From LEP to LHC

1. Physics of the Z boson (I)
2. Physics of the Z boson (II)
3. Physics of the W boson
4. Physics of the top quark
5. Tests of the Standard Model
6. Search for the Higgs boson (I)
7. Search for the Higgs boson (II)

Salvatore Mele
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From LEP to LHC

1. Physics of the Z boson (I)
   • LEP (Statistics interlude)
2. Physics of the Z boson (II)
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   • LEP, Tevatron, LHC (Statistics interlude)
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   • LEP (Statistics interlude)
7. Search for the Higgs boson (II)
   • Tevatron, LHC

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Physics of the Z boson

- Z boson: what to measure?
- The LEP accelerator and detectors
- The Z “lineshape”
- Energy and luminosity measurements
- The tau polarisation
- Measurements with heavy quarks
- The SLD accelerator and SLC detector
- Measurements with polarized electrons
- A problem?
- Extraction of the Z-boson couplings
Main bibliographic reference

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups

[~2500 authors]

Physics Reports 427 (2006) 257
arXiv:hep-ex/0509008
Z boson: what do we want to measure?

Fundamental properties: mass, width, couplings

- $m_Z$ the Z boson mass
- $\Gamma_Z$ the Z boson width
- $g_{Af}$ ($f=e, \mu, \tau, \ldots, c, b$)
- $g_{Vf}$ ($f=e, \mu, \tau, \ldots, c, b$)

Fundamental Standard Model parameters (#5)

Two parts:
1. How to measure $m_Z$ and $\Gamma_Z$
2. How to measure $g_{Af}$ and $g_{Vf}$
How to measure $m_Z$ and $\Gamma_Z$?

1. Produce $Z$ bosons

UA1 PLB 129 (1983) 273
UA1 PLB 134 (1984) 469
What’s on the market?

2. Produce LOTS of Z bosons
The $e^+e^- \rightarrow ff$ process: producing Z bosons

Z bosons decay into quarks (70%) leptons (9%) neutrinos (21%)
### Useful definition in Z-boson physics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_Z )</td>
<td>Z-boson mass</td>
</tr>
<tr>
<td>( \Gamma_Z )</td>
<td>Z-boson width</td>
</tr>
<tr>
<td>( \sigma^0_{\text{had}} )</td>
<td>ee-&gt;Z-&gt;qq cross section</td>
</tr>
<tr>
<td>( R^0_e = \frac{\Gamma_{\text{had}}}{\Gamma_{ee}} )</td>
<td>Leptonic widths (expressed as fraction of hadronic)</td>
</tr>
<tr>
<td>( R^0_\mu = \frac{\Gamma_{\text{had}}}{\Gamma_{\mu\mu}} )</td>
<td></td>
</tr>
<tr>
<td>( R^0_\tau = \frac{\Gamma_{\text{had}}}{\Gamma_{\tau\tau}} )</td>
<td></td>
</tr>
<tr>
<td>( R^0_l = \frac{\Gamma_{\text{had}}}{\Gamma_{ll}} )</td>
<td>As above, with “leptonic universality”</td>
</tr>
<tr>
<td>( A^0_{FB , e}, A^0_{FB , \mu}, A^0_{FB , \tau} )</td>
<td>Leptonic forward-backward asymmetries</td>
</tr>
<tr>
<td>( A^0_{FB , l} )</td>
<td>As above, with “leptonic universality”</td>
</tr>
</tbody>
</table>
Forward-backward asymmetry

\[ A_{FB} = \frac{N_F - N_B}{N_F + N_B} \]
How to measure $m_Z$ and $\Gamma_Z$?

