The rise and the fall of the Z resonance at LEP

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on
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Overview

LEP Program

Cross Section Measurements

Lepton Asymmetry Measurements

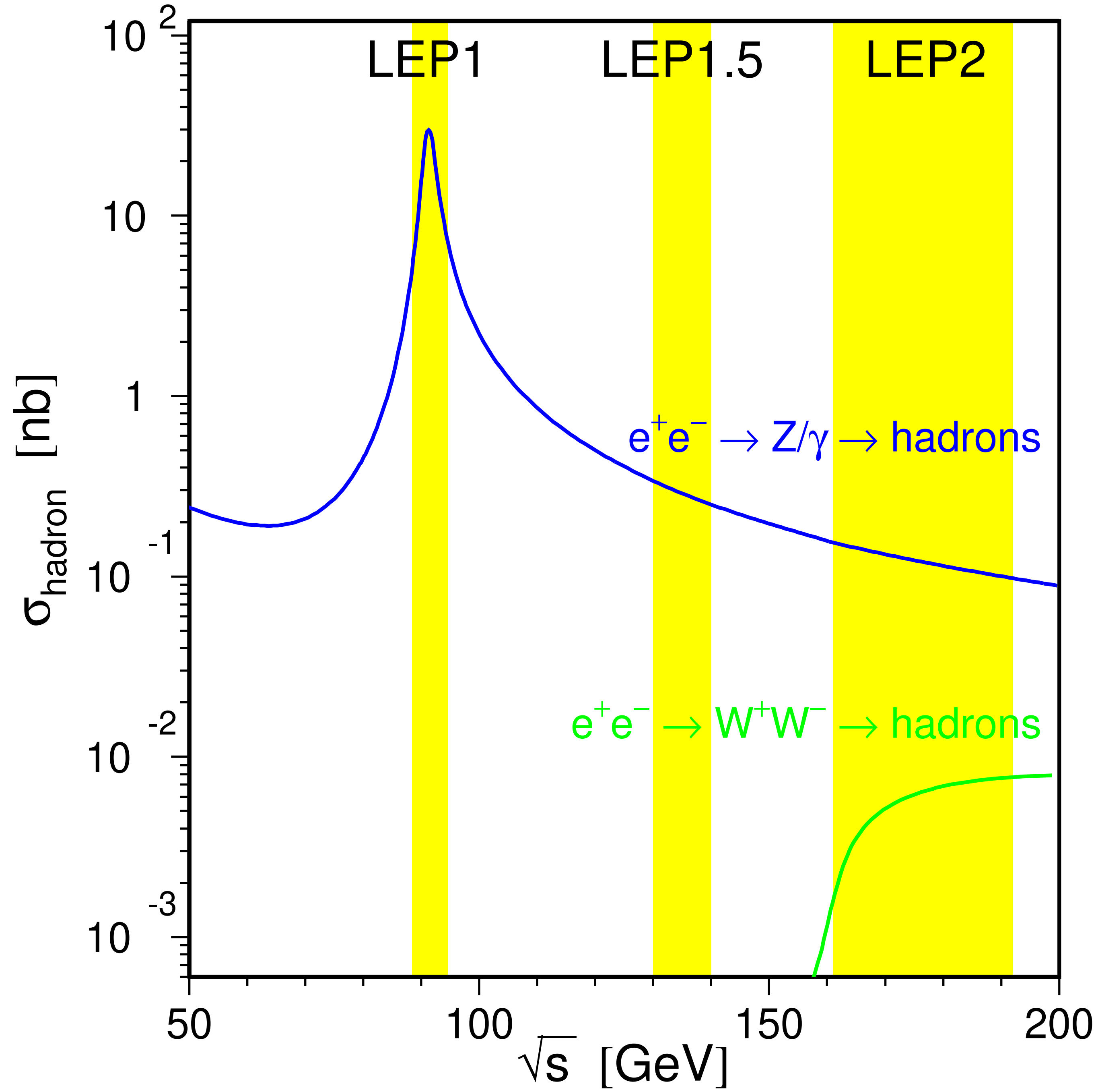
Effective Lepton Couplings and $\sin^2\overline{\theta}^{\ell}_{\mathrm{W}}$

Interpretation in the Standard Model

Reference:
LEP Experiments: ALEPH, DELPHI, L3, OPAL
LEP Electroweak Working Group

Thanks to all people involved,
especially Ch. Paus

LEP Program



Four LEP Experiments (16 million events):

ALEPH, DELPHI, L3, OPAL

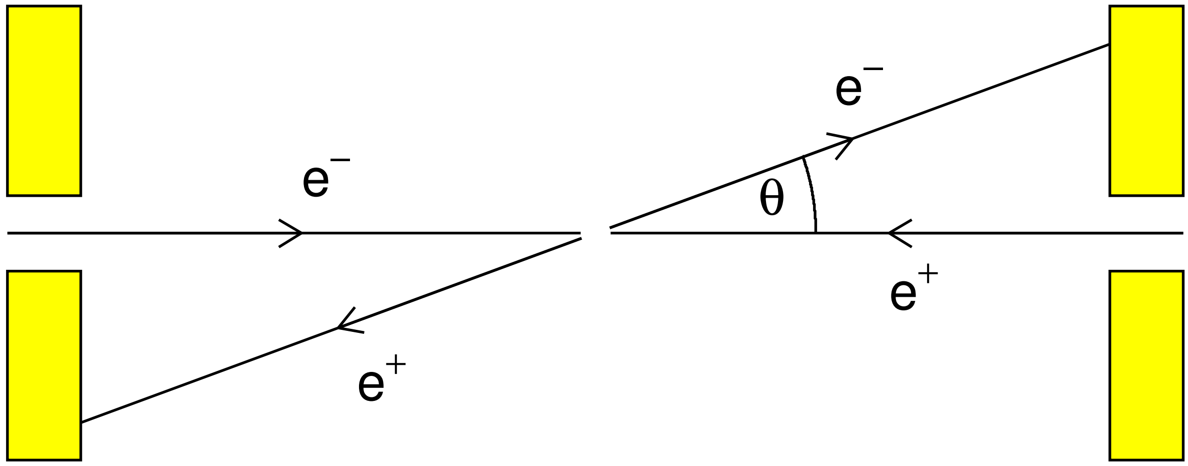
Status of the data presented:

Updated for 1997 Winter Conferences

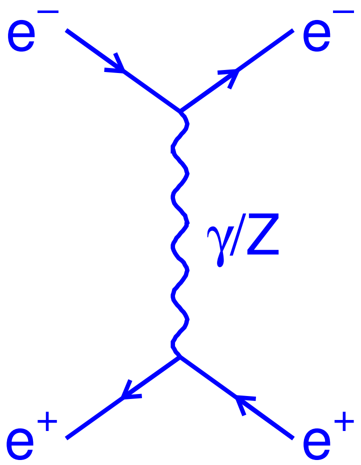
All numbers are still preliminary

Luminosity Measurement

Small angle Bhabha Scattering



Dominant t-channel diagram:



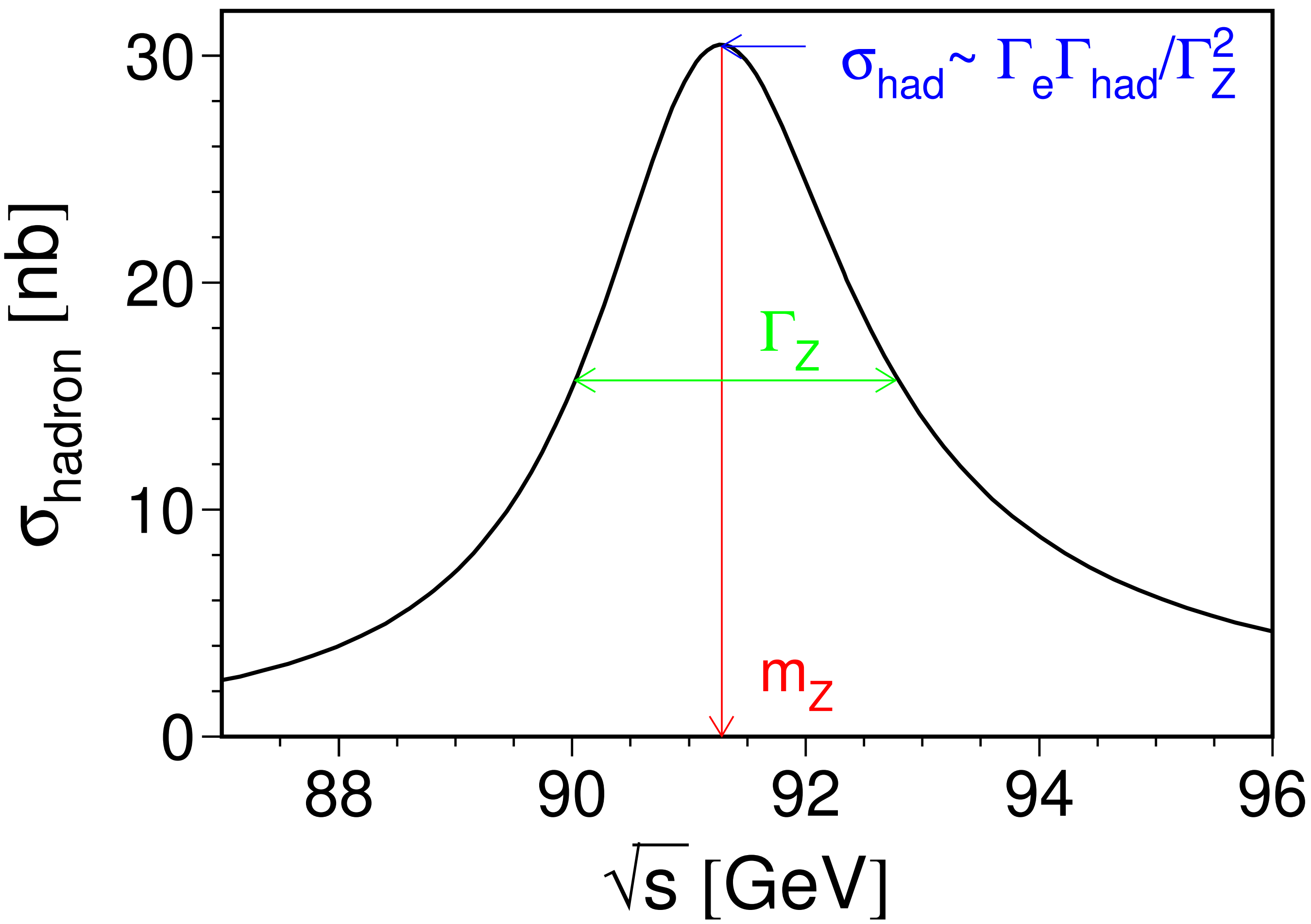
elastic scattering:

