Cross-sections and lepton asymmetry measurements from LEP

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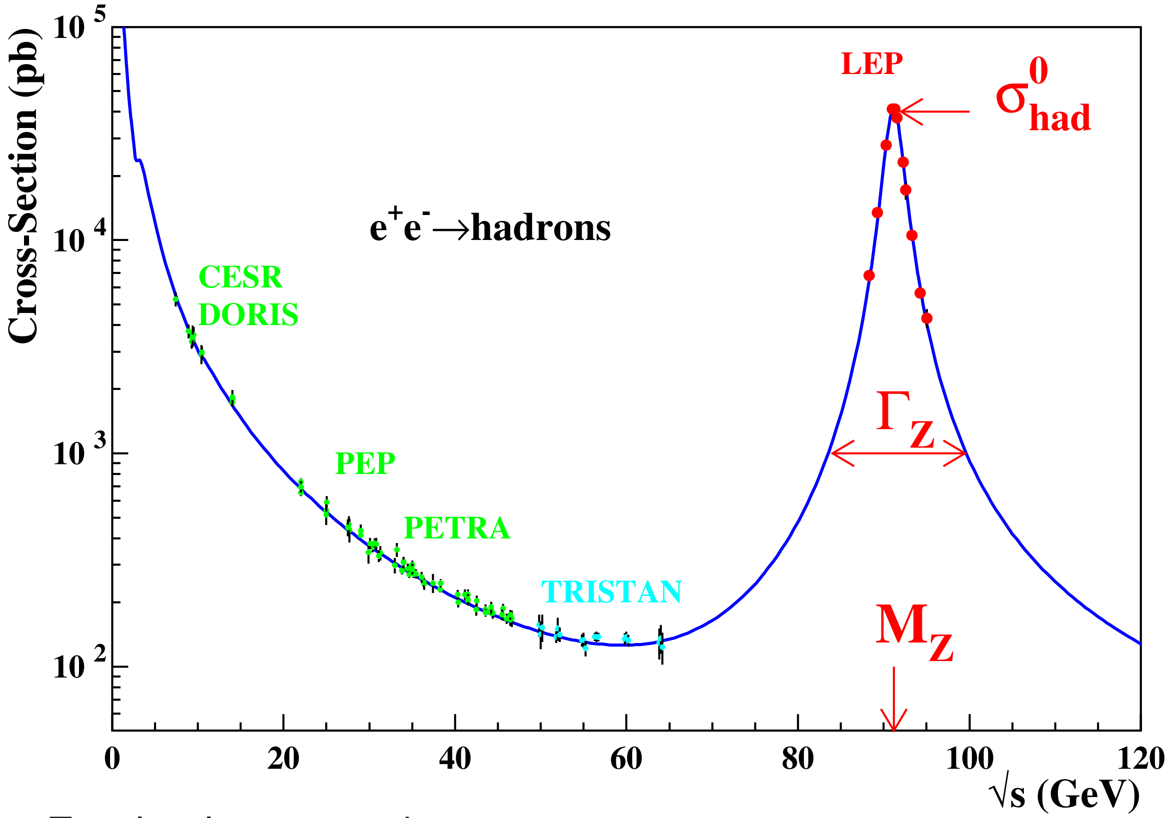
- Introduction to Z^0 lineshape
- Experimental measurements:
  - Event selection
  - Luminosity measurement
  - LEP Energy
- Extracting Z^0parameters
- Standard Model fits
- Results from LEP1.5

Z^0 lineshape



Tree level cross–section:

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

where:

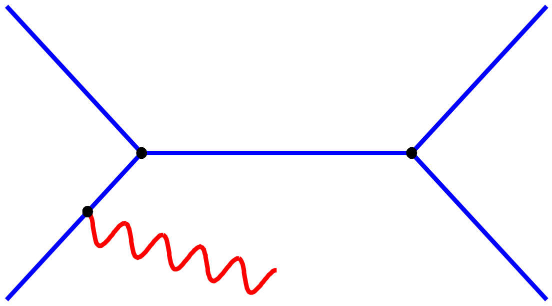
$$\sigma_f^0 = \frac{12\pi\Gamma_e\Gamma_f}{\mathrm{M_Z}{}^2\Gamma_Z{}^2}$$

partial decay widths:

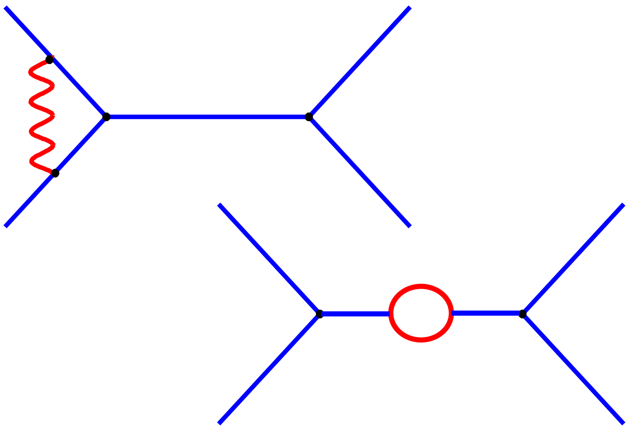
$$\Gamma_f = \frac{G_\mu M_Z{}^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2)N_{col}$$

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

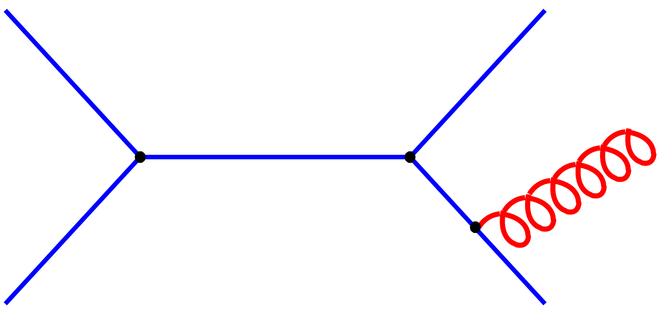
Radiative Corrections



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

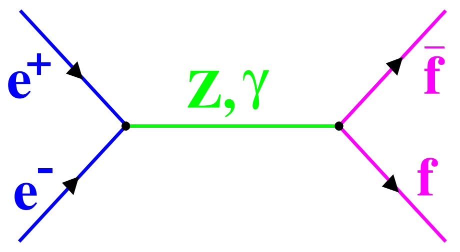


Vertex and loop corrections also give sizeable effects. These are absorbed into 'effective couplings' . Sensitive to m_t and m_H



QCD corrections $\rightarrow$ sensitivity to α_s.

Measuring cross–sections

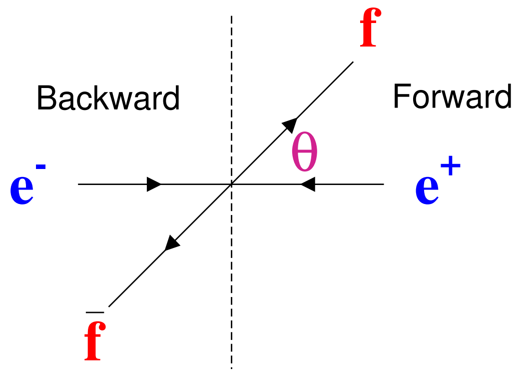


$\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$ measured cross–section:

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

Experimental considerations:

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



Also measure differential cross-section:

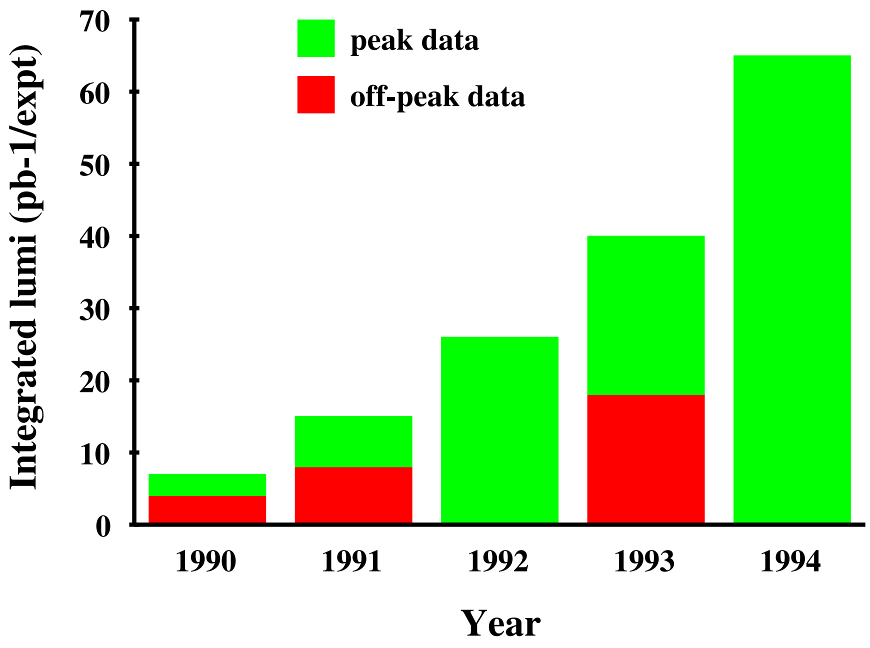
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A^f_{\mathrm{FB}} \cos\theta$$

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

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

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

Data sets



- Published:

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

- Preliminary:

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

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

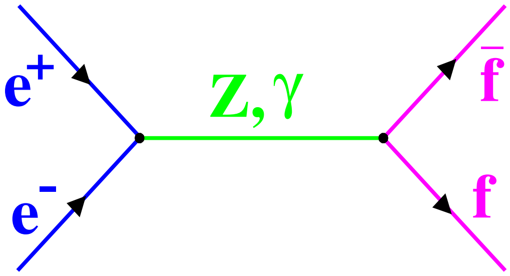
  1994 ($\sim 5.3 \times 10^6$ $\mathrm{q\bar{q}}$, $\sim 0.5 \times 10^6$ leptons)

  All at $\mathrm{Z^0}$peak

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

$\sim 1.3 \times 10^6$ leptons

Event selection

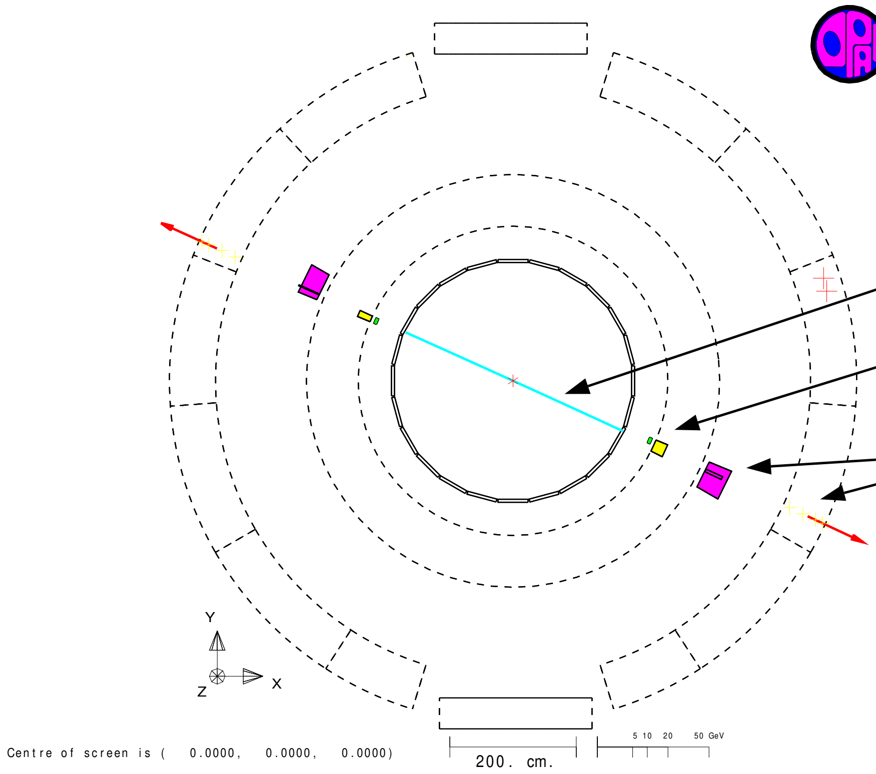


Identify different fermion species (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$) and count events.

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

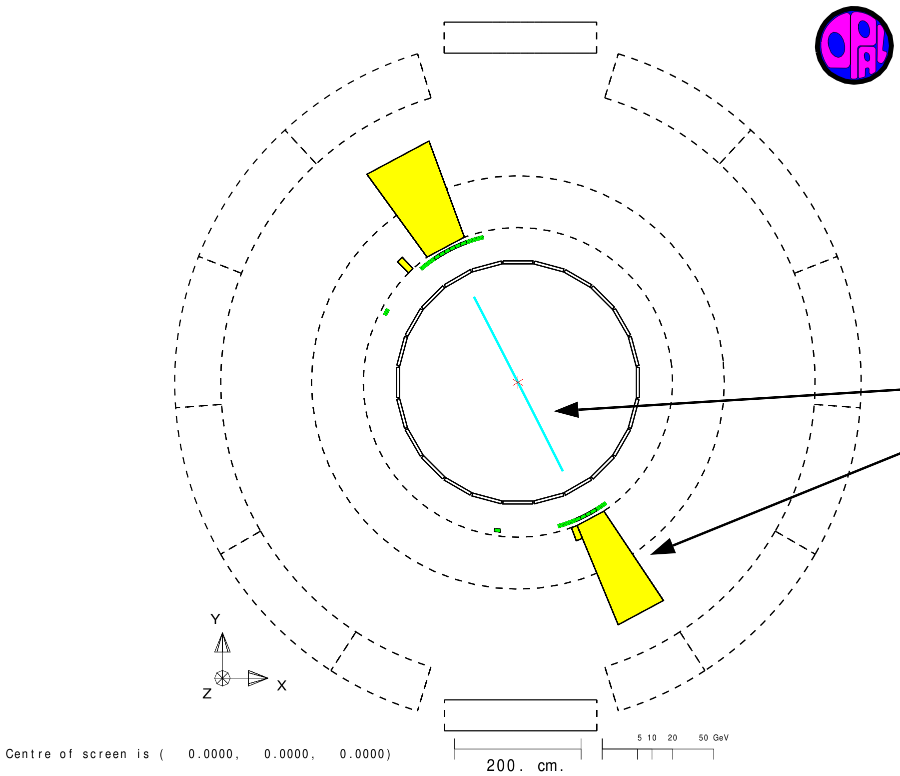
- $q\bar{q}$: high multiplicity ($N_{trk} \geq 5$)
  minimum energy deposits ($E_{ch} > 0.1\sqrt{s}$)
  $\varepsilon \sim 99\%$
  background $\sim 0.3\%$ ($\tau^+\tau^-$ and 2γ).

- l^+l^- : collimated, low multiplicity events.
  separate different species using particle ID and topology.
  e^+e^- : 2 high mom. tracks associated to large ECAL deposits.
  $\varepsilon \sim 97\%$, background $\sim 1.5\%$ ($\tau^+\tau^-$).
  $\mu^+\mu^-$: 2 high mom. tracks with associated muon signals.
  $\varepsilon \sim 95\%$, background $\sim 1-2\%$ ($\tau^+\tau^-$, cosmic) .
  $\tau^+\tau^-$: Require 2 low multiplicity “jets” with minimum energy.
  $e^+e^-$and $\mu^+\mu^-$rejection.
  $\varepsilon \sim 75\%$, background $\sim 2-3\%$ (other channels).



