Electroweak Physics at LEP

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CERN, PPE, L3

Rencontre de la vallée d'Aoste
La Thuile, 2–8 March 1997

Introduction

LEP Performance 1990–1996

Cross Section Measurements

Lepton Asymmetry Measurements

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

Interpretation in the Standard Model

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

Thanks to all people involved!

LEP

Large Electron Positron collider at CERN

LEP phase 1	around Z peak 91 GeV
LEP phase 1.5	at 130–140 GeV
LEP phase 2	at 161–172 GeV

Four LEP Experiments since 1989:

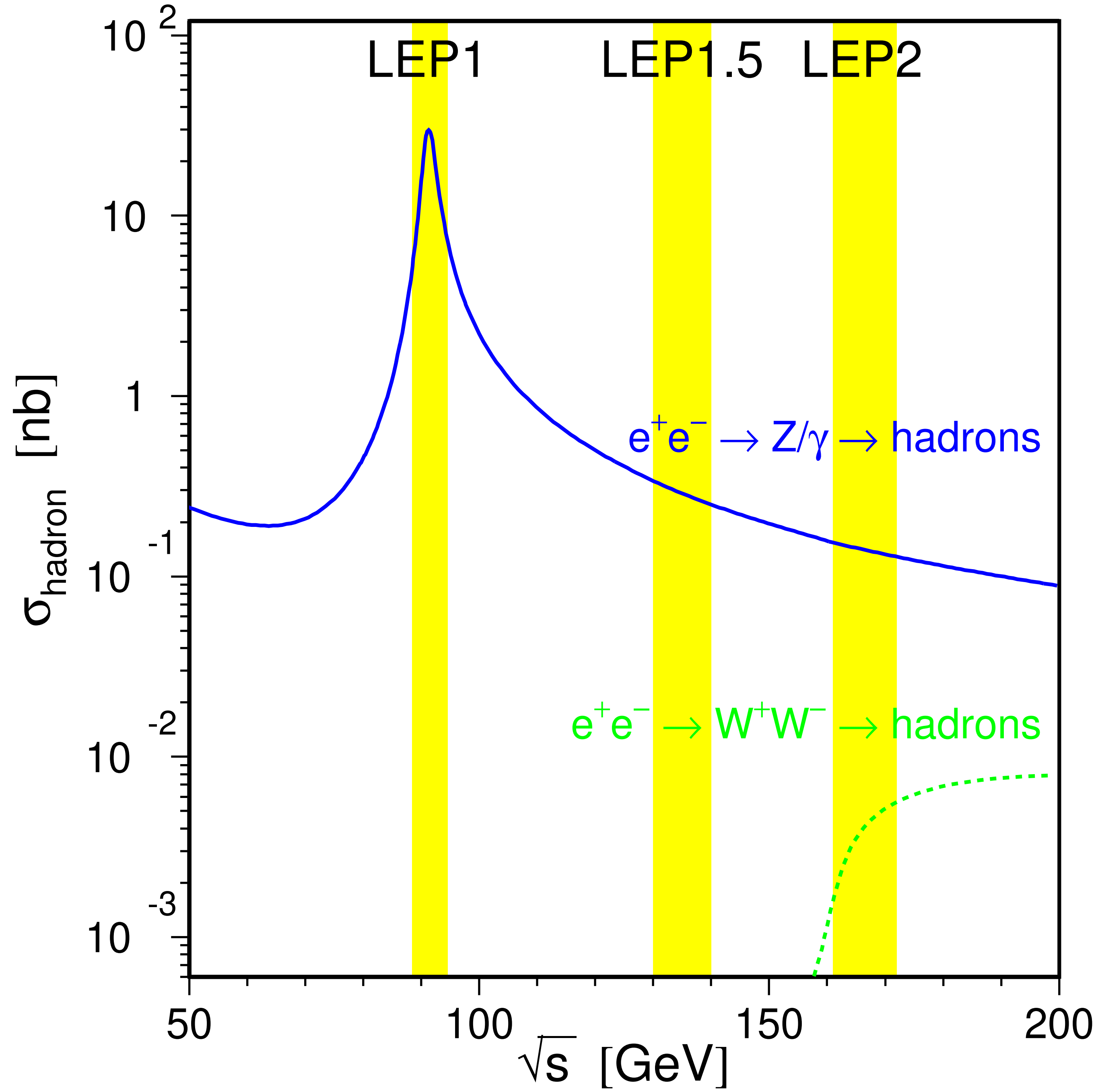
ALEPH, DELPHI, L3, OPAL

Status of the data presented:

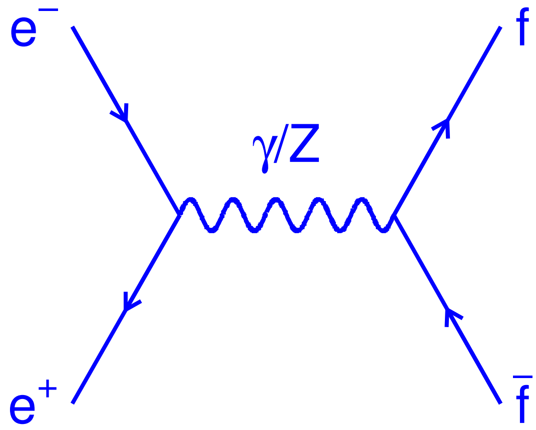
almost no updates since 1996 Summer Conferences

All numbers are still preliminary

LEP Program

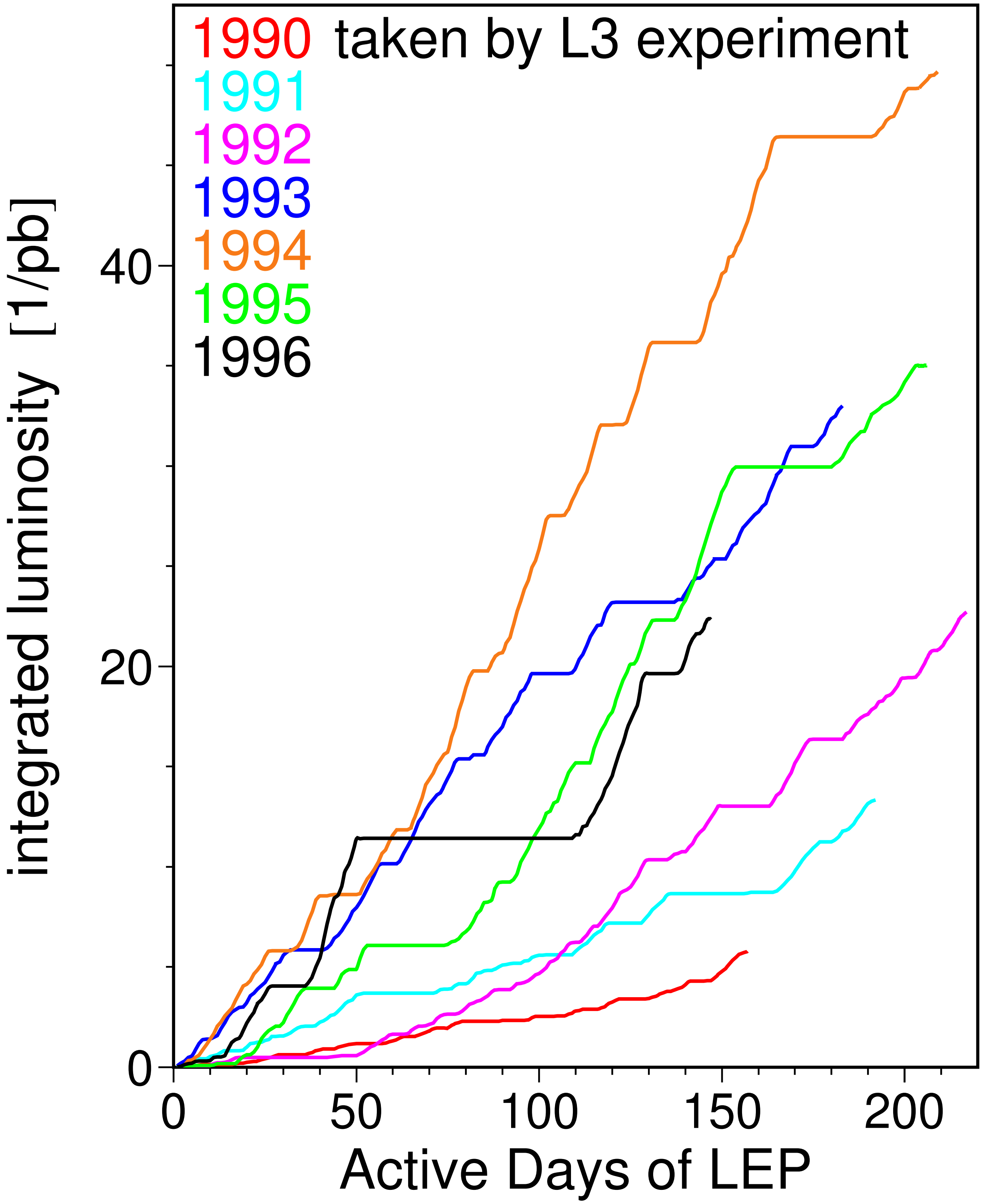


Fermion Pair Production

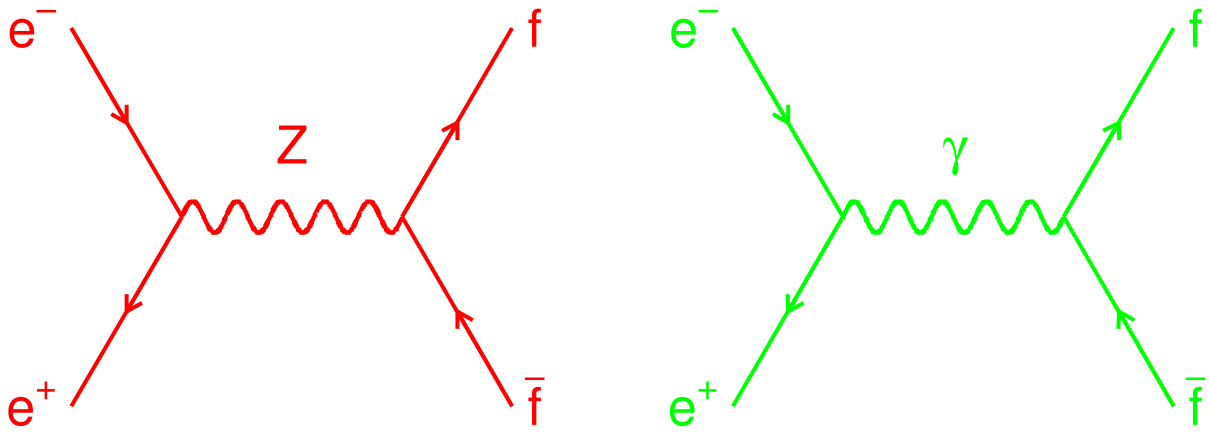


$\approx$ 16 million events at Z peak
$\approx$ 25 thousand events well above

LEP Performance



Lowest-order diagram: $e^+e^- \rightarrow f\bar{f}(\gamma)$



$$\sigma^0 = \sigma^0_{\mathrm{Z}} + \sigma^0_{\gamma} + \sigma^0_{\mathrm{int}}$$

Breit-Wigner parametrisation: m_{Z}, Γ_{Z}, Γ_f, J_f

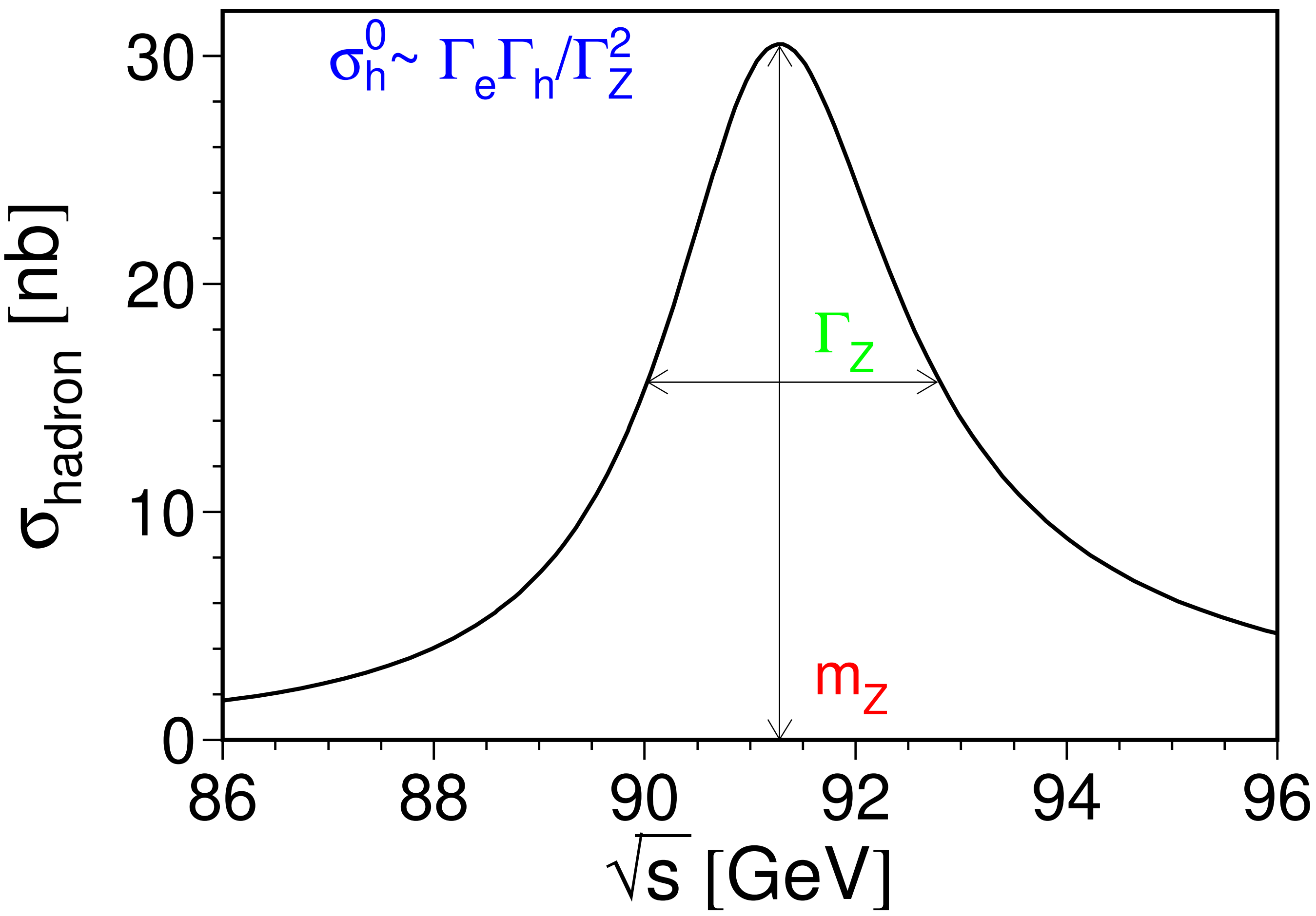
$$\sigma^0_{\mathrm{Z}} = \frac{12\pi}{m_{\mathrm{Z}}^2}\frac{\Gamma_{\mathrm{e}}\Gamma_f}{\Gamma_{\mathrm{Z}}\Gamma_{\mathrm{Z}}}\frac{s\Gamma_{\mathrm{Z}}^2}{(s-m_{\mathrm{Z}}^2)^2 + s^2\Gamma_{\mathrm{Z}}^2/m_{\mathrm{Z}}^2}$$

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

$$\sigma^0_{\mathrm{int}} = \frac{4\pi\alpha^2}{3}J_f\frac{s-m_{\mathrm{Z}}^2}{(s-m_{\mathrm{Z}}^2)^2 + s^2\Gamma_{\mathrm{Z}}^2/m_{\mathrm{Z}}^2}$$

σ^0_{Z} dominant for $\sqrt{s} \approx m_{\mathrm{Z}}$
J_f for hadronic final state is fixed to Standard Model.

