E_{beam} from recoil Z events

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L3 Collaboration

- Motivation
- LEP Energy measurement
- E_{beam} from recoil events
- Extraction methods
- Systematics and Results
- Conclusions

Presenting
preliminary results
on behalf of
the LEP Collaborations

Why has E_{beam} to be known precisely?

- Precise M_W measurement is one of the main aims of LEP II

- δE_{beam} contributes directly to δM_W through constraints of kinematic fit:

$$\frac{\delta M_W}{M_W} = \frac{\delta E_{beam}}{E_{beam}}$$

- Irreducible uncertainty for all experiments

- Reduce uncertainty on E_{beam} to reduce uncertainty on M_W

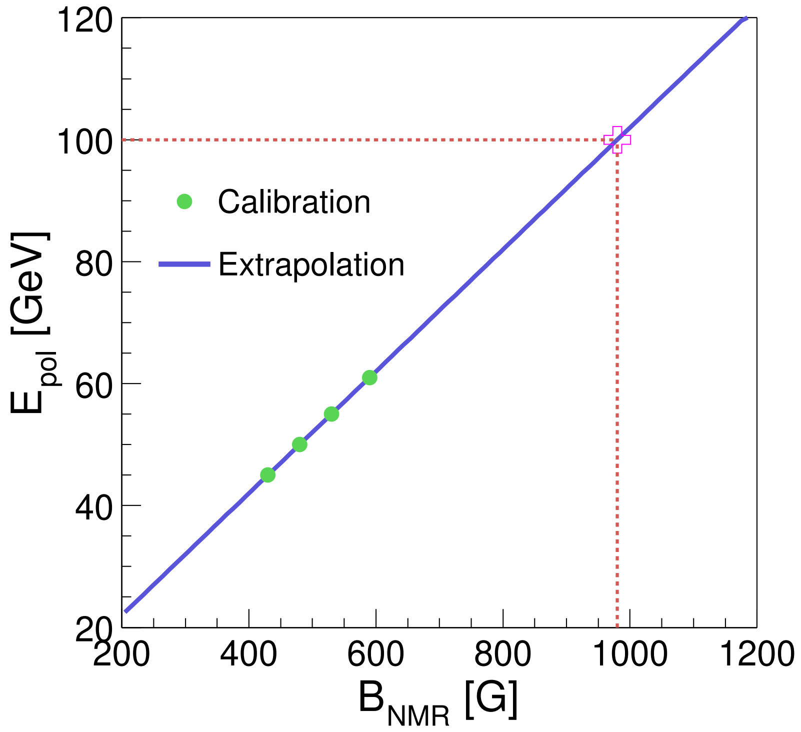
Beam energy determination at LEP

LEP I (Z pole)

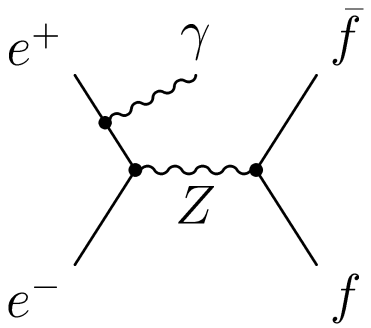
- resonant depolarisation technique
- $\delta E_{beam} \approx \mathcal{O}(1\ \mathrm{MeV})$
- works up to $E_{beam} \approx$ 60 GeV

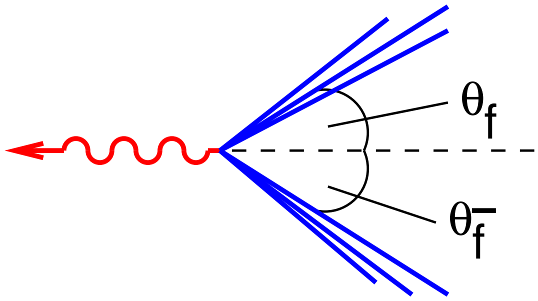
LEP II (above Z pole)