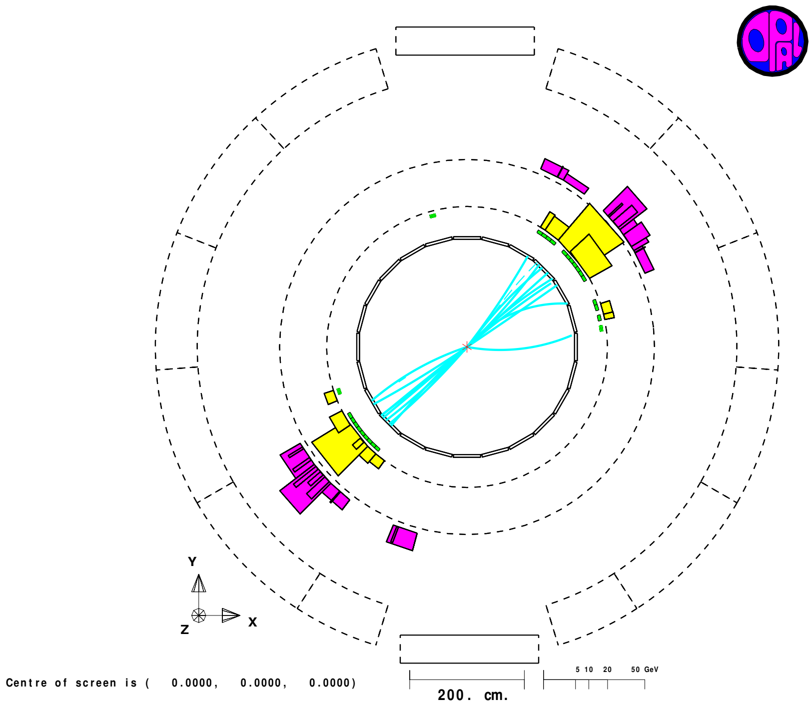
<u>μμ event</u>

2 charged tracks
Min. ion. in TOF, ECAL.
Muon signals in HCAL and muon chambers.



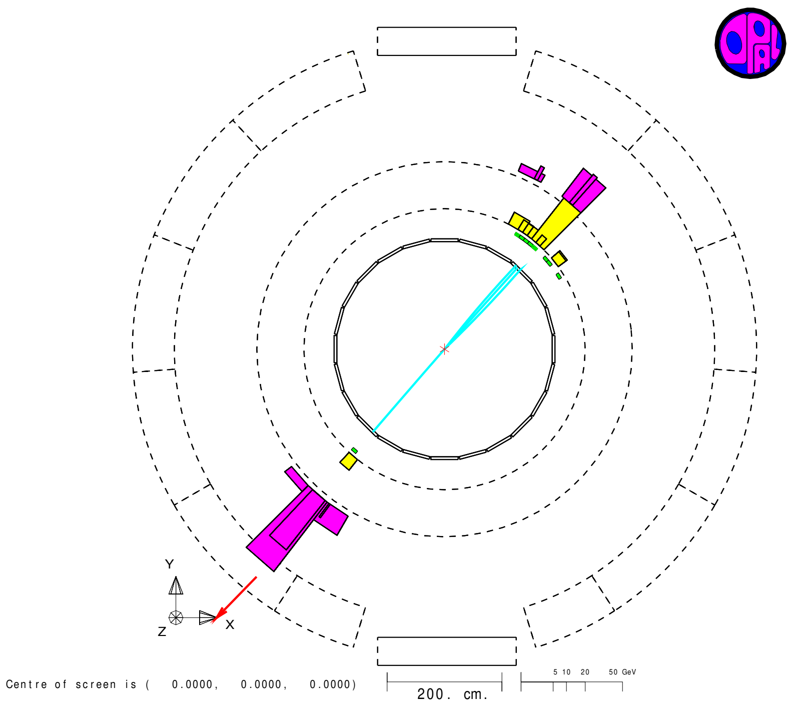
<u>ee event</u>

2 charged tracks
Large ECAL energy $\approx E_{beam}$



qq event

High charged multiplicity
Energy in ECAL and HCAL



$\tau\tau$ event

low multiplicity back-to-back "jets".
In this case: $\tau \rightarrow$hadrons

Systematic errors for preliminary results:

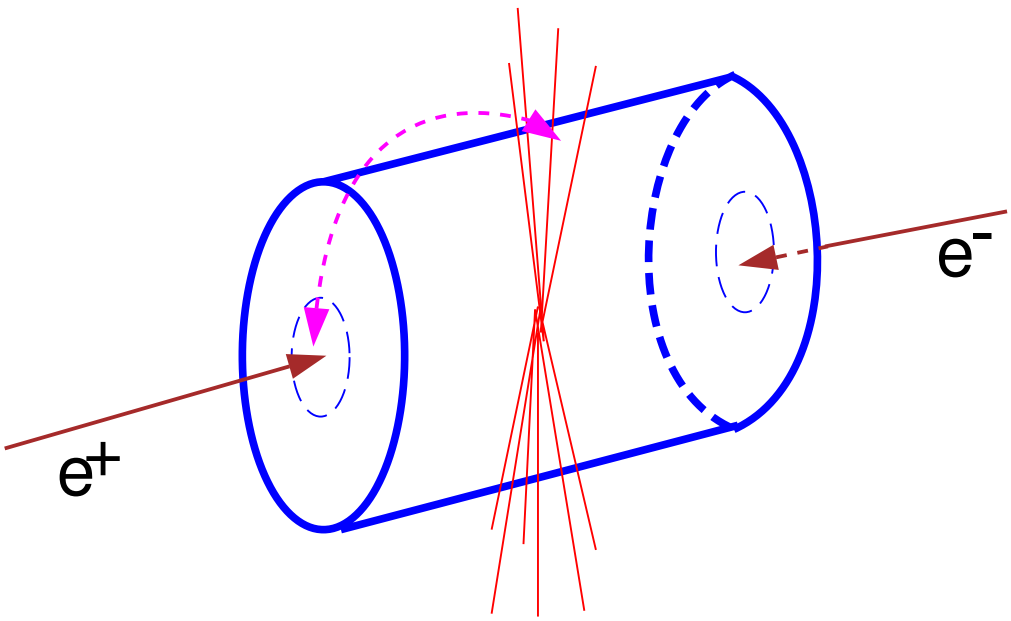
$\mathrm{f\bar{f}}$	$\delta\sigma/\sigma$	δA_{FB}
$\mathrm{q\bar{q}}$	0.07–0.20%	–
$\mathrm{e^+e^-}$	0.23–0.50%	0.002–0.004
$\mu^+\mu^-$	0.15–0.60%	0.001–0.002
$\tau^+\tau^-$	0.32–1.5%	0.002–0.006

Lepton statistical error $\sim 0.4\%$ so still statistics dominated

Multihadron statistical error $\sim 0.1\% \rightarrow$ systematics dominated

$\longrightarrow$ use data as much as possible.

e.g. acceptance hole in forward region:



Luminosity measurement

At LEP the luminosity ($\mathcal{L}$) is measured using the low angle bhabha scattering process $\mathrm{e^+e^-} \longrightarrow \mathrm{e^+e^-}$.

Dominated by t-channel γ exchange.

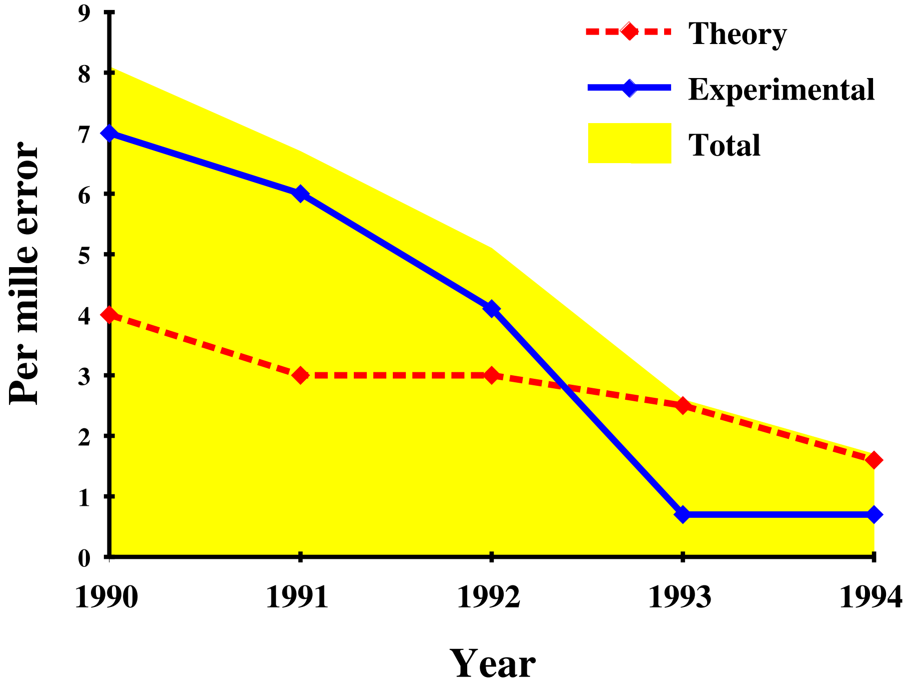
QED cross–section is well known.

Cross–section varies as $\frac{1}{\theta^3}$ so low angles $\longrightarrow$ high rate.

Statistical error $\mathrm{Z^0} \longrightarrow \mathrm{q\overline{q}}$ cross–section is $\approx 0.1\%$.

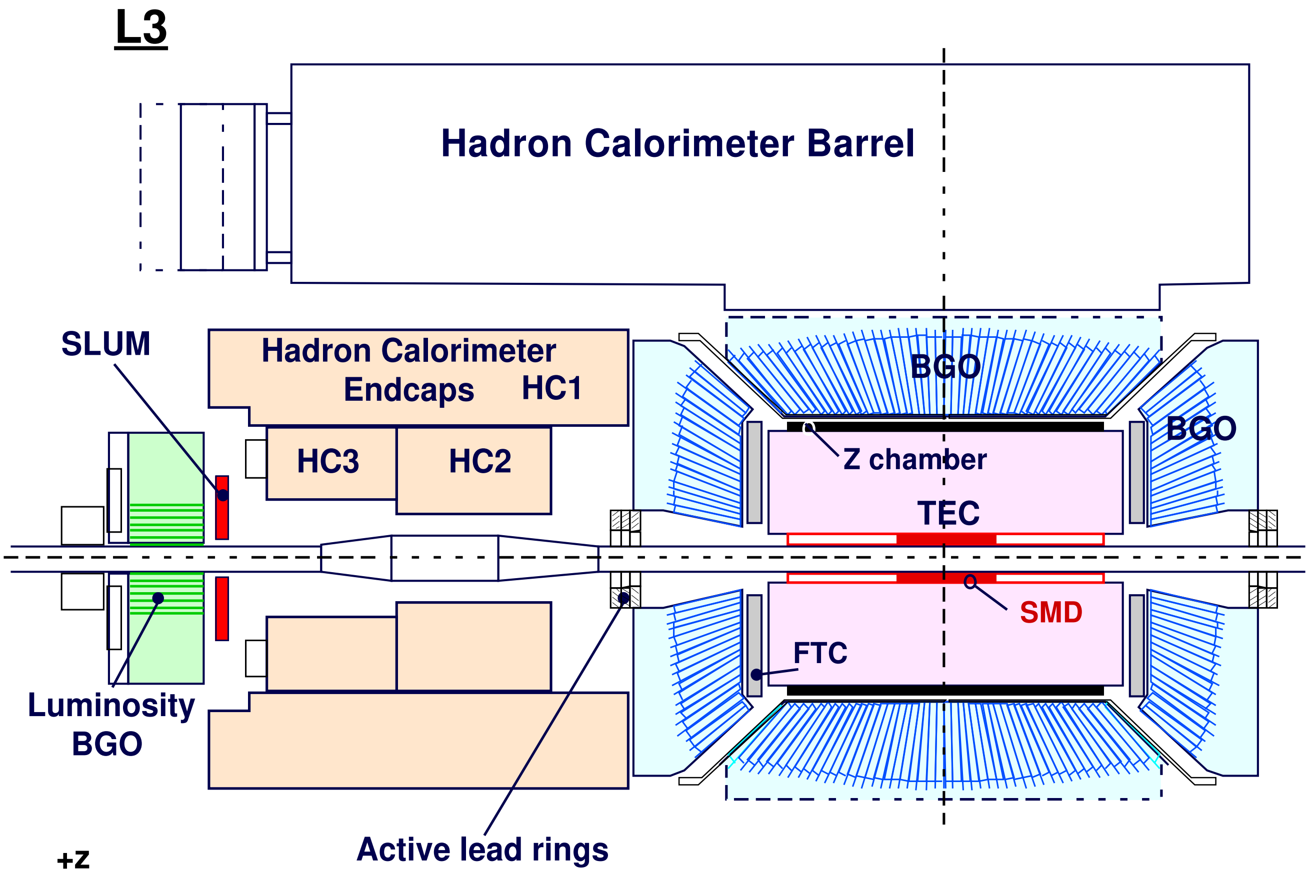
Need a comparable precision on luminosity.

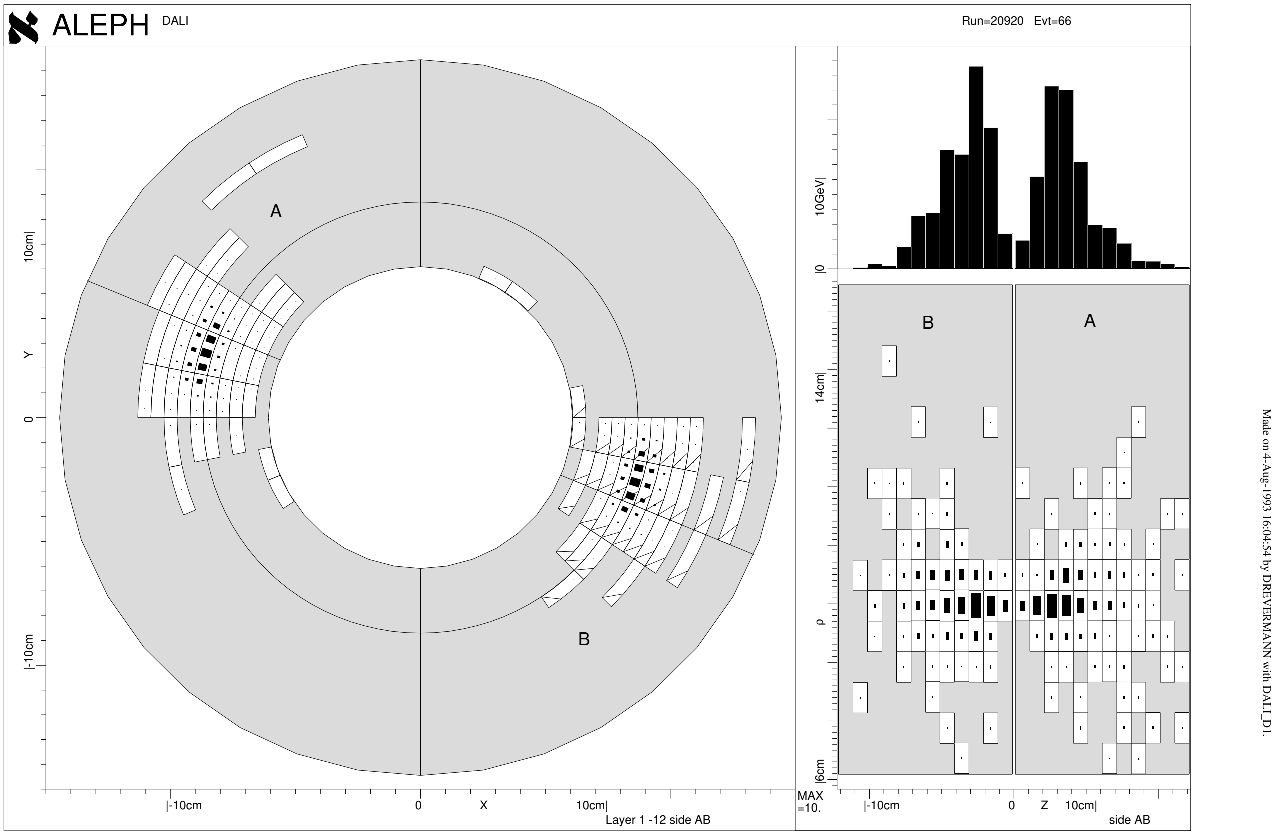
Much progress has been made in the last few years with upgrades to 2nd generation luminosity detectors by all LEP experiments.