Information on $m_Z$ and $\Gamma_Z$ contained in

$$\sigma^0_{\text{had}}, \quad R^0_l = \frac{\Gamma_{\text{had}}}{\Gamma_{ll}}, \quad A_{\text{FB}}^0$$

CERN Report 89-08

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Can’t you just take the invariant mass?
Requirements

- Produce Z bosons
- Count Z bosons decaying into quarks
  \[ \sigma_{0\text{ had}} \propto \frac{(N_{\text{Had}} - N_{\text{Back}})}{\varepsilon_{\text{SelL}}} \]
- Count Z bosons decaying into leptons
  \[ R_{0\text{ l}} \propto \frac{N_{\text{had}}}{N_{ll}} \]
- Study angular distributions of decay products
  \[ A_{0\text{ FB l}} \propto \frac{(N_{F} - N_{B})}{(N_{F} + N_{B})} \]
Producing Z bosons

The graph shows the cross-section for producing Z bosons as a function of the centre-of-mass energy. The data is plotted for different experiments such as CESR, DORIS, PEP, PETRA, SLC, KEKB, PEP-II, TRISTAN, LEP I, and LEP II. The Z boson production is indicated by the reaction $e^+ e^- \rightarrow \text{hadrons}$, and the W bosons are shown as $W^+ W^-$. The graph has a logarithmic scale for the cross-section and a linear scale for the centre-of-mass energy.
Fermion-pair selection

qq, 70%

ee, 3%

μμ, 3%

ττ, 3%

+21% νν
Event selection

Figure 2.1: Experimental separation of the final states using only two variables, the sum of the track momenta, $E_{ch}$, and the track multiplicity, $N_{ch}$, in the central detector of the ALEPH experiment.
## Event selection

<table>
<thead>
<tr>
<th></th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>qq final state</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>acceptance</td>
<td>$s'/s &gt; 0.01$</td>
<td>$s'/s &gt; 0.01$</td>
<td>$s'/s &gt; 0.01$</td>
<td>$s'/s &gt; 0.01$</td>
</tr>
<tr>
<td>efficiency [%]</td>
<td>99.1</td>
<td>94.8</td>
<td>99.3</td>
<td>99.5</td>
</tr>
<tr>
<td>background [%]</td>
<td>0.7</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>e^+e^- final state</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>acceptance</td>
<td>$-0.9 &lt; \cos \theta &lt; 0.7$</td>
<td>$</td>
<td>\cos \theta</td>
<td>&lt; 0.72$</td>
</tr>
<tr>
<td>$s' &gt; 4m^2_\tau$</td>
<td>$\eta &lt; 10^\circ$</td>
<td>$\eta &lt; 25^\circ$</td>
<td>$\eta &lt; 10^\circ$</td>
<td></td>
</tr>
<tr>
<td>efficiency [%]</td>
<td>97.4</td>
<td>97.0</td>
<td>98.0</td>
<td>99.0</td>
</tr>
<tr>
<td>background [%]</td>
<td>1.0</td>
<td>1.1</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>\mu^+\mu^- final state</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>acceptance</td>
<td>$</td>
<td>\cos \theta</td>
<td>&lt; 0.9$</td>
<td>$</td>
</tr>
<tr>
<td>$s' &gt; 4m^2_\tau$</td>
<td>$\eta &lt; 20^\circ$</td>
<td>$\eta &lt; 90^\circ$</td>
<td>$m^2_{ff}/s &gt; 0.01$</td>
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</tr>
<tr>
<td>efficiency [%]</td>
<td>98.2</td>
<td>95.0</td>
<td>92.8</td>
<td>97.9</td>
</tr>
<tr>
<td>background [%]</td>
<td>0.2</td>
<td>1.2</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>\tau^+\tau^- final state</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>acceptance</td>
<td>$</td>
<td>\cos \theta</td>
<td>&lt; 0.9$</td>
<td>$0.035 &lt;</td>
</tr>
<tr>
<td>$s' &gt; 4m^2_\tau$</td>
<td>$s' &gt; 4m^2_\tau$</td>
<td>$\eta &lt; 10^\circ$</td>
<td>$m^2_{ff}/s &gt; 0.01$</td>
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</tr>
<tr>
<td>efficiency [%]</td>
<td>92.1</td>
<td>72.0</td>
<td>70.9</td>
<td>86.2</td>
</tr>
<tr>
<td>background [%]</td>
<td>1.7</td>
<td>3.1</td>
<td>2.3</td>
<td>2.7</td>
</tr>
</tbody>
</table>
The LEP data sample

