Precision Electroweak Experiments at LEP

Joachim Mnich

CERN PPE

IInd Rencontres du Vietnam

Ho Chi Minh City (Saigon)

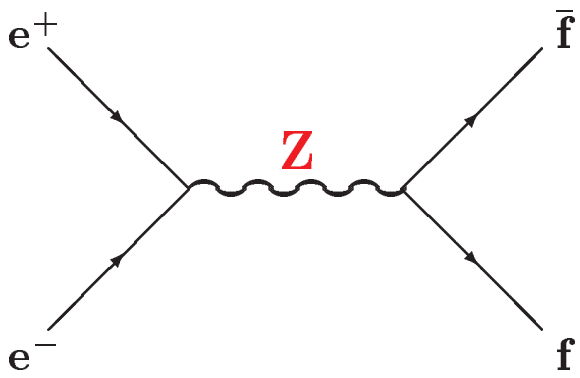
October 22, 1995

Outline:

- LEP operation 1989 – 1995
- Total cross section at the Z resonance
- Mass, total and partial widths
- Asymmetries at the Z
- The weak mixing angle $\sin^2\bar{\vartheta}_{\mathrm{W}}$ and the coupling constants of charged leptons $\bar{g}_{\mathrm{A}}$, $\bar{g}_{\mathrm{V}}$
- Constraints on the Standard Model
- Outlook

LEP I 1989-1995

First part of LEP physics program ($\sqrt{s} \approx m_Z$) finished October 4, 1995



≈ 16 million Z decays

observed by the four LEP experiments
ALEPH, DELPHI, L3, OPAL

From now on the Z will be background!

November 1995: $\sqrt{s} = 140$ GeV

$\geq$ 1996: Start of LEP II

$e^+e^- \rightarrow W^+W^-$

1989 Pilot run

1990/91 Two 7 point scans of the Z resonance

1992 On peak running

1993 3 point scan with precise E_{b} calibration

1994 On peak running

1995 Another 3 point energy scan

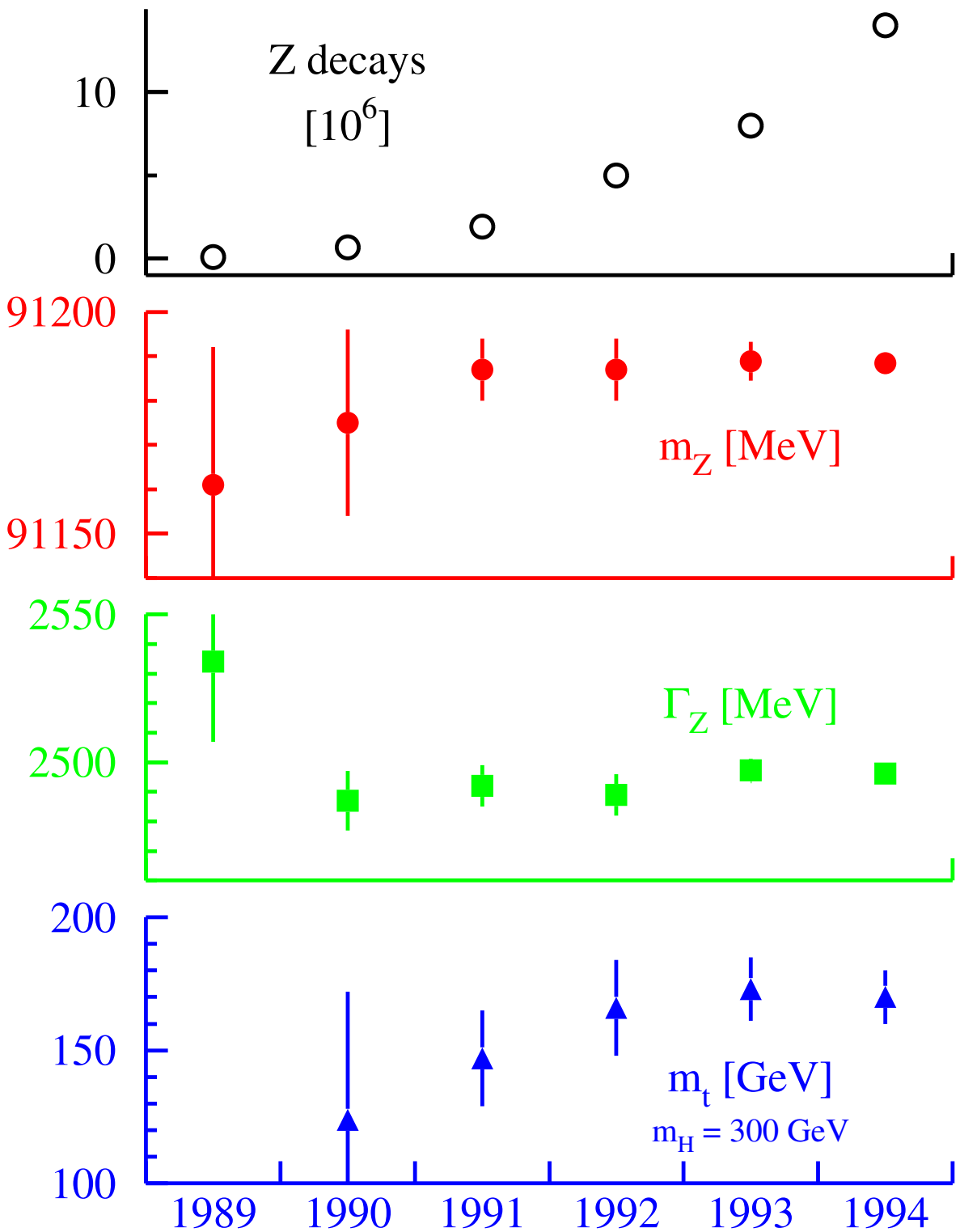
Data 1989-92 are final

Many preliminary results from 1993/94, e.g. σ, A_{FB}^{ℓ}, are available and included,

12.4 million hadronic and 1.3 million leptonic Z decays

Progress in precision with time

e.g. m_Z, Γ_Z and m_t from the LEP experiments:



Precision measurements at the Z resonance:

Large data samples
+ good understanding of detectors
+ clean enviroment at e^+e^- collider

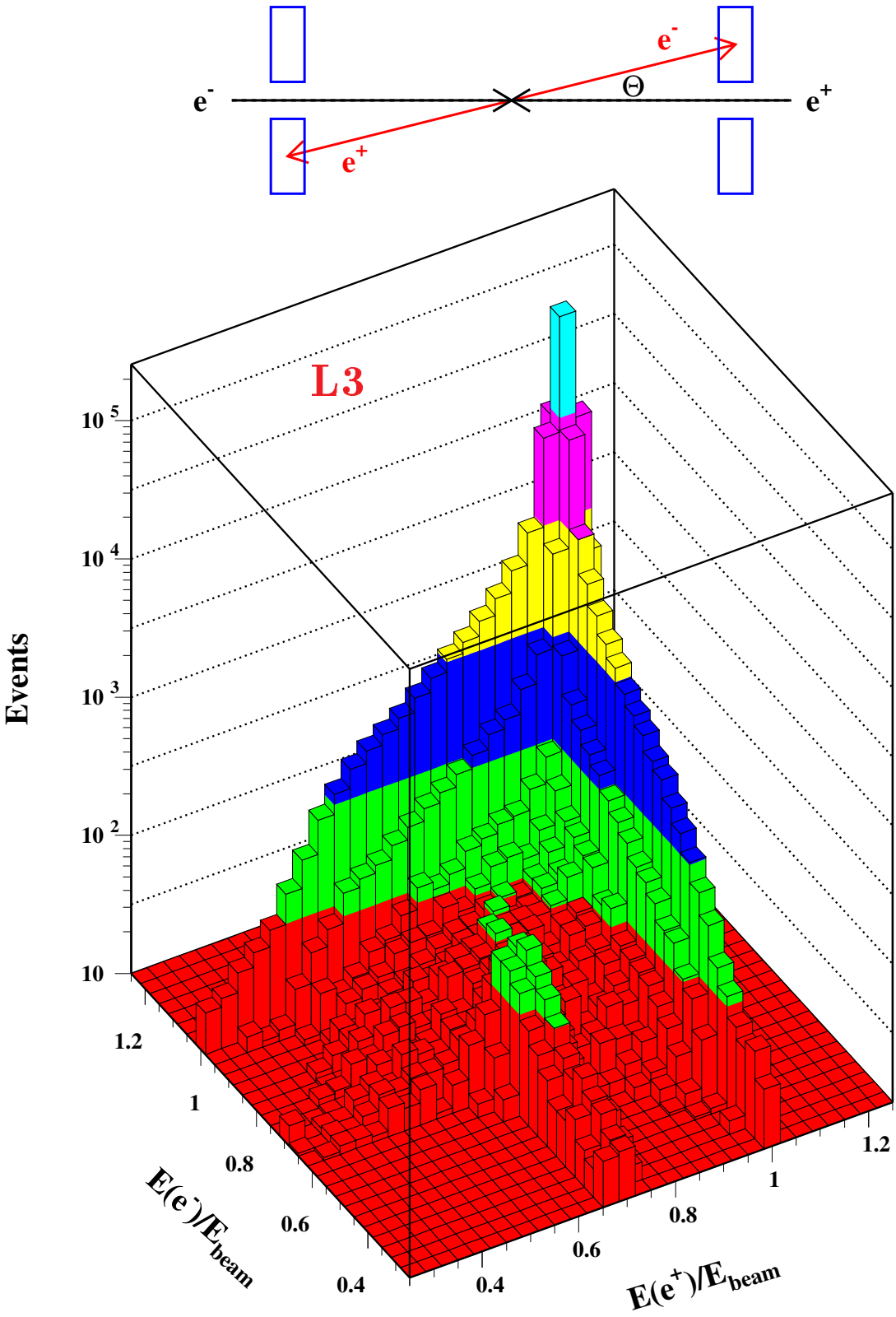
$\Rightarrow$ small systematic errors

prel. sys. errors 1993/94		
	$\Delta\sigma$	ΔA_{FB}
hadrons	0.07 – 0.2%	—
e^+e^-	0.2 – 0.5%	0.0016 – 0.004
$\mu^+\mu^-$	0.15 – 0.6%	0.001 – 0.002
$\tau^+\tau^-$	0.3 – 1.5%	0.002 – 0.006
$\mathcal{L}_{exp}$	0.08 – 0.21%	—

0.16% theoretical systematic error on luminosity measurement, common to all experiments

Leptonic cross section and asymmetries still profit from increase in statistics

Measurement of luminosity with small angle Bhabha scattering:



Measurements of total cross sections

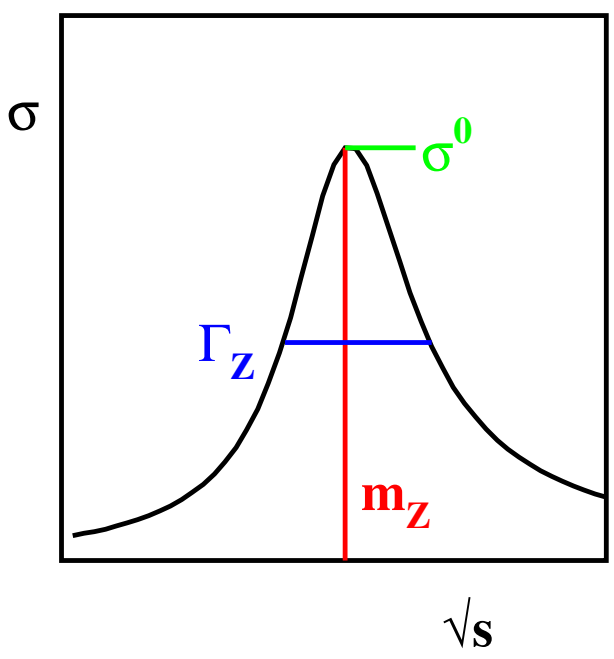
$e^+e^- \to$ hadrons $\qquad e^+e^- \to e^+e^-$

