Precision Electroweak Physics at the Z

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Introduction

The experimental study of the process $e^+e^- \rightarrow Z \rightarrow f\bar{f}$ began 10 years ago and ended (data taking) just over 1 year ago. The first electroweak measurements performed at the Z (by the Mark II Collaboration) were presented at LP89 in this auditorium,

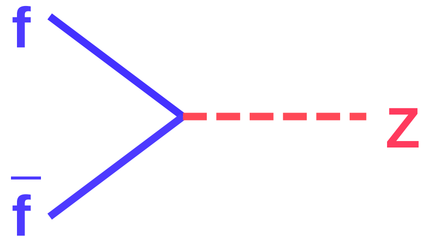
Quantity	LP89 (233 events)	LP99 (18M events)
M_Z (GeV)	91.17±0.18	91.1871±0.0021
Γ_Z (GeV)	$1.95^{+0.40}_{-0.30}$	2.4944±0.0024
N_ν	3.0±0.9	2.9835±0.0083

The LP89 measurements were the best ew measurements available at the time! The last decade has seen remarkable improvements and represents the "Golden Age" of electroweak physics:

- Our best ew info has come from the study of the Z resonance.
- Many "Final" results are now being produced by the five Z-pole experiments: ALEPH, DELPHI, OPAL, L3, and SLD.
- This may be the last LP talk dedicated to electroweak results from the Z.

The Z-Fermion Vertex

The coupling of the Z to a fermion-antifermion pair



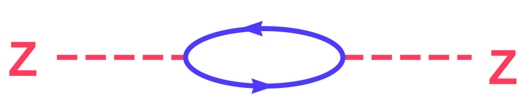
is described by the following Lagrangian,

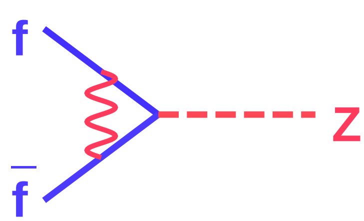
$$\begin{aligned}\mathcal{L} &= \left(\frac{G_F M_Z^2}{2\sqrt{2}}\right)^{1/2} \overline{\Psi}_f \gamma_\mu \left(v_f - a_f \gamma_5\right) \Psi_f Z^\mu \\ &= \left(\frac{G_F M_Z^2}{2\sqrt{2}}\right)^{1/2} \overline{\Psi}_f \gamma_\mu \left[g_L^f \left(1-\gamma_5\right) + g_R^f \left(1+\gamma_5\right)\right] \Psi_f Z^\mu\end{aligned}$$

where v_f and a_f are vector and axial vector coupling constants,

$$\begin{aligned}v_f &= \sqrt{\rho_f}\left(2I_3^f - 4Q_f \sin^2\theta_f\right) \\ a_f &= \sqrt{\rho_f}\left(2I_3^f\right).\end{aligned}$$

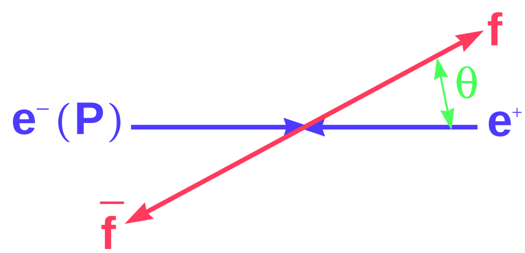
Note that ρ_f and $\sin^2\theta_f$ incorporate electroweak radiative corrections,





The Z-Peak Cross Section

The cross section for the process $e^+e^-(P) \longrightarrow Z \longrightarrow f\bar{f}$



is described by the following expression,

$$\frac{d\sigma_Z^f}{d\Omega} = \frac{9}{4}\frac{s\Gamma_{ee}\Gamma_{f\bar{f}}/M_Z^2}{(s-M_Z^2)^2+s^2\Gamma_Z^2/M_Z^2} \longleftarrow \text{ Breit Wigner Res}$$

$$\times \left\{\underbrace{(1+\cos^2\theta)[1-PA_e]}_{P\text{ modulates c}-\text{even}} + \underbrace{2\cos\theta A_f[-P+A_e]}_{P\text{ increases c}-\text{odd}}\right\}$$

where $\Gamma_{f\bar{f}}$ is the partial width for $Z \longrightarrow f\bar{f}$ and A_f is the left-right coupling constant asymmetry,

$$\Gamma_{f\bar{f}} = N_c \cdot \frac{G_F M_Z^3}{24\pi\sqrt{2}}\left(v_f^2+a_f^2\right)$$

$$A_f = \frac{2v_f a_f}{v_f^2+a_f^2} = \frac{(g_L^f)^2-(g_R^f)^2}{(g_L^f)^2+(g_R^f)^2}.$$

The small size of v_ℓ/a_ℓ (~ 0.08) makes the leptonic coupling asymmetries A_ℓ particularly sensitive to electroweak vacuum polarization corrections. Usually parameterized in terms of $\sin^2\theta_W^{\mathrm{e}ff} = \sin^2\theta_e$ (assume lepton universality),

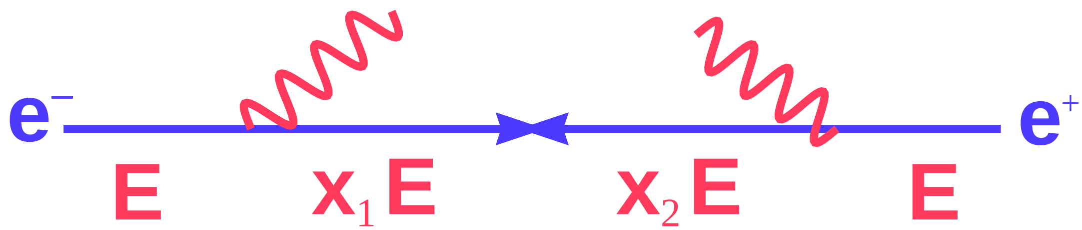
$$A_\ell = \frac{2(1-4\sin^2\theta_W^{\mathrm{e}ff})}{1+(1-4\sin^2\theta_W^{\mathrm{e}ff})^2} \qquad \delta A_\ell \simeq -8\delta\sin^2\theta_W^{\mathrm{e}ff}$$

Z-Pole Electroweak Observables

Real experiments measure the processes $e^+e^- \to Z, \gamma \to f\bar{f}$ (and the interference term),

$$\frac{d\sigma^f_{obs}}{d\Omega}(s) = \frac{d\sigma^f_Z}{d\Omega}(s) + \frac{d\sigma^f_{Z\gamma}}{d\Omega}(s) + \frac{d\sigma^f_\gamma}{d\Omega}(s).$$

The presence of initial state radiation smears the center-of-mass energy which can be represented in terms of electron structure functions,



$$\frac{d\sigma^f_{obs}}{d\Omega}(s) = \int dx_1 dx_2 D_e(x_1, s) D_e(x_2, s) \frac{d\sigma^f_{obs}}{d\Omega}(s x_1 x_2)$$

It is necessary to correct all measurements for energy smearing and for $Z\gamma$ interference (and pure γ-exchange). The following obervables are extracted Z-peak data:

1. The Line Shape Parameters: (measured by scanning the peak)
   - M_Z, Γ_Z, $\sigma^0_{had} = 12\pi\Gamma_{ee}\Gamma_{had}/(M_Z^2\Gamma_Z^2)$
2. Branching Ratios:
   - $R_\ell = \Gamma_{had}/\Gamma_\ell$, $R_b = \Gamma_{bb}/\Gamma_{had}$, $R_c = \Gamma_{cc}/\Gamma_{had}$
3. Unpolarized Forward-Backward Asymmetries:

$$A^f_{FB} = \frac{\sigma^f_F - \sigma^f_B}{\sigma^f_F + \sigma^f_B} = 0.75 A_e A_f, \quad f = \ell, b, c$$

4. Left-Right Asymmetry:

$$A_{LR} = \frac{\sigma^f(-|P|) - \sigma^f(+|P|)}{\sigma^f(-|P|) + \sigma^f(+|P|)} = PA_e, \quad f \neq e$$

5. τ Polarization: (A_{LR} with final state τ's)

$$\begin{aligned} \mathcal{P}_\tau(\cos\theta) &= -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e\cos\theta} \\ \overline{\mathcal{P}}_\tau &= -A_\tau \end{aligned}$$

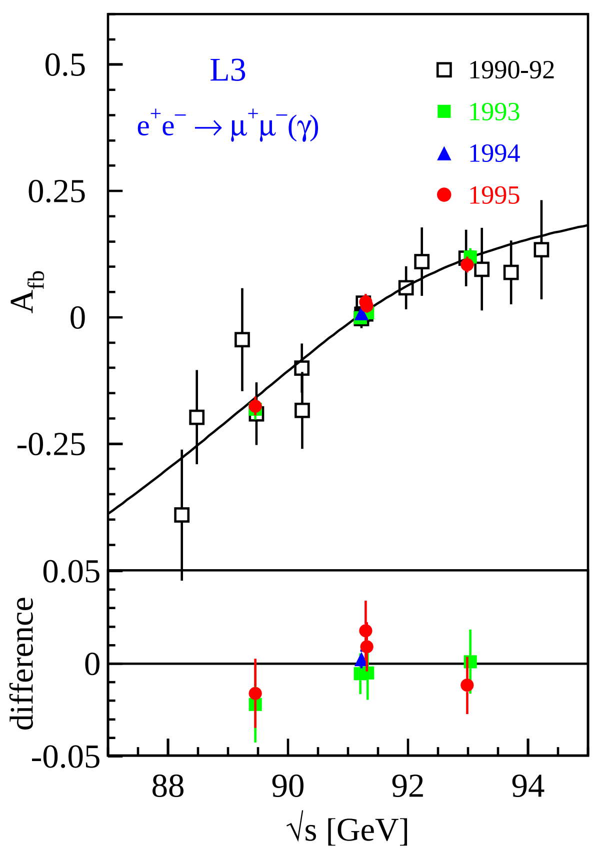
6. Left-Right Forward-Backward Asymmetries:

$$\begin{aligned} \tilde{A}^f_{FB} &= \frac{\sigma^f_F(-|P|) - \sigma^f_B(-|P|) - \sigma^f_F(+|P|) + \sigma^f_B(+|P|)}{\sigma^f_F(-|P|) + \sigma^f_B(-|P|) + \sigma^f_F(+|P|) + \sigma^f_B(+|P|)} \\ &= 0.75PA_f, \quad f = \ell, b, c, s \end{aligned}$$

The Resonance Parameters

Summer 1999: all four LEP experiments have updated their Z resonance parameter results **(ALEPH's are now final)**.

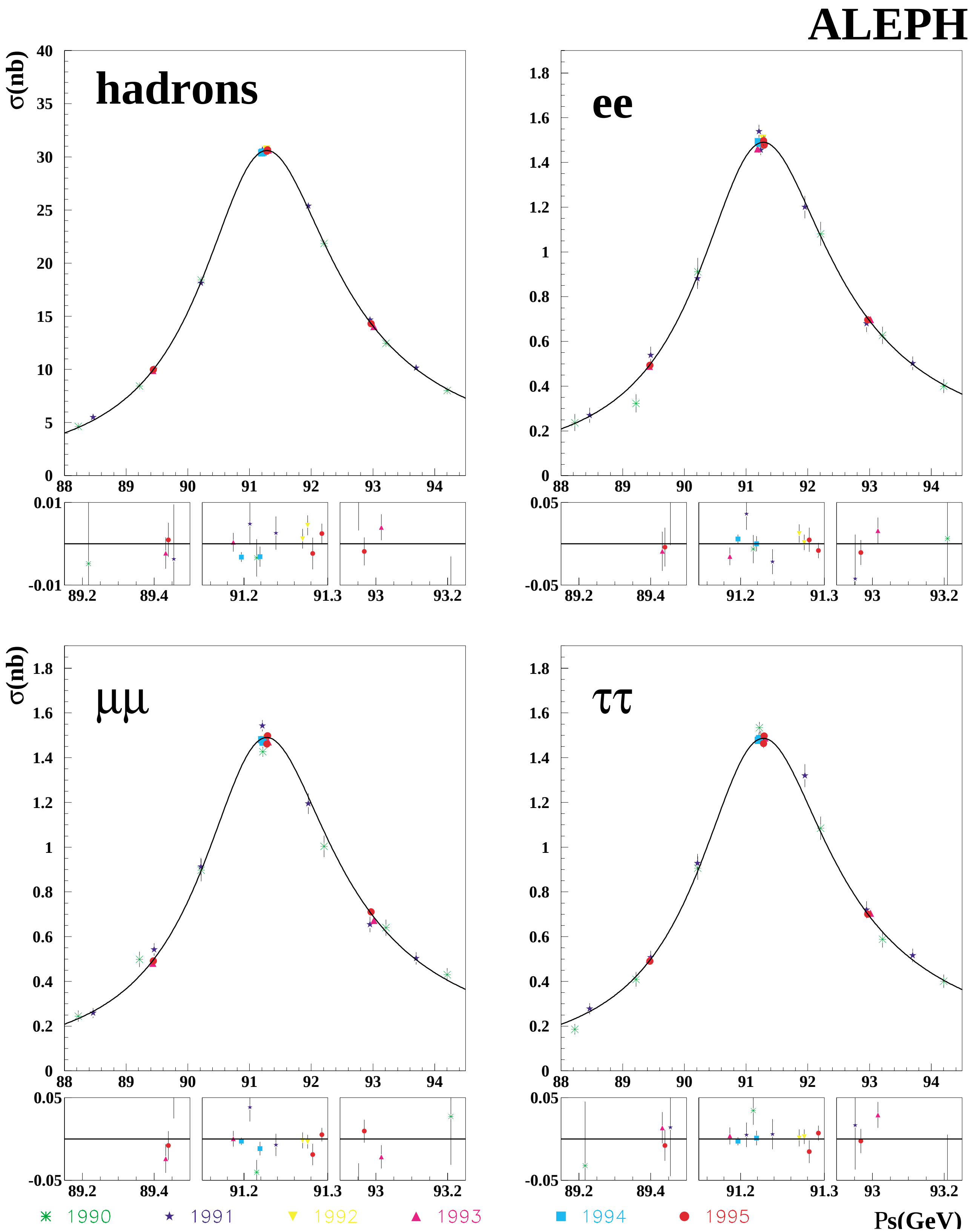
The resonance parameters M_Z, Γ_Z, σ^0_{had}, R_ℓ are measured with final state hadronic and leptonic samples collected during scans of the Z peak. Since the leptonic forward-backward asymmetries are sensitive functions of $\sqrt{s}$,



the A^ℓ_{FB} are extracted from a simultaneous fit to hadronic and leptonic lineshape data.