Combination of four experiments halves statistical uncertainties.
Effects of uncorrelated systematic uncertainties are reduced by the combining experiments.
Off-peak data. Lumi/precision tradeoff

\[
\sigma^0_{\text{had}} \equiv \frac{12\pi \Gamma_{ee} \Gamma_{\text{had}}}{m_Z^2 \Gamma_Z^2}
\]

<table>
<thead>
<tr>
<th>Year</th>
<th>Centre-of-mass energy range [GeV]</th>
<th>Integrated luminosity [pb(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>88.2 - 94.2</td>
<td>1.7</td>
</tr>
<tr>
<td>1990</td>
<td>88.2 - 94.2</td>
<td>8.6</td>
</tr>
<tr>
<td>1991</td>
<td>88.5 - 93.7</td>
<td>18.9</td>
</tr>
<tr>
<td>1992</td>
<td>91.3</td>
<td>28.6</td>
</tr>
<tr>
<td>1993</td>
<td>89.4, 91.2, 93.0</td>
<td>40.0</td>
</tr>
<tr>
<td>1994</td>
<td>91.2</td>
<td>64.5</td>
</tr>
<tr>
<td>1995</td>
<td>89.4, 91.3, 93.0</td>
<td>39.8</td>
</tr>
</tbody>
</table>

\[
A_{FB}(\mu) = \frac{A_{FB}^0}{M_Z}
\]

7/pb off peak
20/pb off peak
20/pb off peak
Life is not as easy as you would like it to be...
The “pseudo-observables”
The “pseudo-observables”

\[ A_{FB}^l \& A_{FB}^0 \]

\[ A_{FB}^l \text{ from fit} \]

QED corrected

average measurements

ALEPH
DELPHI
L3
OPAL

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Z “line shape”, from 15 million Z-> hadrons
Details of the hadron cross-section measurement
Measuring $A_{FB}$

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

- Count $Z$ bosons decaying into quarks to get
  $$\sigma_{\text{had}} = \frac{(N_{\text{Had}} - N_{\text{Back}})}{\varepsilon_{\text{Sel}} L}$$
- Correct $\sigma_{\text{had}}$ to $\sigma_{\text{had}}^0$
- Count $Z$ bosons decaying into leptons
- Correct $N_{\text{had}} / N_{\text{ll}}$ to $R_{\text{l}}^0$ (for each flavour)
- Study angular distributions of decay leptons
- Correct $A_{\text{FB}}^l = \frac{(N_F - N_B)}{(N_F + N_B)}$ to $A_{\text{FB}}^0$ (for each flavour)
- Fit $\sigma_{\text{had}}^0$, $R_{\text{l}}^0$ and $A_{\text{FB}}^0$ to get $m_Z$ and $\Gamma_Z$ (9- and 5-parameter fit)
- (Combine measurements from the four experiments)
## Results of the 9-parameter fit

