LEP II Beam Energy Measurement using Radiative Return Events

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Presentation of preliminary results on behalf of the
LEP Collaborations

ICHEP2002
Amsterdam

Overview

- Motivation for a precise knowledge of the LEP beam energy (E_b).
- The radiative return approach to E_b (first reported on by ALEPH in Phys. Lett. **B464** (1999) 339).
- 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 $\int \mathcal{L} dt$ 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 $E_b \sim 40 - 60$ GeV, together with *magnetic extrapolation* to LEP II energies ($E_b \sim 100$ GeV), assuming $E_b = a + bB \Rightarrow$ *indirect* determination: need to be confident it really works at ~ 20 MeV level LEP claims.

Radiative Return Approach

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

- $\sqrt{s'}$ sensitive to E^{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 (ΔE_b).

Reconstructed $\sqrt{s'}$ Distribution

- 1998–2000 L3 hadronic data (627 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 ($\approx$ independent of E_b) and at full energy.

ΔE_b 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^{new} :

$$w(s', m_Z^{\text{new}}) = \frac{f(s', m_Z^{\text{new}})}{f(s', m_Z^{\text{LEP}})}.$$

- Optimise agreement with data by varying m_Z^{new}

$$\Rightarrow \Delta E_b = -E_b \left(\frac{m_Z^{\text{new}} - m_Z^{\text{LEP}}}{m_Z^{\text{LEP}}} \right).$$

$$\Delta E_b \text{ from } e^+e^- \rightarrow q\bar{q}\gamma$$

(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 ΔE_b from $M_{\text{data}}^*(\Delta E_b) = M_{\text{MC}}^*$.

$$\Delta E_b \text{ from } e^+e^- \rightarrow \ell^+\ell^-\gamma$$

Fit method (DELPHI: $\ell = \mu$; OPAL: $\ell = e, \mu, \tau$):

- 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 ΔE_{cms} in Monte Carlo and in data:

- Extract relative difference in peaks:

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

Systematic Studies

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

Experiment	Dominant systematics /MeV	Total /MeV
DELPHI($q\bar{q}\gamma$)	Data/MC tracking mismatch	65
	Angular scale	
L3($q\bar{q}\gamma$)	Jet energies	75
	Angular scale	
OPAL($q\bar{q}\gamma$)	Fragmentation	70
	Jet/photon energies/angles	
DELPHI($\mu^+\mu^-\gamma$)	Angular scale	27
OPAL($e^+e^-\gamma$)	MC stats	78
	Angular scale	
OPAL($\mu^+\mu^-\gamma$)	Angular scale	22
OPAL($\tau^+\tau^-\gamma$)	Angular scale	148

- 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:

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

$$\Rightarrow \Delta E_b = -83 \pm 37 \pm 75 \text{ MeV}.$$

Results from OPAL

- 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:

- 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.