Event sample consists of 15.5×10^6 $Z \longrightarrow q\bar{q}$ and 1.7×10^6 $Z \longrightarrow \ell^+\ell^-$ events collected at $\sim$7 energies from 1990 to 1995. The

$Z\gamma$ and pure γ cross sections are fixed to MSM values and the data fit to radiatively-corrected lineshape functions [3^{rd}-order corrections now used],

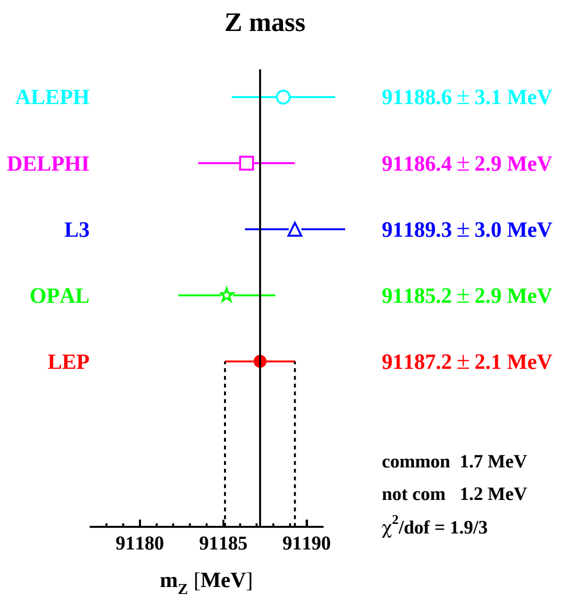


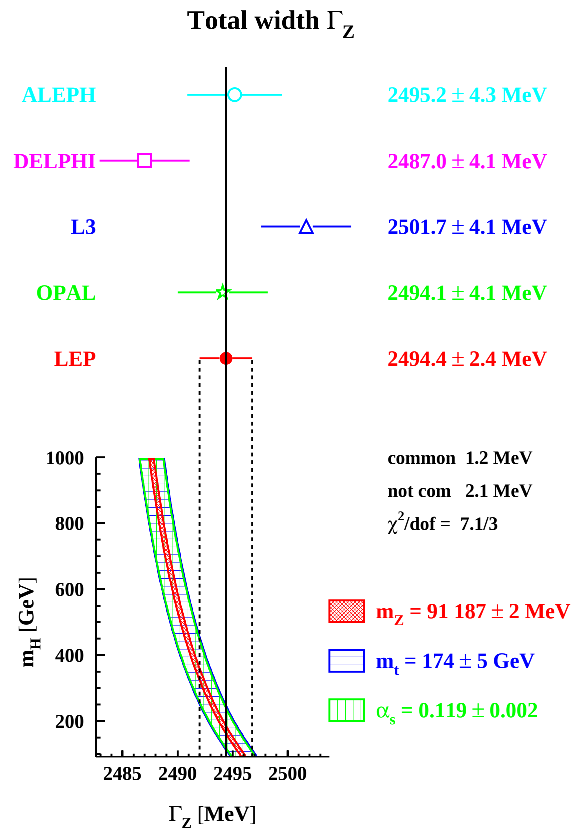
The leptonic parameters are determined separately for each lepton species (9 lineshape parameters) and assuming lepton universality (5 parameters).

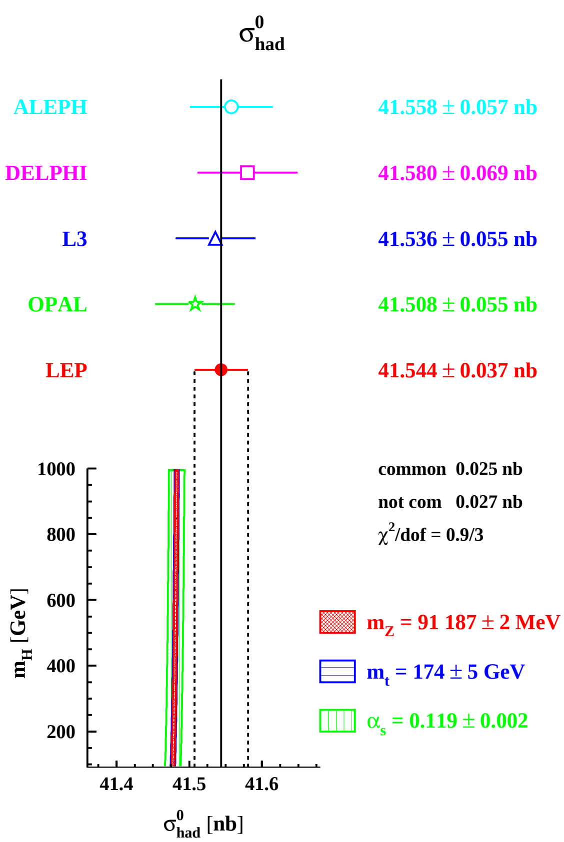
LEP: 4 Expt Average

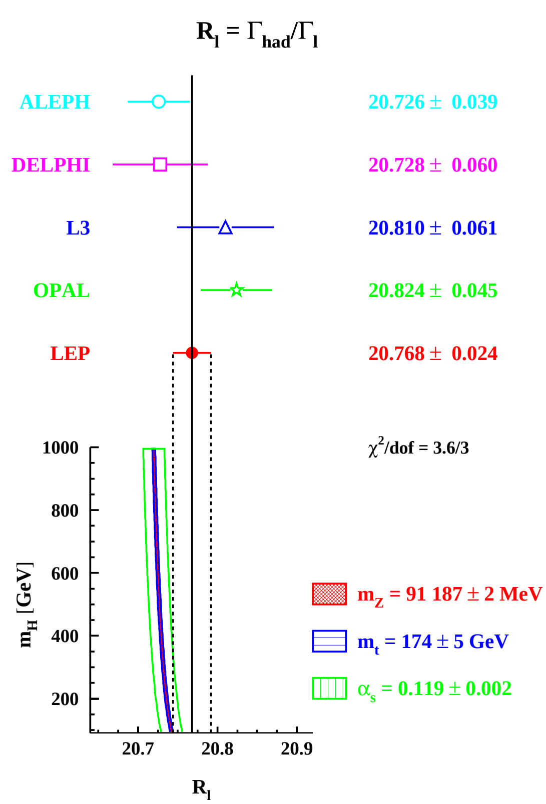
Parameter	Average Value
$m_{\mathrm{Z}}(\mathrm{GeV})$	91.1871 ± 0.0021
$\Gamma_{\mathrm{Z}}(\mathrm{GeV})$	2.4944 ± 0.0024
$\sigma_{\mathrm{h}}^{0}(\mathrm{nb})$	41.544 ± 0.037
R_{e}	20.803 ± 0.049
R_{μ}	20.786 ± 0.033
R_{τ}	20.764 ± 0.045
$A_{\mathrm{FB}}^{0,\,\mathrm{e}}$	0.0145 ± 0.0024
$A_{\mathrm{FB}}^{0,\,\mu}$	0.0167 ± 0.0013
$A_{\mathrm{FB}}^{0,\,\tau}$	0.0188 ± 0.0017
R_{ℓ}	20.768 ± 0.024
$A_{\mathrm{FB}}^{0,\,\ell}$	0.01701 ± 0.00095

- Systematic errors:
  - Event Selection - $\pm$0.04-0.1% ($q\bar{q}$) and $\pm$0.1-0.7% ($\ell^+\ell^-$)
  - Luminosity - $\pm$0.033-0.09% experimental, $\pm$0.054-0.06% Bhabha Cross Section [B. Ward et al., PL B450, 262 (1999)]
  - Beam Energy - $\pm$1.7 MeV on M_Z and $\pm$1.2 MeV on Γ_Z
  - QED Corrections - $\pm$0.02% on σ_{h}^{0} and $\pm$0.5 MeV on m_{Z},Γ_{Z}
- Note $+0.9\sigma$ shift in σ_{h}^{0}:
  - $+20$ pb from $O(\alpha^3)$ radiative corrections
  - $+10$ pb from new ZFITTER version
- Note that M_Z is limited by energy scale uncertainty


Z mass
ALEPH
DELPHI
L3
OPAL
LEP
91188.6 ± 3.1 MeV
91186.4 ± 2.9 MeV
91189.3 ± 3.0 MeV
91185.2 ± 2.9 MeV
91187.2 ± 2.1 MeV
common 1.7 MeV
not com 1.2 MeV
χ^2/dof = 1.9/3
91180
91185
91190
m_Z [MeV]

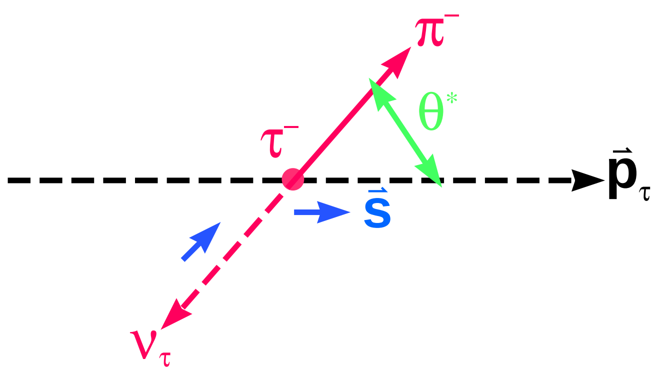

Total width Γ_Z
ALEPH
DELPHI
L3
OPAL
LEP
2495.2 ± 4.3 MeV
2487.0 ± 4.1 MeV
2501.7 ± 4.1 MeV
2494.1 ± 4.1 MeV
2494.4 ± 2.4 MeV
common 1.2 MeV
not com 2.1 MeV
χ^2/dof = 7.1/3
m_Z = 91 187 ± 2 MeV
m_t = 174 ± 5 GeV
α_s = 0.119 ± 0.002
1000
800
600
400
200
m_H [GeV]
2485
2490
2495
2500
Γ_Z [MeV]


σ^0_{had}
ALEPH
DELPHI
L3
OPAL
LEP
41.558 ± 0.057 nb
41.580 ± 0.069 nb
41.536 ± 0.055 nb
41.508 ± 0.055 nb
41.544 ± 0.037 nb
common 0.025 nb
not com 0.027 nb
χ^2/dof = 0.9/3
m_Z = 91 187 ± 2 MeV
m_t = 174 ± 5 GeV
α_s = 0.119 ± 0.002
1000
800
600
400
200
m_H [GeV]
41.4
41.5
41.6
σ^0_{had} [nb]


$R_l = \Gamma_{had}/\Gamma_l$
ALEPH
DELPHI
L3
OPAL
LEP
20.726 ± 0.039
20.728 ± 0.060
20.810 ± 0.061
20.824 ± 0.045
20.768 ± 0.024
χ^2/dof = 3.6/3
m_Z = 91 187 ± 2 MeV
m_t = 174 ± 5 GeV
α_s = 0.119 ± 0.002
1000
800
600
400
200
m_H [GeV]
20.7
20.8
20.9
R_l

Tau Polarization

The LEP Collaborations determine A_τ and A_e from measurements of $\mathcal{P}_\tau(\cos\theta)$. The final state τ-polarization is determined from the 5 decay modes: $\tau^\pm \longrightarrow \pi^\pm\nu,\ \rho^\pm\nu,\ a_1^\pm\nu,\ e^\pm\nu\bar{\nu},\ \mu^\pm\nu\bar{\nu}$. Since the τ decays via a pure V-A current, each mode has a polarization-dependent decay distribution in laboratory variables. For example, the center-of-mass angular distribution of π^- from the decay of a spin-polarized τ^- is very asymmetric,



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \left(1 - \mathcal{P}_\tau Q_\tau \cos\theta^*\right)/2.$$

In the terms of scaled energy in the laboratory frame $x = E_\pi/E_b$, the decay distribution is

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = 1 - \mathcal{P}_\tau Q_\tau\,(2x-1) = A(x) + \mathcal{P}_\tau B(x).$$

The laboratory decay distributions of all 5 final states can be represented in the same form,

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx^N} = A(x_1 \ldots x_N) + \mathcal{P}_\tau B(x_1 \ldots x_N),$$

where $N = 1, 3, 6$ for the $\ell\nu\bar{\nu}$, $\rho\nu$, $a_1\nu$ final states. $\mathcal{P}_\tau$ is extracted by fitting the decay distributions to the data.

