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Electroweak Measurements on the Z Resonance

results from

ALEPH, DELPHI, L3, OPAL and SLD

Outline:

- LEP Lineshape and Lepton Asymmetry Measurements
- LEP tau polarization
- SLD Right-Left Asymmetries
- LEP and SLD heavy quark results

LEP Lineshape and Lepton Asymmetry Measurements

Lowest order differential cross section (ignoring masses and initial and final state QCD and QED corrections):

$$\frac{2s}{\pi\alpha^2}\frac{1}{N_c}\frac{d\sigma}{d\cos\theta} =$$

$$q_f^2\left(1+\cos^2\theta\right)$$

$$-8Re\{\chi(s)q_f(g_{\mathrm{Ve}}g_{\mathrm{Vf}}\left(1+\cos^2\theta\right) \qquad + 2g_{\mathrm{Ae}}g_{\mathrm{Af}}\cos\theta)\}$$

$$16|\chi(s)|^2[(g_{\mathrm{Ve}}^2+g_{\mathrm{Ae}}^2)(g_{\mathrm{Vf}}^2+g_{\mathrm{Af}}^2)\left(1+\cos^2\theta\right) \quad + 8g_{\mathrm{Ve}}g_{\mathrm{Ae}}g_{\mathrm{Vf}}g_{\mathrm{Af}}\cos\theta]$$

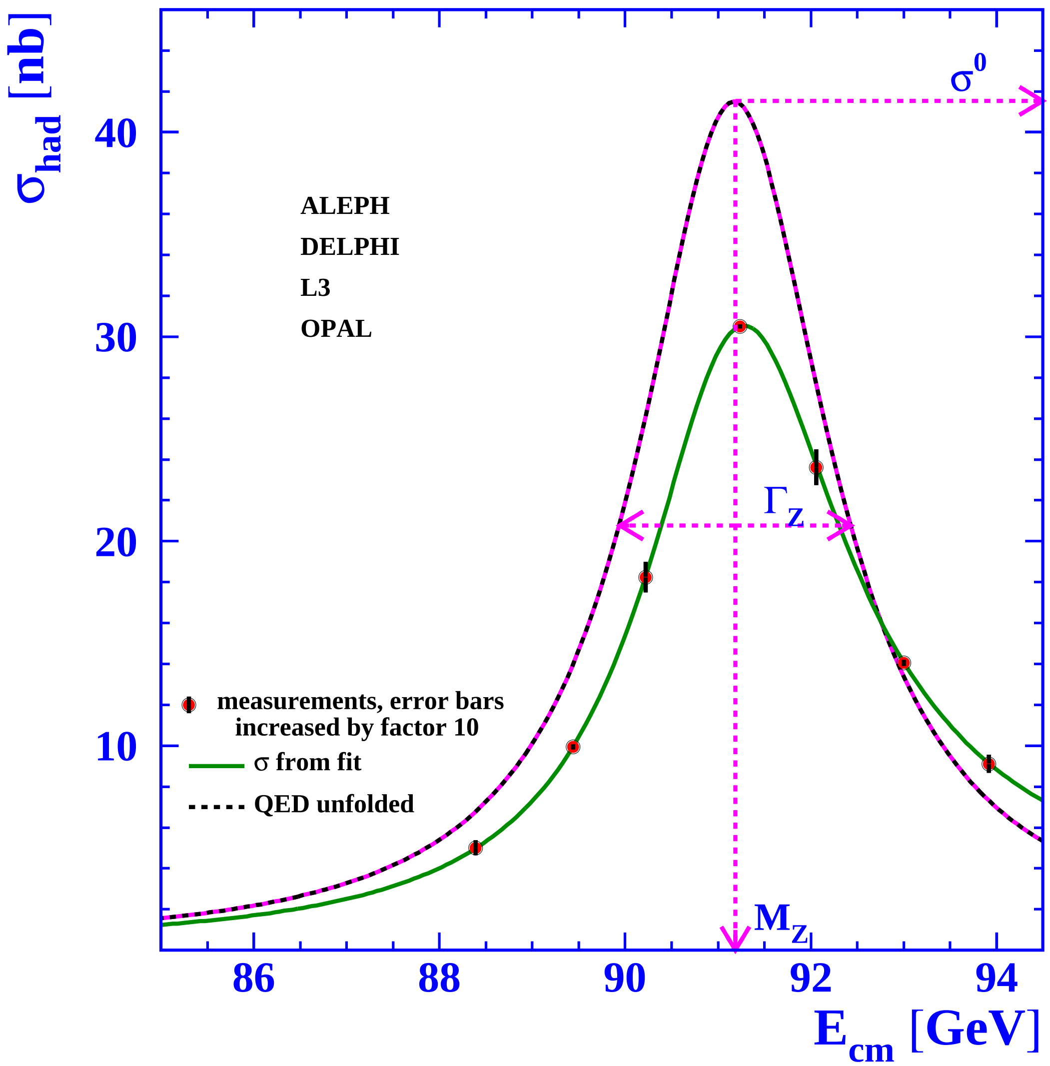
Where:

- $\chi(s) = \frac{G_{\mathrm{F}}m_{\mathrm{Z}}^2}{8\pi\alpha\sqrt{2}}\frac{s}{s-m_{\mathrm{Z}}^2+is\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}}}$
- g_{Vf} and g_{Af} are replaced with *effective* couplings in the IBA which we will use from now on.
- N_c is the number of "colors" for the final state fermions

For standard LEP fits interference term and imaginary parts of g_{Vf} and g_{Af} are fixed to the Standard Model prediction.

(See talk on s-matrix approach)

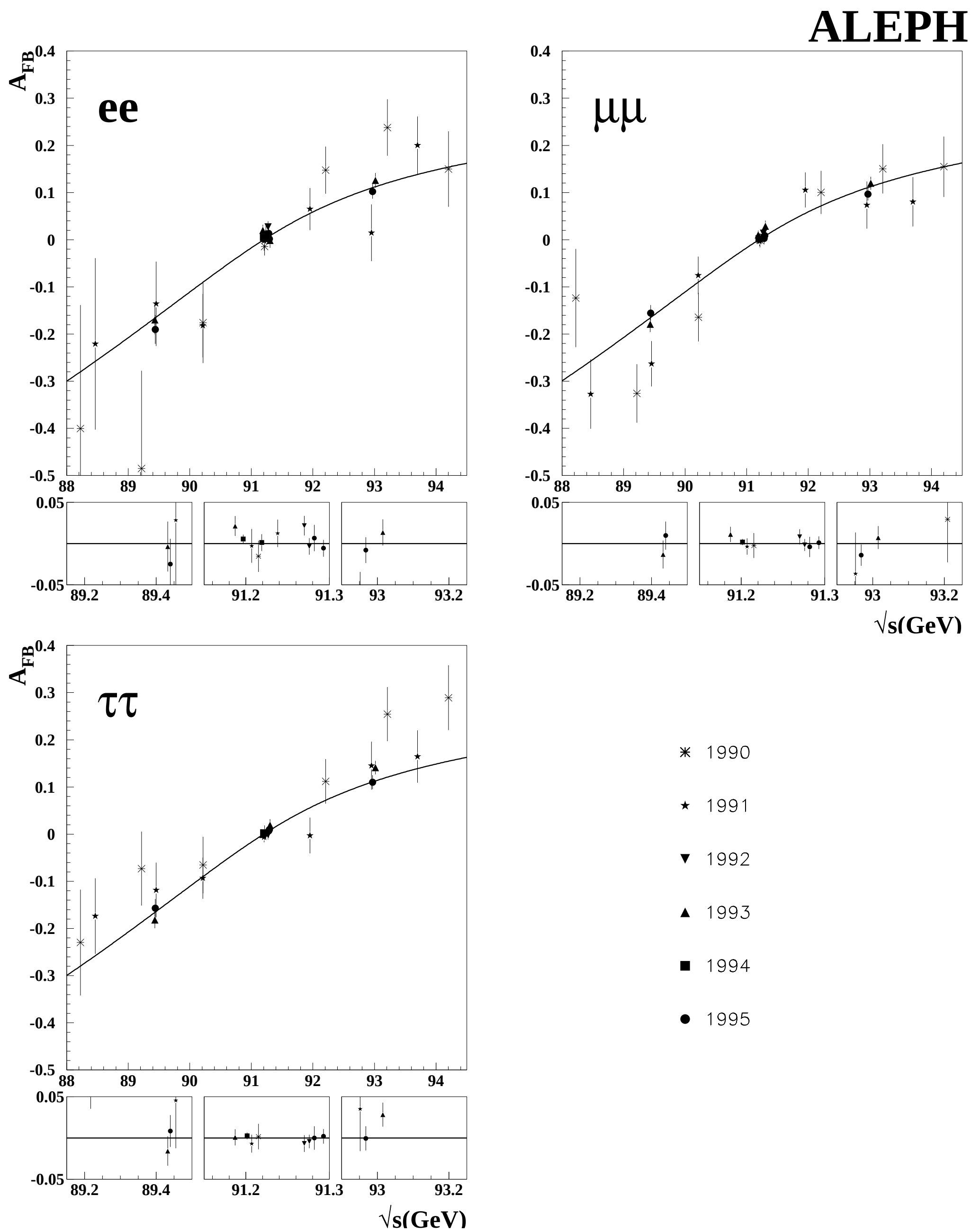
LEP experiments measure cross sections



Experimental results reported after unfolding for huge ($\simeq$ 25%) initial-state radiative corrections. Electrons are corrected for t-channel effects.

