Cross-sections and lepton asymmetry measurements from LEP

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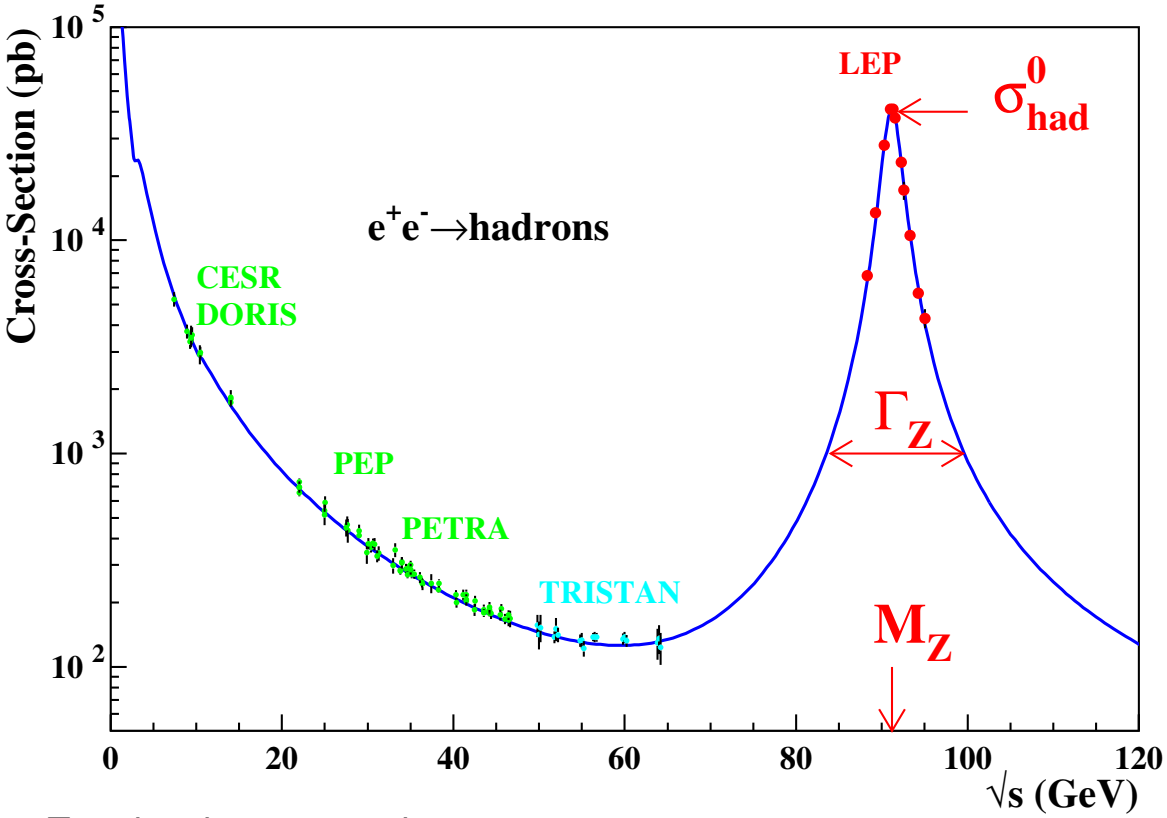
- Introduction to Z^0 lineshape
- Experimental considerations - LEP energy.
- Cross–section and asymmetry results
- Extracting Z^0 parameters
- Standard Model fits

Z^0 lineshape



Tree level cross–section:

$$\sigma_f(s) = \sigma_f^0 \frac{s\Gamma_Z{}^2}{(s - M_Z{}^2)^2 + s^2\Gamma_Z{}^2/M_Z{}^2} + [\gamma] + [\gamma/Z]$$

where:

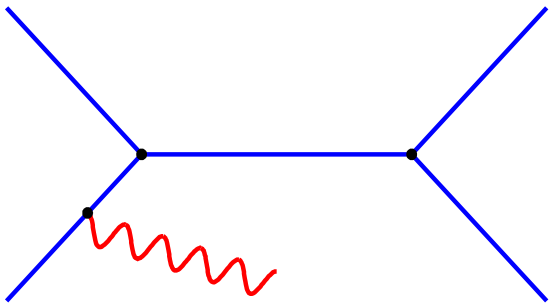
$$\sigma_f^0 = \frac{12\pi\Gamma_e\Gamma_f}{M_Z{}^2\Gamma_Z{}^2}$$

partial decay widths:

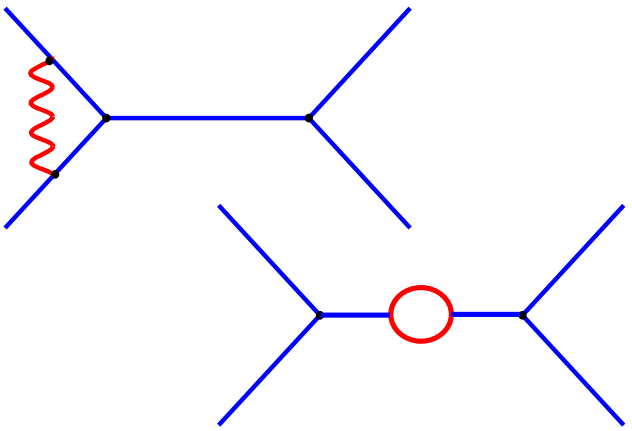
$$\Gamma_f = \frac{G_\mu M_Z{}^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2)N_{col}$$

- Radiative corrections important especially for peak cross-section
- Photon and interference terms small (fixed to SM values)

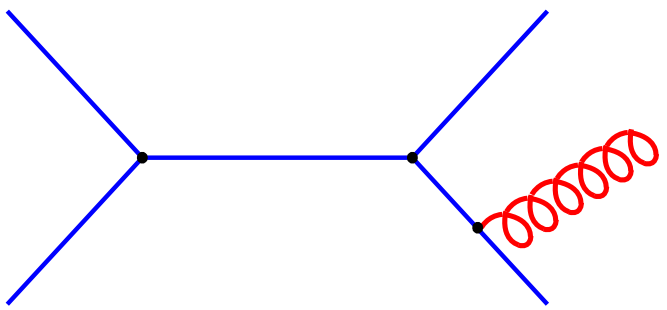
Radiative Corrections



Photonic corrections give biggest effect. Initial state radiation modifies $\sqrt{s}$ $\rightarrow$ 30% reduction in σ°.

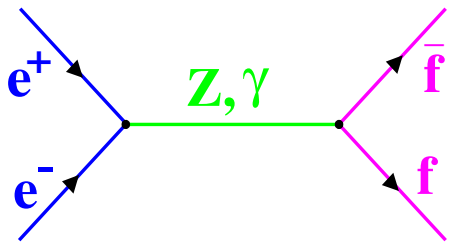


Vertex and loop corrections also give sizeable effects. These are absorbed into 'effective couplings' . Sensitive to m_t and m_H



QCD corrections $\rightarrow$ sensitivity to α_s.

Measuring cross–sections

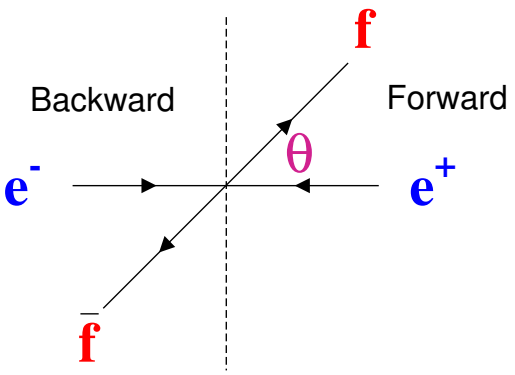


$\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$ measured cross–section:

$$\sigma(\mathrm{E}) = \frac{\mathrm{N_{signal}} - \mathrm{N_{bckgnd}}}{\varepsilon \int \mathcal{L}\,\mathrm{dt}}$$

Experimental considerations:

- Need to understand efficiency and background of event selection
- Precise luminosity measurement
- Centre of mass energy scale



Also measure differential cross-section:

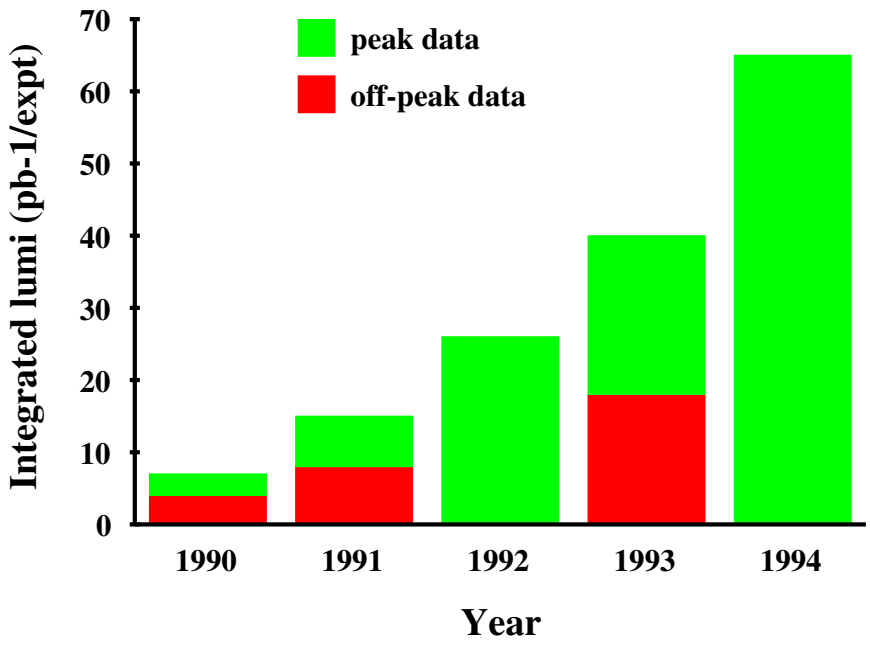
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A^f_{\mathrm{FB}} \cos\theta$$

where forward–backward asymmetry (A^f_{FB}) is:

$$A^f_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}} \text{ and } A^f_{\mathrm{FB}} \approx A^{f,0}_{\mathrm{FB}} \equiv \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_f \qquad \text{when } \sqrt{s} = \mathrm{M_Z}$$

$$\mathcal{A}_f = \frac{2 v_f a_f}{v_f^2 + a_f^2}, \qquad \frac{v_f}{a_f} = (1 - 4|Q_f| \sin^2\theta^{\mathrm{eff,\,f}}_{\mathrm{W}})$$

