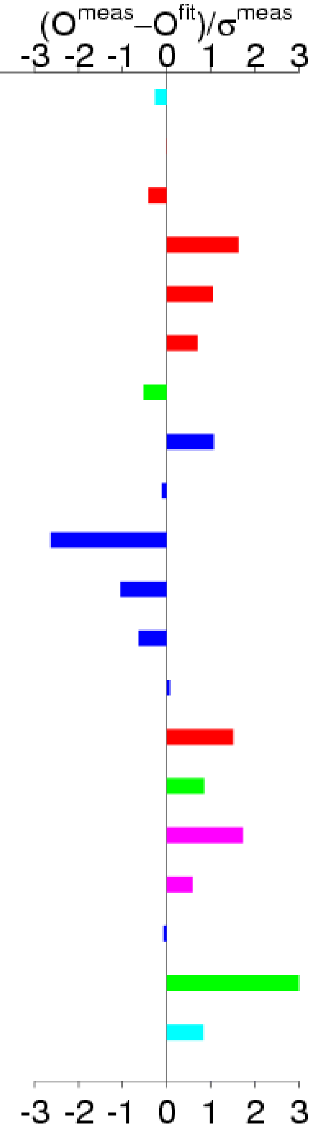
Global electroweak fit

NEW inputs:

- Gw direct meas. for the first time
- $A^{0,b}_{FB}$ $A^{0,c}_{FB}$ from LEP
- $\sin^2 q_W$ from NuTev final result (see talk by K.McFarland) hep-ph/0111059, Phys.Rev.Lett. 88 (2002)
- Qw(Cs) from APV hep-ph/0111019

Winter 2002

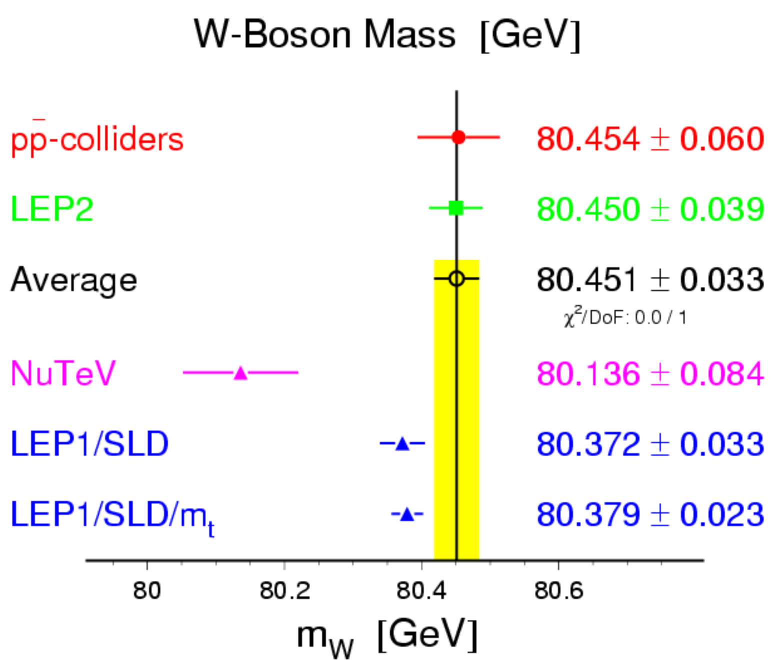
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84



c^2/NDF=28.8/15 Prob.=1.7%

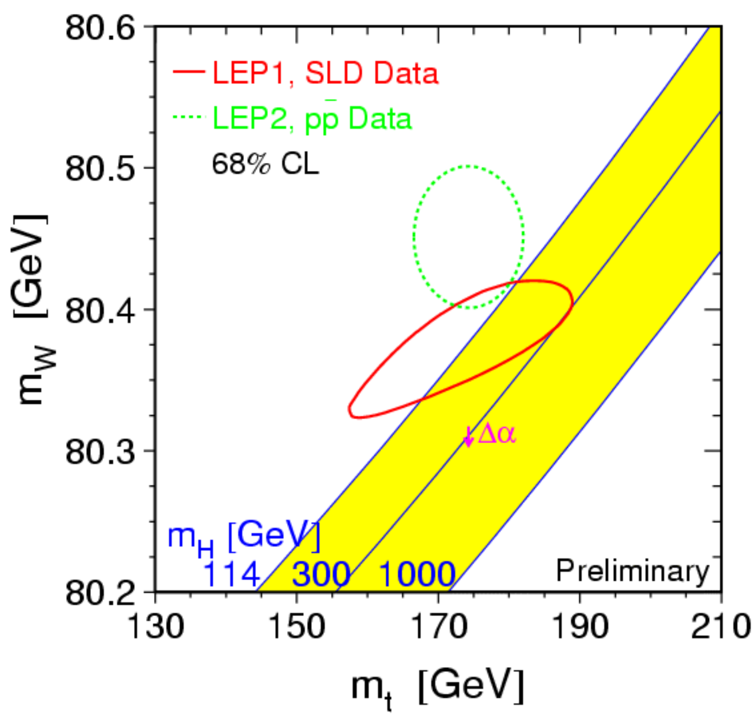
W and top mass: measurement vs predictions