(These correction are known to third-order, see: Berends, Neerven, Burgers / Montagna, Nicrosini, and Piccinini / Skrzypek/ Jadach, Pietrzyk, and Skrzypek).

and forward-backward asymmetries



combination of 200 - 400 data points/experiment too difficult ⇒ use pseudo-observables which are closely related to the measured quantities

LEP Model (in)Dependent Parameter Set

(also called pseudo-observables)

			Total Error	Theory Error
m_Z			2.1 MeV (0.2×10^{-4})	0.3 MeV (0.03×10^{-4})
Γ_Z			2.3 MeV (9.2×10^{-4})	0.2 MeV (0.8×10^{-4})
σ^0_{had}	$\equiv$	$\frac{12\pi}{m_Z^2}\frac{\Gamma_{e^+e^-}\Gamma_{\text{had}}}{\Gamma_Z^2}$	0.037nb (8.9×10^{-4})	0.022nb (5.3×10^{-4})
R_ℓ	$\equiv$	$\frac{\Gamma_{\text{had}}}{\Gamma_\ell}$	0.025 (12×10^{-4})	0.004* (1.9×10^{-4})
$A^{\text{pole}}_{\text{FB}}$	$\equiv$	$\frac{3}{4}A_e A_f$	0.00095 (5.6%)	0.0001* (0.6%)

$$\Gamma_{f\bar{f}} = \frac{G_F N_c m_Z^3}{6\pi\sqrt{2}}\left(R_V^f {g_{Vf}}^2 + R_A^f {g_{Af}}^2\right) + \Delta_{QCD}$$
$$A_f = 2\frac{g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

(R_V^f and R_A^f give corrections for final-state QED and QCD effects as well as quark masses, Δ_{QCD} for non-factorizable QCD effects.)

* Theory error for electrons is larger 0.024 (R_e) and 0.0014 ($A^{\text{pole}}_{\text{FB}}$)

In general our results greatly exceeded expectations:

	Expectation	Result
Z Decays/experiment	5 - 10 $\times 10^6$	5 $\times 10^6$
Systematic on energy	10 MeV	$<$ 2.0 MeV
Systematic on luminosity	$\sim$ 1%	$\sim$ 0.05% (Exp) 0.054% (Th)

In last two years unfolding procedure and theoretical errors on the pseudo-observables examined in great detail:

- Detailed comparisons of MIZA, TOPAZ0, ZFITTER

- Important theory changes

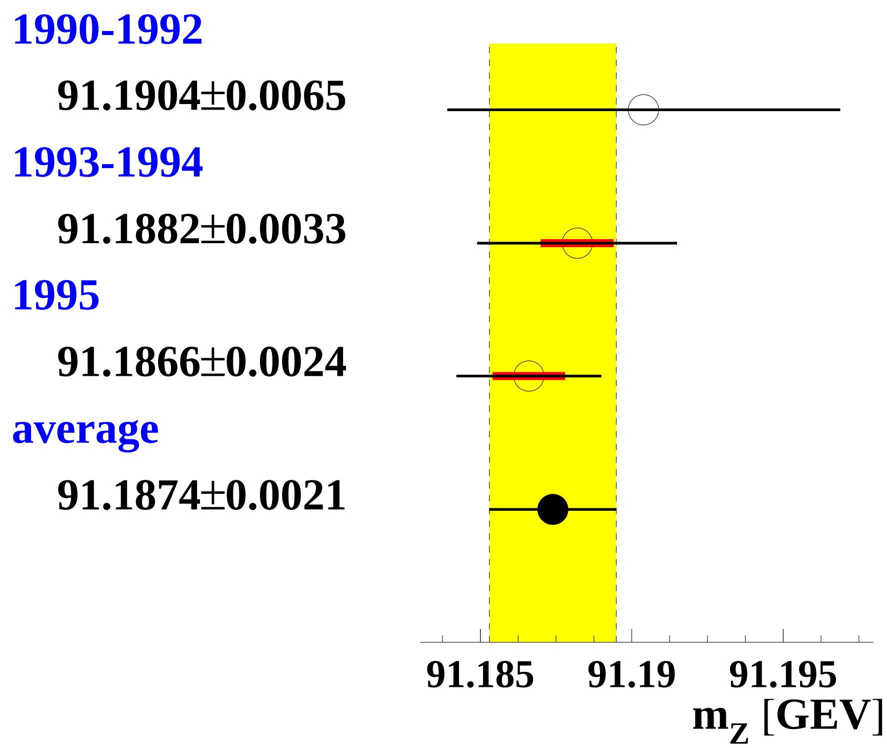
  - 1999 turning on 3rd order corrections shifts:

    * σ^0_{had} by 0.023nb ($\sim 6 \times 10^{-4}$)

    * m_{Z} and Γ_{Z} by $\sim$ 0.5 MeV

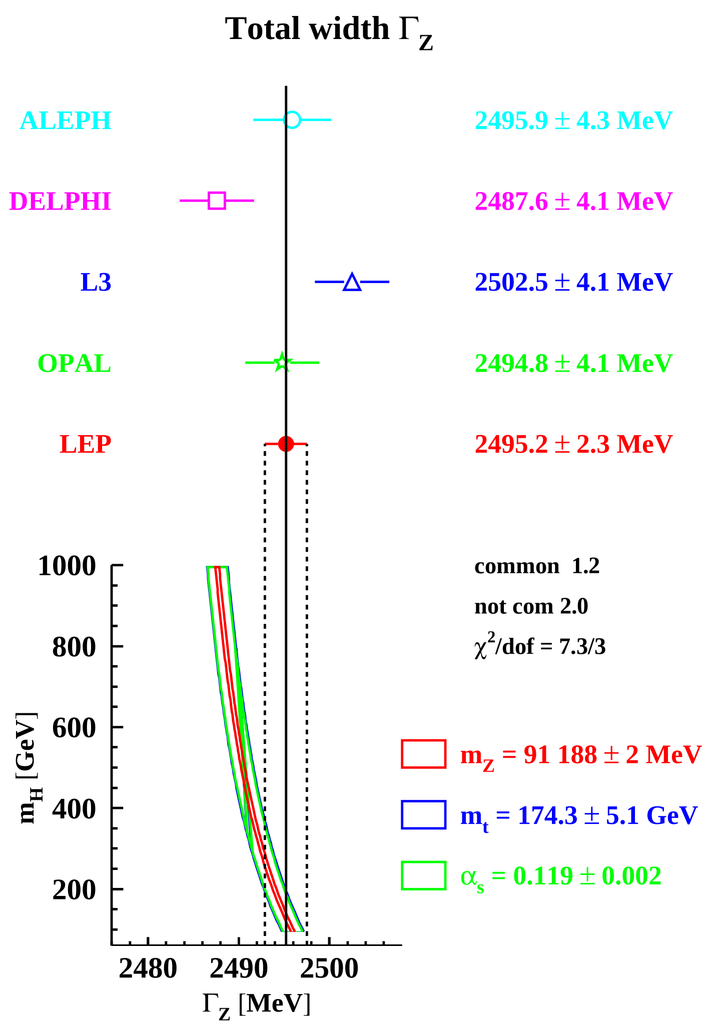
  - 2000 Inclusion of radiative final-state pair correction shifts m_{Z} by $\sim$ 0.5 MeV and Γ_{Z} by $\sim$ 0.8 MeV

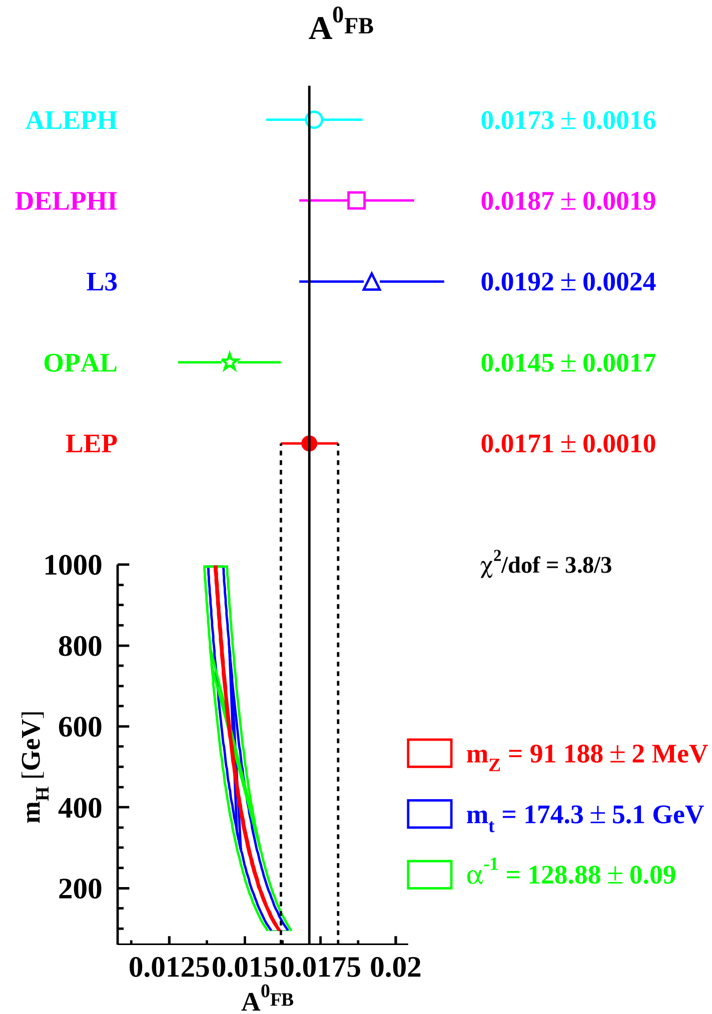
- Experimental change: use optimal weight of 1993 and 1995 data for observables, eg use separate m_Z masses for different energy calibrations:



