LEP II Beam Energy Measurement using Radiative Return Events

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Presentation of preliminary results on behalf of the LEP Collaborations

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Overview

- Motivation for a precise knowledge of the LEP beam energy ($E_b$).


- Measurements by DELPHI, L3 and OPAL.

- Systematic studies.

- Results & LEP combination.

- Conclusion.
Why determine \( E_b \) accurately?

- Knowledge of \( E_b \) important for many precision measurements at LEP.
- Relevant for measurement of \( \int L \, dt \) via Bhabha cross-section \( \Rightarrow \) fundamental to all cross-section determinations.
- Vital for accuracy of \( m_W \) measurement; a principal objective of LEP II \( \rightarrow \) resolution improved through kinematic fit constraints:
  \[
  \frac{\Delta m_W}{m_W} = \frac{\Delta E_b}{E_b}.
  \]
- Standard LEP calibration relies on LEP I technique of resonant depolarisation at \( E_b \sim 40 - 60 \text{ GeV} \), together with magnetic extrapolation to LEP II energies \( (E_b \sim 100 \text{ GeV}) \), assuming \( E_b = a + bB \) \( \Rightarrow \) indirect determination: need to be confident it really works at \( \sim 20 \text{ MeV} \) level LEP claims.
Radiative Return Approach

- $E_b$ measured directly by LEP experiments.
- Use radiative fermion-pair events and construct $\sqrt{s'} = \text{centre-of-mass energy after initial state radiation (ISR)}$.

\[
\begin{align*}
\text{e}^+ & \quad \gamma \quad \text{Z/}\gamma \quad \text{f} \\
\text{e}^- & \quad \text{Z/}\gamma \quad \bar{f}
\end{align*}
\]

- $\sqrt{s'}$ sensitive to $E_{\text{LEP}}$ through energy and momentum constraints in kinematic fits.
- Use ISR events with $\sqrt{s'} \sim m_Z$ to reconstruct ‘pseudo’-Z peak in MC ($\sqrt{s}$ known exactly) and in data ($\sqrt{s}$ known by measurement).
- Attribute any relative shift to a discrepancy in the measurement of the beam energy ($\Delta E_b$).
Reconstructed $\sqrt{s'}$ Distribution

- 1998–2000 L3 hadronic data ($627 \text{ pb}^{-1}$):
  \[ E_b \sim 94 - 104 \text{ GeV}. \]

- $\sqrt{s'}$ reconstructed from angles only:
  \[ \sqrt{\frac{s'}{s}} = \sqrt{\frac{\sin \chi_{q\gamma} + \sin \chi_{\bar{q}\gamma} - |\sin(\chi_{q\gamma} + \chi_{\bar{q}\gamma})|}{\sin \chi_{q\gamma} + \sin \chi_{\bar{q}\gamma} + |\sin(\chi_{q\gamma} + \chi_{\bar{q}\gamma})|}}. \]

- Dominated by events under radiative return peak ($\sim$ independent of $E_b$) and at full energy.
\[ \Delta E_b \text{ from } e^+e^- \rightarrow q\bar{q}\gamma \]

(1) Re-weighting method (DELPHI, L3):

- Use knowledge of \( m_Z \) from LEP I.
- Re-weight Monte Carlo \( \sqrt{s'} \) distribution with Breit-Wigner-like function \( f(s', m_Z) \) assuming different \( m_Z^{\text{new}} \):
  \[
  w(s', m_Z^{\text{new}}) = \frac{f(s', m_Z^{\text{new}})}{f(s', m_Z^{\text{LEP}})}.
  \]

\[ \sqrt{s} = 189 - 208 \text{ GeV} \]

\[ M_Z^{\text{fit}} = 91.266 \pm 0.080 \text{ GeV} \]

- Optimise agreement with data by varying \( m_Z^{\text{new}} \)
  \[
  \Rightarrow \Delta E_b = -E_b \left( \frac{m_Z^{\text{new}} - m_Z^{\text{LEP}}}{m_Z^{\text{LEP}}} \right).
  \]
(2) Fit method (OPAL):

- Fit Breit-Wigner-like function to $\sqrt{s'}$ distribution in MC (at known $\sqrt{s}$) around ‘pseudo’-Z peak.
- Fit same function to $\sqrt{s'}$ distribution in data as a function of $\Delta E_b = E_b^{\text{OPAL}} - E_b^{\text{LEP}}$, allowing normalisation/peak position ($M^*$) to vary.

- Extract $\Delta E_b$ from $M^*_{\text{data}} (\Delta E_b) = M^*_{\text{MC}}$. 