Parameters of the Lineshape



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

- absolute uncertainty on $\sqrt{s}$ (1.5 MeV)

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

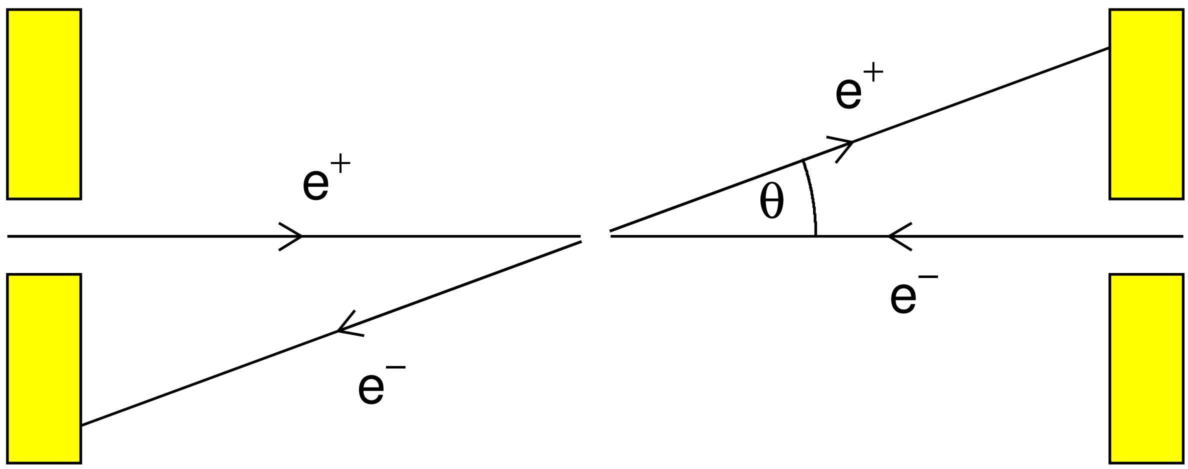
- local uncertainty on $\sqrt{s}$ (1.7 MeV)

Z pole cross section, σ^0, $\approx$ height of peak

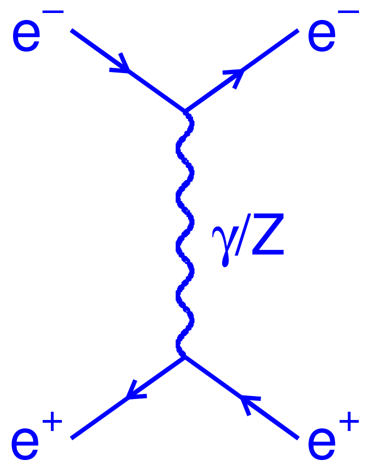
- uncertainty on $\mathcal{L}$ measurement (46 pb)

Measurement of integrated Luminosity

Small angle Bhabha Scattering



Additional t-channel diagrams:



elastic scattering:

- γ exchange dominant
- small dependence on Z parameters

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

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

Selected[1] events 1989-1995 in units of 10^3:

	hadrons	leptons
ALEPH	4,164	485
DELPHI	3,556	376
L3	3,358	317
OPAL	3,357	454
total	14,435	1,632

Hadrons determine m_Z and Γ_Z because:

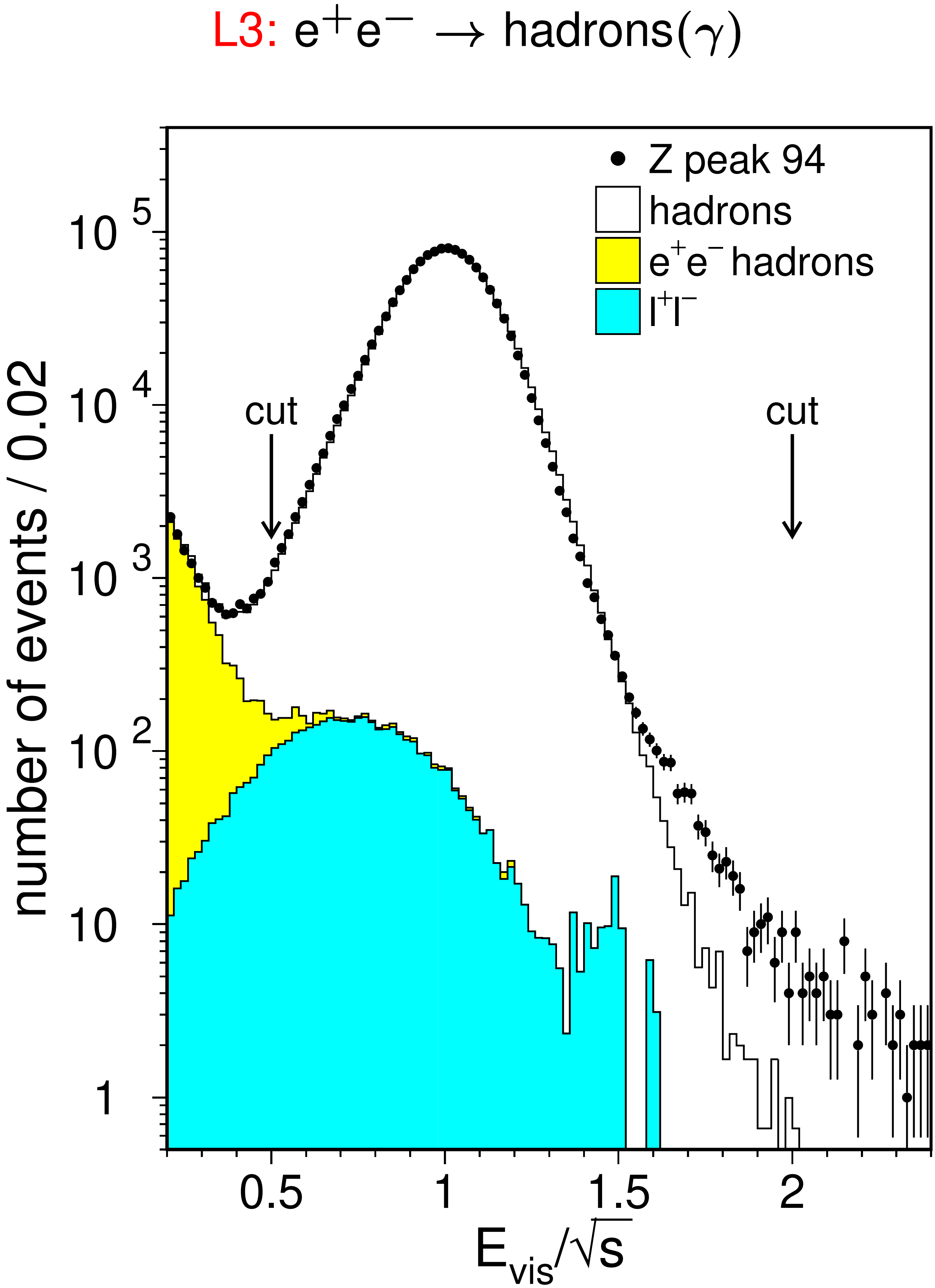
$\sigma_{\text{had}} \approx 20\sigma_\mu$

Typical experimental uncertainty (1994):

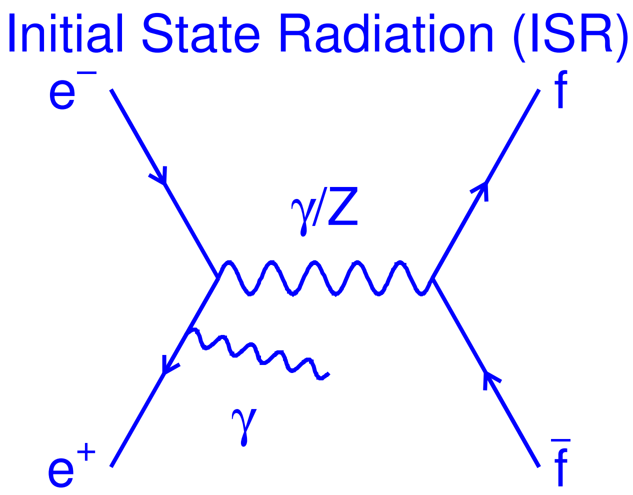
	hadrons	muons	taus	electrons
ALEPH	0.073%	0.26%	0.32%	0.48%
DELPHI	0.10%	0.30%	0.60%	0.50%
L3	0.051%	0.31%	0.65%	0.23%
OPAL	0.16%	0.15%	0.46%	0.24%

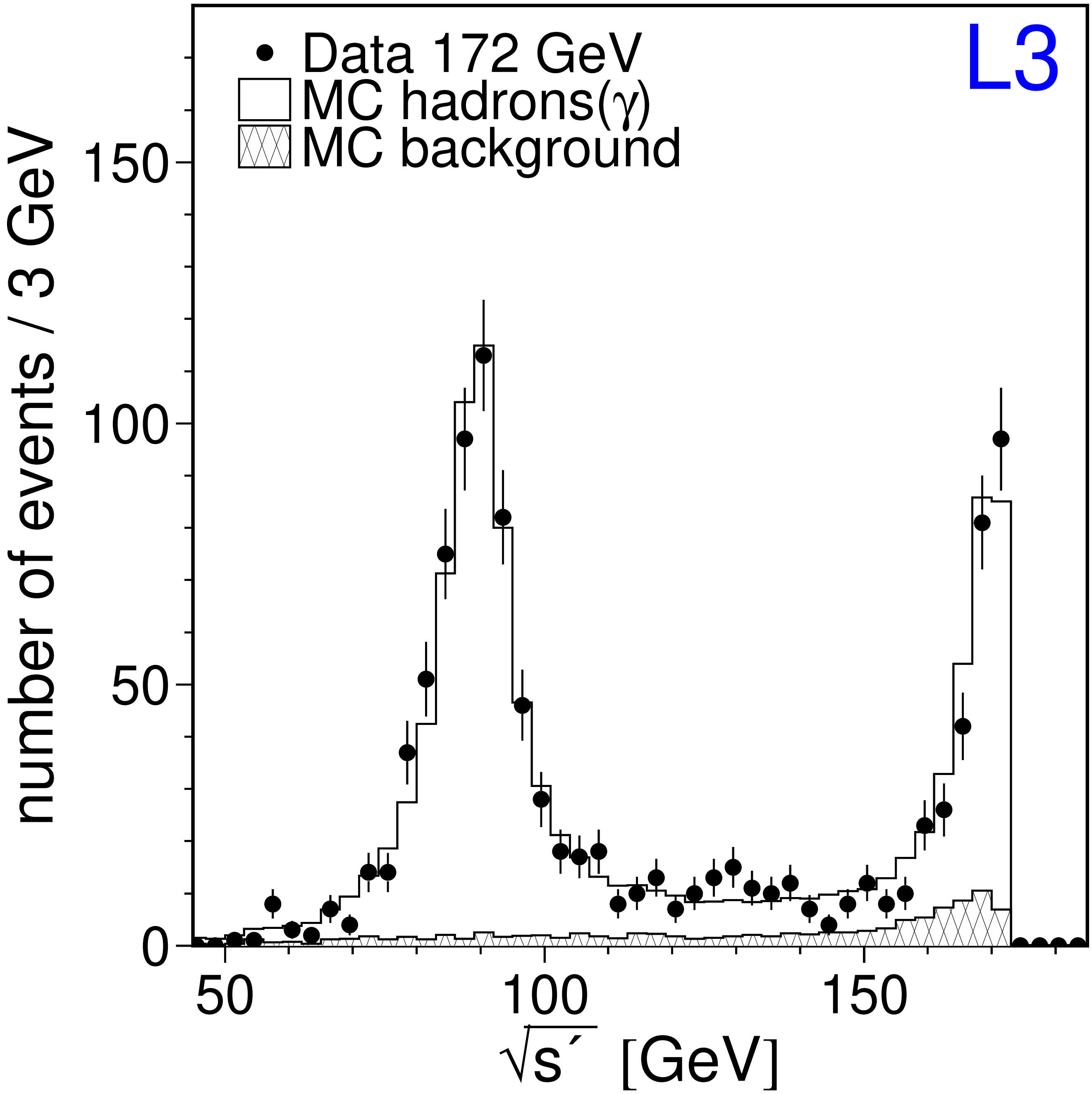
[1] Not all experiments have yet analysed the full data set.