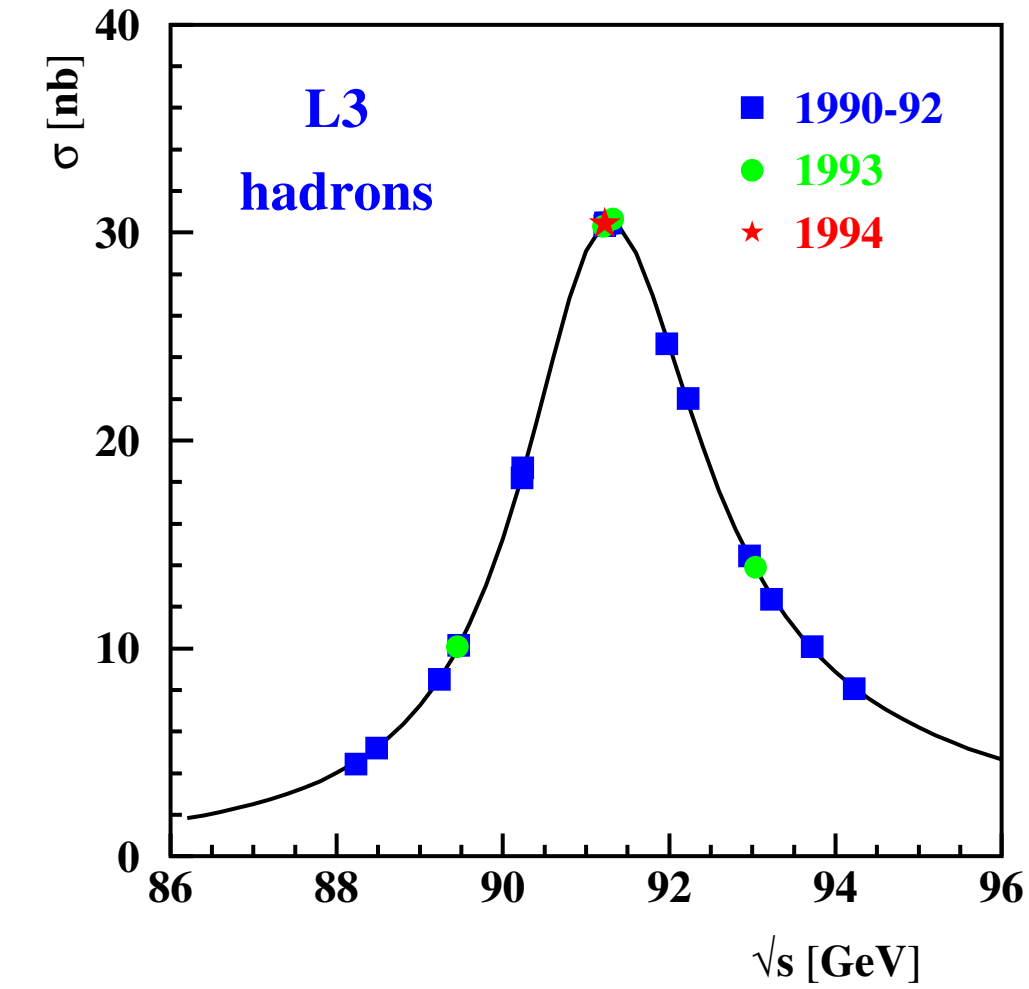
$e^+e^- \to \mu^+\mu^- \qquad e^+e^- \to \tau^+\tau^-$

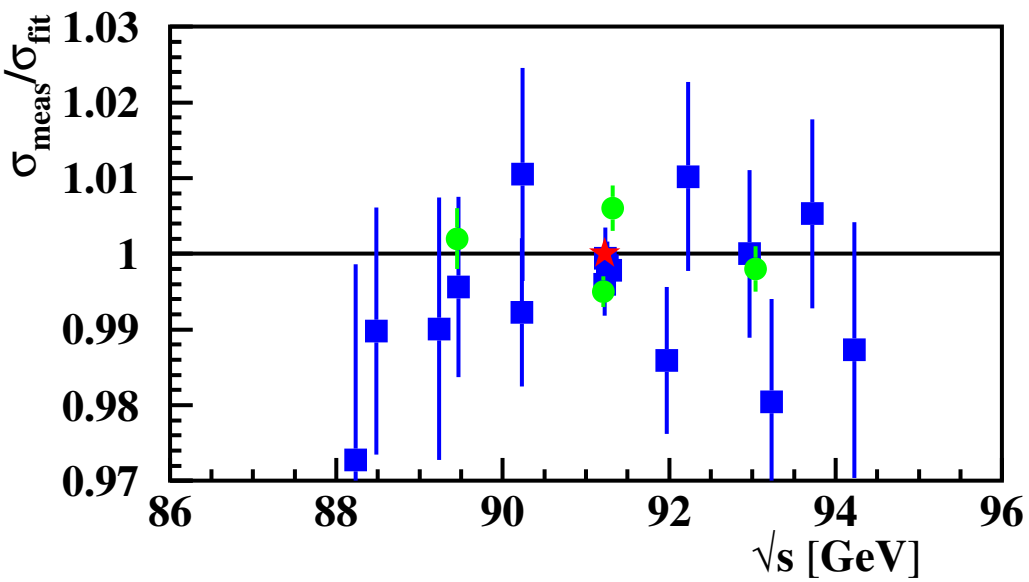
at $\sqrt{s} \approx m_Z$ determine:

- Z mass m_Z
- total width Γ_Z
- partial width Γ_f:

$$\sigma_f^0(m_Z) = \frac{12\,\pi}{m_Z^2} \cdot \frac{\Gamma_e\,\Gamma_f}{\Gamma_Z^2} \qquad \text{(lowest order)}$$




L3
hadrons
1990-92
1993
1994
σ [nb]
40
30
20
10
0
86
88
90
92
94
96
√s [GeV]


σmeas/σfit
1.03
1.02
1.01
1
0.99
0.98
0.97
86
88
90
92
94
96
√s [GeV]

Precise determination of LEP beam energy E_{b}

- calibration runs with transversally polarized electrons (positrons)
- destruction of polarization by external RF magnet

$$E_{\mathrm{b}} = \frac{2}{g_{\mathrm{e}} - 2} m_0 c^2 \nu_s$$

$$= 440.6486(1)\ \mathrm{MeV} \cdot \nu_{\mathrm{s}}$$

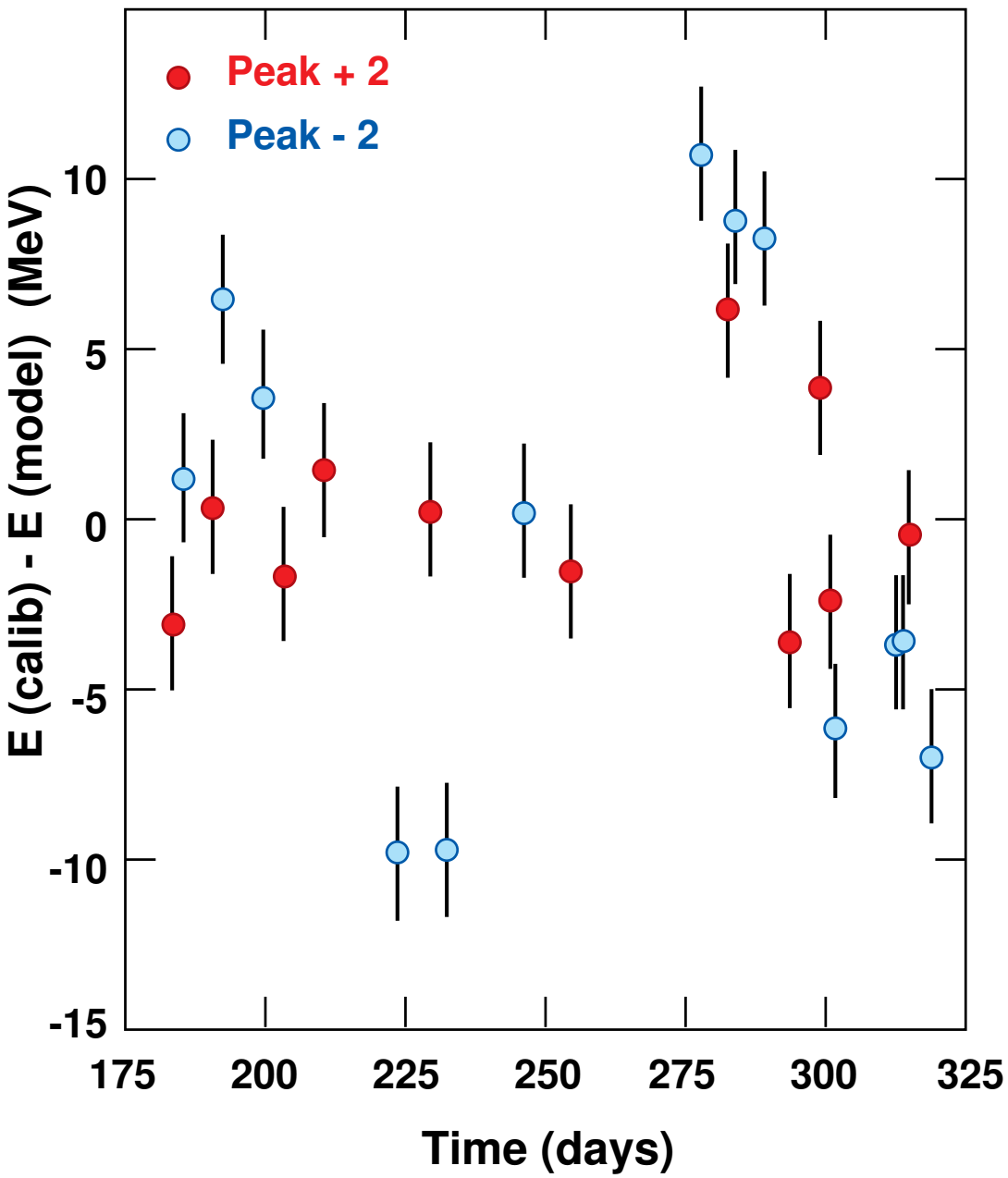
ν_s: number of precessions over one turn in LEP,
e.g. $\nu_s = 101.48\ldots$ at $\sqrt{s} \approx m_{\mathrm{Z}} - 2$

$$\Rightarrow \frac{\Delta E_{\mathrm{b}}}{E_{\mathrm{b}}} < 10^{-5}$$

Model for E_{b} during luminosity run

$$E_{\mathrm{b}} = f(B_{\mathrm{mag}}, T_{\mathrm{mag}}, \text{tides, RF, } \ldots)$$