Data sets



- Published:

  1990-92 ($\sim 4.5 \times 10^6$ $q\overline{q}$, $\sim 0.5 \times 10^6$ leptons)

- Preliminary:

  1993 ($\sim 2.6 \times 10^6$ $q\overline{q}$, $\sim 0.3 \times 10^6$ leptons)

  Scan at 3 energy points (peak, "peak $\pm$ 2")

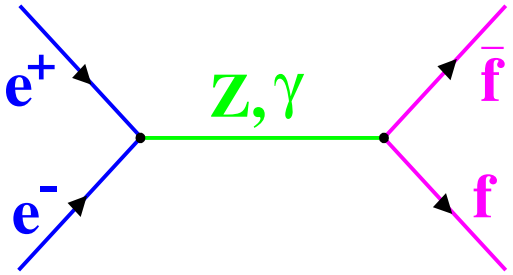
  1994 ($\sim 5.3 \times 10^6$ $q\overline{q}$, $\sim 0.5 \times 10^6$ leptons)

  All at Z^0 peak

Total: $\sim 12.4 \times 10^6$ $q\overline{q}$

$\sim 1.3 \times 10^6$ leptons

Event selection



Identify different fermion species (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$) and count events.

LEP is a very clean environment so able to select signal events with high efficiency and purity:

	ε	background
$q\bar{q}$	$\sim 99\%$	$\sim$ 0.3% ($\tau^+\tau^-$ and 2γ)
e^+e^-	$\sim 97\%$	$\sim$ 1.5% ($\tau^+\tau^-$)
$\mu^+\mu^-$	$\sim 95\%$	$\sim$ 1-2% ($\tau^+\tau^-$, cosmic)
$\tau^+\tau^-$	$\sim 75\%$	$\sim$ 2-3% (other channels)

Systematic errors for preliminary results:

$f\bar{f}$	$\delta\sigma/\sigma$	δA_{FB}	$\sim \Delta$**(stat)**
$q\bar{q}$	**0.07–0.20%**	**–**	**0.1%**
e^+e^-	**0.23–0.50%**	**0.002–0.004**	**0.4%**
$\mu^+\mu^-$	**0.15–0.60%**	**0.001–0.002**	**0.4%**
$\tau^+\tau^-$	**0.32–1.5%**	**0.002–0.006**	**0.4%**

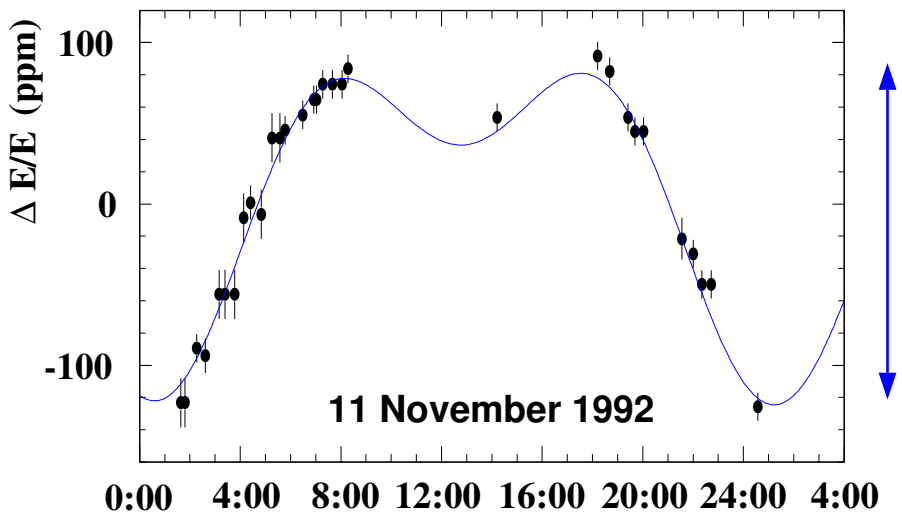
LEP energy error

- LEP energy error is an essential component in the measurement of $\mathrm{M_Z}$ and Γ_Z
- Statistical precision of data samples gives $\Delta \mathrm{M_Z} \sim 3\mathrm{MeV}$ and $\Delta \Gamma_\mathrm{Z} \sim 2\mathrm{MeV}$
- Energy calibration using resonant depolarisation technique was carried out at end of $\sim 1/3$ of off-peak fills in 1993 scan.
  - Intrisic resolution on $\mathrm{E_{e^-}} \sim 200\mathrm{keV}$.
  - e^+ correction $\simeq 0.3 \pm 0.3\mathrm{MeV}$
  - Extrapolate to energy at interaction point:
    - ☐ synchrotron radn: lose $\sim 125\mathrm{MeV}$ around ring
    - ☐ acceleration from RF system

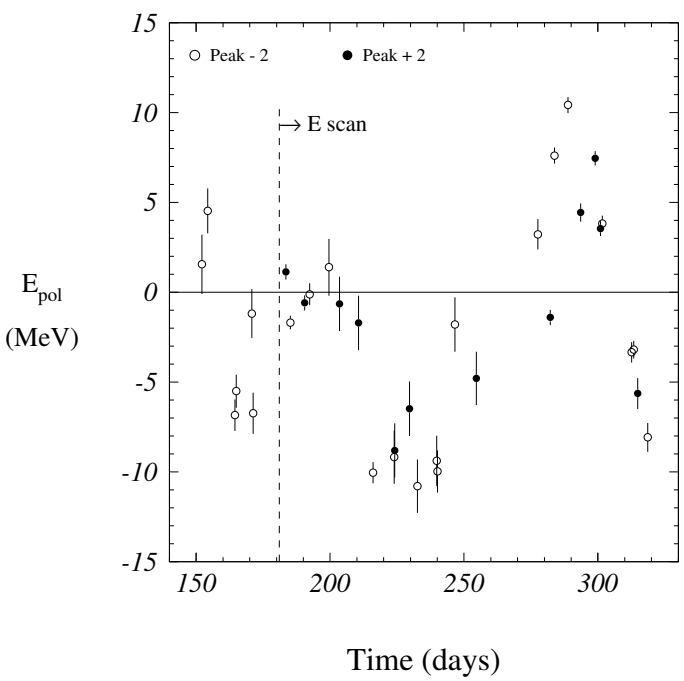
    $\Longrightarrow$ $\sim 1\mathrm{MeV}$ accuracy at IP at time of calibn.
- Time evolution: energy change by about $1\mathrm{MeV}$ per hour.
  Main sources of change:
  - Changes in dipole magnetic field due to current, temperature, etc.
  - Off–centre particles in quadrupole magnets see $\mathrm{B} \propto \Delta \mathrm{x}$. Length of closed orbit is defined by RF freq. but changes in ring size due to ground motion $\rightarrow$ off centre beam ($1\mathrm{MeV}/13\mu\mathrm{m}$ displacement).
- Need to log as much information as possible to make corrections

Effect of ground motion on LEP energy

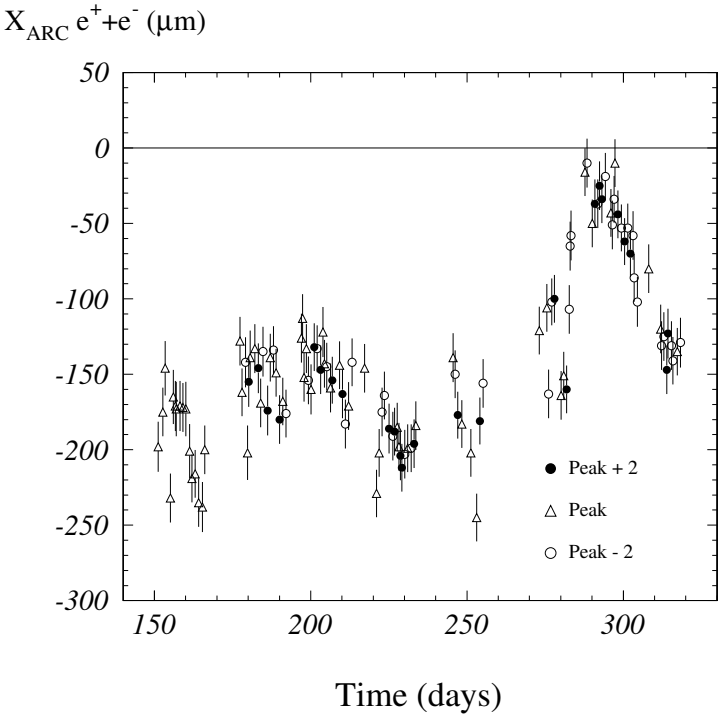
Effect of moon (tidal effect on earth) :



