The Z^0 Lineshape and Lepton Asymmetries at LEP

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on behalf of the
LEP collaborations
ALEPH, DELPHI, L3, OPAL

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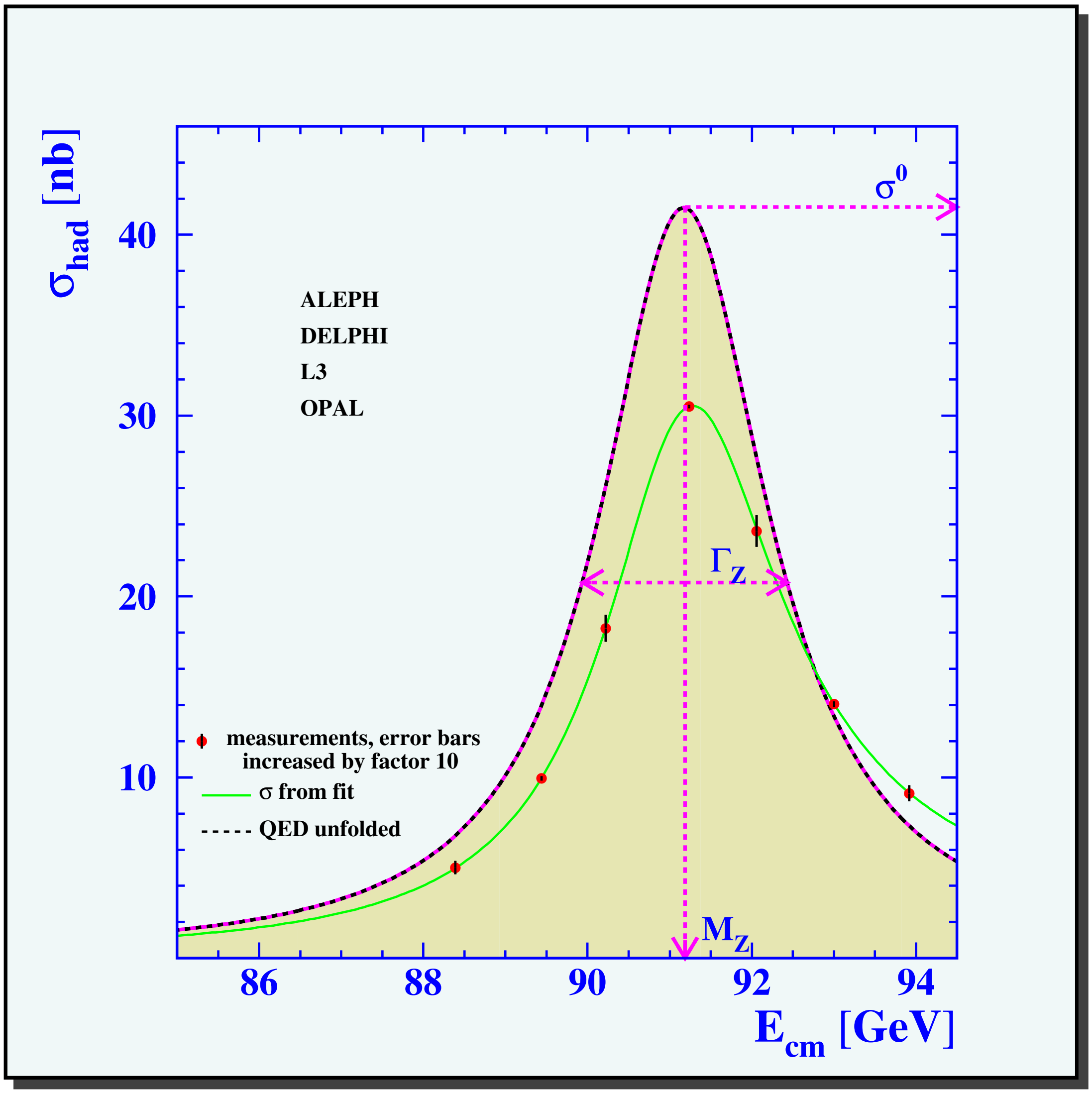
- Introduction
- History & Status
- σ/A_{FB} Measurements & Fits
- Combination & Common Errors
- Results

Z^0 Lineshape

Cross-sections for

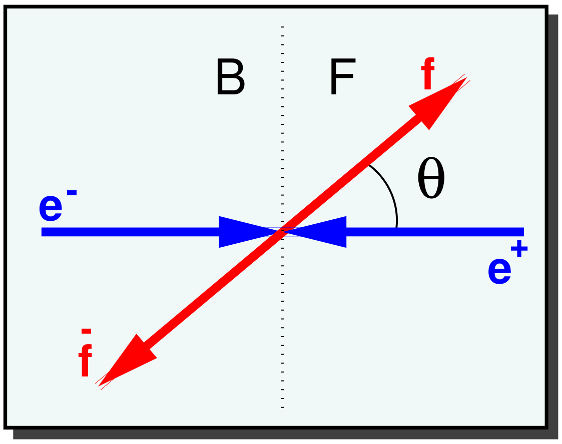
$e^+e^- \to q\bar{q}$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ at $E_{cm} = m_Z \pm 3\,\mathrm{GeV}$



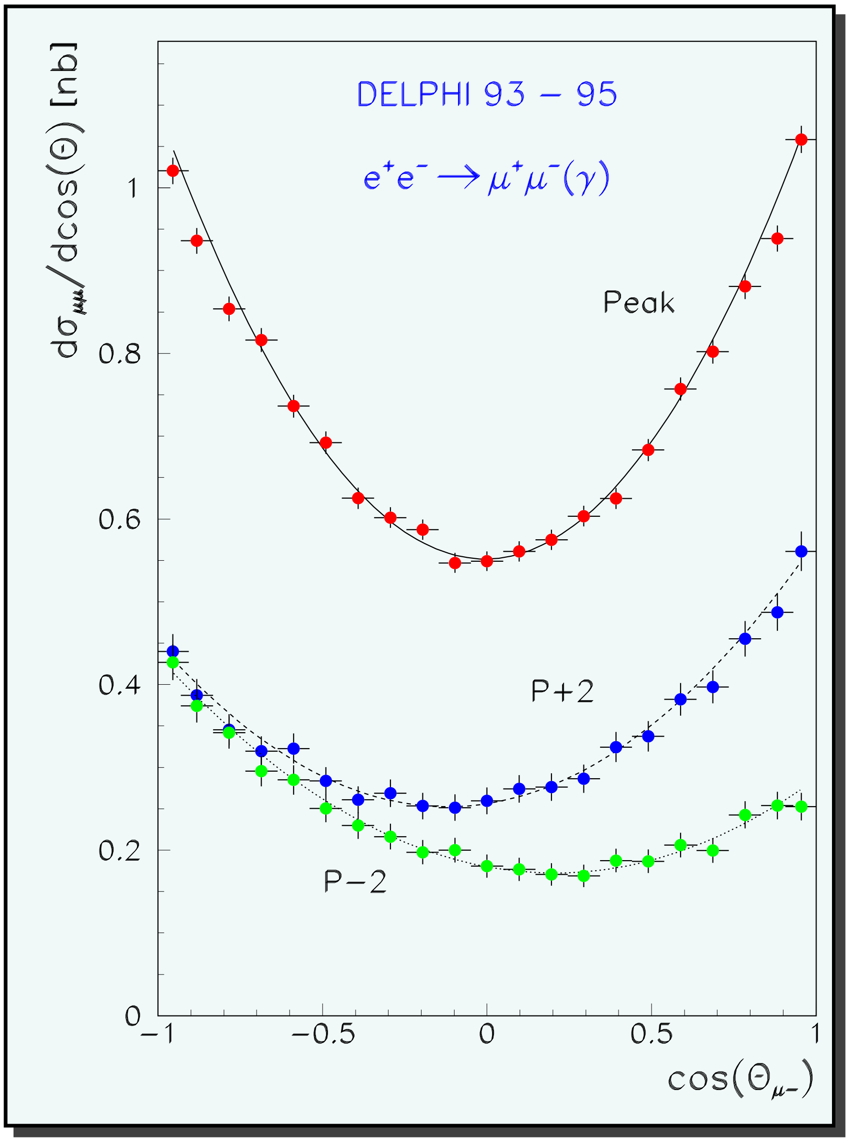
Determine basic Z^0 parameters:

mass m_Z, width Γ_Z and pole-cross-sections σ_f^0.