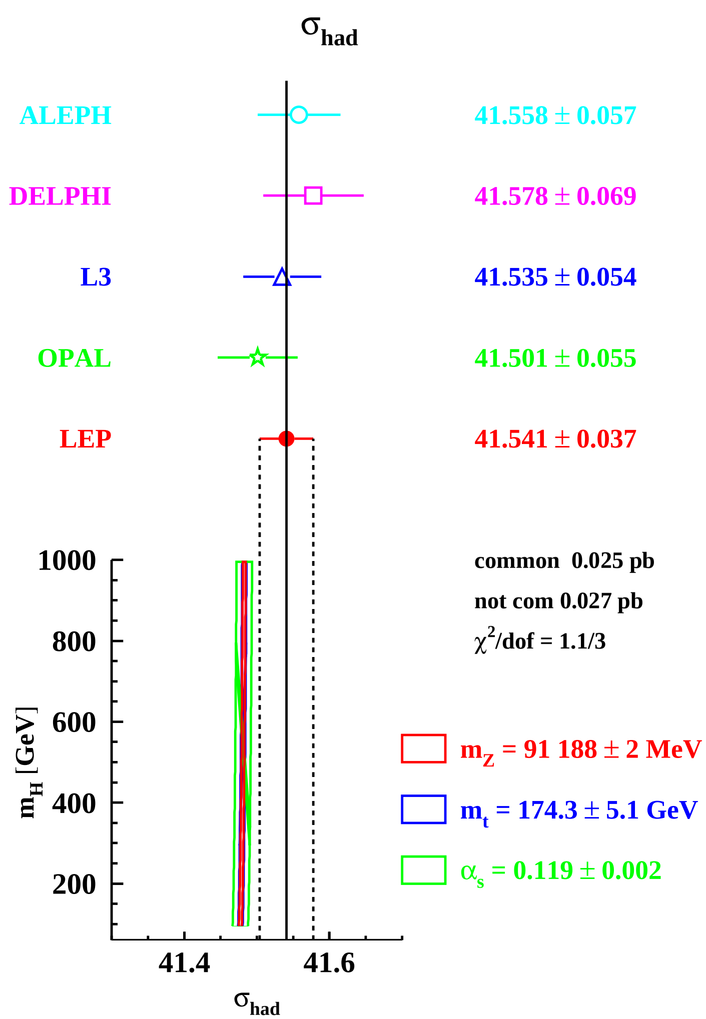
Status

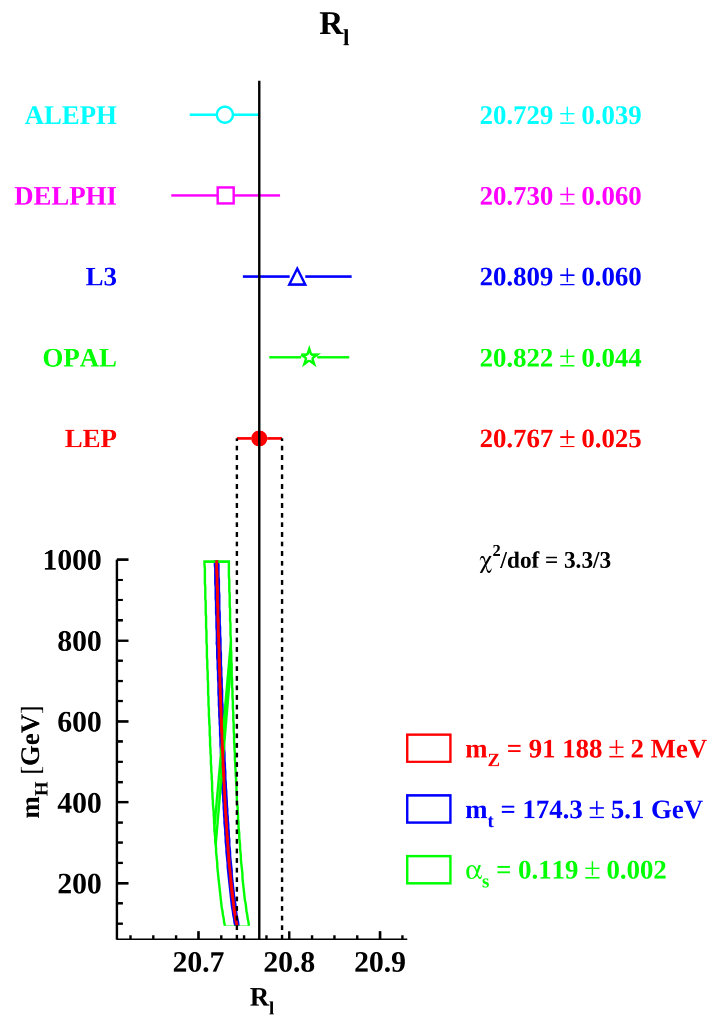
ALEPH	Final
DELPHI	Final
L3	Final
OPAL	“public reading”





Γ_Z and A_{FB}^{pole} both favor a light Higgs, but this interpretation depends on $\Delta\alpha_{had}$





$\sigma^0_{\rm had}$ and R_ℓ are important for $\Gamma_{\rm inv}$ and α_s because they depend on the ratio of widths.

Ratio of invisible to leptonic widths:

$$\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = \frac{Br(\text{Z} \to \text{inv})}{Br(\text{Z} \to \ell^+\ell^-)} = 5.942 \pm 0.016$$

$$(\text{SM } \frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = 5.9736 \pm 0.0048)$$

or

$$N_\nu = 2.984 \pm 0.008$$

or

$$\Delta\Gamma_{\text{inv}} < 2.0\text{MeV} \quad (95\%\text{C.L.})$$

This result benefits from the improved Bhabha theory error (Jadach, Placzek, Richter-Was, Ward,Z. Was/ Montagna, Moretti, Nicrosini, Pallavicini, Piccinini) and from the improved initial-state radiative corrections.

In terms LEP observables:

$$\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = \left(\frac{12\pi}{m_{\text{Z}}^2}\frac{R_\ell}{\sigma^0_{\text{had}}}\right)^{\frac{1}{2}} - R_\ell - 3$$

Determination of α_s from $R_l \propto 1 + \frac{\alpha_s}{\pi}...$

(take $m_h = 100$GeV for the following)

$$\alpha_s(m_Z) = 0.1228 \pm 0.0038 \begin{array}{l} +0.0033 (m_h = 900\,\text{GeV}) \\ -0.0000\,(m_h = 100\,\text{GeV}) \end{array}$$

and surprisingly from $\sigma_\ell^0 \propto (\frac{\Gamma_{\ell\ell}}{\Gamma_Z})^2 \propto 1 - 1.4\frac{\alpha_s}{\pi}...$

$$\alpha_s(m_Z) = 0.1183 \pm 0.0030 \begin{array}{l} +0.0026 (m_h = 900\,\text{GeV}) \\ -0.0000 (m_h = 100\,\text{GeV}) \end{array}$$

Grand LEPEWG fit:

$$\alpha_s(m_Z) = 0.1183 \pm 0.0027$$

(Note: Theory error is under discussion.)

PDG 2000 average $\quad \alpha_s(m_Z) = 0.1181 \pm 0.002$

NNLO average (no LEP) $\quad \alpha_s(m_Z) = 0.1178 \pm 0.0034$

(S. Behtke J. Phys. G 26(2000) R27-R66)

Tau Polarization

$$P_\tau \equiv \frac{(\sigma_+ - \sigma_-)}{(\sigma_+ + \sigma_-)}$$

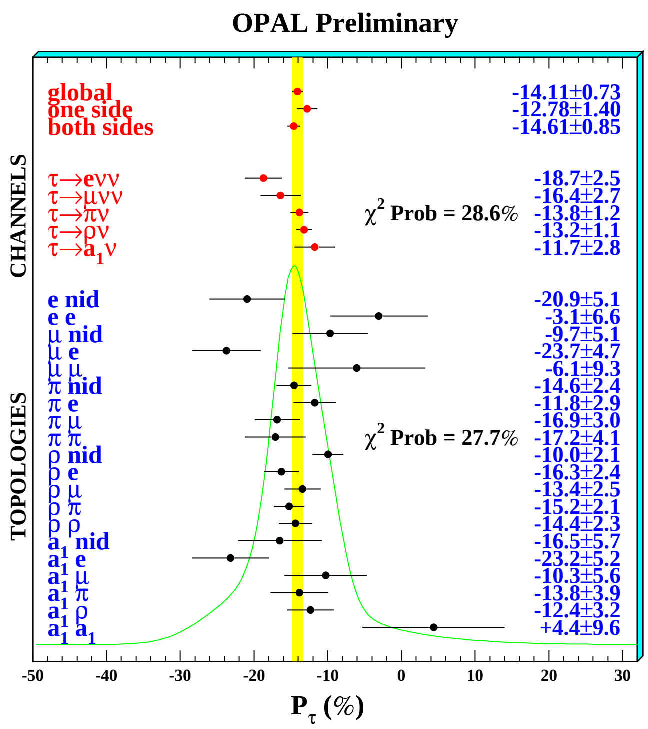
where $\sigma_{+(-)}$ is for positive(negative) helicity

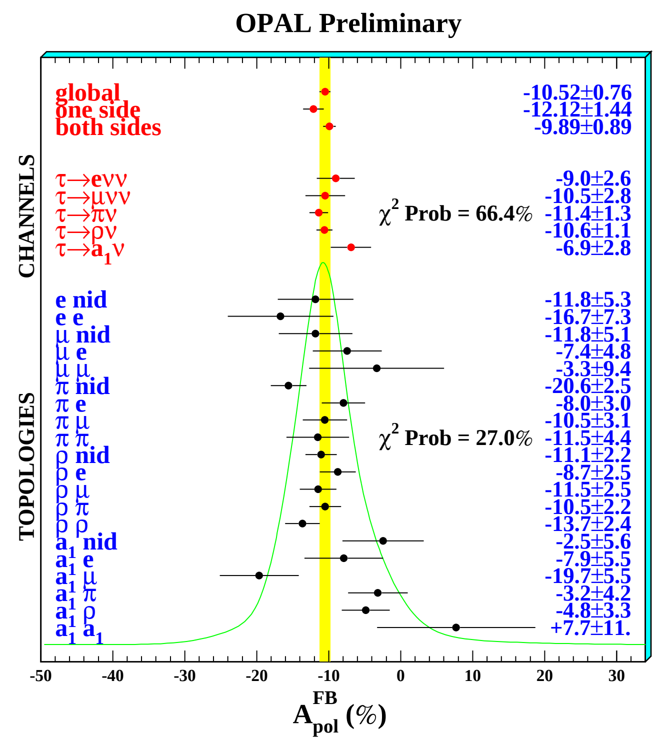
At Born level

$$P_\tau(\cos\theta_{\tau^-}) = \frac{\langle P_\tau \rangle \; (1 + \cos^2\theta_{\tau^-}) + \frac{8}{3} \mathrm{A}_{\mathrm{pol}}^{\mathrm{FB}} \; \cos\theta_{\tau^-}}{(1 + \cos^2\theta_{\tau^-}) + \frac{8}{3} \mathrm{A}_{\mathrm{FB}} \; \cos\theta_{\tau^-}}$$