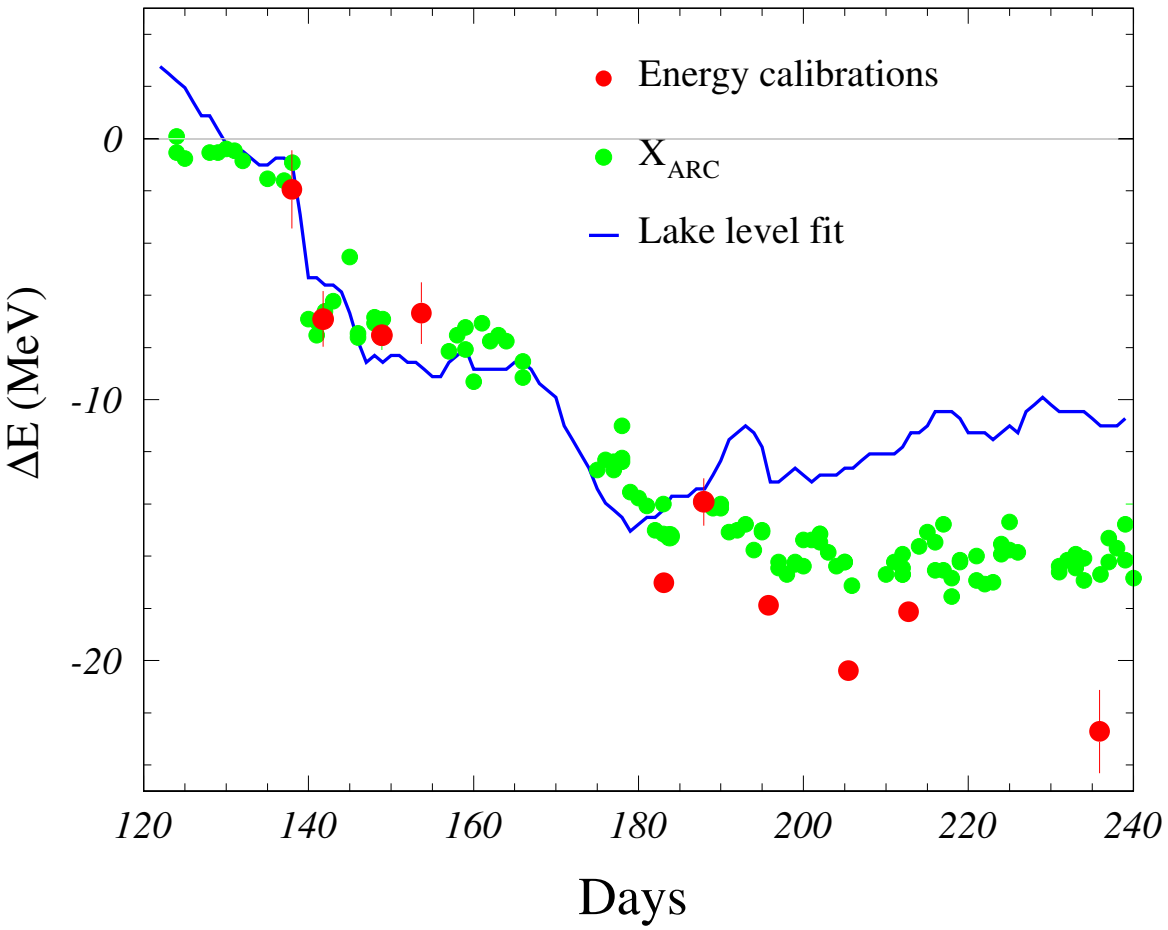
20 MeV for large ‘tides’.



Average beam energy versus time (corrected for changes in dipole fields and tides



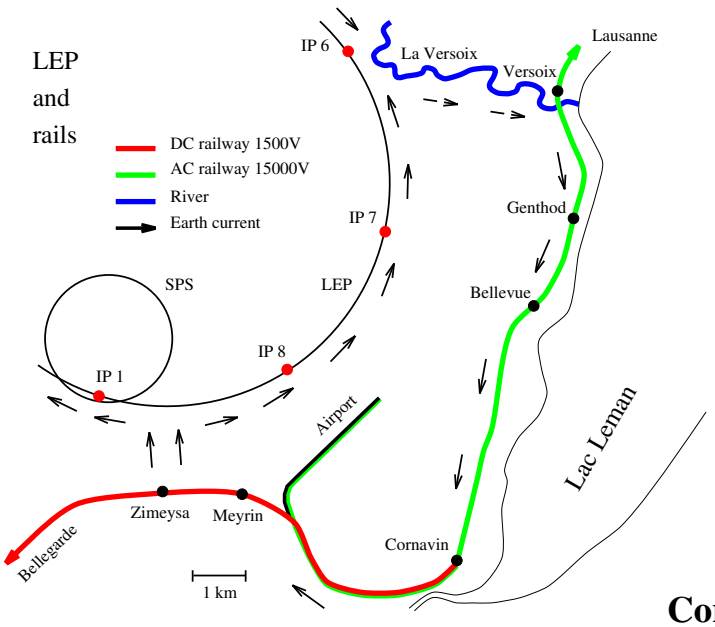
Mean X position of beam versus time



- Remaining RMS scatter after all correction is $5.4 \pm 0.8\mathrm{MeV}$
  (c.f. 15MeV before corrections)

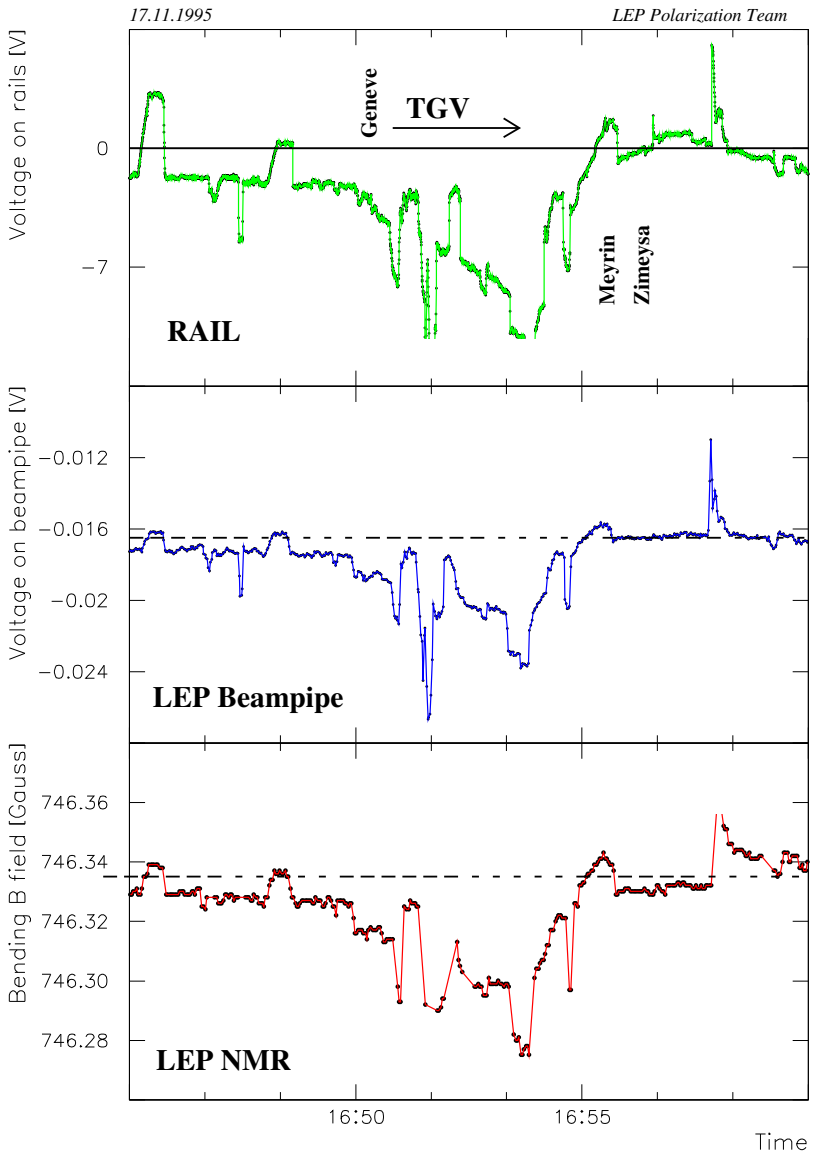
- This leads to:
  $\Delta M_Z \sim 1.5\mathrm{MeV}$ and $\Delta \Gamma_Z \sim 1.7\mathrm{MeV}$