Selection Variable

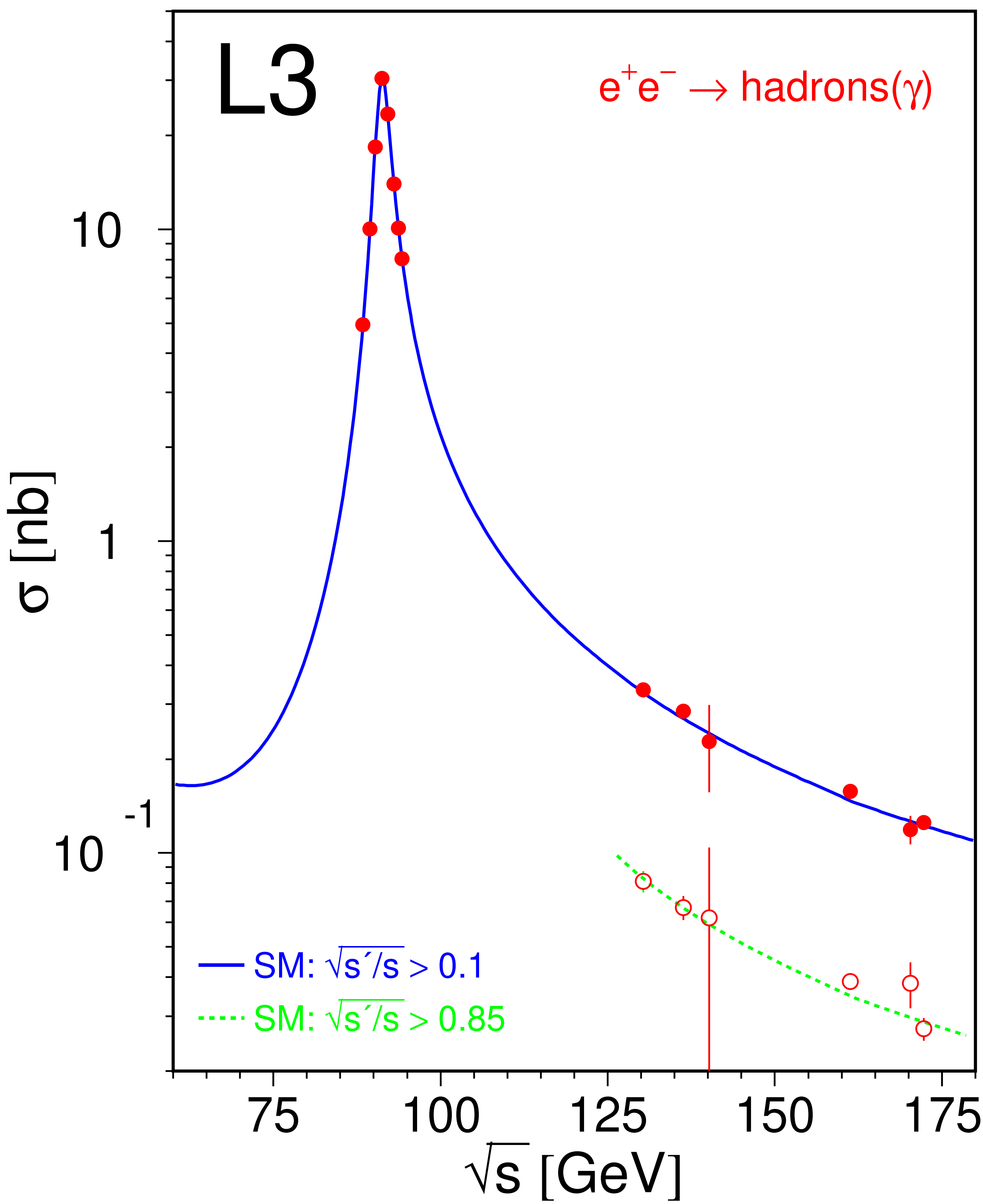


Effective Centre–of–Mass Energy, $\sqrt{s'}$

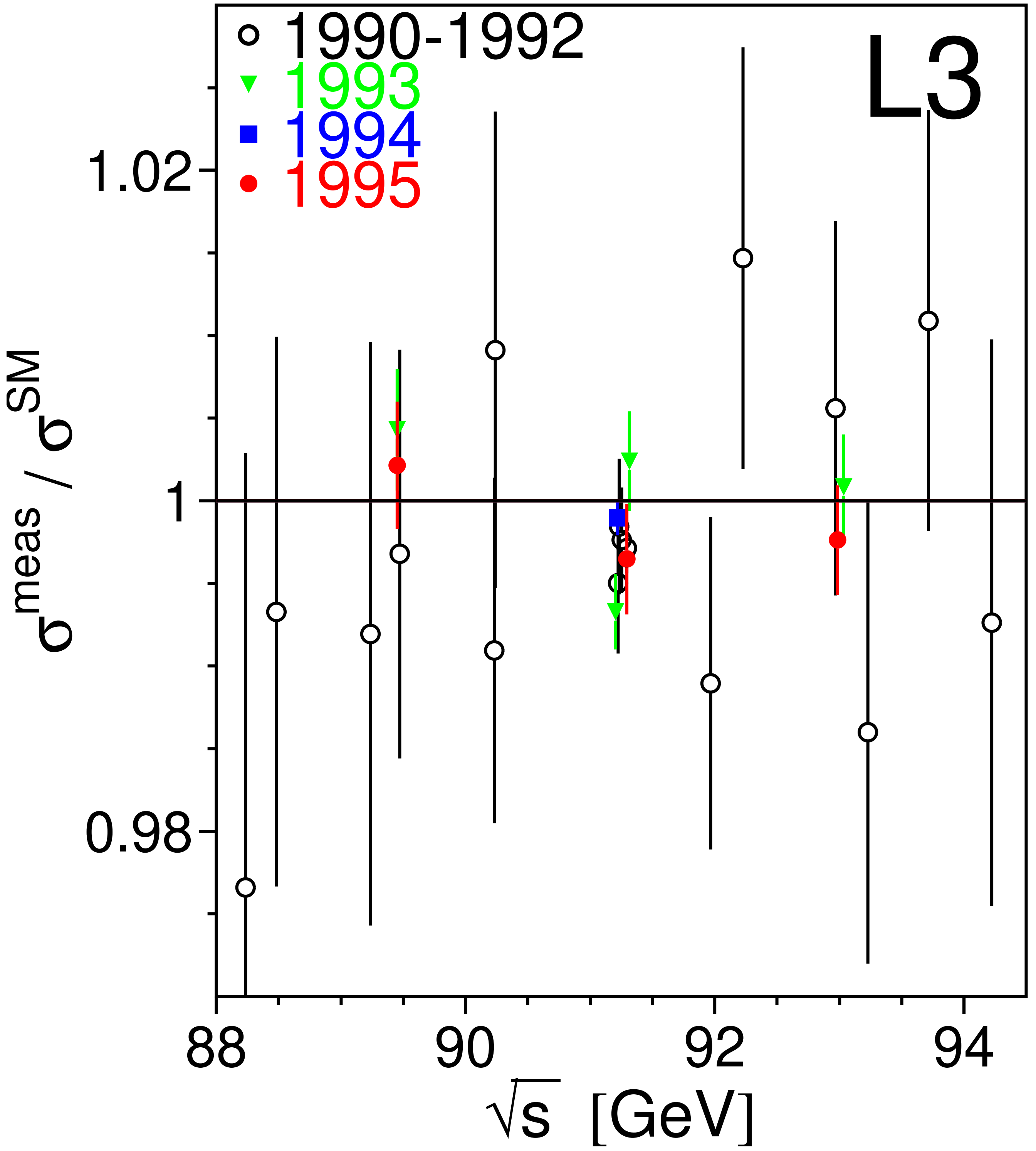


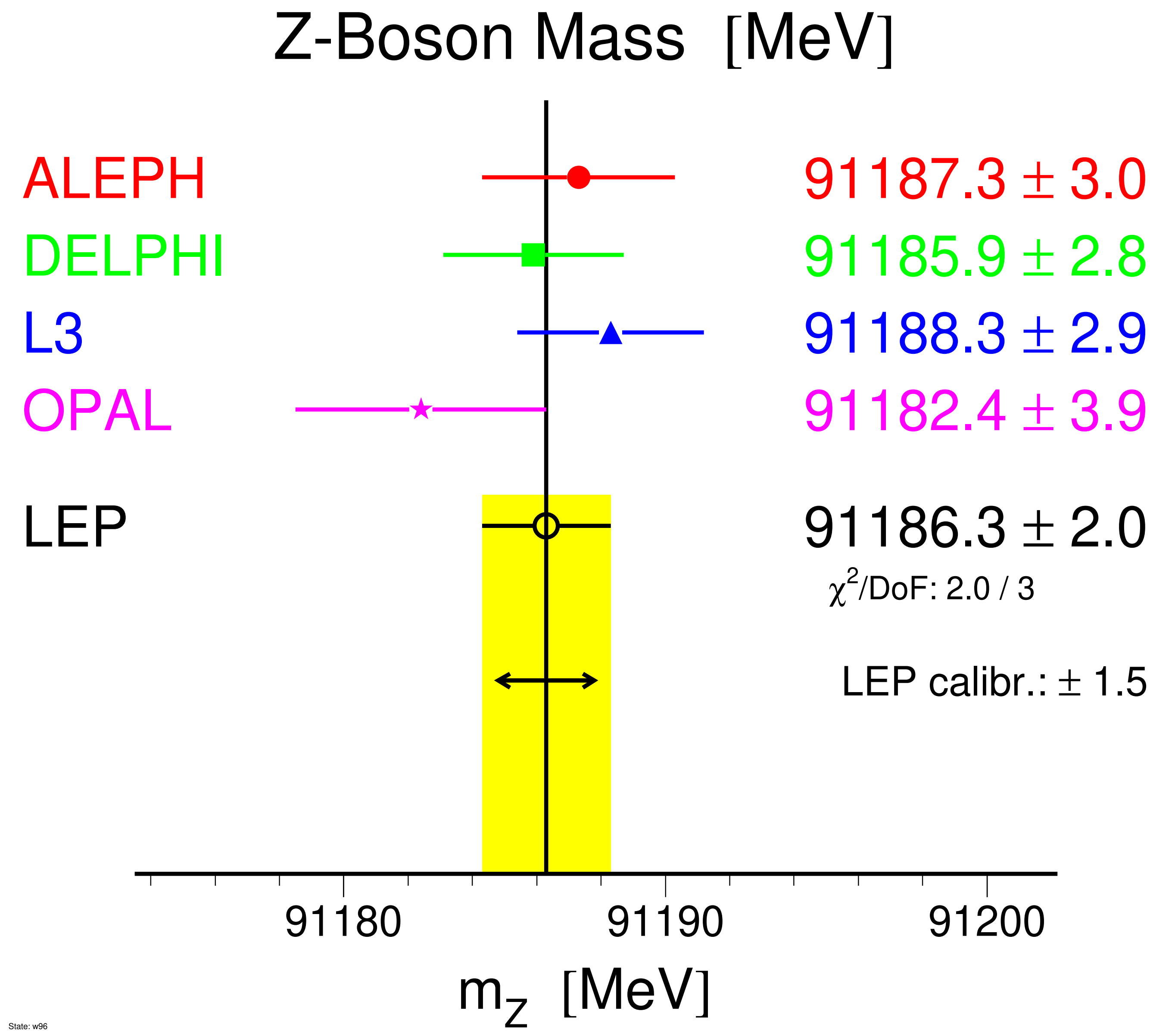


Hadron Cross Section 88 - 172 GeV



Ratio: $\frac{\sigma^{\rm meas}}{\sigma^{\rm SM}}$ for $e^+e^- \rightarrow$ hadrons(γ)



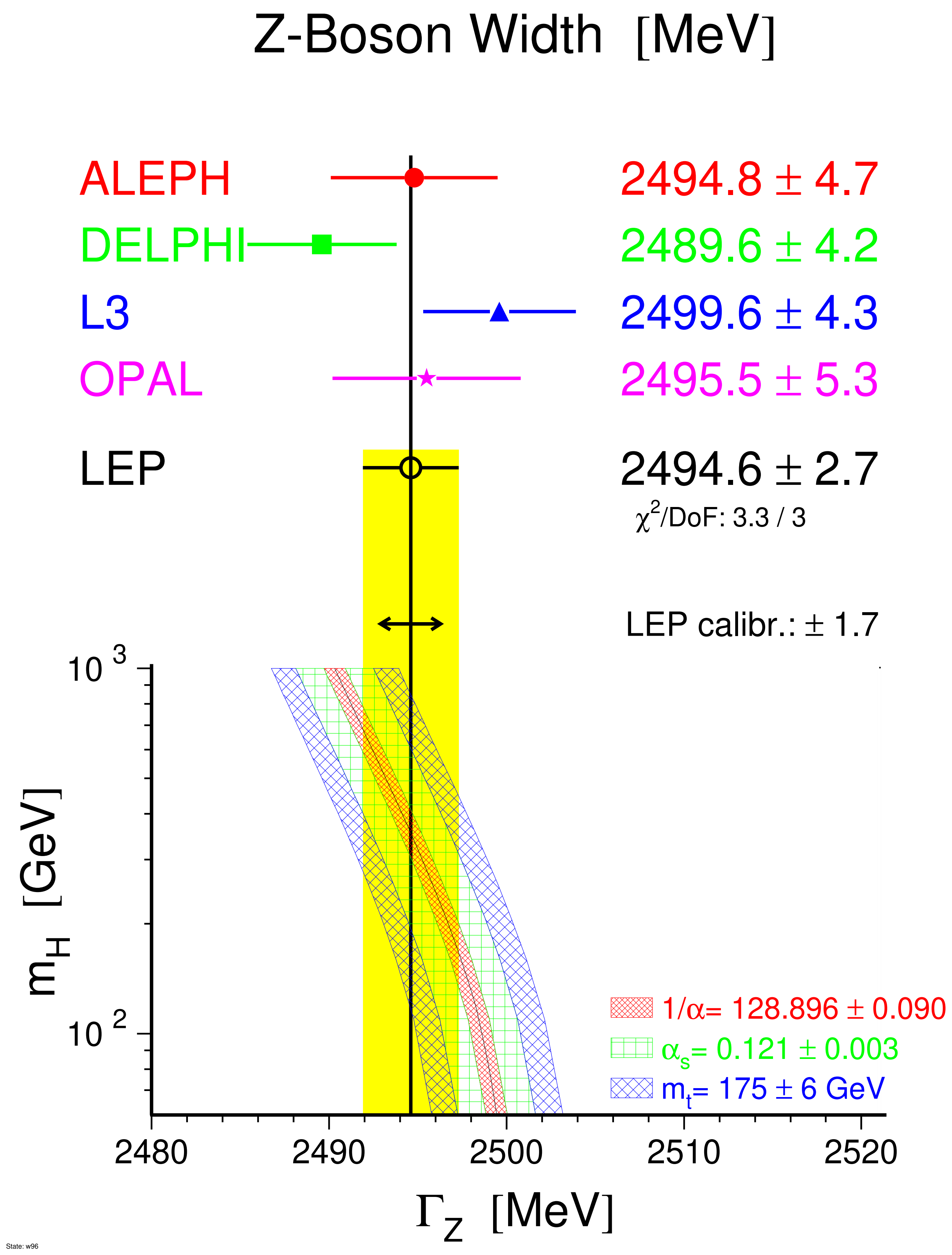


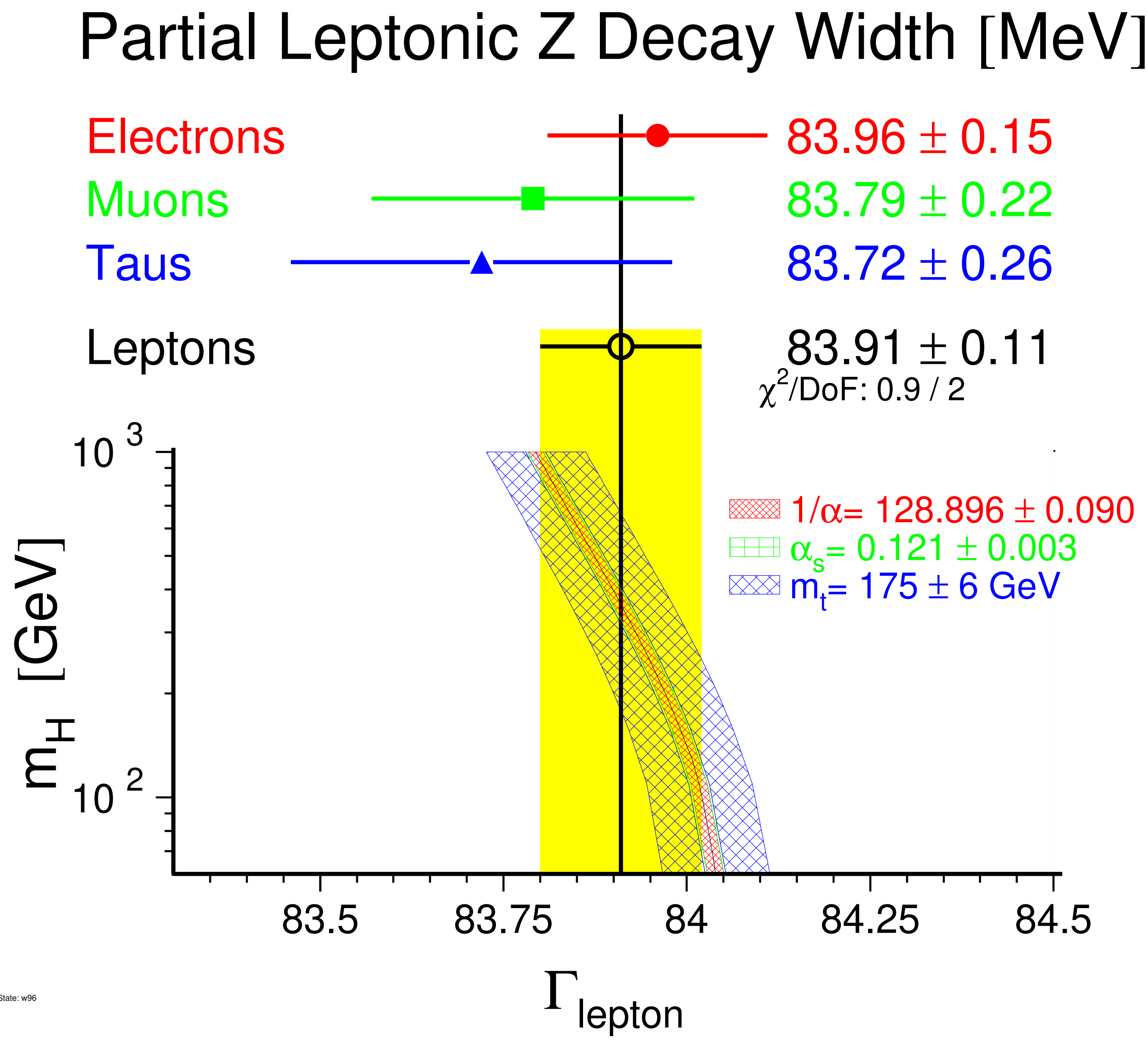
Compare to other precise measurements:

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

$$\Delta m_Z/m_Z = 22 \cdot 10^{-6}$$

$$\Delta\alpha/\alpha = 700 \cdot 10^{-6} \text{ at } m_Z^2$$


Z-Boson Width [MeV]
ALEPH
2494.8 ± 4.7
DELPHI
2489.6 ± 4.2
L3
2499.6 ± 4.3
OPAL
2495.5 ± 5.3
LEP
2494.6 ± 2.7
χ2/DoF: 3.3 / 3
LEP calibr.: ± 1.7
10 3
10 2
mH [GeV]
1/α= 128.896 ± 0.090
αs= 0.121 ± 0.003
mt= 175 ± 6 GeV
2480
2490
2500
2510
2520
ΓZ [MeV]
State: w96



Hadronic partial Z decay width, Γ_{had}:

$$\Gamma_{\mathrm{had}} = 1743.6 \pm 2.5 \ \ \mathrm{MeV}$$

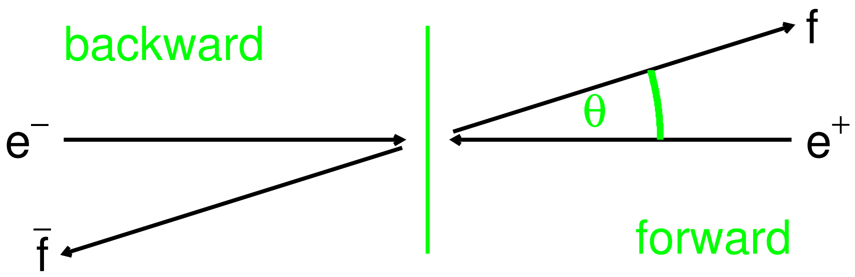
Invisible partial Z decay width, Γ_{inv}:

$$\Gamma_{\mathrm{inv}} = 499.5 \pm 2.0 \ \ \mathrm{MeV}$$

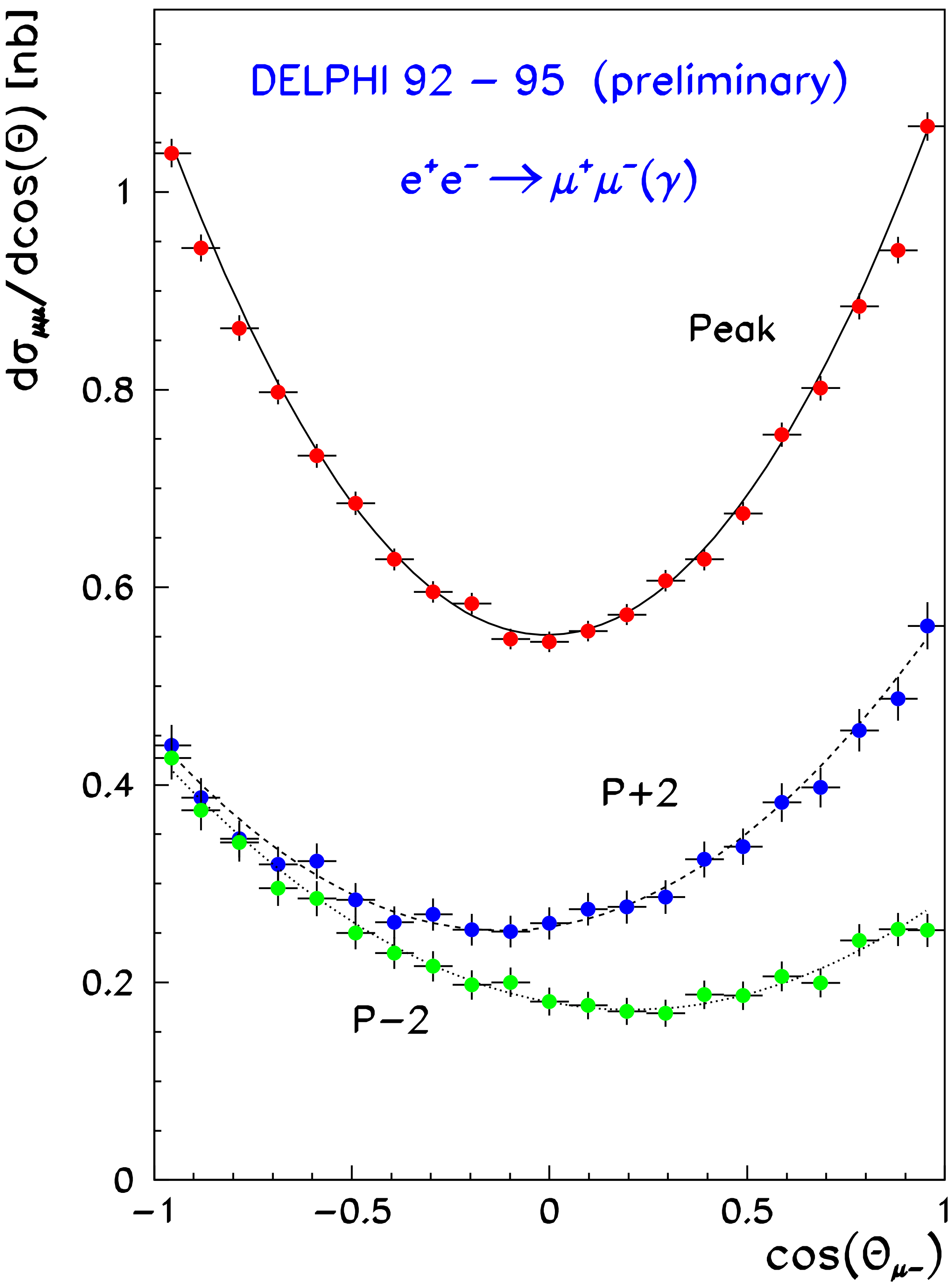
Number of light neutrino species, N_ν:

$$N_\nu = 2.989 \pm 0.012$$

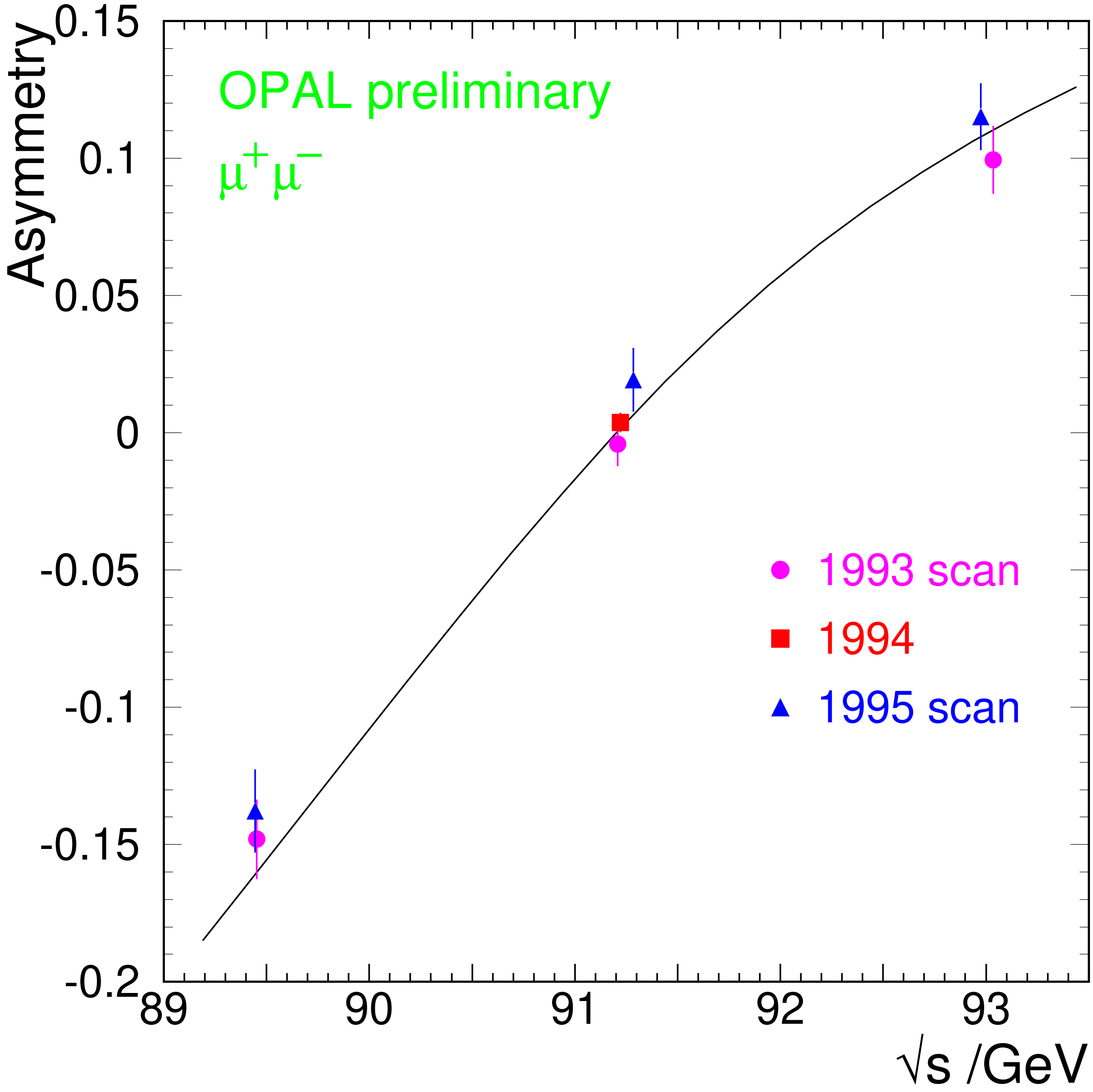
Asymmetry Measurements



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

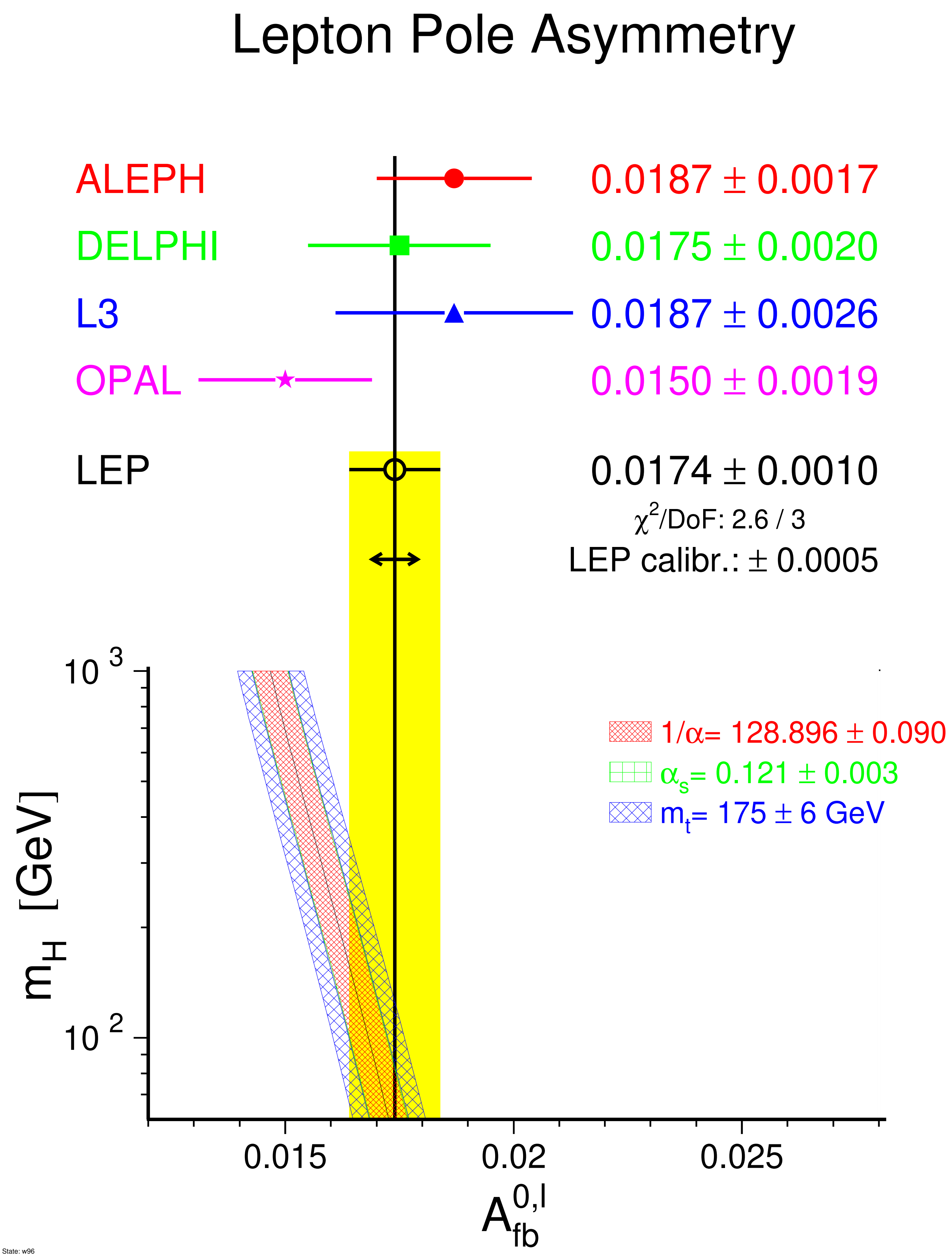


Asymmetry Measurements



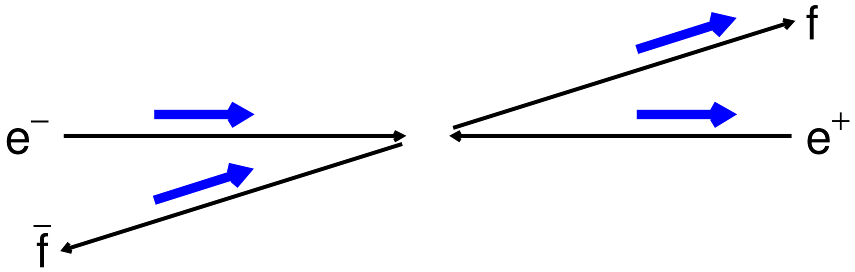
Combine all measurements to obtain the pole asymmetry, $A_{fb}^{0,\ell}$:

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



Lepton Pole Asymmetry
ALEPH
0.0187 ± 0.0017
DELPHI
0.0175 ± 0.0020
L3
0.0187 ± 0.0026
OPAL
0.0150 ± 0.0019
LEP
0.0174 ± 0.0010
χ²/DoF: 2.6 / 3
LEP calibr.: ± 0.0005
10 3
10 2
m_H [GeV]
1/α= 128.896 ± 0.090
α_s= 0.121 ± 0.003
m_t= 175 ± 6 GeV
0.015
0.02
0.025
A_fb^0,l
State: w96

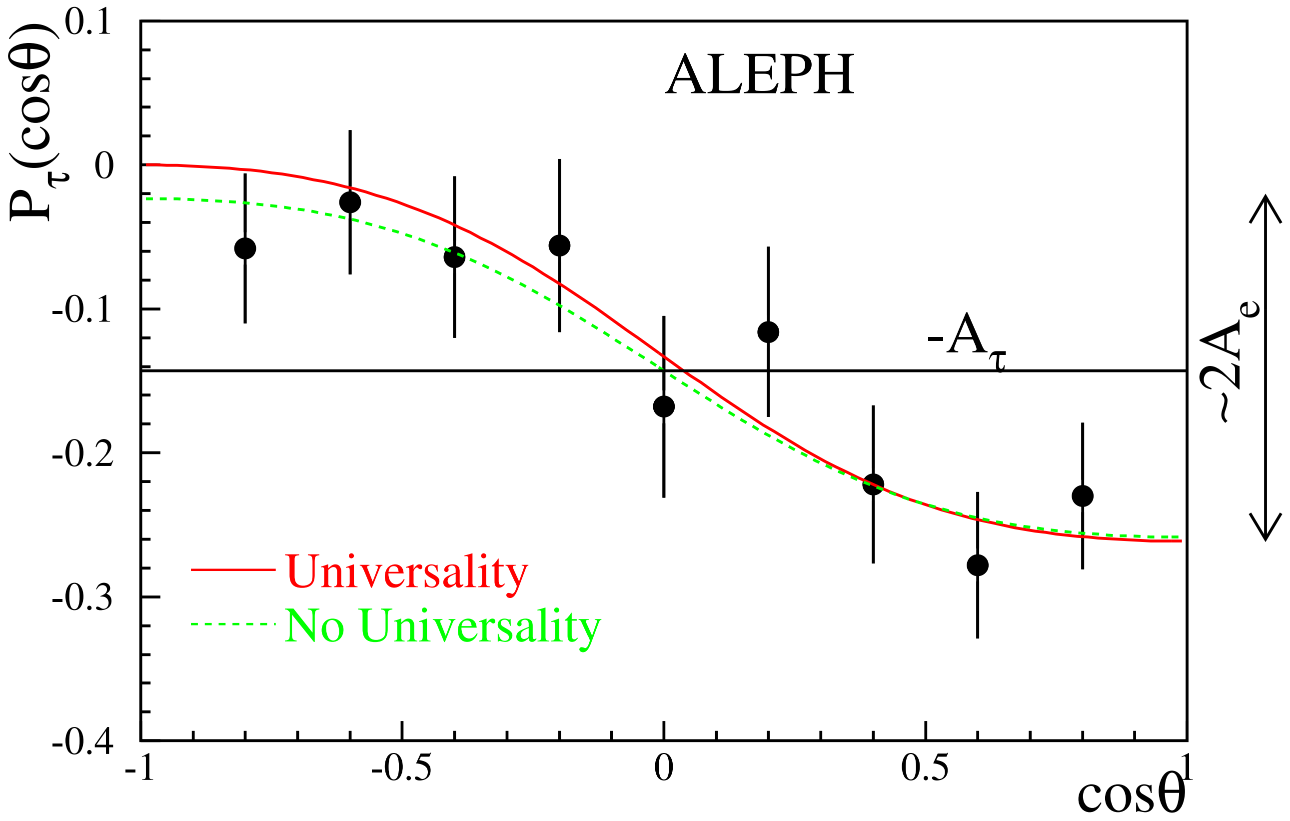
Asymmetry Measurements



Tau Polarisation: $\mathcal{P}_\tau = \frac{\sigma(\tau_R)-\sigma(\tau_L)}{\sigma(\tau_R)+\sigma(\tau_L)}$

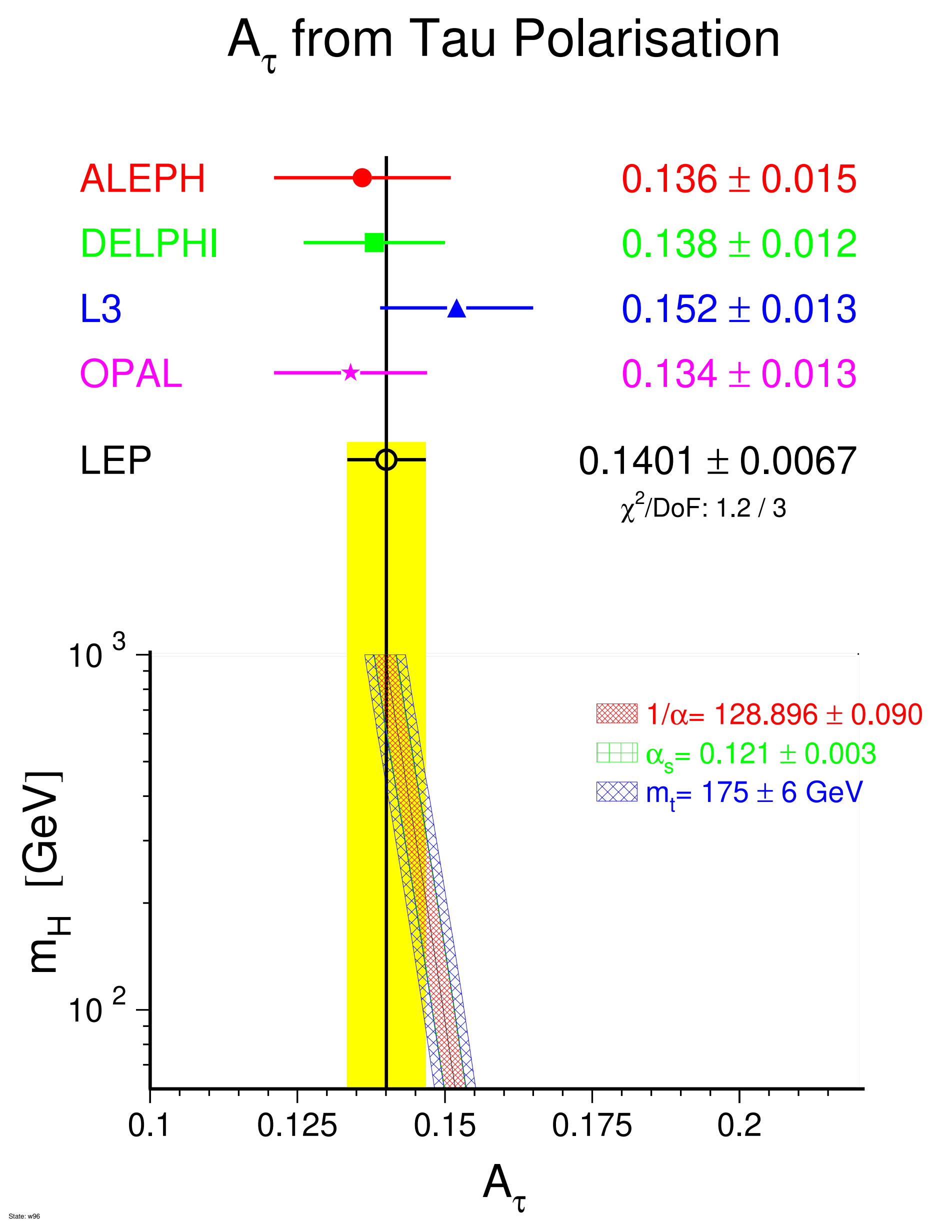
Tau lepton decays within the detector:

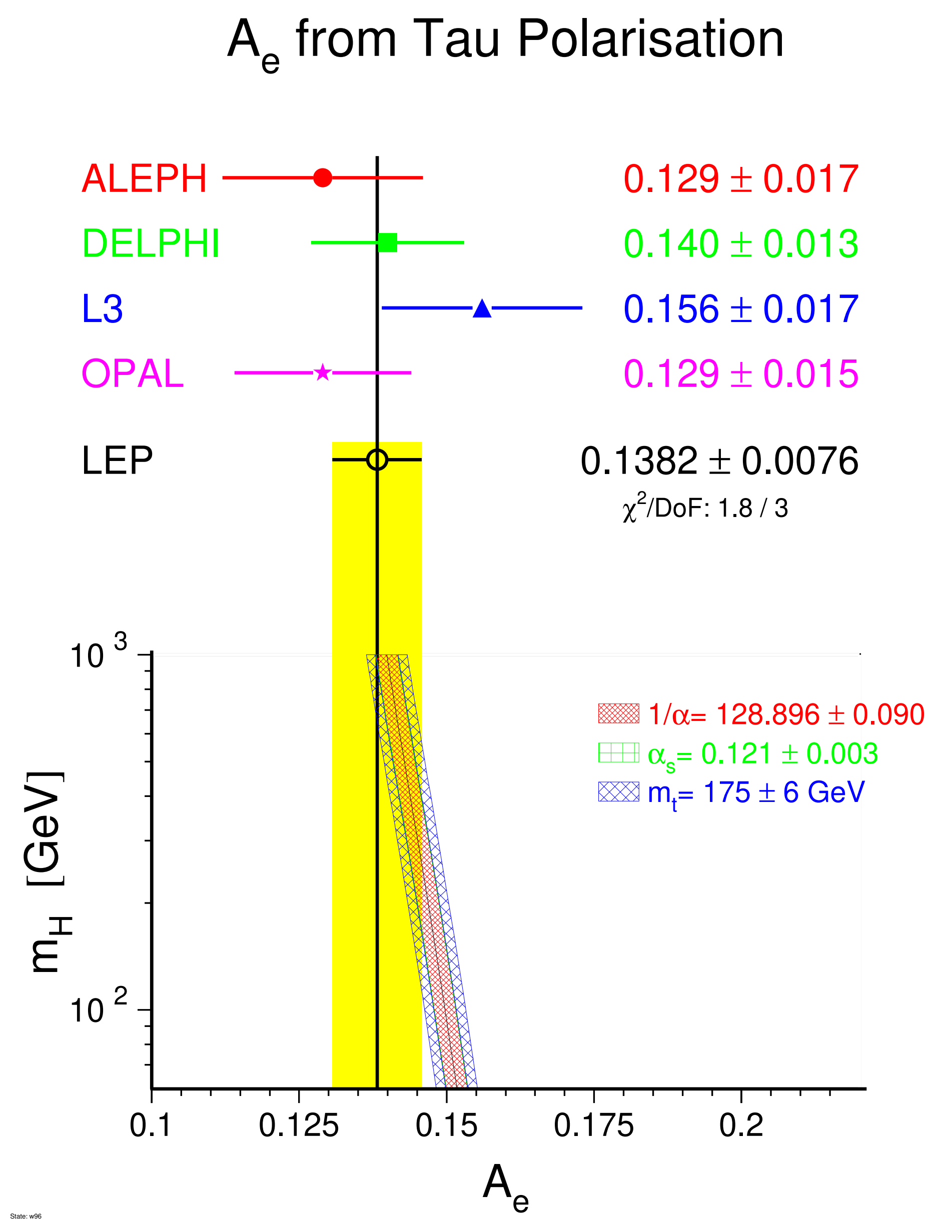
helicity is measured from decay products



$$\mathcal{P}_\tau(\cos\theta) = -\frac{(1+\cos^2\theta)A_\tau + 2A_e\cos\theta}{(1+\cos^2\theta) + 2A_eA_\tau\cos\theta}$$

Results from Asymmetry Measurements



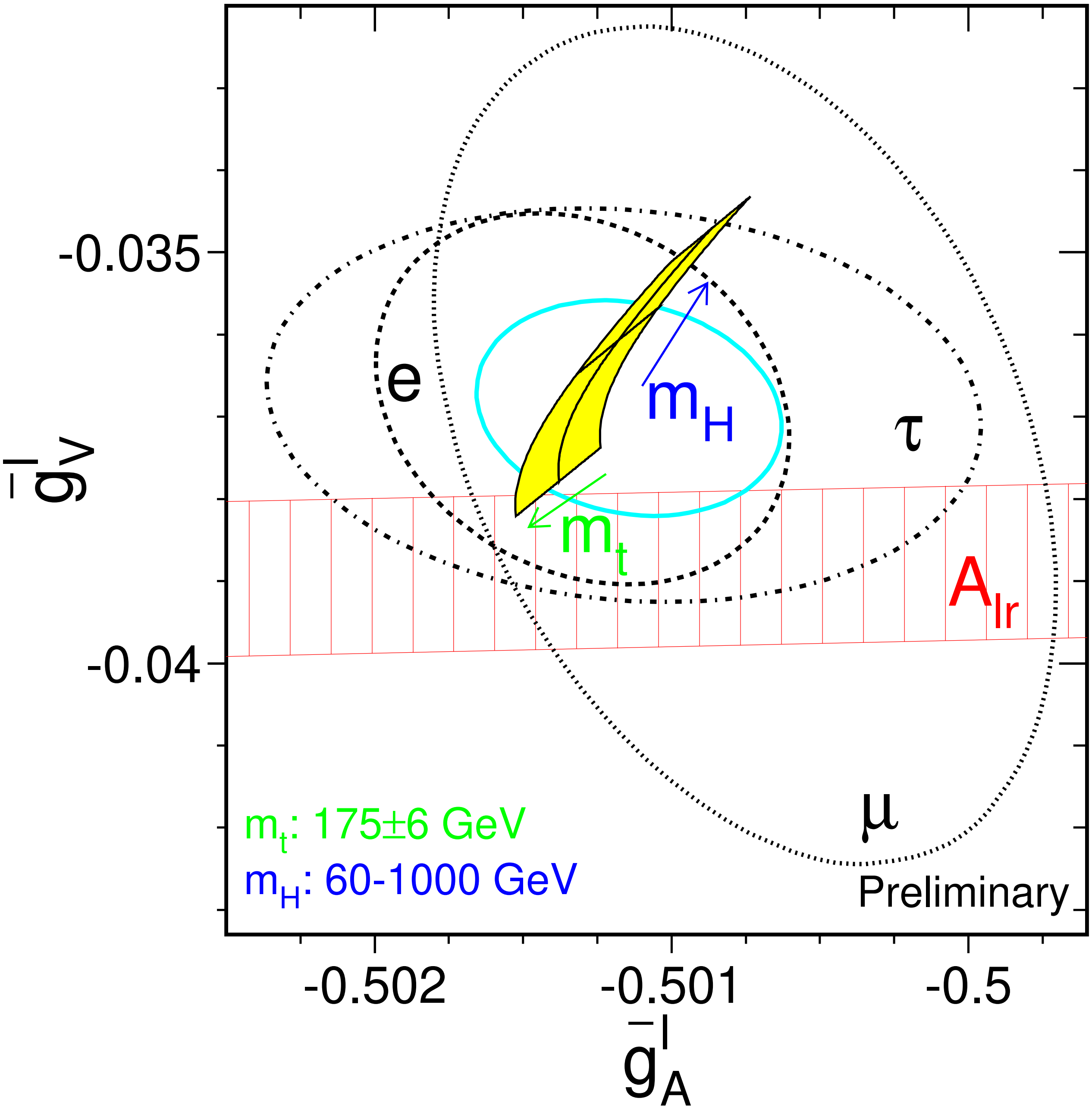


Effective Lepton Couplings to the Z-Boson

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

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

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



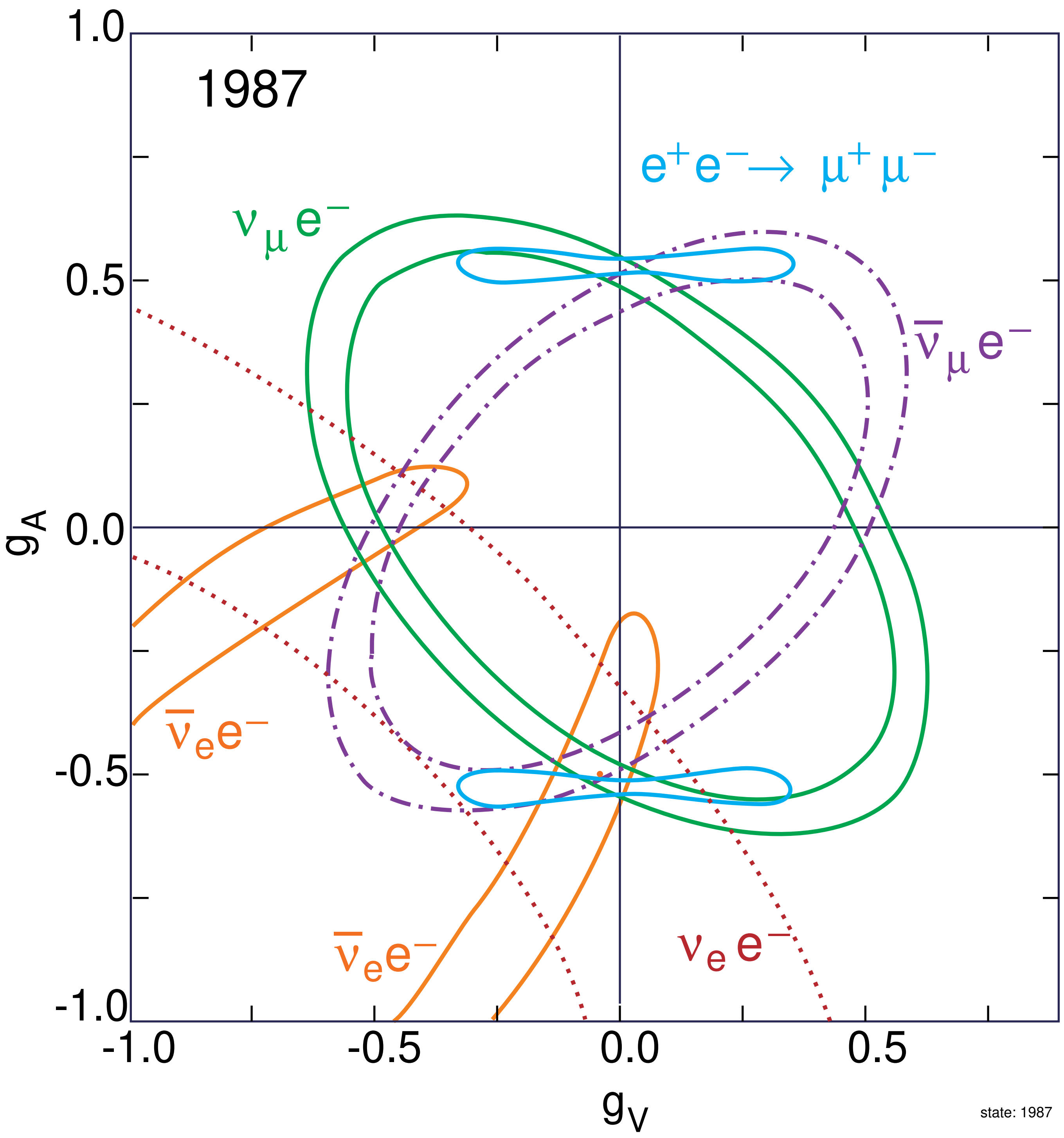
Compare with:

Left–right asymmetry from SLD: $A_{lr} = A_e$

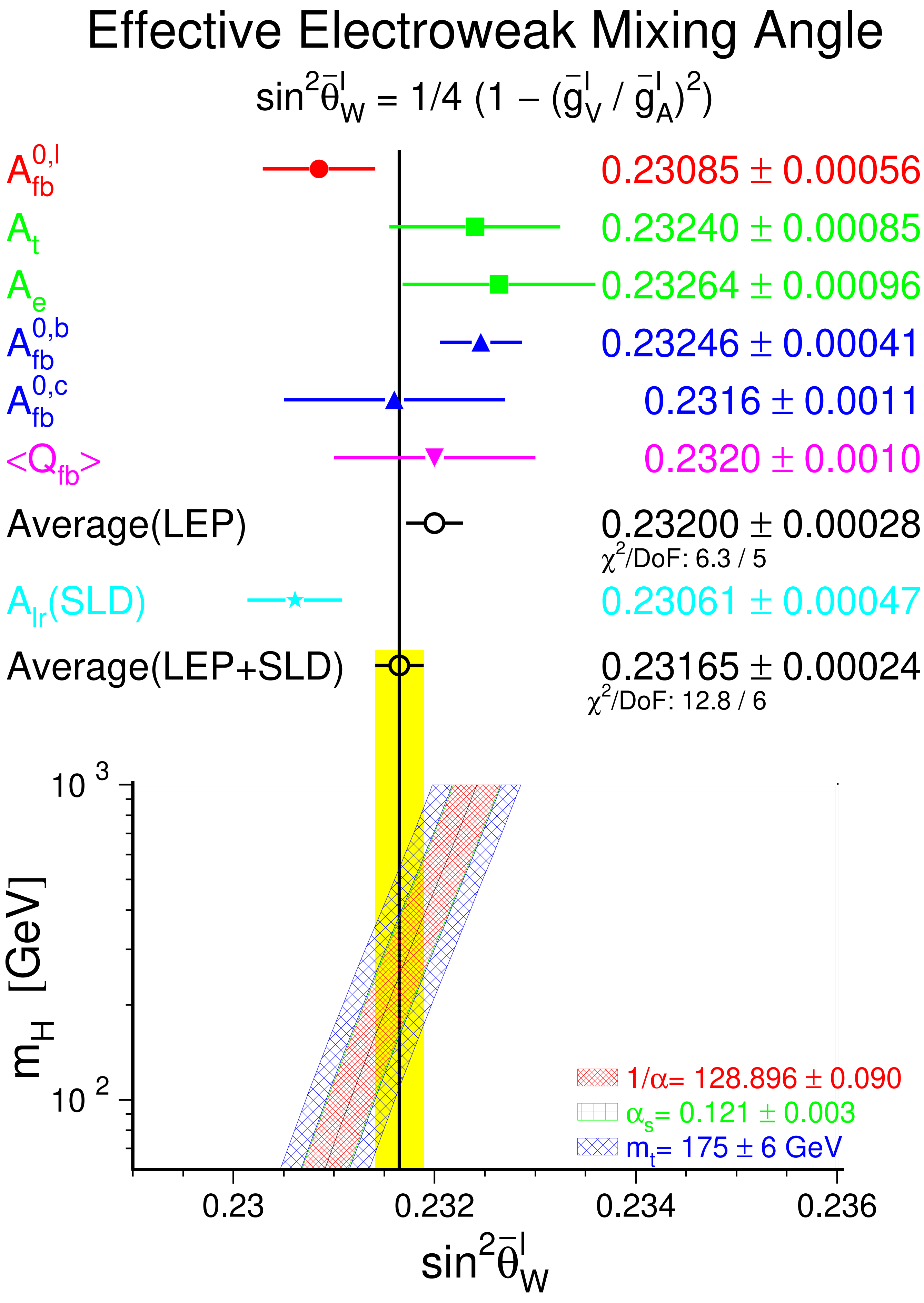
LEP effective lepton couplings:

$$\overline{g}_A^\ell = -0.50115 \pm 0.00034$$
$$\overline{g}_V^\ell = -0.03688 \pm 0.00085$$

The situation 1987 before LEP



Effective Couplings to the Z-Boson



lineshape and A_{fb}

m_Z [GeV]	91.1863 ± 0.0020
Γ_Z [GeV]	2.4946 ± 0.0027
σ^0_{had} [nb]	41.508 ± 0.056
R_ℓ	20.778 ± 0.029
$A_{fb}^{0,\ell}$	0.0174 ± 0.0010
	+ correlation matrix

τ polarisation

A_τ	0.1401 ± 0.0067
A_e	0.1382 ± 0.0076

b and c quark results

R_b	0.2179 ± 0.0012
R_c	0.1715 ± 0.0056
$A_{fb}^{0,b}$	0.0979 ± 0.0023
$A_{fb}^{0,c}$	0.0733 ± 0.0049
	+ correlation matrix

$q\bar{q}$ charge asymmetry

$\sin^2\overline{\theta}_W^\ell$ ($< Q_{fb} >$)	0.2320 ± 0.0010

The Standard Model is parametrised by:

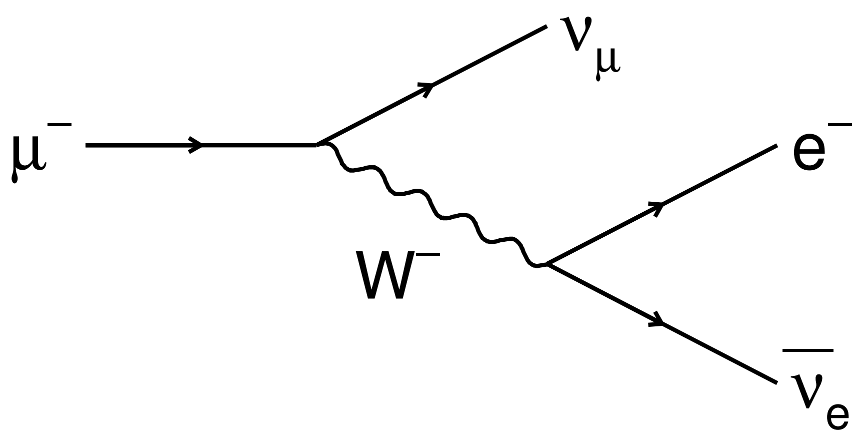
- electromagnetic and strong coupling (α, α_s)
- boson masses (m_Z, m_W, m_H)
- fermion masses + CKM matrix (m_t)

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:

$$1/\alpha = 128.896 \pm 0.090$$

LEP data and G_F and α measurements:

$1/\alpha$	128.916	± 0.083	$^{+0.019}_{-0.035}$
α_s	0.122	± 0.003	± 0.002
m_W [GeV]	80.292	± 0.046	$^{+0.010}_{-0.017}$
m_t [GeV]	171	$^{+8.1}_{-8.5}$	$^{+17}_{-19}$
χ^2/DoF	10.2 / 9		

m_H fixed to 300 GeV
m_H variation 60-1000 GeV gives second error.