The statistical precision obtainable with a sample of N_{dec} decays for each final state can be parameterized as $\delta\mathcal{P}_\tau = a_p/\sqrt{N_{dec}}$ where

Final State	$e\nu\bar{\nu}$	$\mu\nu\bar{\nu}$	$\pi\nu$	$\rho\nu$	$a_1\nu$
Branching Ratio (%)	18	18	12	24	8
Acceptance	0.4	0.7	0.6	0.5	0.5
Analyzing Power a_p	5	5	1.8	2.3	3.1
Relative Precision	2.7	2.1	1.0	1.0	2.2

Most of the information comes from the $\pi\nu$ and $\rho\nu$ channels. The 5-channel averages yield the following values for A_τ and A_e:

Experiment		$\mathcal{A}_\tau$
ALEPH	(90 - 95), final	$0.1452 \pm 0.00052 \pm 0.0032$
DELPHI	(90 - 95), final 99	$0.1359 \pm 0.0079 \pm 0.0055$
L3	(90 - 95), final	$0.1476 \pm 0.0088 \pm 0.0062$
OPAL	(90 - 94), final	$0.1340 \pm 0.0090 \pm 0.0100$
LEP Average		0.1425 ± 0.0044
χ^2/dof		1.3/3
Experiment		$\mathcal{A}_e$
ALEPH	(90 - 95), final	$0.1505 \pm 0.0069 \pm 0.0010$
DELPHI	(90 - 94), final 99	$0.1382 \pm 0.0116 \pm 0.0005$
L3	(90 - 95), final	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	(90 - 94), final	$0.1290 \pm 0.0140 \pm 0.0050$
LEP Average		0.1483 ± 0.0051
χ^2/dof		4.8/3

The systematic uncertainties are assumed to be uncorrelated in the averaging procedure.

A_{LR} Measurements

$$A_{LR} = \frac{1}{\mathcal{P}_e} \frac{N_Z(L) - N_Z(R)}{N_Z(L) + N_Z(R)} = \frac{1}{\mathcal{P}_e} A_m$$

Helicity of the SLC e^- beam chosen pseudo-randomly pulse-to-pulse (to excellent approximation, $\mathcal{L}_L = \mathcal{L}_R$). To measure A_{LR}:

1. Count Z hadronic events produced with left- and right-handed beams (excluding final state e^+e^- pairs), form asymmetry A_m.
2. Measure the beam polarization $\mathcal{P}_i$ associated with each Z and form the luminosity-weighted average,

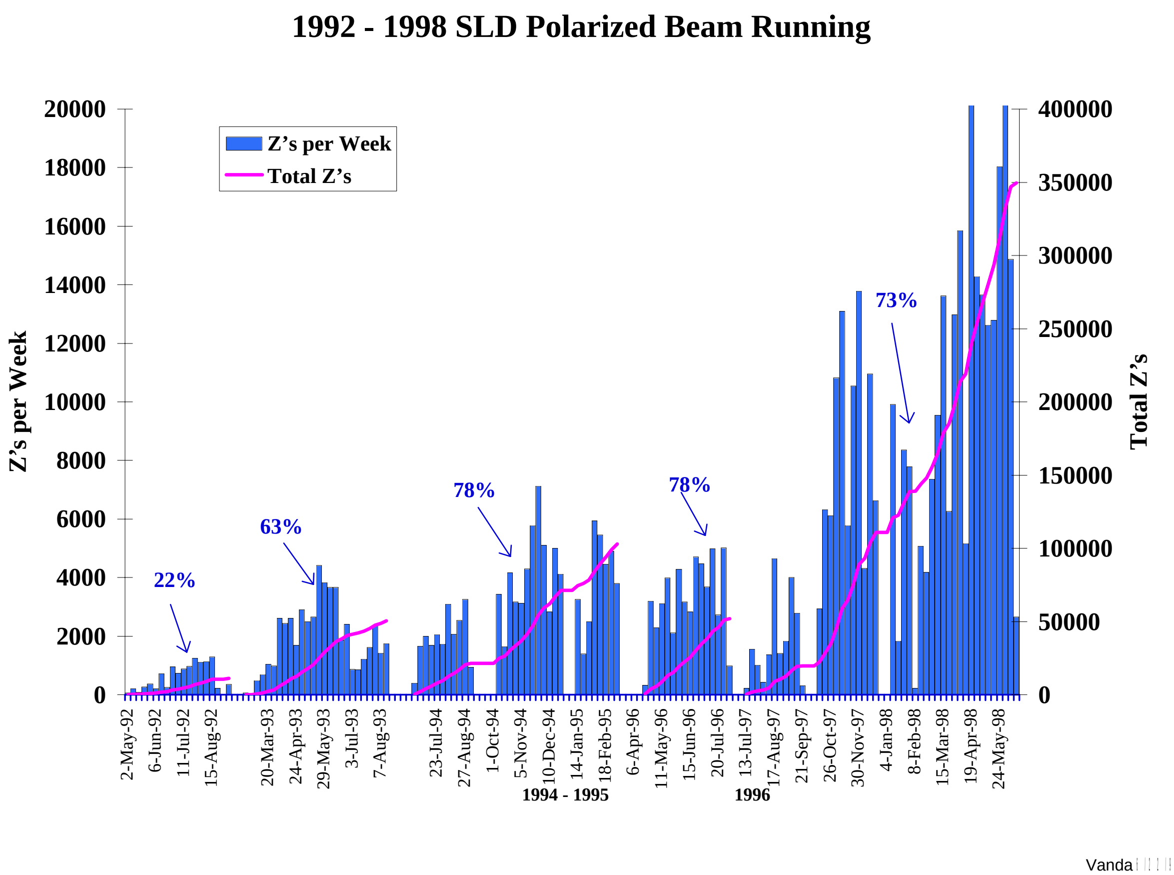
$$\mathcal{P}_e = (1 + \xi) \frac{1}{N_Z} \sum_i^{N_Z} \mathcal{P}_i$$

   where ξ is a small correction (0.001-0.002) for chromatic and beam transport effects.
3. Correct for residual background to Z sample and for residual left-right asymmetries in luminosity, polarization, beam energy, etc. Correction is at $\Delta A_{LR}/A_{LR} \sim 10^{-3}$ level
4. Correct for electroweak interference to extract $A^0_{LR} = A_e$.

New: final result based upon a sample of 343K events collected in 1997/8 run.

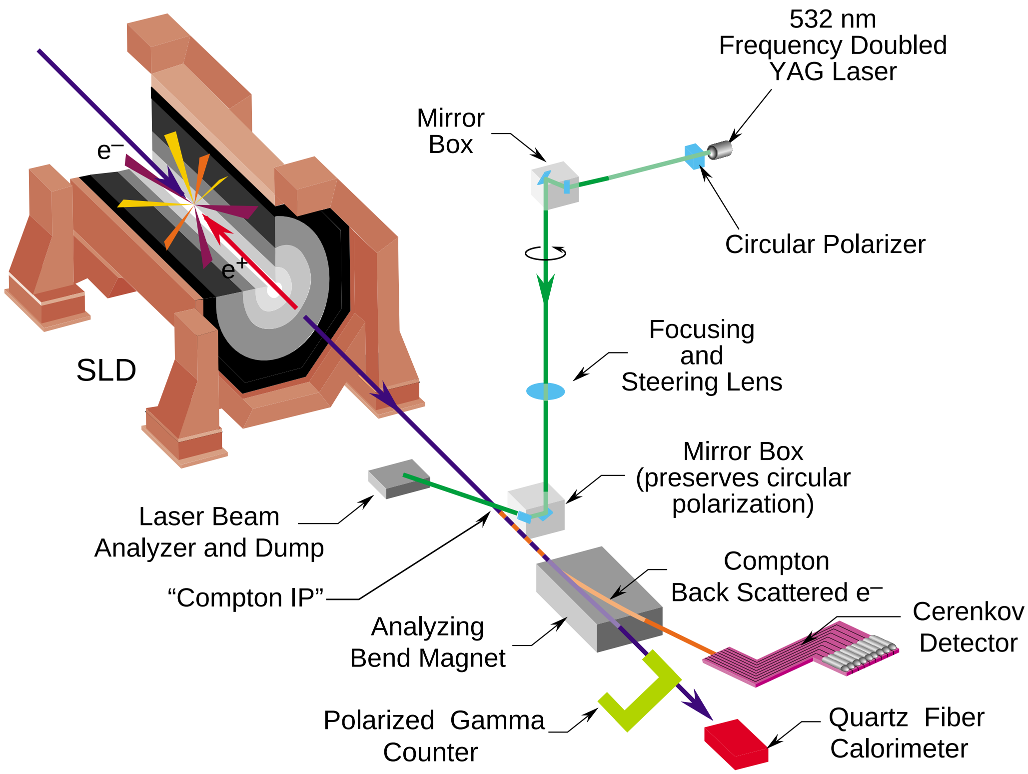
The 1997/8 run of the SLC was, by far, its best:

- 350K events produced with 73% electron polarization
- By the end of the run, SLC instaneous luminosity was approaching the design value
  - 5400 Z-events produced in last 24 hours



The SLD experiment finished with approximately 555K events,

Year	Number of Z	$\mathcal{P}_e$	$\delta\mathcal{P}_e/\mathcal{P}_e$
1992	11K	0.224±0.006	2.7%
1993	50K	0.626±0.012	1.7%
1994/5	100K	0.772±0.005	0.7%
1996	50K	0.765±0.004	0.7%
1997/8	343K	0.729±0.004	0.5%



The 1997/8 result incorporates a number of improvements and checks:

- **Polarimetery:**
  - Two additional independent Compton polarimeters measure backscattered photons $\longrightarrow$ reduce calibration uncertainty
  - Polarimeter operated with interspersed high/low background running $\longrightarrow$ reduce linearity uncertainty
  - Polarimeter syst error $\delta\mathcal{P}_e/\mathcal{P}_e = 0.5\%$ is largest
- **Center-of-mass collision energy:**
  - Scan of Z resonance done to confirm energy scale $\longrightarrow \Delta E_{cm} = -46 \pm 25$ MeV
  - Energy uncertainty leads to $\delta A^0_{LR}/A^0_{LR} = 0.4\%$
- **Positron Polarization:**
  - Use Møller polarimeter in Endstation A to measure e^+ polarization $\longrightarrow \mathcal{P}_p = -0.02 \pm 0.07\%$

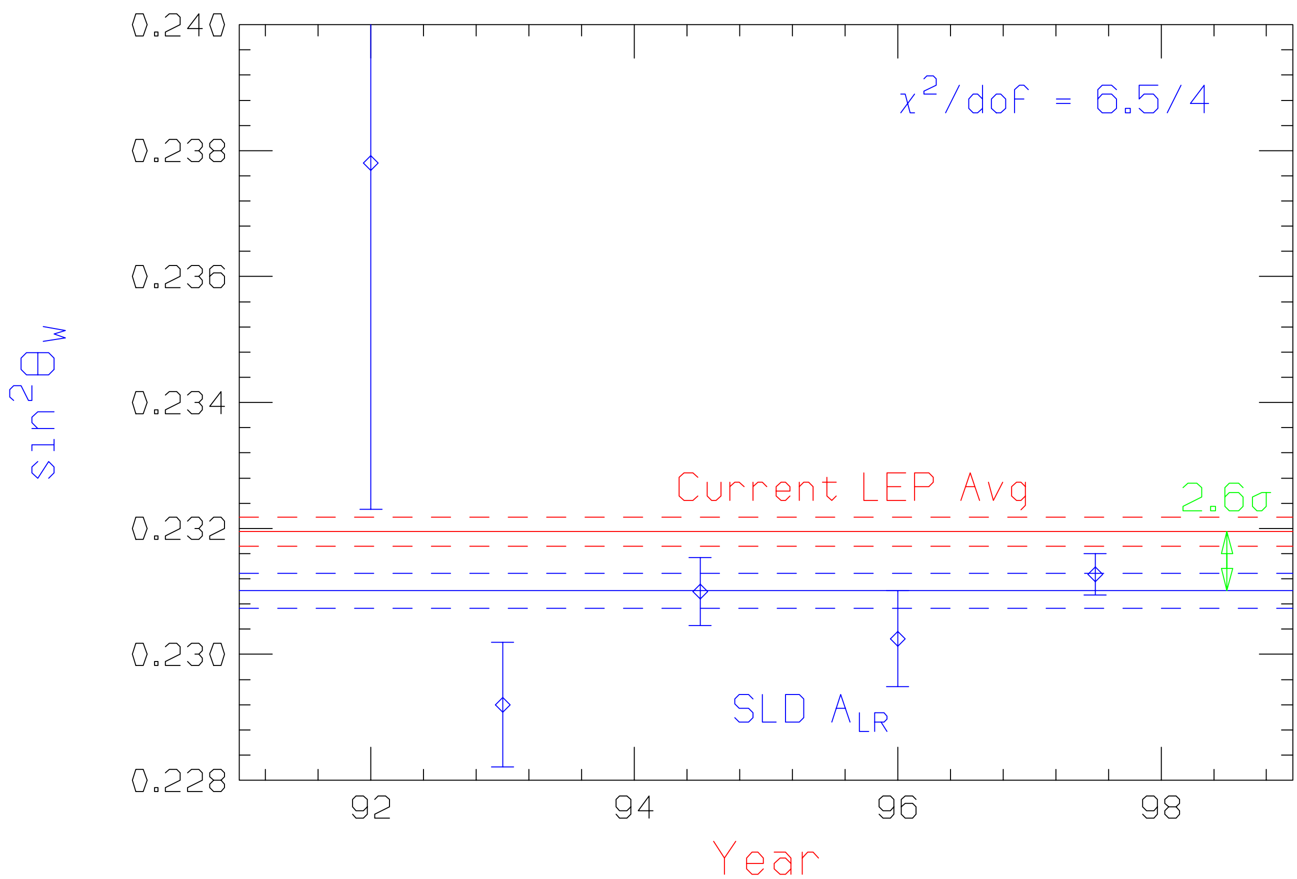
After application of the interference corrections, the following results are obtained:

Year	A^0_{LR}
1992	$0.100 \pm 0.044 \pm 0.004$
1993	$0.1656 \pm 0.0071 \pm 0.0028$
1994/5	$0.15116 \pm 0.00421 \pm 0.00111$
1996	$0.15703 \pm 0.00573 \pm 0.00111$
1997/8	$0.14904 \pm 0.00240 \pm 0.00097$
Total	0.15108 ± 0.00218

Note that the total statistical error is still about twice as large as the systematic uncertainty. A^0_{LR} is entirely equivalent to the effective weak mixing angle,

$$\sin^2\theta_W^{\mathrm{e}ff} = 0.23101 \pm 0.00028$$

In terms of $\sin^2\theta_W^{\mathrm{e}ff}$, the six measurements are,



Polarized Forward-Backward Asymmetries

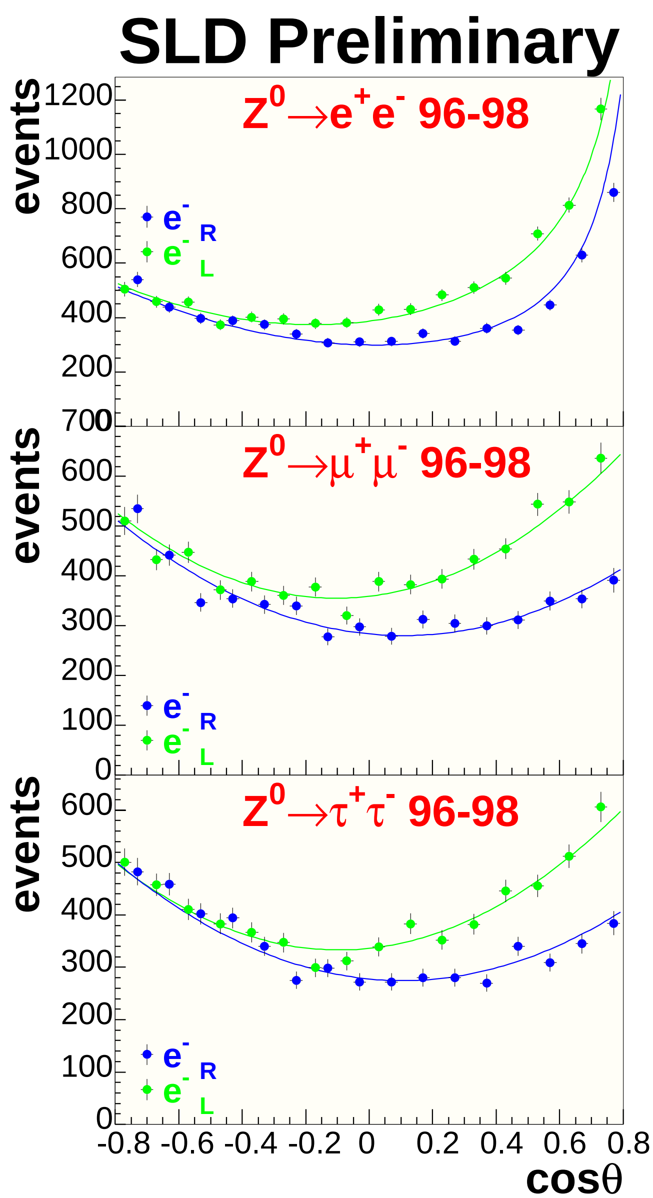
The left-right forward-backward asymmetries $\tilde{A}_{FB}^{f}$ allow the extraction of the Final State coupling asymmetries A_f. For $f \neq e$, A_f and A_e are extracted from fits to the polar angle distributions,

$$\frac{d\sigma}{d\cos\theta} \propto (1 - \mathcal{P}_e A_e)\left(1 + \cos^2\theta\right) + 2A_f\,(A_e - \mathcal{P}_e)\cos\theta$$

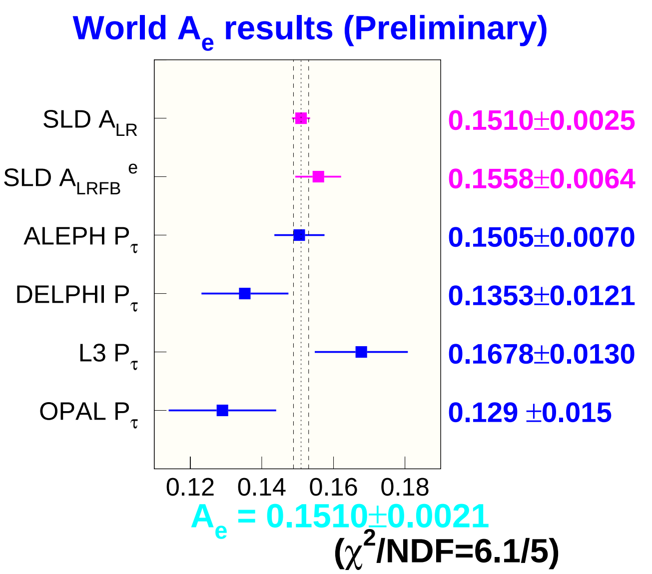
(Final state e^+e^- events must be fit to a more sophisticated expression that includes t-channel effects.)

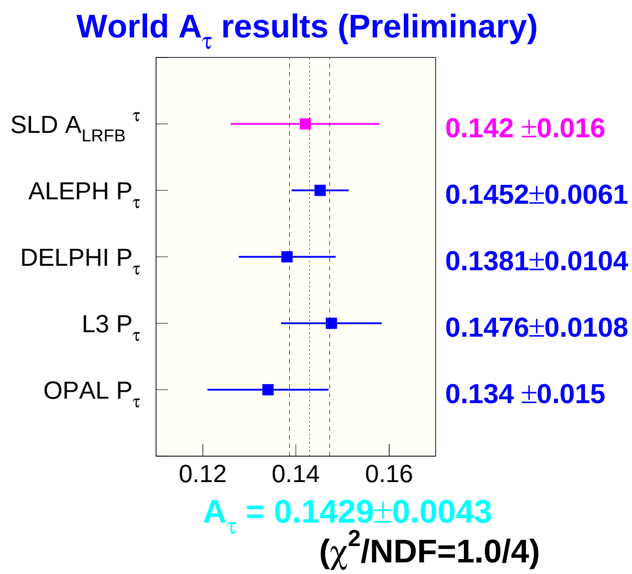
The SLD Collaboration has used this technique to measure A_e, A_μ, and A_τ from samples of 15K e^+e^-, 12K $\mu^+\mu^-$, and 12K $\tau^+\tau^-$ events.

- Tests lepton universality:
  $A_e = 0.1558 \pm 0.0064$
  $A_\mu = 0.137 \pm 0.016$
  $A_\tau = 0.142 \pm 0.016$
- Provides another (reasonably accurate) determination of A_ℓ:
  $A_\ell = 0.1523 \pm 0.0057$

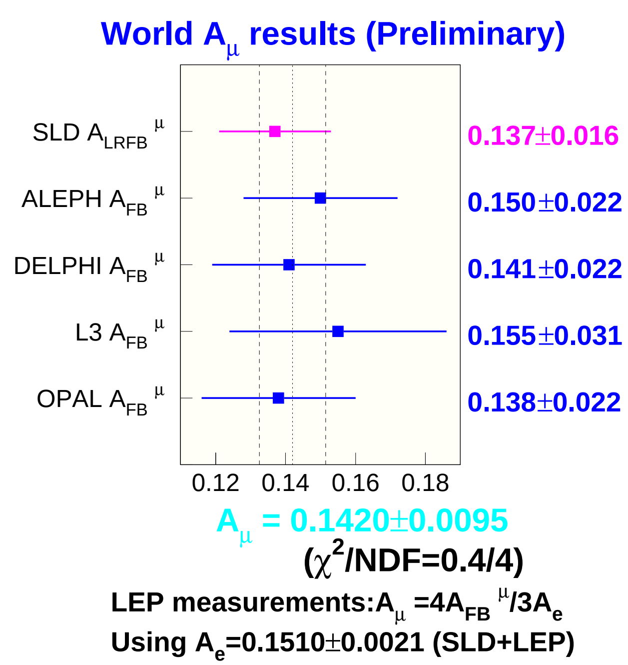


These results can be compared directly with measurements of A_e and A_τ coming from tau-polarization measurements and indirectly with measurements of A_μ coming from A^{μ}_{FB},





- A_{LR} and $\tilde{A}^{\ell}_{FB}$ yield the best determination of A_e
- $\tilde{A}^{\mu}_{FB}$ the best single measurement of A_μ
- Consistent with lepton universality (χ^2/dof=3.5/2)



R_b, R_c Measurements

The measurement of R_b and R_c is conceptually simple. One applies some tagging criteria to a sample of hadronic Z decays, measures the fraction events which satisfy the criteria, and corrects for the efficiency of the criteria. Unfortunately, it is difficult to determine the efficiency of a tagging procedure at the desired $<$1% level and a more sophisticated double-tag approach is used to perform the most precise measurements:

- Select clean sample of hadronic events
- Apply b-tag/c-tag (exclusive of each other) in each thrust hemisphere
- Determine rate of single (b_s,c_s), double (b_d,c_d), and mixed (m) tags

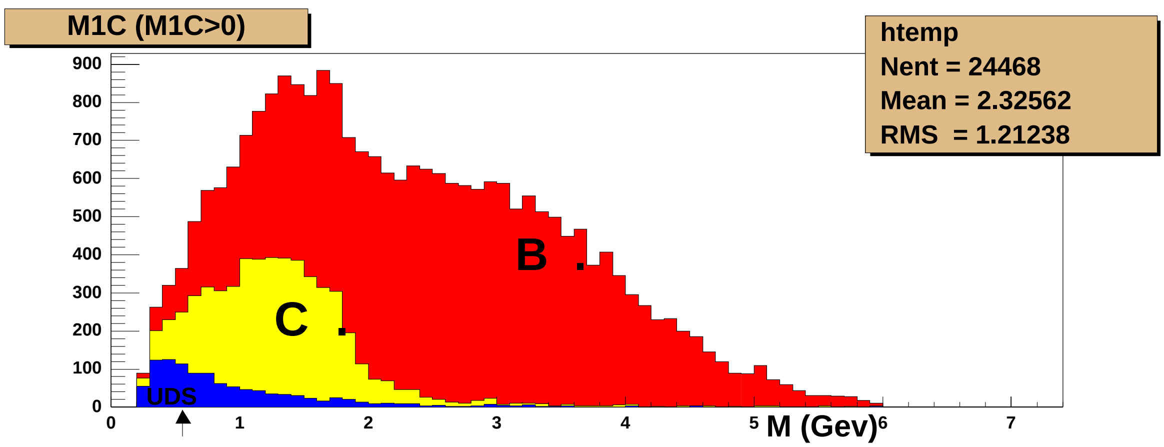
$$
\begin{aligned}
b_s &= \varepsilon_b R_b + \varepsilon_c R_c + \varepsilon_{uds}\,(1 - R_b - R_c) \\
b_d &= \varepsilon_b^d R_b + \varepsilon_c^d R_c + \varepsilon_{uds}^d\,(1 - R_b - R_c) \\
c_s &= \eta_b R_b + \eta_c R_c + \eta_{uds}\,(1 - R_b - R_c) \\
c_d &= \eta_b^d R_b + \eta_c^d R_c + \eta_{uds}^d\,(1 - R_b - R_c) \\
m &= 2\left[\varepsilon_b \eta_b R_b + \varepsilon_c \eta_c R_c + \varepsilon_{uds}\eta_{uds}\,(1 - R_b - R_c)\right]
\end{aligned}
$$

- Correlations: $\varepsilon^d = \varepsilon^2 + \lambda$, $\eta^d = \eta^2 + \lambda'$, $(\lambda_{uds} = \lambda'_{uds} = 0)$
- R_b: take R_c SM value; ε_c,ε_{uds},λ_b from MC; $\longrightarrow$ solve 2 eqs for R_b, ε_b
- R_c: η_{uds},λ'_b,λ'_c from MC; $\longrightarrow$ solve 5 eqs for R_b, η_b, ε_b, R_c, η_c

The large efficiencies (which would dominate the systematic uncertainty) are determined from the data themselves.