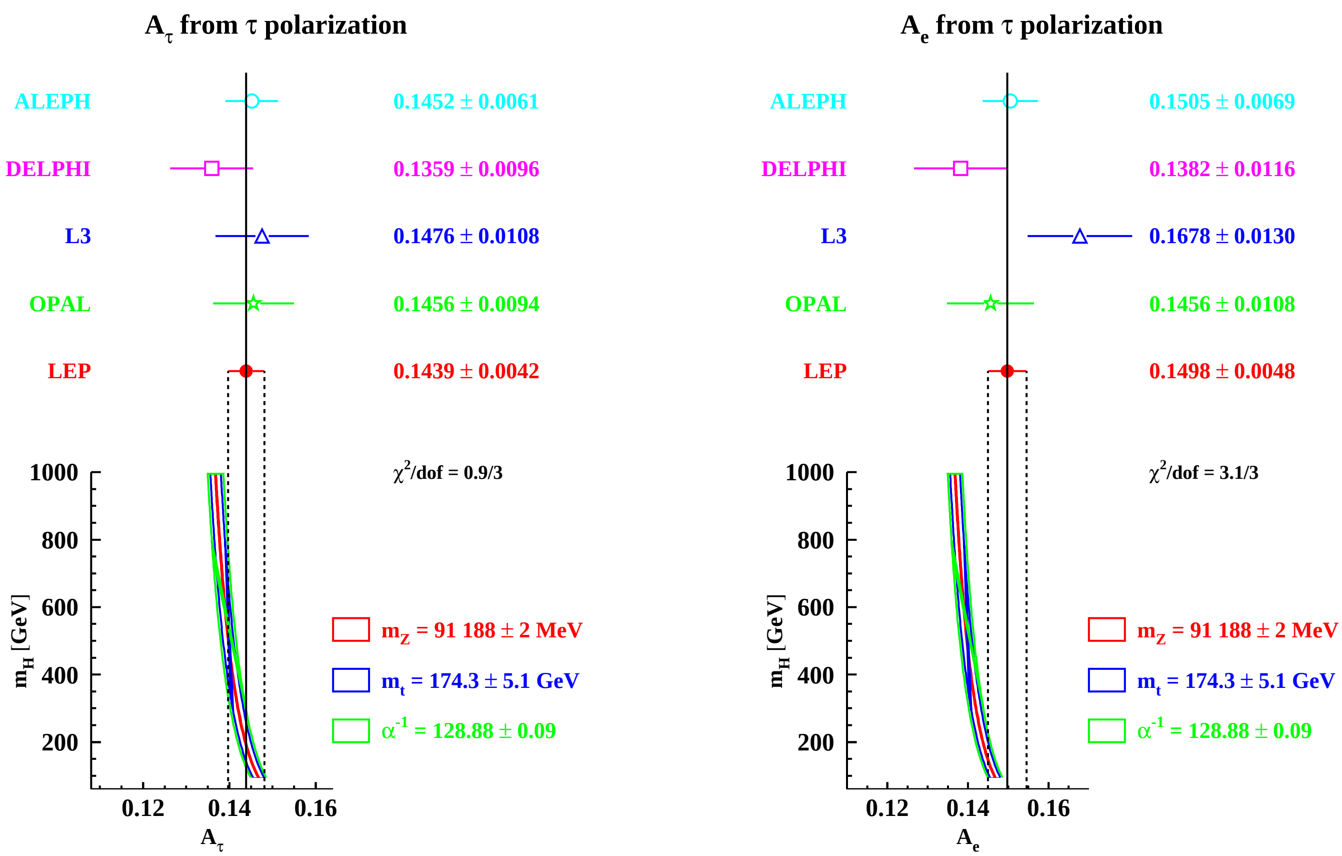
with $\langle P_\tau \rangle \; = -A_\tau$ and $\mathrm{A}_{\mathrm{pol}}^{\mathrm{FB}} \; = -\frac{3}{4} A_e$

New result from OPAL:





Combined results favor a low Higgs mass:



Status:

ALEPH	preliminary
DELPHI	Final
L3	Final
OPAL	new result, paper in preparation

SLD

Flag ship measurement:

$$A_{\mathsf{LR}} \simeq \frac{1}{|P_e|}\frac{\sigma_l - \sigma_r}{\sigma_l + \sigma_r} = A_e$$

σ_r and σ_l are cross section with left and right polarization

• In contrast to LEP radiative and interference corrections are very small.

Measurement statistics limited ($\sim$ 1.5%), main systematics:

- Polarization (0.5%)
- Energy dependence (0.4%, based on energy scan)

Final SLD result on A_{e} (including input from electrons) is

$$A_{\mathsf{e}} = 0.1516 \pm 0.0021$$

From polarized forward-backward asymmetry

$$A_f^{\mathsf{FB}} = \frac{4}{3|P_e|}\frac{(\sigma_l(F)-\sigma_l(B))-(\sigma_r(F)-\sigma_r(B))}{(\sigma_l(F)+\sigma_l(B))+(\sigma_r(F)+\sigma_r(B))}$$

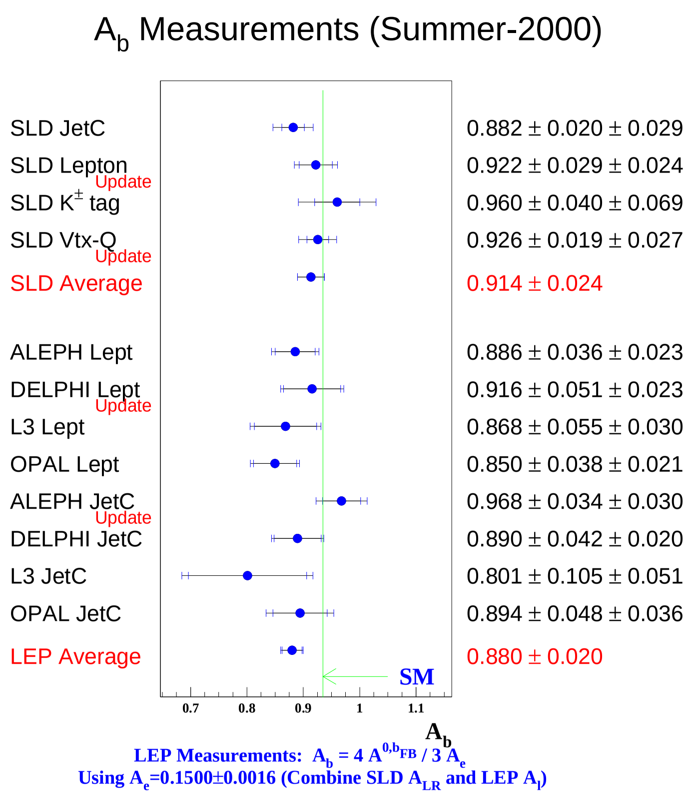
SLD obtains:

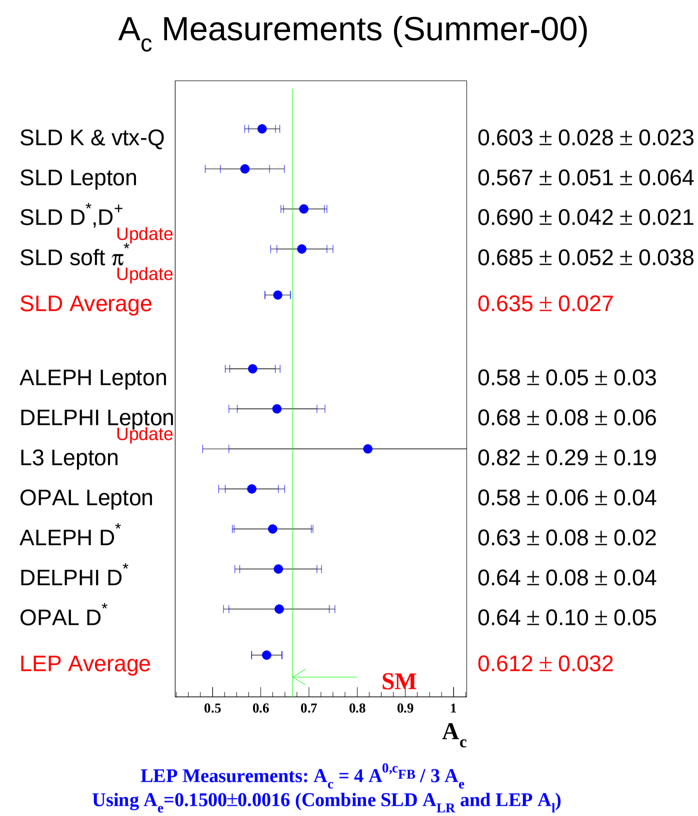
$$A_e = 0.1455 \pm 0.0060$$

$$A_\mu = 0.142 \pm 0.015$$

$$A_\tau = 0.136 \pm 0.015$$

The polarized forward-backward asymmetry can also be used for $\mathrm{b\overline{b}}$ and $\mathrm{c\overline{c}}$ final states ...