Compare direct measurements of m_W (and m_{top}) with values predicted from fit to the rest of EW data

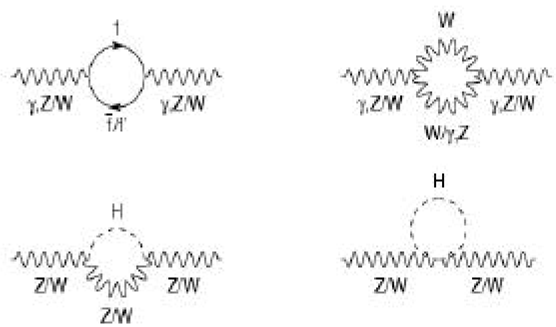


The precision of direct measurement is comparable to that of the prediction

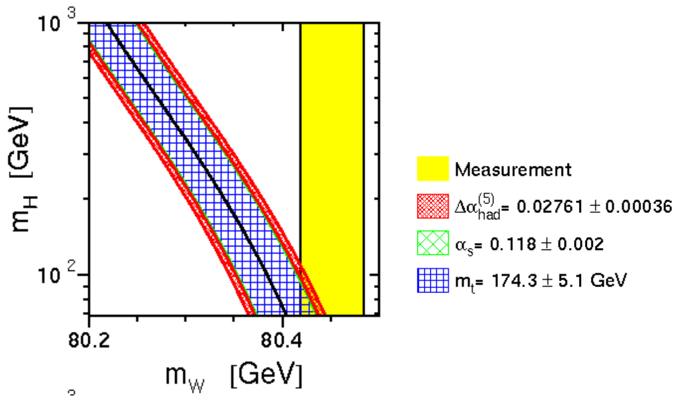
Masses of W, top are correctly predicted by the EW fit (m_W within 2 s slightly improved w.r.t. Summer'01)