Lepton Asymmetries



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}\left(1+\cos^2\theta\right) + A_{\mathrm{FB}}\ \cos\theta$$



At $\sqrt{s} = m_{\mathrm{Z}}$:

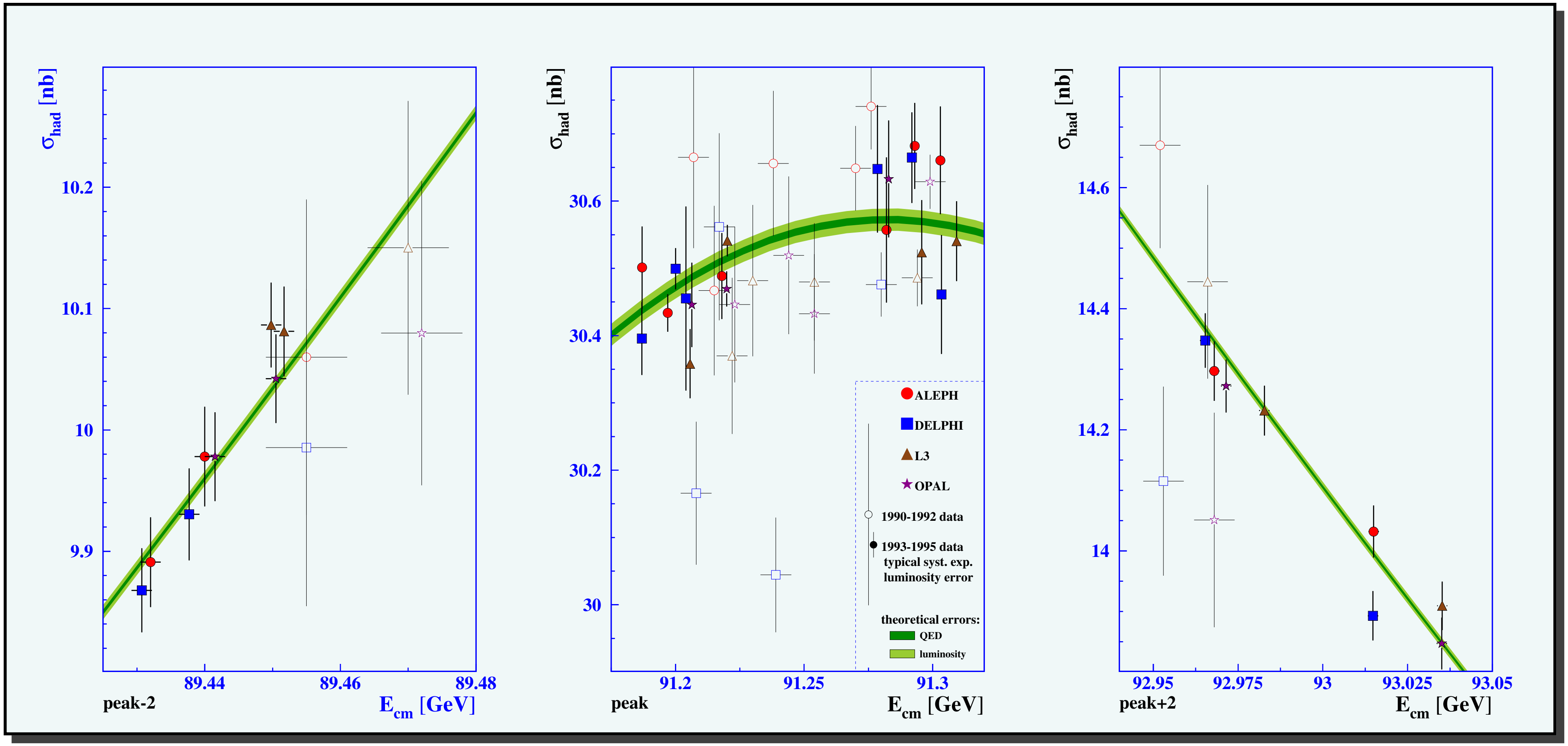
$A^{0,\mathrm{f}}_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{f}}$ with

$$\mathcal{A}_{\mathrm{f}} = 2\,\frac{g_{\mathrm{Vf}}\,g_{\mathrm{Af}}}{g^2_{\mathrm{Vf}} + g^2_{\mathrm{Af}}}$$

LEP 1 History and Status

- 1989 Start of LEP, wide 11 pt energy scan, $\mathcal{L} = 1.3\,\text{pb}^{-1}$.
- 1990-92 1st phase, ≈ 5 M Z^0 decays, $\approx 1/3\ \mathcal{L}$ off-peak.
- 1991 First precision calibration of E_{cm} with resonant depol.
- 1992/93 All four LEP expts. upgrade their luminometers $\Rightarrow (\delta\mathcal{L}/\mathcal{L})_{\text{exp}} < 1 \times 10^{-3}$
- 1993-95 2nd phase, ≈ 12 M Z^0 decays, $\approx 1/3\ \mathcal{L}$ off-peak.
- End 1997 LEP energy calibration finalized
- 1995 Precision calculation workshop — D. Bardin *et al.* YR-CERN-95-03
- 1998 Theoretical lumi error reduced to 0.6×10^{-3} — B.F.L Ward *et al.* PL**B 450** (1999) 262
- 1999 Detailed ZFITTER/TOPAZ comparison — D. Bardin *et al.* hep-ph/9902452
- 1999 $\mathcal{O}(\alpha^3)$ evaluation of ISR corrections , improved ISPP evaluation — S. Jadach *et al.* PL**B 456** (1999) 77; A. Arbuzov hep-ph/9907500
- ALEPH summer 99, CERN-EP/99-104, EPJ **C14** (2000) 1.
- L3, DELPHI early 2000, CERN-EP/00-022, EP/00-037.
- OPAL almost finished, currently approved by collaboration, $\mathcal{O}$(weeks).

Hadron cross-sections at LEP 1



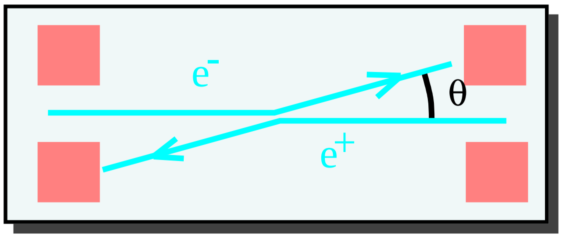
$$\sigma_f(\sqrt{s}) = \frac{N^f_{\text{sel}} - N_{\text{bg}}}{\varepsilon \int \mathcal{L}\,\mathrm{dt}}$$

Selections: Clear signatures for $\mathrm{e^+e^-}$, $\mu^+\mu^-$, $\tau^+\tau^-$, $\mathrm{q\bar{q}}$, high efficiencies ($\approx 99\,\%$) and low background ($\leq 1\,\%$).