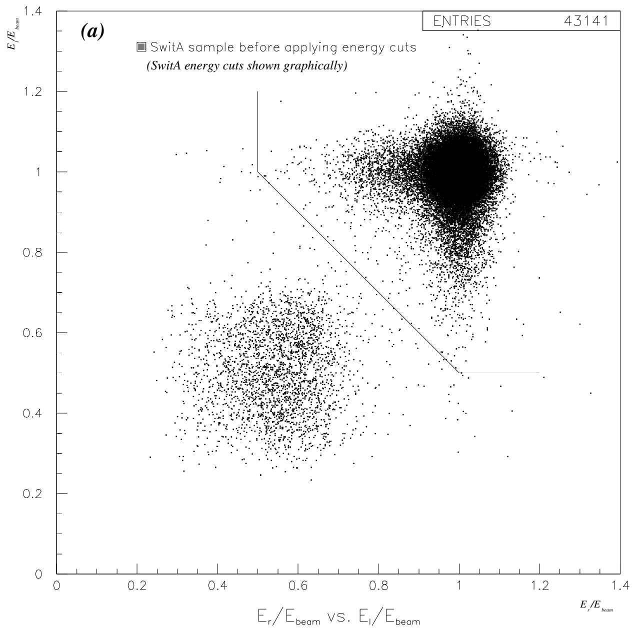


1st generation : $\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim 0.3 - 0.5\%$

2nd generation : $\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim 0.07 - 0.2\%$

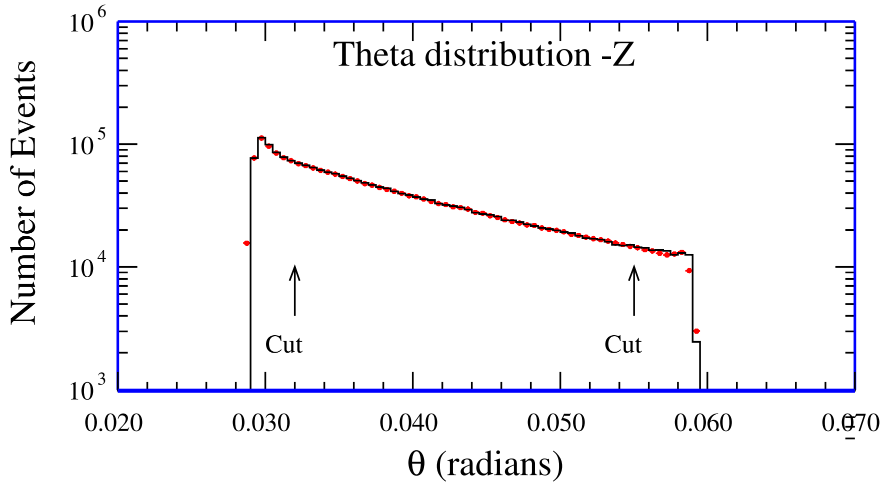

L3
Hadron Calorimeter Barrel
SLUM
Hadron Calorimeter
Endcaps HC1
HC3
HC2
BGO
BGO
Z chamber
TEC
SMD
FTC
Luminosity
BGO
Active lead rings
+Z


ALEPH DALI
Run=20920 Evt=66
A
B
10cm|
Y
0
|-10cm
|-10cm
0
X
10cm|
Layer 1 -12 side AB
10GeV|
|0
14cm|
ρ
|6cm
MAX
=10.
|-10cm
0
Z
10cm|
side AB
B
A
Made on 4-Aug-1993 16:04:54 by DREVERMANN with DALI_D1.



Calorimetric measurement →
simple event selection and
background rejection.

Cut on :
- energy
- acoplanarity



Require precise
knowledge of inner
acceptance cut.

Mechanical alignment < 10 μm

Reconstruction bias < 6μm

Main improvements come from:

- Reduced beampipe radii (17cm $\longrightarrow$ 11cm):

  $\sigma \propto 1/\theta^3 \Longrightarrow$ higher event rate at lower angle.

  1st gen. : Lumi. rate $\approx \mathrm{Z}^0$ rate .

  2nd gen. : Lumi. rate $\approx 3 \times \mathrm{Z}^0$ rate .

- Use of precision technology (eg. Si) for determining inner edge of acceptance:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta} \propto \frac{1}{\theta^3} \Rightarrow \sigma \sim \frac{1}{\theta^2_{\mathrm{min}}} - \frac{1}{\theta^2_{\mathrm{max}}}$$

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \simeq 2\frac{\delta\theta_{\mathrm{min}}}{\theta_{\mathrm{min}}} = 2\frac{\delta\mathrm{R}_{\mathrm{min}}}{\mathrm{R}_{\mathrm{min}}}$$

  With $\mathrm{R}_{\mathrm{min}} \sim 10\mathrm{cm}$ an error of $50\mu\mathrm{m}$ at the inner edge gives a 0.1% luminosity error.

Expt.	technology	$\Delta\mathcal{L}/\mathcal{L}$
ALEPH	SiCAL	0.09%
DELPHI	Pb/scin	0.09%
L3	BGO/Si	0.12%
OPAL	SiW	0.08%

- Overall error in now dominated by theory error.

	Glasgow(94)	Now	Future
$\Delta\mathcal{L}/\mathcal{L}$	0.25%	0.16%	0.11%*

* Reduced error from LEP2 workshop studies.

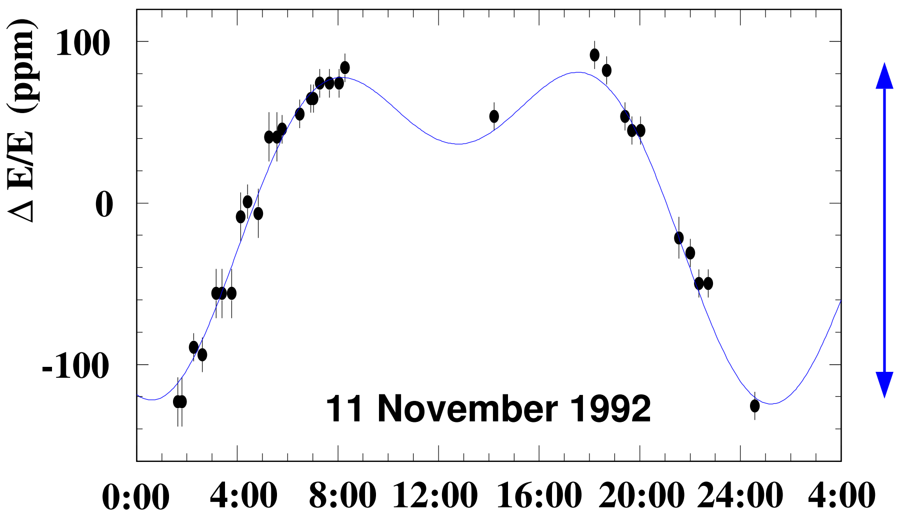
LEP energy error

- 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

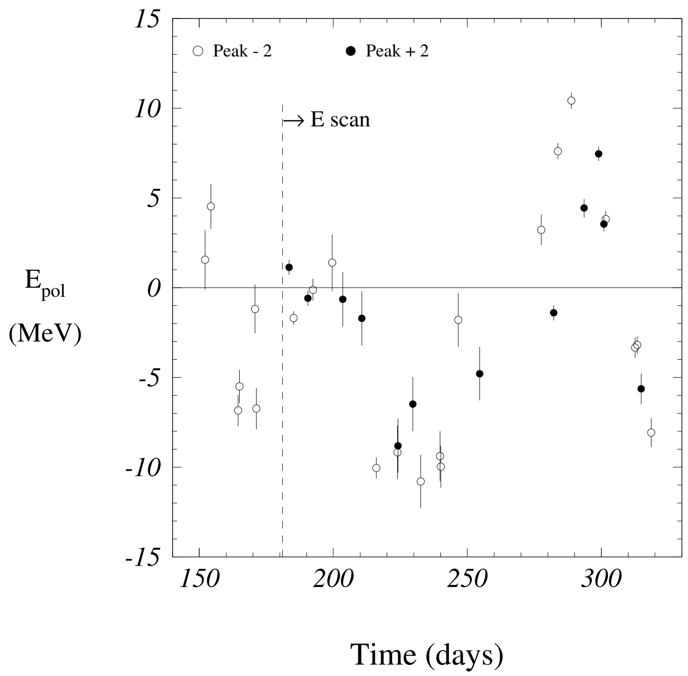
  $\Longrightarrow$ $\sim 1\mathrm{MeV}$ accuracy at IP at time of calibn.
- Time evolution: energy change by about $1\mathrm{MeV}$ per hour. Main sources of change:
  - Changes in dipole magnetic field due to current, temperature, etc.
  - Off–centre particles in quadrupole magnets see $\mathrm{B} \propto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

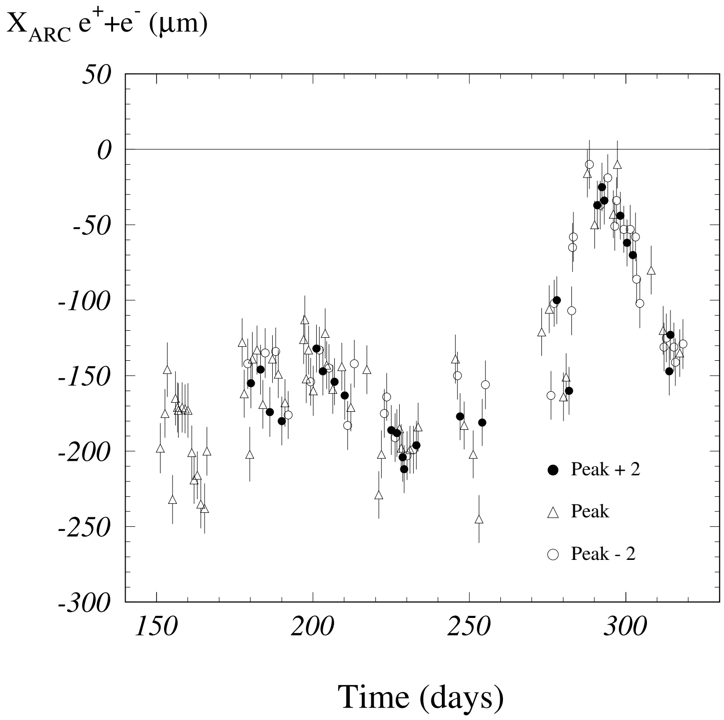
Effect of ground motion on LEP energy

Effect of moon (tidal effect on earth) :



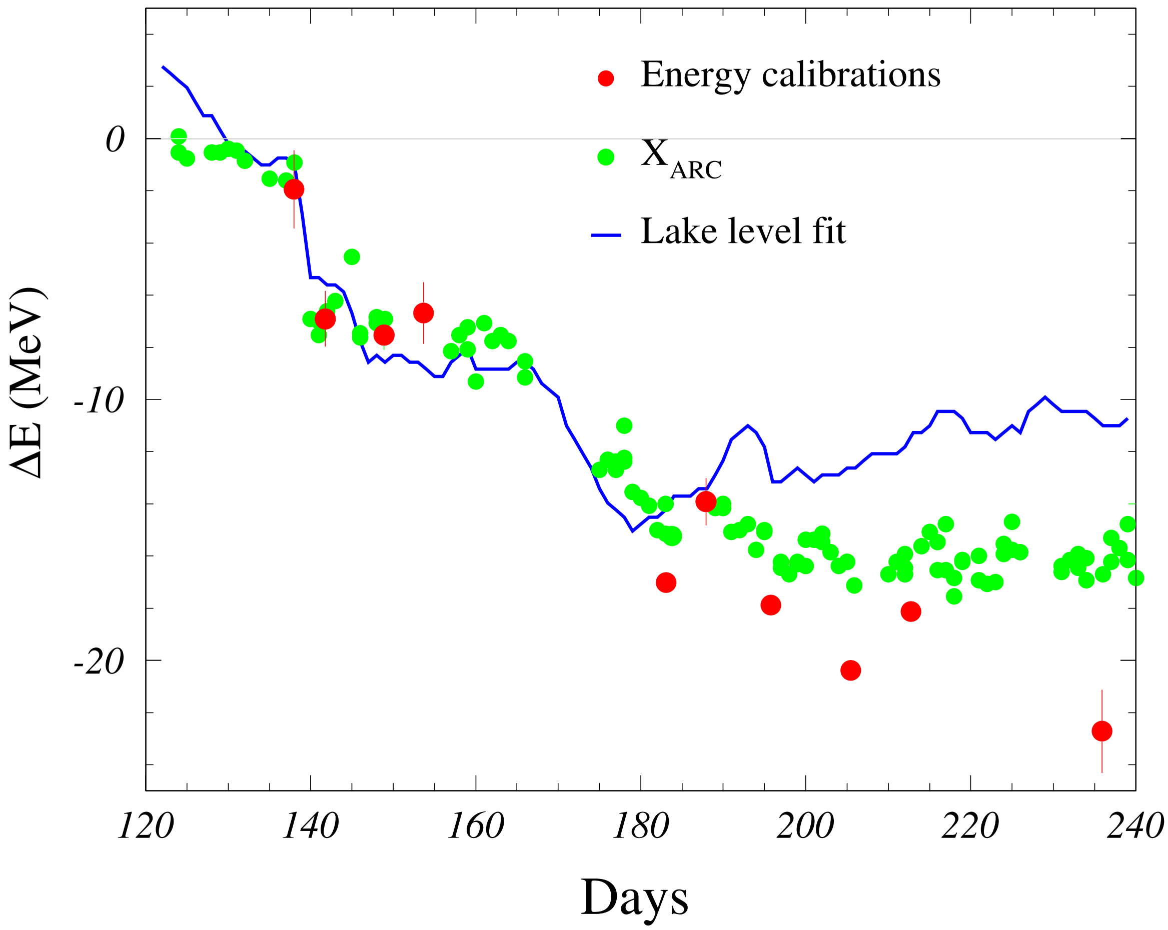
20 MeV for large 'tides'.