The latest energy effect

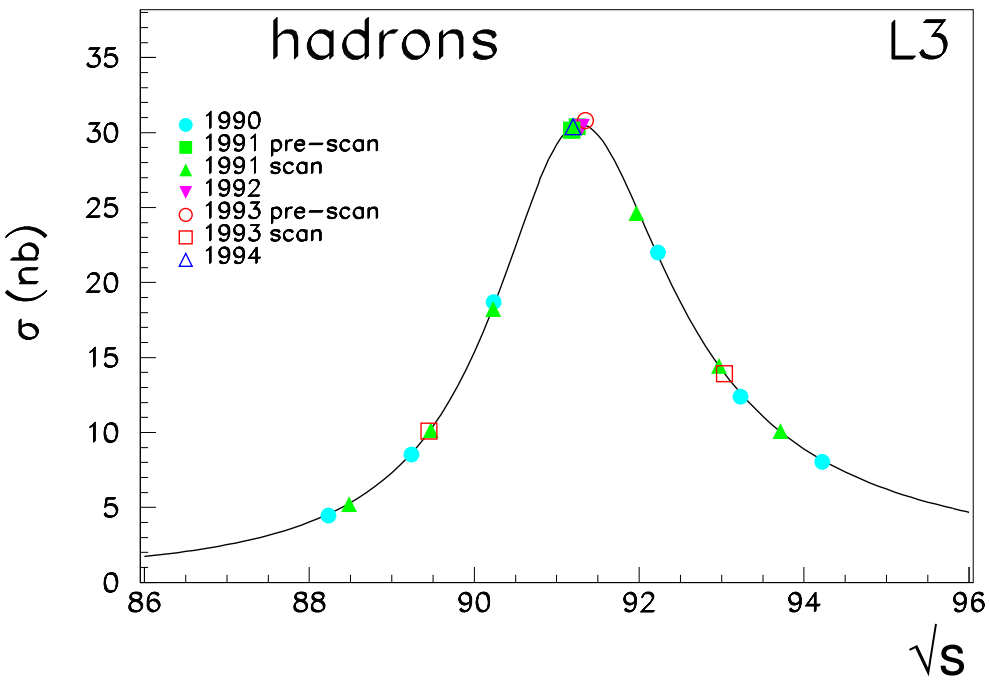


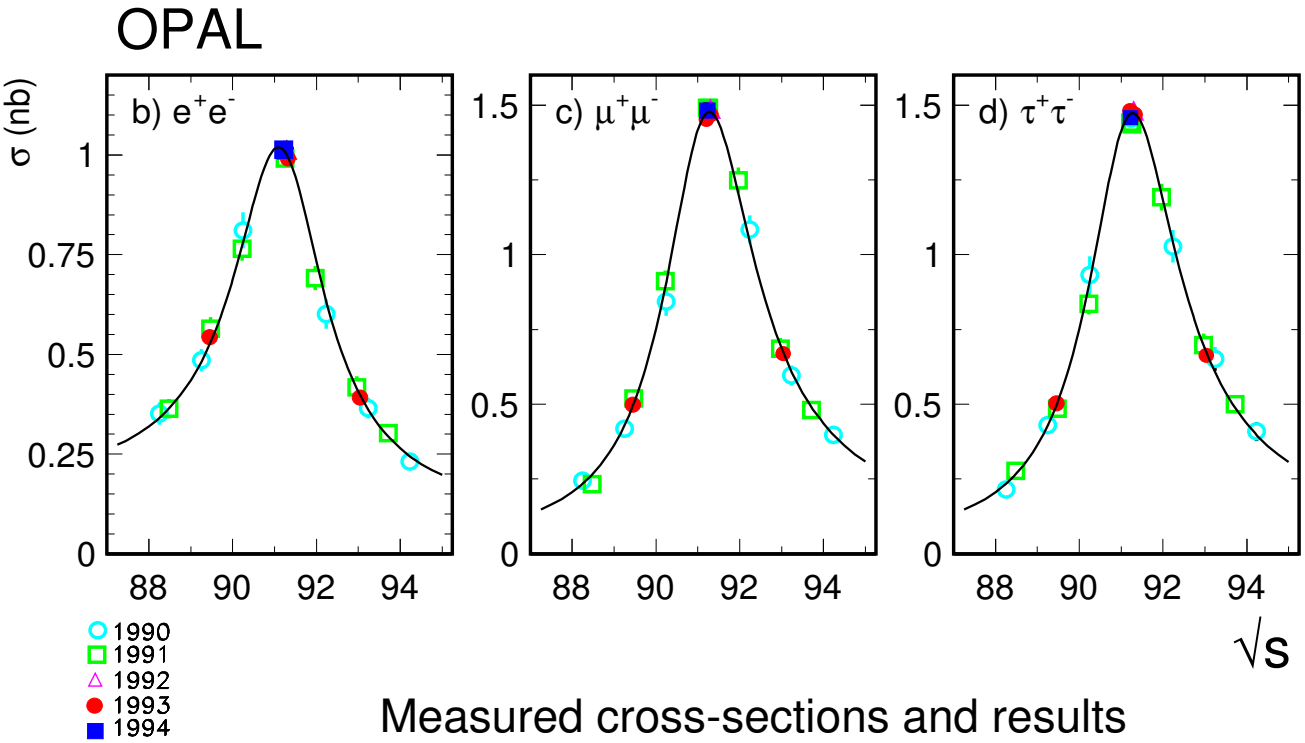
"TGV effect"

Correlation between trains and LEP



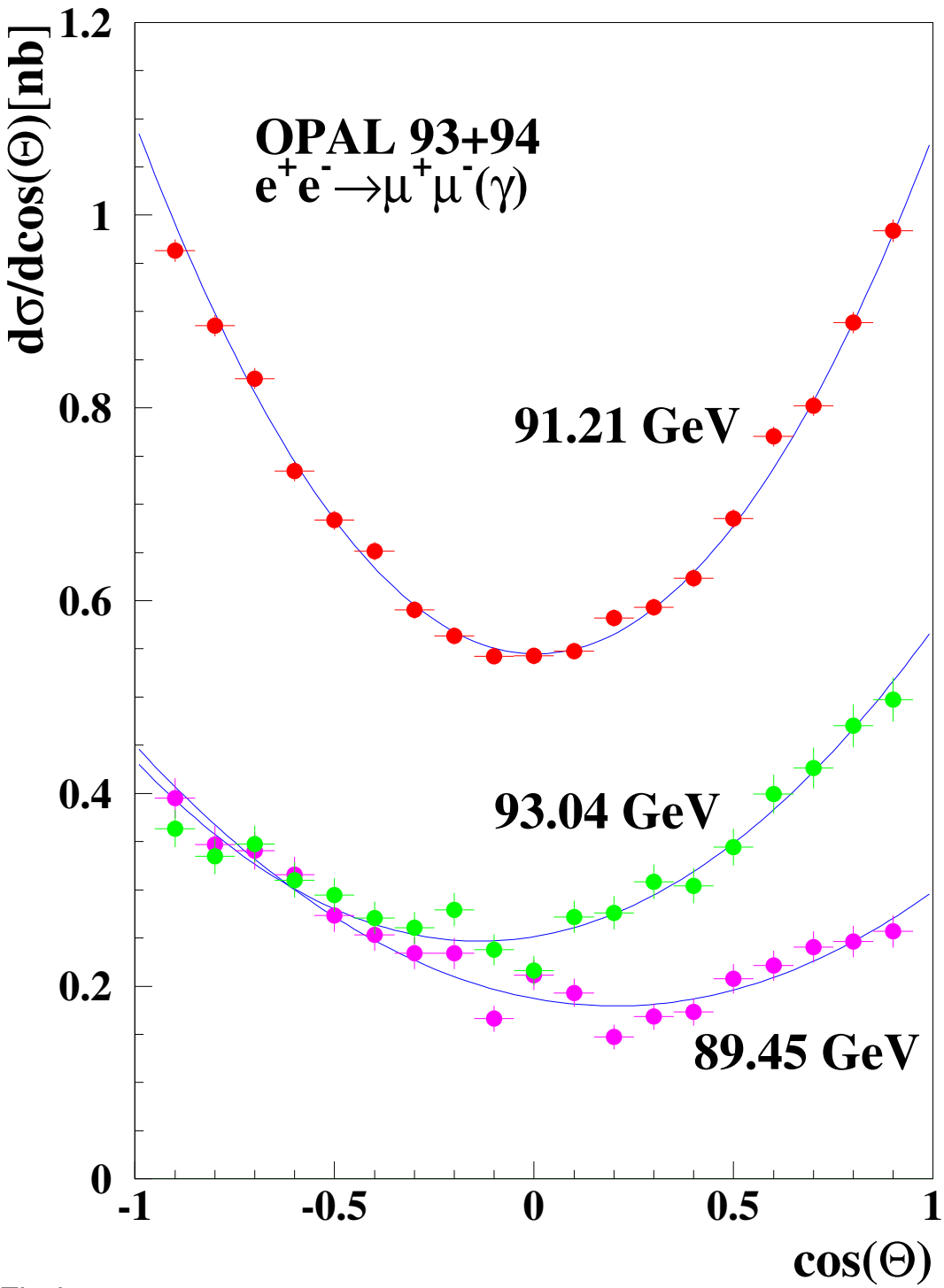
Cross-sections





Measured cross-sections and results of fit to combined data.

$\mathrm{d}\sigma / \mathrm{d}\cos\theta$

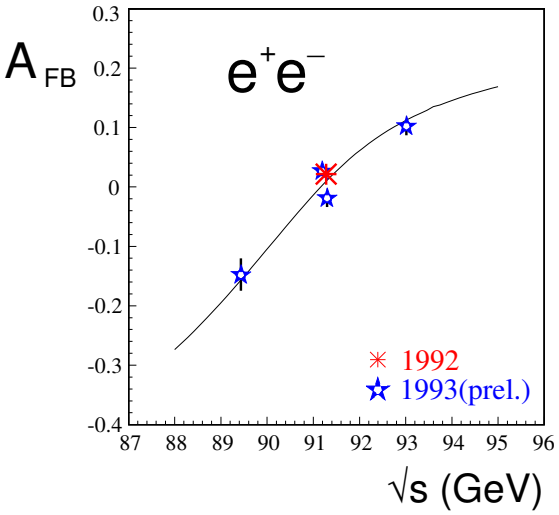


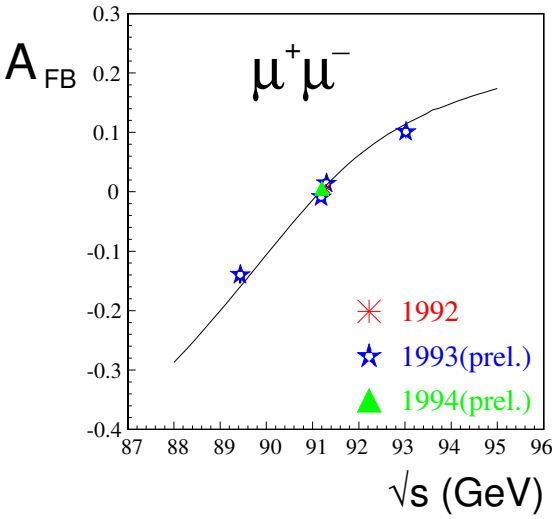
Fit data to:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A_{\mathrm{FB}} \cos\theta$$