A number of techniques are used to tag final-state b and c jets:

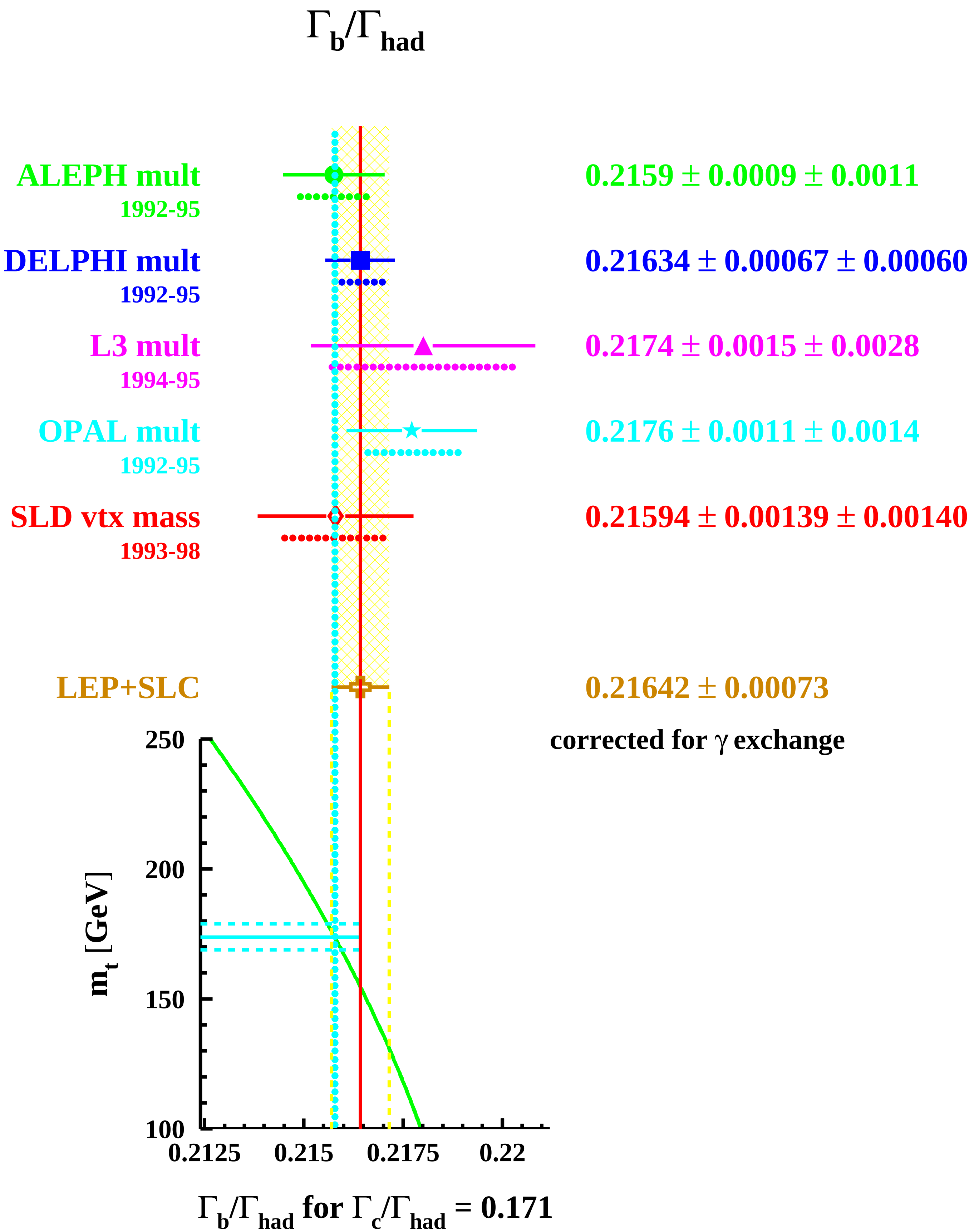
1. b-Jet Tags:
   (a) Large P, P_T leptons
   (b) Event Shapes
   (c) Lifetime Tags
      i. Traditional (require large impact parameter tracks or poor fit to single vertex hypothesis)
      ii. Topological (reconstruct secondary or tertiary vertices): new tags are enhanced by requirements on vertex mass, energy
      mass requirement greatly improves purity



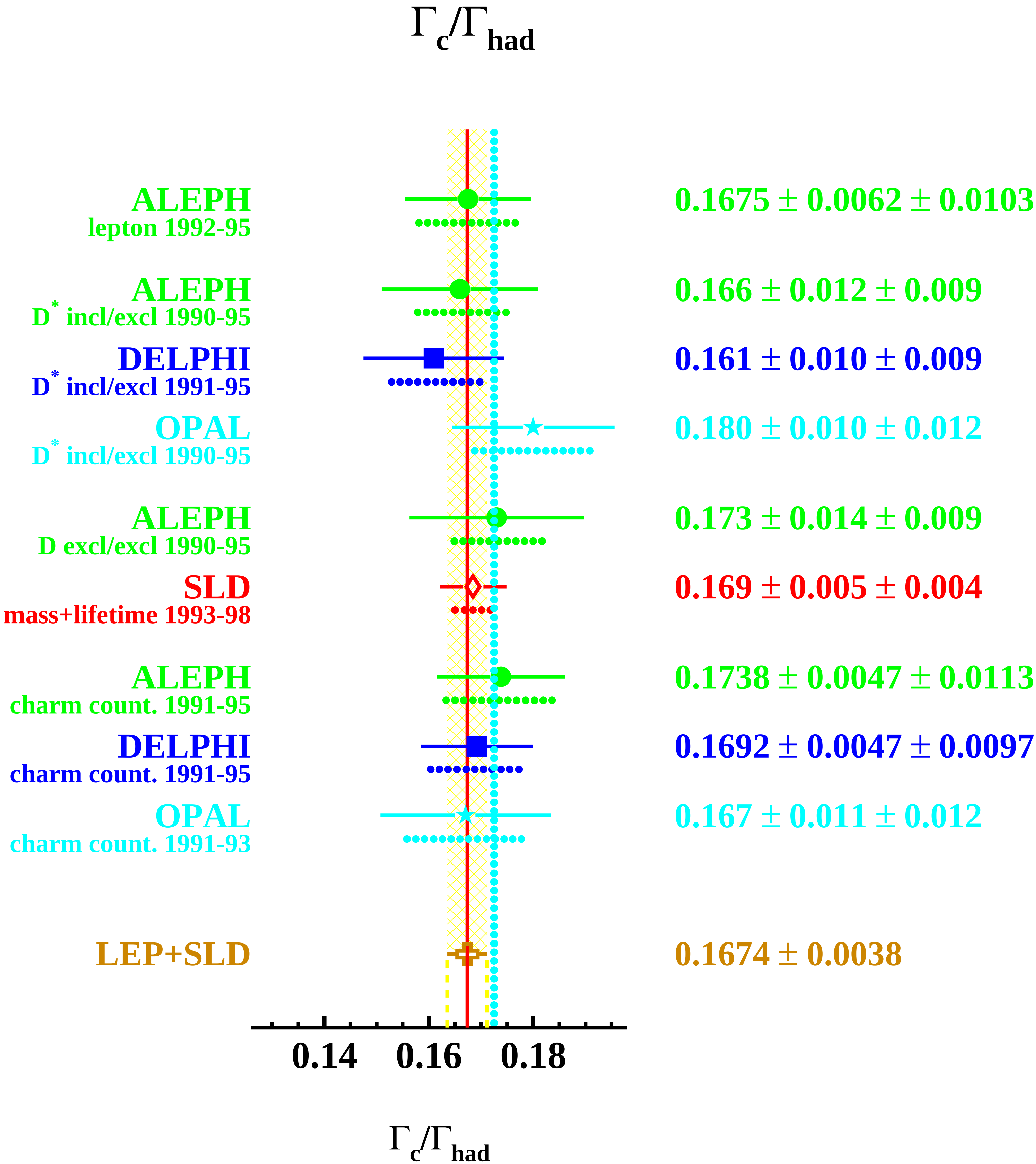
2. c-Jet Tags:
   (a) Large P, P_T leptons (usually in conjunction with a b-quark analysis)
   (b) Reconstruct D/D^* Mesons (inclusively or exclusively)
   (c) Topological Lifetime + Vertex Mass Tag + Vertex Momentum

Several measurements have been updated recently:

- R_b: DELPHI has very precise new result, SLD has update
- R_c: DELPHI and SLD Updates



Γ_b/Γ_{had}
ALEPH mult
1992-95
0.2159 ± 0.0009 ± 0.0011
DELPHI mult
1992-95
0.21634 ± 0.00067 ± 0.00060
L3 mult
1994-95
0.2174 ± 0.0015 ± 0.0028
OPAL mult
1992-95
0.2176 ± 0.0011 ± 0.0014
SLD vtx mass
1993-98
0.21594 ± 0.00139 ± 0.00140
LEP+SLC
0.21642 ± 0.00073
corrected for γ exchange
m_t [GeV]
250
200
150
100
0.2125
0.215
0.2175
0.22
Γ_b/Γ_{had} for Γ_c/Γ_{had} = 0.171



Γ_c/Γ_{had}
ALEPH
lepton 1992-95
$0.1675 \pm 0.0062 \pm 0.0103$
ALEPH
D^* incl/excl 1990-95
$0.166 \pm 0.012 \pm 0.009$
DELPHI
D^* incl/excl 1991-95
$0.161 \pm 0.010 \pm 0.009$
OPAL
D^* incl/excl 1990-95
$0.180 \pm 0.010 \pm 0.012$
ALEPH
D excl/excl 1990-95
$0.173 \pm 0.014 \pm 0.009$
SLD
mass+lifetime 1993-98
$0.169 \pm 0.005 \pm 0.004$
ALEPH
charm count. 1991-95
$0.1738 \pm 0.0047 \pm 0.0113$
DELPHI
charm count. 1991-95
$0.1692 \pm 0.0047 \pm 0.0097$
OPAL
charm count. 1991-93
$0.167 \pm 0.011 \pm 0.012$
LEP+SLD
0.1674 ± 0.0038
0.14
0.16
0.18
Γ_c/Γ_{had}

F-B Asymmetries with b-, c-, and s-quarks

In order to measure the angular distributions of $b\bar{b}$, $c\bar{c}$, and $s\bar{s}$ final states it is necessary to:

1. Tag the event flavor
2. Measure the polar angle of the thrust axis
3. Identify which hemisphere contains the quark (as opposed to antiquark)

Tagging and $Q/\bar{Q}$ separation is achieved via several techniques:

1. b-Events: Tagging discussed in R_b section, $b/\bar{b}$ separation:
   (a) Large P/P_Tlepton-tagged events - use the sign of the lepton to tag $q/\bar{q}$
   (b) Jet Charge - use momentum-weighted charge sums

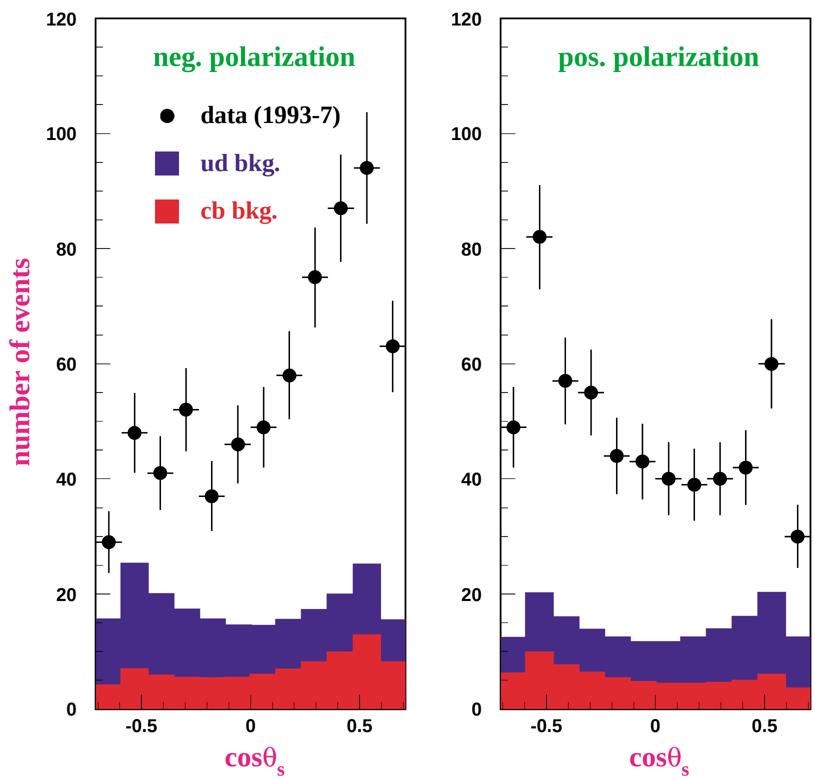
$$Q_F^f = \frac{\sum_i^{\vec{p}_i\cdot\vec{T}>0} |\vec{p}_i \cdot \vec{T}|^\kappa q_i}{\sum_i^{\vec{p}_i\cdot\vec{T}>0} |\vec{p}_i \cdot \vec{T}|^\kappa} \qquad Q_B^f = \frac{\sum_i^{\vec{p}_i\cdot\vec{T}<0} |\vec{p}_i \cdot \vec{T}|^\kappa q_i}{\sum_i^{\vec{p}_i\cdot\vec{T}<0} |\vec{p}_i \cdot \vec{T}|^\kappa}$$