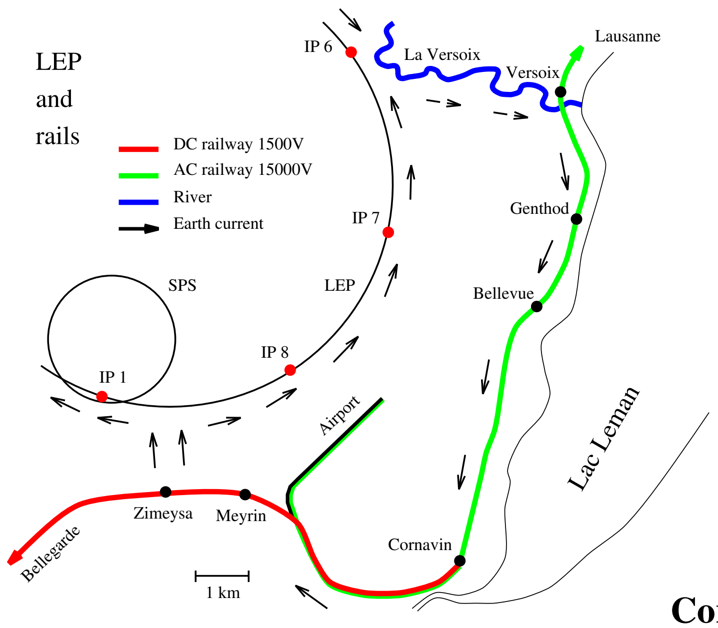
Average beam energy versus time (corrected for changes in dipole fields and tides

Mean X position of beam versus time



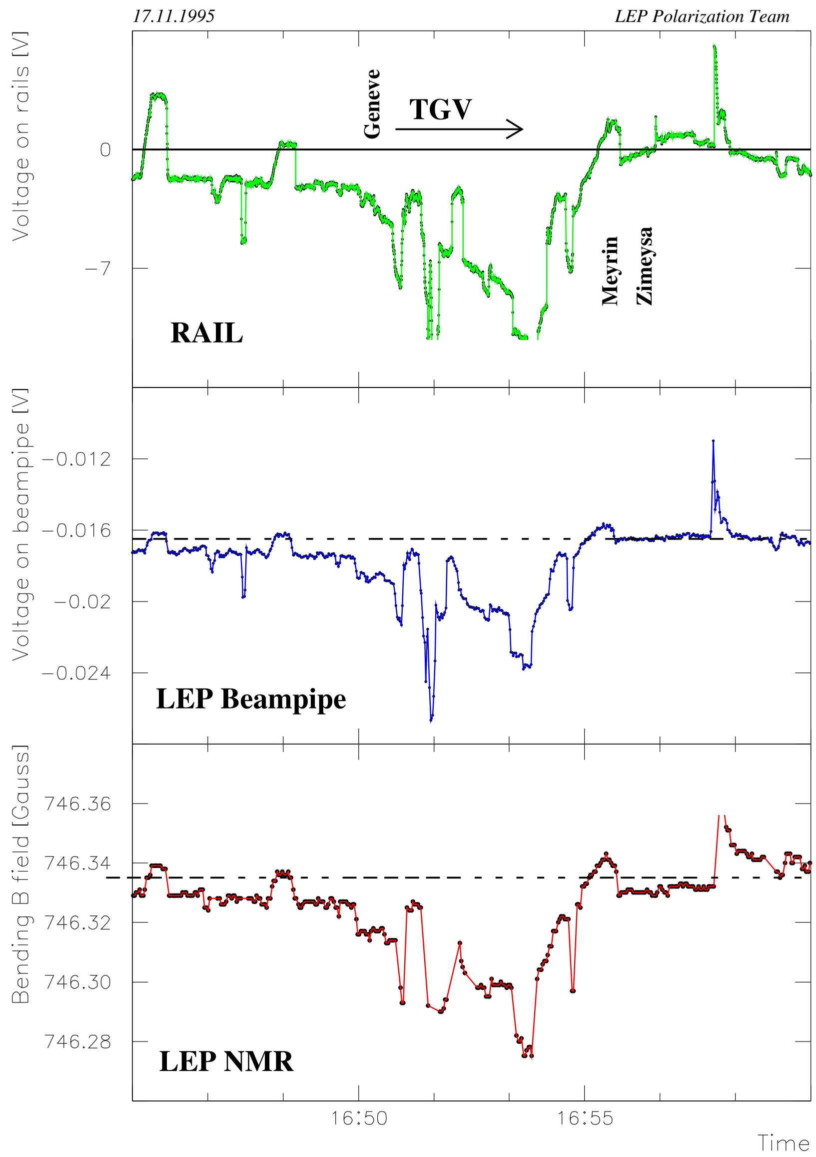
- Remaining RMS scatter after all correction is $5.4 \pm 0.8\mathrm{MeV}$ (c.f. 15MeV before corrections)
- This leads to:
  $\Delta M_Z \sim 1.5\mathrm{MeV}$ and $\Delta\Gamma_Z \sim 1.7\mathrm{MeV}$

The latest energy effect

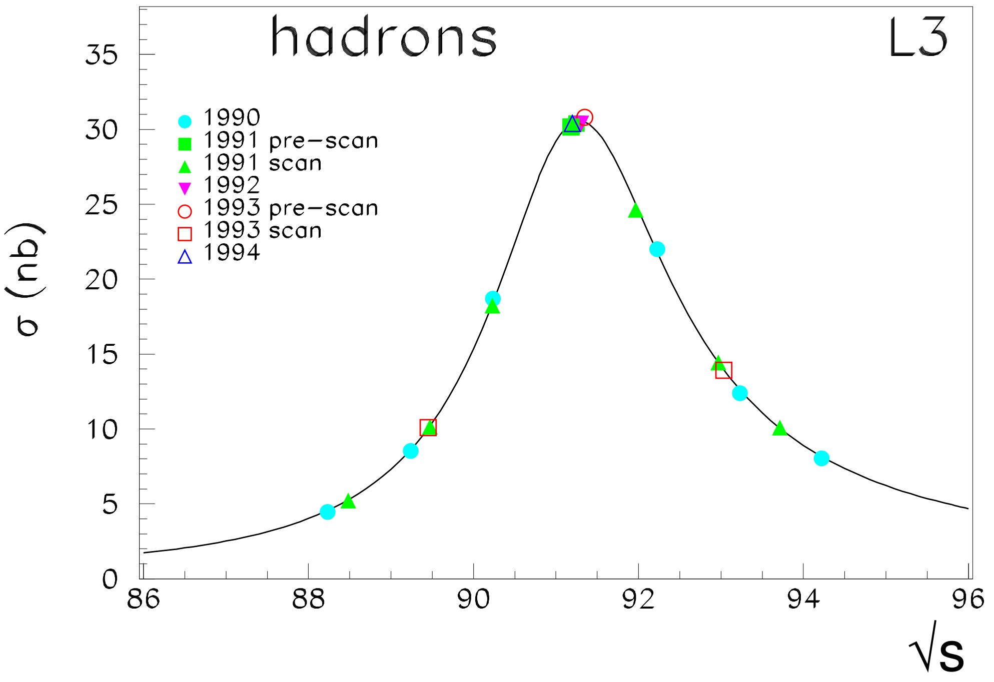


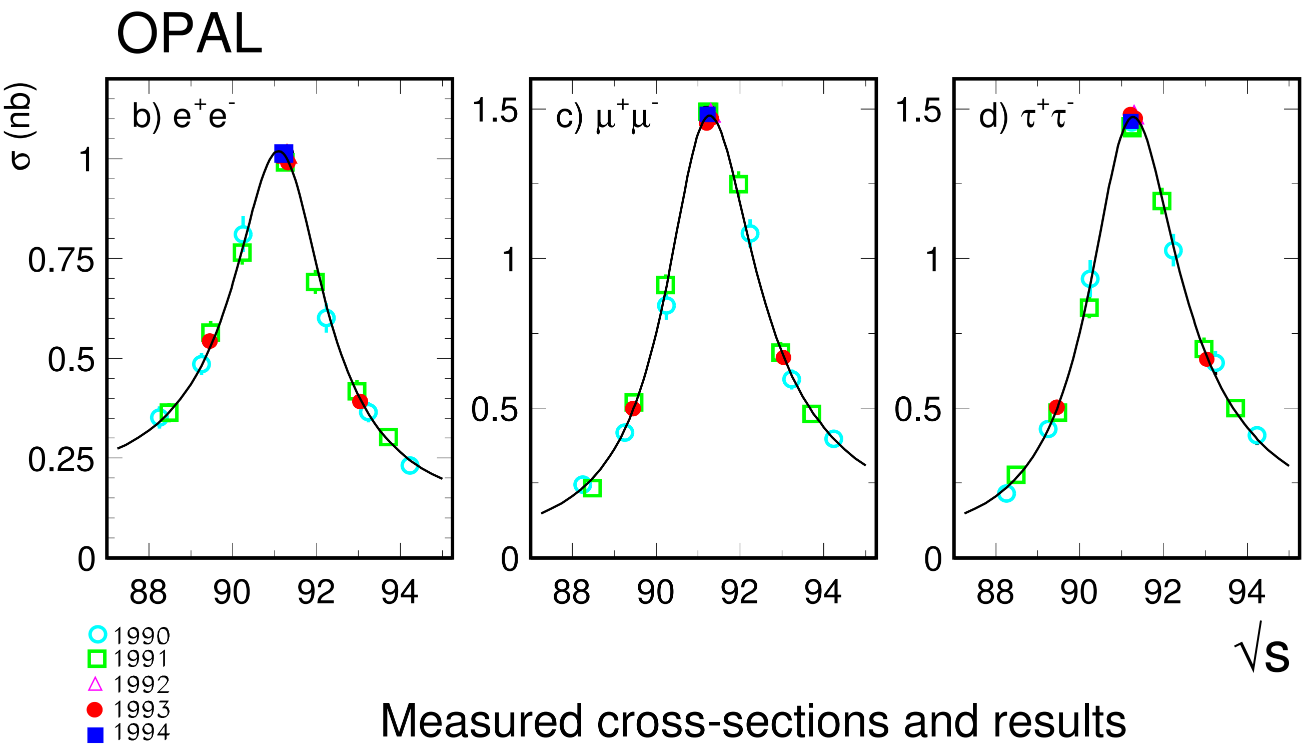
"TGV effect"

Correlation between trains and LEP



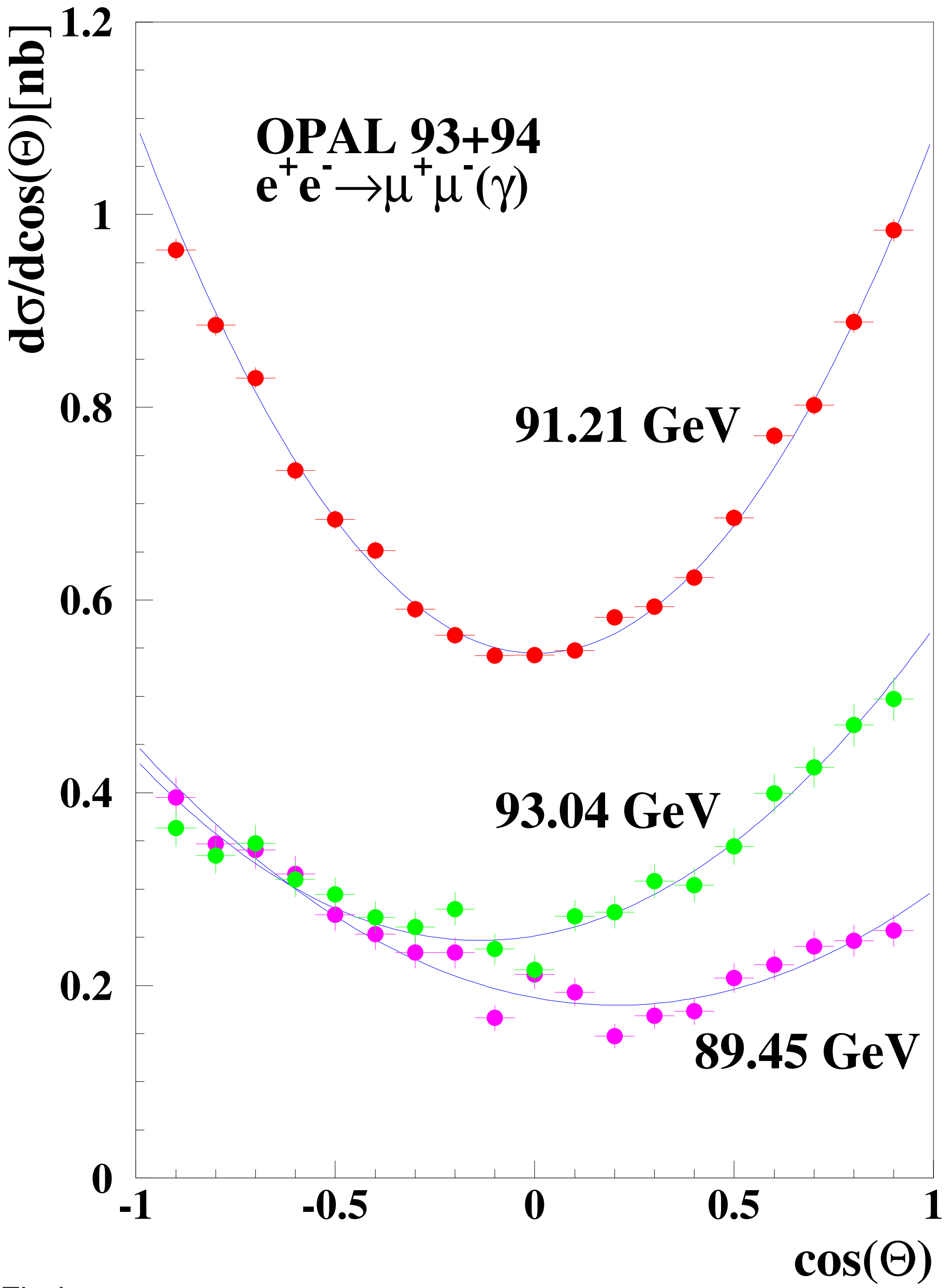
Cross-sections





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

$d\sigma / d\cos\theta$

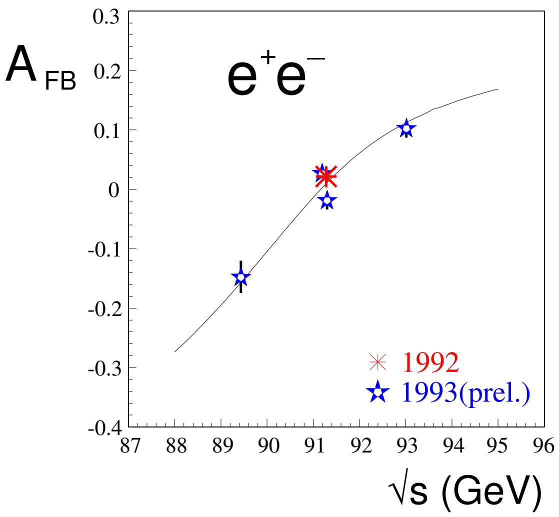


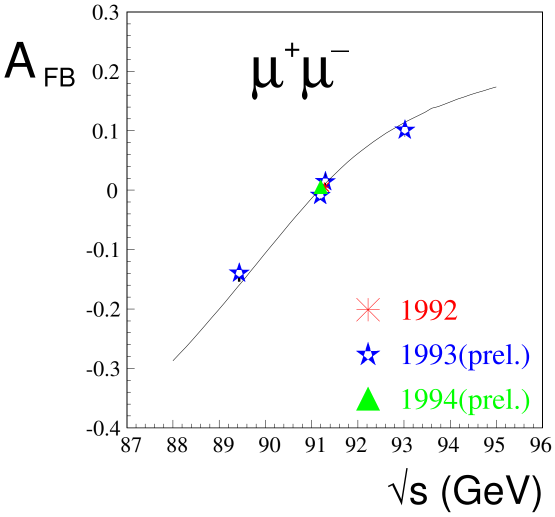
Fit data to:

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

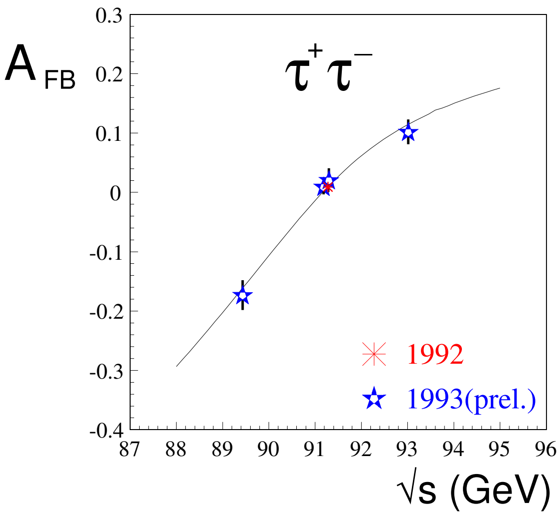
to extract A_{FB}

Forward backward asymmetry





DELPHI



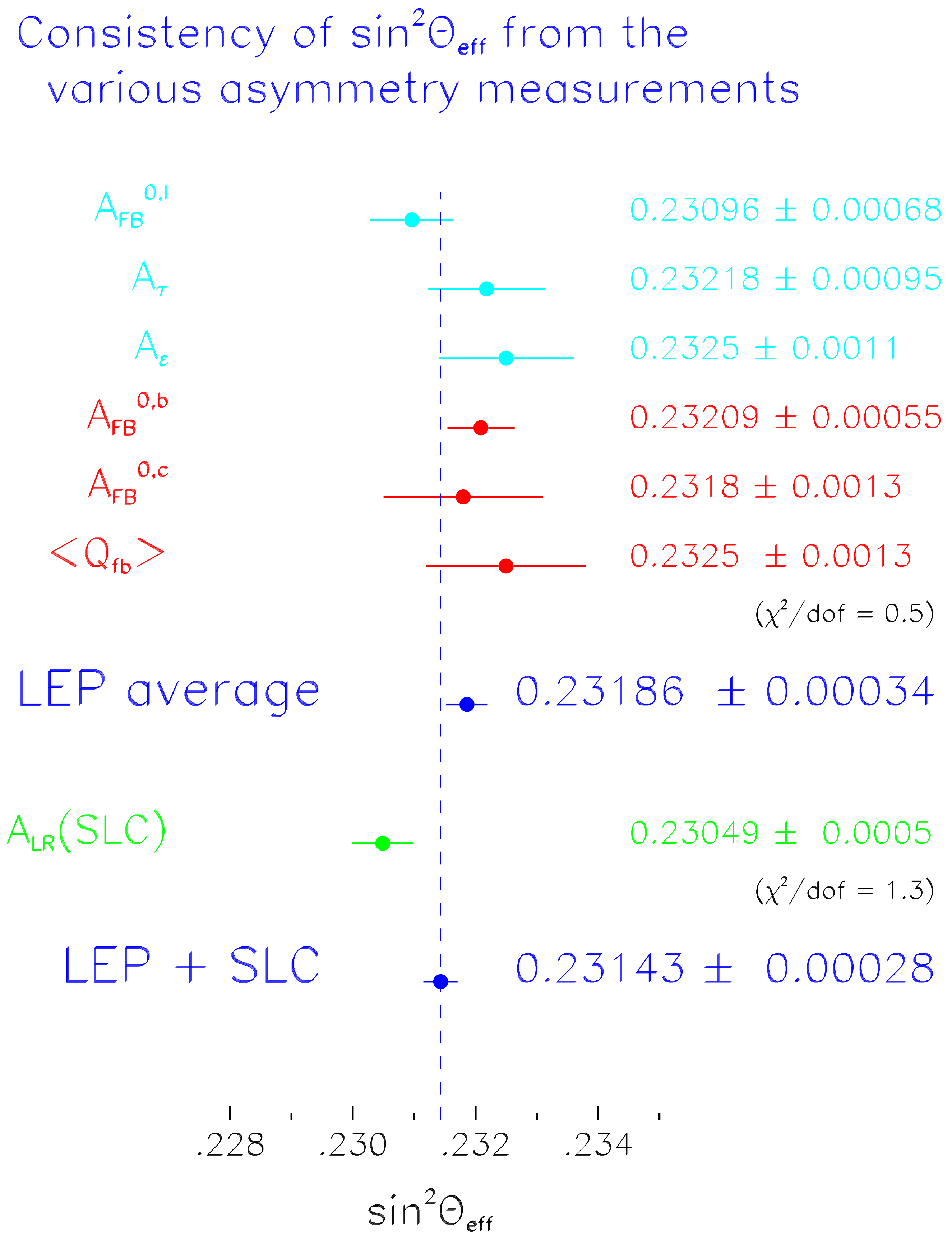
Measured asymmetries and results of fit to all data.

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

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

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

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

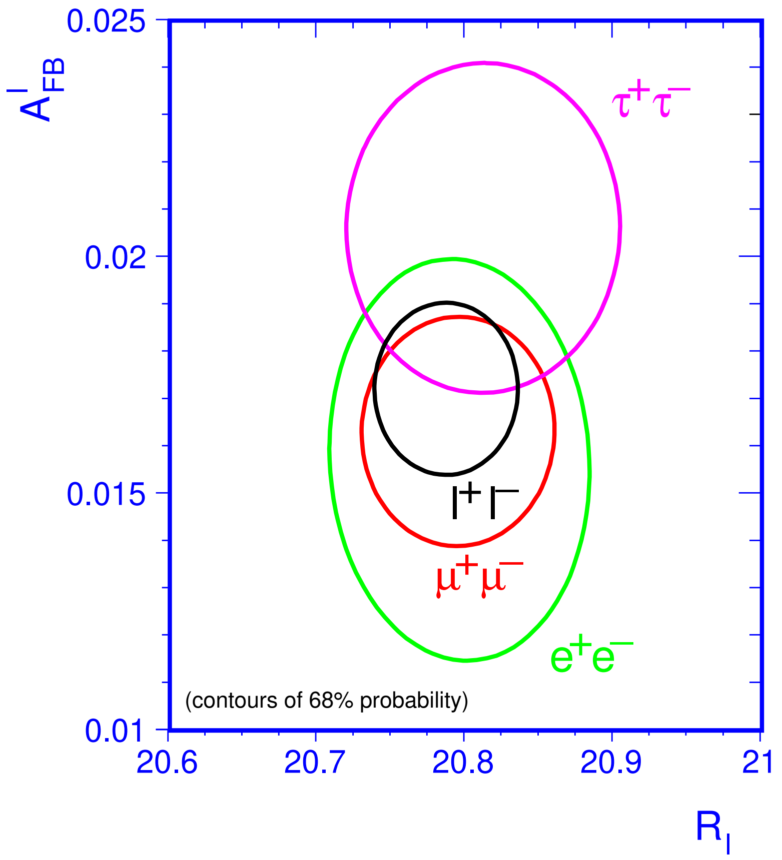

Consistency of $\sin^2\Theta_{eff}$ from the
various asymmetry measurements
$A_{FB}^{0,l}$
0.23096 ± 0.00068
A_{τ}
0.23218 ± 0.00095
A_{ε}
0.2325 ± 0.0011
$A_{FB}^{0,b}$
0.23209 ± 0.00055
$A_{FB}^{0,c}$
0.2318 ± 0.0013
$\langle Q_{fb} \rangle$
0.2325 ± 0.0013
$(\chi^2/\mathrm{dof} = 0.5)$
LEP average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

Combined lineshape results

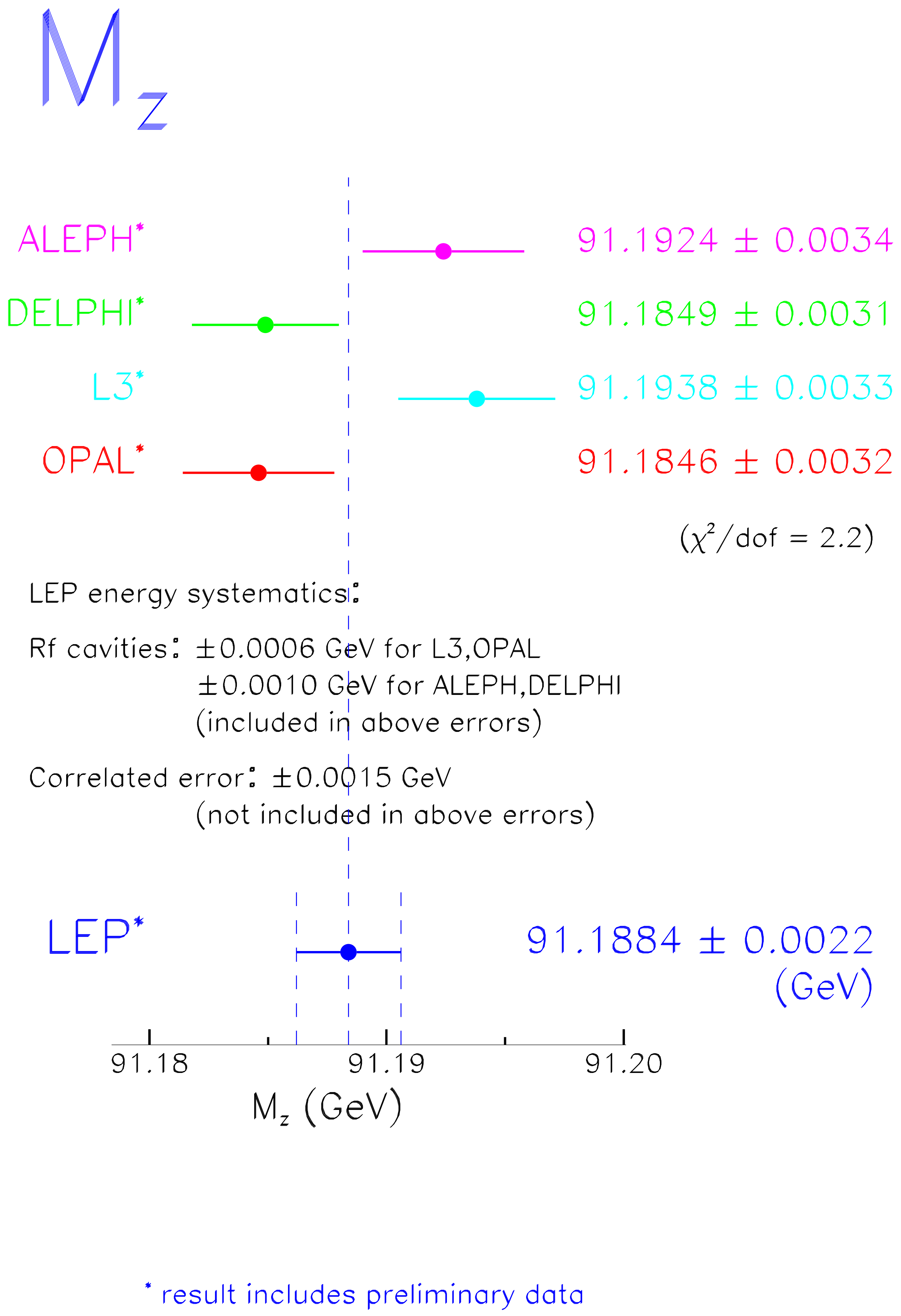
- Each experiment provides 9 parameters derived from the cross-section and lepton forward-backward asymmetry results:
  $M_Z,\ \Gamma_Z,\ \sigma^{\mathrm{pole}}_{\mathrm{had}}$
  $R_e (= \Gamma_{\mathrm{had}}/\Gamma_{ee}),\ R_\mu,\ R_\tau,$
  $A^{0,e}_{\mathrm{FB}},\ A^{0,\mu}_{\mathrm{FB}},\ A^{0,\tau}_{\mathrm{FB}}$

- Combine these using covariance matrix including correlated errors (LEP energy, lumi. theory)

- Check lepton universality:

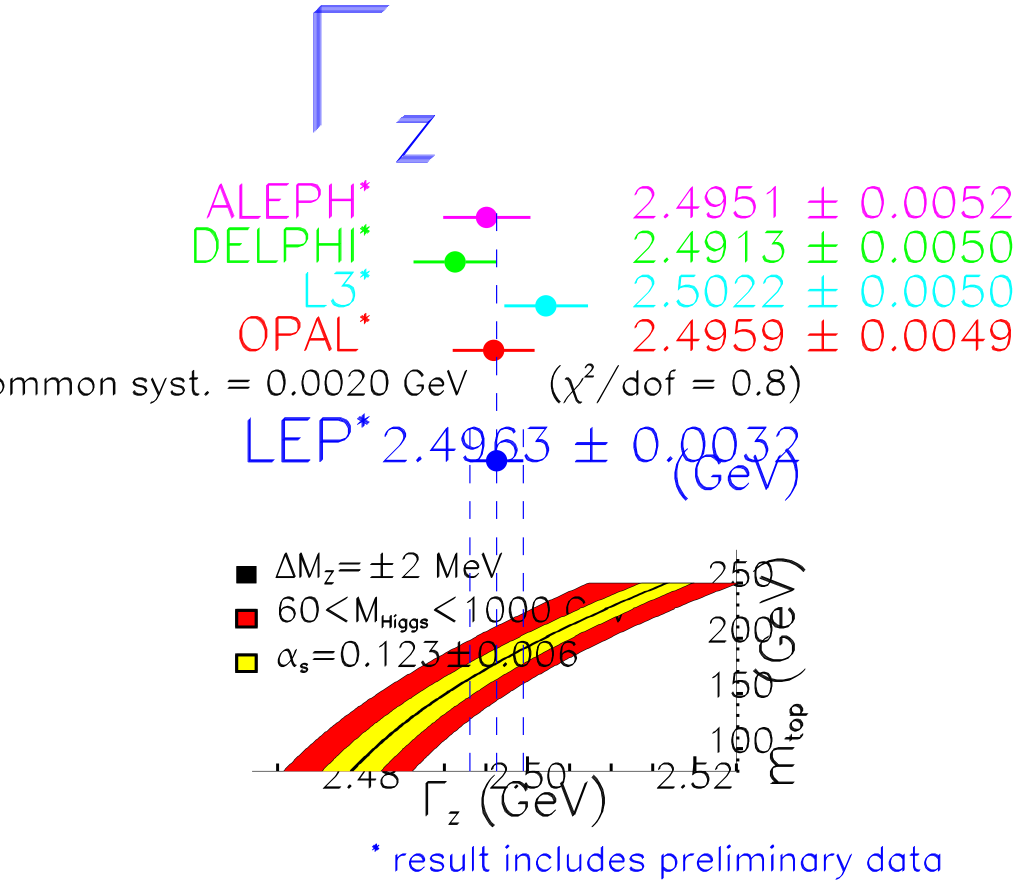


- Then assuming lepton universality derive 5 parameter set and recombine:
  $M_Z,\ \Gamma_Z,\ \sigma^{\mathrm{pole}}_{\mathrm{had}}$
  $R_l\ (= \Gamma_{\mathrm{had}}/\Gamma_{ll}),\ A^{0,l}_{\mathrm{FB}}$

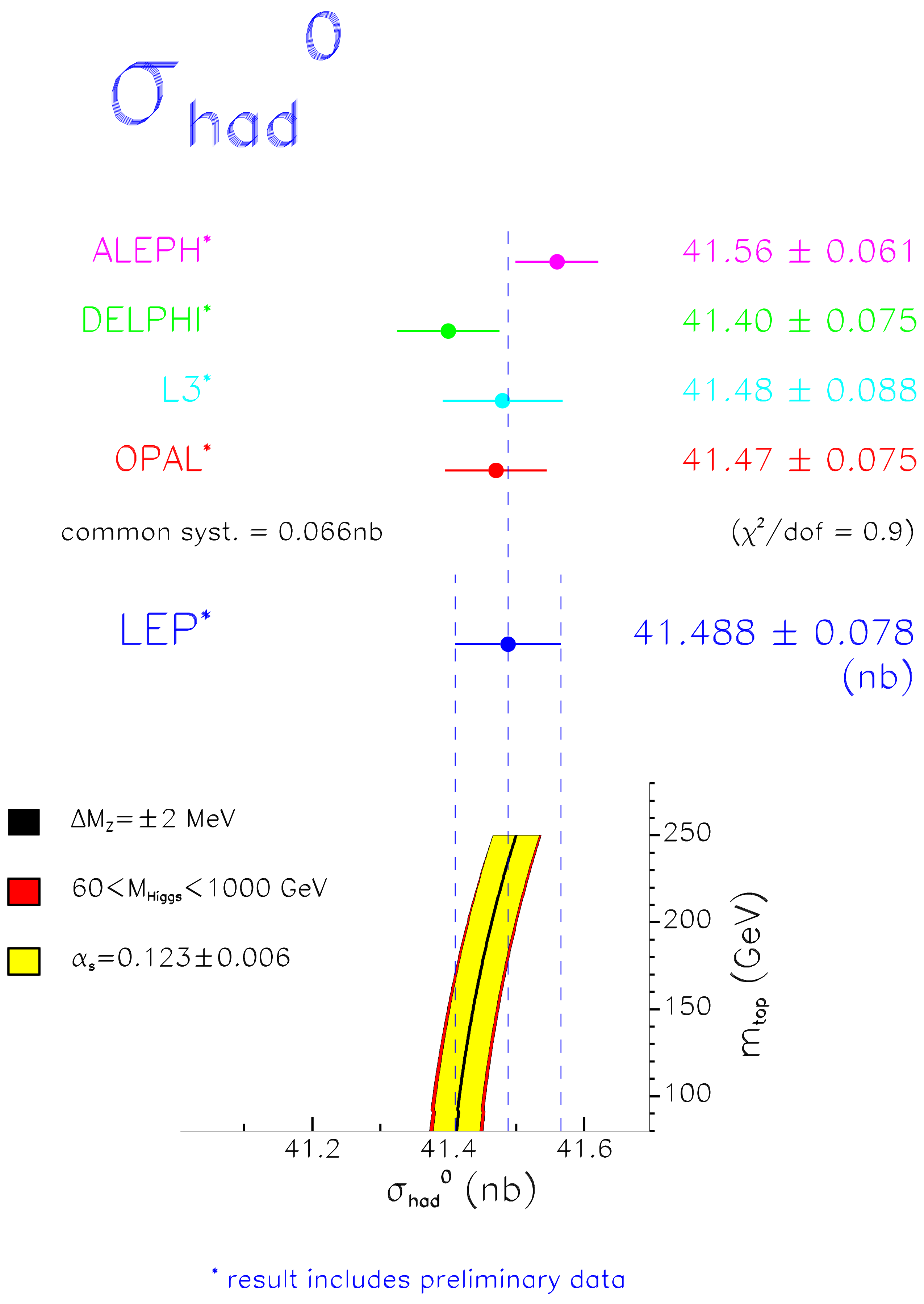


M_Z
ALEPH*
91.1924 ± 0.0034
DELPHI*
91.1849 ± 0.0031
L3*
91.1938 ± 0.0033
OPAL*
91.1846 ± 0.0032
(χ²/dof = 2.2)
LEP energy systematics:
Rf cavities: ±0.0006 GeV for L3,OPAL
±0.0010 GeV for ALEPH,DELPHI
(included in above errors)
Correlated error: ±0.0015 GeV
(not included in above errors)
LEP*
91.1884 ± 0.0022
(GeV)
91.18
91.19
91.20
M_z (GeV)
* result includes preliminary data