LEP/SLD average

$A_b = 0.898 \pm 0.015$ $A_c 0.624 \pm 0.020$

Standard Model

0.935 ($-2.5\ \sigma$) 0.668 ($-2.2\ \sigma$)

Updates to LEP results heavy flavor results:

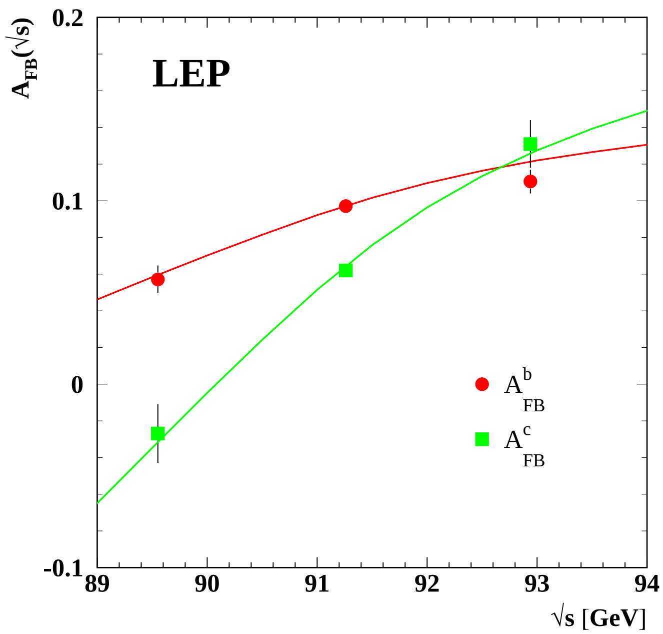
- New b and c lepton based asymmetries from DELPHI
- New results on b-branching ratios from DELPHI (DELPHI 2000-114) and ALEPH (ALEPH 2000-69)

The asymmetry results are mostly final, but updates expected for the high p_t leptons and improved jet-charge from ALEPH and DELPHI.

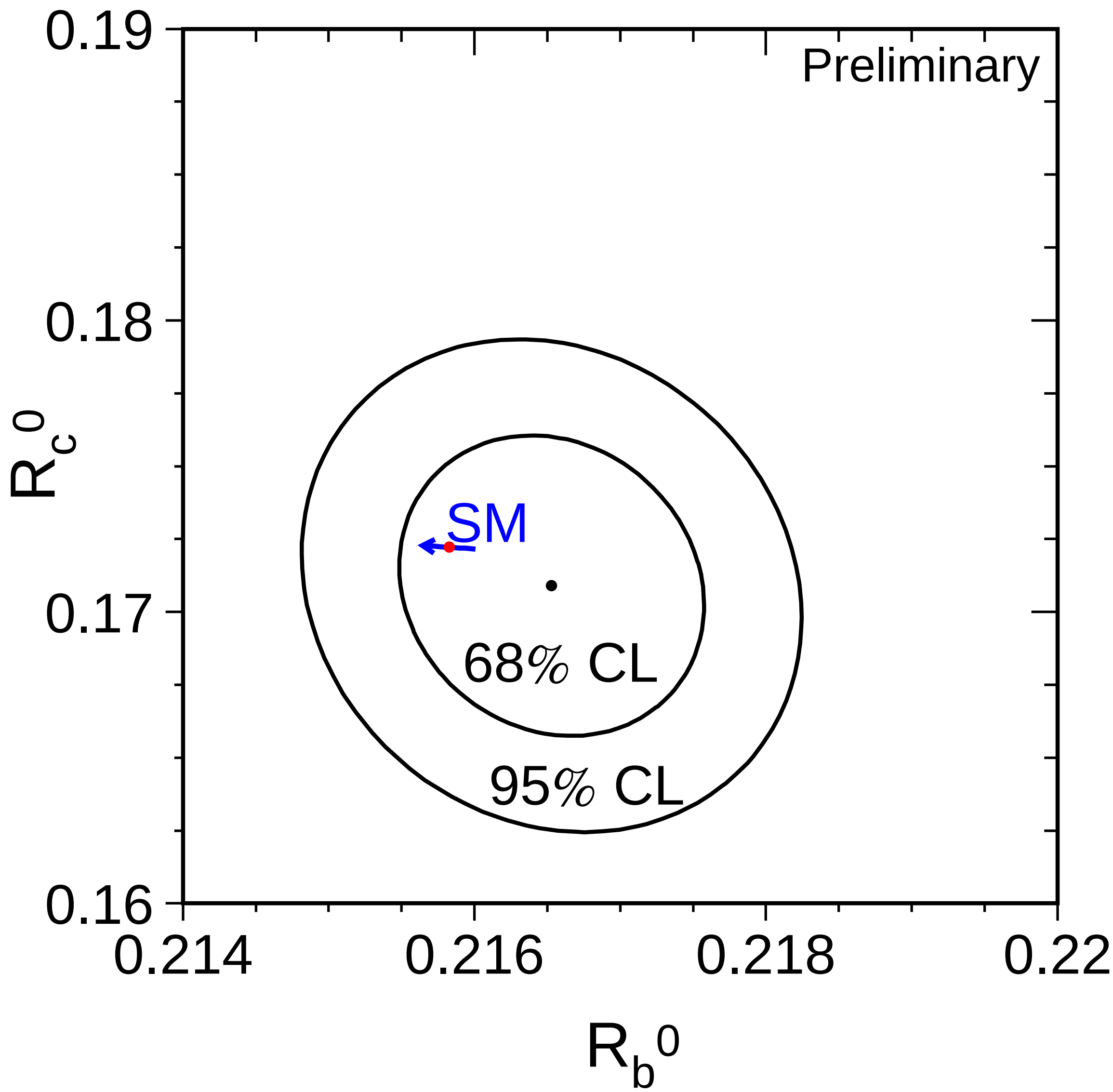
Contributions to error (from CERN-EP-2000-016):

	$A_{FB}^{b\ 0}$ $(\times 10^{-3})$	$A_{FB}^{c\ 0}$ $(\times 10^{-3})$
statistics	1.8	3.2
internal sys.	0.8	1.5
light quarks	0.5	0.1
QCD	0.2	0.1
$Br(D^+ \to K^-\pi^+\pi^+)$	0.1	0
$Br(D_s \to \phi\pi^+)$	0.1	0
gluon splitting	0.1	0

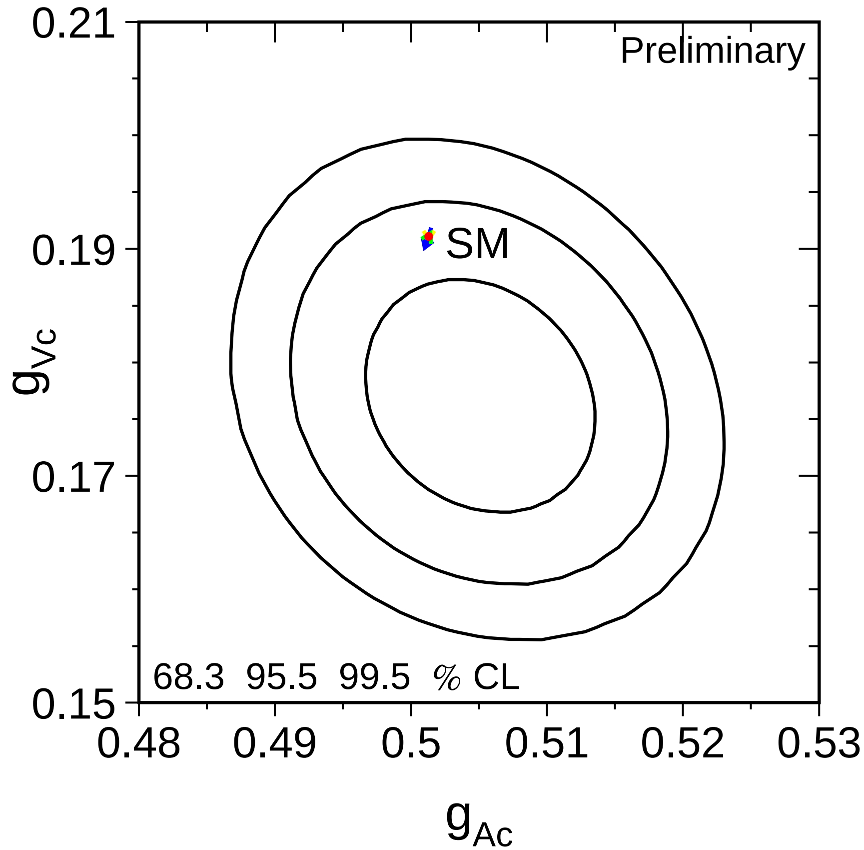
Energy Dependence (see also LEP 2 results):