<table>
<thead>
<tr>
<th></th>
<th>$m_2$ (GeV)</th>
<th>$\Gamma_2$ [GeV]</th>
<th>$s_{\text{had}}^2$ (nb)</th>
<th>$R_0^2$</th>
<th>$R_2^0$</th>
<th>$A_{TT}^0$</th>
<th>$A_{TT}^2$</th>
<th>$A_{TT}^4$</th>
<th>$A_{TT}^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ALEPH</strong></td>
<td>91.1891 ± 0.0031</td>
<td>2.4959 ± 0.0043</td>
<td>41.636 ± 0.057</td>
<td>20.600 ± 0.015</td>
<td>20.600 ± 0.015</td>
<td>20.082 ± 0.035</td>
<td>20.082 ± 0.035</td>
<td>0.001 ± 0.001</td>
<td>0.001 ± 0.001</td>
</tr>
<tr>
<td><strong>DELPHI</strong></td>
<td>91.1891 ± 0.0031</td>
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<td>20.082 ± 0.035</td>
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<td>0.001 ± 0.001</td>
<td>0.001 ± 0.001</td>
</tr>
<tr>
<td><strong>L3</strong></td>
<td>91.1891 ± 0.0031</td>
<td>2.4959 ± 0.0043</td>
<td>41.636 ± 0.057</td>
<td>20.600 ± 0.015</td>
<td>20.600 ± 0.015</td>
<td>20.082 ± 0.035</td>
<td>20.082 ± 0.035</td>
<td>0.001 ± 0.001</td>
<td>0.001 ± 0.001</td>
</tr>
<tr>
<td><strong>OPAL</strong></td>
<td>91.1891 ± 0.0031</td>
<td>2.4959 ± 0.0043</td>
<td>41.636 ± 0.057</td>
<td>20.600 ± 0.015</td>
<td>20.600 ± 0.015</td>
<td>20.082 ± 0.035</td>
<td>20.082 ± 0.035</td>
<td>0.001 ± 0.001</td>
<td>0.001 ± 0.001</td>
</tr>
</tbody>
</table>
Results of the 5-parameter fit

<table>
<thead>
<tr>
<th></th>
<th>Correlations</th>
<th>(m_Z)</th>
<th>(\Gamma_Z)</th>
<th>(\sigma_{\text{had}}^0)</th>
<th>(R_f^0)</th>
<th>(A_{FB}^{0,\ell})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>(\chi^2/\text{dof} = 172/180)</td>
<td>91.1893 ± 0.0031</td>
<td>2.4959 ± 0.0043</td>
<td>41.559 ± 0.057</td>
<td>20.729 ± 0.039</td>
<td>0.0173 ± 0.0016</td>
</tr>
<tr>
<td>DELPH</td>
<td>(\chi^2/\text{dof} = 183/172)</td>
<td>91.1863 ± 0.0028</td>
<td>2.4876 ± 0.0041</td>
<td>41.578 ± 0.069</td>
<td>20.730 ± 0.060</td>
<td>0.0187 ± 0.0019</td>
</tr>
<tr>
<td>L3</td>
<td>(\chi^2/\text{dof} = 163/170)</td>
<td>91.1894 ± 0.0030</td>
<td>2.5025 ± 0.0041</td>
<td>41.536 ± 0.055</td>
<td>20.809 ± 0.060</td>
<td>0.0192 ± 0.0024</td>
</tr>
<tr>
<td>OPAL</td>
<td>(\chi^2/\text{dof} = 158/198)</td>
<td>91.1853 ± 0.0029</td>
<td>2.4947 ± 0.0041</td>
<td>41.502 ± 0.055</td>
<td>20.822 ± 0.044</td>
<td>0.0145 ± 0.0017</td>
</tr>
</tbody>
</table>
Statistical interlude

Combine $X_A \pm \delta_A$ and $X_B \pm \delta_B$

1. $\delta_A$ and $\delta_B$ are uncorrelated
2. $\delta_A$ and $\delta_B$ are partially correlated

1. trivial answer: weighted average

\[
\begin{align*}
< x > &= \frac{X_A}{2} + \frac{X_B}{2} \\
\delta_x &= \frac{1}{\sqrt{\frac{1}{\delta_A^2} + \frac{1}{\delta_B^2}}} \\
2\text{ measurements} - 1 \text{ parameter to determine} &= 1 \text{ d.o.f.}
\end{align*}
\]

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2. partially correlated uncertainties

- Split the uncertainties in correlated and uncorrelated parts
  \[ x_A \pm \delta_A^C \pm \delta_A^U \quad x_B \pm \delta_B^C \pm \delta_B^U \]