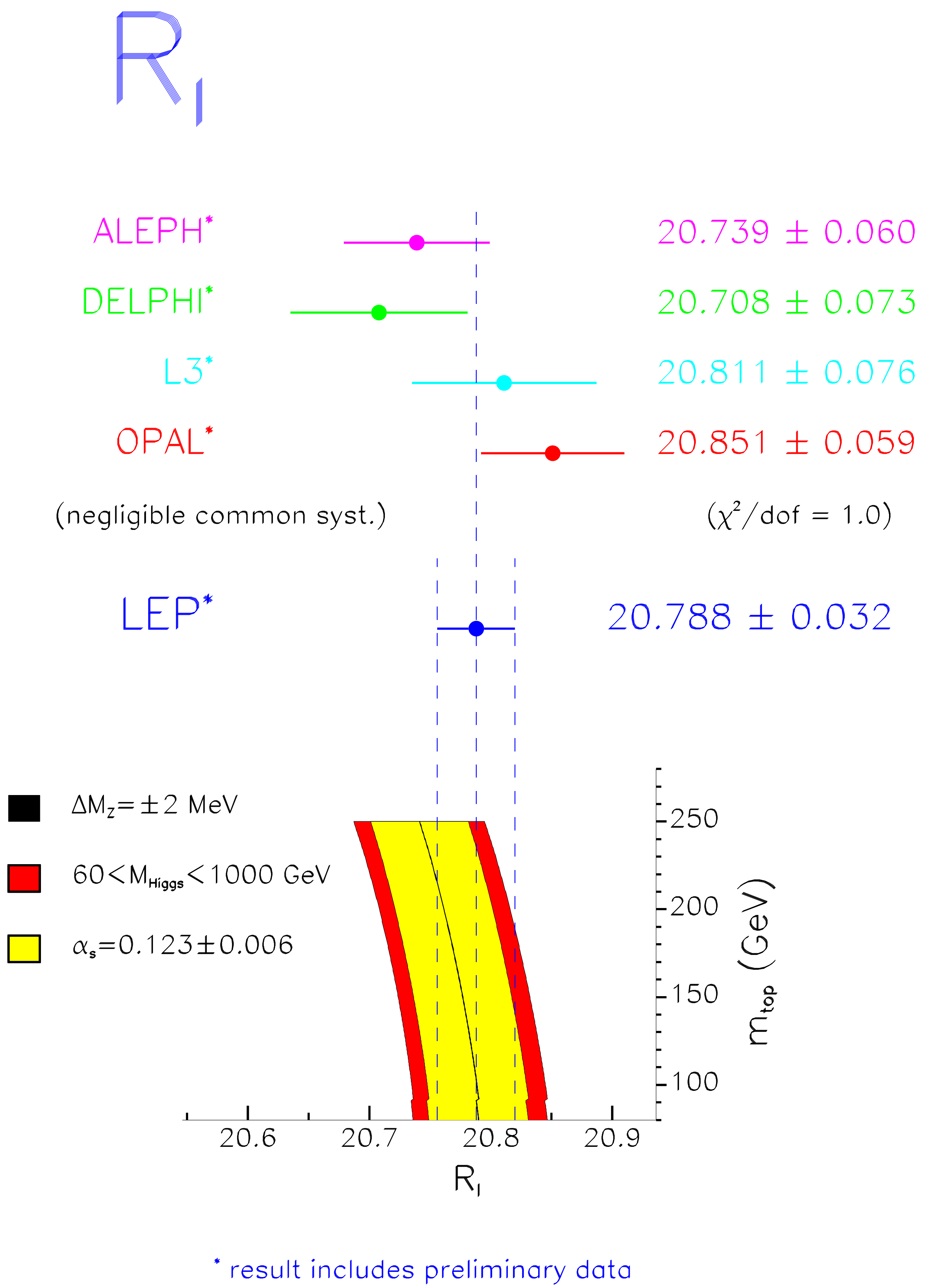
96/03/19 14.11



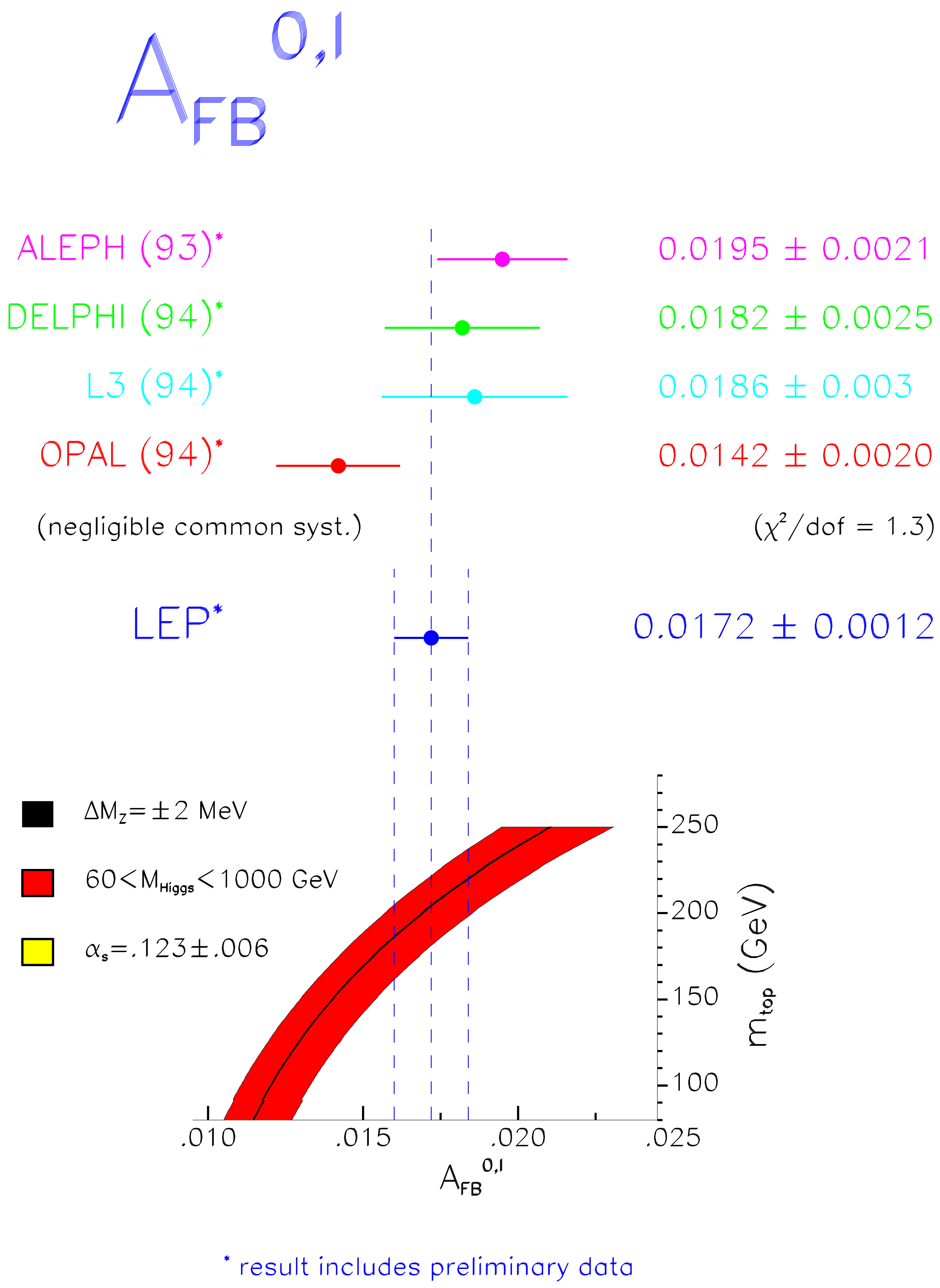
ΓZ
ALEPH* 2.4951 ± 0.0052
DELPHI* 2.4913 ± 0.0050
L3* 2.5022 ± 0.0050
OPAL* 2.4959 ± 0.0049
ommon syst. = 0.0020 GeV
(χ²/dof = 0.8)
LEP* 2.4963 ± 0.0032
(GeV)
ΔMZ=±2 MeV
60<MHiggs<1000 GeV
αs=0.123±0.006
250
200
150
100
mtop (GeV)
2.48
2.50
2.52
Γz (GeV)
* result includes preliminary data



σ_{had}^0
ALEPH*
41.56 ± 0.061
DELPHI*
41.40 ± 0.075
L3*
41.48 ± 0.088
OPAL*
41.47 ± 0.075
common syst. = 0.066nb
(χ^2/dof = 0.9)
LEP*
41.488 ± 0.078
(nb)
$\Delta M_Z = \pm 2$ MeV
$60 < M_{Higgs} < 1000$ GeV
$\alpha_s = 0.123 \pm 0.006$
250
200
150
100
m_{top} (GeV)
41.2
41.4
41.6
σ_{had}^0 (nb)
* result includes preliminary data



R_l
ALEPH*
20.739 ± 0.060
DELPHI*
20.708 ± 0.073
L3*
20.811 ± 0.076
OPAL*
20.851 ± 0.059
(negligible common syst.)
$(\chi^2/\text{dof} = 1.0)$
LEP*
20.788 ± 0.032
$\Delta M_Z = \pm 2$ MeV
$60 < M_{Higgs} < 1000$ GeV
$\alpha_s = 0.123 \pm 0.006$
250
200
150
100
m_{top} (GeV)
20.6
20.7
20.8
20.9
R_l
* result includes preliminary data



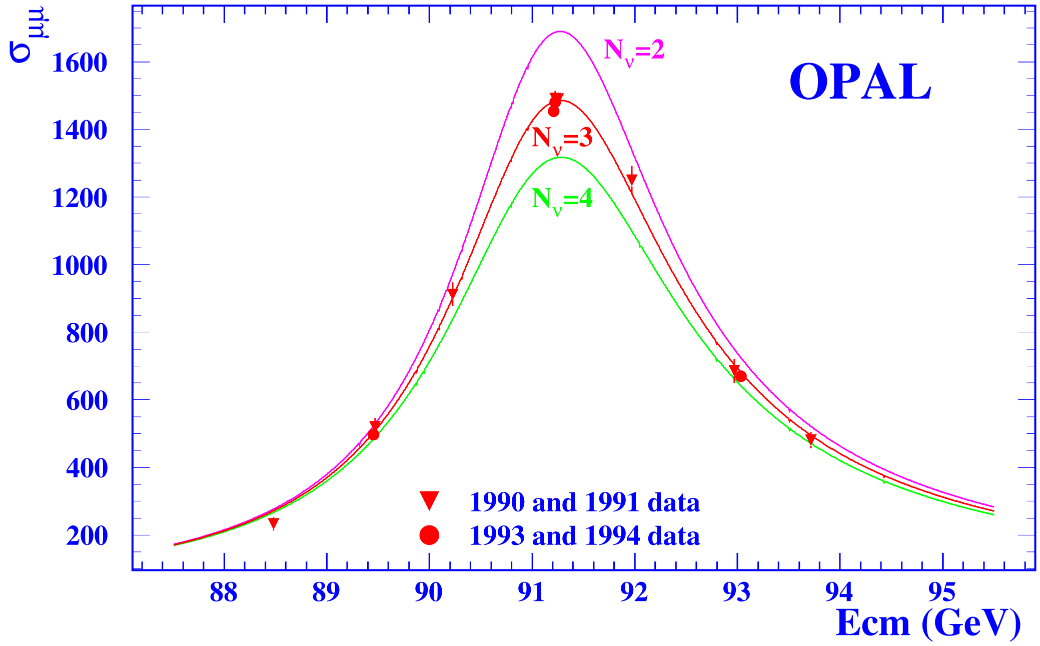
$A_{FB}^{0,l}$
ALEPH (93)*
0.0195 ± 0.0021
DELPHI (94)*
0.0182 ± 0.0025
L3 (94)*
0.0186 ± 0.003
OPAL (94)*
0.0142 ± 0.0020
(negligible common syst.)
(χ^2/dof = 1.3)
LEP*
0.0172 ± 0.0012
$\Delta M_Z = \pm 2$ MeV
$60 < M_{Higgs} < 1000$ GeV
$\alpha_s = .123 \pm .006$
250
200
150
100
m_{top} (GeV)
.010
.015
.020
.025
$A_{FB}^{0,l}$
* 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



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

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

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: $m_{\rm top} = 180 \pm 12{\rm GeV}$
$60 < m_{\rm H} < 1000{\rm GeV}$)

$$\implies \mathrm{N}_\nu = 2.991 \pm 0.016$$

Standard Model fits

- SM parameters: $\alpha,\ \mathrm{G_F}$ and $\mathrm{M_Z}$.

  Recent reevaluations of $\alpha(\mathrm{M_Z}) \to 128.896 \pm 0.090$.

- 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 $\nu\mathrm{N}$ ($\sin^2\theta_W$)

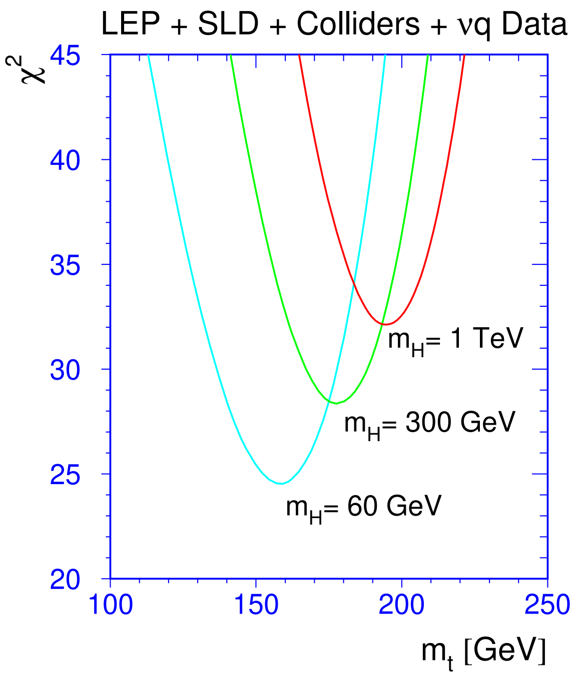
- Fit to SM with m_{top} and $\alpha_s(\mathrm{M_Z})$ as free parameters.