	ALEPH	DELPHI	L3	OPAL
σ_{had}	0.072 %	0.11 %	0.041 %	0.073 %
σ_e	0.16 %	0.52 %	0.17 %	0.14 %
σ_μ	0.09 %	0.26 %	0.31 %	0.10 %
σ_τ	0.18 %	0.60 %	0.65 %	0.42 %
$\mathcal{L}_{\text{exp}}$	0.073 %	0.09 %	0.064 %	0.033 %

Luminosity: Small-angle Bhabha-scattering as reference

- Precisely calculable in QED
- Large statistics
- High precision after upgrades

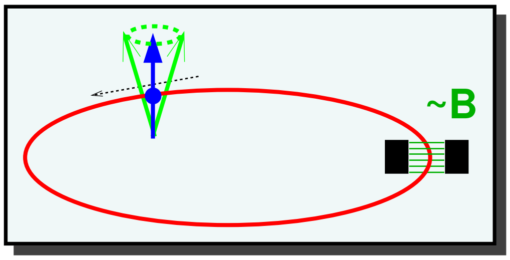


LEP energy: $g-2$ experiment, $\Delta E^{\text{RD}}_{\text{beam}}$ $\mathcal{O}(0.1\,\text{MeV})$

But special LEP configuration

$\Rightarrow$ extrapolation to average physics

- Tidal deformations
- Leakage currents
- IP specific corrections



Effective uncertainties: $\Delta m_Z = 1.7$ MeV $\Delta\Gamma_Z = 1.2$ MeV

Lineshape Fits

Complete 1990-95 data set about ≈ 200 measured σ and A_{FB} per experiment.

Lineshape parameters determined in χ^2 fit using the latest versions of ZFITTER (6.23) and TOPAZ0 (4.4)

$$\boxed{\chi^2 = \sum (\sigma_i^{\mathsf{meas}} - \sigma_i^{\mathsf{fit}})\, C_{ij}^{-1}\, (\sigma_j^{\mathsf{meas}} - \sigma_j^{\mathsf{fit}})}$$

The covariance matrix accounts for all uncertainties from statistic, selection, luminosity, t-channel correction and LEP E_{cm}:

$$\boxed{C_{ij} = C_{ij}^{\mathsf{stat}} + C_{ij}^{\mathsf{syst}} + C_{ij}^{\mathsf{lumi}} + C_{ij}^{\mathsf{t-chan}} + C_{ij}^{E_{\mathsf{cm}}}}$$

Ideally, combined LEP results based on combined fit to all $4 \times 200\ \sigma/A_{\mathsf{FB}}$. However, too complex a task, approaches of the 4 expts in detail quite different.

Instead, average at the level of 9 pseudo-observables, the standard LEP 9 parameter set:

- $m_{\mathsf{Z}},\ \Gamma_{\mathsf{Z}},\ \sigma_{\mathsf{h}}^0$
- $R_{\mathsf{e}},\ R_\mu,\ R_\tau \qquad (R_\ell \equiv \frac{\Gamma_{\mathsf{had}}}{\Gamma_{\ell\ell}})$
- $A_{\mathsf{FB}}^{0,\mathsf{e}},\ A_{\mathsf{FB}}^{0,\mu},\ A_{\mathsf{FB}}^{0,\tau}$

accounting for correlations and common errors.

Common Errors

'Easy' to estimate for theoretical errors, no dependence on data-taking, similar for all expts:
Compare 2 fits switching on/off specific error source
$\Rightarrow$ quadratic difference of parameter-covariance matrix gives common error + correlations.

- **Luminosity theory:** Small-angle Bhabha cross-section calculated with BHLUMI 4.04, error estimate $\pm 0.061\,\%$
  B.F.L Ward *et al.*, PL**B 450** (1999) 262

  OPAL includes light-pair correction, error reduced to $\pm 0.054\,\%$ G. Montagna *et al.*, NP**B 547** (1999) 39

  Corresponding common error on σ^0_{h}

- ***t*-channel:** For large-angle Bhabha scattering corrections for t and s-t interference calculated with ALIBABA. Theoretical uncertainties evaluated comparing ALIBABA and TOPAZ0
  W. Beenakker and G. Passarino, PL**B 425** (1998) 199

  Specified in terms of σ_{F} and σ_{B}, effects consistent for ADLO

	R_{e}	$A^{0,\mathrm{e}}_{\mathrm{FB}}$
R_{e}	0.024	-0.0054
$A^{0,\mathrm{e}}_{\mathrm{FB}}$		0.0014

- **Fit programs:**

  Photonic corrections (ISR deconvolution) include leading $\mathcal{O}(\alpha^3)$ contributions. Comparing two different schemes and missing higher order corrections

  S. Jadach *et al.*, PL**B** **456** (1999) 77

  $\Rightarrow$ only 0.1 MeV (m_Z, Γ_Z) and 0.01 % σ_h^0.

  Fermion-pair radiation recently calculated in $\mathcal{O}(\alpha^3)$

  A. Arbuzov, hep-ph/9907500

  Error reduced to $m_Z \pm 0.3$ MeV, $\Gamma_Z \pm 0.2$ MeV, $\sigma_h^0 \pm 0.02\,\%$

  (Tampere '99: 0.5, 0.3, 0.02)

  TOPAZ and ZFITTER SM and MI calculations compared in detail in D. Bardin *et al.*, hep-ph/9902452

  Effective differences for fits small, only notable for $R_\ell \pm 0.004$

  Overall effects small, $\leq 20\,\%$ of total uncertainties

m_Z	Γ_Z	σ_h^0	R_ℓ	$A_{FB}^{0,\ell}$
0.3 MeV	0.2 MeV	0.008 nb	0.004	0.0001

- **LEP energy** uncertainties specified as covariance matrix, giving uncertainties and correlations of each energy point. Translation into uncertainties on POs more complicated. Method: vary energy errors by ε, repeat full σ/A_{FB} fit and extract effective energy error matrix for POs:

$$\boxed{\mathcal{V}_\pm = (1 \pm \varepsilon)\mathcal{V}_{E_{cm}} + \mathcal{V}_{exp} \;\rightarrow\; \mathcal{V}_{E_{cm}} = \frac{\mathcal{V}_+ - \mathcal{V}_-}{2\varepsilon}}$$

Studied by all expts, consistent $\mathcal{V}_{E_{cm}}$

m_Z	0.0017^2	-0.0006^2	-0.0018^2	0.0017^2
Γ_Z		0.0012^2	-0.0027^2	-0.0014^2
σ_h^0			0.011^2	0.0073^2
R_e				0.013^2

Changes since last summer

- Changes of experimental numbers marginal
- Rather large effect from ZFITTER 6.10 $\Rightarrow$ 6.23
  $\mathcal{O}(\alpha^3)$ treatment of fermion-pair radiation:
  $\Rightarrow\; m_Z \; + 0.5$ MeV , $\Gamma_Z \; + 0.7$ MeV ($\approx 25\,\%$ of error)

(ALEPH data re-fitted)