- Build error matrix
  \[
  V = \begin{pmatrix}
  \delta_A^U^2 & 0 \\
  0 & \delta_B^U^2
  \end{pmatrix}
  + \begin{pmatrix}
  \delta_A^C^2 & \delta_A^C \delta_B^C \\
  \delta_A^C \delta_B^C & \delta_B^C^2
  \end{pmatrix}
  = \begin{pmatrix}
  \delta_A^2 & \delta_A^C \delta_B^C \\
  \delta_A^C \delta_B^C & \delta_B^2
  \end{pmatrix}
  \]

- Calculate correlation coefficient
  \[
  \rho = \frac{\delta_A^C \delta_B^C}{\sqrt{\delta_A^2 \delta_B^2}}
  \]

- Get the average, the uncertainty and the \( \chi^2 \)
  \[
  \langle x \rangle = \frac{\sum V_{ij}^{-1} x_i}{\sum V_{ij}^{-1}}, \quad \delta_x = \sqrt{\sum V_{ij}^{-1}}, \quad \chi^2 = \sum \left( x_i - \langle x \rangle \right) V_{ij}^{-1} \left( x_j - \langle x \rangle \right)
  \]

- Rephrase: the \( \langle x \rangle \) is the one minimising the \( \chi^2 \)
Combining experiments

\[ X_m = (m_Z, \Gamma_Z, \sigma^0_{\text{had}}, R^0_e, R^0_\mu, R^0_\tau, A^{0,e}_{FB}, A^{0,\mu}_{FB}, A^{0,\tau}_{FB}, m_Z, \Gamma_Z, \sigma^0_{\text{had}}, R^0_e, R^0_\mu, R^0_\tau, A^{0,e}_{FB}, A^{0,\mu}_{FB}, A^{0,\tau}_{FB}, \ldots) \]

Parameters of the fit

\[ X = (m_Z, \Gamma_Z, \sigma^0_{\text{had}}, R^0_e, R^0_\mu, R^0_\tau, A^{0,e}_{FB}, A^{0,\mu}_{FB}, A^{0,\tau}_{FB}, x4) \]

The solution minimises:

\[ \chi^2 = (X - X_m)^T (C)^{-1} (X - X_m) \]

<table>
<thead>
<tr>
<th>(C)</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( (C_A) + (C_{QED,th}) )</td>
<td>( (C_D) + (C_{QED,th}) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>( (C_c) )</td>
<td>( (C_c) )</td>
<td>( (C_L) + (C_{QED,th}) )</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>( (C_c) )</td>
<td>( (C_c) )</td>
<td>( (C_c) )</td>
<td>( (C_O) + (C_{QED,th}) )</td>
</tr>
<tr>
<td>O</td>
<td>( (C_c) )</td>
<td>( (C_c) )</td>
<td>( (C_c) )</td>
<td>( (C_c) )</td>
</tr>
</tbody>
</table>

Correlation matrix of the common uncertainties

\[ (C_c) = (C_E) + (C_L) + (C_t) + (C_{QED,th}) \]

Correlation matrices of:

- LEP energy uncertainty
- t-channel correction
- Luminosity uncertainty
- theoretical uncertainties
A matrix at the time

Matrix of the correlation matrices

<table>
<thead>
<tr>
<th>(C)</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$C_A + (C_{QED,th})$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>$C_c$</td>
<td>$C_D + (C_{QED,th})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$C_c$</td>
<td>$C_c$</td>
<td>$C_{L} + (C_{QED,th})$</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>$C_c$</td>
<td></td>
<td>$C_O + (C_{QED,th})$</td>
<td></td>
</tr>
</tbody>
</table>

Correlation matrix:

```
c1 c2 c3 c4 c5 c6

1 c2 c3 c4 c5 c6
2 c3 c4 c5 c6
c3 c4 c5 c6
4 c5 c6
5 c6

```

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A matrix at the time

\( (C_c) = (C_E) + (C_L) + (C_t) + (C_{QED,th}) \)