- Determine magnetic field from NMR probes in 16 dipole magnets
- Calibrate $E_{beam}^{NMR} \sim \oint B \cdot dl$ with E_{beam}^{depol} at energies $<$ 60 GeV
- Assume linear relation $E_{beam} = a \cdot B + b$ and extrapolate to LEP II energies of $\approx$ 100 GeV
- Uncertainty $\approx$ 20 MeV (from comparison to flux loop measurements) $\rightarrow \delta M_W \approx$ 17 MeV
- Cross checks: Spectrometer, flux loop, Q_s



Recoil events





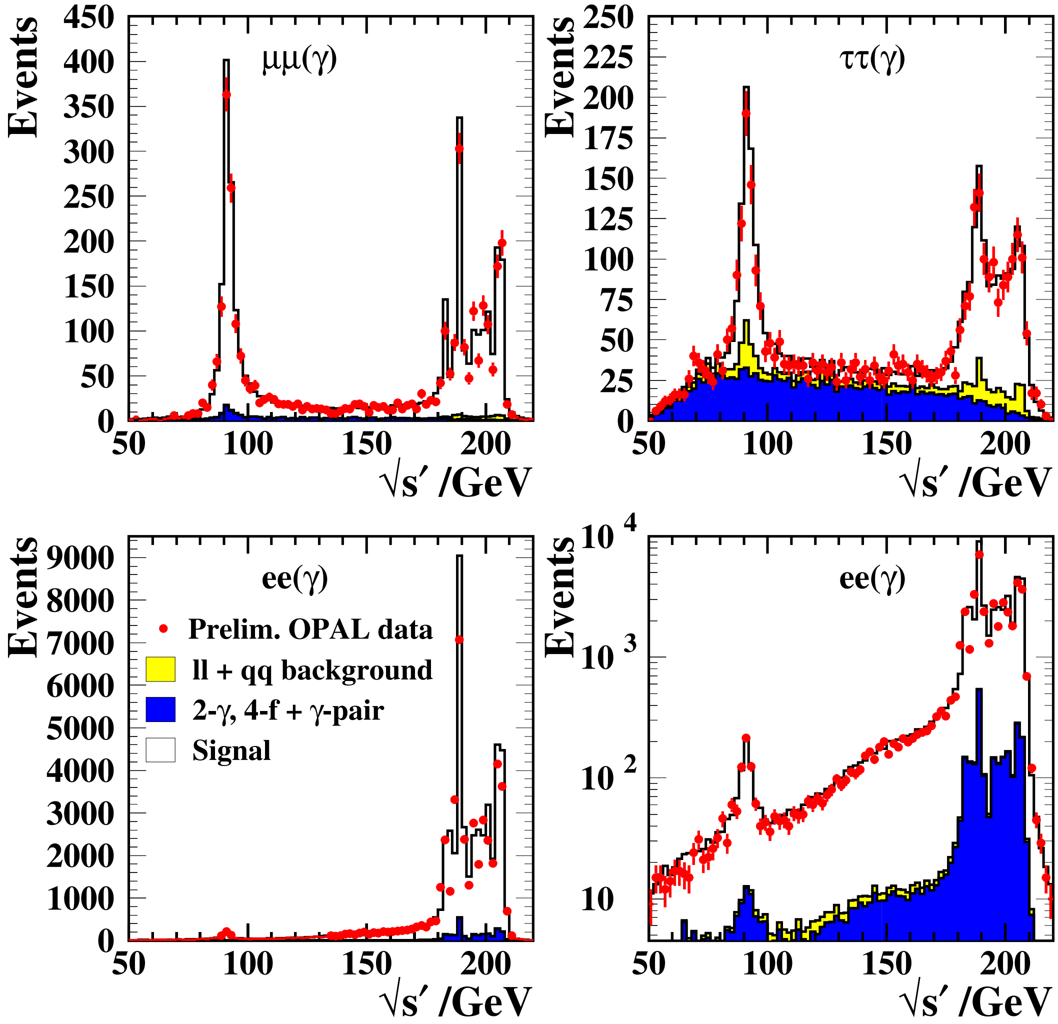
- Two fermion final states often produced with accompanying hard ISR photon
- Photon sometimes detected; in most cases escapes along beam pipe
- ISR leads to reduced "effective" centre-of-mass energy $\sqrt{s'}$
- Measure $\sqrt{s'}$ via three particle kinematics

$$\sqrt{s'} = \sqrt{s} \cdot \sqrt{\frac{\sin(\theta_f) + \sin(\theta_{\bar{f}}) - |\sin(\theta_f + \theta_{\bar{f}})|}{\sin(\theta_f) + \sin(\theta_{\bar{f}}) + |\sin(\theta_f + \theta_{\bar{f}})|}}$$