   to form the forward-backward charge asymmetry,

$$Q_{FB}^f = Q_F^f - Q_B^f = \delta_f A_{FB}^f,$$

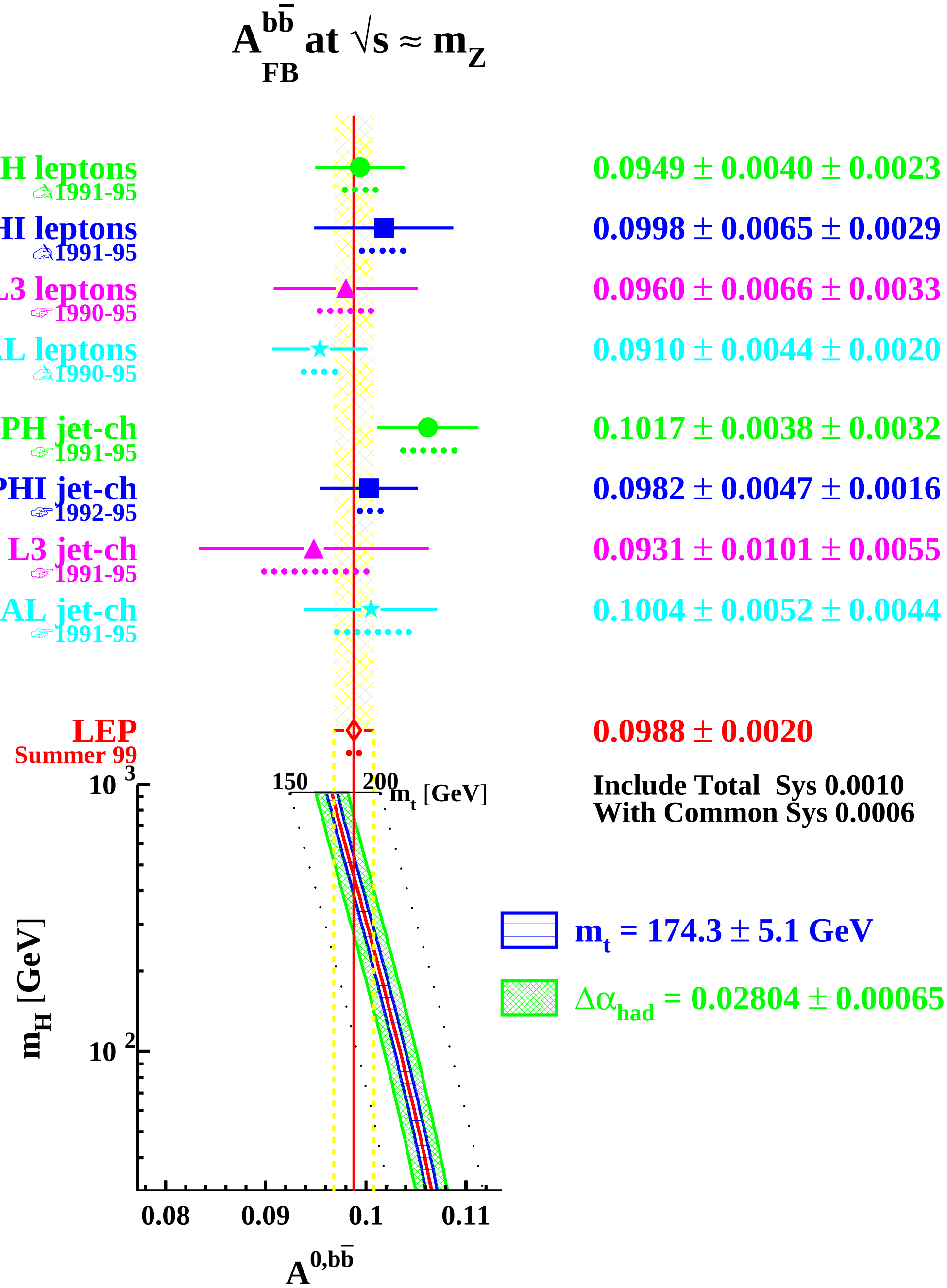
   where the hemisphere charge separation δ_f is extractable from the sums and differences of the thrust hemisphere jet charges. Self-calibrating except for hemisphere correlation effects.
   (c) $K^\pm$ Sum - Use charge of the $K^\pm$ from the $b \longrightarrow c \longrightarrow s$ cascade to separate $b/\bar{b}$ (sum the $K^\pm$ charges in each hemisphere). Self-calibrates
   (d) Topological Vertex Charge - total charge of tracks associated with a reconstructed secondary vertex. Self-calibrates

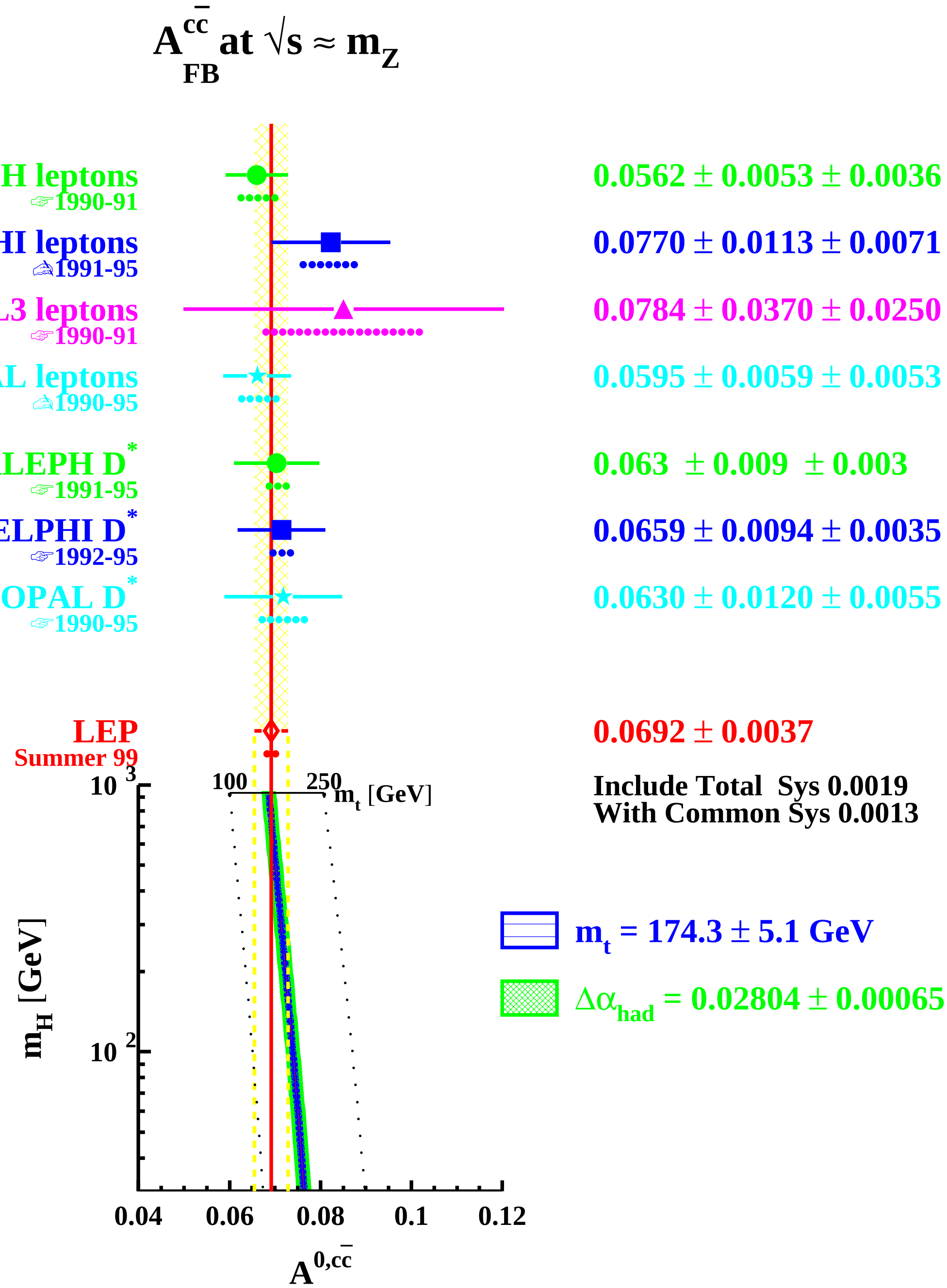
2. c-Events: Tagging discussed in R_c section, $c/\bar{c}$ separation:
   (a) Large P/P_Tlepton-tagged events - use the sign of the lepton to tag $q/\bar{q}$
   (b) D/D^*-tagged Events - use charge of reconstructed $D^\pm$
   (c) Topological Vertex Charge - total charge of tracks associated with a reconstructed secondary vertex
   (d) $K^\pm$ Sum - Use charge of the $K^\pm$ from the $c \longrightarrow s$ cascade to separate $c/\bar{c}$ (sum the $K^\pm$ charges in each hemisphere).
3. s-Events: (SLD Update) Tagging and sign selection done as follows:
   - Select events with no detached vertices - anti-tags $b\bar{b}$ and $c\bar{c}$ events.
   - Require fast strange particles - $K^\pm$ with $p > 9$ GeV or K_s^0, Λ, $\bar{\Lambda}$ with $p > 5$ GeV
   - Require tag in both hemispheres - ≥ 1 signed-hemisphere ($K^\pm$, $\Lambda/\bar{\Lambda}$), take largest momentum tag in hemisphere
   - Moderate Purity - 50% to 73% depending upon final state
   - Analyzing power self-calibrates from hemisphere correlations



Unpolarized $Q\bar{Q}$ Asymmetries

Fitting the angular distributions (or measuring Q_{FB} as a function of $\cos\theta$) correcting for the charge-signing analyzing powers, backgrounds, B^0-$\bar{B}^0$ mixing, QCD effects, and electroweak interference yields,





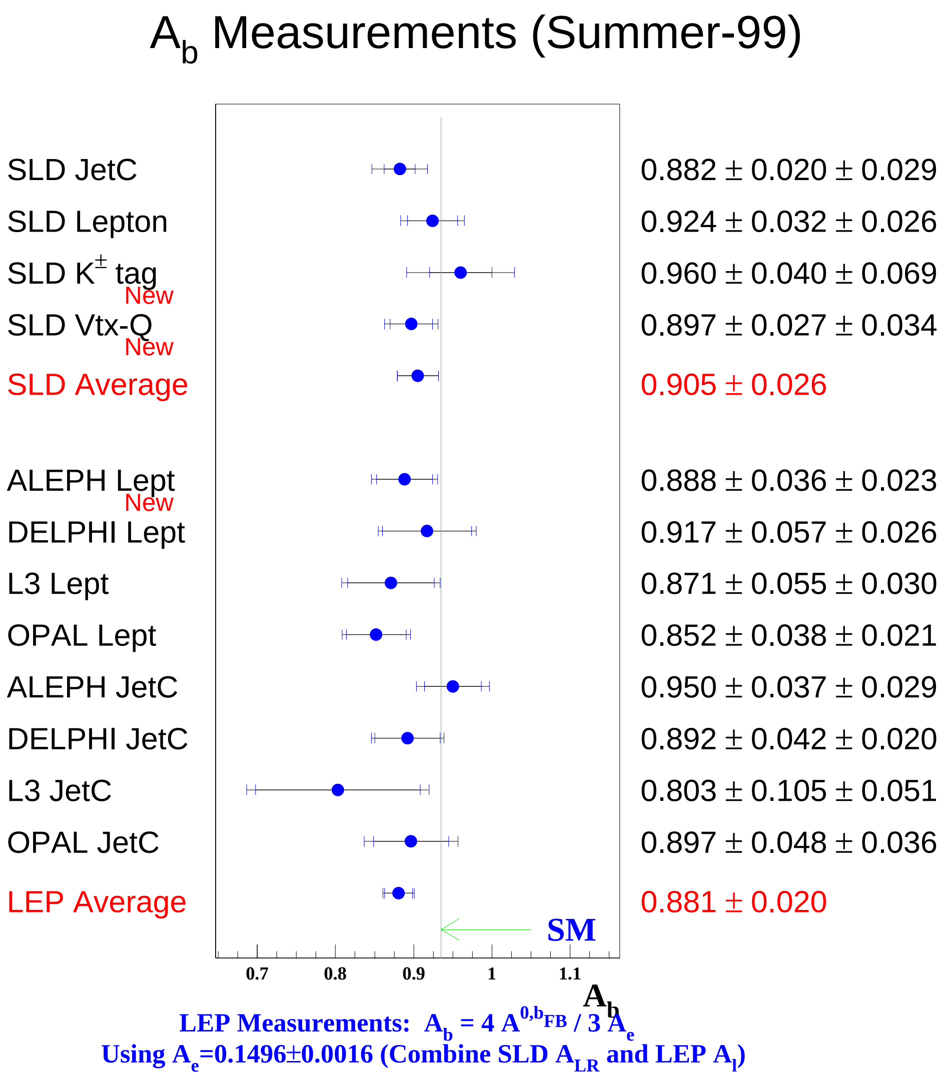
The unpolarized asymmetries depend upon A_e,