1993: Energy calibrations at $m_Z \pm 2$ GeV
Residual of center-of-mass energy

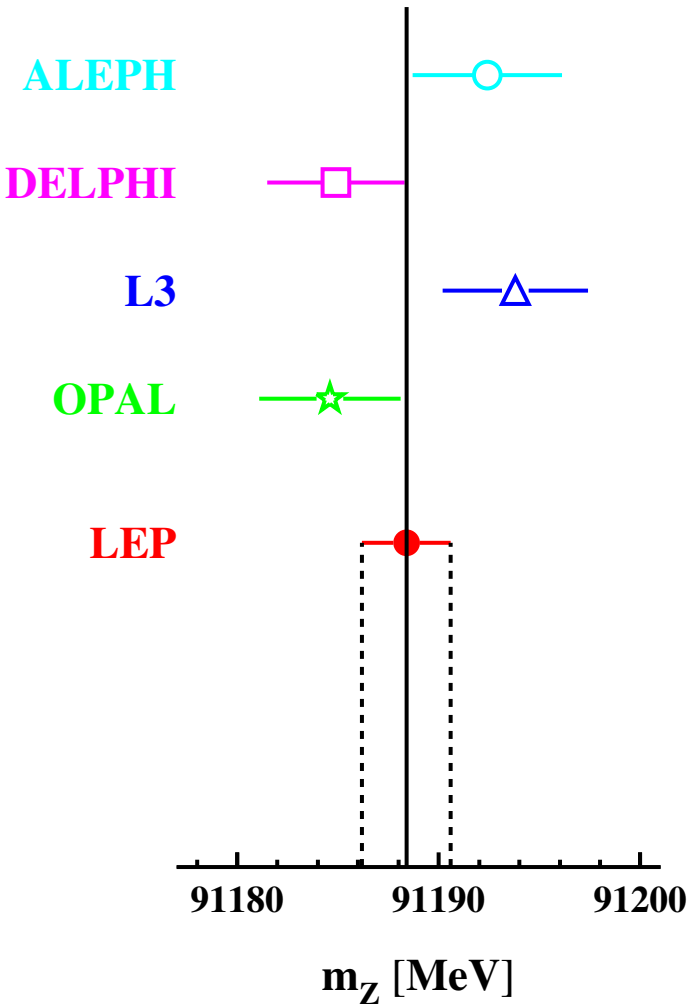


Error contribution to mass and total width:

$$\Delta m_Z = 1.5 \text{ MeV}$$

$$\Delta \Gamma_Z = 1.7 \text{ MeV}$$

Z mass



ALEPH 91 192.4 ± 3.7 MeV

DELPHI 91 184.9 ± 3.4 MeV

L3 91 193.8 ± 3.6 MeV

OPAL 91 184.6 ± 3.5 MeV

LEP 91 188.4 ± 2.2 MeV

common 1.5 MeV

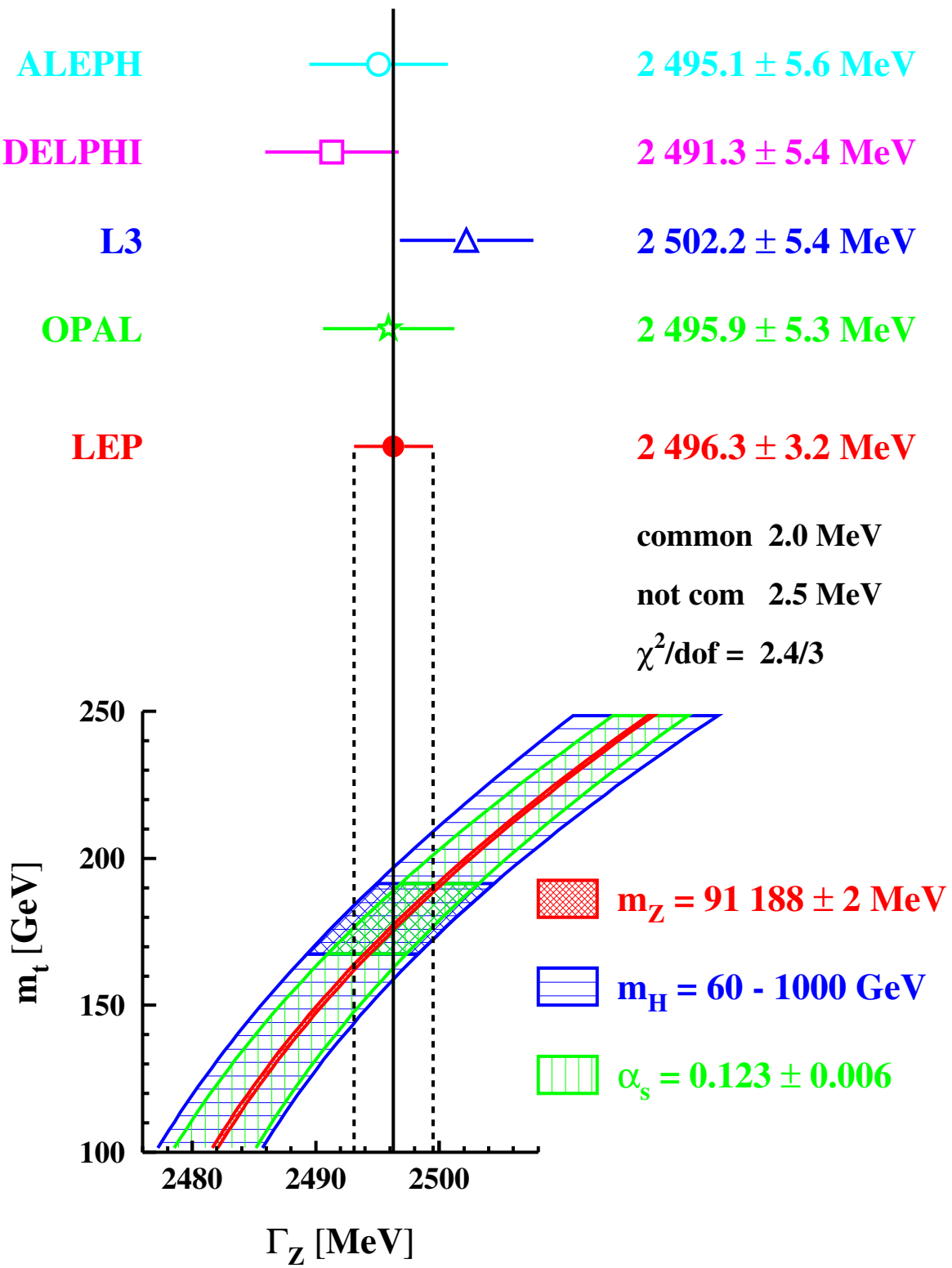
not com 1.6 MeV

χ^2/dof = 6.9/3

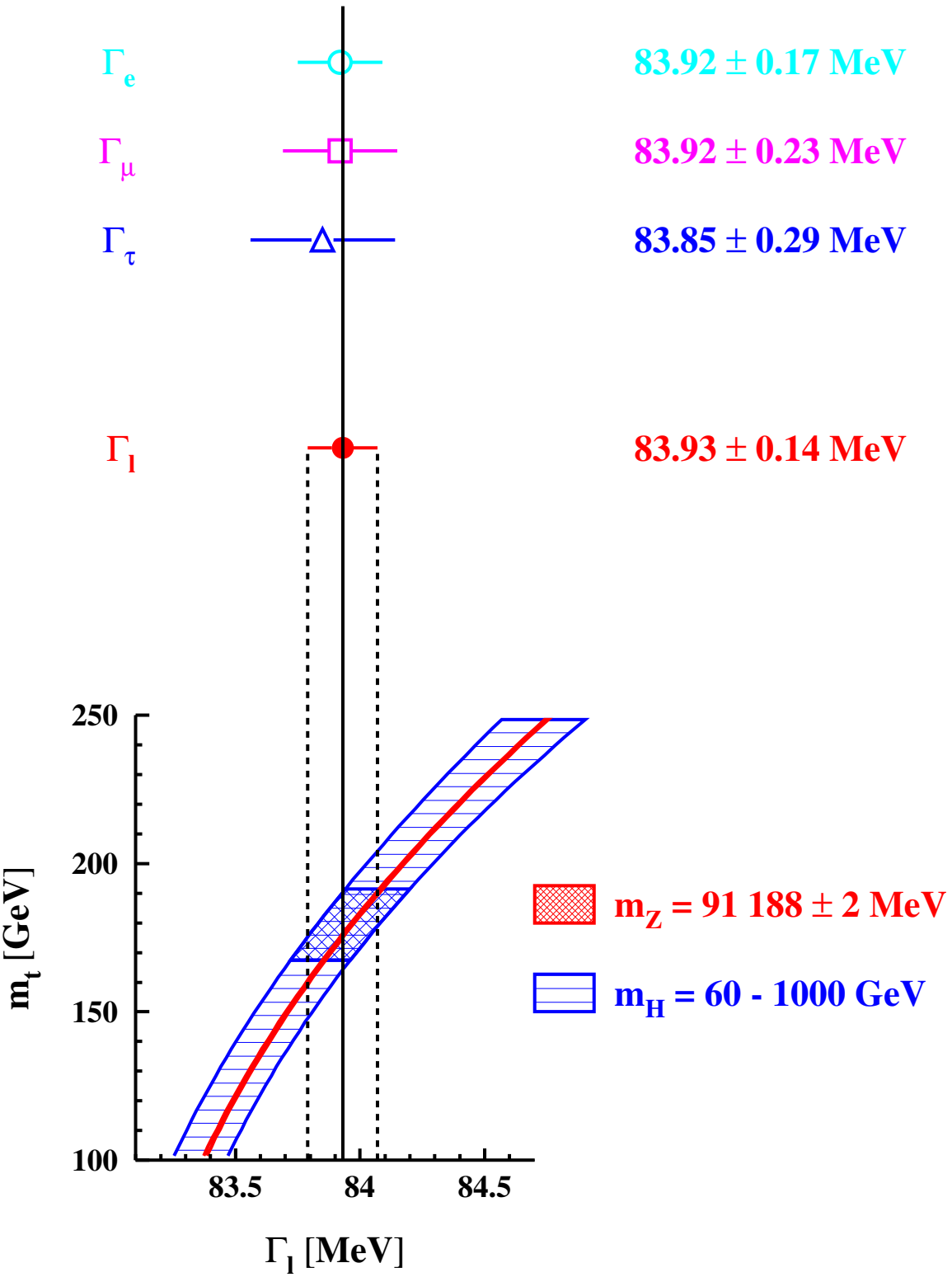
$$\frac{\Delta m_Z}{m_Z} = 2.4 \cdot 10^{-5}$$

Same precision as Fermi constant G_F

Total width Γ_Z



LEP averages of leptonic widths



Ratio of hadronic to leptonic width:

$$R_\ell = \frac{\Gamma_{\mathrm{had}}}{\Gamma_\ell} \approx \frac{\sigma_{\mathrm{had}}}{\sigma_\ell}$$

- Independent of luminosity
- Only weak dependence on m_{t}, m_{H}
- Allows measurement of α_{s}
  (QCD corrections to $\mathrm{e^+e^-} \to$ hadrons)

