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)

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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)
   • LEP (Statistics interlude)
3. Physics of the W boson
   • LEP, Tevatron, LHC (Statistics interlude)
4. Physics of the top quark
   • Tevatron, LHC
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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

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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
- $g_{Af}$ ($f=e, \mu, \tau, \ldots, c, b$)
- $g_{Vf}$ ($f=e, \mu, \tau, \ldots, c, b$)

Provide unique insight on Standard Model (#5)

Two parts:
1. How to measure $m_Z$ and $\Gamma_Z$
2. How to measure $g_{Af}$ and $g_{Vf}$
Z boson couplings through the asymmetry parameters $A_f$

$$A_f = \frac{g_{L_f}^2 - g_{R_f}^2}{g_{L_f}^2 + g_{R_f}^2} = \frac{2g_{V_f}g_{A_f}}{g_{V_f}^2 + g_{A_f}^2} = 2 \frac{g_{V_f}/g_{A_f}}{1 + (g_{V_f}/g_{A_f})^2}$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \Rightarrow A_{FB}^0 = \frac{3}{4} A_e A_f$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \frac{1}{\langle |P_e| \rangle} \Rightarrow A_{LR}^0 = A_e$$

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \frac{1}{\langle |P_e| \rangle} \Rightarrow A_{LRFB}^0 = \frac{3}{4} A_f$$

$$P_\tau \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \Rightarrow P_\tau = f(A_e, A_\tau)$$
Short reminder: polarisation and parity violation

Left-handed polarisation  Right-handed polarisation

Parity is violated in weak interactions:
• $W$ bosons do not couple to R-handed particles
• $Z$ bosons couple differently to L- and R-handed particles
Short reminder: helicity

Positive helicity

Negative helicity

Spin

Momentum
Measurements of asymmetries to extract $A_f$ and therefore $g_{Af}$ and $g_{Vf}$

\[ A_{FB}^{0,1} = \frac{3}{4} A_e A_1 \]
\[ A_{FB}^{0,b} = \frac{3}{4} A_e A_b \]
\[ A_{LR}^{0} = A_e \]
\[ A_{LRFB}^{0} = \frac{3}{4} A_f \]

Measurements with heavy quarks
Measurements with polarised beams

Additional information from the tau polarisation

\[ \mathcal{P}_\tau(\cos \theta_{\tau-}) = -\frac{A_\tau (1 + \cos^2 \theta_{\tau-}) + 2 A_e \cos \theta_{\tau-}}{(1 + \cos^2 \theta_{\tau-}) + \frac{8}{3} A_{FB}^\tau \cos \theta_{\tau-}} \]
Principle of the measurement

- **V-A charged weak current violates parity**

  ![Diagram showing the principle of the measurement with V-A charged weak current violating parity.](image)

  - Left-handiness of neutrino implies a boost for the pion in the tau direction for positive helicity and a depletion otherwise.
Cannot measure the polarisation event per event
Fit the two components to discriminating variables
Measure the polarisation (through the two helicity components) as a function of the tau angle and then fit $A_r$ and $A_\tau$.
Measurements with heavy quarks

Identify b quarks with hard leptons and displaced vertices
Tagging heavy flavours with leptons

10% of b-quarks decay semileptonically $b\rightarrow c l \nu$.

Owing to the relatively large mass of the b-quark, leptons have larger momenta and larger transverse momentum w.r.t. the remaining jet.
What do you think $e^+e^-\rightarrow qq$ looks like...

...at a centre-of-mass energy of 10GeV?

...at a centre-of-mass energy of 91GeV?
Jets and quarks

- Jets are the footprints of quark production

- Jets are NOT hadronic or electromagnetic showers in the calorimeters

- Jets are NOT fundamental particles of the Standard Model

- Jets are the results of algorithms which aggregates information from visible tracks and energy deposits to extract information about the quarks

How does one (re-)construct jets?
The jade algorithm

(From the names of an experiment at the $e^+e^- 27\text{GeV}$ collider PETRA, DESY, 1979)

- The distance between two particles $i$ and $j$ is:
  \[ d_{ij} = 2 E_i E_j (1 - \cos \theta_{ij}) \]
- A threshold $d_{\text{cut}}$ is chosen a priori
- The distance is calculated for each particle pair
- The pair $hk$ with minimal distance $d_{hk}$ is chosen
- If $d_{hk} < d_{\text{cut}}$ the four-vectors of $h$ and $k$ are summed into a new, fictive, particle: $l$. A “jetlet”
- $h$ and $k$ are removed from the list of particles and the jetlet $l$ is added
- Iterate until $d_{ij} > d_{\text{cut}}$ for all possible pairs (of particles, jetlets, and mixed)
- The remaining particles/jetlets are the jets!