- Or determine fermion pair invariant mass M_{inv} after kinematic fit

Spectra

- Clear peak at M_Z in $\sqrt{s'}$ and M_{inv} spectra



- $M_Z = 91.1876 \pm 0.0021$ GeV known very precisely

Deviation from "true" M_Z can be due to shift in beam energy:
$\Delta E_{beam} = E_{beam}^{meas} - E_{beam}^{LEP}$

Events

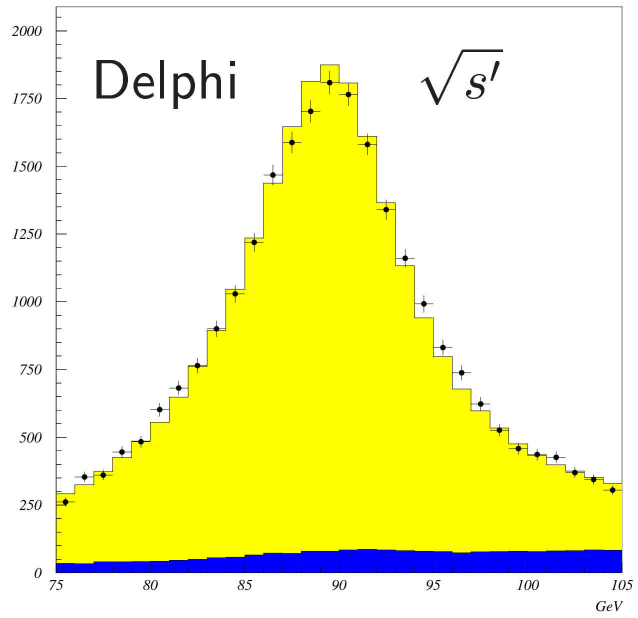
Lepton pair events

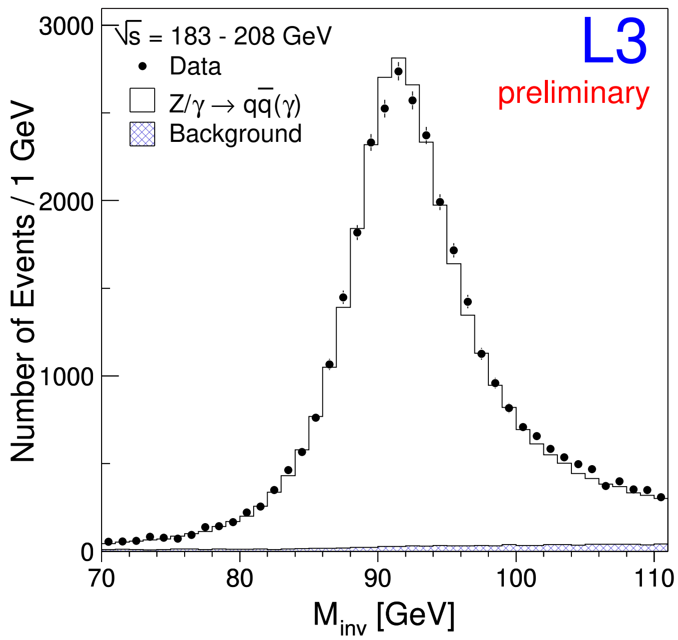
- ADLO use $e^+e^- \to \mu^+\mu^-\gamma$
  Very clear signature and very low background

- Opal includes also $\tau^+\tau^-\gamma$ and $e^+e^-\gamma$ final states

Two-jet events (DLO)