Results

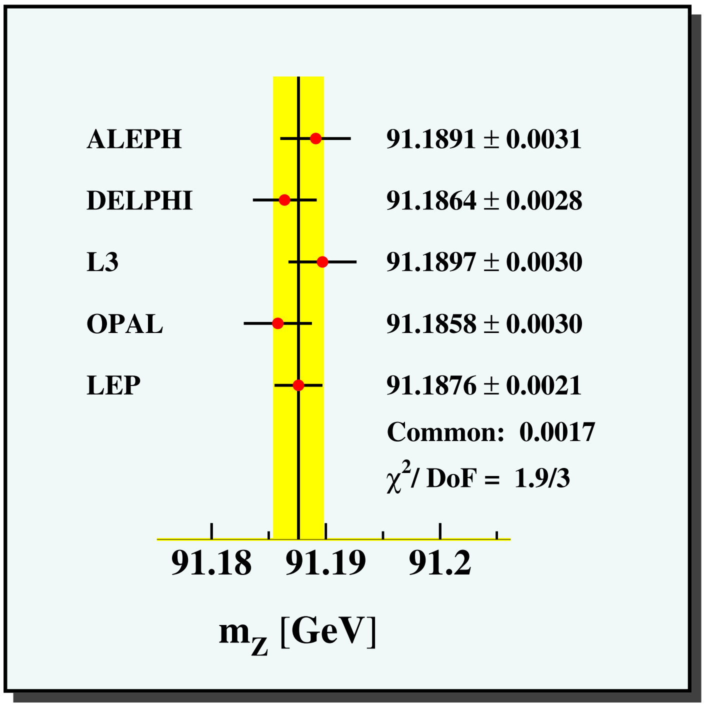
Combination: Fit to 4×9 PO

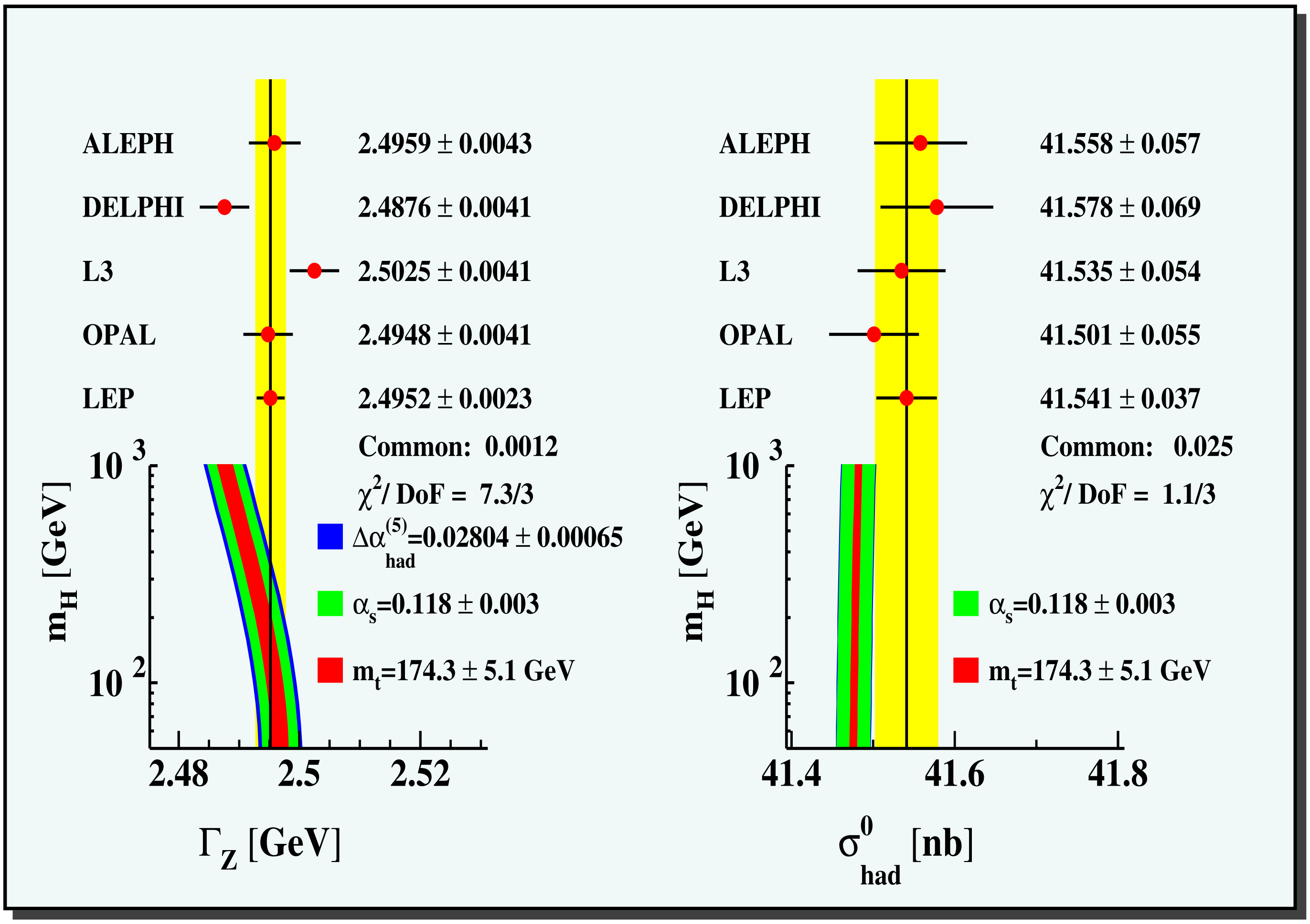
m_Z, Γ_Z, σ^0_h, R_e, R_μ, R_τ, $A^{0,e}_{FB}$, $A^{0,\mu}_{FB}$, $A^{0,\tau}_{FB}$

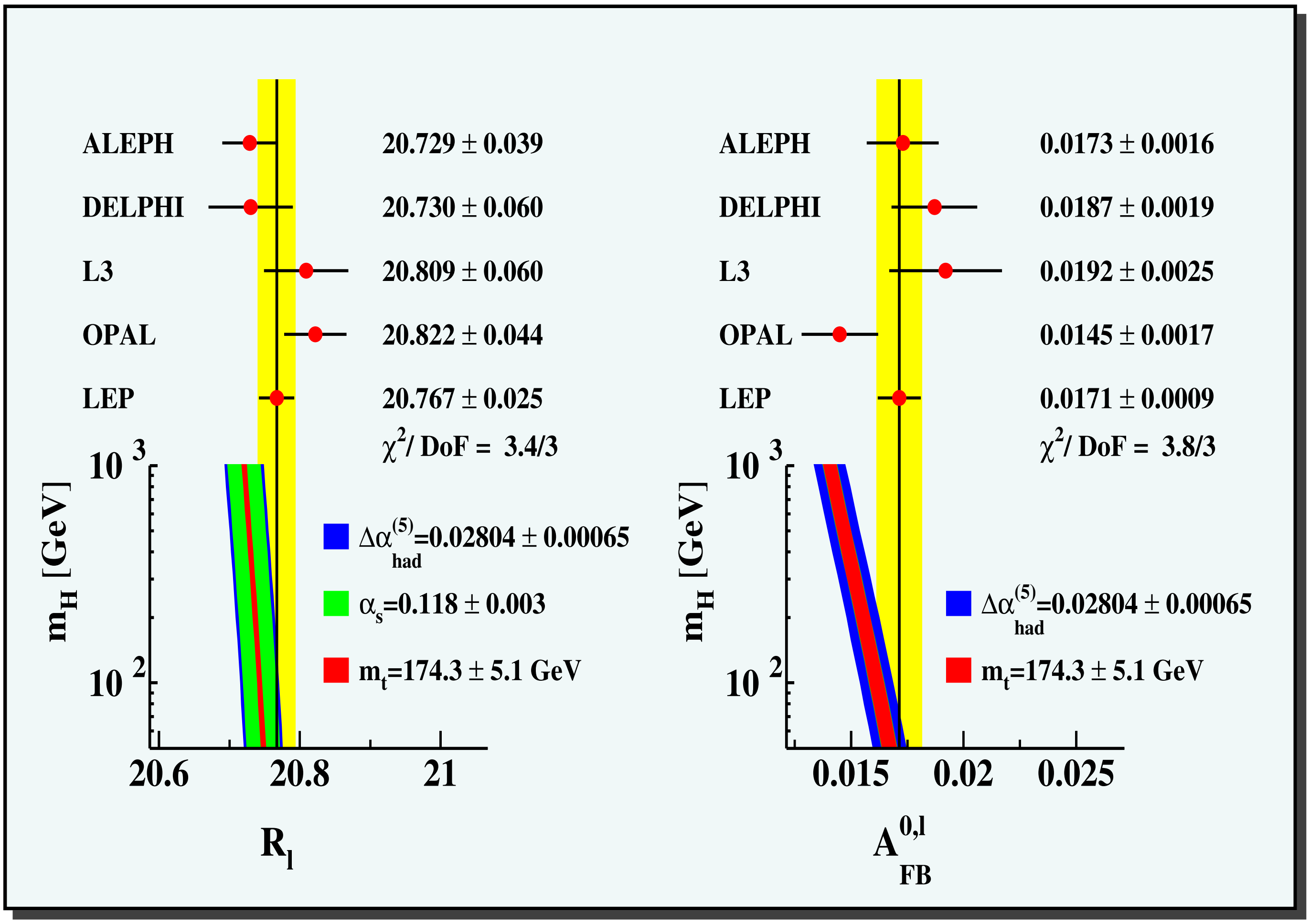
accounting for common errors and correlations.