to extract A_{FB}

Forward backward asymmetry





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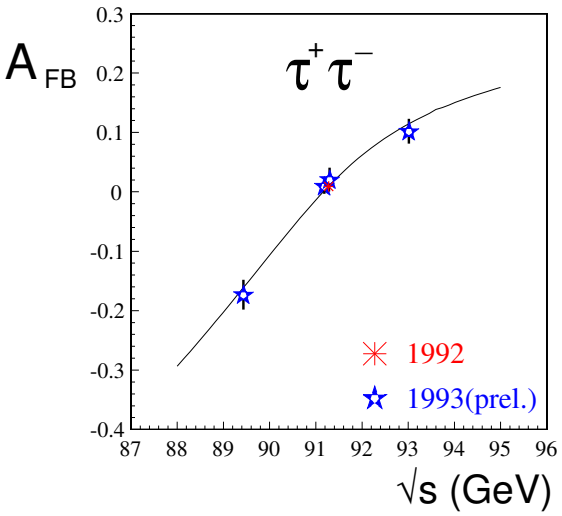


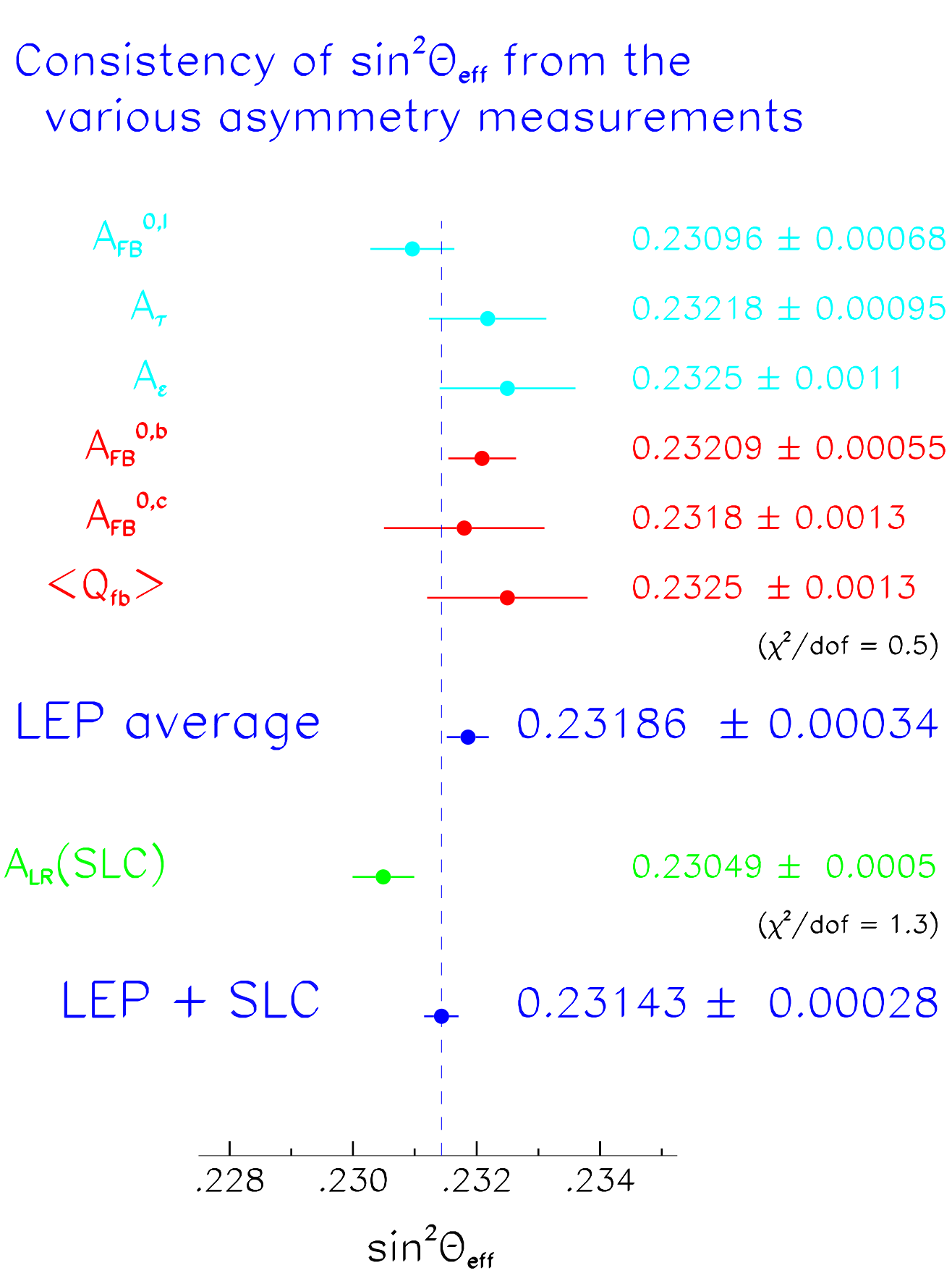
Measured asymmetries and results of fit to all data.

$A_{\rm FB}^{f,0} \longrightarrow v_f/a_f \longrightarrow \sin^2\theta_{\rm eff}^{\rm lept}$:

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23096 \pm 0.00068 \quad ({\rm LEP}\, A_{\rm FB})$$

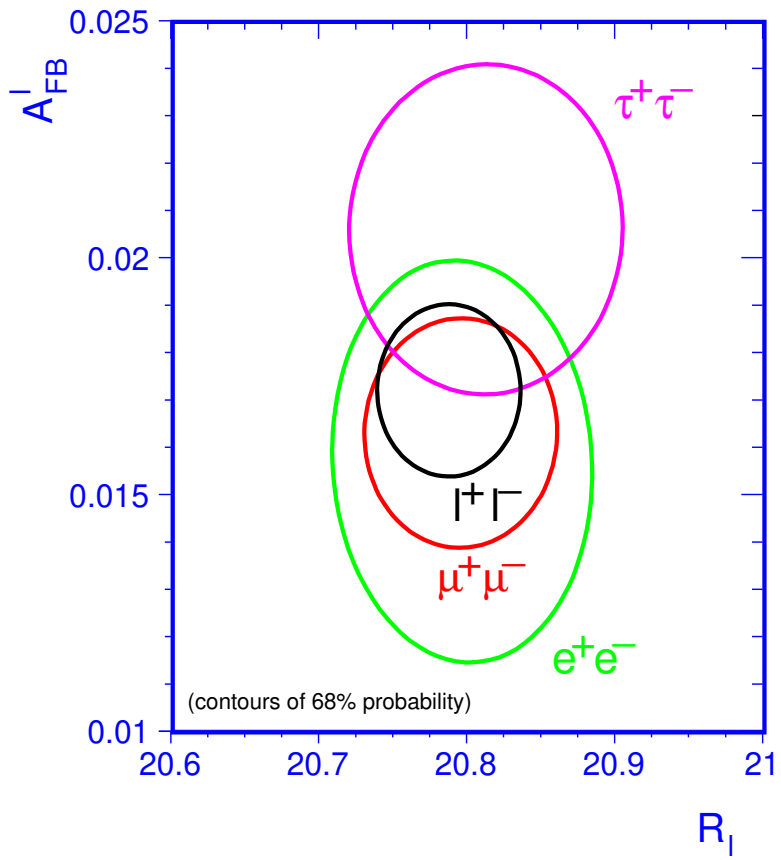
If include tau polarisation, b and c asymmetries and SLD $A_{\rm LR}$:

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23143 \pm 0.00028 \quad ({\rm All})$$


Consistency of $\sin^2\Theta_{eff}$ from the various asymmetry measurements
$A_{FB}^{0,l}$
0.23096 ± 0.00068
A_τ
0.23218 ± 0.00095
A_ε
0.2325 ± 0.0011
$A_{FB}^{0,b}$
0.23209 ± 0.00055
$A_{FB}^{0,c}$
0.2318 ± 0.0013
$\langle Q_{fb} \rangle$
0.2325 ± 0.0013
(χ^2/dof = 0.5)
LEP average
0.23186 ± 0.00034
A_{LR}(SLC)
0.23049 ± 0.0005
(χ^2/dof = 1.3)
LEP + SLC
0.23143 ± 0.00028
.228
.230
.232
.234
$\sin^2\Theta_{eff}$