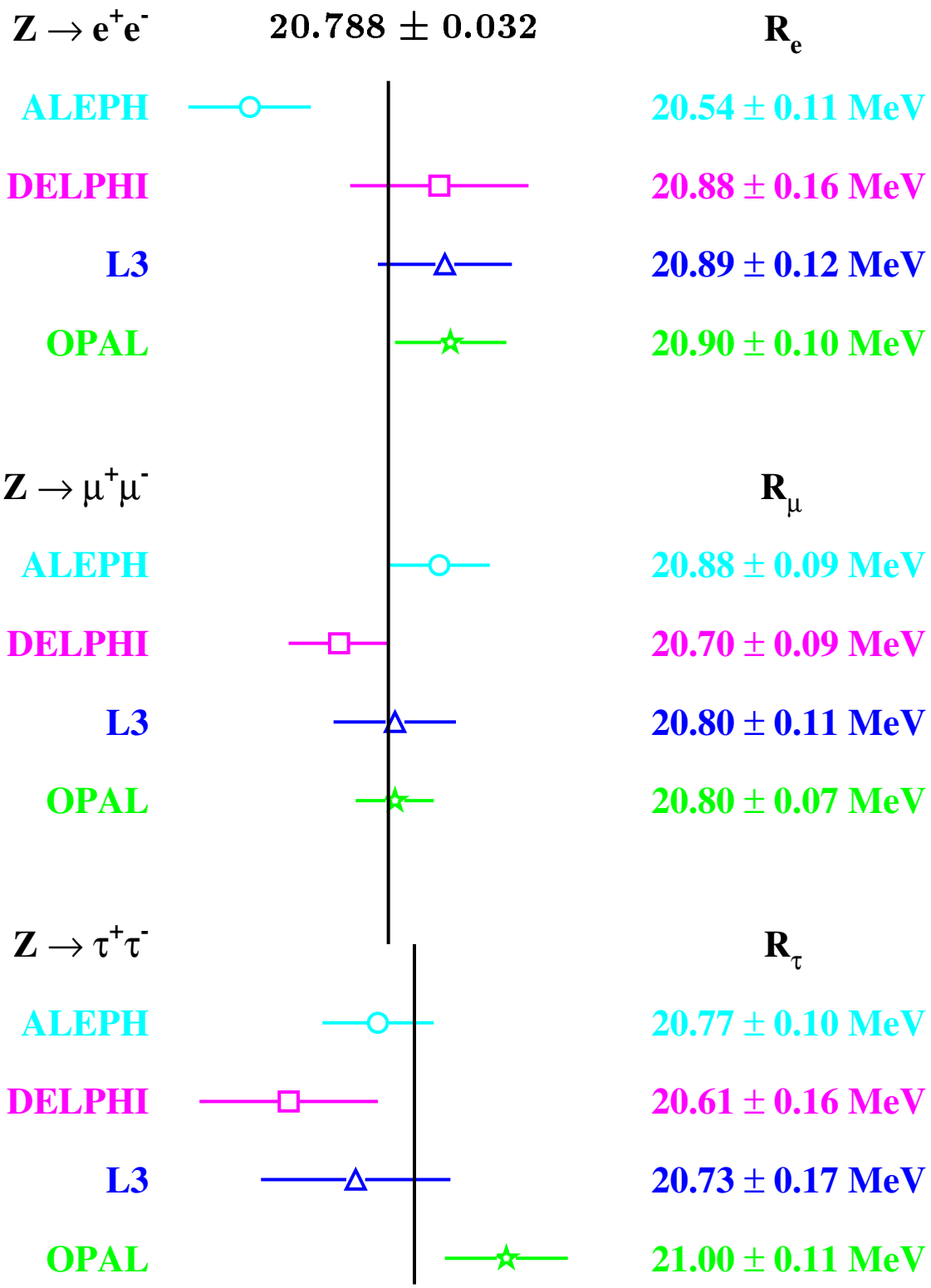
$$R_\ell = 20.788 \pm 0.032 \qquad (0.15\%)$$

$$\Longrightarrow \alpha_{\mathrm{s}}(m_{\mathrm{Z}}) = 0.124 \pm 0.005 \pm 0.005(\mathrm{th})$$

For comparison $\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$ from topology of hadronic Z decays (3-jet events):

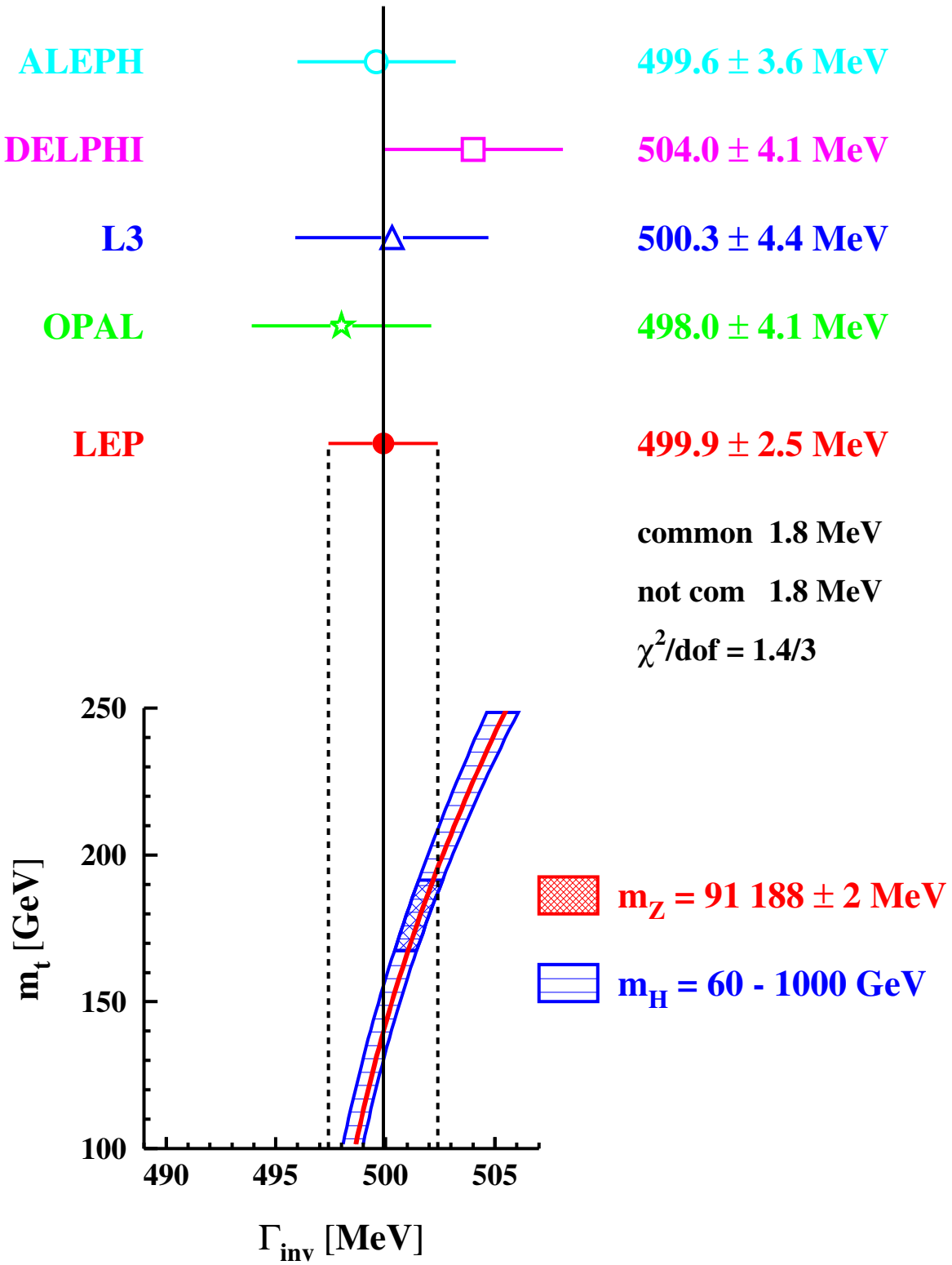
$$\alpha_{\mathrm{s}}(m_{\mathrm{Z}}) = 0.123 \pm 0.006$$

$R_\ell = \Gamma_{had}/\Gamma_\ell$



$\chi^2/\text{dof} = 14/11$ (neglecting small correlations)

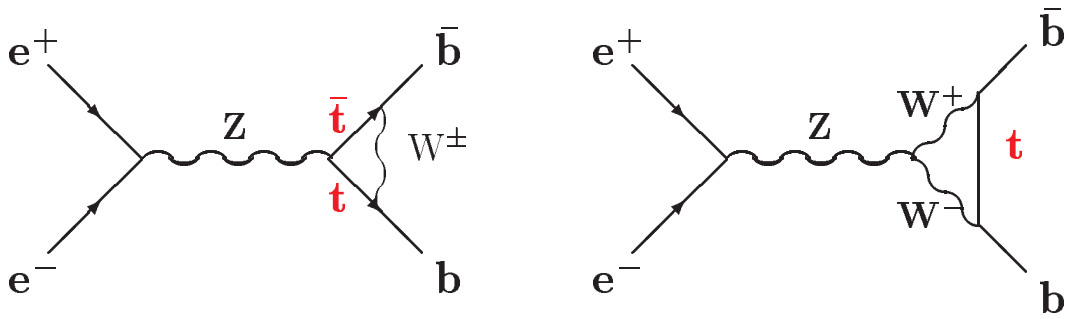
$$\Gamma_{\rm inv} = \Gamma_{\rm Z} - \Gamma_{\rm had} - 3\,\Gamma_{\ell}$$



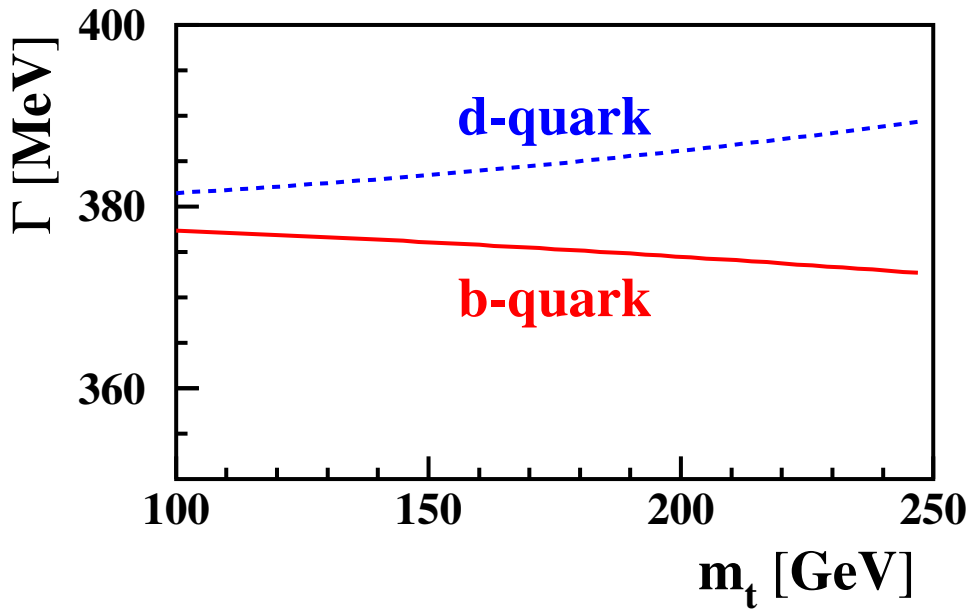
$$N_\nu = 2.991 \pm 0.016$$

$Z \rightarrow b\bar{b}$

Corrections from virtual top-quark exchange:



Modify $Z \rightarrow b\bar{b}$ couplings:

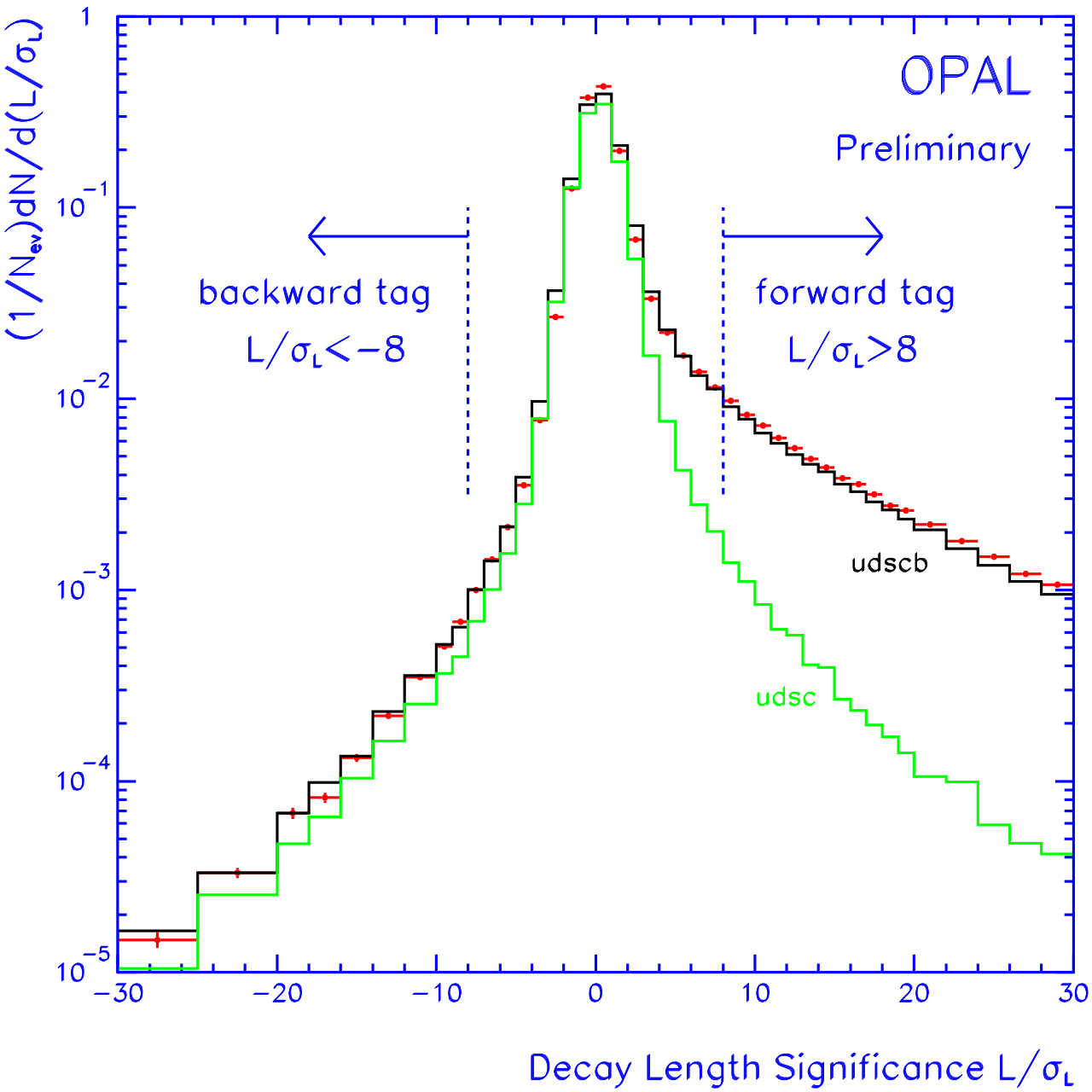


$R_b \equiv \Gamma_b/\Gamma_{had}$ is sensitive to m_t,
but independent of m_H and α_s

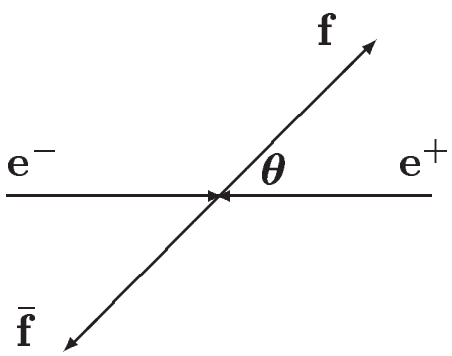
New physics at $Z \rightarrow b\bar{b}$ vertex, coupling to mass?

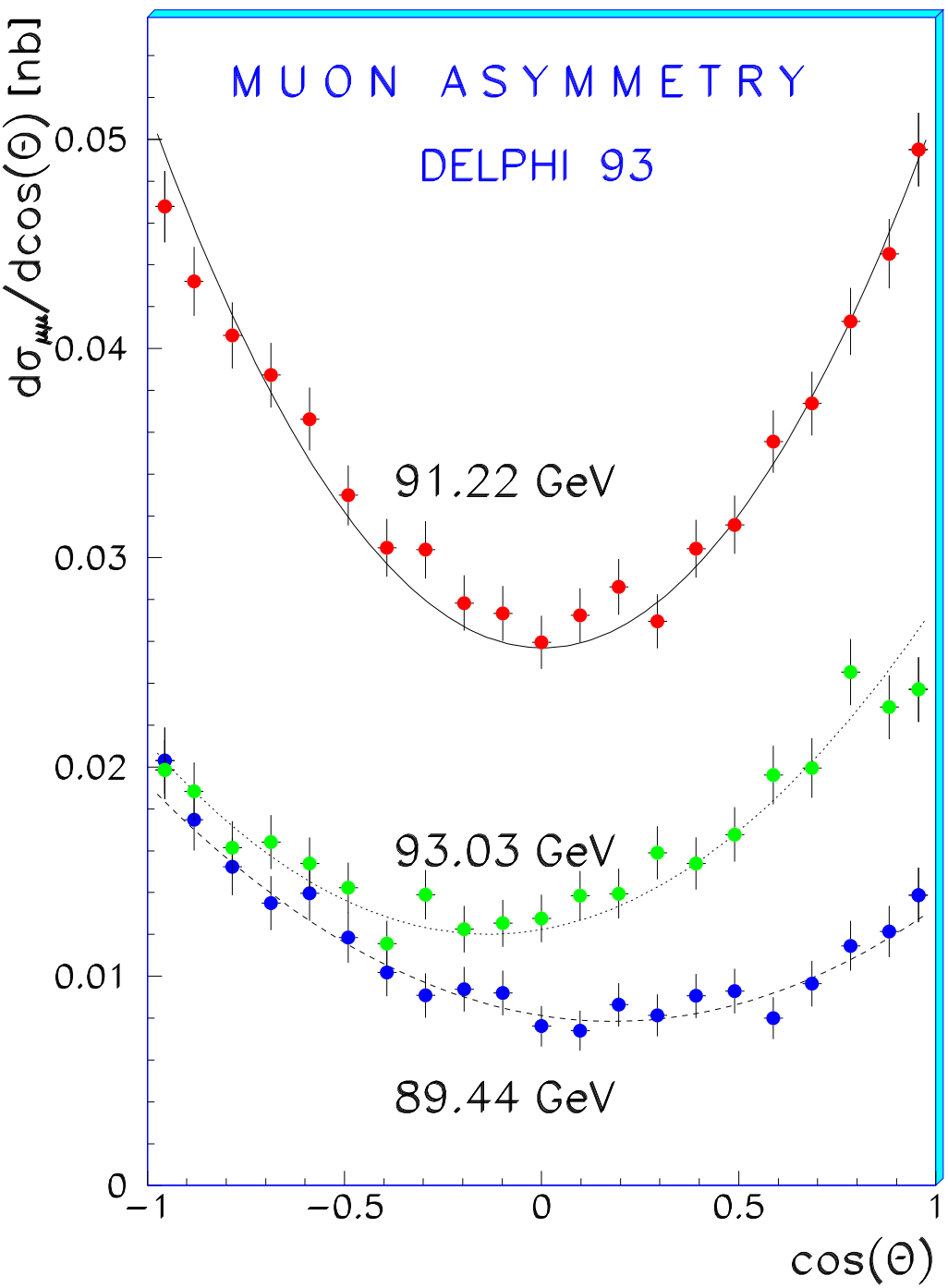
Identification of $Z \to b\bar{b}$ decays:

- **lifetime**
  (impact parameter, secondary vertices)
- **semileptonic decays**
- **event shape**

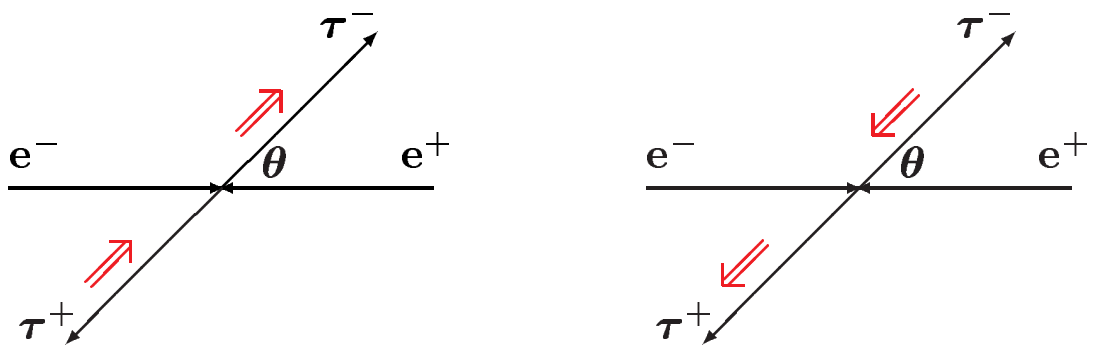


Forward-backward asymmetry A_{FB}:





τ-polarization



$$P_{\tau^-} = \frac{\sigma(\tau_R^-) - \sigma(\tau_L^-)}{\sigma(\tau_R^-) + \sigma(\tau_L^-)}$$

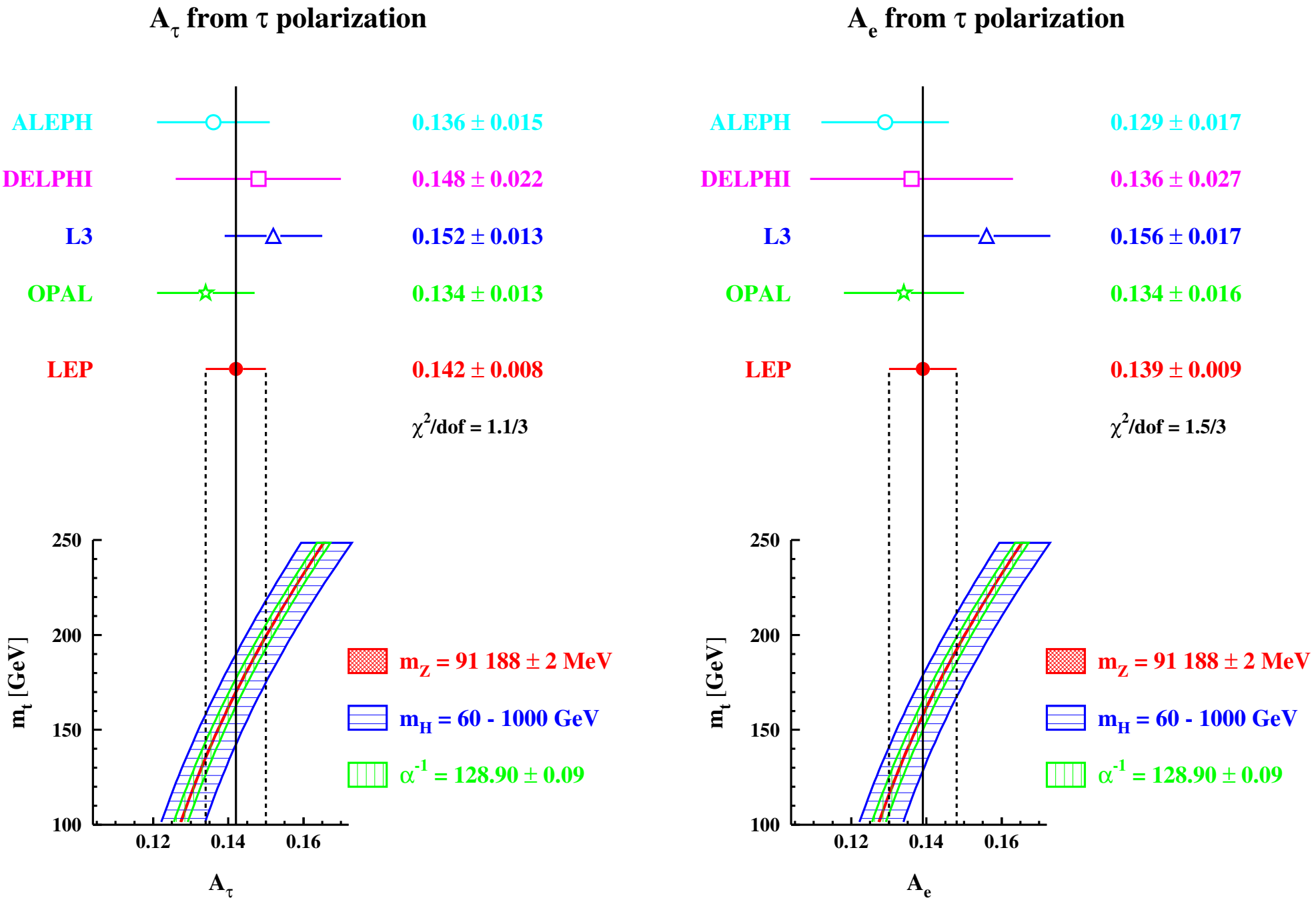
$$= -\frac{2\,\bar{g}_{\rm A}^{\tau}\,\bar{g}_{\rm V}^{\tau}}{\left(\bar{g}_{\rm A}^{\tau}\right)^2 + \left(\bar{g}_{\rm V}^{\tau}\right)^2} \equiv -A_\tau \quad (\sqrt{s} = m_Z)$$