Good consistency:

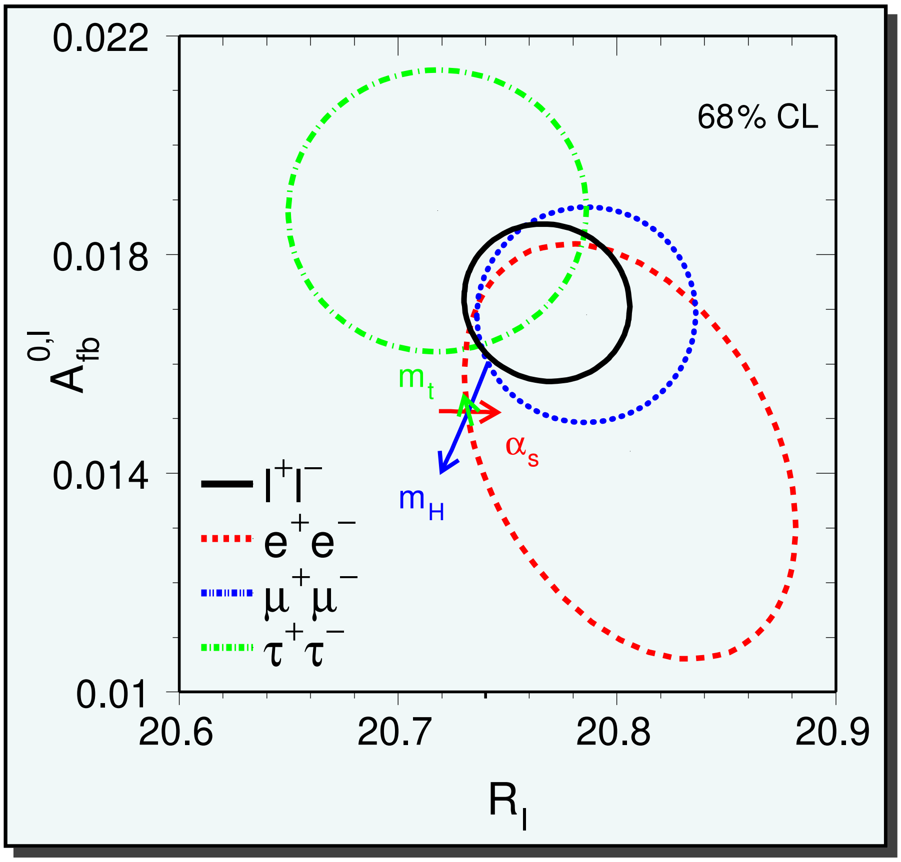
$\chi^2/\mathrm{d.o.f.} = 32.6/27$ (21 % prob., 9-par average)



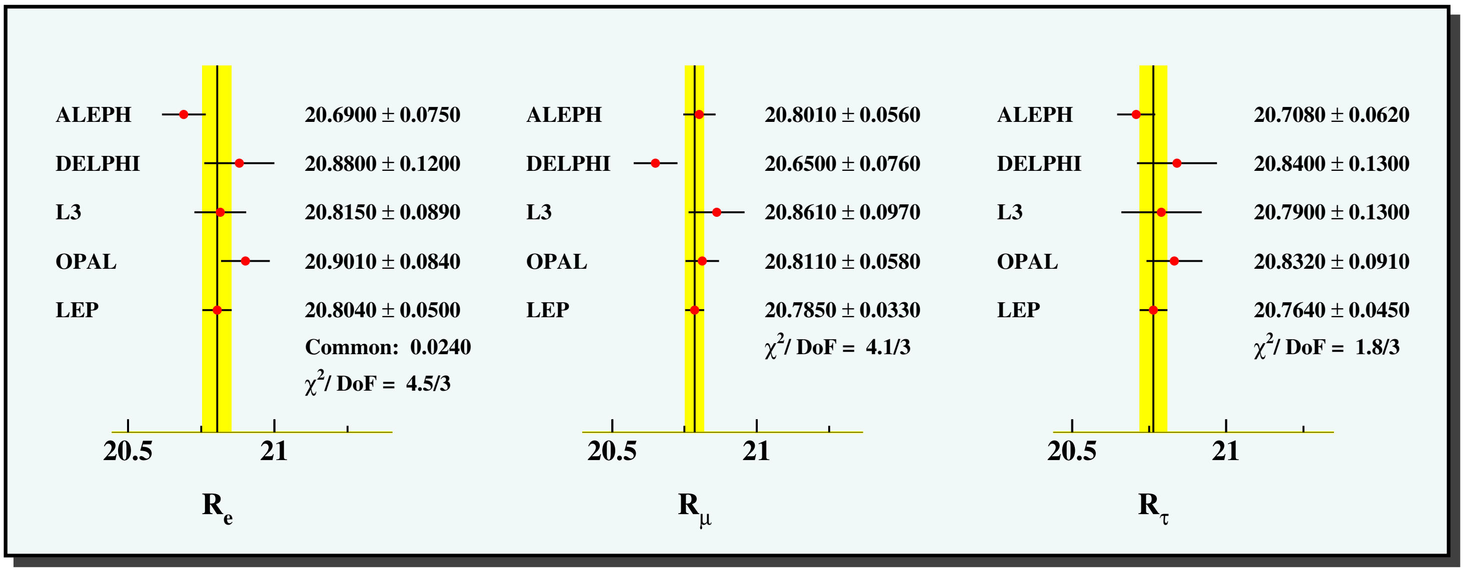




Results for R_ℓ and $A_{\mathrm{FB}}^{0,\ell}$ consistent with lepton universality