Comments:

- fit result for m_t agrees with direct measurements:
  $m_t = 175 \pm 6$ GeV CDF/DØ
- fit result for m_W is in agreement with the direct measurements:
  $m_W = 80. \quad \pm 0.$ GeV LEP2
  $m_W = 80.356 \pm 0.125$ GeV CDF/DØ
- fit error on m_W is significantly smaller than error from direct measurements

LEP data only (no G_F, α):

$1/\alpha$	129.01	± 0.22	${}^{+0.10}_{-0.23}$
α_s	0.114	± 0.006	
m_W [GeV]	80.00	${}^{+0.18}_{-0.22}$	± 0.06
m_t [GeV]	98	${}^{+46}_{-54}$	
χ^2/DoF	7.1 / 7		

m_H fixed to 300 GeV
m_H variation 60-1000 GeV gives second error.
Correlation between parameters:

	$1/\alpha$	α_s	m_W	m_t
$1/\alpha$	1.000	–0.024	–0.248	–0.283
α_s		1.000	0.791	0.802
m_W			1.000	0.998
m_t				1.000

Comments:

- G_F measurement has a large influence on m_W and m_t determination
- LEP1 without G_F not very sensitive to m_W
- error of G_F measurement has no influence
- Sensitivity to m_t and m_H mostly via radiative corrections Δr

Further Input data to Standard Model Fits

left–right asymmetry	SLD	
$\sin^2\overline{\theta}^{\ell}_{W}$ (A_{lr})		0.23061 ± 0.00047
b and c quark results	SLD	
R_b		0.2149 ± 0.0038
A_b		0.863 ± 0.049
A_c		0.625 ± 0.084
weak mixing angle	CCFR, CDHS, CHARM	
$1 - m^2_W/m^2_Z$		0.2244 ± 0.0042
m_W and m_t	CDF, DØ, UA2	
m_W		80.356 ± 0.125
m_t		175 ± 6

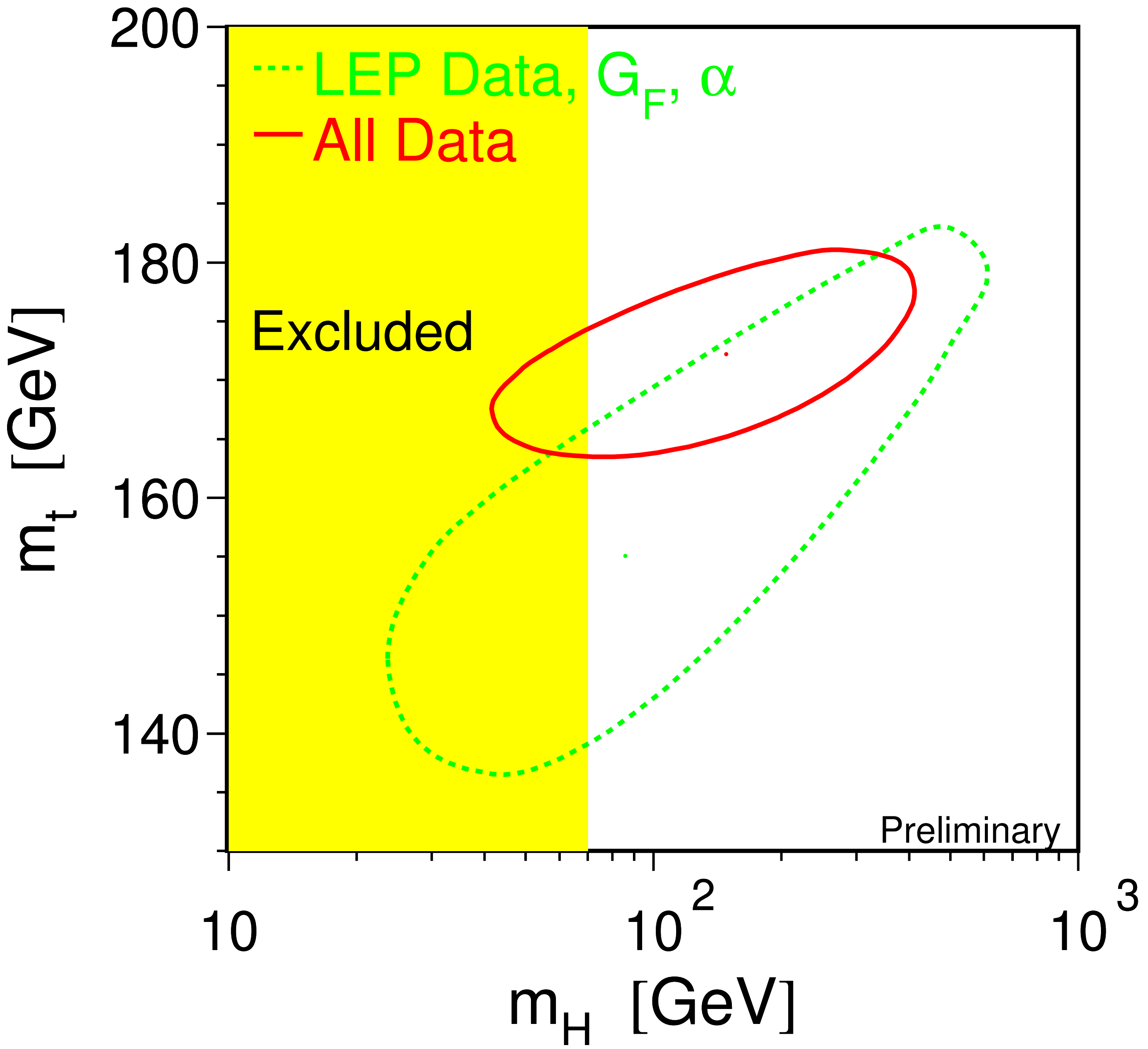
All electroweak Data as Input:

$1/\alpha$	128.905 ± 0.090
α_s	0.120 ± 0.003
m_W [GeV]	80.352 ± 0.033
m_t [GeV]	172 ± 6
m_H [GeV]	$149\ ^{+148}_{-82}$
χ^2/DoF	19.5 / 14

Attention:
m_H enters radiative corrections as $\log(m_H)$

Using all data:

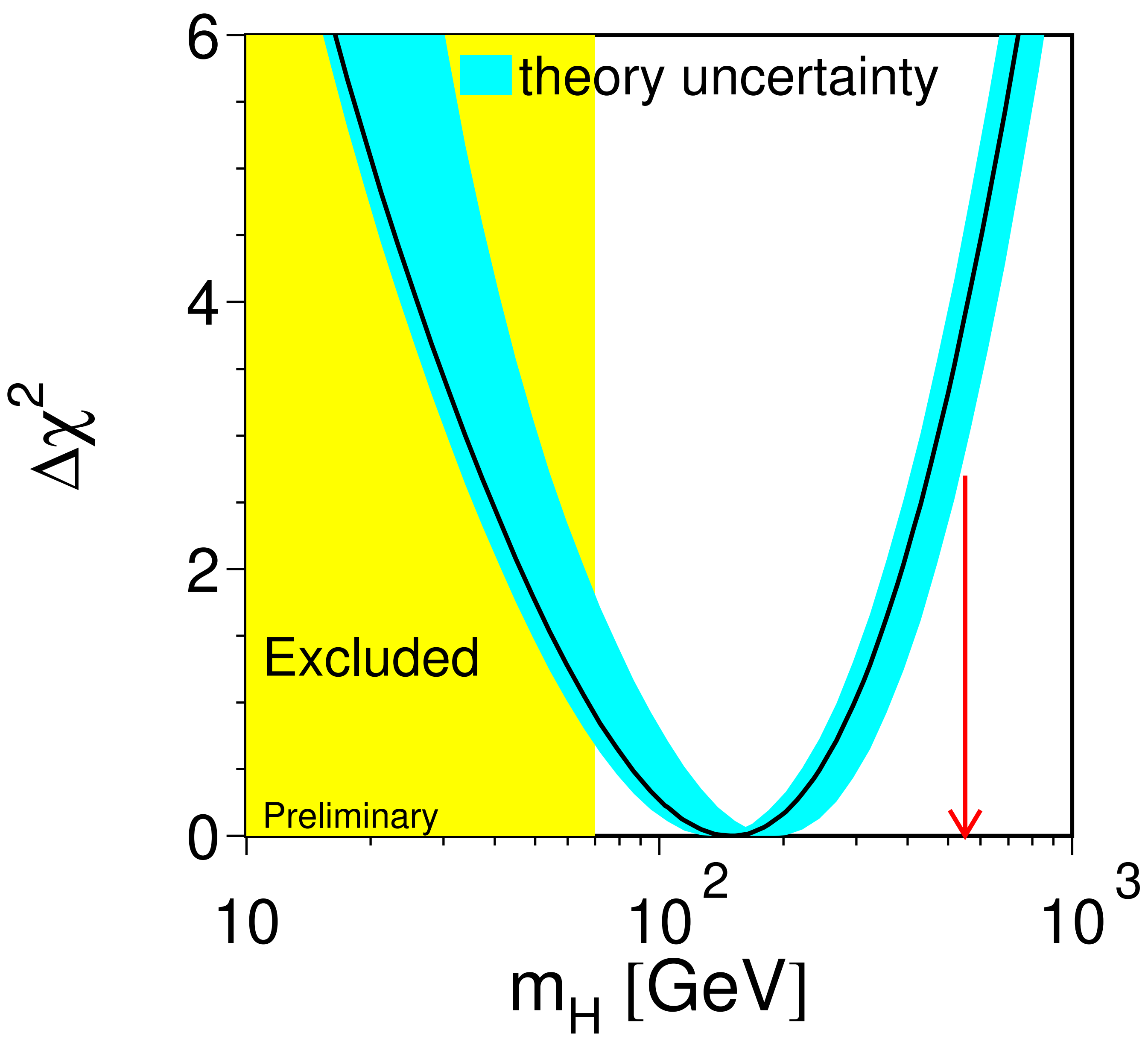
$$m_H = 149^{+148}_{-82} \qquad \log(m_H) = 2.17^{+0.30}_{-0.35}$$



Upper Limit Higgs–Boson Mass?

Theoretical uncertainties from comparing:
 BHM (Burgers et.al.),
 ZFITTER (Bardin et.al.),
 TOPAZ0 (Montagna et.al.)
Upper limit at 95% confidence level:

$m_{\mathrm{H}} < 550 \;\; \mathrm{GeV}$

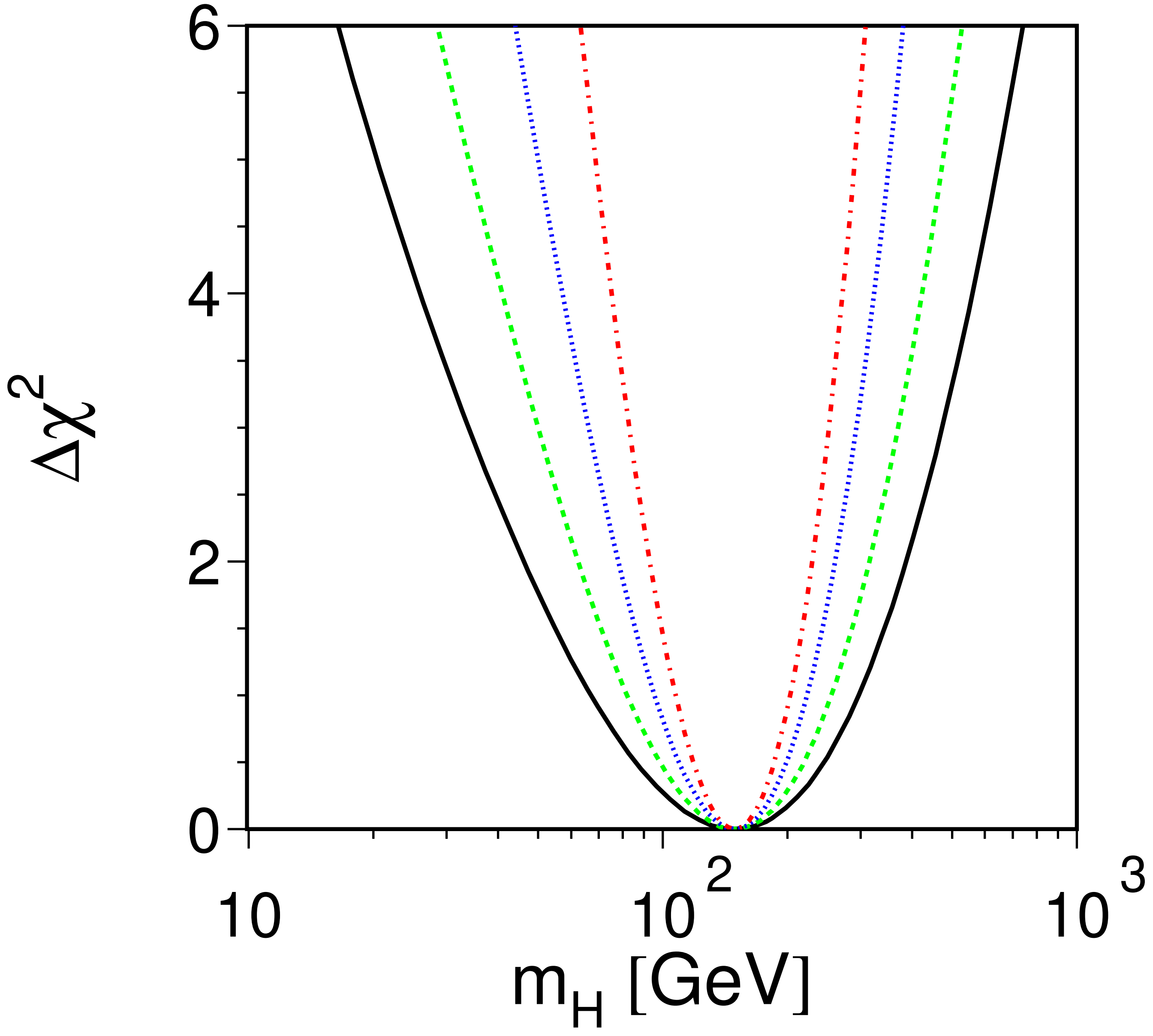


Improvement in calculations desirable!