Angular dependence:

$$P_{\tau^-}(\cos\theta) = \frac{(1+\cos^2\theta)\,A_\tau + 2\cos\theta\,A_e}{(1+\cos^2\theta) + 2\cos\theta\,A_\tau A_e}$$

Tau-polarization is derived from the momentum spectra of the decay products

$$\tau \to e,\ \mu,\ \pi,\ \rho,\ a_1 \quad (+\nu)$$



e − τ universality from one reaction

Vector and axial-vector coupling constants of charged leptons:

- **Partial decay widths:**

$$\Gamma_\ell \propto (\bar{g}_{\rm A}^\ell)^2 + (\bar{g}_{\rm V}^\ell)^2$$

- **Forward-backward asymmetry** $(\sqrt{s} = m_{\rm Z})$**:**

$$A_{\rm FB}^\ell = 3\,\frac{\bar{g}_{\rm A}^{\rm e}\bar{g}_{\rm V}^{\rm e}}{(\bar{g}_{\rm A}^{\rm e})^2 + (\bar{g}_{\rm V}^{\rm e})^2}\,\frac{\bar{g}_{\rm A}^{\ell}\bar{g}_{\rm V}^{\ell}}{(\bar{g}_{\rm A}^{\ell})^2 + (\bar{g}_{\rm V}^{\ell})^2}$$

  $A_{\rm FB}(\sqrt{s} \neq m_{\rm Z})$ **solves ambiguity in** $\bar{g}_{\rm V}$ **and** $\bar{g}_{\rm A}$

- **Tau-polarization:**

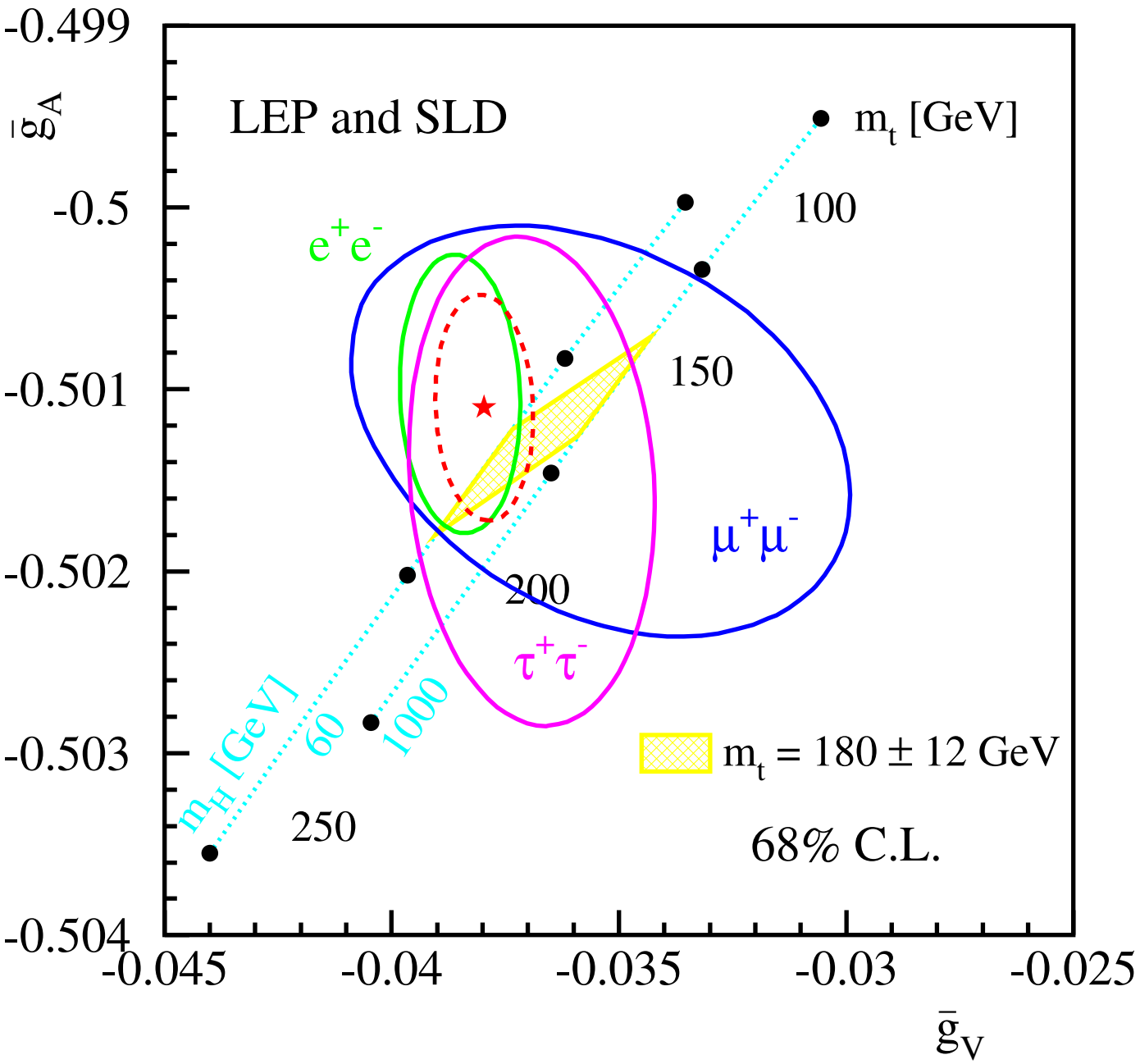
$$A_\tau = 2\,\frac{\bar{g}_{\rm A}^{\tau}\bar{g}_{\rm V}^{\tau}}{(\bar{g}_{\rm A}^{\tau})^2 + (\bar{g}_{\rm V}^{\tau})^2}$$

$$A_{\rm e} = 2\,\frac{\bar{g}_{\rm A}^{\rm e}\bar{g}_{\rm V}^{\rm e}}{(\bar{g}_{\rm A}^{\rm e})^2 + (\bar{g}_{\rm V}^{\rm e})^2}$$

- **From SLD left-right asymmtery**

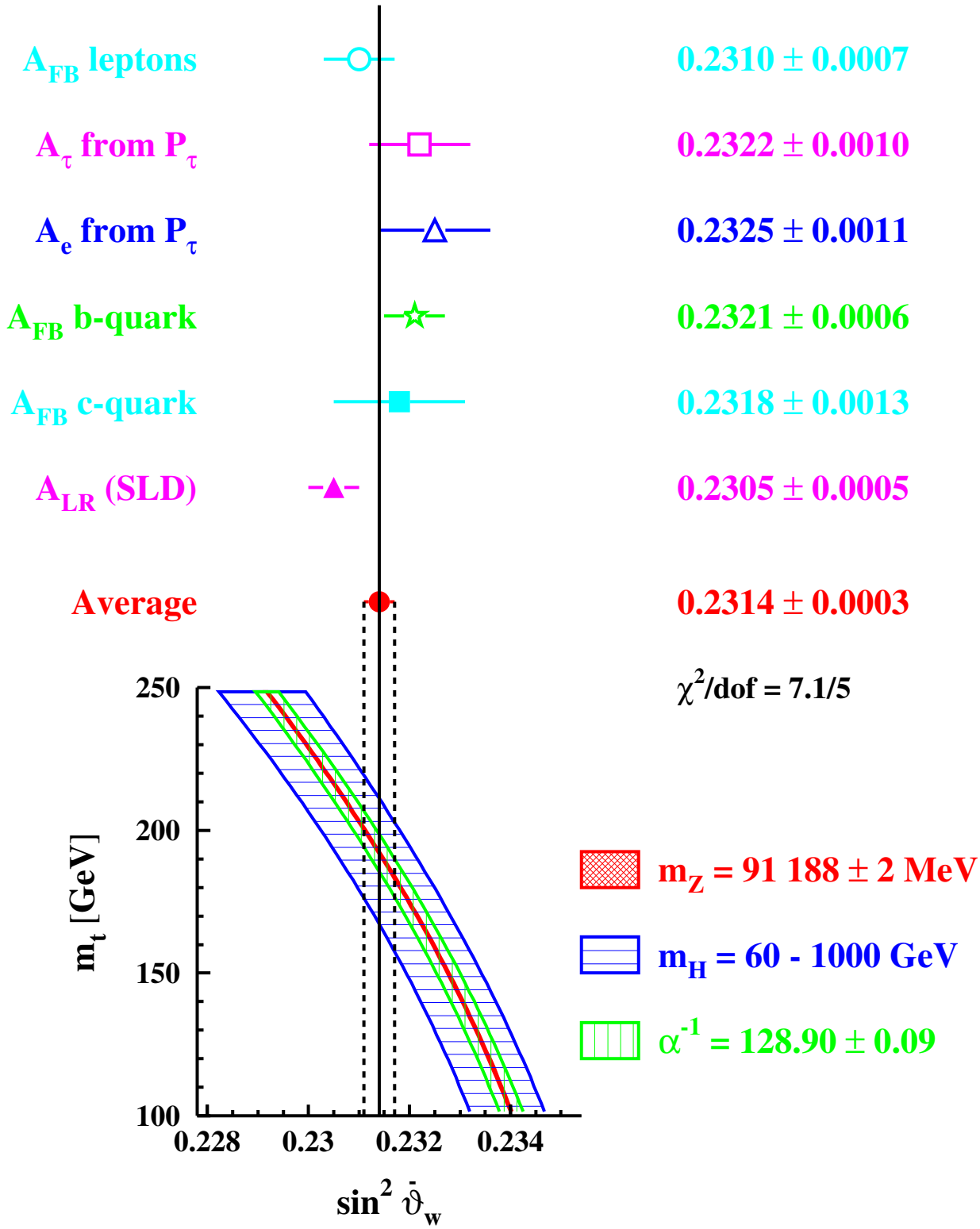
$$A_{\rm LR} = A_{\rm e}$$

$\Longrightarrow$ **Determination of** $\bar{g}_{\rm A}^\ell$ **and** $\bar{g}_{\rm V}^\ell$
Test of lepton universality