- γ exchange dominant
- small dependence on Z parameters

Theory uncertainty 0.11% at Z peak
Experimental uncertainties (1994):

ALEPH	0.073 %
DELPHI	0.090 %
L3	0.078 %
OPAL	0.079 %

Lineshape Parameters



Z mass, m_Z, $\approx$ position of peak

– 1.5 MeV error from uncertainty on $\sqrt{s}$

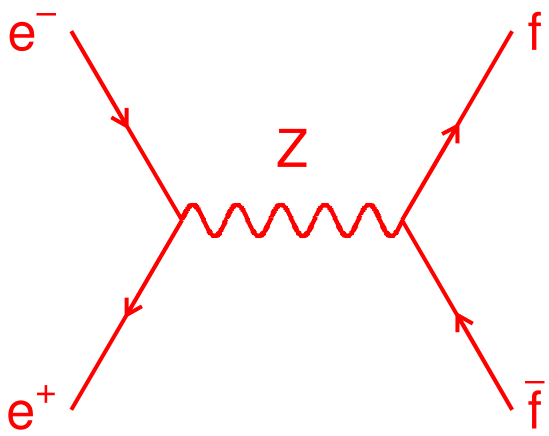
Z decay width, Γ_Z, $\approx$ width of resonance

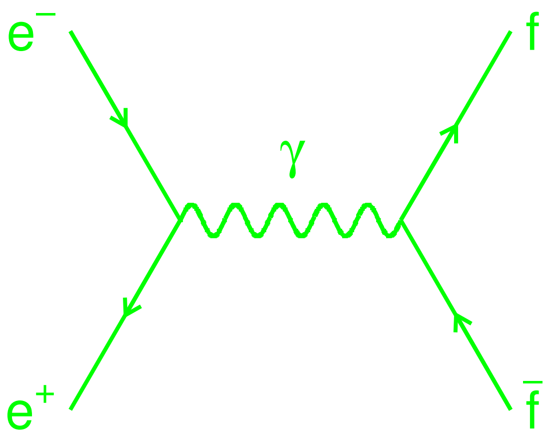
– 1.7 MeV error from uncertainty on $\sqrt{s}$

Z pole cross section, σ, $\approx$ height of peak

– 0.11% error from theoretical uncertainty on Luminosity

Lowest-Order $e^+e^- \to f\bar{f}$





$$\sigma^0 = \sigma^0_Z + \sigma^0_\gamma + \sigma^0_{\text{int}}$$

Breit-Wigner parametrisation: m_Z, Γ_Z, Γ_f, J_f

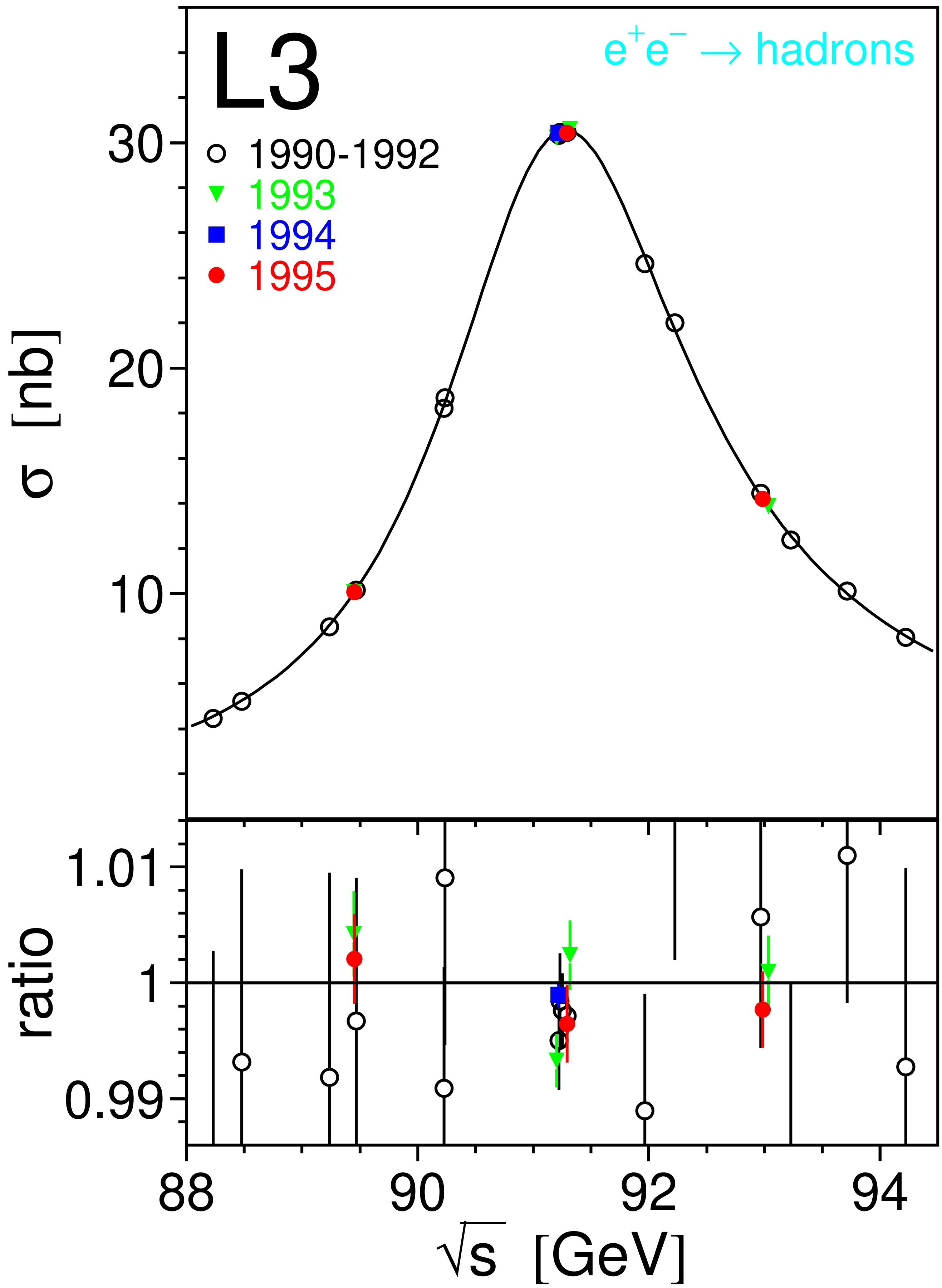
$$\sigma^0_Z = \frac{12\pi\Gamma_e\Gamma_f}{m_Z^2}\frac{s}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