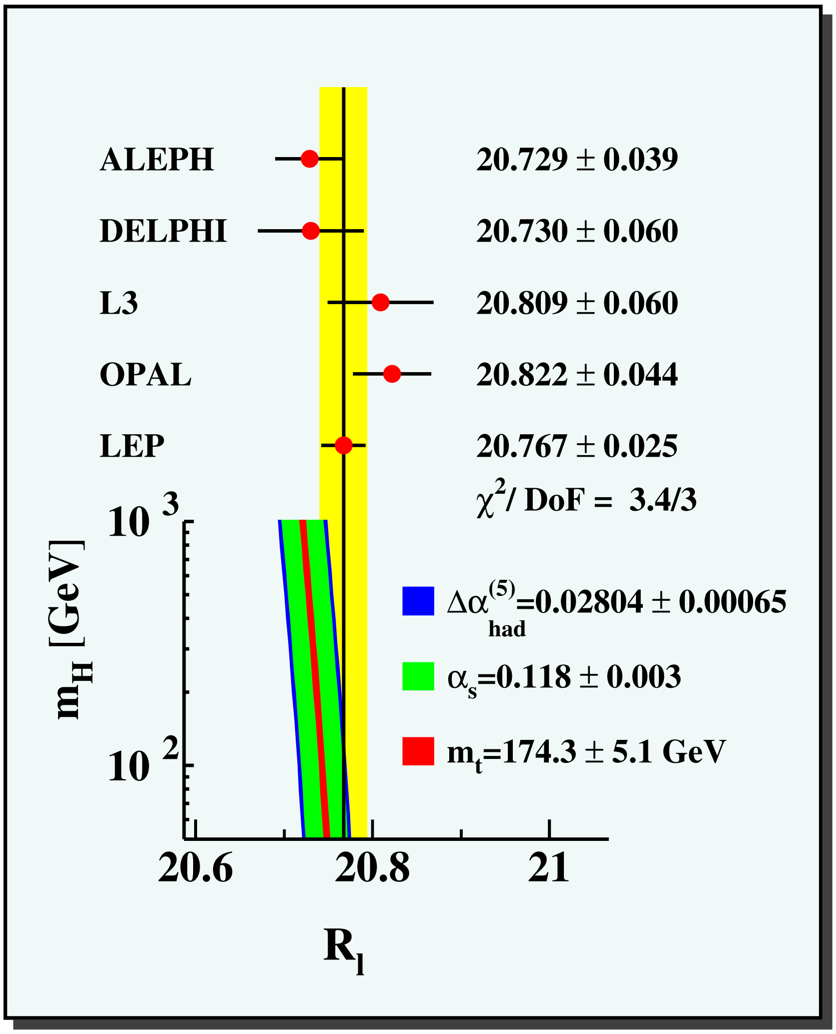
R_ℓ



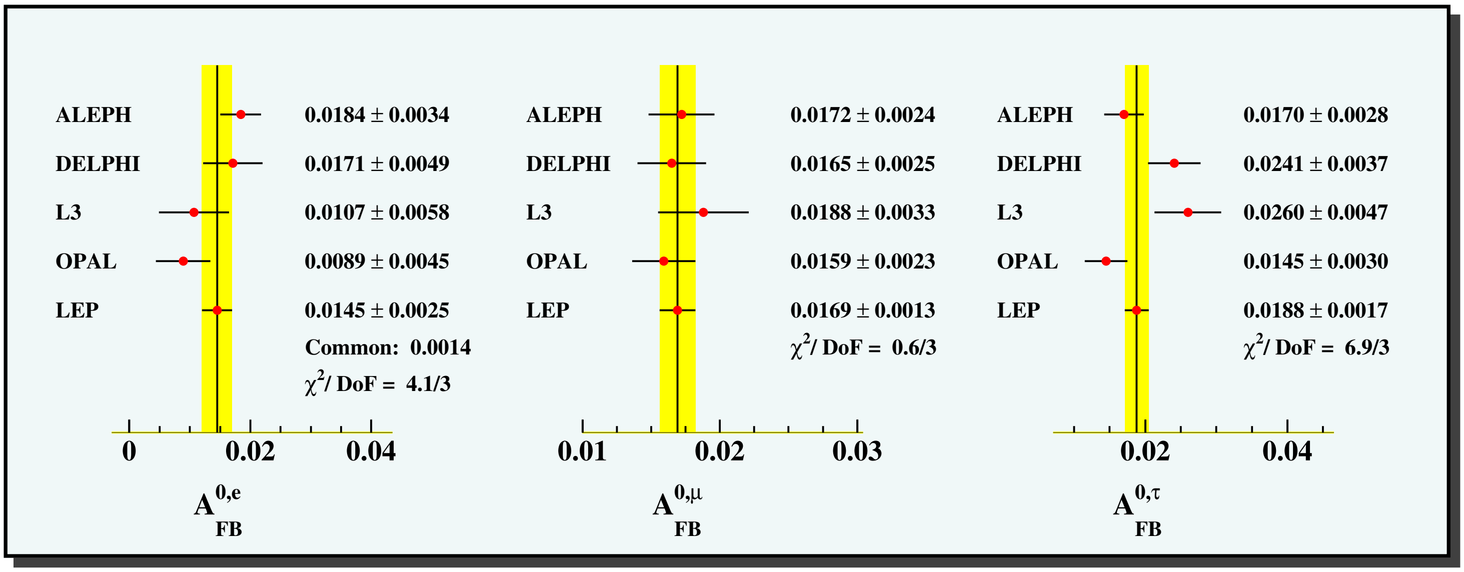
Results for R_ℓ consistent with lepton universality

α_s from R_ℓ:

$$\alpha_s = 0.1228 \pm 0.0037_{\text{exp}}$$
$$\pm 0.002_{\text{QCD}}$$

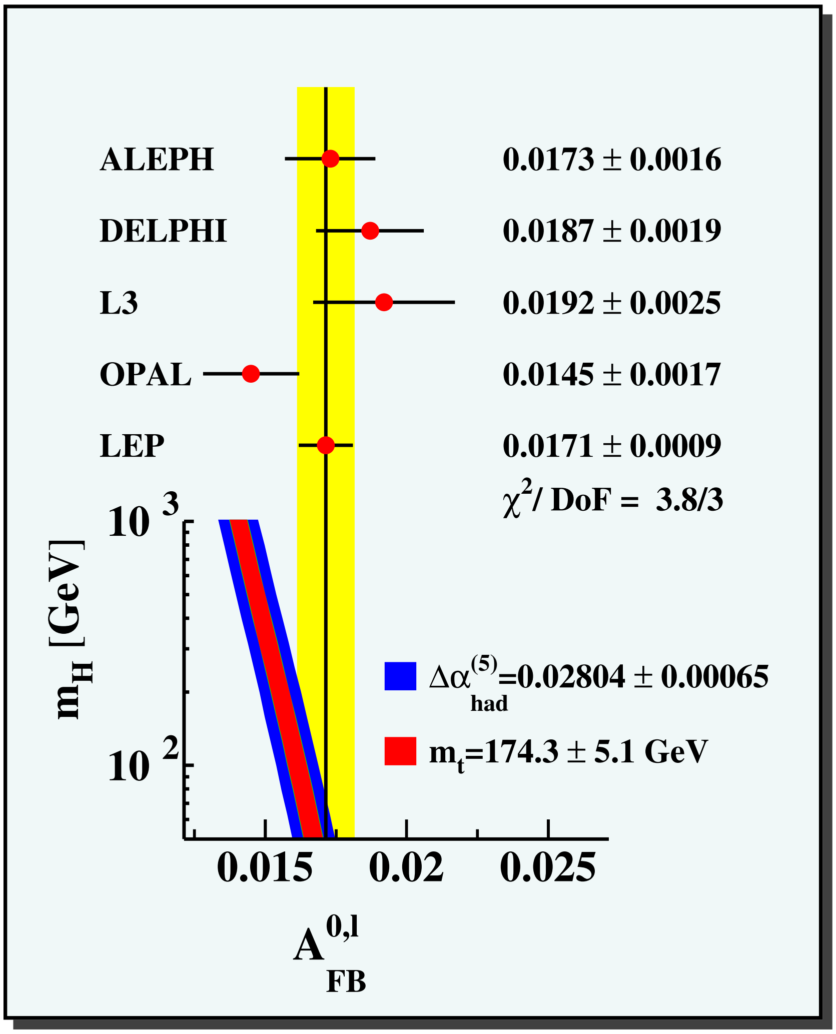


$A_{FB}^{0,\ell}$

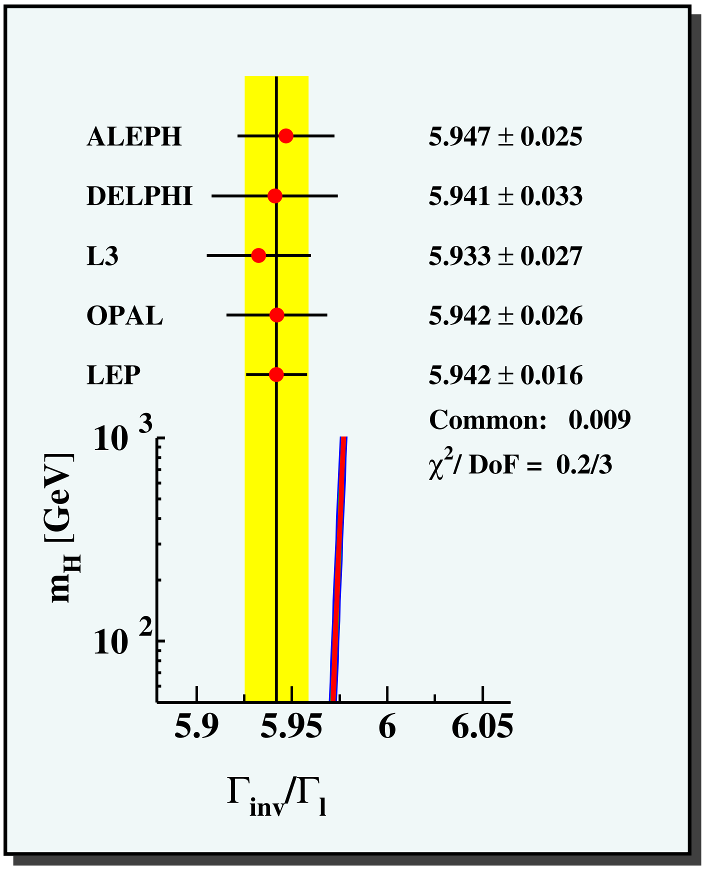


Results for $A_{FB}^{0,\ell}$ consistent with lepton universality

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23099 \pm 0.00054$$



Derived Parameters



$$\sigma_h^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}\ , R_\ell = \frac{\Gamma_{had}}{\Gamma_{\ell\ell}}$$

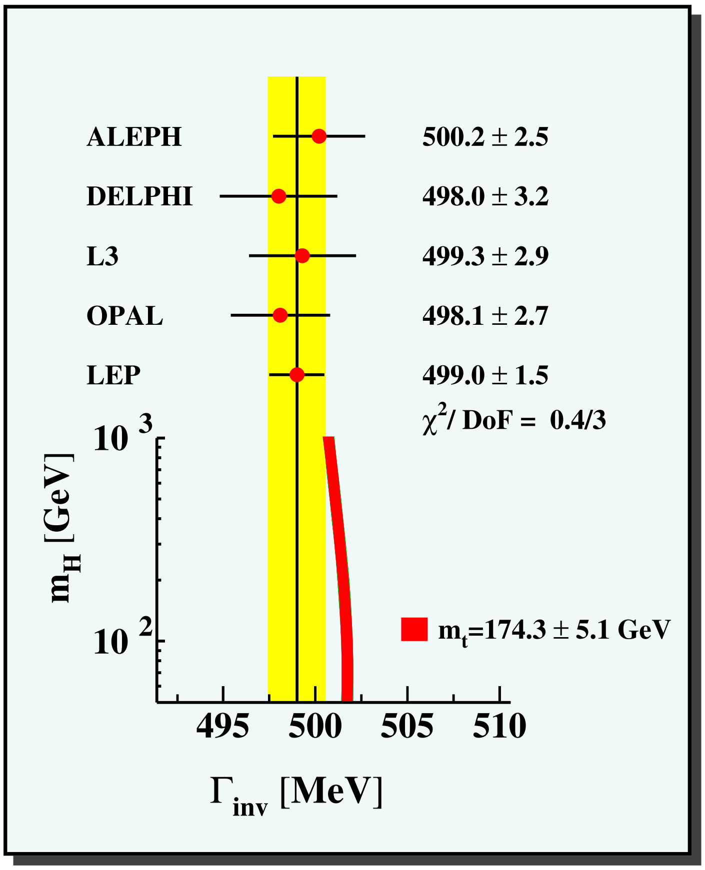
$\Rightarrow$ Γ_{had}, $\Gamma_{\ell\ell}$ and

$$\Gamma_{inv} \equiv \Gamma_Z - \Gamma_{had} - 3\Gamma_{\ell\ell}$$

$\Rightarrow$ neutrino generations

$$N_\nu = \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM}\frac{\Gamma_{inv}}{\Gamma_{\ell\ell}} = 2.984 \pm 0.008$$

with $\left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = 1.9912^{+0.0012}_{-0.0003}$

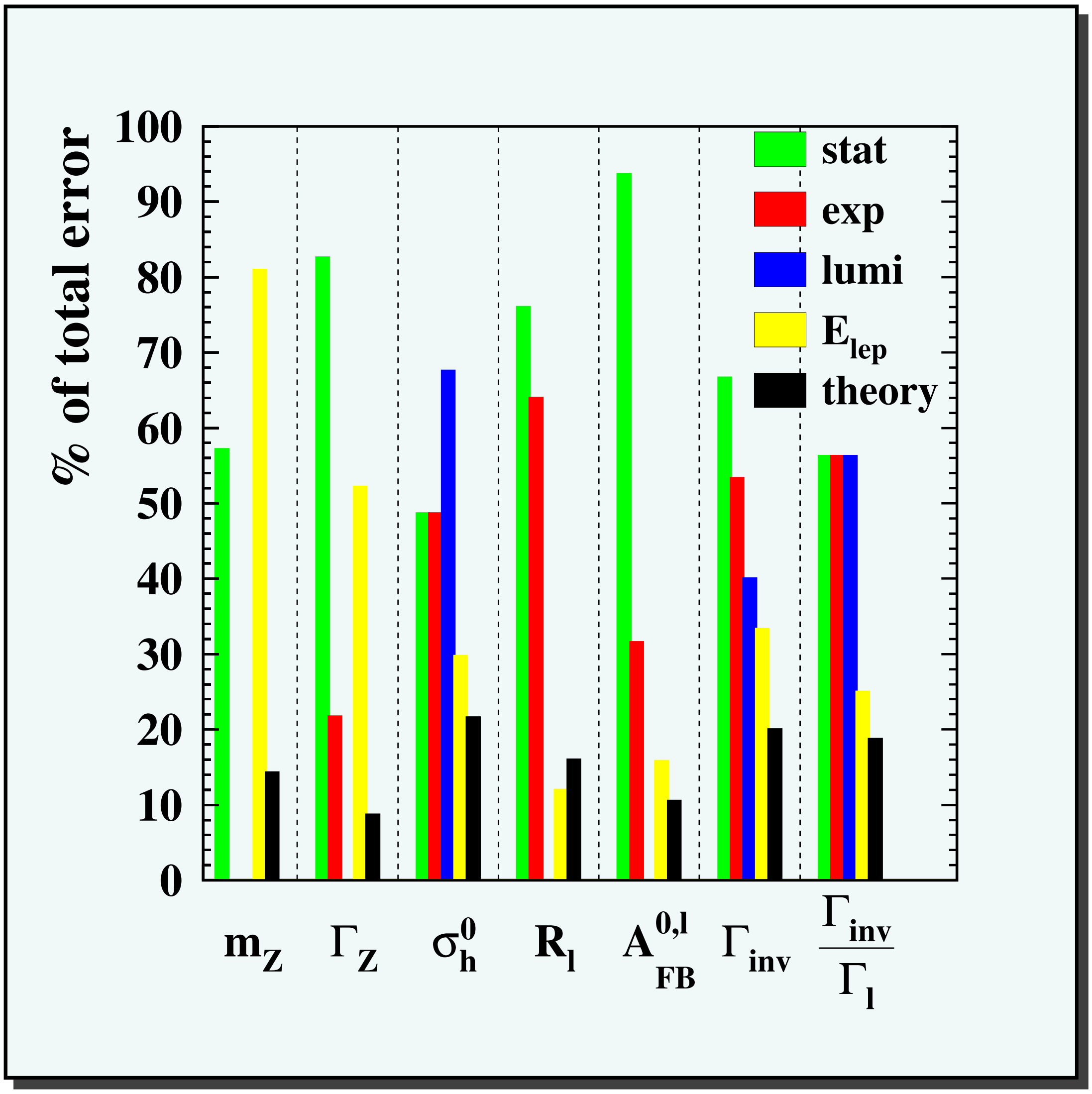


Alternatively, assuming $N_\nu = 3$ and $(\Gamma_{inv})_{SM} = 501.7^{+0.1}_{-0.9}$ MeV extra contributions are