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

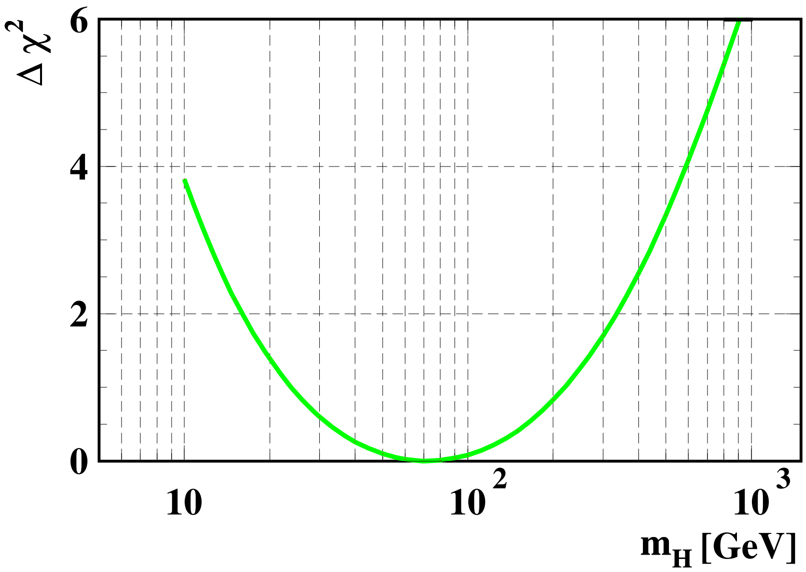
Constraint on m_{H}?



- 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



The LEP-1.5 Run

31 Oct – 22 Nov 1995

Main aim: Learn about high energy operation of superconducting RF.

Physics aim: Collect $\geq 5\mathrm{pb}^{-1}$ at high energy.
In practise:

- $3\mathrm{pb}^{-1}$ at 130 GeV
- $3\mathrm{pb}^{-1}$ at 136 GeV
- $0.05\mathrm{pb}^{-1}$ at 140 GeV

Measure cross–sections and asymmetries in exactly same way as at LEP1 and compare to SM predictions.
(OPAL biased)

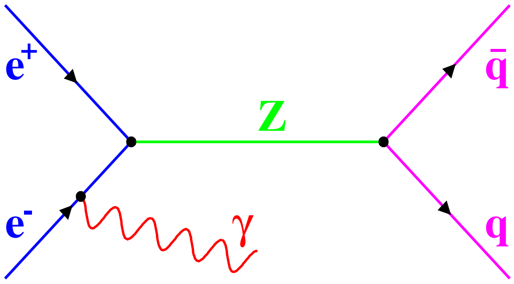
$$\begin{array}{lll}
\text{Statistics}: & \mathrm{q\overline{q}} & 1488 \\
 & \mathrm{e^+e^-} & 247 \\
 & \mu^+\mu^- & 110 \\
 & \tau^+\tau^- & 49
\end{array}$$

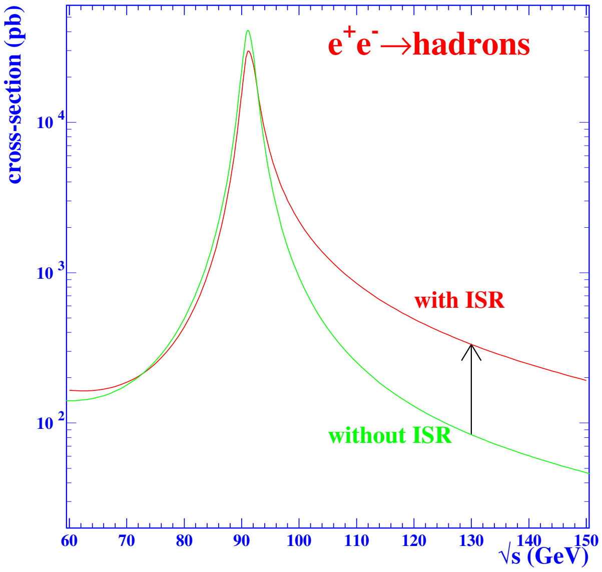
Fermion-pair production above the Z^0

Hadronic cross-section:

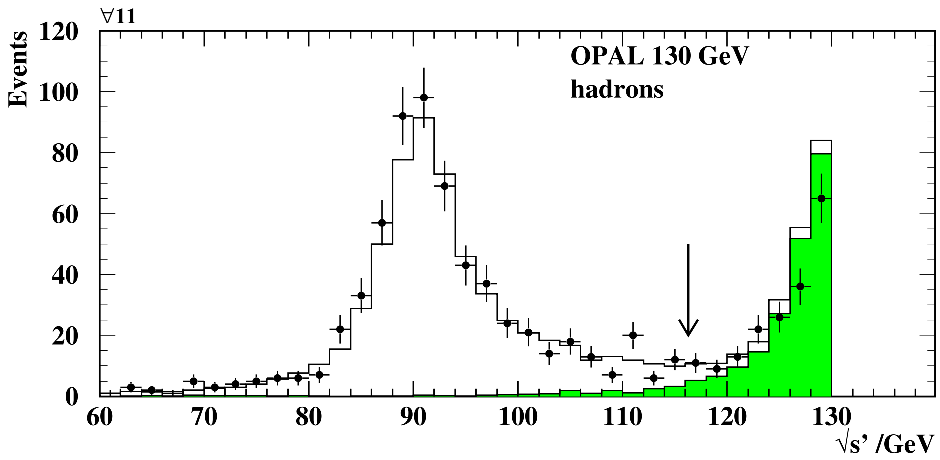
$$\sigma_{q\bar{q}}(130\mathrm{GeV}) \simeq 300\ \mathrm{pb}$$

factor 100 less than $\sigma_{q\bar{q}}(M_Z)$





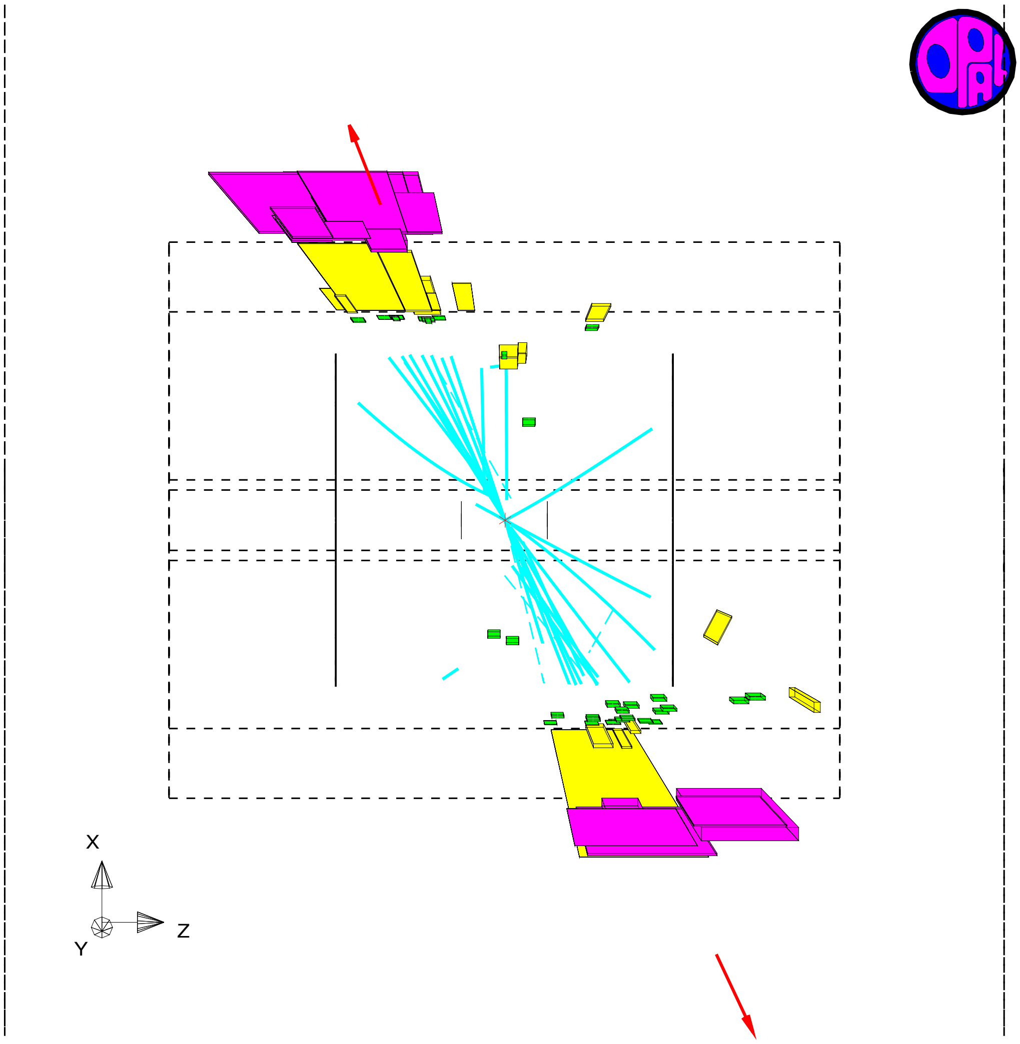
Effective centre-of-mass energy, $\sqrt{s'}$, distribution:

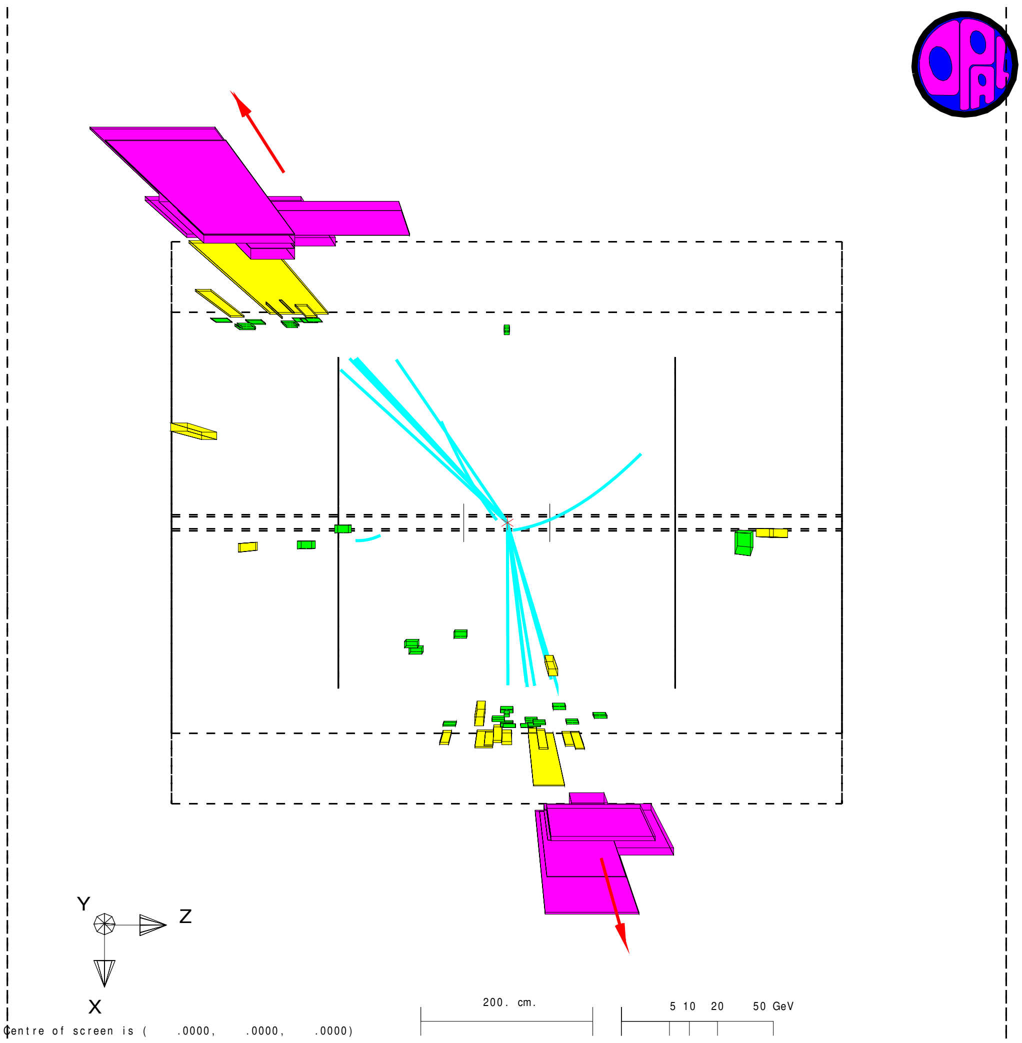


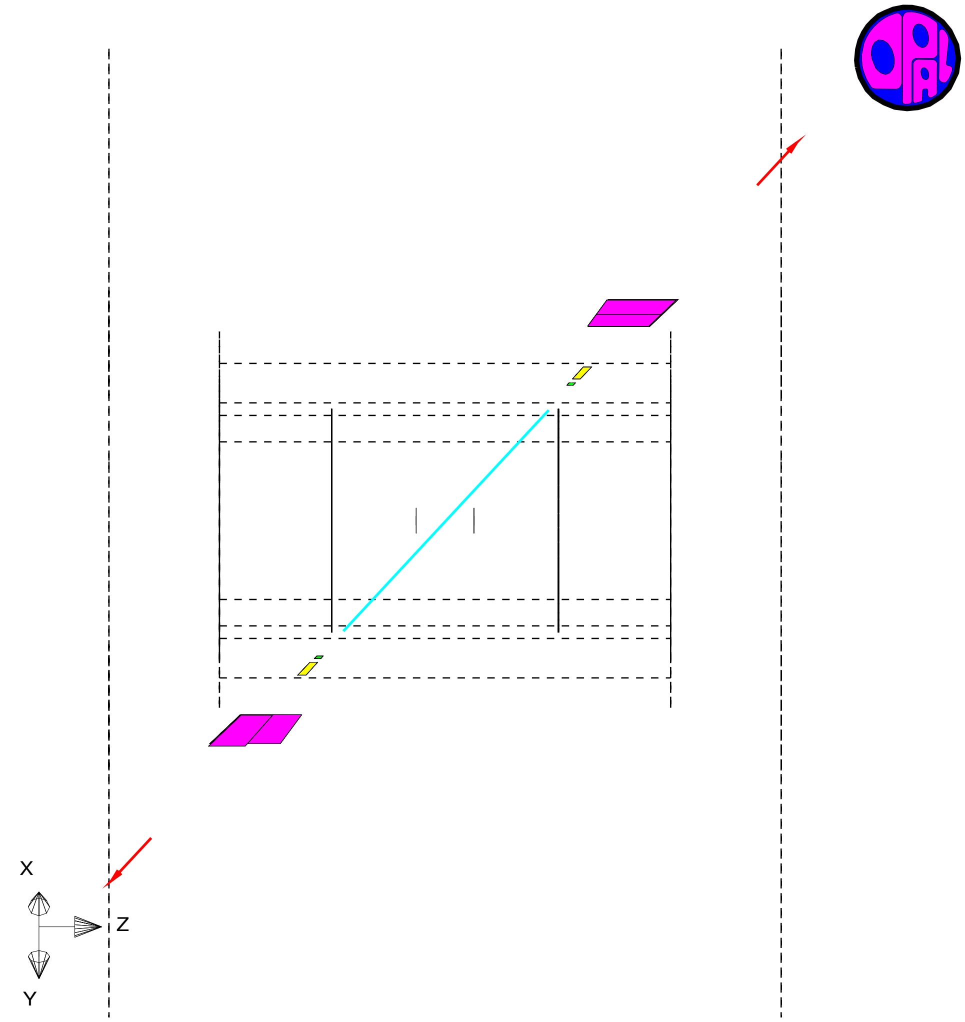
Broadly, two types of events:

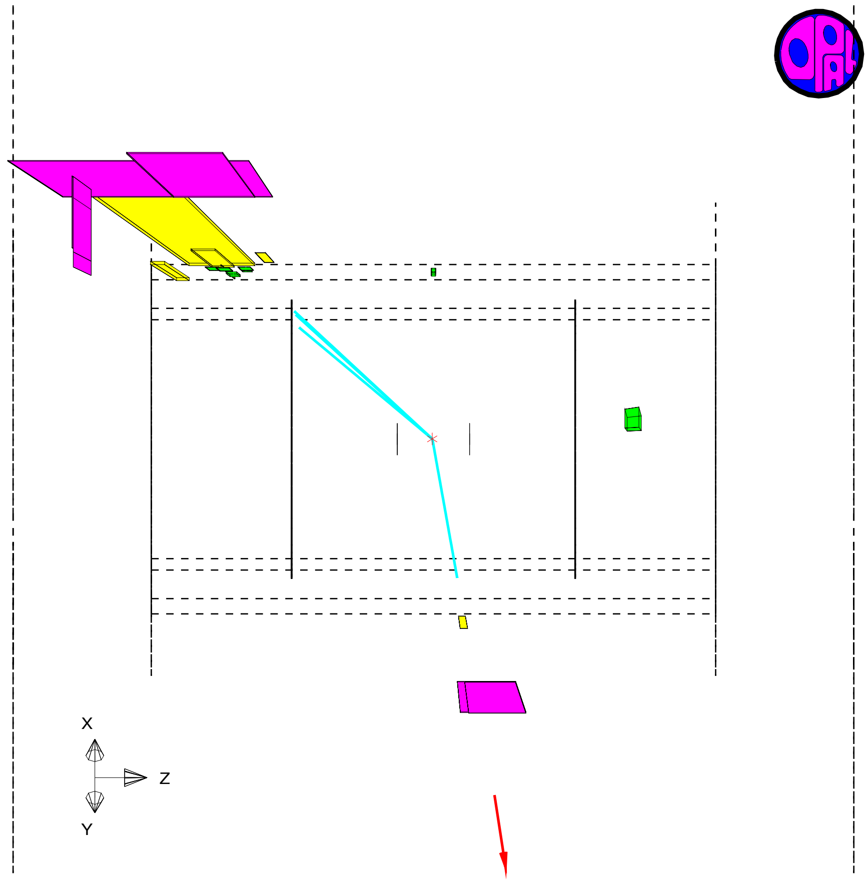
- "Radiative return" $\sqrt{s'} \simeq M_Z \longrightarrow$
- "Non-radiative" $\sqrt{s'} \simeq \sqrt{s} \longrightarrow$

Non-radiative events are more interesting!