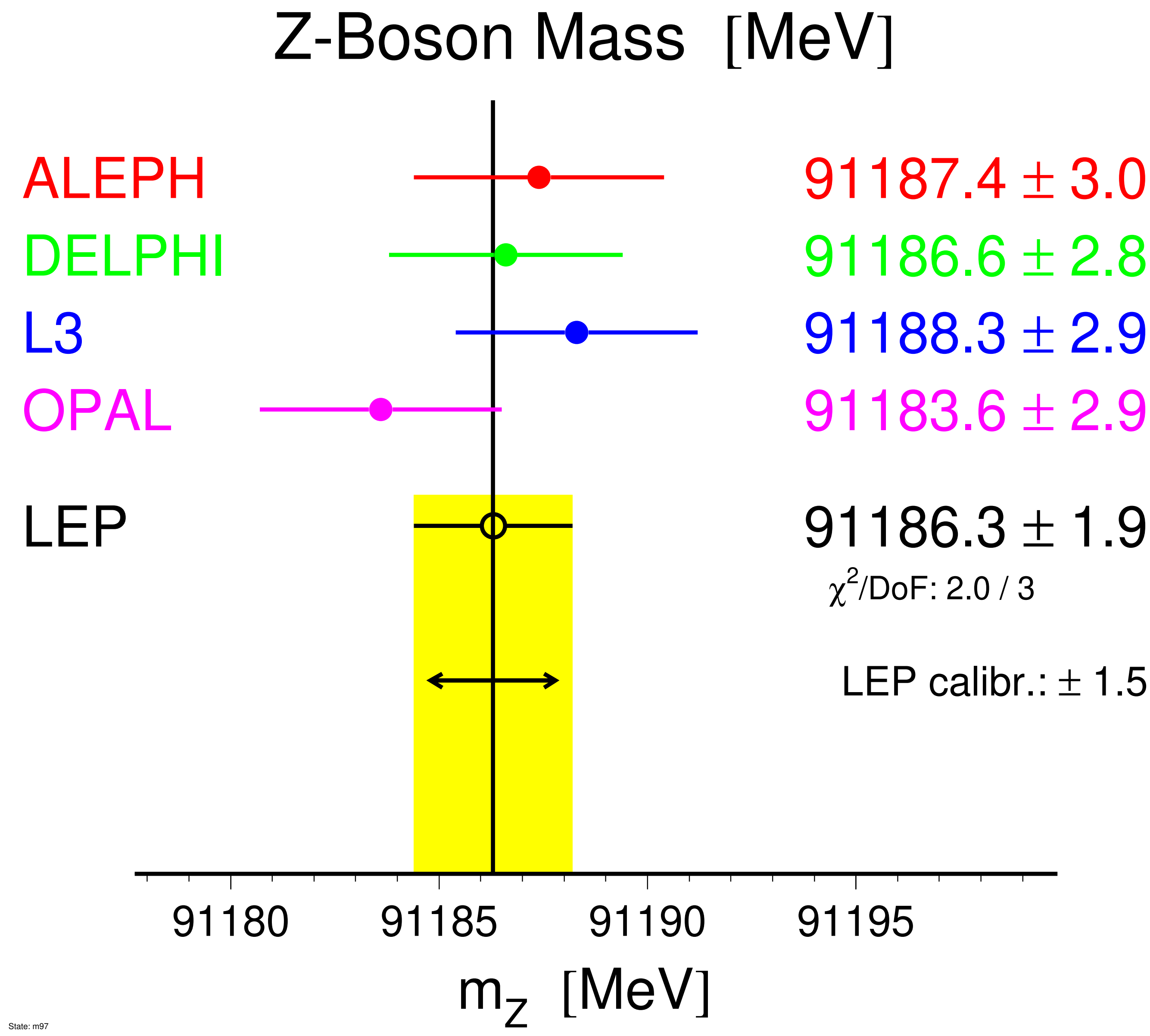
$$\sigma^0_\gamma = \frac{4\pi\alpha^2}{3s}Q_e{}^2Q_f{}^2N_f^C$$

$$\sigma^0_{\text{int}} = \frac{4\pi\alpha^2}{3}J_f\frac{s-m_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

σ^0_Z dominant for $\sqrt{s} \approx m_Z$

J_f for hadronic final state is fixed to Standard Model.


L3
e+e− → hadrons
1990-1992
1993
1994
1995
σ [nb]
30
20
10
ratio
1.01
1
0.99
88
90
92
94
√s [GeV]



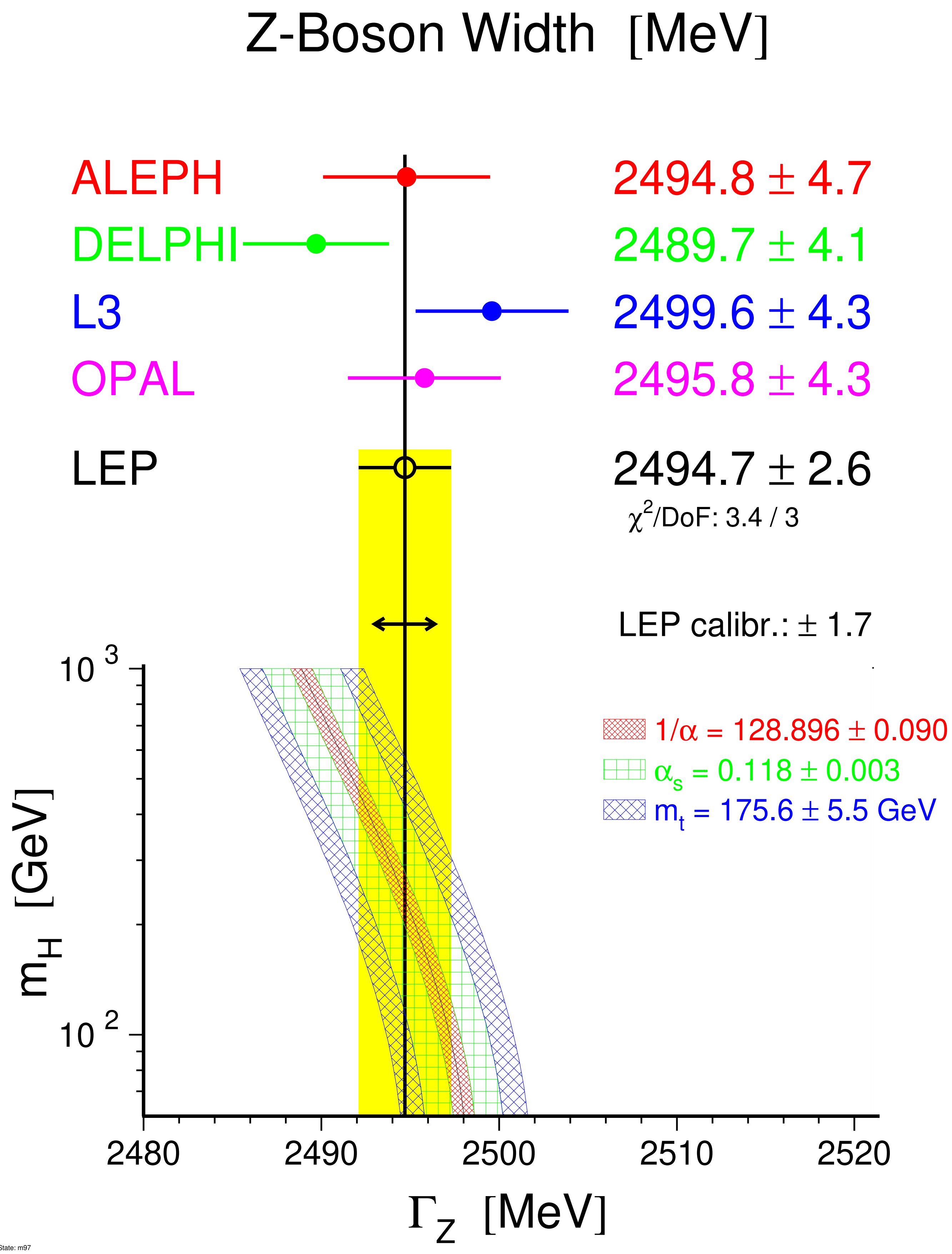
$$\Delta m_Z / m_Z = 21 \cdot 10^{-6}$$

Compare to other precise measurements:

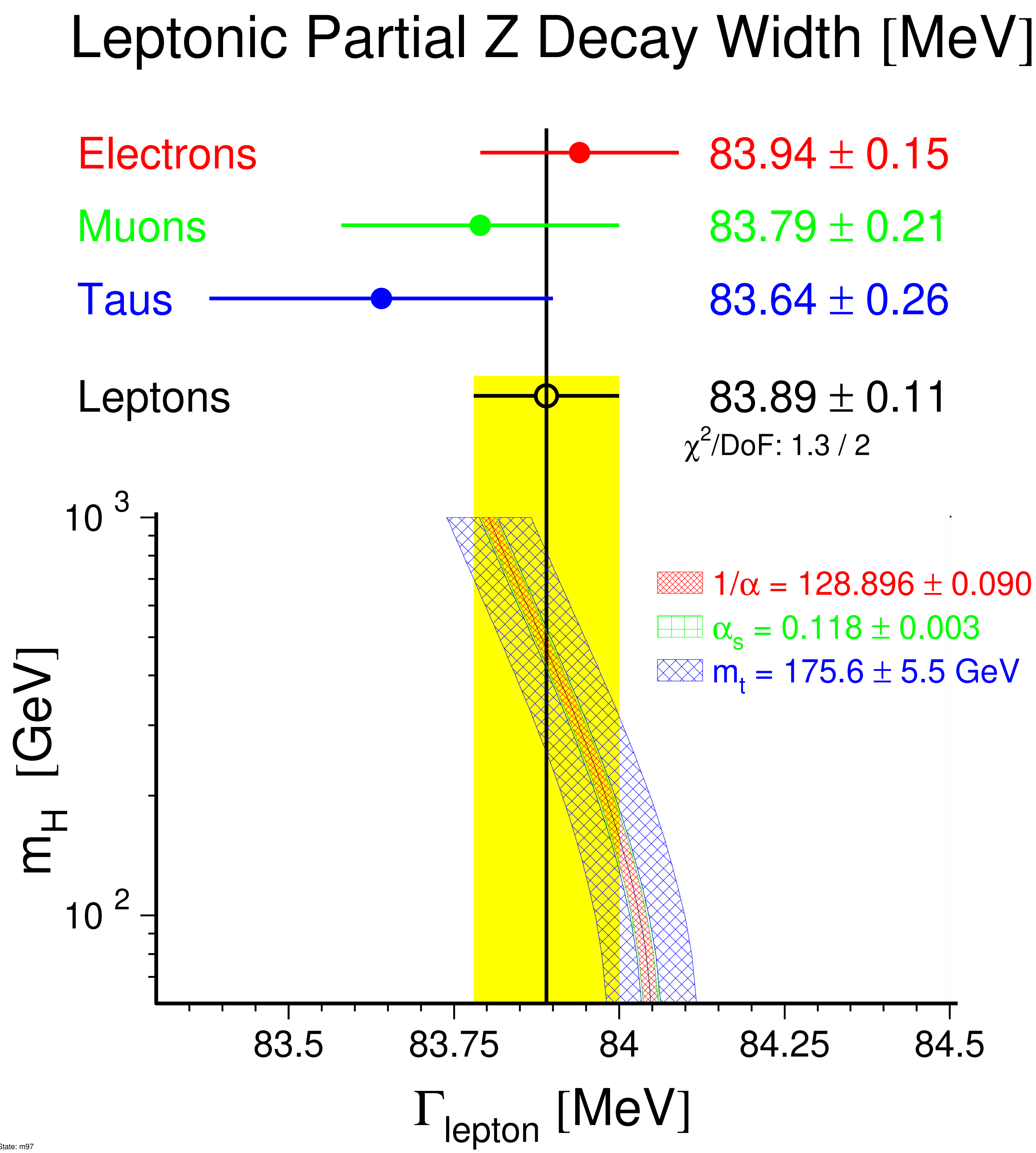
$$\Delta G_F / G_F = 20 \cdot 10^{-6}$$

$$\Delta G_N / G_N = 128 \cdot 10^{-6}$$

Results from Cross Section Measurements

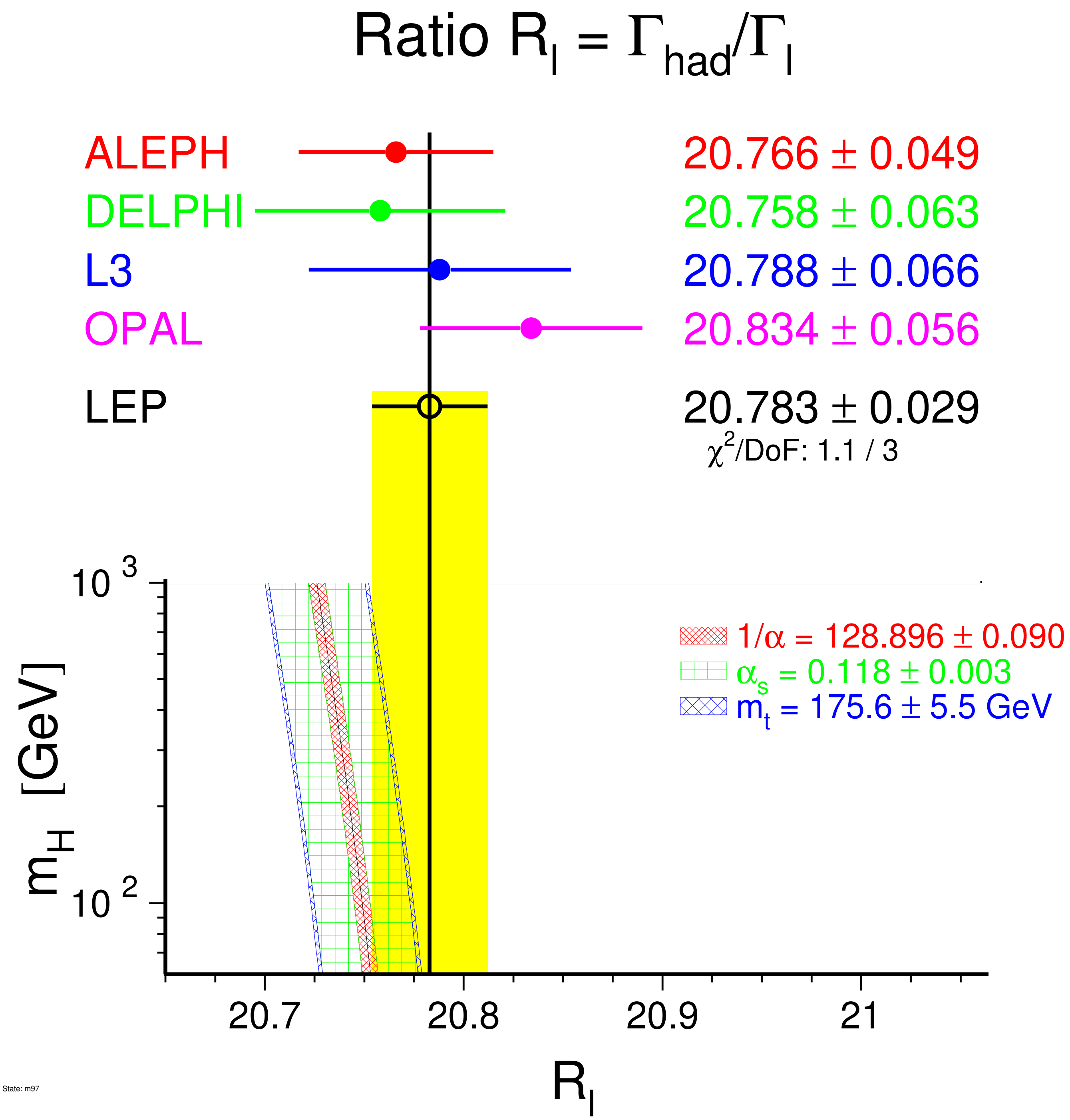


m_t and m_H dependence via radiative corrections



Hadronic partial Z decay width, Γ_{had}:

$$\Gamma_{\text{had}} = 1743.5 \pm 2.4 \ \text{MeV}$$



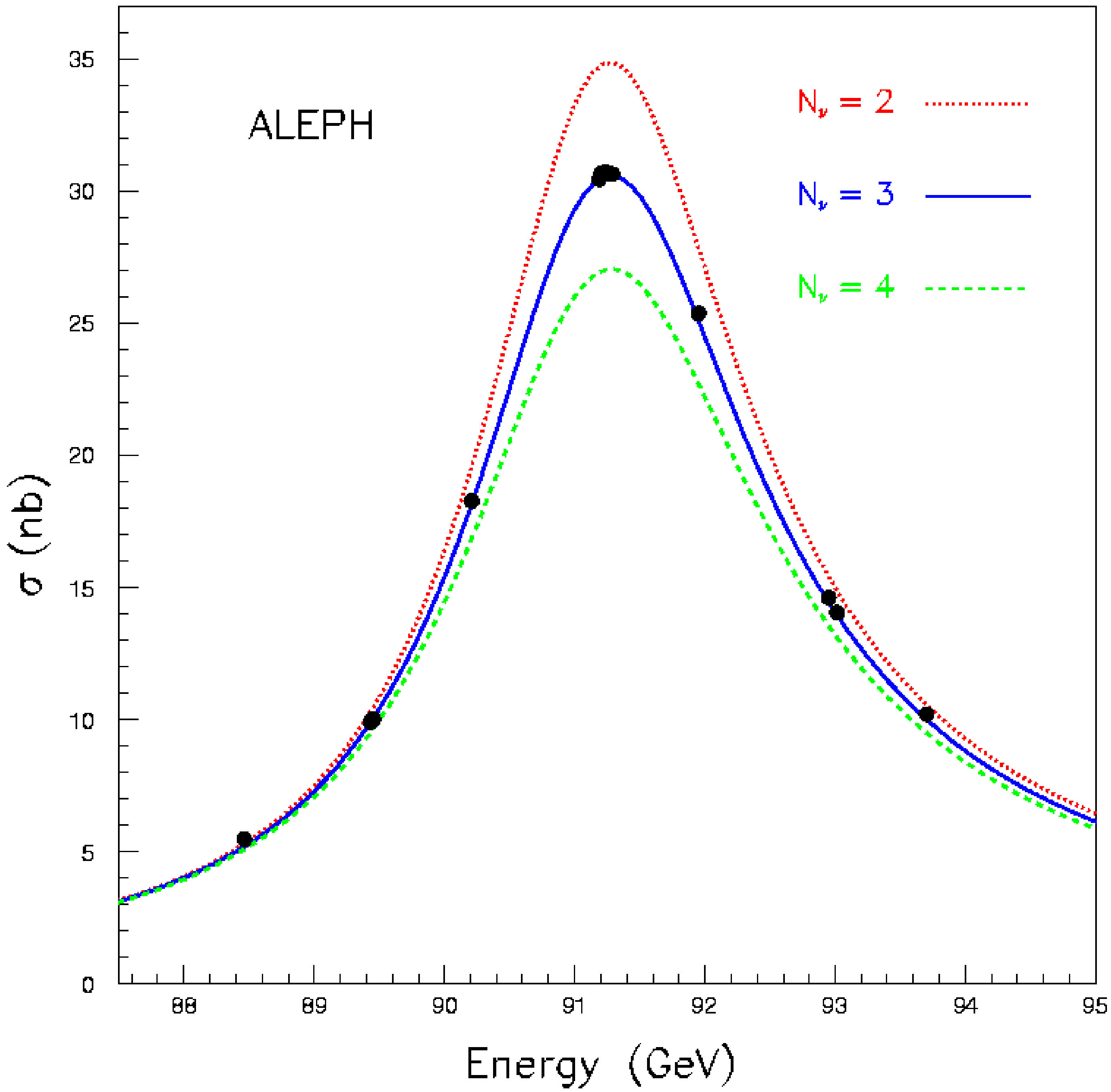
independent of luminosity

weak dependence on m_t, m_H

sensitive to α_s

Number of Light Neutrino Species

Indirect measurement: $e^+e^- \rightarrow$ hadrons

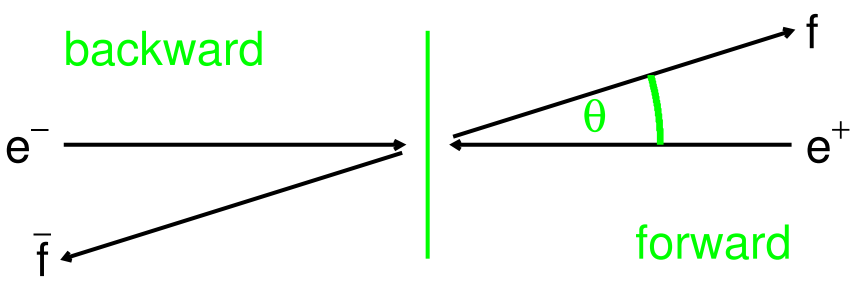


Z decays into invisible particles (Neutrinos)

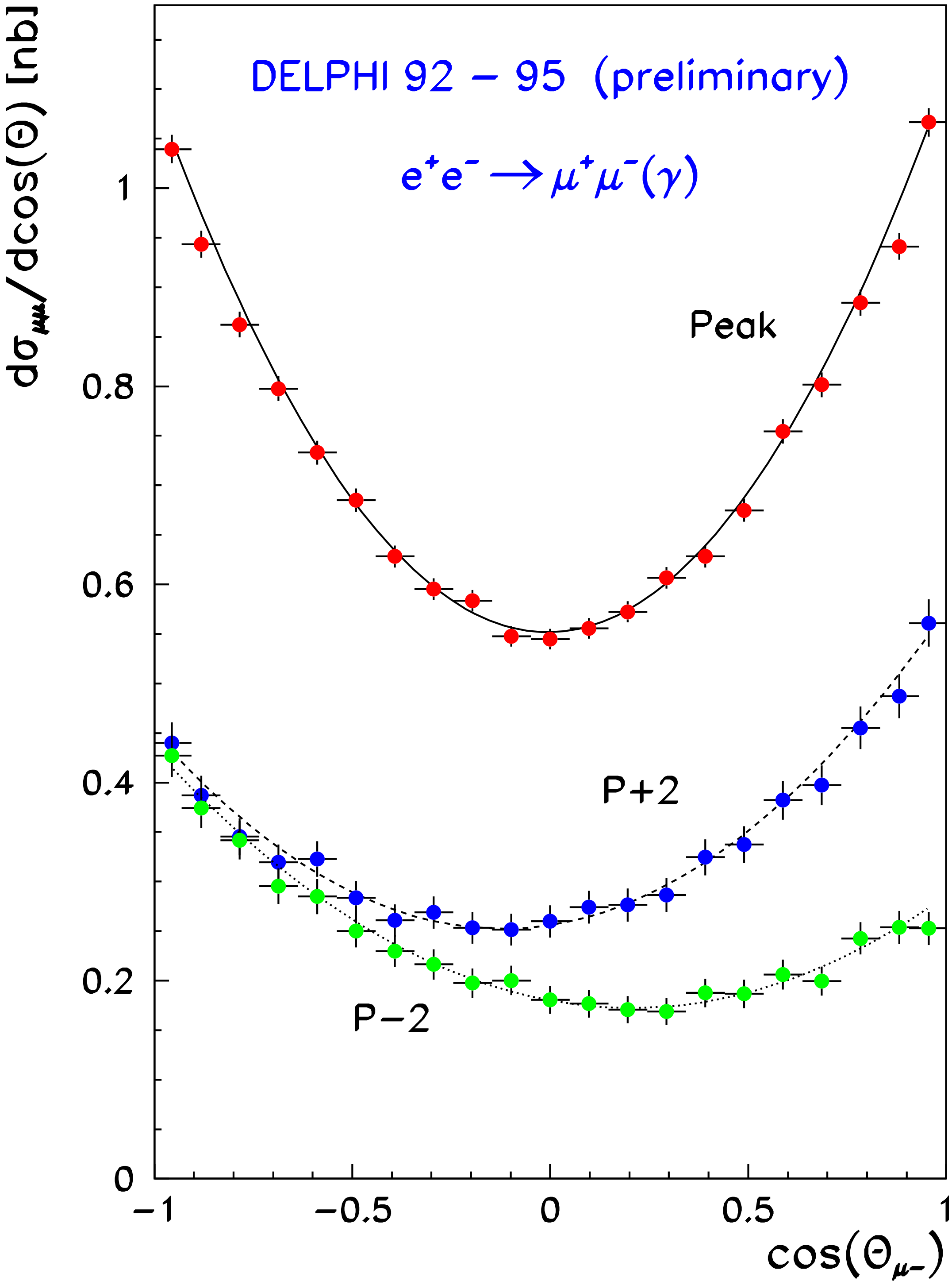
$$\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - 3\Gamma_\ell = 499.8 \pm 1.9 \text{ MeV}$$

Standard Model fit: $N_\nu = 2.992 \pm 0.011$

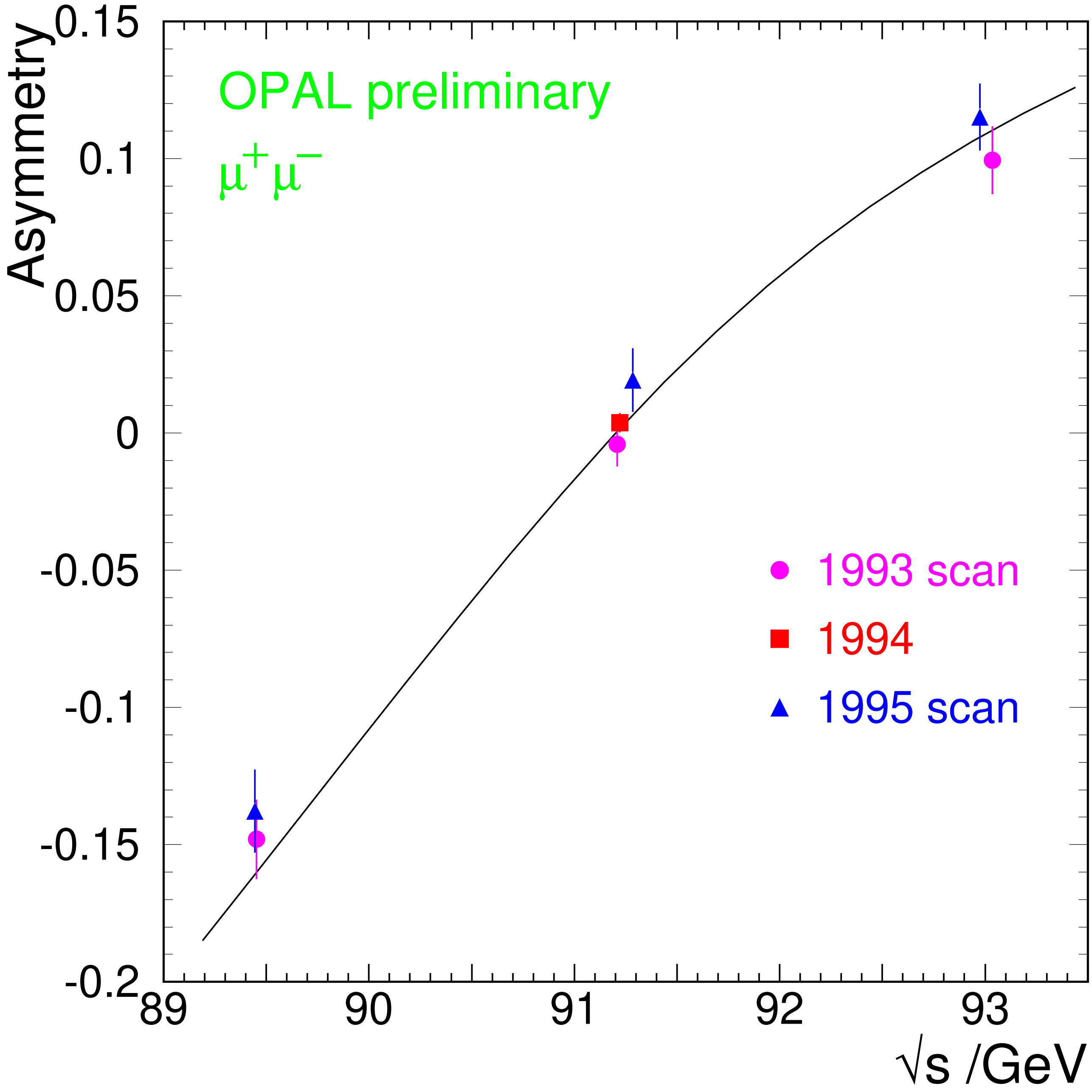
Asymmetry Measurements



Forward–Backward Asymmetry: $A_{fb} = \frac{\sigma_f - \sigma_b}{\sigma_f + \sigma_b}$