0.061\% diagonal + small correlation between \( \Gamma_Z, \sigma^0_{\text{had}} \).
### Results of the 9-parameter fit

<table>
<thead>
<tr>
<th>Without lepton universality</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/dof = 32.6/27</td>
<td>$m_Z$, $\Gamma_Z$, $\sigma_{\text{had}}^0$, $R_e^0$, $R_\mu^0$, $R_\tau^0$, $A_{FB}^{0,e}$, $A_{FB}^{0,\mu}$, $A_{FB}^{0,\tau}$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1876 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^0$ [nb]</td>
<td>41.541 ± 0.037</td>
</tr>
<tr>
<td>$R_e^0$</td>
<td>20.804 ± 0.050</td>
</tr>
<tr>
<td>$R_\mu^0$</td>
<td>20.785 ± 0.033</td>
</tr>
<tr>
<td>$R_\tau^0$</td>
<td>20.764 ± 0.045</td>
</tr>
<tr>
<td>$A_{FB}^{0,e}$</td>
<td>0.0145 ± 0.0025</td>
</tr>
<tr>
<td>$A_{FB}^{0,\mu}$</td>
<td>0.0169 ± 0.0013</td>
</tr>
<tr>
<td>$A_{FB}^{0,\tau}$</td>
<td>0.0188 ± 0.0017</td>
</tr>
</tbody>
</table>

### Results of the 5-parameter fit

<table>
<thead>
<tr>
<th>With lepton universality</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/dof = 36.5/31</td>
<td>$m_Z$, $\Gamma_Z$, $\sigma_{\text{had}}^0$, $R_\ell^0$, $A_{FB}^{0,\ell}$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
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</tr>
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<td>$\sigma_{\text{had}}^0$ [nb]</td>
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</tr>
<tr>
<td>$R_\ell^0$</td>
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</tr>
<tr>
<td>$A_{FB}^{0,\ell}$</td>
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</tr>
</tbody>
</table>
Results of the 5-parameter fit

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result</th>
<th>Result</th>
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</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>91.1893±0.0031</td>
<td>2.4959±0.0043</td>
<td>41.559±0.057</td>
</tr>
<tr>
<td>DELPHI</td>
<td>91.1863±0.0028</td>
<td>2.4876±0.0041</td>
<td>41.578±0.069</td>
</tr>
<tr>
<td>L3</td>
<td>91.1894±0.0030</td>
<td>2.5025±0.0041</td>
<td>41.536±0.055</td>
</tr>
<tr>
<td>OPAL</td>
<td>91.1853±0.0029</td>
<td>2.4947±0.0041</td>
<td>41.502±0.055</td>
</tr>
<tr>
<td>LEP</td>
<td>91.1875±0.0021</td>
<td>2.4952±0.0023</td>
<td>41.540±0.037</td>
</tr>
</tbody>
</table>

Common: 0.0017
$\chi^2$/DoF = 2.2/3
$\chi^2$/DoF = 7.3/3
$\chi^2$/DoF = 1.2/3

With lepton universality

$\chi^2$/dof = 36.5/31

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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Measure of $m_Z$ to 23 p.p.m.

Control of systematic uncertainties is essential:
- Theoretical uncertainties
- Luminosity uncertainties
- Energy calibration
The LEP luminosity

\[ L = \frac{N_{b^+} N_{b^-} f_{\text{rev}} k b \xi}{\sigma_x \sigma_y} \]

Need accurate measurement, beam parameters not enough to estimate \( L \) with the precision needed to measure the electroweak parameters
How to measure the LEP luminosity

\[ \sigma = \frac{N_{\text{sel}} - N_{\text{bg}}}{\epsilon_{\text{sel}} \mathcal{L}} \]

Cross sections are calculated knowing counts, efficiency, background and luminosity.

Luminosity can be calculated knowing counts, efficiency, background and cross section!