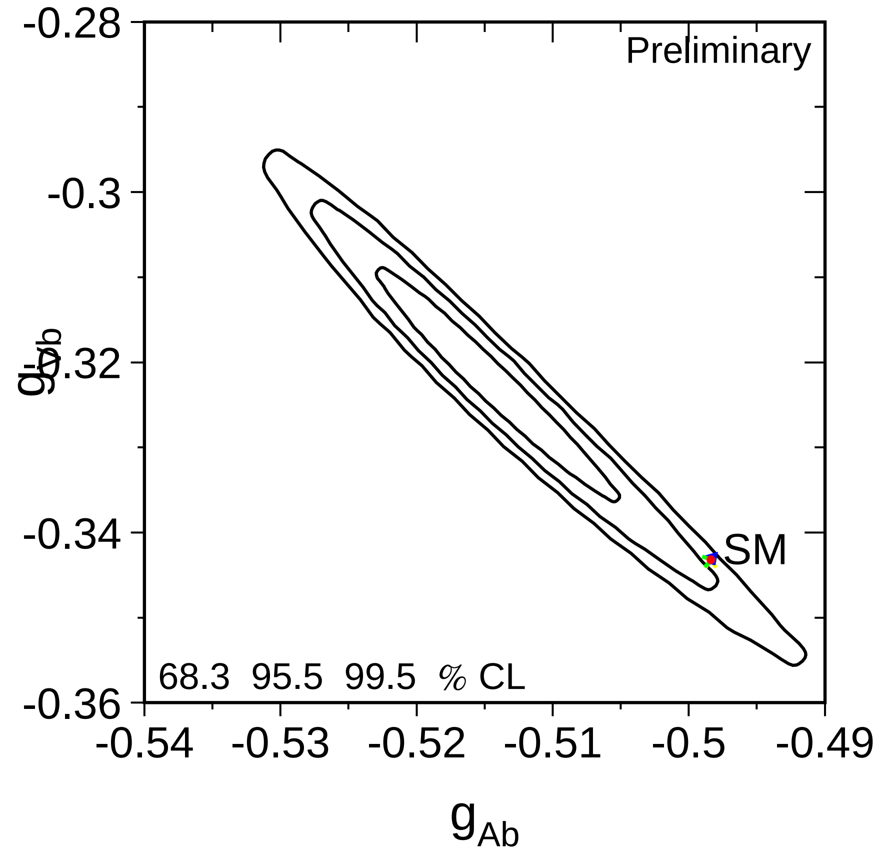


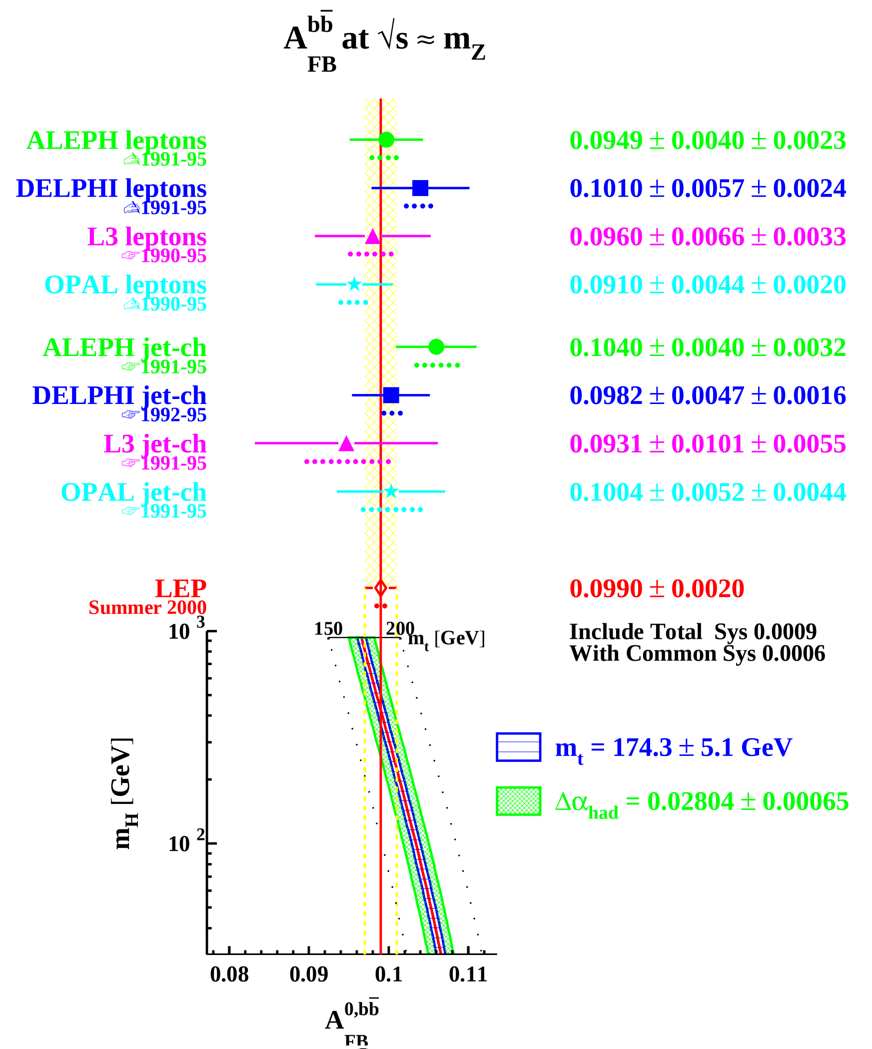
R_b and R_c no longer important for grand electroweak fit:

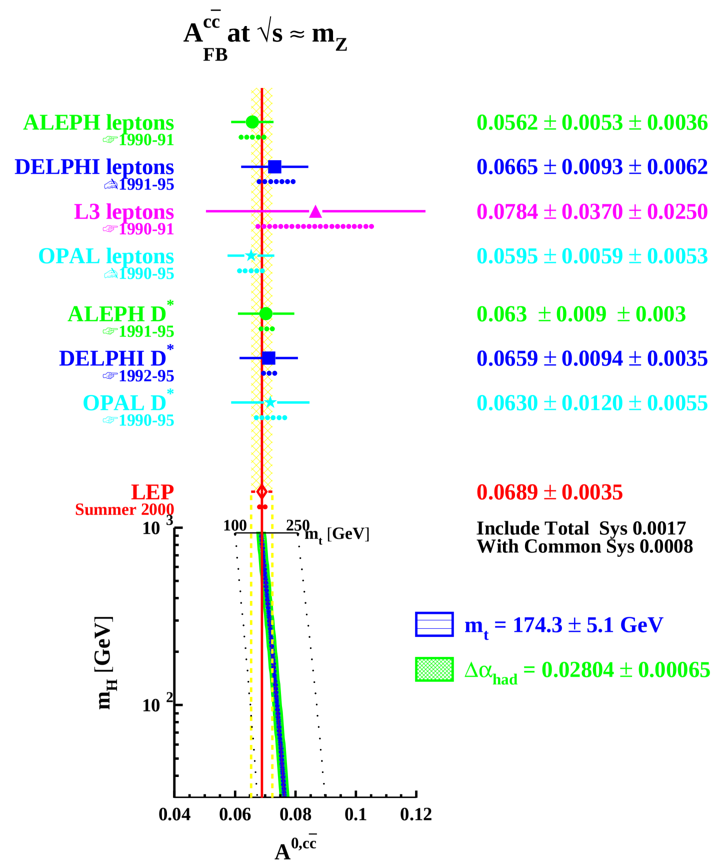


b-quark and c-quark couplings :



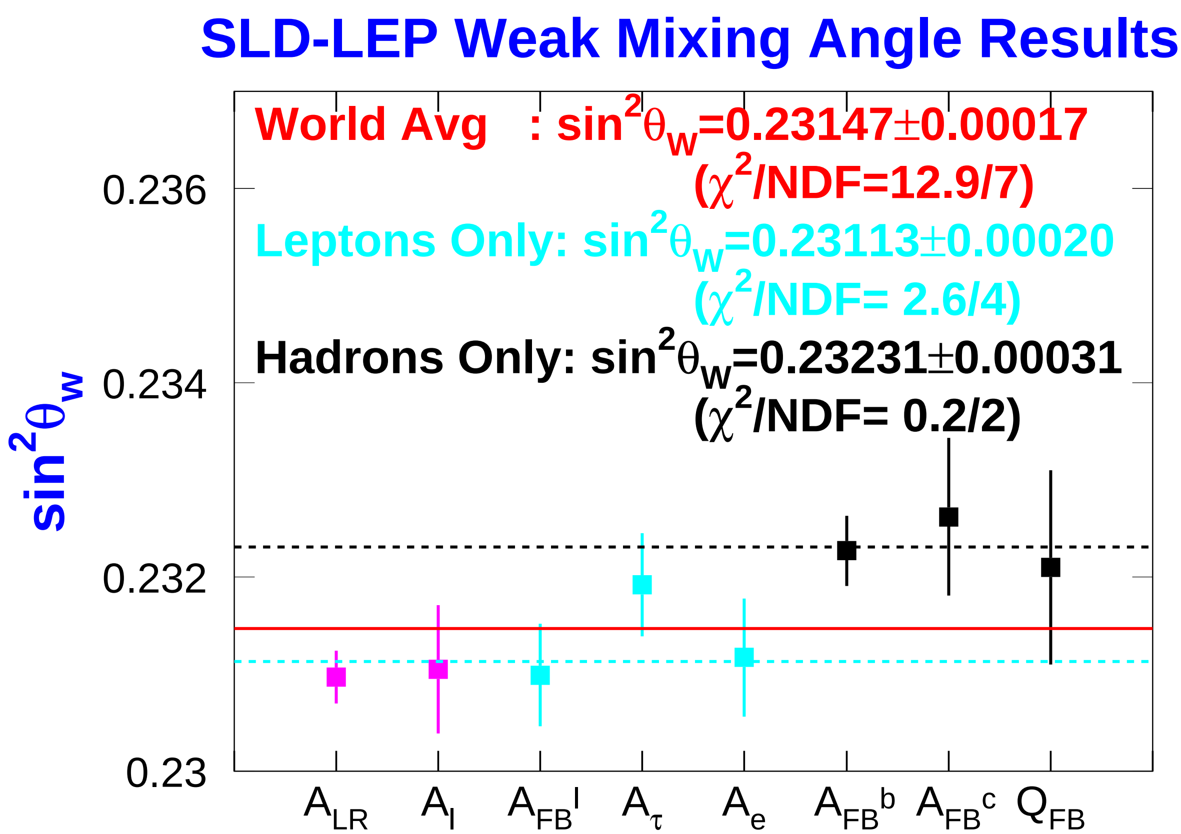






$A_{FB}^{b} = \frac{3}{4} A_e A_b$ and $A_{FB}^{c} = \frac{3}{4} A_e A_c$ both favor a heavy Higgs.