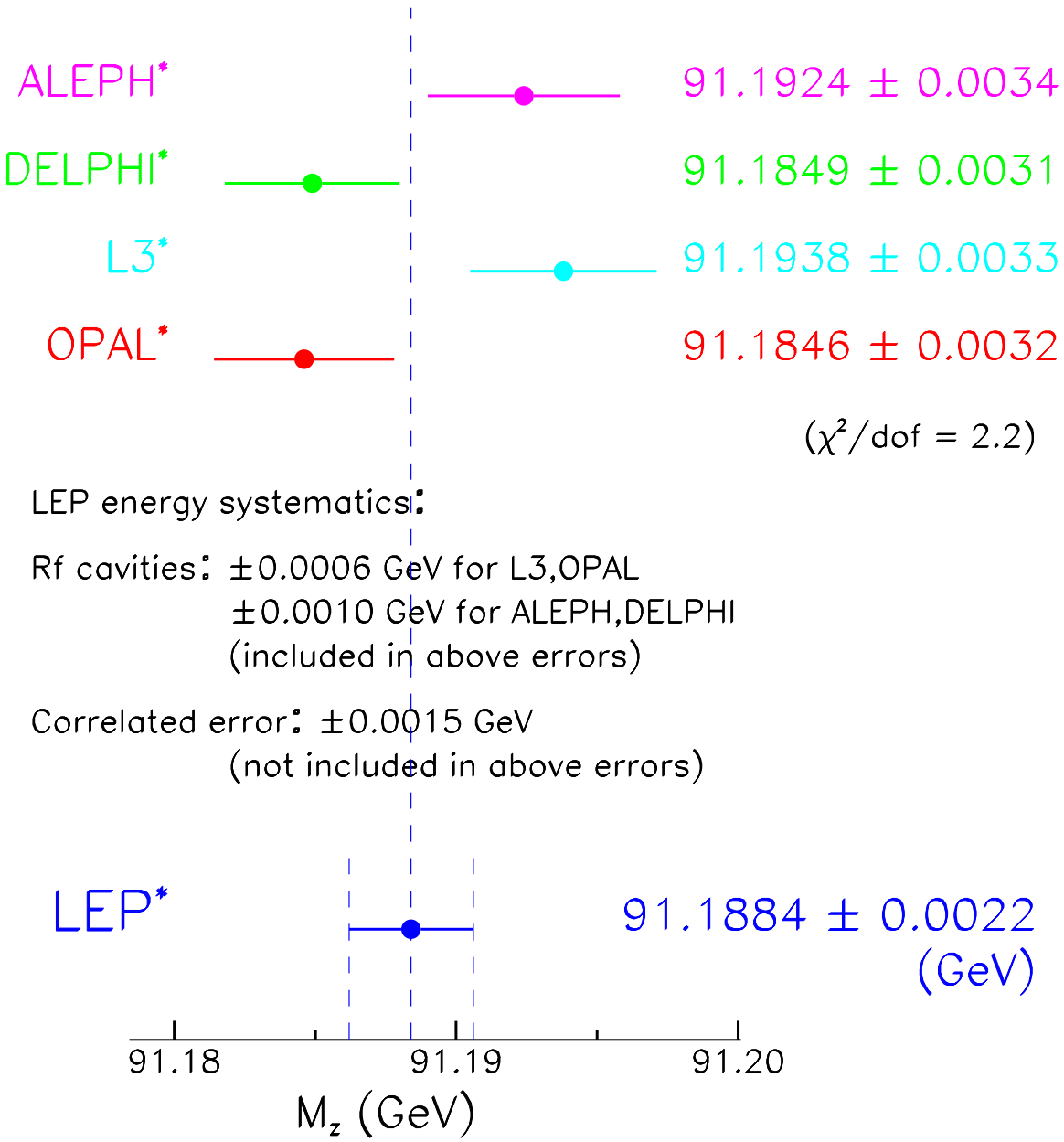
Combined lineshape results

- Each experiment provides 9 parameters derived from the cross-section and lepton forward-backward asymmetry results:
  $\mathrm{M_Z},\ \Gamma_\mathrm{Z},\ \sigma^{\mathrm{pole}}_{\mathrm{had}}$
  $R_e (= \Gamma_{\mathrm{had}}/\Gamma_{ee}),\ R_\mu,\ R_\tau,$
  $A^{0,e}_{\mathrm{FB}},\ A^{0,\mu}_{\mathrm{FB}},\ A^{0,\tau}_{\mathrm{FB}}$
- Combine these using covariance matrix including correlated errors (LEP energy, lumi. theory)
- Check lepton universality:

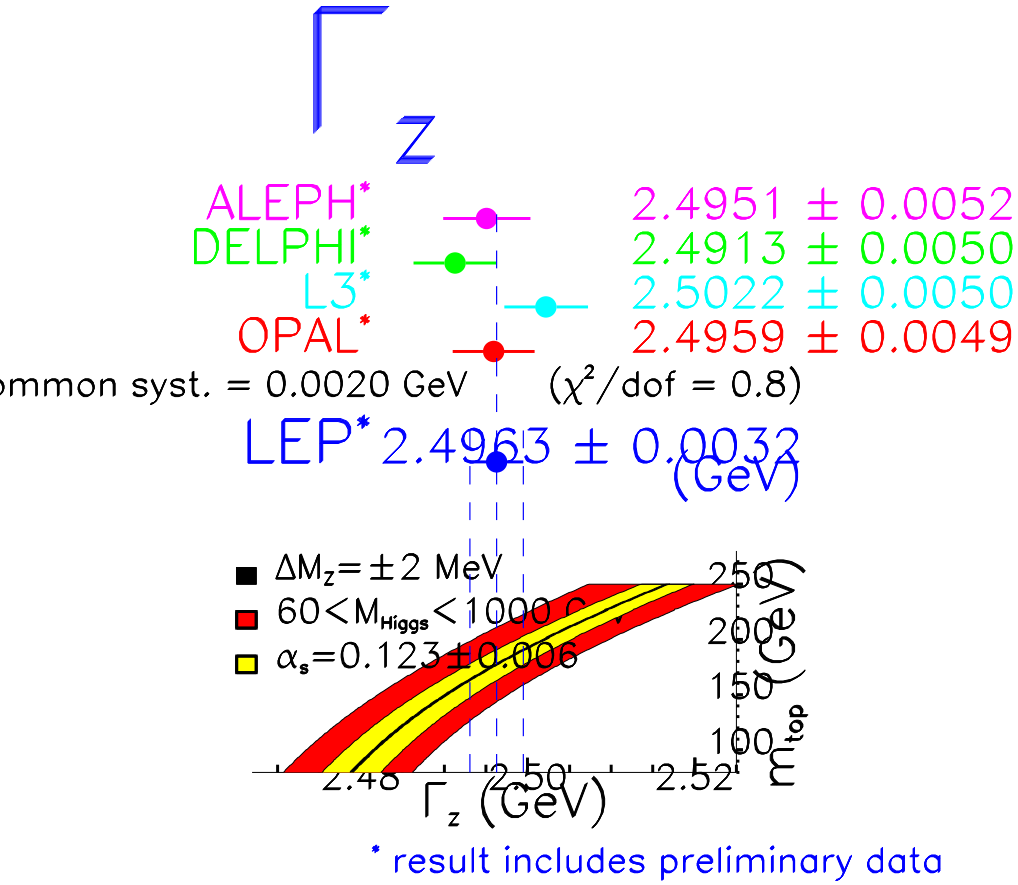


- Then assuming lepton universality derive 5 parameter set and recombine:
  $\mathrm{M_Z},\ \Gamma_\mathrm{Z},\ \sigma^{\mathrm{pole}}_{\mathrm{had}}$
  $R_l\ (= \Gamma_{\mathrm{had}}/\Gamma_{ll}),\ A^{0,l}_{\mathrm{FB}}$