- Main advantage: High statistics





E_{beam} extraction – Aleph $\mu^+\mu^-$

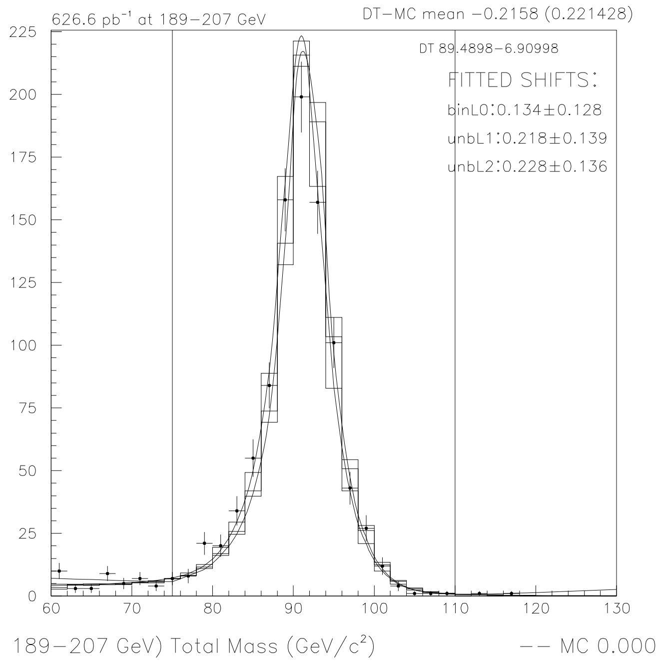
- Use $\sqrt{s'}$ and "raw" invariant mass (without kinematic fit)

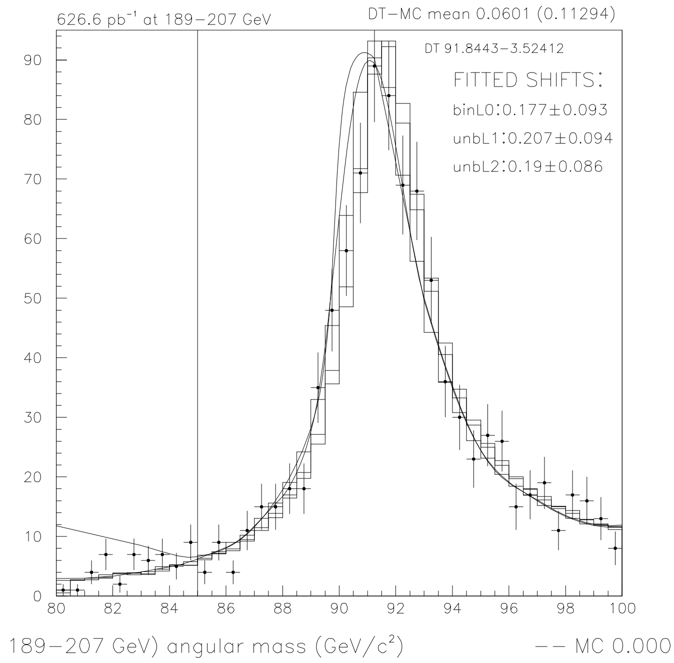
$$M_{raw} = \sqrt{2 \cdot p_1 p_2 \cdot (1 - \cos\theta_{12})}$$

- Obtain MC - Data shifts $\Delta\sqrt{s'}$ and ΔM_{raw} using unbinned likelihood fit

- Create $\chi^2 = f(E_{beam})$ using $\Delta\sqrt{s'}$ and ΔM_{raw}

- Minimize χ^2 to determine ΔE_{beam}





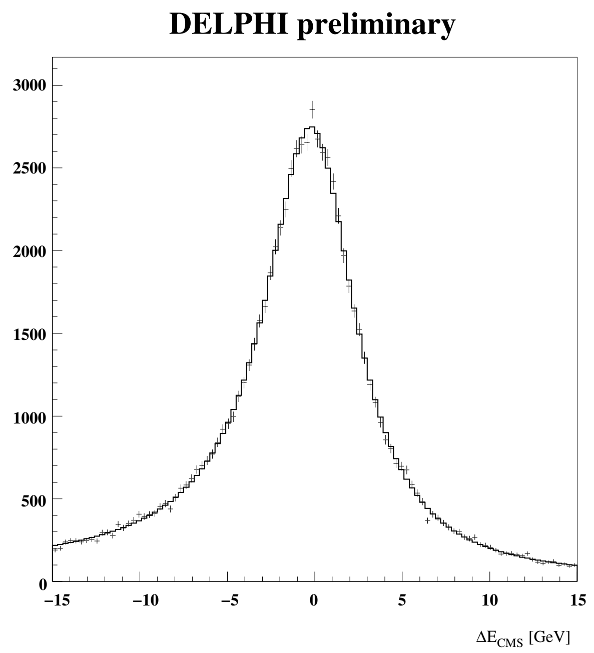
E_{beam} extraction – D $\mu^+\mu^-$, O l^+l^-