$$\Gamma_{inv}^{new} = -2.7^{+1.7}_{-1.5}\ \text{MeV or}$$

$$\Gamma_{inv}^{new} < 2.0\ \text{MeV @ 95\% CL}$$

Approximate Error Breakdown

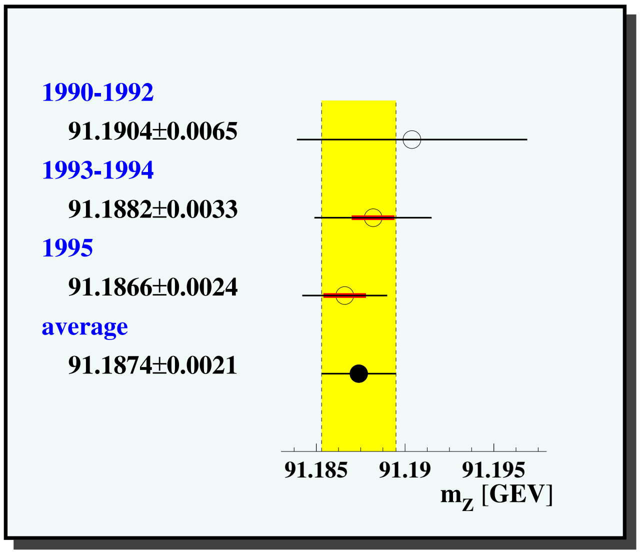


- Common error sources largely disentangled for standard LEP parameters
- Systematics dominate only for m_Z (ΔE_{cm}) and σ_{h}^{0} (lumi-theory).

m_Z checks

- Special fits with independent m_Z for main stages of LEP calibration.
- Direct fit to 1993-1995 hadron cross-sections of all expts

$\Rightarrow$ results consistent

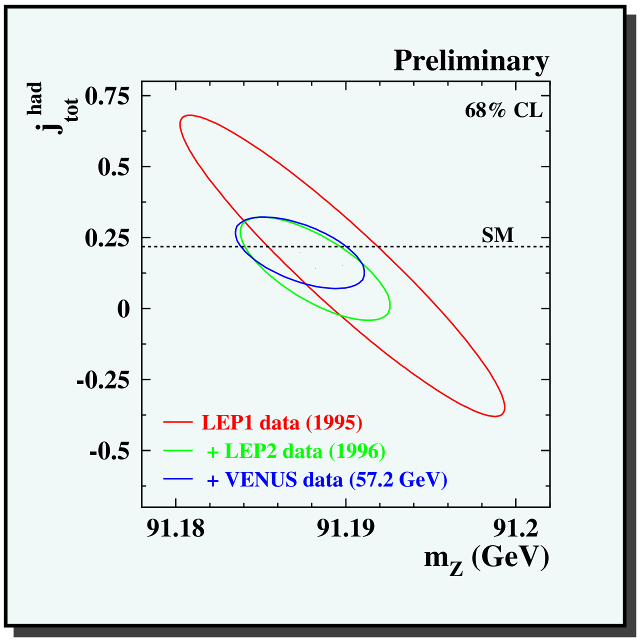


‘Former’ caveat:

- γ/Z intereference term ($j^{\mathrm{tot}}_{\mathrm{had}}$) taken from SM.
- With LEP 1 data alone poor discrimination $m_Z \leftrightarrow j^{\mathrm{tot}}_{\mathrm{had}}$
- Now precise data away from Z^0 peak available

LEP 2, TOPAZ,
new VENUS result
PL**B447** (1999) 167

$\Rightarrow \Delta m_Z \approx 2.5\,\mathrm{MeV},\ \Delta j^{\mathrm{tot}}_{\mathrm{had}} < 0.1$



Fits in the SM

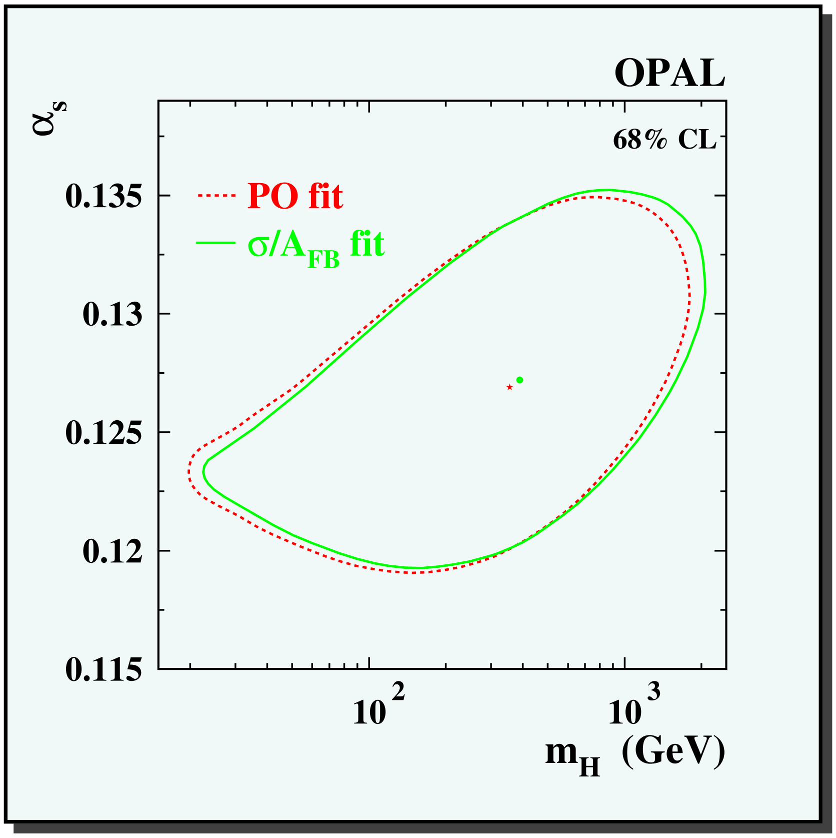
LEP 9 parameters equivalent to σ/A_{FB} when fitted in the SM ?

Each experiment performed SM fits both to PO and RO

(constraining m_{t} and $\Delta\alpha^{(5)}_{\mathsf{had}}$)

	ALEPH	DELPHI	L3	OPAL
Δm_{Z} (MeV)	-0.7	$+0.5$	0.0	$+0.1$
$\Delta\log_{10}(m_{\mathsf{H}})$	-0.01	$+0.04$	$+0.02$	$+0.04$
$\Delta\alpha_s$	0.0000	-0.0002	$+0.0002$	$+0.0002$

Small differences, caused e.g. by small m_{H} dependence of γ/Z interference, but all $\leq 10\,\%$ of the error.



In the SM fits to RO and PO practically identical !

Summary

Presumably final LEP lineshape results (OPAL ≈ weeks)

m_Z (GeV)	91.1875	$\pm$	0.0021	23 ppm
Γ_Z (GeV)	2.4952	$\pm$	0.0023	0.9×10^{-3}
σ_{had} (nb)	41.540	$\pm$	0.037	0.9×10^{-3}
R_ℓ	20.767	$\pm$	0.025	1.2×10^{-3}
A^0_{FB}	0.01714	$\pm$	0.00095	

Details of the combination of the lineshape results will be presented in a forthcoming CERN-EP note.

The history ...