If QCD holds (1976), quarks can radiate gluons provided enough energy is available. Think bremsstrahlung.
How do you see a gluon? As a third jet in a 2-jet event!

27GeV e^+e^- collisions PETRA, DESY, 1979

Useful variation of the JADE algorithm

- The distance between particles is defined as
  \[ y_{ij} = 2 \frac{E_i E_j (1-\cos \theta_{ij})}{E_{\text{vis}}^2} \]
- The re-scaling by the visible energy \( E_{\text{vis}}^2 \) allows:
  - to cancel-out some systematics in the measurement
  - to define separation values \( y_{\text{cut}} \) which are less sensitive to the collision energy
Multijet events at LEP

- Without gluon emission: 2 jets
- With emission of a gluon 3 jets
- With emission of two gluons 4 jets

The counting of such events allows to measure the strong coupling constant

\[ \alpha_s = k \frac{N_{3\text{jet}}}{N_{2\text{jet}}} (k \approx 0.2) \]
Fraction of n jet events at LEP

N-jet Fraction = Number of events with 2, 3, 4 or 5 jets / Number of events with jets

--- QCD + hadronization
\[ \Lambda = 190 \text{ MeV} \]
\[ \mu^2 = 0.08 \text{ s} \]
Tagging heavy flavours with leptons

10% of b-quarks decay semileptonically $b \rightarrow c l \nu$

Owing to the relatively large mass of the b-quark, leptons have larger momenta and larger transverse momentum w.r.t. the remaining jet

+ quark charge can be tagged
- purity of the sample
Tagging through the b lifetime

- b-hadrons have a lifetime $\tau \sim 1.5\text{ps}$
- ...and a boost in $Z\rightarrow bb \gamma \sim 6$

- Decay length $<L> = <\gamma\beta>c\tau \sim 2.7\text{mm}$
- Impact parameter $D = \gamma\beta c\tau \sin\phi$
  - $<\sin\phi> = 1/\beta\gamma$
  - $<D> = c\tau = 450 \mu\text{m}$

- Effects $\sim 10$ times the resolutions!
Impact parameter and secondary vertices significance

"Beam spot" 100 \( \mu \text{m} \times 5 \mu \text{m} \times 1 \text{ cm} \)

Reconstruct secondary vertices and measure their distance from interaction point

Reconstruction studies

b-tagging

Salvatore Mele | From LEP to LHC | Troisième cycle
Tagging charmed hadrons

1. Reconstruct c-hadrons
2. Hard from Z→cc, soft from Z→bb
Measurement of $A_{FB}$ for b quarks

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\frac{\partial \sigma^{q\bar{q}}}{\partial \cos \theta} = \sigma_{tot}^{q\bar{q}} \left[ \frac{3}{8} (1 + \cos^2 \theta) + A_{FB}^{q\bar{q}} \cos \theta \right]$$

$$A_{FB}^{q\bar{q}}(\cos \theta) = \frac{8}{3} A_{FB}^{q\bar{q}} \frac{\cos \theta}{1 + \cos^2 \theta}$$

Measure $A_{FB}^{q\bar{q}}(\cos \theta)$ to fit $A_{FB}^{q\bar{q}}$. Define $\theta$ as the thurst angle.
Thurst? What’s the thurst

The Thrust vector is the one which maximizes:

\[ T = \sum \frac{|\vec{p}_i \cdot \vec{n}_T|}{\sum |\vec{p}_i|} \]
Making a long story short
The whole (heavy quark) enchillada

Reduce uncertainties by fitting 18 parameters at once:

1. $R_b$ The fraction of $b$ quark for hadronic event
2. $R_c$ The fraction of $b$ quark for hadronic event
3. $A_{FB}^{bf}(89.55\text{GeV})$ Off-peak
4. $A_{FB}^{cc}(89.55\text{GeV})$ Off-peak
5. $A_{FB}^{bb}(91.26\text{GeV})$ Peak
6. $A_{FB}^{cc}(91.26\text{GeV})$ Peak
7. $A_{FB}^{bb}(92.94\text{GeV})$ Off-peak
8. $A_{FB}^{cc}(92.94\text{GeV})$ Off-peak
9. $A_b$ Asymmetry parameters measured...
10. $A_c$ ...by SLD with $A_{FBLR}^{q\bar{q}}$
11. BR($b \rightarrow \ell^-$) Semileptonic branching ratio
12. BR($b \rightarrow c \rightarrow \ell^+$) Semileptonic branching ratio
13. BR($c \rightarrow \ell^+$) Semileptonic branching ratio
14. $\bar{\chi}$ Mixing parameter
15. $f(D^+)$ Fraction of produced meson
16. $f(D_s)$ Fraction of produced meson
17. $f(c_{\text{baryon}})$ Fraction of produced baryon
18. P($c \rightarrow D^{*+}) BR(D^{*+} \rightarrow D^0 \pi^+)$ $D^{*+}$ decays for $c$ quark

A total of 105 measurements with full statistical and systematic correlation matrix...
SLC (SLAC Linear Collider)
Polarised electron beams

\[ A_{LR} = \frac{N_L - N_R}{N_L + N_R \langle P_e \rangle} \]

Beam Polarization SLD 1992-1998 Data

Salvatore Mele | From LEP to LHC | Troisième cycle
Measurement of the $e^-$ polarisation

\[ \frac{d\sigma}{dx} = \frac{d\sigma_0}{dx} [1 - P_\gamma P_e A(x)] \]
Measurement of $A_{LR}$

Count Z decays (into quark, muons, tau) for L and R polarised electron beams

\[ A_{LR} = \frac{N_L - N_R}{N_L + N_R} \left( \frac{1}{P_e} \right) \]

\[ A_{LR}^0 = 0.1514 \pm 0.0022 \]
Measurement of $A_{\text{FBLR}}^l$

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \left( \frac{1}{|P_\ell|} \right)$$

Measure differences between forward and backward lepton production for left and right polarization

- 22254 electron pairs
- 16844 muon pairs
- 16084 tau pairs
Measurement of $A_{FBLR}^b$

Measure differences between forward and backward $b$-quark production for left and right polarization

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \frac{1}{\langle |P_e| \rangle}$$

Identify $b$ quarks with displaced vertices. Small beam size of SLC means detectors close to the beam line and high resolution and $b$-tagging performance.
Measurement of $A^{b}_{FBLR}$

Measure differences between forward and backward b-quark production for left and right polarization

$$A_{LRFB} = \frac{(\sigma_{F} - \sigma_{B})_{L} - (\sigma_{F} - \sigma_{B})_{R}}{(\sigma_{F} + \sigma_{B})_{L} + (\sigma_{F} + \sigma_{B})_{R}} \cdot \frac{1}{\langle |\mathcal{P}_{e}| \rangle}$$

![Graphs showing tagged events for SLD with L and R polarization](image)
The $A_f$ parameters

Measurements

\[ A_{FB}^{0,1} = \frac{3}{4} A_e A_1 \]
\[ A_{FB}^{0,b} = \frac{3}{4} A_e A_b \]
\[ A_{LR}^0 = A_e \]
\[ A_{LRFB}^0 = \frac{3}{4} A_f \]

\[ \mathcal{P}_\tau = f(A_e, A_\tau) \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$A_{FB}^{0,\ell}$</th>
<th>$A_{LR}^0, A_{LRFB}^\ell$</th>
<th>$\mathcal{P}_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>0.139±0.012</td>
<td>0.1516±0.0021</td>
<td>0.1498±0.0049</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>0.162±0.019</td>
<td>0.142±0.015</td>
<td>—</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.180±0.023</td>
<td>0.136±0.015</td>
<td>0.1439±0.0043</td>
</tr>
</tbody>
</table>