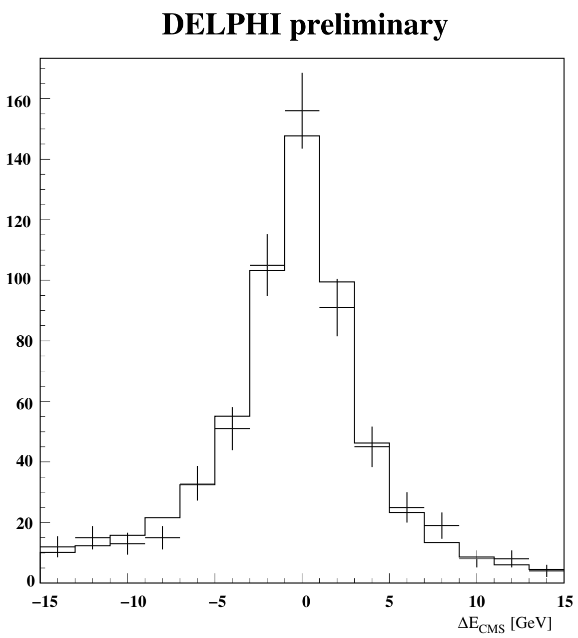
- Compute per event E_{beam}-shift

$$x = \frac{\sqrt{s'}}{\sqrt{s}} = f(\theta_f, \theta_{\bar{f}})$$

$$\Delta E_{beam} = \frac{1}{2} \cdot \left(\frac{M_Z}{x} - \sqrt{s}_{LEP} \right)$$

- Fit Breit-Wigner like function to Monte Carlo and data spectra
- Obtain E_{beam}^{data} from MC - data comparison





E_{beam} extraction – D $q\bar{q}$, L $q\bar{q}, \mu^+\mu^-$

- Use $\sqrt{s'}$ or M_{inv} spectrum
- Construct Monte Carlo event weights:

$$w = \frac{f(\sqrt{s'}, M_{test})}{f(\sqrt{s'}, M_Z)}$$

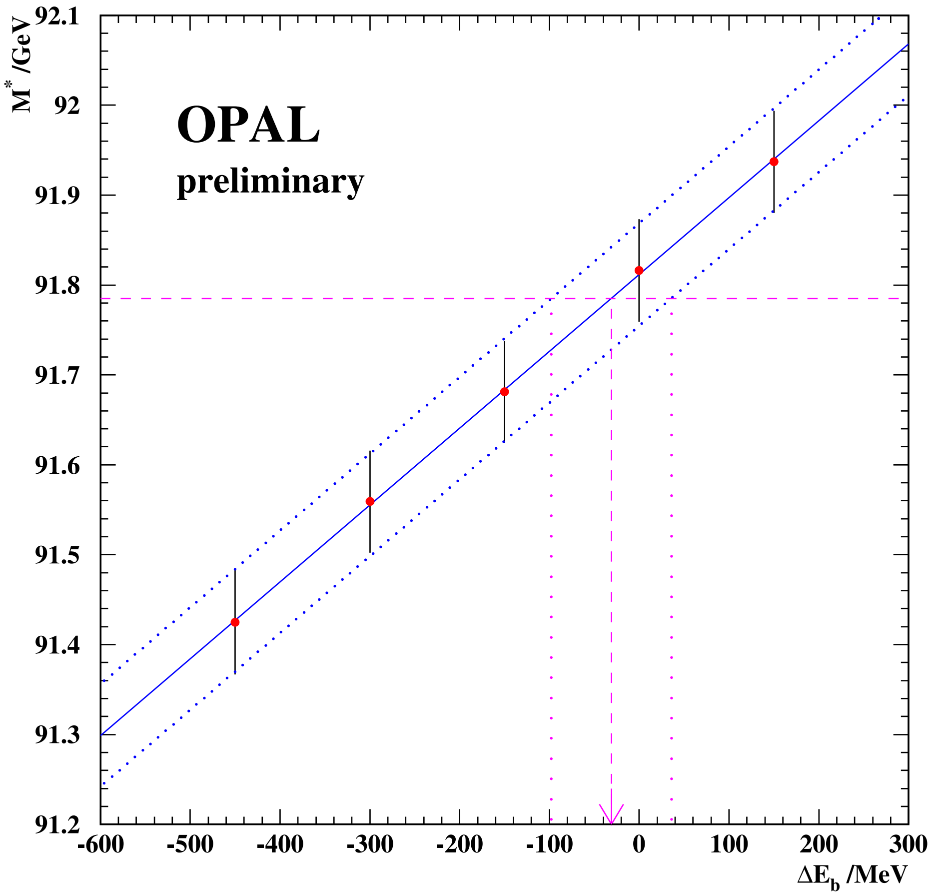
$f(\sqrt{s'}, M)$: Breit-Wigner like function