X
Y
Z


Y
Z
X
200. cm.
5 10 20 50 GeV
Centre of screen is (.0000, .0000, .0000)


X
Z
Y

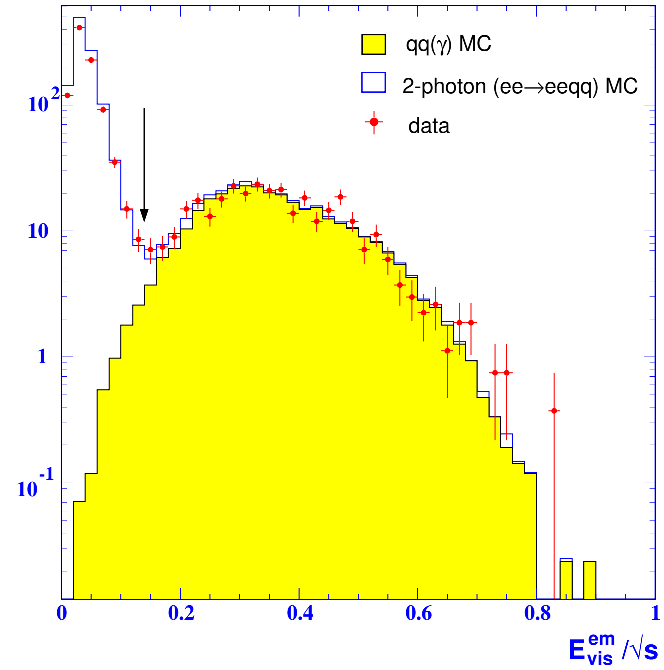

X
Z
Y

Event selection

Event selection almost same as at LEP1. Tighten some cuts because of 2-photon background.

e.g. $\Sigma \mathrm{E_{ECAL}}/\sqrt{\mathrm{s}} > 0.14$

for $\mathrm{q\overline{q}}$ (was 0.1)



Separation of non–radiative events: $s'/s > 0.8$

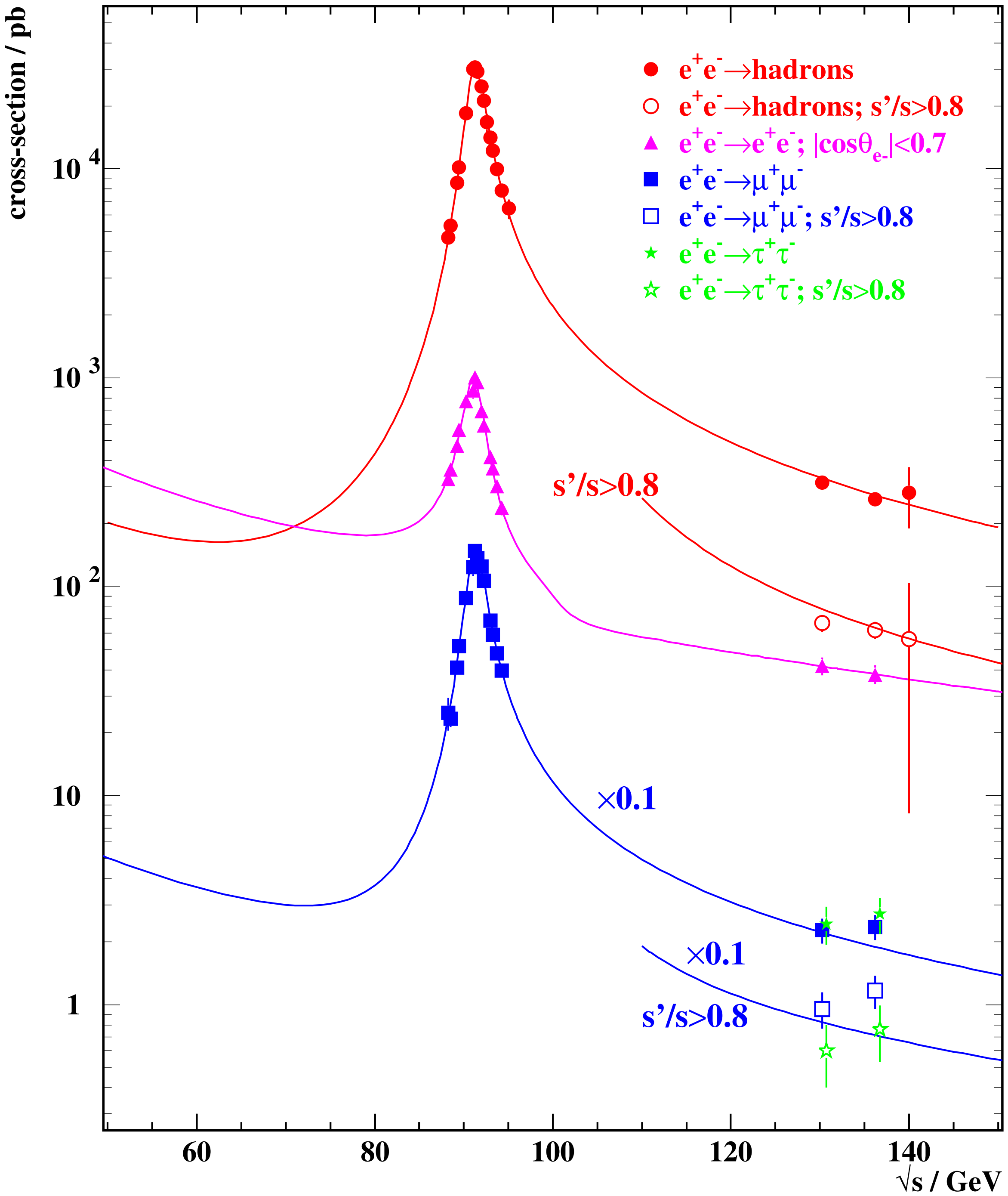
2 methods of determining $\sqrt{s'}$:

1. If observe isolated photon in event from ISR $\longrightarrow \mathrm{E}_\gamma$
2. Measure polar angles of jet/leptons $(\theta_1,\ \theta_2)$

   Determine E_γ from $\theta_1,\ \theta_2$ assuming γ to be collinear with beam.

Measure cross-sections and asymmetries for both inclusive and non–radiative samples.

Measured cross–sections



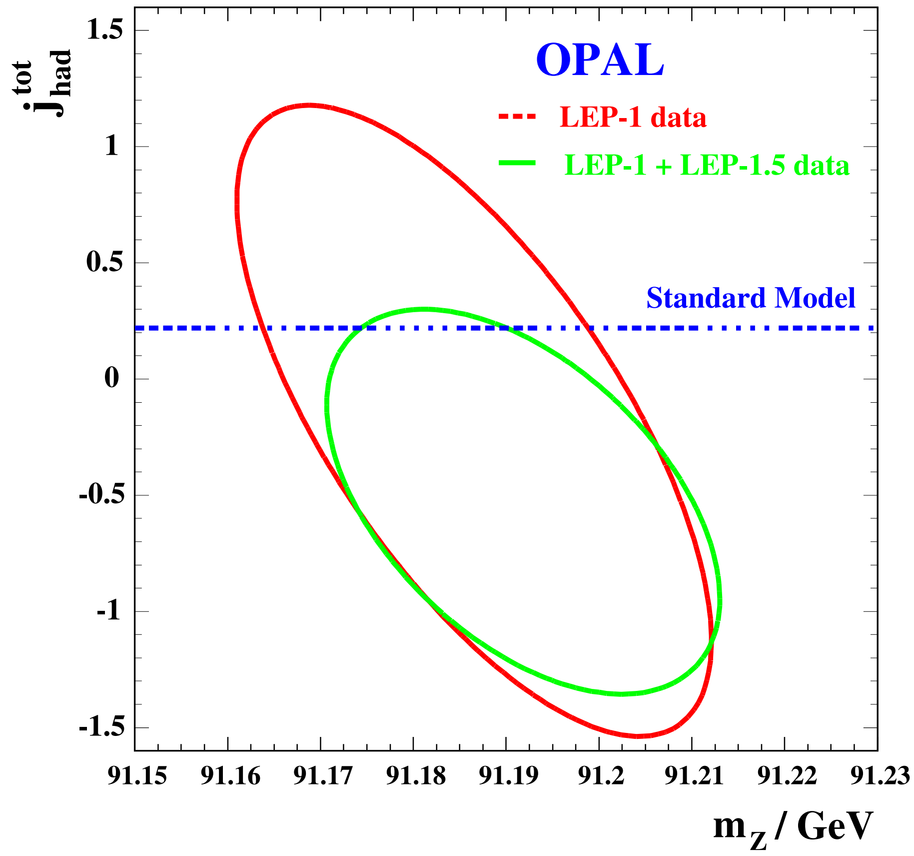
Measured cross-sections compared to predictions from ZFITTER ($q\overline{q}$, $\mu^+\mu^-$ and $\tau^+\tau^-$) and ALIBABA (e^+e^-)

Impact on Z^0 Lineshape Fits

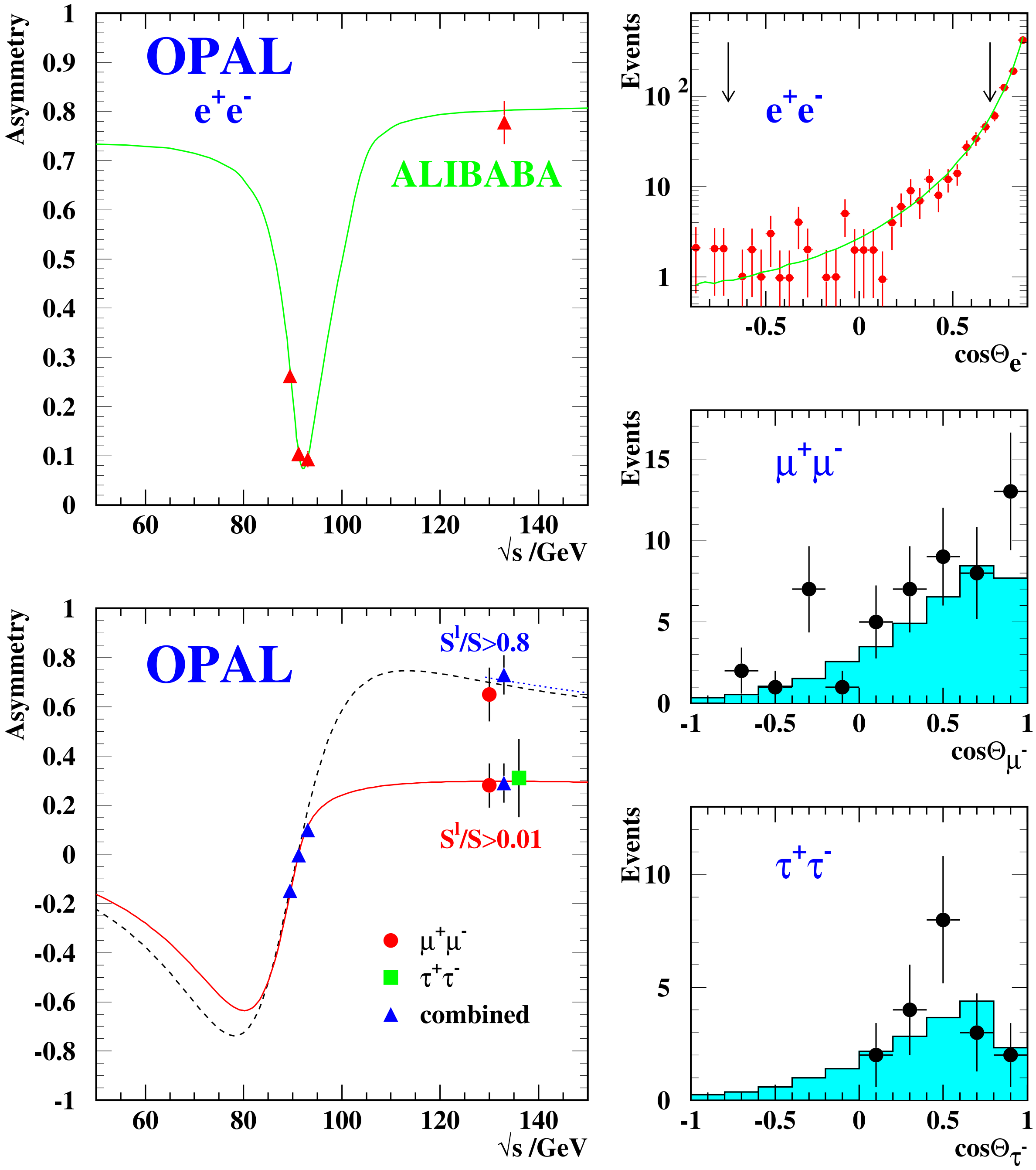
Without radiative corrections:

$$\sigma_{\mathrm{q\overline{q}}}(\sqrt{s}) = \frac{A_\gamma}{s} + \frac{A_{\gamma\mathrm{Z}}(s - {M_\mathrm{Z}}^2) + A_\mathrm{Z} s}{(s - {M_\mathrm{Z}}^2)^2 + s^2 {\Gamma_\mathrm{Z}}^2 / {M_\mathrm{Z}}^2}$$

- Standard fit: relative sizes of A_γ, $A_{\gamma\mathrm{Z}}$, A_Z fixed by SM $\longrightarrow$ $M_\mathrm{Z}, \Gamma_\mathrm{Z}$
- "S-Matrix" fit effectively allows interference term $A_{\gamma\mathrm{Z}}$ to float $\longrightarrow$ J_had
- M_Z precision reduced in this case where $A_{\gamma\mathrm{Z}}$ floats
- 130 GeV data particularly sensitive to interference term



Asymmetries



Leptonic forward-backward asymmetry

- $\mathrm{e}^+\mathrm{e}^-$: t-channel scattering dominates $\longrightarrow A_{\mathrm{FB}}$ large
- $\mu^+\mu^-/\tau^+\tau^-$: γZ-interference effect large

Conclusions

LEP1:

- Precise experimental techniques:

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

- $\Longrightarrow$ precise measurements of electroweak parameters:

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

- 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 ...

LEP1.5 :

- LEP successful in upgrade to $\sqrt{s} = 136\mathrm{GeV}$.

- Measured cross–sections and lepton asymmetries
  $\longrightarrow$ consistent with Standard Model expectations.