M_Z

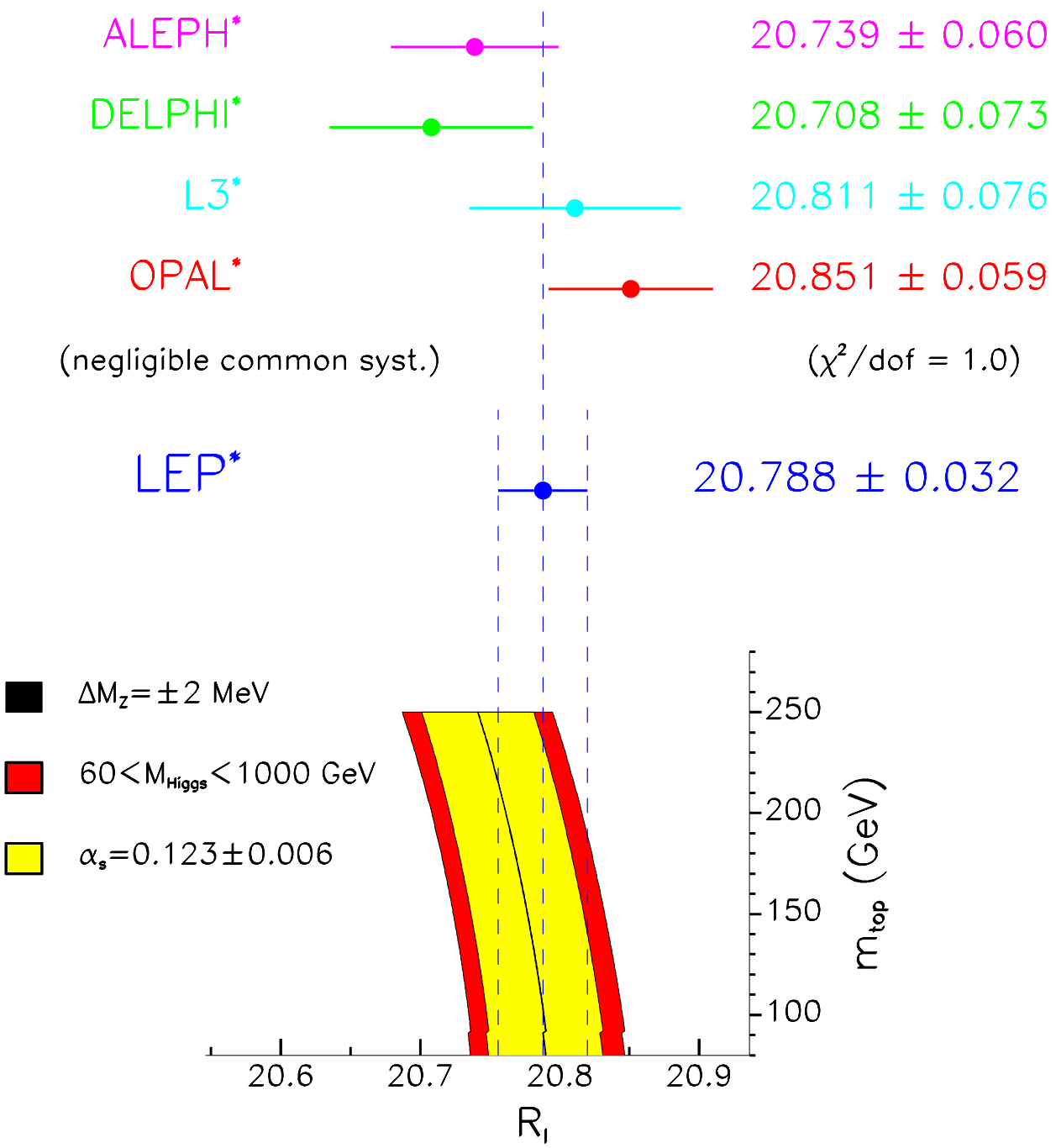


* result includes preliminary data



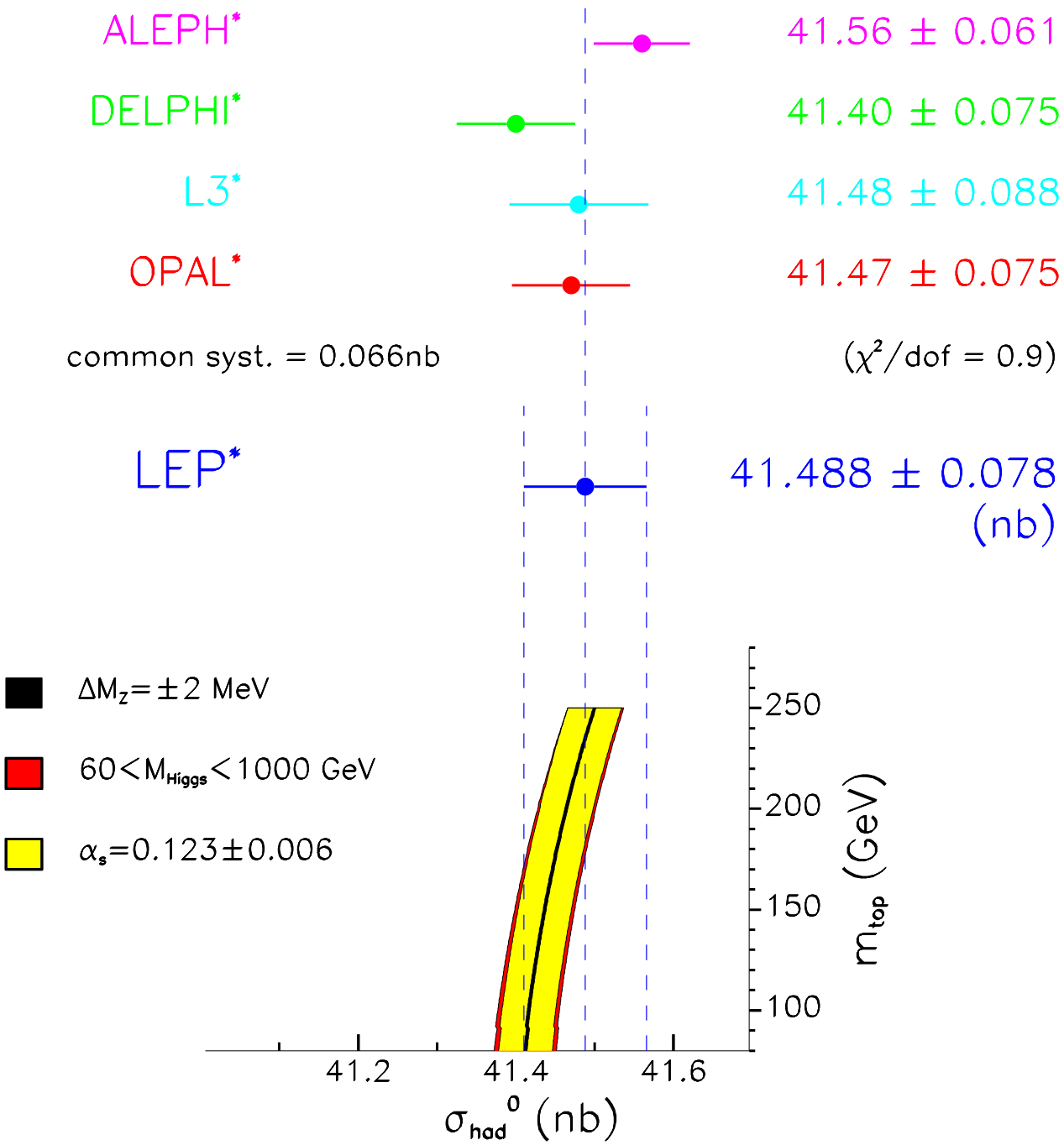
* result includes preliminary data

R_l



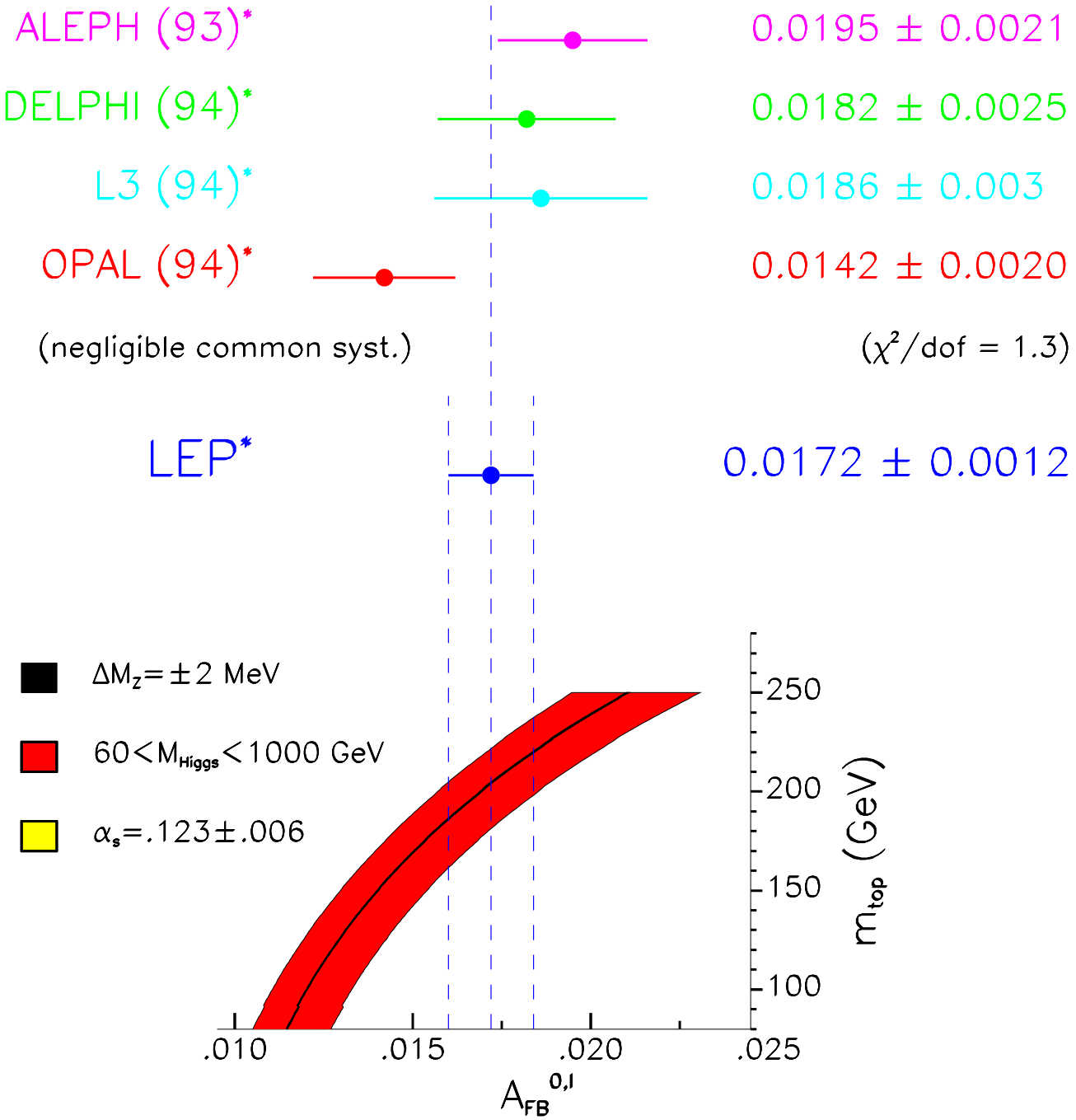
* result includes preliminary data

σ_{had}^0



* result includes preliminary data

$A_{FB}^{0,l}$



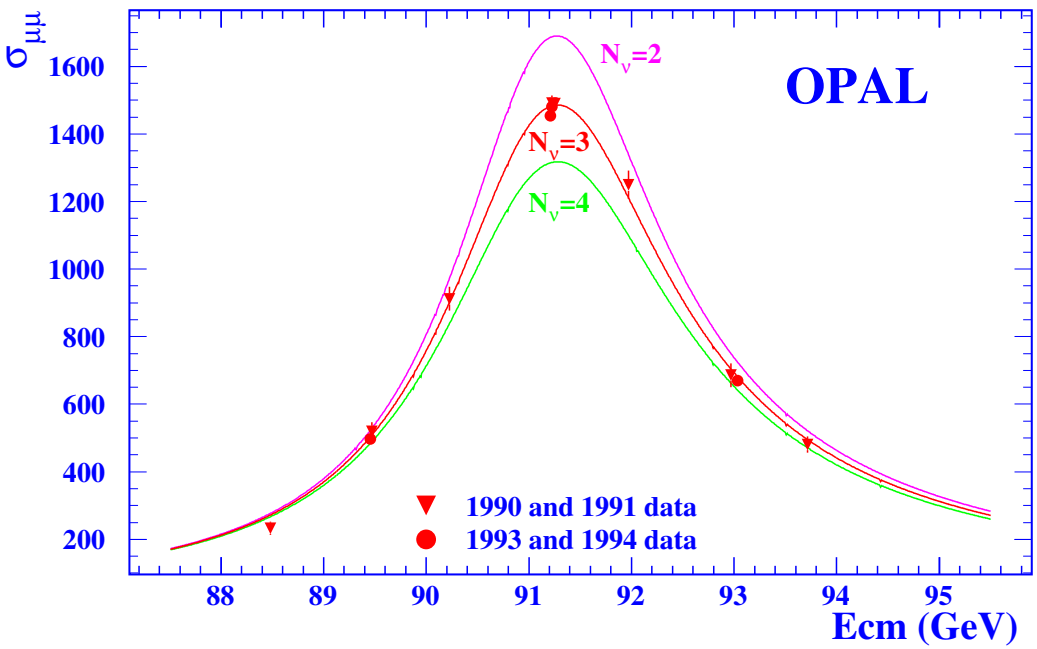
* result includes preliminary data

Lineshape measurements

Parameter	No lepton universality	With lepton universality
$\mathrm{M_Z(GeV)}$	91.1885 ± 0.0022	91.1884 ± 0.0022
$\Gamma_\mathrm{Z}(\mathrm{GeV})$	2.4963 ± 0.0032	2.4963 ± 0.0032
$\sigma^0_\mathrm{had}(\mathrm{nb})$	41.488 ± 0.078	41.488 ± 0.078
R_e	20.797 ± 0.058	–
R_μ	20.796 ± 0.043	–
R_τ	20.813 ± 0.061	$R_l = 20.788 \pm 0.032$
$A^{0,\mathrm{e}}_\mathrm{FB}$	0.0157 ± 0.0028	–
$A^{0,\mu}_\mathrm{FB}$	0.0163 ± 0.0016	–
$A^{0,\tau}_\mathrm{FB}$	0.0206 ± 0.0023	$A^{0,l}_\mathrm{FB} = 0.0172 \pm 0.0012$

no lepton universality		with lepton universality	
$\Gamma_\mathrm{ee}(\mathrm{MeV})$	83.92 ± 0.17	$\Gamma_{ll}(\mathrm{MeV})$	83.93 ± 0.14
$\Gamma_{\mu\mu}(\mathrm{MeV})$	83.92 ± 0.23	$\Gamma_\mathrm{had}(\mathrm{MeV})$	1744.8 ± 3.0
$\Gamma_{\tau\tau}(\mathrm{MeV})$	83.85 ± 0.29	$\Gamma_\mathrm{inv}(\mathrm{MeV})$	499.9 ± 2.5

Number of neutrino species



$$\Gamma_{\rm inv} = \Gamma_{\rm Z} - \Gamma_{\rm had} - 3\Gamma_{\rm ll} \implies \Gamma_{\rm inv} = 499.9 \pm 2.5\ {\rm MeV}$$

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_{\rm ll}} \left(\frac{\Gamma_{\rm ll}}{\Gamma_{\nu\nu}} \right)_{\rm SM}$$

Measured :

$$\frac{\Gamma_{\rm inv}}{\Gamma_{\rm ll}} = 5.956 \pm 0.031$$

S.M. gives

$$\frac{\Gamma_{\nu\nu}}{\Gamma_{ll}} = 1.991 \pm 0.001$$

(error from: $m_{\rm top} = 180 \pm 12 {\rm GeV}$

$60 < m_{\rm H} < 1000 {\rm GeV}$)

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

Standard Model fits

- SM parameters: α, $\mathrm{G_F}$ and $\mathrm{M_Z}$.