In terms of $\sin^2\theta_{\rm lep}^{\rm eff} \equiv \frac{1}{4}\left(1 - \frac{g_{V\ell}}{g_{A\ell}}\right)$

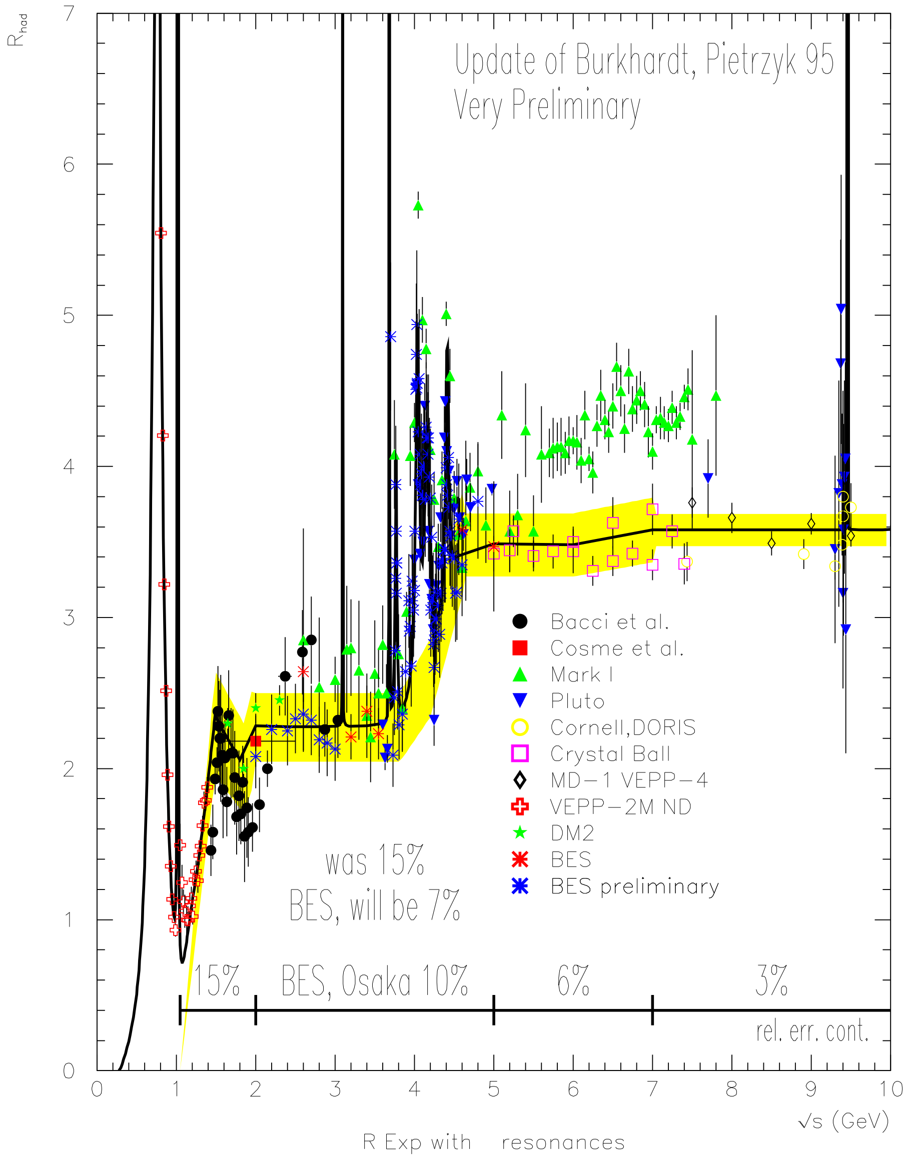


Difference between leptons and hadrons is -3.2 σ, but overall χ^2 is ok (C.L = 7.5%).

Interpretation in terms of Higgs mass depends on crucially on running of α

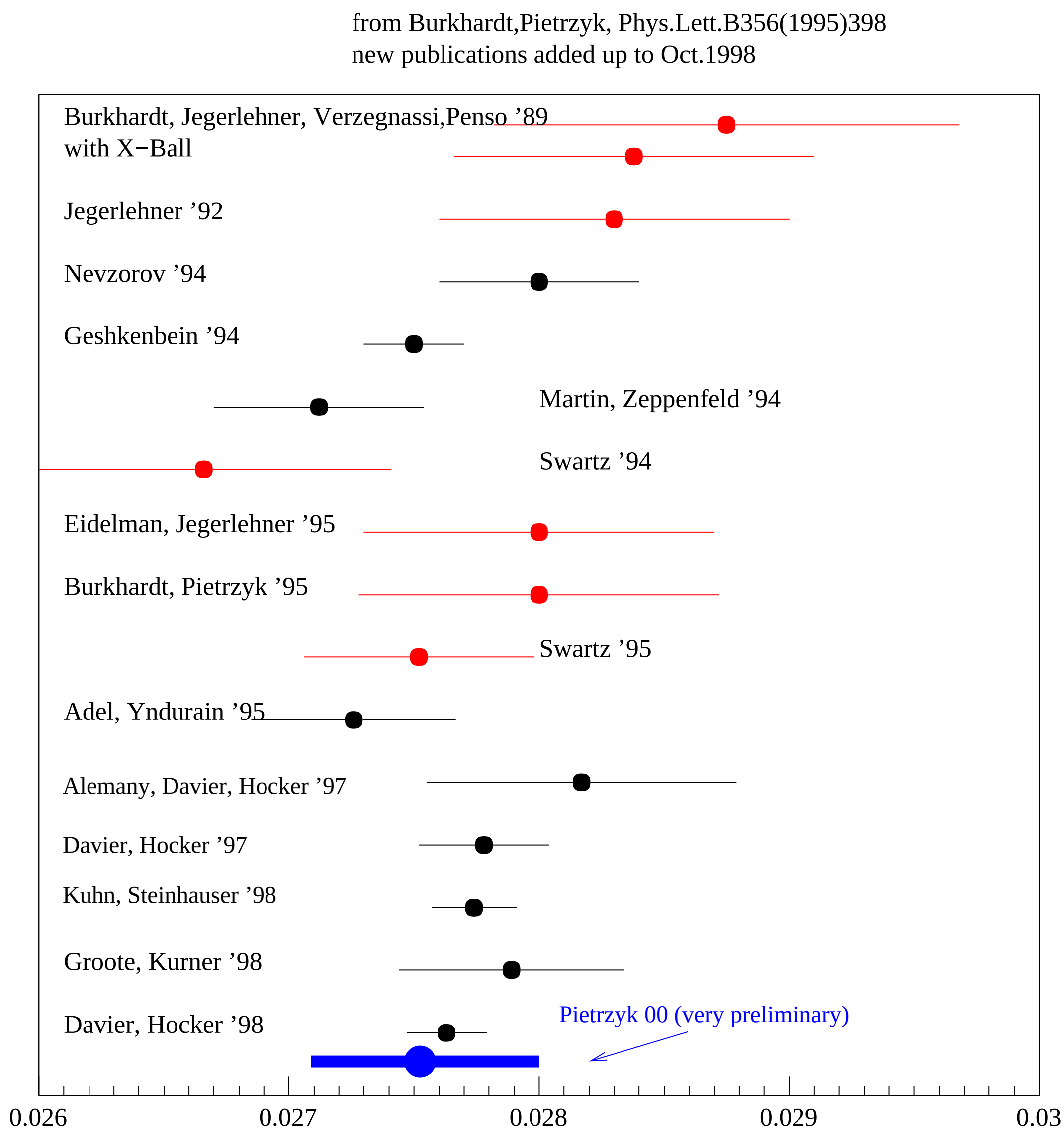
$$\alpha(m_Z{}^2) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(m_Z{}^2) - \Delta\alpha^5_{\rm had}(m_Z{}^2) - \Delta\alpha_{\rm top}(m_Z{}^2)}$$

New value of $\Delta\alpha^5_{\rm had}$ from BES (*Very Preliminary*)

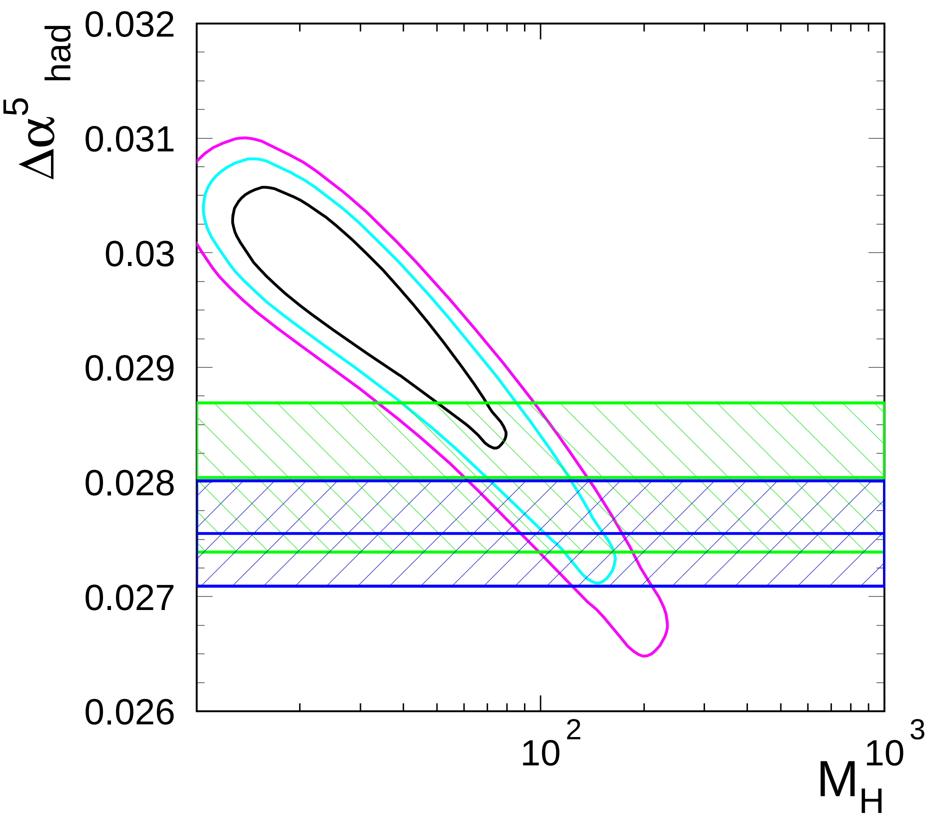


Comparison with other results:

Red error bars indicate determination with minimal theoretical input.