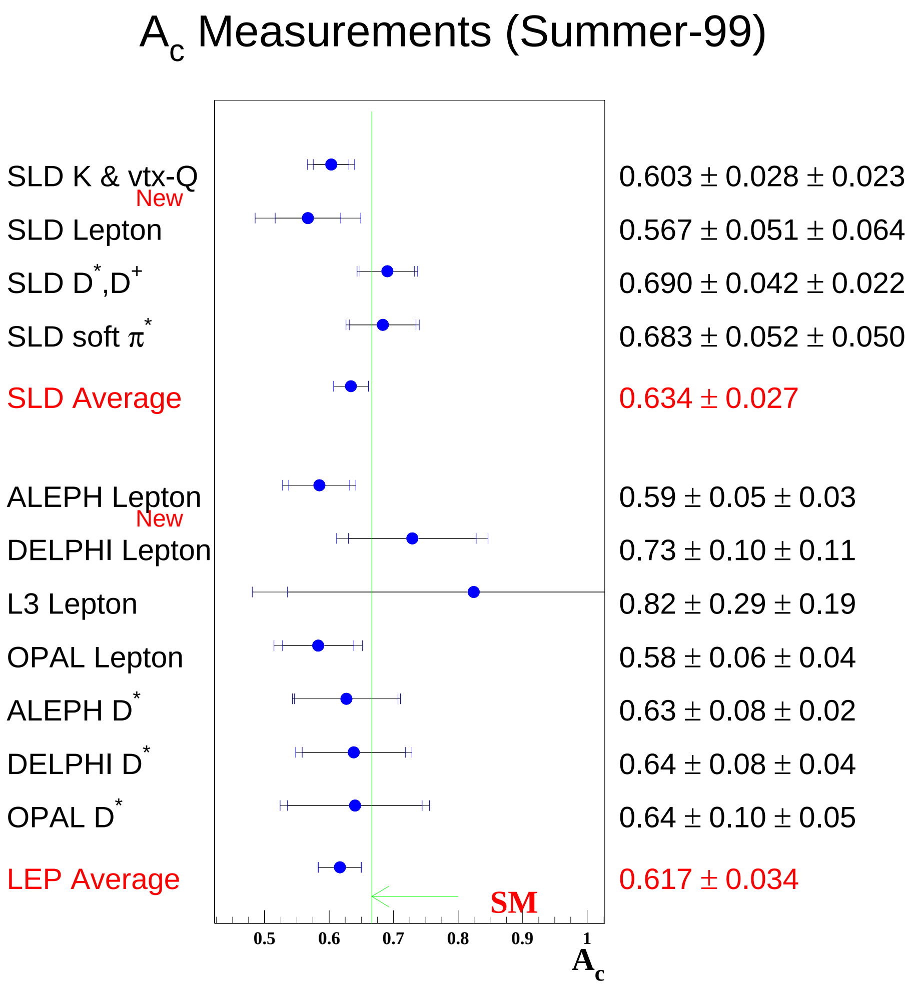
$$A_{FB}^{f} = 0.75 A_e A_f,$$

and are quite sensitive to the effective weak mixing angle (the quark asymmetries A_q are very insensitive to it). They are used to determine $\sin^2\theta_W^{eff}$. In order to isolate the final state coupling asymmetries A_b and A_c, it is necessary to divide the FB asymmetries by an average value of A_ℓ determined from A_{FB}^{ℓ}, $\mathcal{P}_\tau$, and A_{LR}.

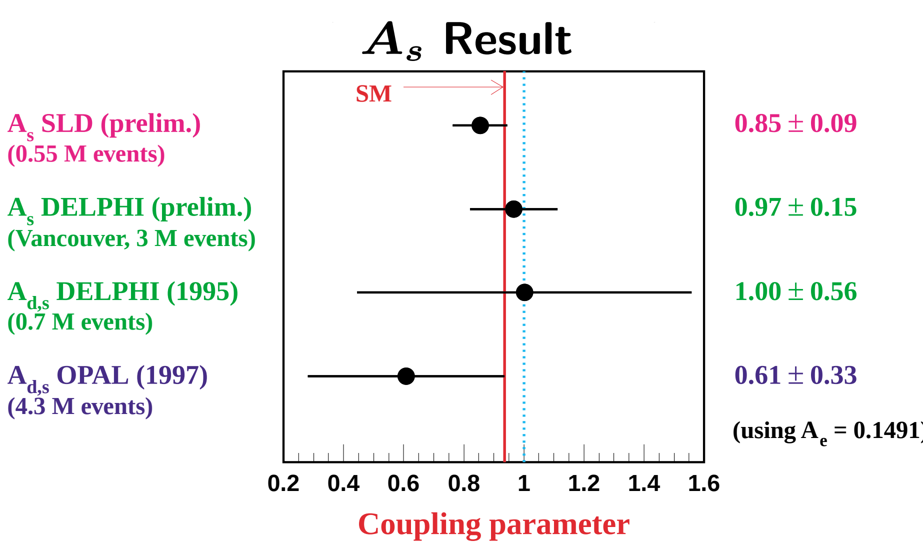
Polarized $Q\bar{Q}$ Asymmetries

The left-right forward-backward asymmetries measured by SLD directly isolate the final state coupling asymmetries. Using similar techniques to tag and sign identify $b\bar{b}$ and $c\bar{c}$ final states, the parameters A_b and A_c are measured directly,





LEP Measurements: $A_c = 4\, A^{0,c}_{FB} / 3\, A_e$
Using A_e=0.1496±0.0016 (Combine SLD A_{LR} and LEP A_l)



Extracted Parameters

The lineshape parameters, leptonic forward-backward asymmetries, and τ-polarization are used (by the LEP EWWG) to extract a number of parameters. Partial decays widths to leptons, hadrons, and invisible particles are,

Without Lepton Universality		
$\Gamma_{\rm ee}$	(MeV)	83.90 ± 0.12
$\Gamma_{\mu\mu}$	(MeV)	83.96 ± 0.18
$\Gamma_{\tau\tau}$	(MeV)	84.05 ± 0.22
With Lepton Universality		
$\Gamma_{\ell\ell}$	(MeV)	83.96 ± 0.09
$\Gamma_{\rm had}$	(MeV)	1743.9 ± 2.0
$\Gamma_{\rm inv}$	(MeV)	498.8 ± 1.5

The ratio of the invisible and leptonic widths,

$$\Gamma_{\rm inv}/\Gamma_{\ell\ell} = 5.941 \pm 0.016,$$

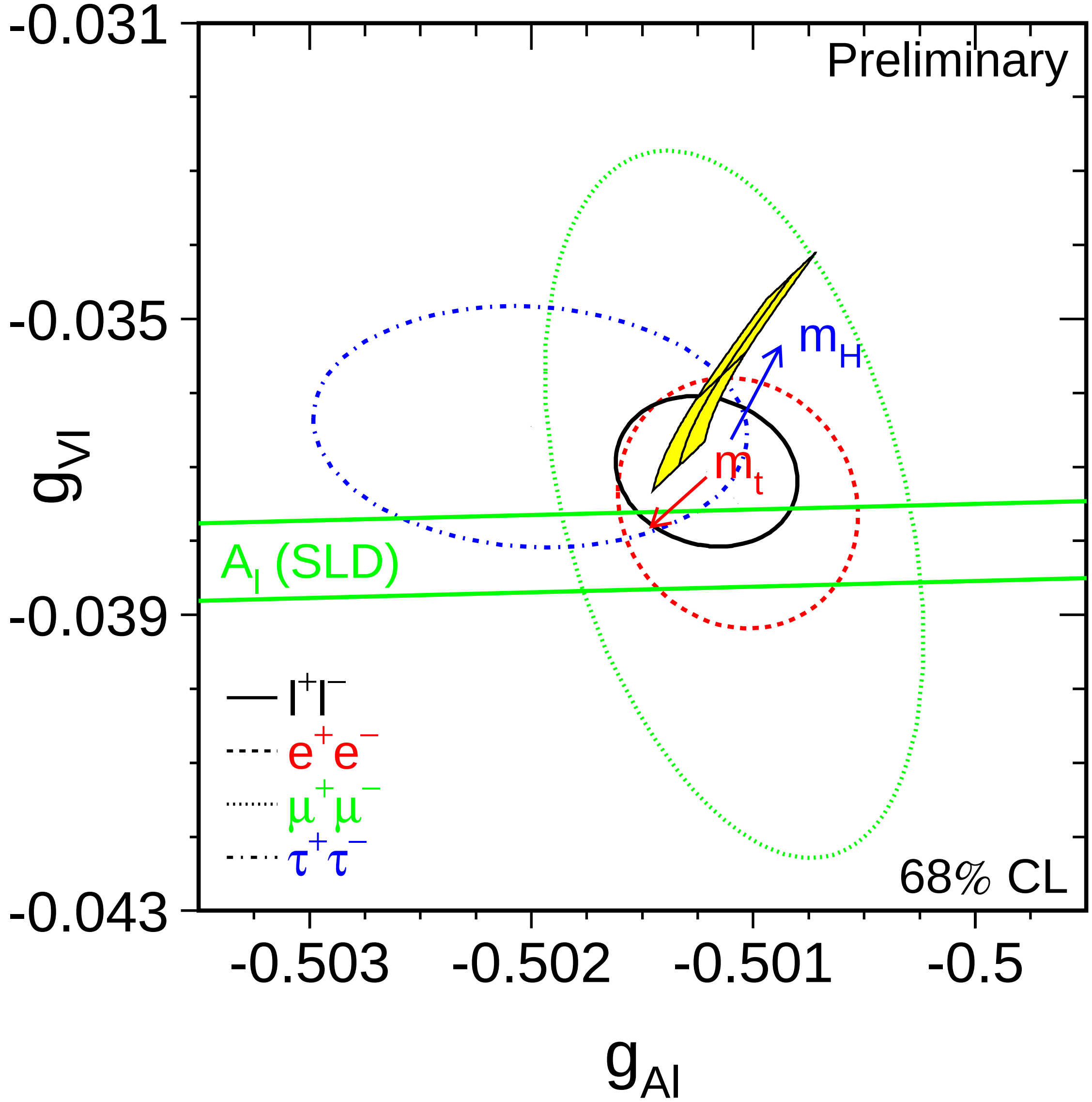
can be divided by the MSM value for $\Gamma_{\nu\nu}/\Gamma_{\ell\ell}$ (1.9912$\pm$0.0012) to yield the number of neutrinos,

$$N_\nu = 2.9835 \pm 0.0083,$$

or converted into a 95% upper limit on additional width $\Delta\Gamma_{\rm inv}$ (assuming $N_\nu = 3$),

$$\Delta\Gamma_{\rm inv} < 2.0 \text{ MeV}.$$

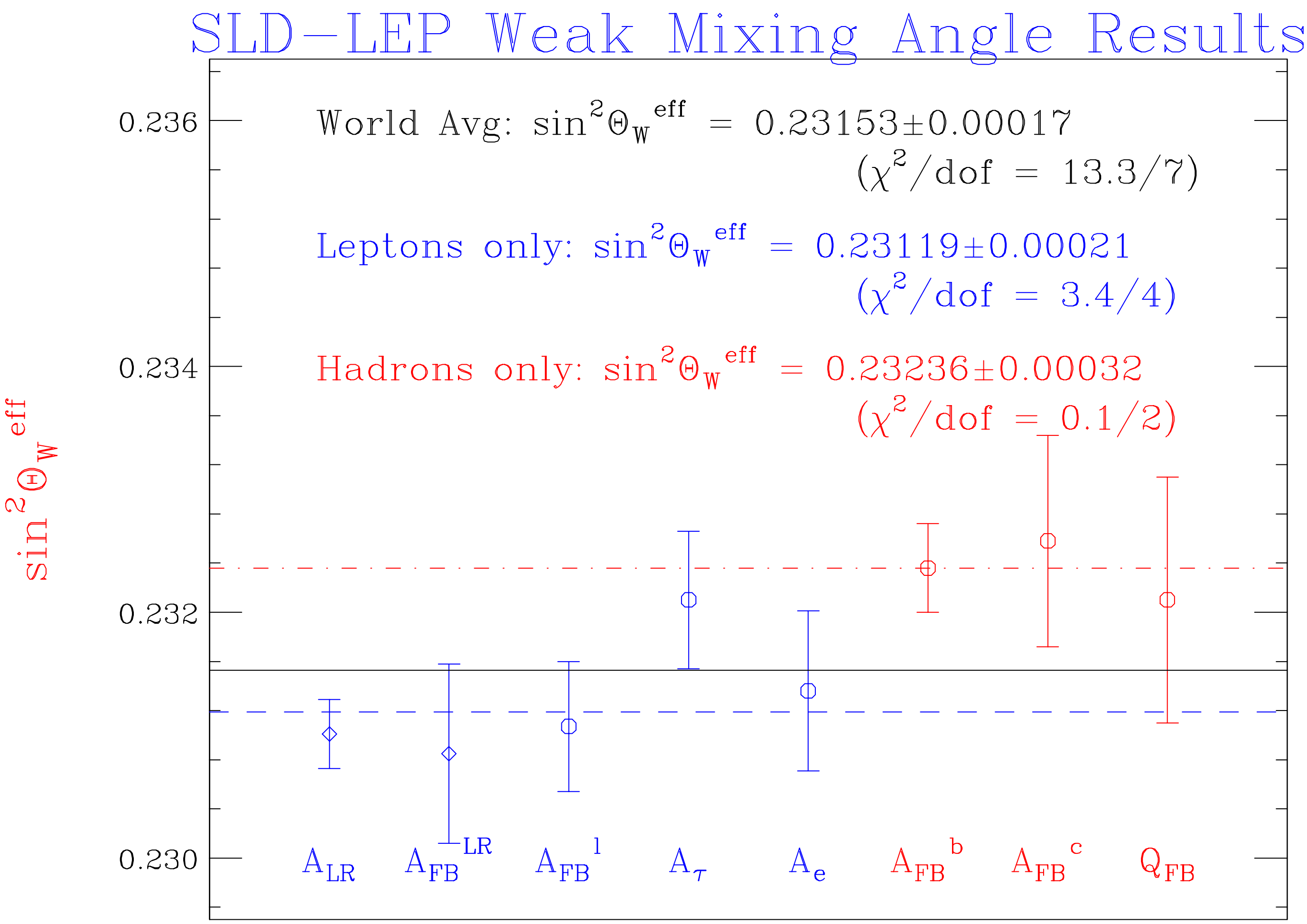
The measurements of $\Gamma_{\ell\ell}$, A^{ℓ}_{FB}, and A_ℓ can be used to unfold values of $g_{V\ell} = v_\ell/2$ and $g_{A\ell} = a_\ell/2$,



$$\frac{g_A^\mu}{g_A^e} = 1.0001 \pm 0.0014 \qquad \frac{g_V^\mu}{g_V^e} = 0.981 \pm 0.082$$

$$\frac{g_A^\tau}{g_A^e} = 1.0019 \pm 0.0015 \qquad \frac{g_V^\tau}{g_V^e} = 0.964 \pm 0.032$$