  Recent reevaluations of $\alpha(\mathrm{M_Z}) \rightarrow 128.896 \pm 0.090$.

- Sensitive to m_{top} (qudratic), m_{H} (logarithmic) through loop corrections and to $\alpha_s(\mathrm{M_Z})$ through QCD corrections.

- Input all electroweak data :

  5 lineshape parameters

  τ polarization measurement (A_τ and A_{e})

  LEP and SLD heavy flavour results (R_b, R_c, $A_{\mathrm{FB}}^{0,\mathrm{b}}$, $A_{\mathrm{FB}}^{0,\mathrm{c}}$)

  $\mathrm{q\bar{q}}$ charge asymmetry ($\mathrm{Q_{FB}}$)

  SLD A_{LR}

  $\mathrm{p\bar{p}}$ ($\mathrm{M_W}$) and $\nu\mathrm{N}$ ($\sin^2\theta_W$)

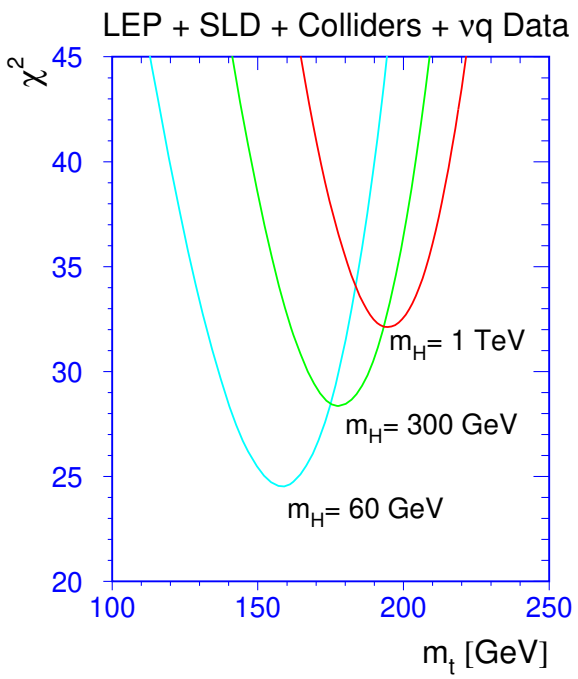
- Fit to SM with m_{top} and $\alpha_s(\mathrm{M_Z})$ as free parameters.

  $m_{\mathrm{top}} = 178 \pm 8^{+17}_{-20}\mathrm{GeV}$ c.f. 180 ± 12 from CDF/D0

  $\alpha_s(\mathrm{M_Z}) = 0.123 \pm 0.004 \pm 0.002$ c.f. 0.123 ± 0.006 from LEP event shapes

  - $\chi^2/\mathrm{d.o.f} = 28/14$
  - $m_{\mathrm{H}} = 300\mathrm{GeV}$ for central value, varied 60-1000 GeV for second error

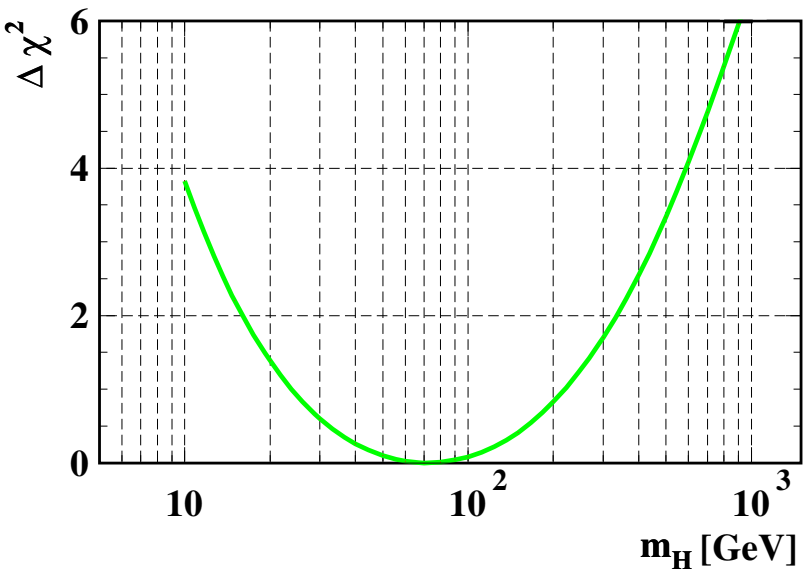
Constraint on m_{H}?



- Add constraint from CDF/DO $m_{\mathrm{top}} = 180 \pm 12\mathrm{GeV}$

  $\Longrightarrow$ some information on m_{H} :

  $m_{\mathrm{H}} < 500\mathrm{GeV}$ at 95% conf. level



Conclusions

- Precise experimental techniques:

errors from event selection and $\mathcal{L}$	$\sim 0.1\%$
LEP energy error	$\sim 0.002\%$

- Precise measurements of electroweak parameters:

$$\begin{aligned} \mathrm{M_Z} &= \quad 91.1884 \pm 0.0022 \text{ GeV} \\ \Gamma_\mathrm{Z} &= \quad 2.4963 \pm 0.0032 \text{ GeV} \\ \mathrm{N}_\nu &= \quad 2.991 \pm 0.016 \\ \sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} &= \quad 0.23143 \pm 0.00028 \end{aligned}$$

- All in good agreement with Standard Model.
  Radiative corrections $\Longrightarrow$

$$m_{\mathrm{top}} = 178 \pm 8^{+17}_{-20}\mathrm{GeV}$$

  In good agreement with 180 ± 12 from CDF/D0

- Future : Still have 1995 scan data ...