Contours in $\Delta\alpha^5_{\text{had}}$, m_{Higgs} plane are shown below (includes data presented here, m_{W} and m_{t}):



Bands show Eidelmann and Jegerlehner 95

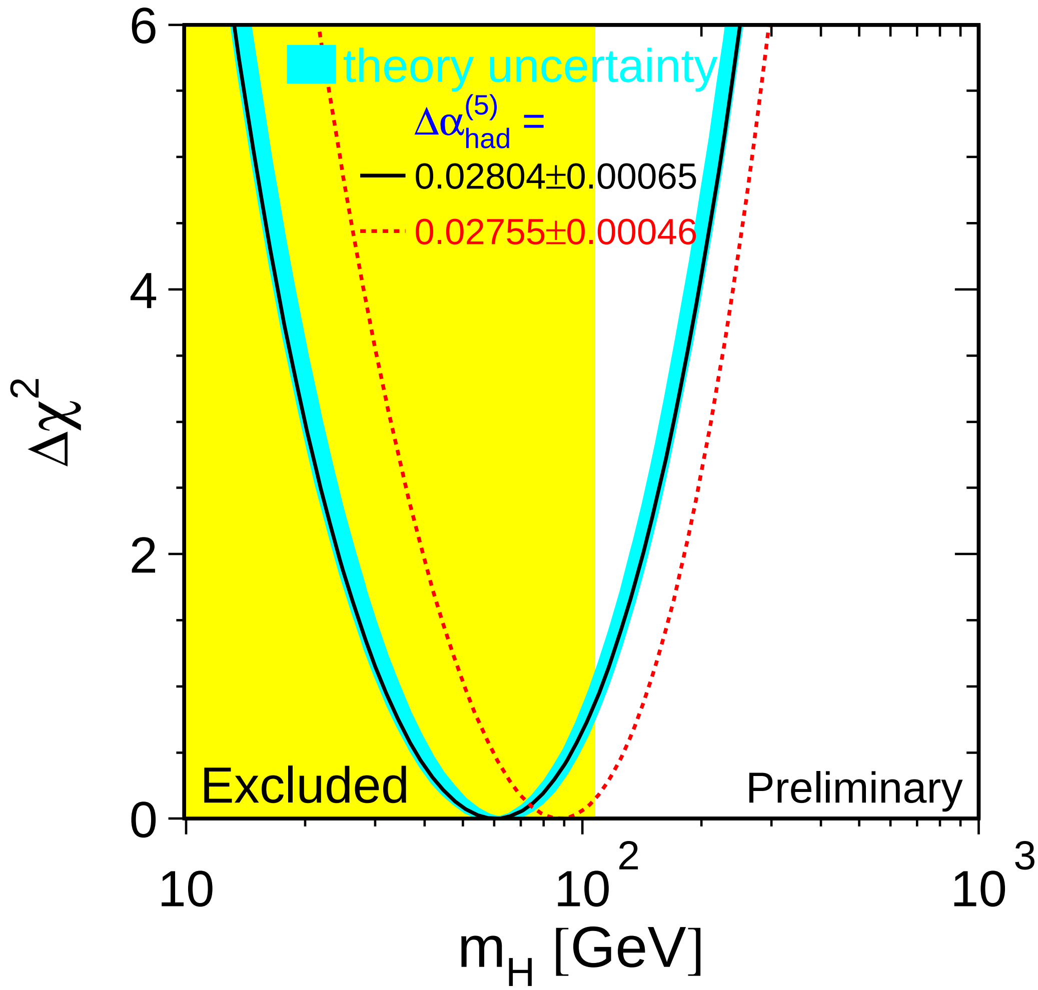
$$\Delta\alpha^5_{\text{had}} = 0.02804 \pm 0.00065$$

and *very preliminary* Pietrzyk, ICHEP 2000

$$\Delta\alpha_{\text{had}} = 0.02755 \pm 0.00046$$

Contours are 1σ (46% C.L.), 2σ (91%) and 3σ (99.5% C.L.)

Higgs limit (including m_t, m_W, νN results to be presented, see talks by Scott Willenbrock, Kevin McFarland, and Stephan Wynhoff):



$$\Delta\alpha^5_{\text{had}} = 0.02804 \pm 0.00065 \quad m_{\text{Higgs}} = 62^{+53}_{-30}\ \text{GeV}$$

$$\Delta\alpha^5_{\text{had}} = 0.02755 \pm 0.00046 \quad m_{\text{Higgs}} = 90^{+63}_{-39}\ \text{GeV}$$

LEPEWWG 95% C.L. upper limit

$$m_{\text{Higgs}} < 170\text{GeV}$$

Very preliminary Pietryzk update gives 95% C.L.

$$m_{\text{Higgs}} < 210\text{GeV}$$

Conclusion

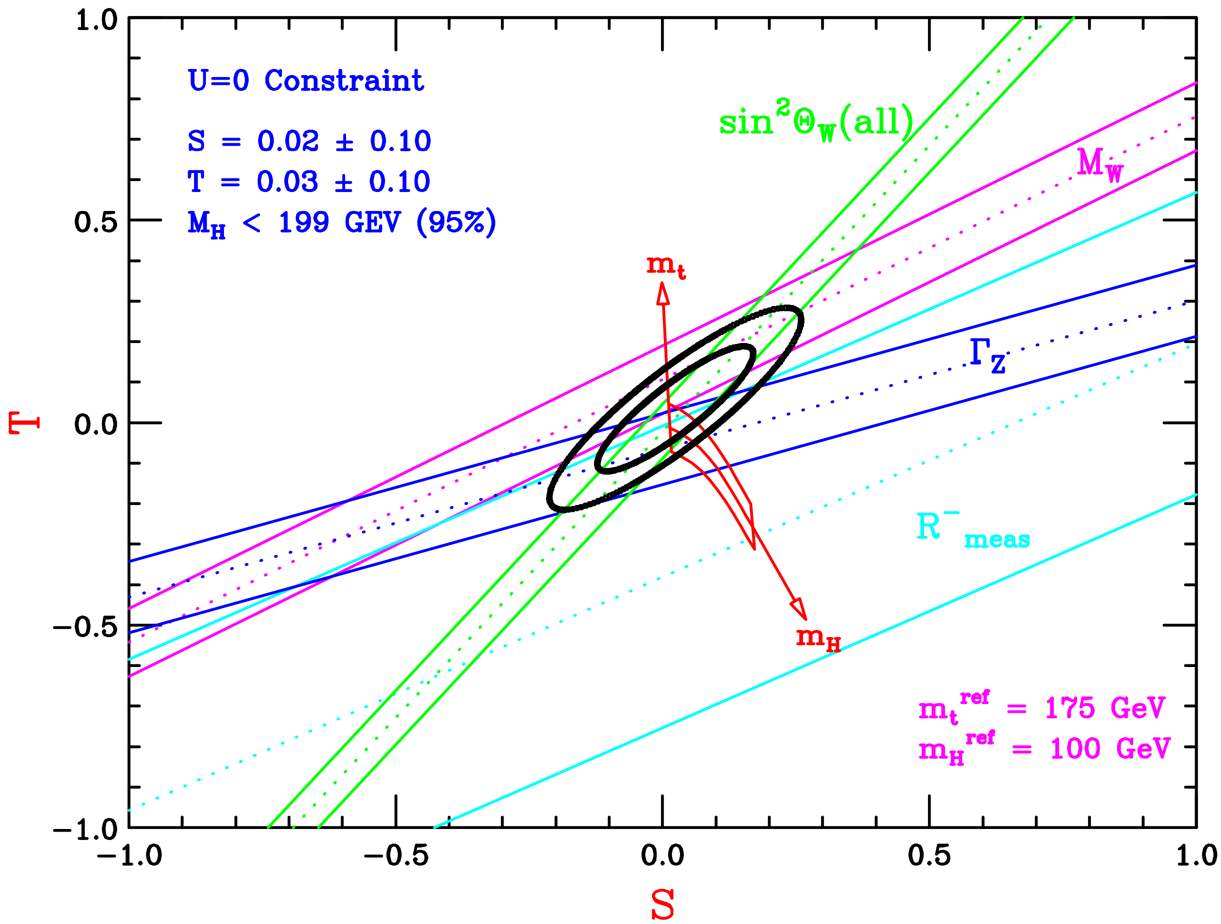
- Z-resonance measurements are nearly complete, most results are final

- Most of the precision observables favor a light Higgs, but $A_{\mathrm{FB}}^{\mathrm{b}}$ and $A_{\mathrm{FB}}^{\mathrm{c}}$ favor a heavy Higgs.

- Interpretation of result crucially depends on an acurate value of $\Delta\alpha_{\mathrm{had}}$

Thanks to ALEPH, DELPHI, L3, OPAL, SLD, LEP-EWWG, and for fits from T. Abe, M. Grünewald, G. Quast, K. Mönig and B. Pietrzyk.

S-T plot:



U=0 Constraint
S = 0.02 ± 0.10
T = 0.03 ± 0.10
M_H < 199 GEV (95%)
sin²Θ_W(all)
M_W
m_t
Γ_Z
R⁻_meas
m_H
m_t^ref = 175 GeV
m_H^ref = 100 GeV
1.0
0.5
0.0
−0.5
−1.0
T
S

Osaka 2000

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29