All of these quantities and the hadronic forward-backward asymmetries (assuming that there are no anomalous vertex corrections) can be used to extract the effective weak mixing angle,

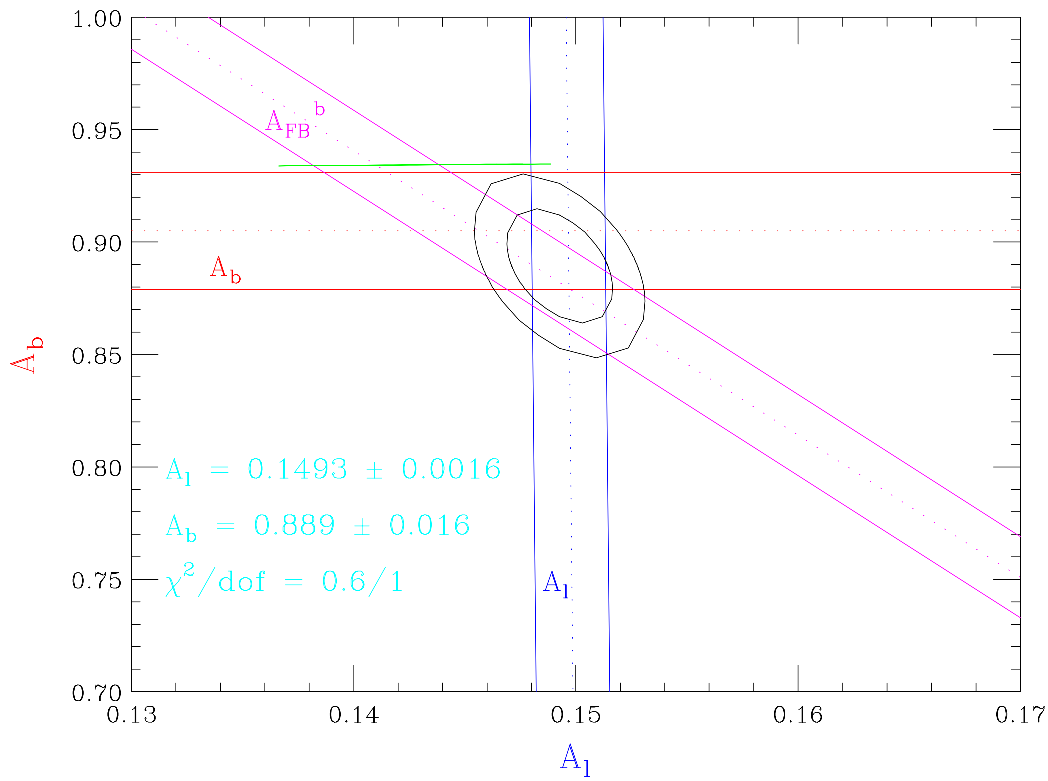


- $P(\chi^2) = 0.065 \longrightarrow$ **OK, but not terrific ....**
- **The leptonic measurements and hadronic measurements agree well within their groups**
- **The two most precise measurements, A_{LR} and A_{FB}^b, deviate by 3.0 σ**

Is there something going on???

Three possilities:

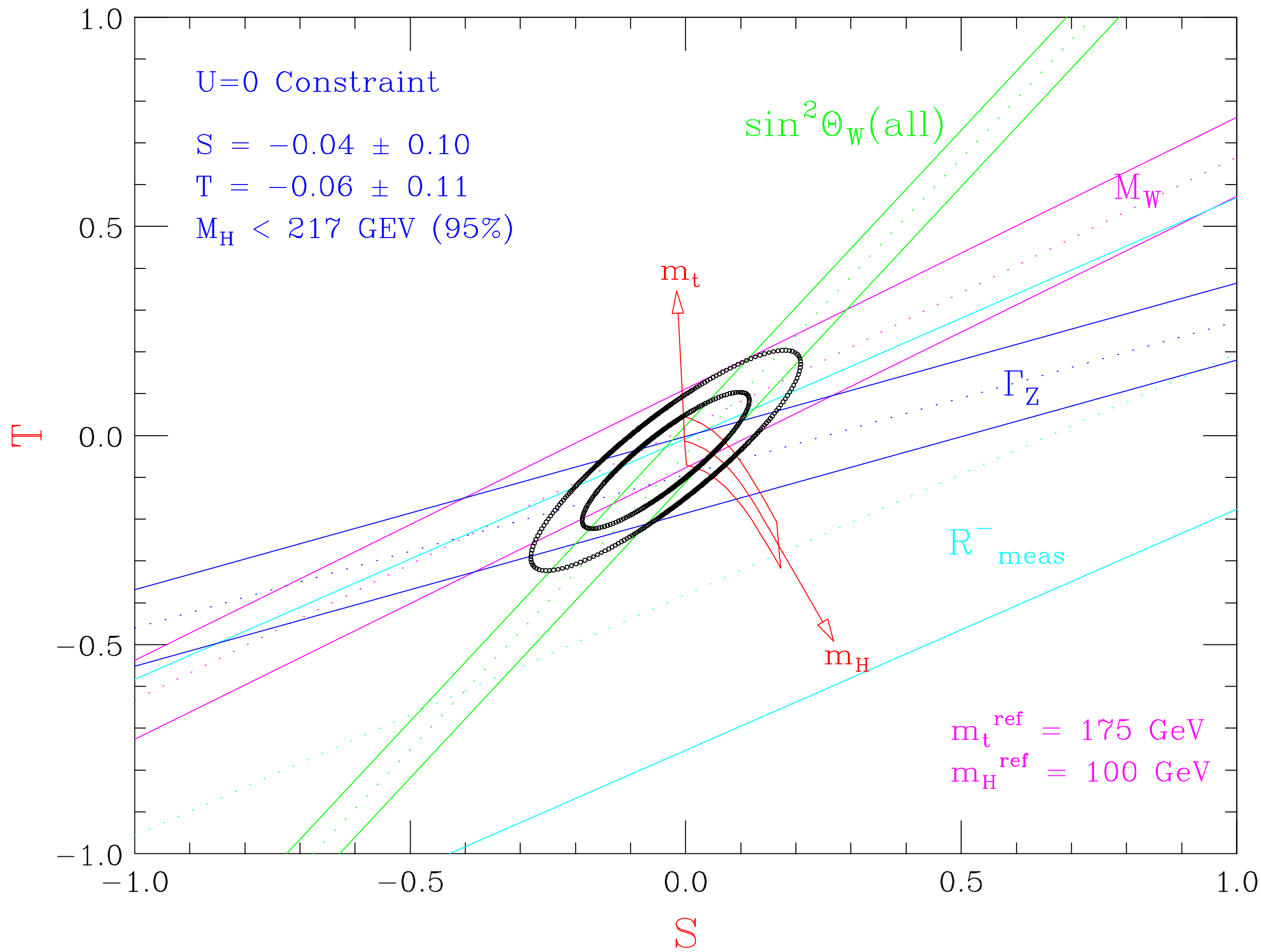
1. **Unknown systematic effects distort some or all of the results.**
2. **It's just a statistical fluctuation.**
3. **It's new physics ...**
   If the b-quark coupling asymmetry is anomalous (A_b deviates from 0.935), it is possible to reconcile the discrepancy. Fit to A_ℓ, A_b and $A^b_{FB} = 0.75 A_\ell A_b$,



The best fit for A_b deviates from the MSM by 2.7 σ! The possibility that new physics might be affecting the $Zb\bar{b}$ couplings has been studied by M. Chanowitz (hep-ph/9905478):
$\longrightarrow$ may be observable consequences in the study of flavor-changing neutral currents, rare K decays.

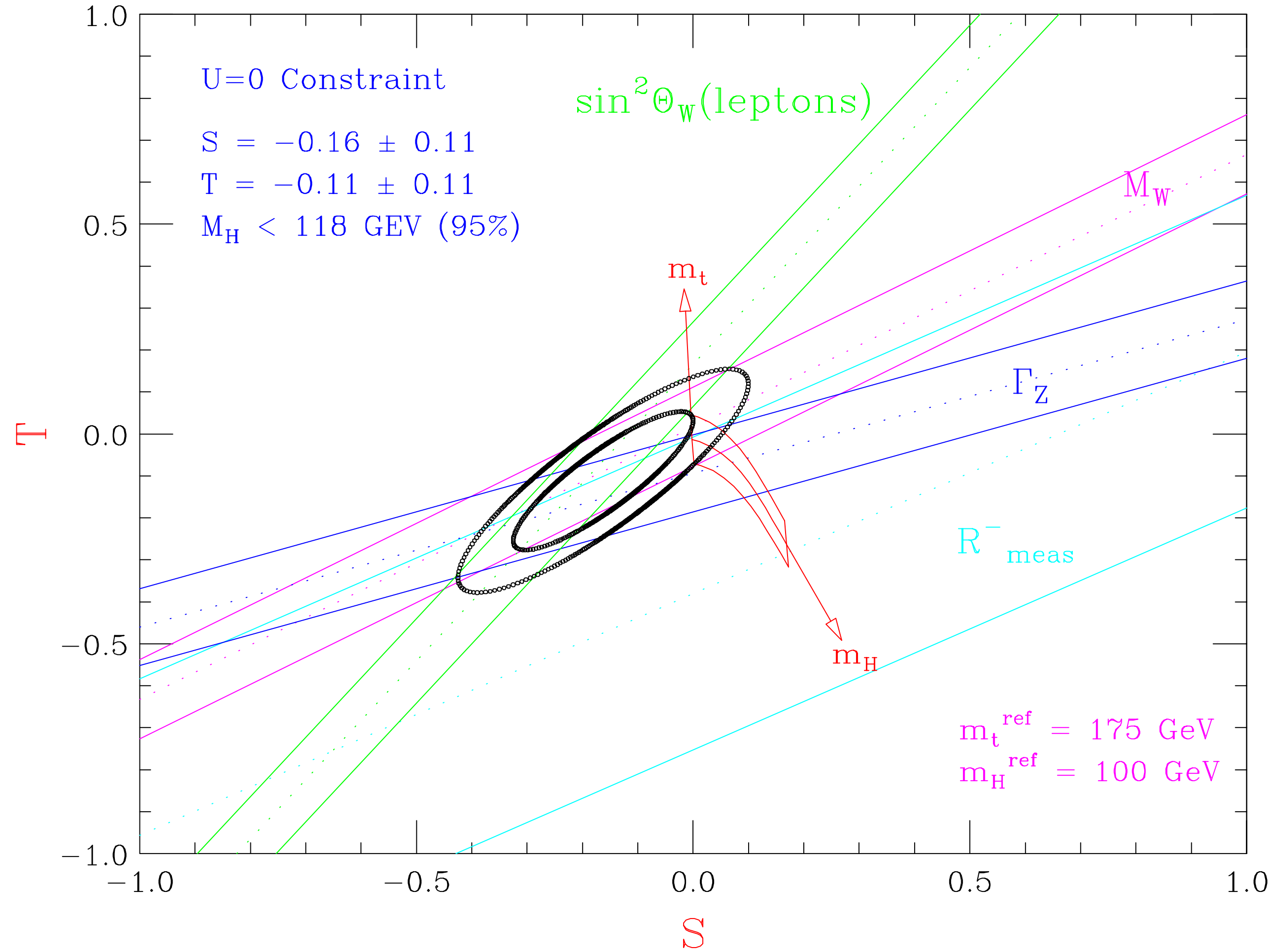
Consistency With the Standard Model

We can compare the best Z-pole electroweak measurements with others and the Standard Model using the "Model-Independent" S-T parameters of Peskin and Takeuchi [PRL 65, 964 (1990)]. 14 EW measurements are fit to S, T, α_s, $\Delta\alpha^5_{had}$ (constrained to $277.5 \pm 1.7 \times 10^{-4}$). The resulting confidence region can be used to find an upper limit for m_H by including $m_t = 174.3 \pm 5.1$ GeV as a constraint,



- **$\sin^2\theta_W^{eff}$ is the most precisely-measured observable**
- **Global M_W is now number 2, close to Γ_Z**
- **Data agree well with Standard Model $\longrightarrow$ "light" Higgs favored**

We can perform the analysis but excluding the hadronic determinations of $\sin^2\theta_W^{eff}$. The picture changes a little bit,



- $\sin^2\theta_W^{eff}$ **is still the most precisely-measured observable**
- **Data with Standard Model is becoming marginal:**
  - S **disagreement with SMS is approaching the 1-sided 95% level (1.6 σ)**
  - **Very light Higgs mass preferred (central value is 42 GeV)**

Conclusions

- The era of Z-pole electroweak physics has come to an end
- Decade has been a "Golden Age" for precise electroweak meas:
  - M_Z is measured to 2.2×10^{-5}!!! (used as input)
  - Γ_Z is measured to 10^{-3}!!!
  - $\sin^2\theta_W^{eff}$ determines most of what we know about loop-level processes
  - Three light left-handed neutrinos and NO additional invisible width
- Generally good agreement with MSM, but ...
- Still some lingering inconsistencies with leptonic and hadronic determinations of $\sin^2\theta_W^{eff}$
  - Has consequence for interpretation in terms of MSM
  - A_b is anomalous by 2.7σ
- We are leaving the Z a bit too soon.....

10 Years Ago