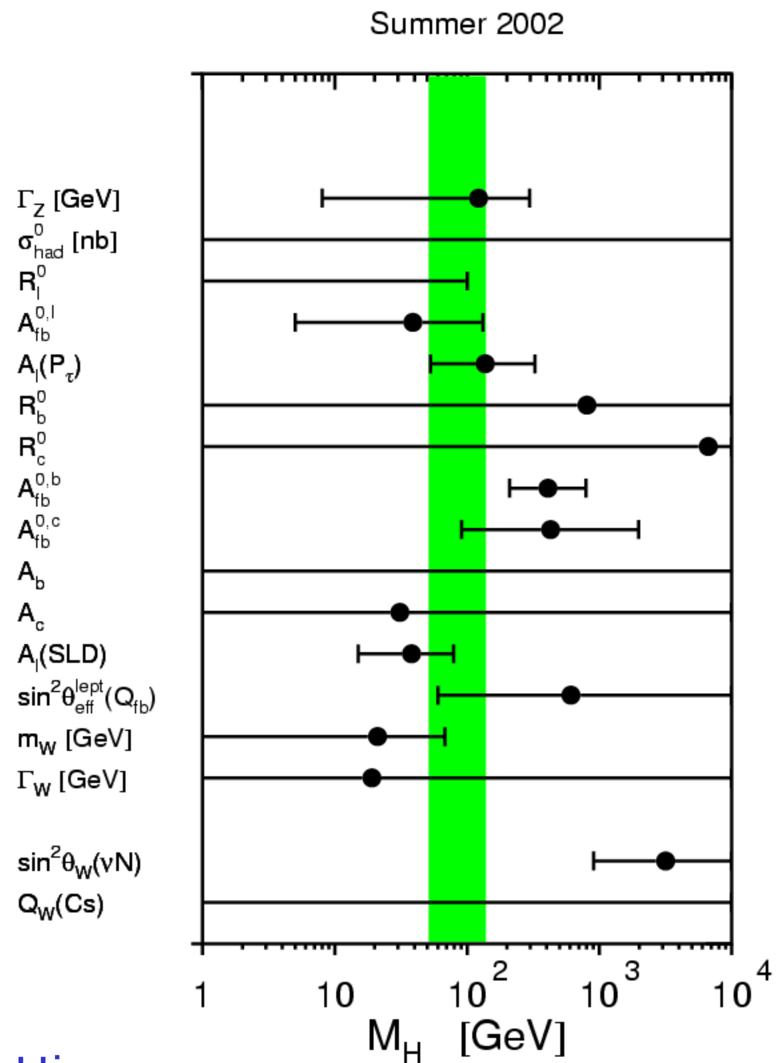


Sensitivity to Higgs boson mass



corrections = $f(m^2_{top}, \log m_{Higgs}, \ldots)$

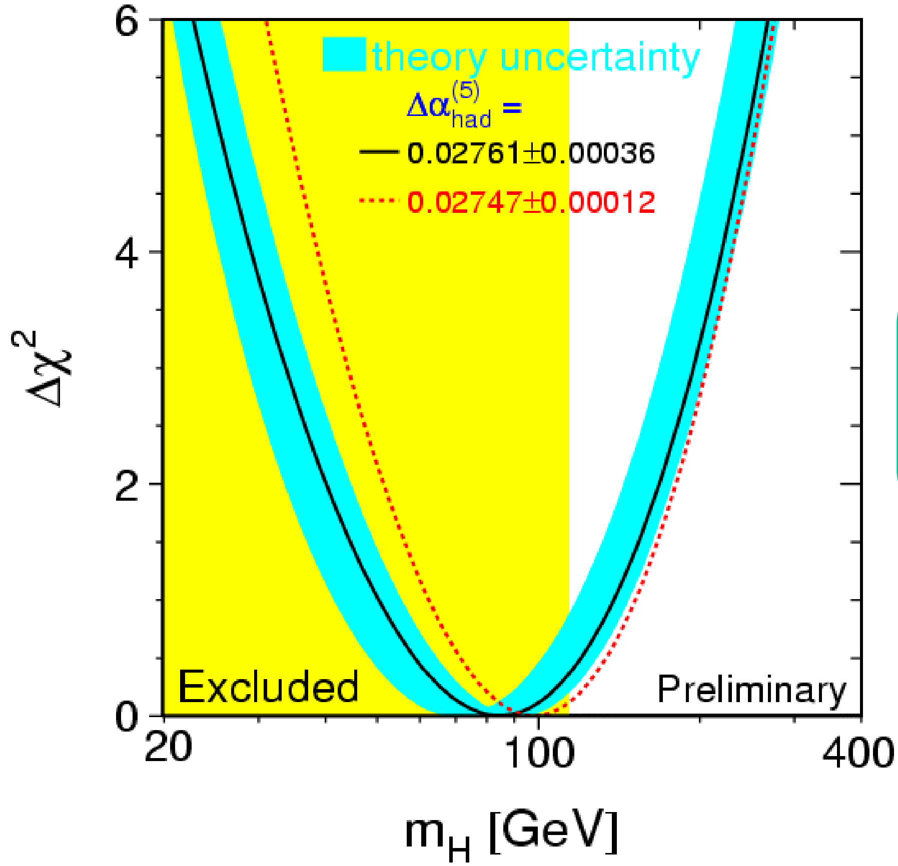




Leptons and m_W tend to favour low Higgs mass

Hadrons tend to favour high Higgs mass

Global fit of EW data to Higgs boson mass



m_{Higgs} = 85 $^{+54}$ / $_{-34}$ GeV
m_{Higgs} < 196 GeV (95% c.l.)

Da$^{(5)}{}_{had}(m_Z)$:

- experiment-driven: Burkhard-Pietrzyk Phys.Lett. B513 (2001) 46-52
- NEW theory-driven: Troconiz-Yndurain hep-ph/0107318 moves upper limit to 199 GeV

Conclusions

LEP has provided an unprecedented set of high precision data and tested the Standard Model at loop level

LEP-1 results are (almost) final
LEP-2 results are all available (preliminary)

Still a lot of activity going on !
• improve some of the measurements (m_W...)
• finalize results
• understand remaining puzzles

The Higgs has not been seen, but LEP is the place where most of the information about it has been found !