LEP and SLD
m_t [GeV]
100
150
200
250
m_H [GeV]
60
1000
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$m_t = 180 \pm 12$ GeV
68% C.L.
$\bar{g}_A$
$\bar{g}_V$
-0.499
-0.5
-0.501
-0.502
-0.503
-0.504
-0.045
-0.04
-0.035
-0.03
-0.025

Effective weak mixing angle $\sin^2\bar{\vartheta}_W$:

$$\frac{\bar{g}_V}{\bar{g}_A} = 1 - 4\,\sin^2\bar{\vartheta}_W$$



Standard model fits:

Using the LEP results on

σ, A_{FB} leptons, b- and c-quark

tau-polarization

R_{b}, R_{c}

$$1/\alpha(m_{\mathrm{Z}}) = 128.896 \pm 0.090$$
$$m_{\mathrm{H}} = 300 \text{ GeV} \qquad [60,\ 1000 \text{ GeV}]$$

$$m_{\mathrm{t}} = 170 \pm 10\ ^{+17}_{-19}(m_{\mathrm{H}}) \text{ GeV}$$

(omitting R_{b}, R_{c}: $m_{\mathrm{t}} = 174$ GeV)

$$\sin^2\bar{\vartheta}_{\mathrm{W}} = 0.23206 \pm 0.00028\ ^{+0.00008}_{-0.00017}$$
$$\sin^2\vartheta_{\mathrm{W}} = 0.2247 \pm 0.0010\ ^{+0.0004}_{-0.0002}$$
$$m_{\mathrm{W}} = 80.295 \pm 0.057\ ^{+0.011}_{-0.019} \text{ GeV}$$

Compare to direct measurement at $\mathrm{p\bar{p}}$ collider:

$$m_{\mathrm{W}} = 80.26 \pm 0.16 \text{ GeV}$$

Using also SLD results, m_{W} from $\mathrm{p\bar{p}}$ and νN data:

$$m_{\mathrm{t}} = 178 \pm 8\,^{+17}_{-20}(m_{\mathrm{H}})\ \mathrm{GeV}$$

Both numbers are in good agreement with direct measurement:

$$\mathrm{CDF} \quad \mathrm{m_t} = 176 \pm 8 \pm 10\ \mathrm{GeV}$$

$$\mathrm{D0} \quad \mathrm{m_t} = 199\,^{+19}_{-21} \pm 22\ \mathrm{GeV}$$

Constraint on m_{H}?

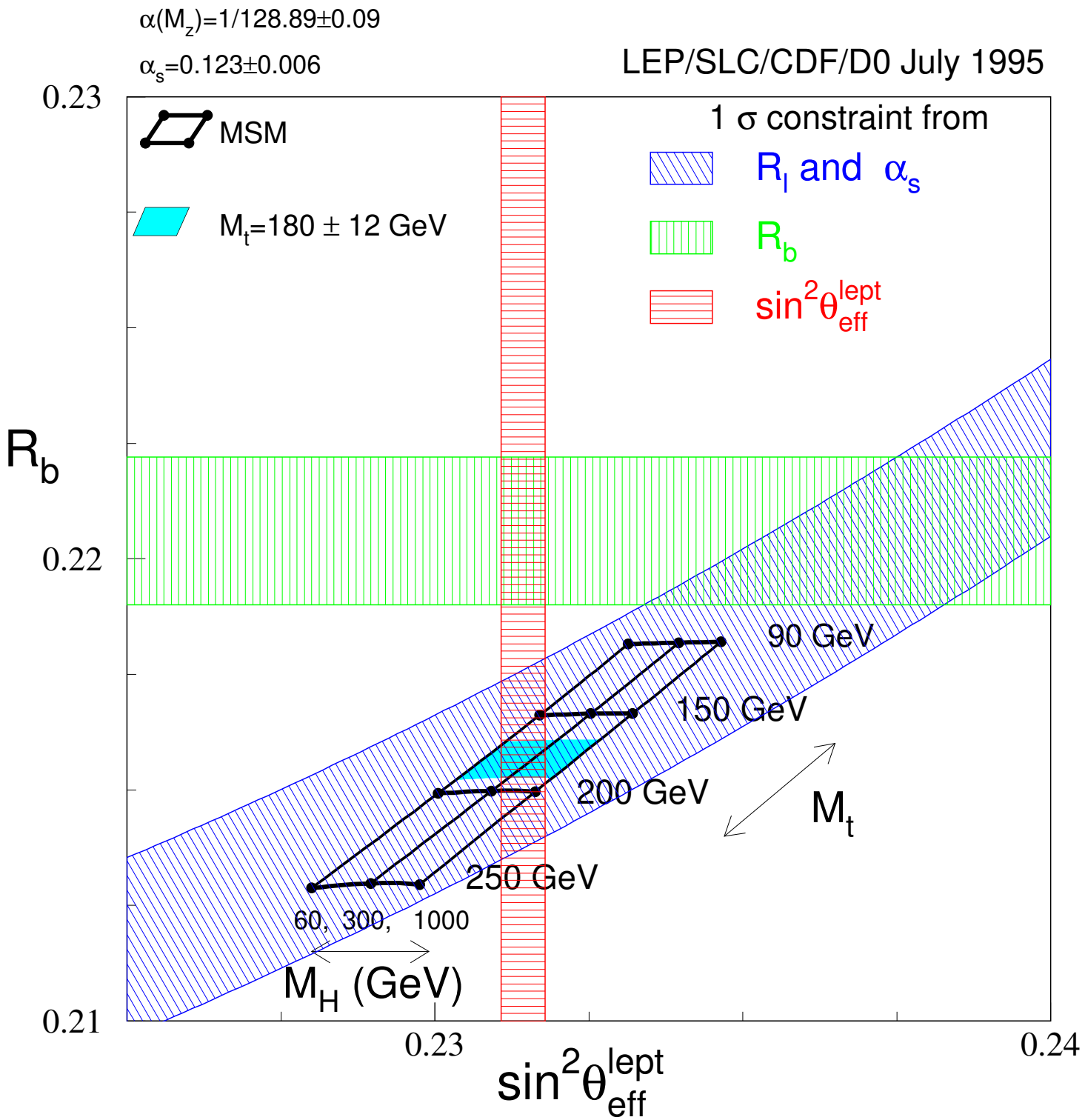
Use also $m_{\mathrm{t}} = 180 \pm 12$ GeV

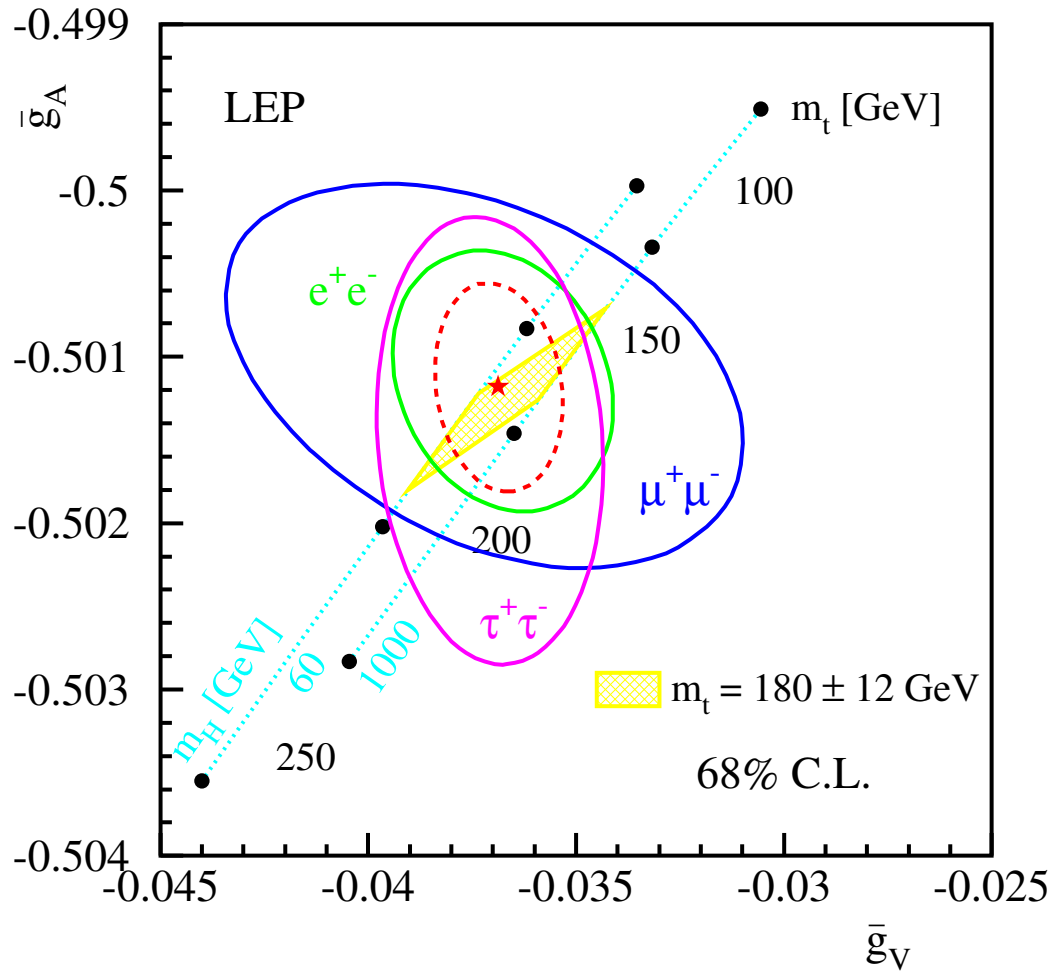
Observables at the Z depend on $\log m_{\mathrm{H}}$, except R_{b}:

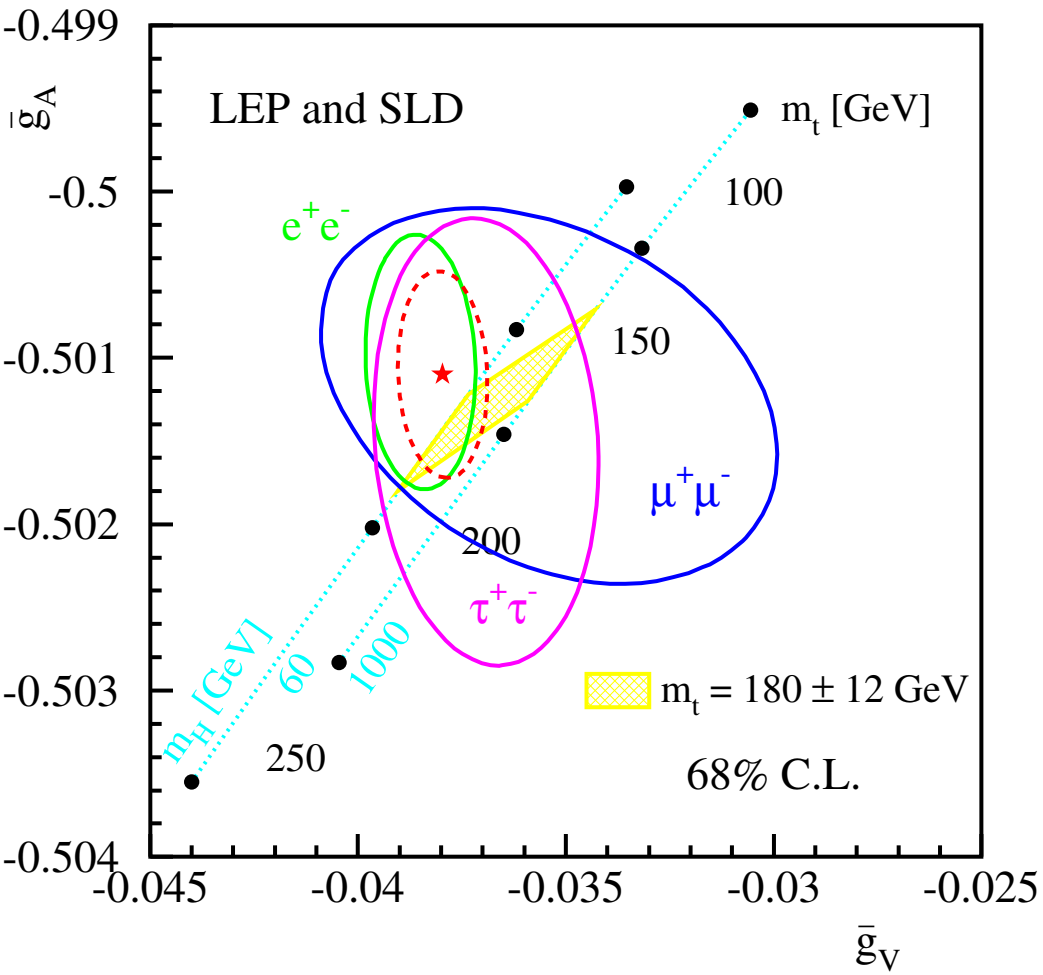
Outlook and conclusions

- LEP I experimental program finished
  $\approx$ 16 million Z decays
- significant improvement on m_{Z} and Γ_{Z} expected from 1995 data
- All observables at the Z in excellent agreement with SM ($m_{\mathrm{t}} = 180$ GeV)
- Except: Measurement of R_{b} (R_{c}) in conflict with SM

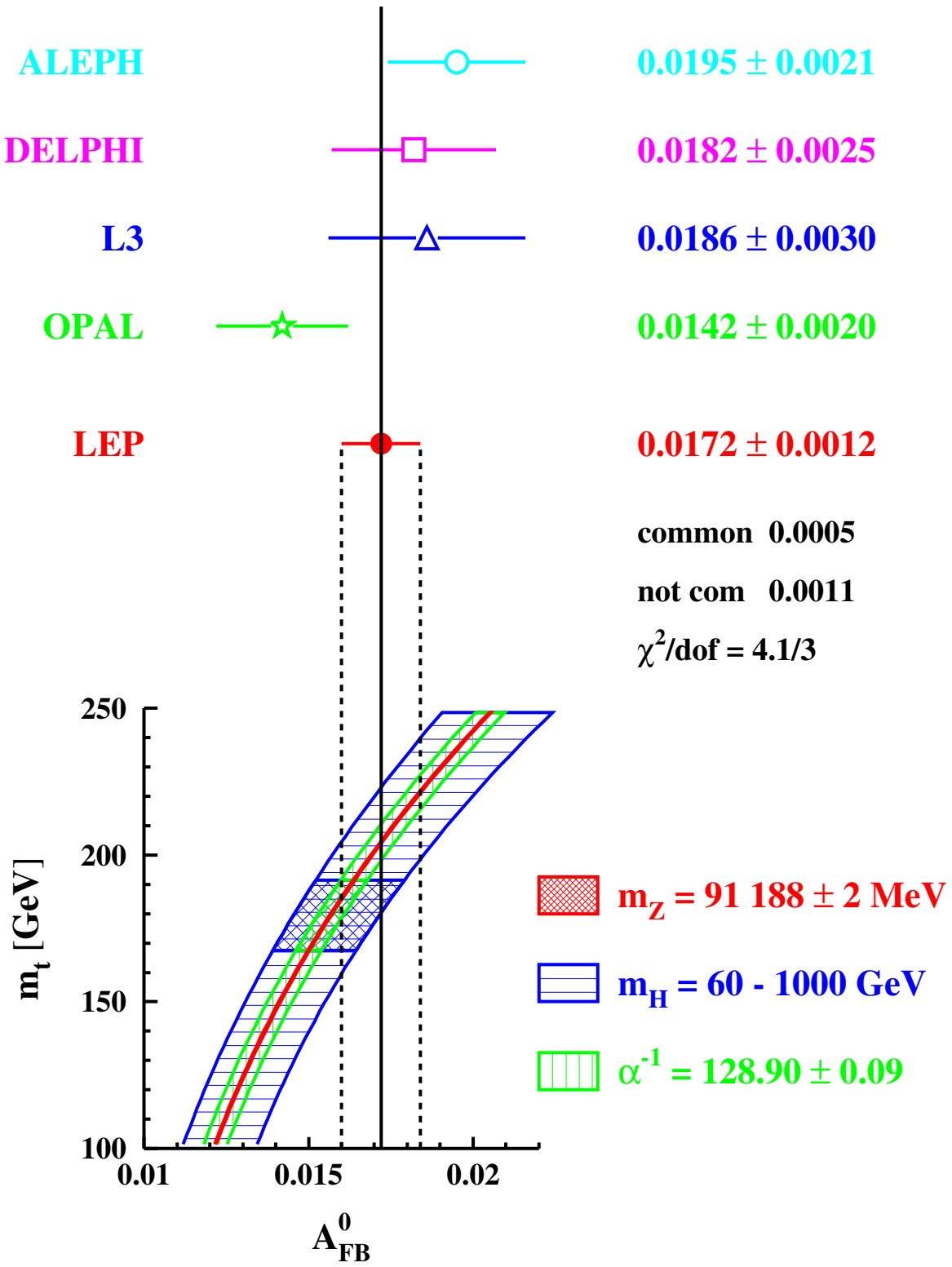
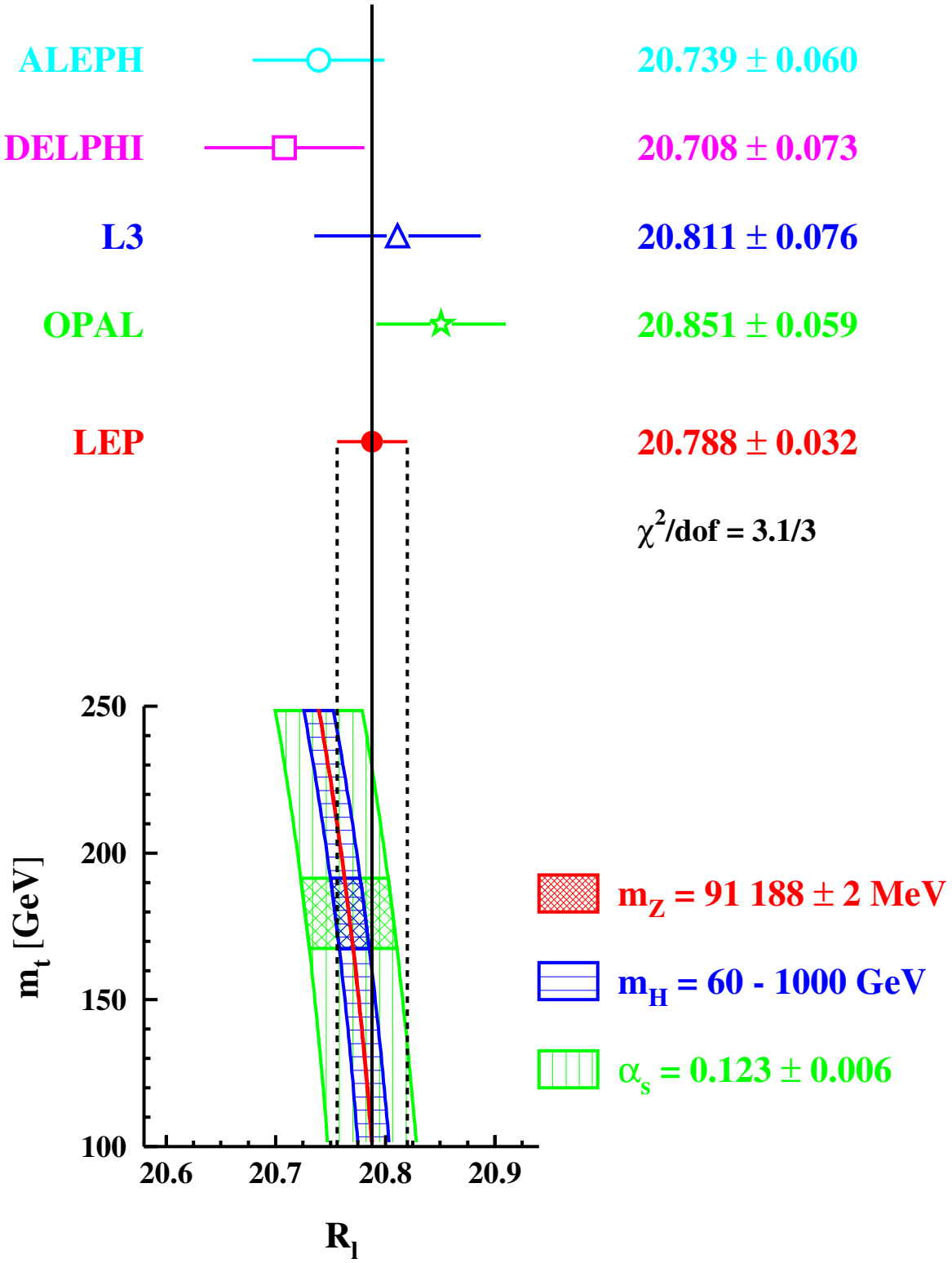
- November 1995: increase of LEP energy ($\sqrt{s} = 140$ GeV)
- June 1996: Start of LEP II program
  $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$
  m_{W} measurement at threshold (161 GeV)
  $\Delta m_{\mathrm{W}} \approx 100$ MeV
- October 1996 – 1999:
  increase $\sqrt{s}$ to 176–193 GeV
  $\approx 7\,000$ W^+W^- per experiment


α(M_z)=1/128.89±0.09
α_s=0.123±0.006
LEP/SLC/CDF/D0 July 1995
MSM
M_t=180 ± 12 GeV
1 σ constraint from
R_l and α_s
R_b
sin²θ^lept_eff
90 GeV
150 GeV
200 GeV
250 GeV
M_t
60, 300, 1000
M_H (GeV)
R_b
0.23
0.22
0.21
0.23
0.24
sin²θ^lept_eff


LEP
m_t [GeV]
100
150
200
250
1000
60
m_H [GeV]
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$m_t = 180 \pm 12$ GeV
68% C.L.
$\bar{g}_A$
$\bar{g}_V$
-0.499
-0.5
-0.501
-0.502
-0.503
-0.504
-0.045
-0.04
-0.035
-0.03
-0.025


LEP and SLD
m_t [GeV]
100
150
200
250
1000
60
m_H [GeV]
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$m_t = 180 \pm 12$ GeV
68% C.L.
$\bar{g}_A$
$\bar{g}_V$
-0.499
-0.5
-0.501
-0.502
-0.503
-0.504
-0.045
-0.04
-0.035
-0.03
-0.025

$$A_{FB}^{\ell} = \frac{3}{4} A_e A_\ell$$



$$R_\ell = \frac{\Gamma_{\mathrm{had}}}{\Gamma_\ell}$$