Combinations ($\chi^2 = 3.6/5$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_e$</td>
<td>$A_\mu$</td>
</tr>
<tr>
<td>$A_e$</td>
<td>0.1514±0.0019</td>
<td>1.00</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>0.1456±0.0091</td>
<td>-0.10</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.1449±0.0040</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Leptonic universality

\[ A_\ell = 0.1501 ± 0.0016 \]
The $A_f$ parameters

Measurements from heavy quarks

$A_{FB}^{0,1} = \frac{3}{4} A_e A_1$

$A_{FB}^{0,b} = \frac{3}{4} A_e A_b$

$A_{LR}^0 = A_e$

$A_{LRFB}^0 = \frac{3}{4} A_f$

$P_\tau = f(A_e, A_\tau)$

<table>
<thead>
<tr>
<th>Flavour $q$</th>
<th>$A_q = \frac{4}{3} \frac{A_{FB}^{0,q}}{A_e}$</th>
<th>Direct $A_q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.881±0.017</td>
<td>0.923±0.020</td>
</tr>
<tr>
<td>c</td>
<td>0.628±0.032</td>
<td>0.670±0.027</td>
</tr>
</tbody>
</table>

Combinations from leptons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Correlations $A_e$ $A_\mu$ $A_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>0.1514±0.0019</td>
<td>1.00</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>0.1456±0.0091</td>
<td>-0.10 -0.01 1.00</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.1449±0.0040</td>
<td>-0.02 -0.01 1.00</td>
</tr>
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</table>

Results of all the above

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Correlations $A_\ell$ $A_b$ $A_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_\ell$</td>
<td>0.1489±0.0015</td>
<td>1.00</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.899±0.013</td>
<td>-0.42 1.00</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.654±0.021</td>
<td>-0.10 0.15 1.00</td>
</tr>
</tbody>
</table>
Compare $A_f$ from different measurements

$A^0_{LRFB} = \frac{3}{4} A_f$

$\chi^2 / \text{dof} = 4.5 / 4$

$34%$

$A^0_\text{FB} = \frac{3}{4} A_e A_f$

$A^0_{LRFB} = \frac{3}{4} A_1$

$A^{0,1}_\text{FB} = \frac{3}{4} A_e A_1$

$P_\tau = f(A_e, A_\tau)$
Statistical interlude

How to combine two measurements of the same physical quantity $X$, $X_A \pm \delta_A$ and $X_B \pm \delta_B$, if the uncertainties $\delta_A$ and $\delta_B$ are partially correlated?

- Split the uncertainties in correlated and uncorrelated parts
  
  $x_A \pm \delta_A \pm \delta_C^A$  
  $x_B \pm \delta_B \pm \delta_C^B$

- Build error matrix

$$V_{ij} = \begin{pmatrix} \delta_A^U & 0 \\ 0 & \delta_B^U \end{pmatrix} + \begin{pmatrix} \delta_A^C & \delta_A \delta_B \\ \delta_A \delta_B & \delta_B^C \end{pmatrix} = \begin{pmatrix} \delta_A^2 & \delta_A \delta_B \\ \delta_A \delta_B & \delta_B^2 \end{pmatrix}$$
Version #1

- Use $x_i$ and $V_{ij}$ to get the average and the uncertainty

$$< x > = \frac{\sum_{i,1} V_{ij}^{-1} x_i}{\sum_{i,1} V_{ij}^{-1}}$$
$$\delta_x = \sqrt{\sum_{i,1} V_{ij}^{-1}}$$

- Calculate the $\chi^2$

$$\chi^2 = \sum_{i,1} (x_i - < x >) V_{ij}^{-1} (x_j - < x >)$$

- The $\chi^2$ helps estimating the agreement of the measurements (more in #5)

(d.o.f = measurements-parameters)
• Use $x_i$, and $V_{ij}$ to get the $\chi^2$

$$\chi^2 = \sum_{i,1} (x_i - <x>)V_{ij}^{-1}(x_j - <x>)$$

• The solution is the value of $<x>$ which minimizes the $\chi^2$

$$<x> = \frac{\sum_{i,1} V_{ij}^{-1} x_i}{\sum_{i,1} V_{ij}^{-1}}$$

• $V_{ij}$ gives the uncertainty

$$\delta_x = \sqrt{\sum_{i,1} V_{ij}^{-1}}$$

• The $\chi^2$ also helps estimating the agreement of the measurements (more in #5)