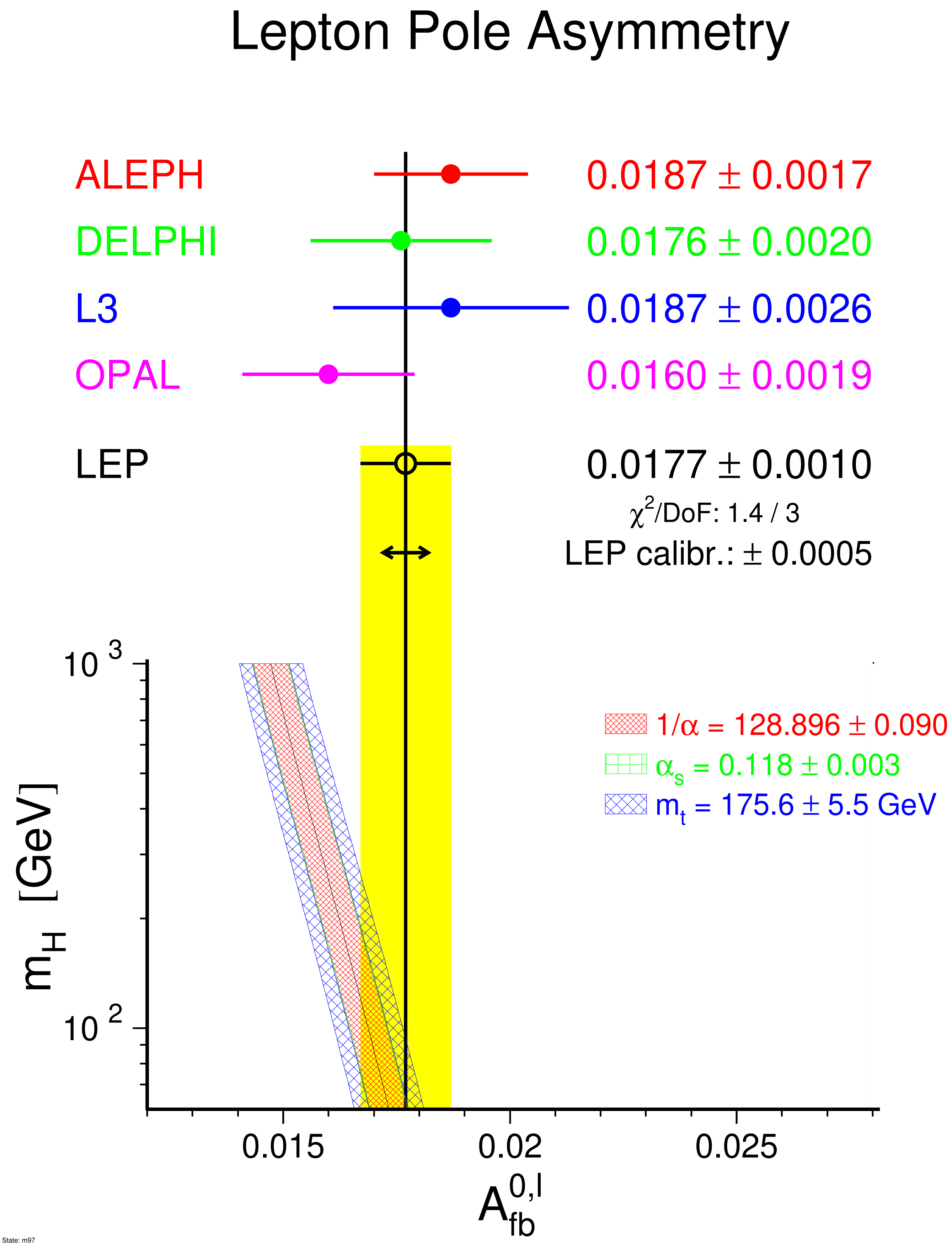


Asymmetry Measurements



Combine all measurements to obtain the pole asymmetry, $A_{fb}^{0,\ell}$:

$$A_{fb}^{0,\ell} = \frac{3}{4} A_e A_\ell \,, \qquad A_\ell = \frac{2\overline{g}_A^\ell \overline{g}_V^\ell}{(\overline{g}_A^\ell)^2 + (\overline{g}_V^\ell)^2}$$



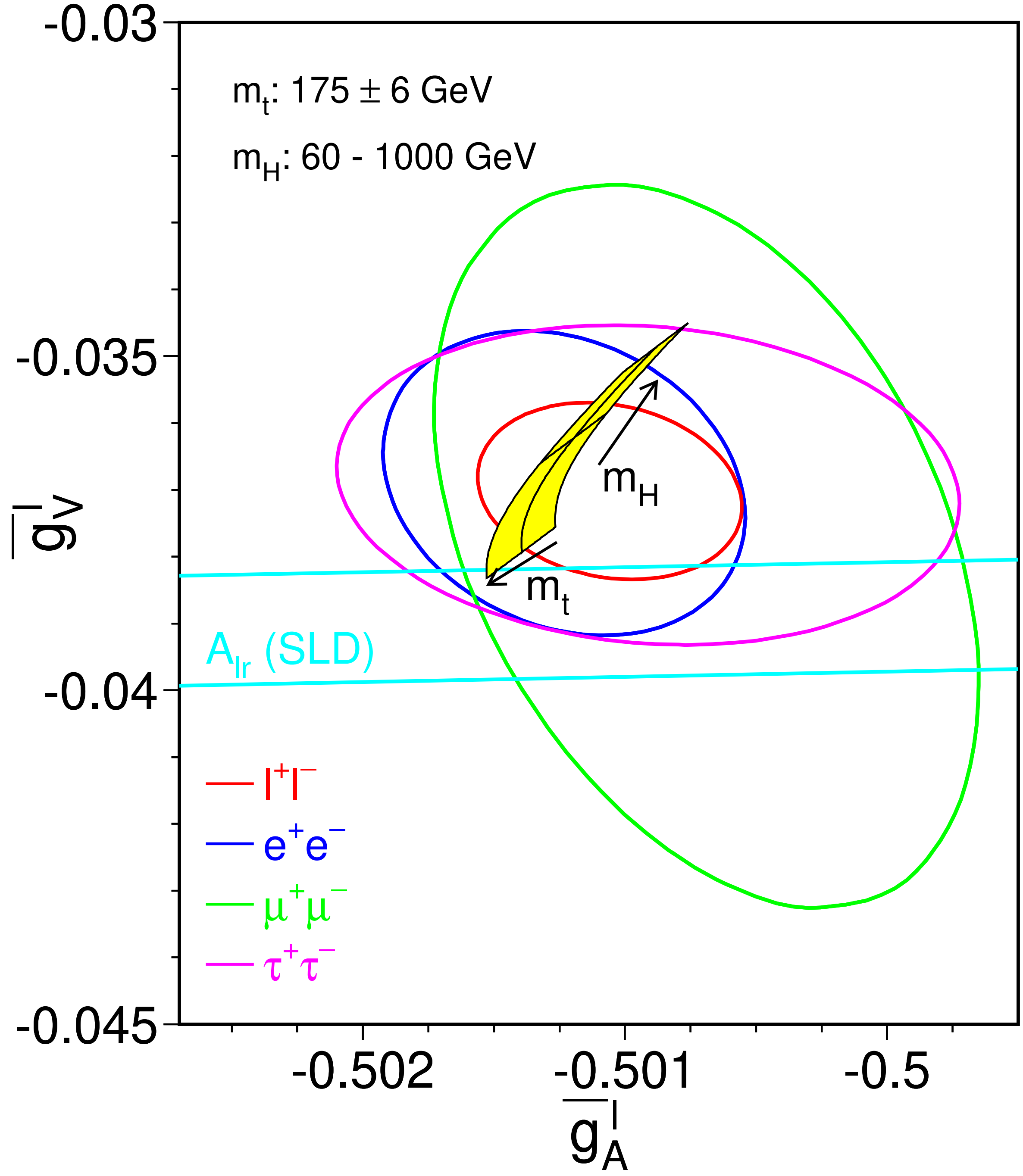
Lepton Pole Asymmetry
ALEPH
0.0187 ± 0.0017
DELPHI
0.0176 ± 0.0020
L3
0.0187 ± 0.0026
OPAL
0.0160 ± 0.0019
LEP
0.0177 ± 0.0010
χ²/DoF: 1.4 / 3
LEP calibr.: ± 0.0005
1/α = 128.896 ± 0.090
αs = 0.118 ± 0.003
mt = 175.6 ± 5.5 GeV
10 3
10 2
mH [GeV]
0.015
0.02
0.025
A fb 0,l
State: m97

Effective Lepton Couplings to the Z-Boson

Cross sections: $\Gamma_\ell \propto (\overline{g}_A^\ell)^2 + (\overline{g}_V^\ell)^2$

Asymmetries: $A_\ell = \frac{2\overline{g}_A^\ell \overline{g}_V^\ell}{(\overline{g}_A^\ell)^2+(\overline{g}_V^\ell)^2}$

$$A_{fb}^{0,\ell} = \frac{3}{4} A_e A_\ell, \qquad \mathcal{P}_\tau(\cos\theta) = f(A_e, A_\tau)$$