- Apply unbinned likelihood fit to $\sqrt{s'}$ or M_{inv} spectrum using Monte Carlo weights and extract Z mass
- Determine ΔE_{beam} from comparison between fitted Z mass and Z mass from LEP 1

$$\Delta E_{beam} = E_{beam}^{meas} - E_{beam}^{LEP} = -E_{beam}^{LEP} \cdot \frac{M_{fit} - M_Z}{M_Z}$$

E_{beam} extraction – Opal $q\bar{q}$

- Fit Breit-Wigner like function to MC $\sqrt{s'}$ spectrum
- Fit same function to data, varying only normalisation and peak position M^* as function of E_{beam}
- Determine ΔE_{beam} from $M^*_{data}(\Delta E_{beam}) = M^*_{MC}$



Main systematic uncertainties for lepton pair events

	Aleph		
Fit calibration		32 MeV	
Angular bias		26 MeV	
Total		**48 MeV**	
	Delphi		
Angular bias		24 MeV	
Fit properties		11 MeV	
Total		**27 MeV**	
	L3		
Monte Carlo statistics		14 MeV	
Angular bias		12 MeV	
Total		**22 MeV**	
	Opal		
Angular bias	43 MeV	20 MeV	140 MeV
ISR modelling	30 MeV	1 MeV	30 MeV
Total	**78 MeV**	**22 MeV**	**148 MeV**
	(e^+e^-)	$(\mu^+\mu^-)$	$(\tau^+\tau^-)$

Further error sources are Background uncertainties and LEP parameters.

ISR uncertainties are tested by using different orders of radiation in the KK2f model.

Main Systematics for hadron channel

Delphi	
Data/MC disagreement	60 MeV
(Number of tracks in forward region)	
Angular bias	20 MeV
Total	**65 MeV**
L3	
Fragmentation	36 MeV
Jet energies	23 MeV
Total	**51 MeV**
Opal	
Fragmentation	61 MeV
Detector modelling	30 MeV
Total	**70 MeV**