(d.o.f = measurements-parameters)
Statistical Interlude

The graph shows the relationship between the p-value for test and the confidence intervals for different values of $\chi^2$ and $n$. The highlighted area indicates $n = 1$, and the p-value for test $\alpha$ is $4.5/4$. This suggests a specific threshold or condition within the statistical analysis context.
Statistical Interlude

\[ \chi^2/n = 4.5/4 = 1.125 \]
Extract $g_{Af}$ and $g_{Vf}$ from asymmetry parameters $A_f$

$$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2 \frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

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<th>Parameter</th>
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<tbody>
<tr>
<td></td>
<td>$g_{A\nu}$</td>
<td>$g_{Ae}$</td>
</tr>
<tr>
<td>$g_{A\nu} \equiv g_{V\nu}$</td>
<td>$+0.5003 \pm 0.0012$</td>
<td>1.00</td>
</tr>
<tr>
<td>$g_{Ae}$</td>
<td>$-0.50111 \pm 0.00035$</td>
<td>-0.75</td>
</tr>
<tr>
<td>$g_{A\mu}$</td>
<td>$-0.50120 \pm 0.00054$</td>
<td>0.39</td>
</tr>
<tr>
<td>$g_{A\tau}$</td>
<td>$-0.50204 \pm 0.00064$</td>
<td>0.37</td>
</tr>
<tr>
<td>$g_{Ve}$</td>
<td>$-0.03816 \pm 0.00047$</td>
<td>-0.10</td>
</tr>
<tr>
<td>$g_{V\mu}$</td>
<td>$-0.0367 \pm 0.0023$</td>
<td>0.02</td>
</tr>
<tr>
<td>$g_{V\tau}$</td>
<td>$-0.0366 \pm 0.0010$</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Measurement of $g_{\text{Al}}$ and $g_{\text{Vl}}$
Z couplings pre-LEP and post-LEP
Extraction of quark couplings

\[
A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}
\]

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<tr>
<td></td>
<td></td>
<td>$g_{\nu\nu}$ $g_{\Delta l}$ $g_{\Delta b}$ $g_{\Delta c}$ $g_{V\ell}$ $g_{Vb}$ $g_{Vc}$</td>
</tr>
<tr>
<td>$g_{\nu\nu}$</td>
<td>+0.50075±0.00077</td>
<td>1.00</td>
</tr>
<tr>
<td>$g_{\Delta l}$</td>
<td>−0.50125±0.00026</td>
<td>−0.49 1.00</td>
</tr>
<tr>
<td>$g_{\Delta b}$</td>
<td>−0.5144±0.0051</td>
<td>0.01 −0.02 1.00</td>
</tr>
<tr>
<td>$g_{\Delta c}$</td>
<td>+0.5034±0.0053</td>
<td>−0.02 −0.02 0.00 1.00</td>
</tr>
<tr>
<td>$g_{V\ell}$</td>
<td>−0.03753±0.00037</td>
<td>−0.04 −0.04 0.41 −0.05 1.00</td>
</tr>
<tr>
<td>$g_{Vb}$</td>
<td>−0.3220±0.0077</td>
<td>0.01 0.05 −0.97 0.04 −0.42 1.00</td>
</tr>
<tr>
<td>$g_{Vc}$</td>
<td>+0.1873±0.0070</td>
<td>−0.01 −0.02 0.15 −0.35 0.10 −0.17 1.00</td>
</tr>
</tbody>
</table>

Assume leptonic universality
Couplings of Z boson and b quarks
LEP Legacy: Z boson physics

<table>
<thead>
<tr>
<th>With lepton universality</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/dof = 36.5/31</td>
</tr>
<tr>
<td>$m_Z$ [GeV] 91.1875 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV] 2.4952 ± 0.0023</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^0$ [nb] 41.540 ± 0.037</td>
</tr>
<tr>
<td>$R_{\ell}^0$ 20.767 ± 0.025</td>
</tr>
<tr>
<td>$A_{\text{FB}}^{0,\ell}$ 0.0171 ± 0.0010</td>
</tr>
</tbody>
</table>

ALEPH
DELPHI
L3
OPAL

$E_{\text{cm}}$ [GeV]

$N_\nu = 2.9840 \pm 0.0082$