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**ΔE_b from e^+e^- → ℓ^+ℓ^-γ**

Fit method (DELPHI: ℓ = μ; OPAL: ℓ = e, μ, τ):

- Define $x \equiv \sqrt{\frac{s'}{s}}$.
- Construct $\Delta E_{\text{cms}} = \frac{m_Z}{x} - \sqrt{s}$ for each event.
- Fit Breit-Wigner-like function to distribution of $\Delta E_{\text{cms}}$ in Monte Carlo and in data:

- Extract relative difference in peaks:

$$
\Rightarrow \Delta E_b = \frac{1}{2} (\Delta E_{\text{data}}^{\text{cms}} - \Delta E_{\text{MC}}^{\text{cms}}).
$$
Systematic Studies

• Motivated by $m_W$ systematics; dominated by *detector modelling* and quark *fragmentation*.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Dominant systematics</th>
<th>Total /MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DELPHI($q\bar{q}\gamma$)</td>
<td>Data/MC tracking mismatch 60, Angular scale 20</td>
<td>65</td>
</tr>
<tr>
<td>L3($q\bar{q}\gamma$)</td>
<td>Jet energies 46, Angular scale 40</td>
<td>75</td>
</tr>
<tr>
<td>OPAL($q\bar{q}\gamma$)</td>
<td>Fragmentation 61, Jet/photon energies/angles 29</td>
<td>70</td>
</tr>
<tr>
<td>DELPHI($\mu^+\mu^-\gamma$)</td>
<td>Angular scale 24</td>
<td>27</td>
</tr>
<tr>
<td>OPAL($e^+e^-\gamma$)</td>
<td>MC stats 52, Angular scale 43</td>
<td>78</td>
</tr>
<tr>
<td>OPAL($\mu^+\mu^-\gamma$)</td>
<td>Angular scale 20</td>
<td>22</td>
</tr>
<tr>
<td>OPAL($\tau^+\tau^-\gamma$)</td>
<td>Angular scale 140</td>
<td>148</td>
</tr>
</tbody>
</table>

• ISR modelling in $\mathcal{K}\mathcal{K}2f$ MC, backgrounds, fit parameters give only small uncertainties.
Results from DELPHI

- 1997–2000 $q\bar{q}\gamma$ data:

$$\Rightarrow \Delta E_b = -55 \pm 53 \pm 65 \text{ MeV}.$$ 

- 1997–2000 $\mu^+\mu^-\gamma$ data:

$$\Rightarrow \Delta E_b = +113 \pm 75 \pm 27 \text{ MeV}.$$ 

- DELPHI combined:

$$\Rightarrow \Delta E_b = +34 \pm 47 \pm 37 \text{ MeV}.$$
Results from L3

- 1998–2000 $q\bar{q}\gamma$ data:

\[ \sqrt{s} \text{ [GeV]} \quad \text{M}_Z^{\text{fit}} \text{ [GeV]} \]

\begin{align*}
189 & \quad \circ \text{ Likelihood} \\
192 & \quad \square \chi^2 \\
196 & \quad \triangle \text{ Averaging} \\
200 & \\
202 & \\
205 & \\
207 & \\
208 & \\
\text{Mean} & \\
\end{align*}

\[ \Rightarrow \Delta m_Z = +76 \pm 34 \pm 72 \text{ MeV} \]

\[ \Rightarrow \Delta E_b = -83 \pm 37 \pm 75 \text{ MeV}. \]
1997–2000 $q\bar{q}\gamma$ data:
\[ \Rightarrow \Delta E_b = -65 \pm 34 \pm 70 \text{ MeV}. \]

1997–2000 $\ell^+\ell^-\gamma$ ($\ell = e, \mu, \tau$) data:
\[ \Rightarrow \Delta E_b = -1 \pm 68 \pm 26 \text{ MeV}. \]

OPAL combined:
\[ \Rightarrow \Delta E_b = -31 \pm 40 \pm 36 \text{ MeV}. \]
**Combination**

- Summary of all radiative return results:

<table>
<thead>
<tr>
<th>DELPHI / L3 / OPAL preliminary</th>
<th>DELPHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/L/O combination</td>
<td></td>
</tr>
</tbody>
</table>

- Averaged over all $q\bar{q}\gamma$ data:

$$\Rightarrow \Delta E_b = -65 \pm 24 \pm 45 \text{ MeV}.$$  

- Averaged over all $\ell^+\ell^-\gamma$ data:

$$\Rightarrow \Delta E_b = +51 \pm 50 \pm 19 \text{ MeV}.$$  

- Averaged over all data:

$$\Rightarrow \Delta E_b = -10 \pm 27 \pm 26 \text{ MeV}.$$
Conclusions

• Beam energy from radiative returns is *entirely consistent* with standard LEP calibration
  ⇒ good news for LEP calibration team;
  ⇒ good news for $m_W$ determination.

• Radiative return systematics $\sim$ uncertainty on magnetic extrapolation.

• Approach works with/without *circulating* beams
  ⇒ potential method for evaluating $E_b$ at a high-statistics future linear collider.