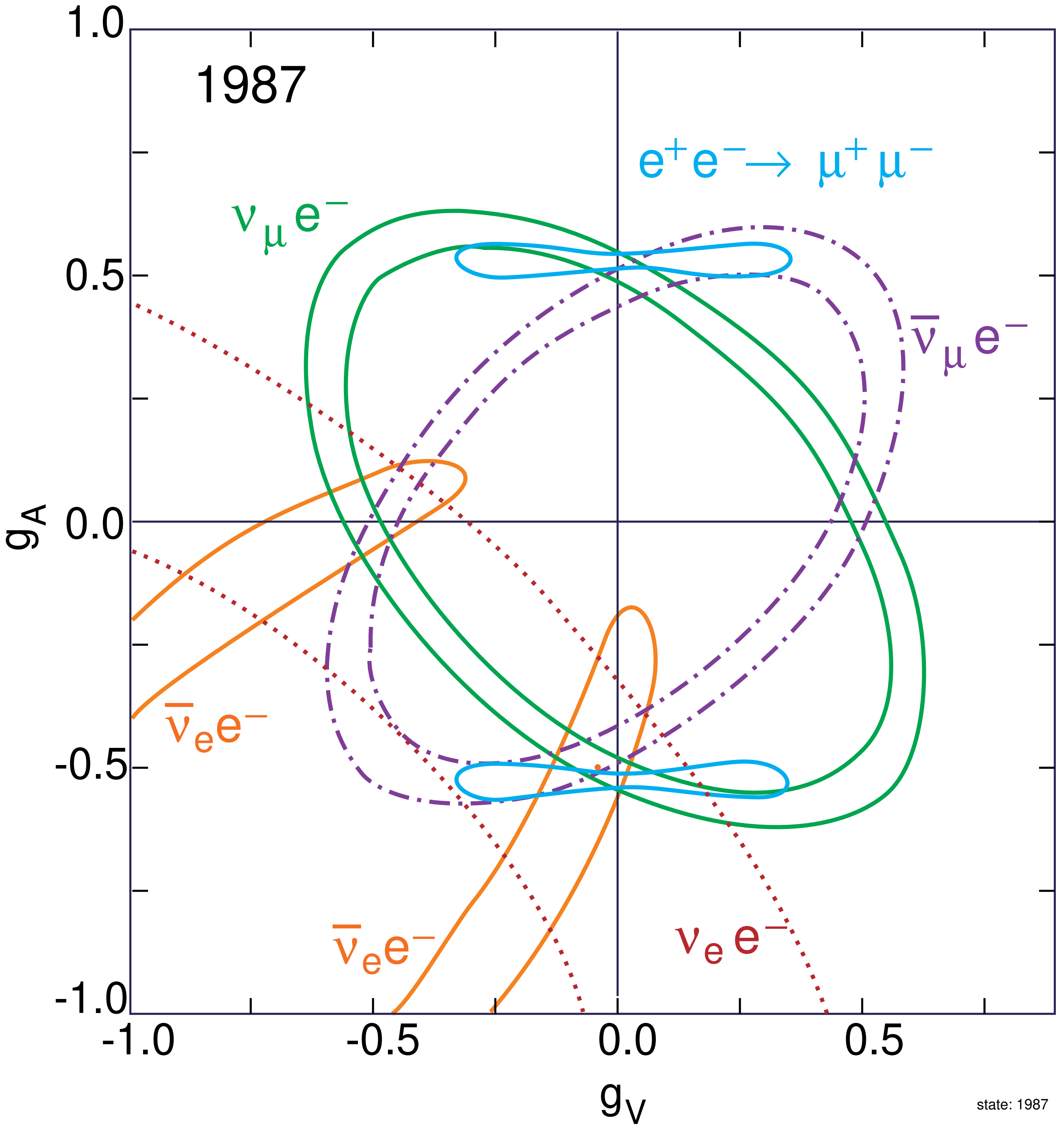


LEP effective lepton couplings:

$$\overline{g}_A^{\ell} = -0.50106 \pm 0.00033$$

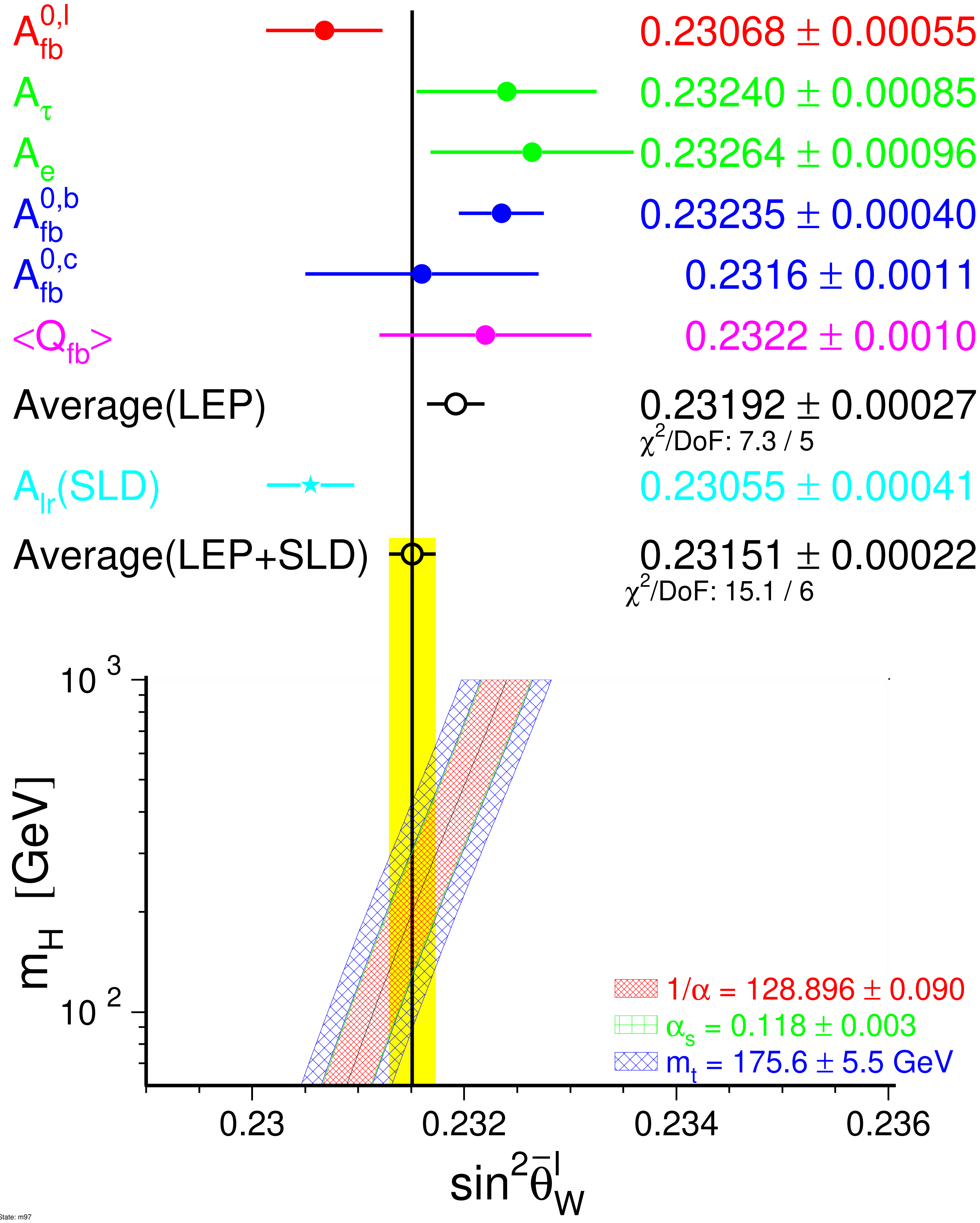
$$\overline{g}_V^{\ell} = -0.03703 \pm 0.00087$$

The situation 1987 before LEP



Effective Electroweak Mixing Angle

$\sin^2\bar{\theta}^l_W = 1/4\,(1 - (\bar{g}^l_V / \bar{g}^l_A)^2)$



The Standard Model is parametrised by:

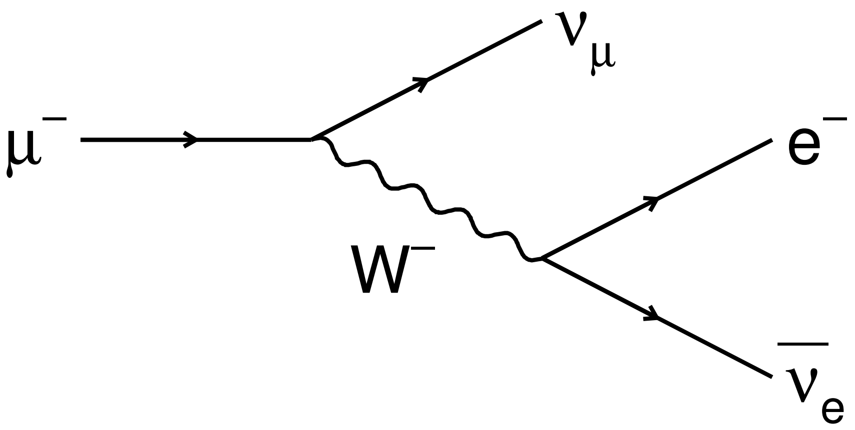
- electromagnetic and strong coupling (α, α_s)
- boson masses (m_Z, m_W, m_H)
- fermion masses (i.e. m_t) + CKM matrix