Need to go to the per-mille. Need process with:
- Extremely low background
- Extremely well known cross section
- Very high statistics
Need to go to the per-mille. Need process with:
• Extremely low background
• Extremely well known cross section
• Very high statistics

**Bhabha scattering**

&plusmn;\(e^+ \sqrt{\alpha(Q^2)}\)&plusmn;\(e^+ e^+ e^+ e^+\)

\(e^- \sqrt{\alpha(Q^2)} e^- e^-\)

**t-channel dominated at small angle**

Experimental uncertainty <0.07-0.10%/exp

Exp. unc. mostly uncorrelated -> 0.05% tot

Theoretical uncertainty 0.11%
Luminosity monitors

- Small-angle calorimeters, possibly with tracker in front
- $1.4-1.8^\circ < \theta < 3.1-3.3^\circ$
- Mechanical precision/position measurement crucial
- Select events, count events, control efficiency and background

Luminosity measurement at LEP
Measurement of the beam energy

Direct inference from the measurement of the magnetic field

\[ < E_{\text{beam}} > = \frac{e}{2\pi} \oint_{\text{orbit}} Bdl \]

Flux loop and NMR allow a precision of $3 \times 10^{-4}$
Need 1 order of magnitude better!
In electron storage rings, the bending in the XZ plane and the associated radiation give vertical polarisation in the transverse (Y) direction.

Electron spins precess with
\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} \quad \vec{\Omega} = -\frac{e}{a_e \gamma} (1 + a_e \gamma) \vec{B}
\]

Vertical bending field does not induce polarisation. An additional horizontal field does.

The precession carries information on E_{beam}:
\[
a_e \gamma = \frac{a_e}{m_e c^2} E_{beam}
\]
Resonant depolarization

Variation of Bx can bring S in the horizontal plane, where polarisation disappears

Use a single coil in the ring, oscillate Bx and look for a resonance with the turning beams

\[ v = \frac{f_{\text{depolarisation}}}{f_{\text{revolution}}} \text{ gives } E_{\text{beam}} \text{ through } \Omega = -\frac{e}{a_e \gamma c} \left( 1 + \frac{a_e}{m_e c^2} E_{\text{beam}} \right) B \]
Other parts of the saga

• Resonant depolarisation precision of 200KeV!
• Polarisation disrupted by beam-beam effect
• Measurement performed with single-beam special runs
• Need extrapolations, including other info as direct measurements of magnetic field.
• Final precision $1\text{MeV} \ (2 \times 10^{-5})$
The energy is not the same for all the experiments

\[ \Delta E \text{ [MeV]} \quad 19.1 \quad -0.3 \quad 19.8 \quad 0.2 \]

(e for positrons, \(e^-\) for electrons)

(L3 ALEPH OPAL DELPHI L3)

(the 9- and 5- parameters fits need to know this!)
Attraction of the moon (Earth crust tides)

- Beam movement of 13\(\mu\)m changes \(E_{\text{beam}}\) of 1MeV!
- Earth tides change diameter of the ring
- Quadrupoles move off the orbit (or vice versa...)

10MeV effect daily, continuously corrected for
Level of Geneva lake

10MeV effect weekly

Days
Effects of the TGV

NMR measures the field, needed in the estrapolation for $E_{\text{beam}}$
Three flavours and a Standard Model
Number of “light” neutrino species

\[ R_{\text{inv}}^0 = \left( \frac{12\pi R_{\ell}^0}{\sigma_{\text{had}}^0 m_Z^2} \right)^{\frac{1}{2}} - R_{\ell}^0 - (3 + \delta_\tau) \]

\[ R_{\text{inv}}^0 \equiv \frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = N_\nu \left( \frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}} \right)_{\text{SM}} \]

\( \tau \) mass correction -0.23%

\[ \sigma_{\text{had}} \text{ [nb]} \]

ALEPH
DELPHI
L3
OPAL

average measurements, error bars increased by factor 10

\[ R_{\text{inv}}^0 = 5.943 \pm 0.016 \]

\[ N_\nu = 2.9840 \pm 0.0082 \]