Prospects for the m_H Constraints

Possible future improvements:

- measure m_t to 1 GeV
- measure m_W to 30 MeV
- measure $1/\alpha$ to 0.010

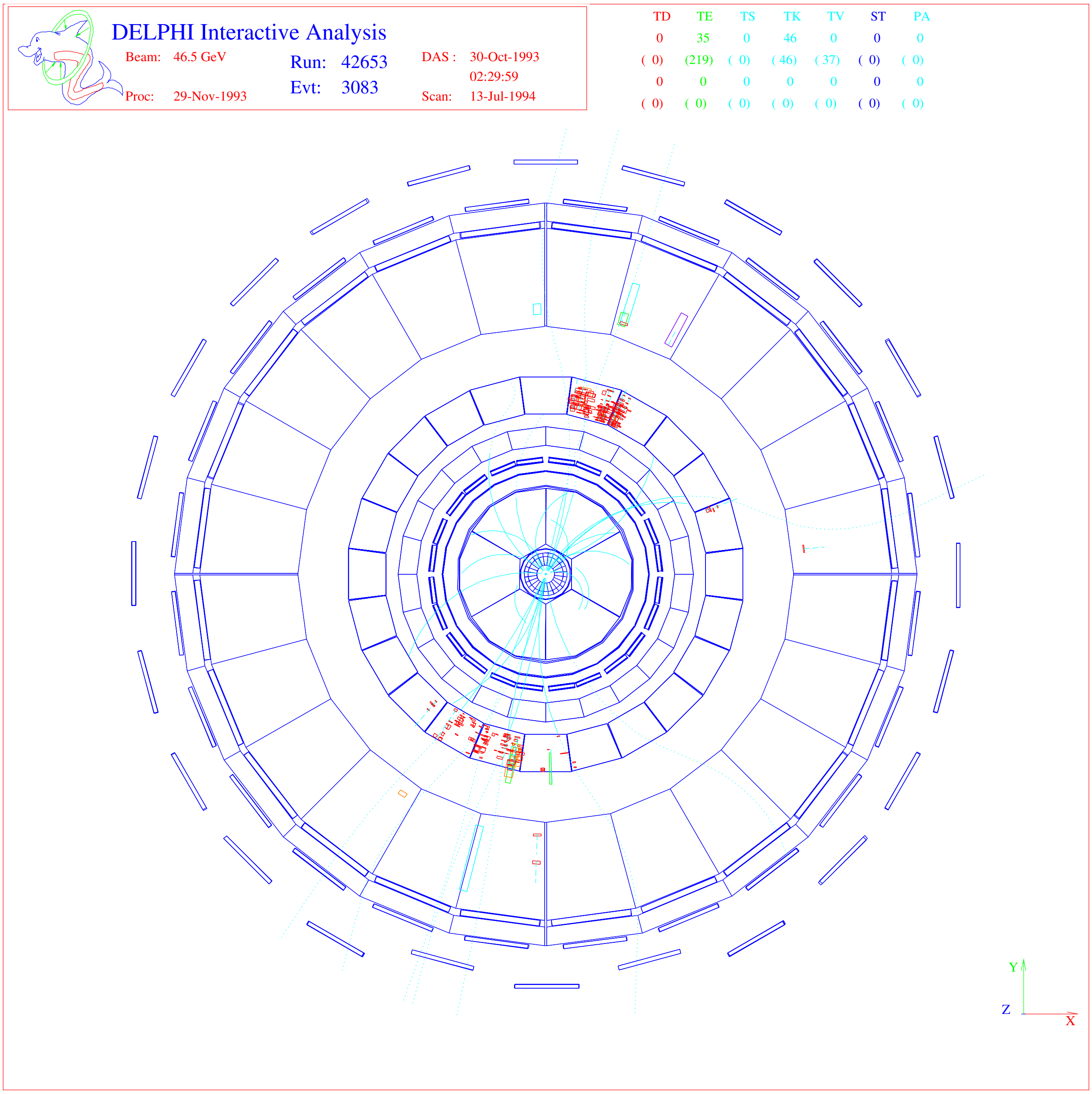


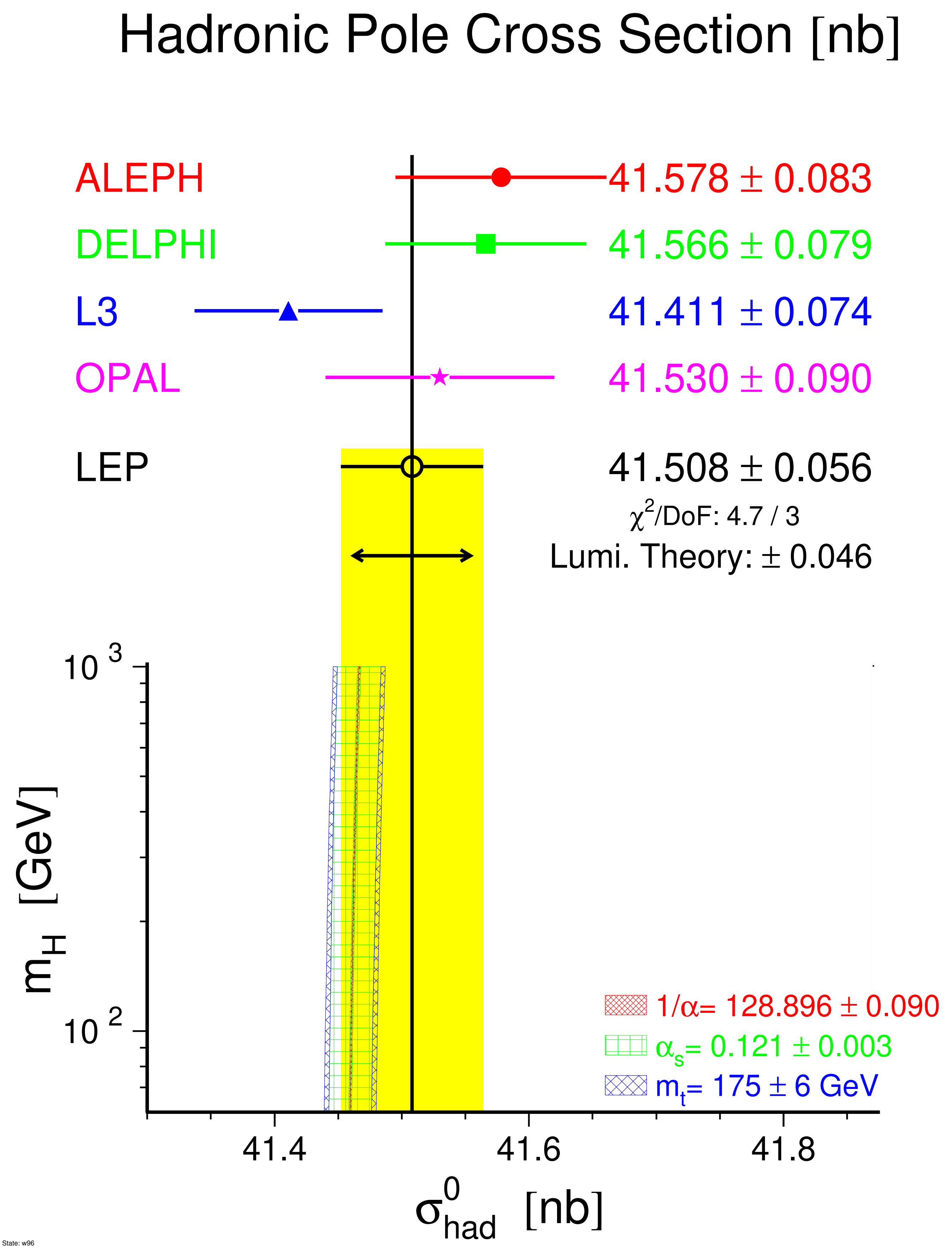
Conclusion

* LEP1 is a great success:
  - m_Z measured: $m_Z = 91186.3 \pm 2.0$ MeV
  - lepton couplings measured:
    $\sin^2\overline{\theta}_W^{\ell} = 0.23200 \pm 0.00028$
  - lepton universality is confirmed
  - α_s measured:
    $\alpha_s = 0.122 \pm 0.003 \pm 0.002(m_H)$
    with comparable precision as PDG.
  - m_t predicted by LEP in agreement with CDF/DØ
  - upper limit on m_H: $m_H < 550$ GeV
  - further improvement on m_Z, Γ_Z expected

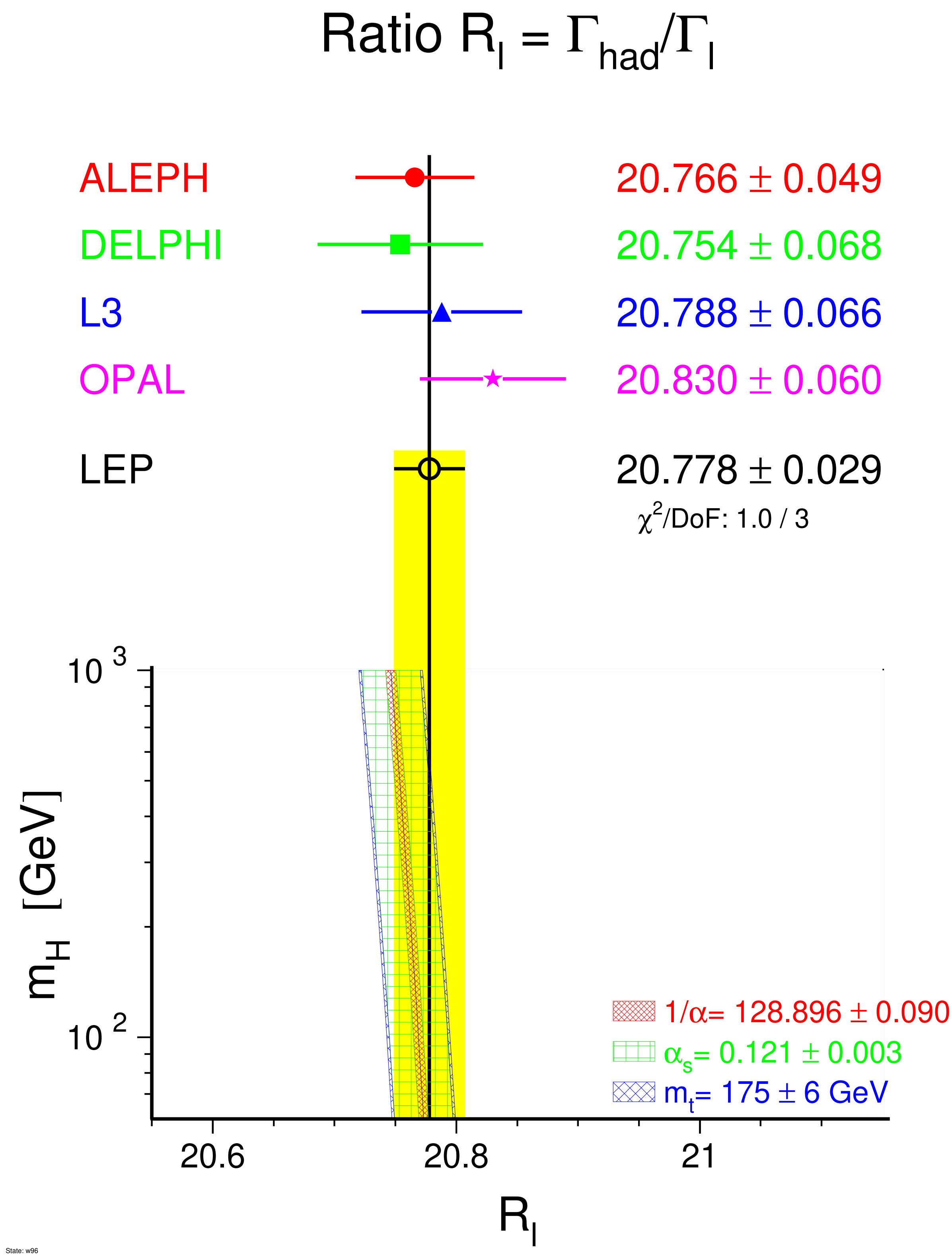
* LEP2 program offers new important measurements and we hope for more data and measurements to come
* The Standard Model is in perfect shape !

DELPHI: $e^+e^- \rightarrow$ hadrons(γ)



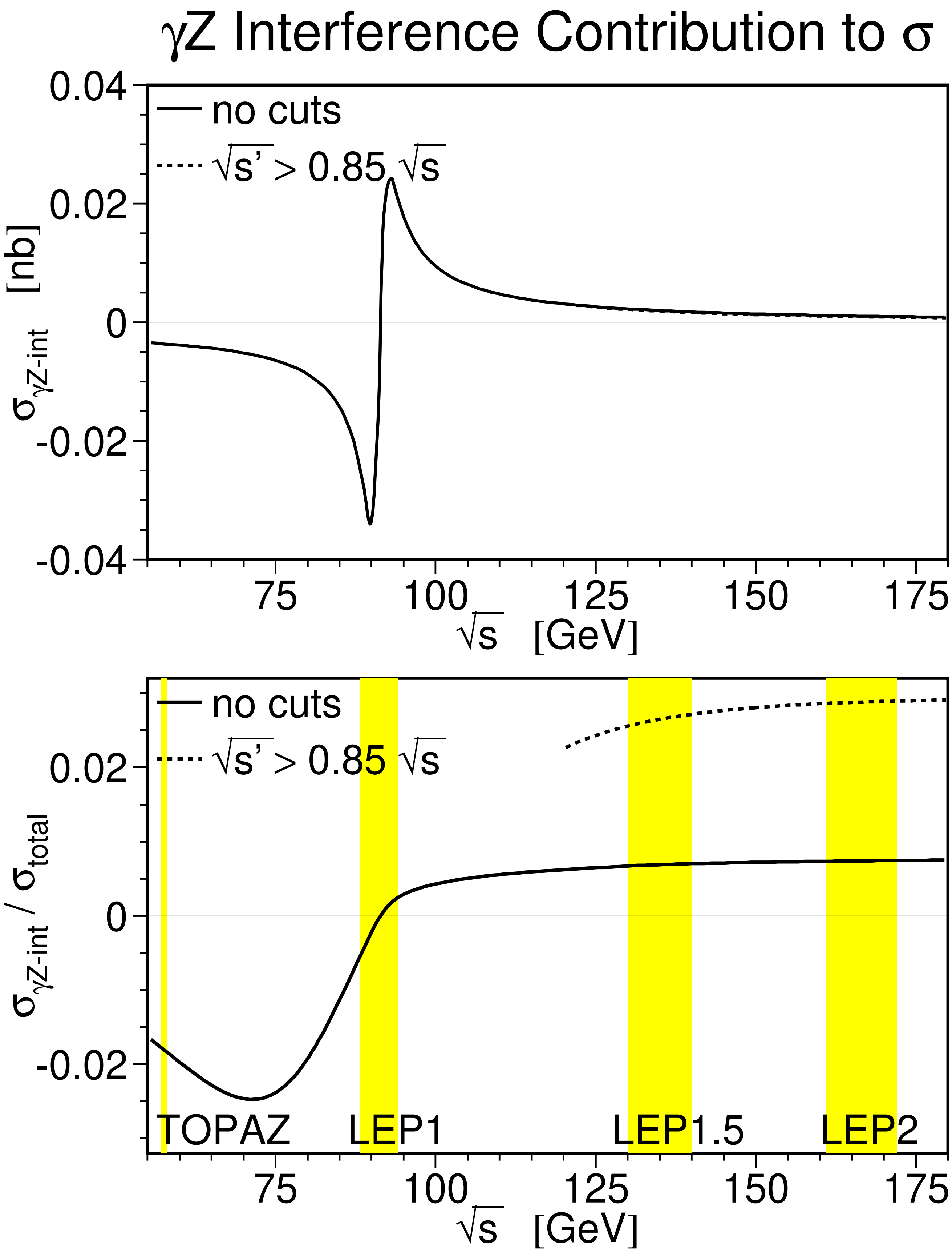

Hadronic Pole Cross Section [nb]
ALEPH
41.578 ± 0.083
DELPHI
41.566 ± 0.079
L3
41.411 ± 0.074
OPAL
41.530 ± 0.090
LEP
41.508 ± 0.056
χ2/DoF: 4.7 / 3
Lumi. Theory: ± 0.046
10 3
10 2
mH [GeV]
1/α= 128.896 ± 0.090
αs= 0.121 ± 0.003
mt= 175 ± 6 GeV
41.4
41.6
41.8
σ0had [nb]
State: w96

Results from Cross Section Measurements

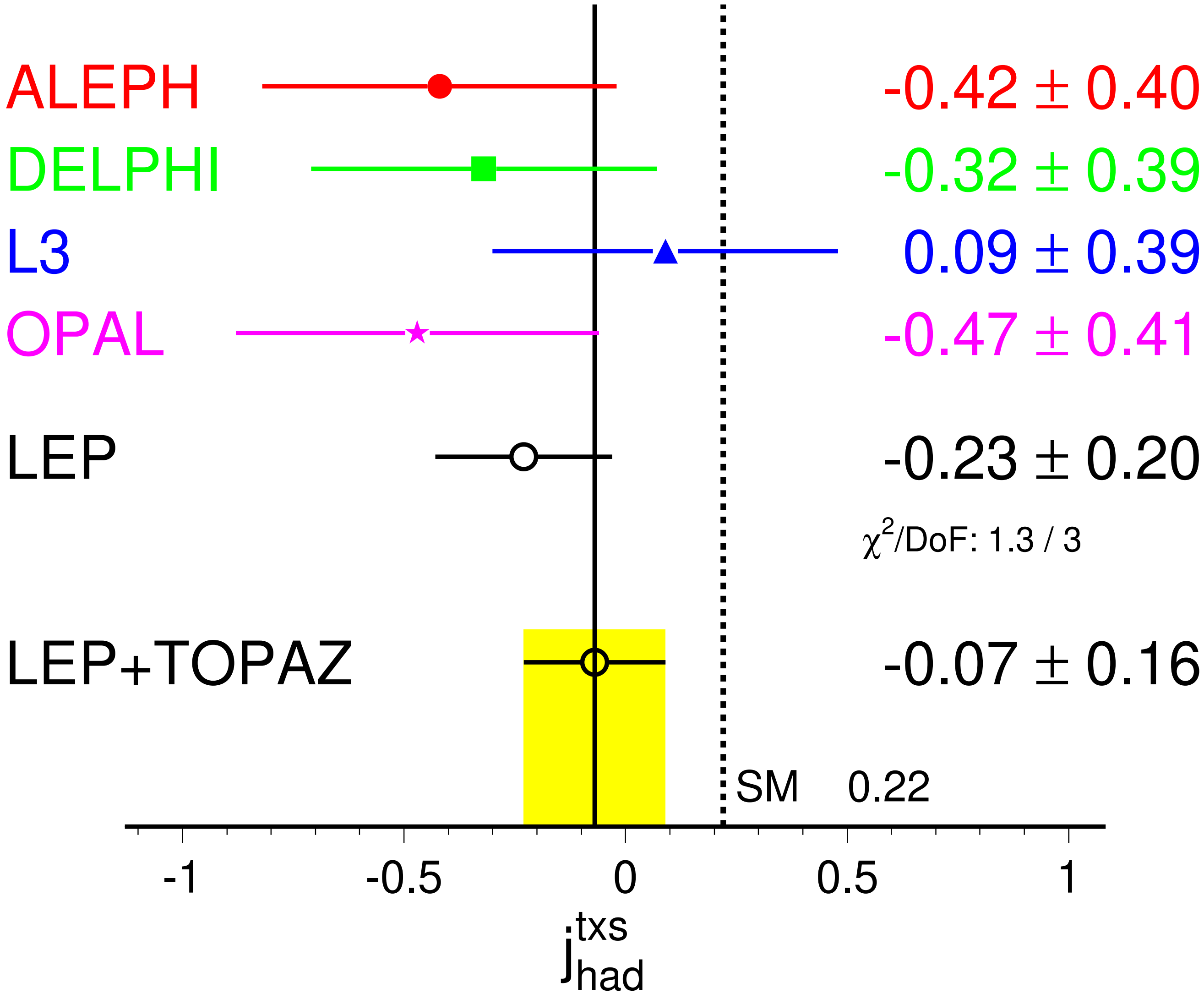


m_t and m_H dependencies mostly cancel:

- sensitivity to α_S


γZ Interference Contribution to σ
0.04
0.02
0
-0.02
-0.04
$\sigma_{\gamma Z\text{-int}}$ [nb]
no cuts
$\sqrt{s'} > 0.85\sqrt{s}$
75
100
125
150
175
$\sqrt{s}$ [GeV]
0.02
0
-0.02
$\sigma_{\gamma Z\text{-int}} / \sigma_{total}$
TOPAZ
LEP1
LEP1.5
LEP2

Hadronic γZ interference term

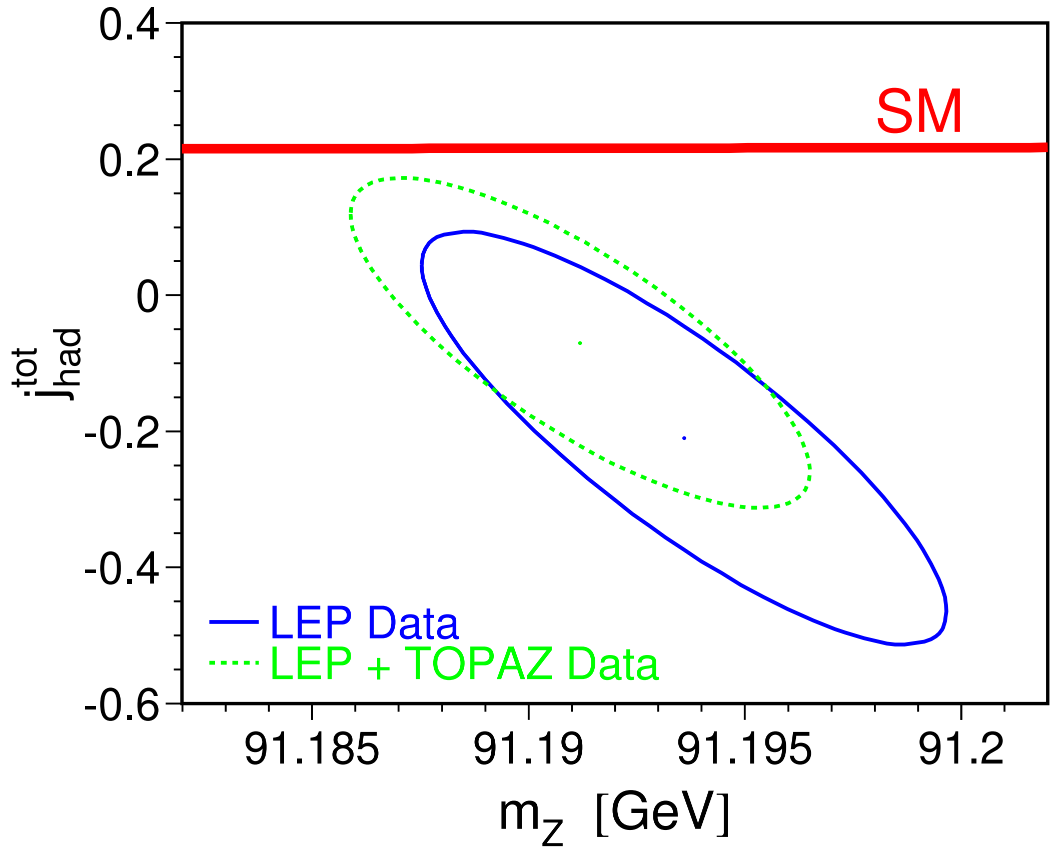


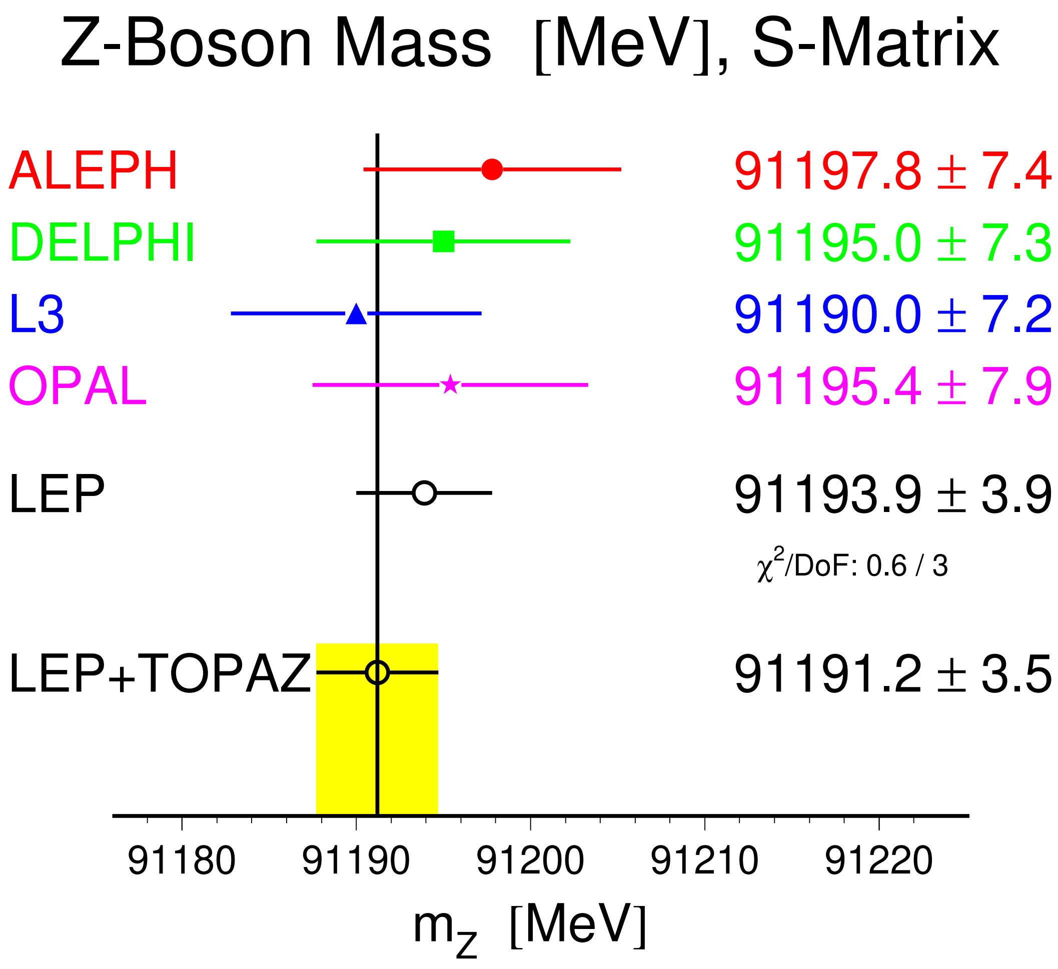
TOPAZ measures at 57.77 GeV:

$$\sigma_{had}^{born} = 143.6 \pm 4.7 \text{ pb}$$

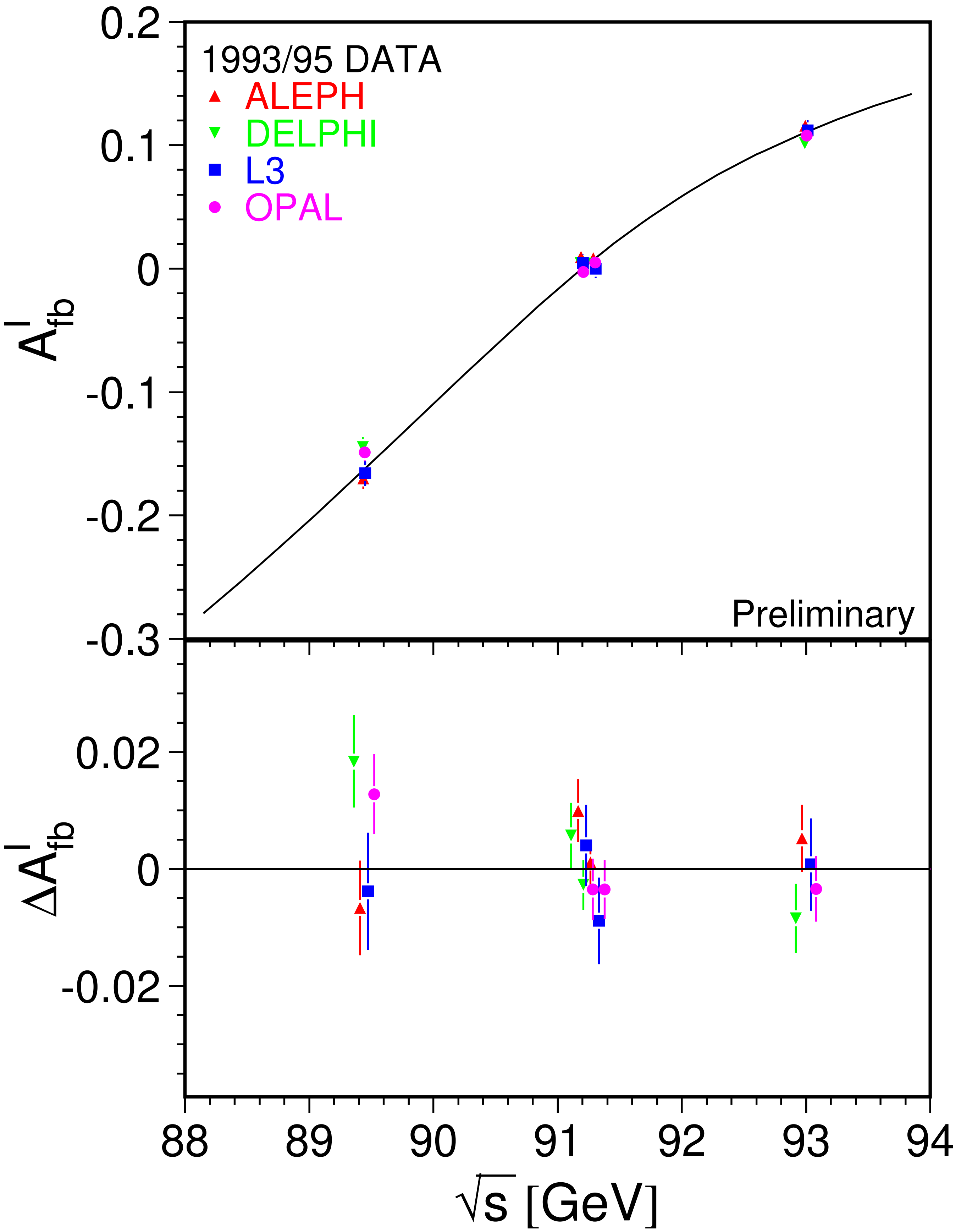
Further improvement from 1996 LEP2 data by a factor of ≈ 1.5.

S-Matrix Interpretation of Cross Sections



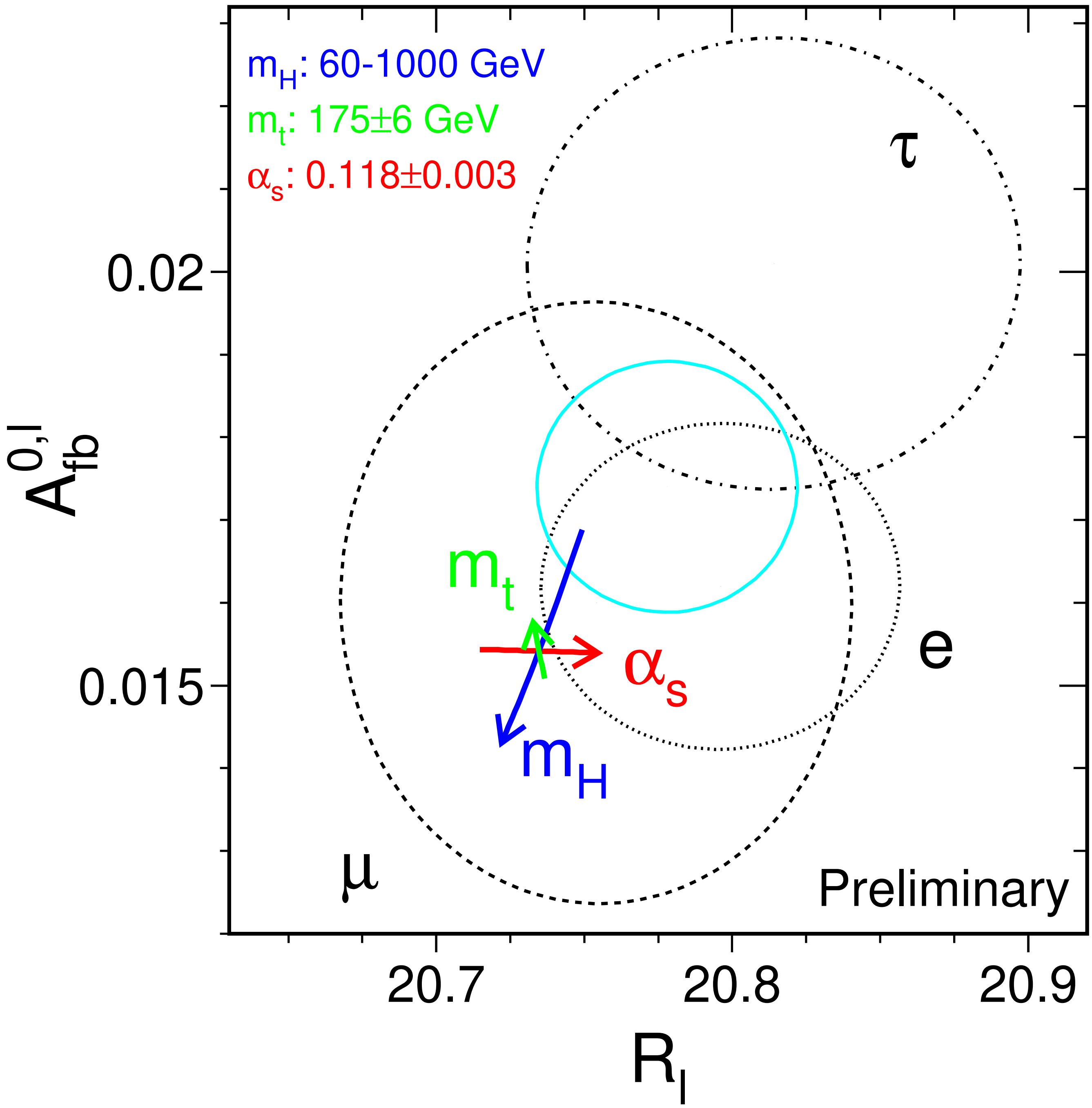


Asymmetry Measurements



All lepton asymmetries are combined

Test of lepton universality



La Thuile 1997

	Measurement	Pull
m_Z [GeV]	91.1863 ± 0.0020	.09
Γ_Z [GeV]	2.4946 ± 0.0027	-.50
σ^0_{hadr} [nb]	41.508 ± 0.056	.77
R_e	20.778 ± 0.029	.72
$A^{0,e}_{fb}$	0.0174 ± 0.0010	1.45
A_τ	0.1401 ± 0.0067	-.85
A_e	0.1382 ± 0.0076	-1.00
R_b	0.2178 ± 0.0011	1.82
R_c	0.1715 ± 0.0056	-.14
$A^{0,b}_{fb}$	0.0979 ± 0.0023	-1.88
$A^{0,c}_{fb}$	0.0735 ± 0.0048	.11
A_b	0.863 ± 0.049	-1.46
A_c	0.625 ± 0.084	-.50
$\sin^2\bar{\theta}^e_w$	0.2320 ± 0.0010	.33
$\sin^2\bar{\theta}^e_w$	0.23061 ± 0.00047	-2.27
m_W [GeV]	80.36 ± 0.13	.03
$\sin^2\theta_w$	0.2244 ± 0.0042	.21
m_t [GeV]	175.0 ± 6.0	.47
$1/\alpha$	128.894 ± 0.090	-.12