Constrain m_W by Fermi coupling constant, G_F:

$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}} \frac{m_Z^2}{m_W^2(m_Z^2 - m_W^2)} \frac{1}{1 - \Delta r}$$

G_F is precisely measured in the muon decay:

$$G_F = (1.16639 \pm 0.00002) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$

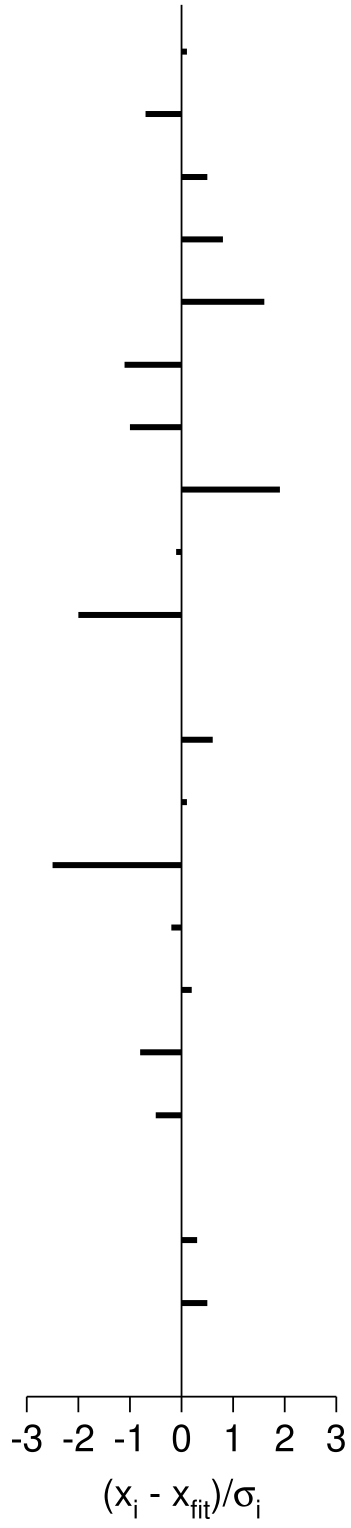


Use also α from low energy measurements:

$$1/\alpha(m_Z^2) = 128.896 \pm 0.090$$

Input Data to Standard Model Fits

	Measurement	$(x_i - x_{fit})/\sigma_i$
m_Z [GeV]	91.1863 ± 0.0019	0.1
Γ_Z [GeV]	2.4947 ± 0.0026	-0.7
σ_{had}^{0} [nb]	41.489 ± 0.055	0.5
R_l	20.783 ± 0.029	0.8
$A_{fb}^{0,l}$	0.0177 ± 0.0010	1.6
A_τ	0.1401 ± 0.0067	-1.1
A_e	0.1382 ± 0.0076	-1
R_b	0.2179 ± 0.0011	1.9
R_c	0.1720 ± 0.0056	-0.1
$A_{fb}^{0,b}$	0.0985 ± 0.0022	-2
$A_{fb}^{0,c}$	0.0734 ± 0.0048	0
$\sin^2\bar{\theta}_W^l$	0.2322 ± 0.0010	0.6
m_W [GeV]	80.28 ± 0.14	0.1
$\sin^2\bar{\theta}_W^l$	0.23055 ± 0.00041	-2.5
R_b	0.2152 ± 0.0038	-0.2
R_c	0.1756 ± 0.0181	0.2
A_b	0.897 ± 0.047	-0.8
A_c	0.623 ± 0.085	-0.5
m_W [GeV]	80.37 ± 0.10	0
$1-m_W^2/m_Z^2$	0.2244 ± 0.0042	0.3
m_t [GeV]	175.6 ± 5.5	0.5



Use data from:

LEP, SLD, $p\bar{p}$ and νN

Use LEP data and G_F and α measurements:

$\alpha_s(m_Z^2)$	0.122 ± 0.003
m_t [GeV]	$155\ ^{+15}_{-11}$
m_W [GeV]	80.285 ± 0.045
m_H [GeV]	$70\ ^{+147}_{-40}$
χ^2/DoF	10 / 9

Comments:

- fit result for m_t agrees with direct measurements:

  $m_t = 175.6 \pm 5.5$ GeV CDF/DØ

- fit result for m_W is in agreement with the direct measurements:

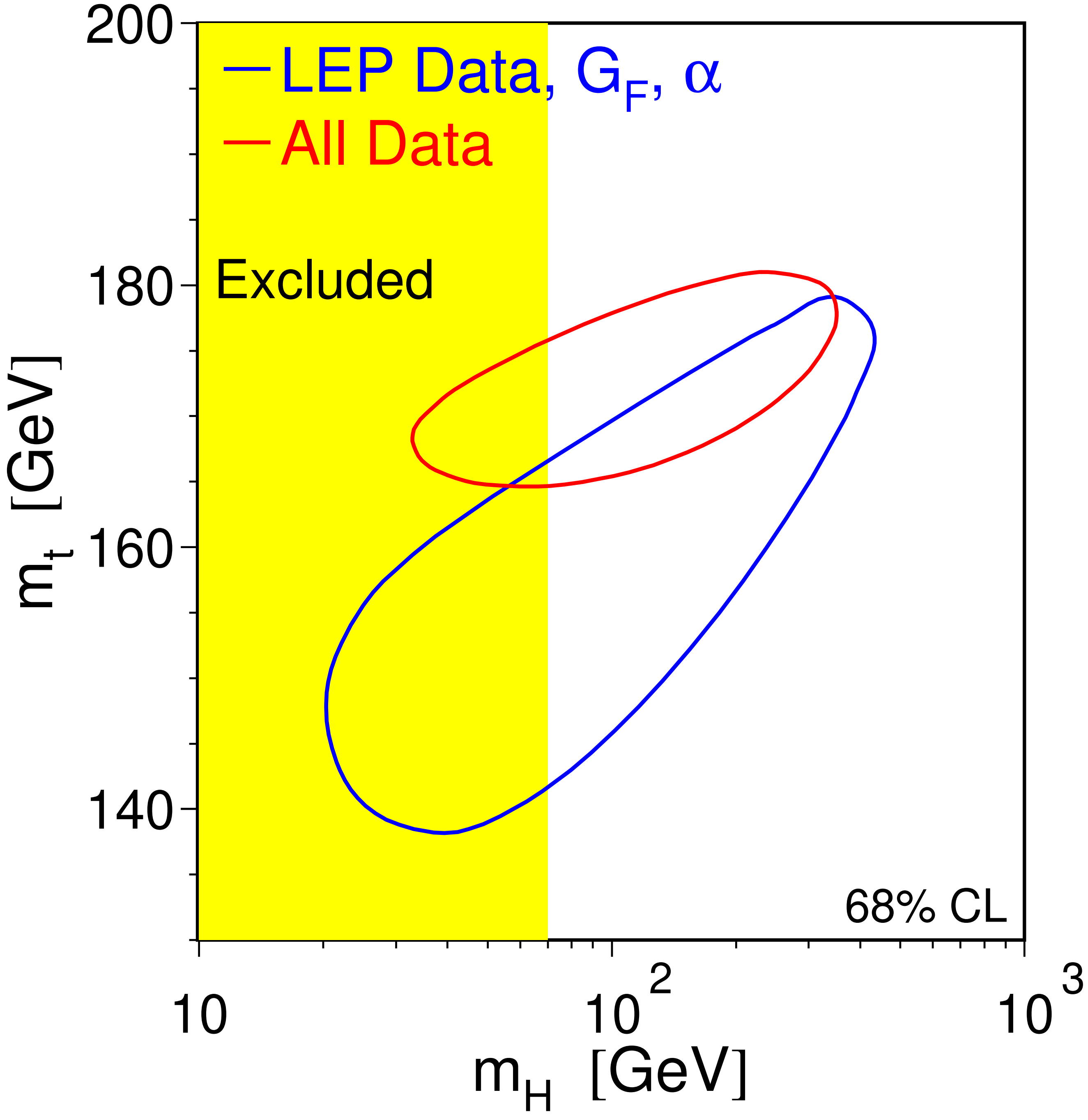
  $m_W = 80.38 \pm 0.14$ GeV LEP2

  $m_W = 80.37 \pm 0.10$ GeV CDF/DØ

- fit error on m_W is significantly smaller than error from direct measurements

Attention:
m_H enters in radiative corrections as $\log(m_H)$,
while m_t enters as m_t^2
Using all data:

$$m_H = 127^{+127}_{-72}\ \text{GeV}$$



Conclusion

LEP is a great success:

- Z mass measured:
  $m_Z = 91186.3 \pm 1.9$ MeV
- lepton couplings measured:
  $\sin^2\overline{\theta}^{\ell}_{W} = 0.23192 \pm 0.00027$
- lepton universality is confirmed
- 3 light neutrino species
- α_s measured:
  $\alpha_s = 0.122 \pm 0.003$
  with comparable precision as PDG.
- m_t predicted by LEP in agreement with CDF/DØ
- limits on m_H:
  $70\ \mathrm{GeV} < m_H < 465\ \mathrm{GeV}$ (95% CL)
- no further improvement on m_Z, Γ_Z expected

The Standard Model is irresistible !