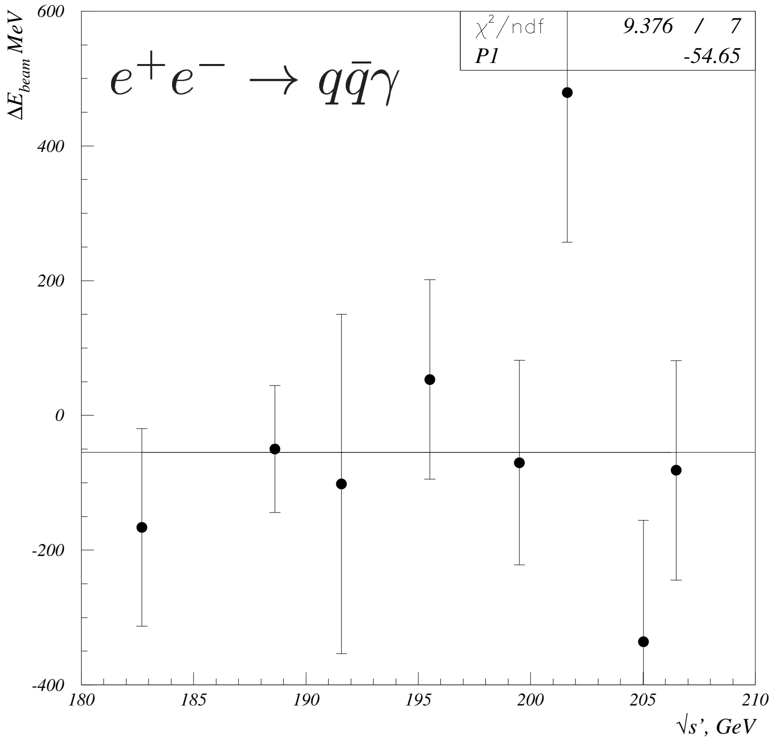
Further minor error sources include ISR modelling, background expectations, and MC statistics.

Results from Aleph and Delphi

Aleph

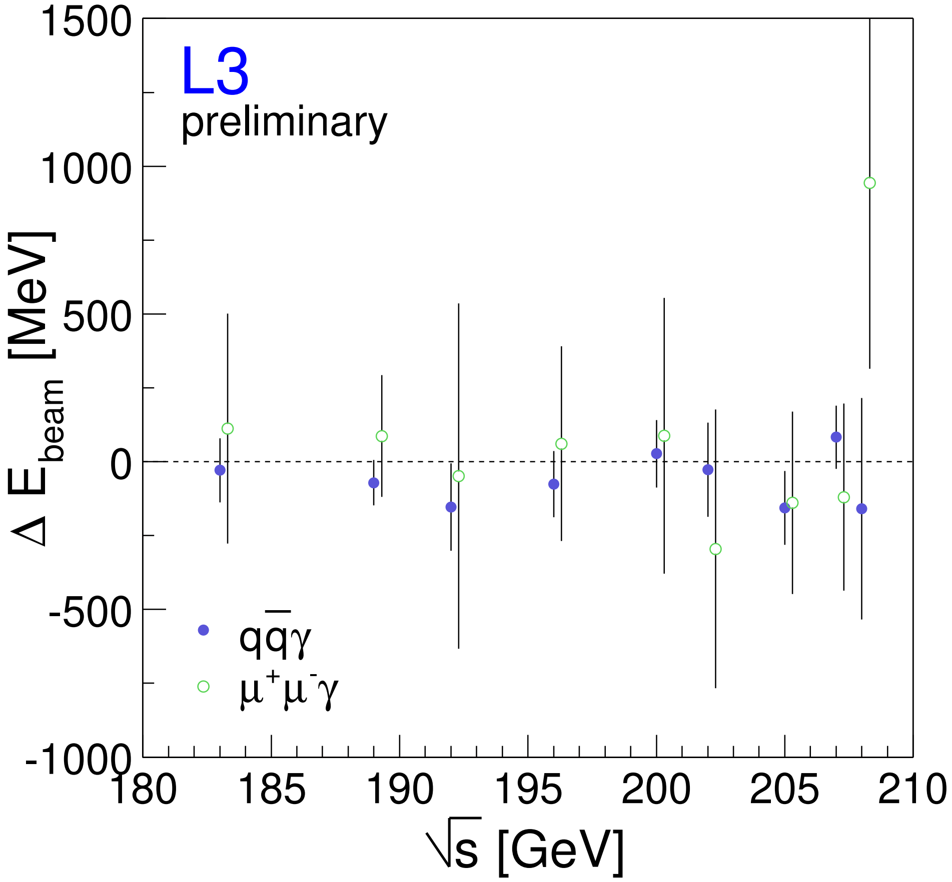
Channel	Result
$e^+e^- \to \mu^+\mu^-\gamma$	$-\ 167 \pm 91 \pm 48$ MeV

Delphi



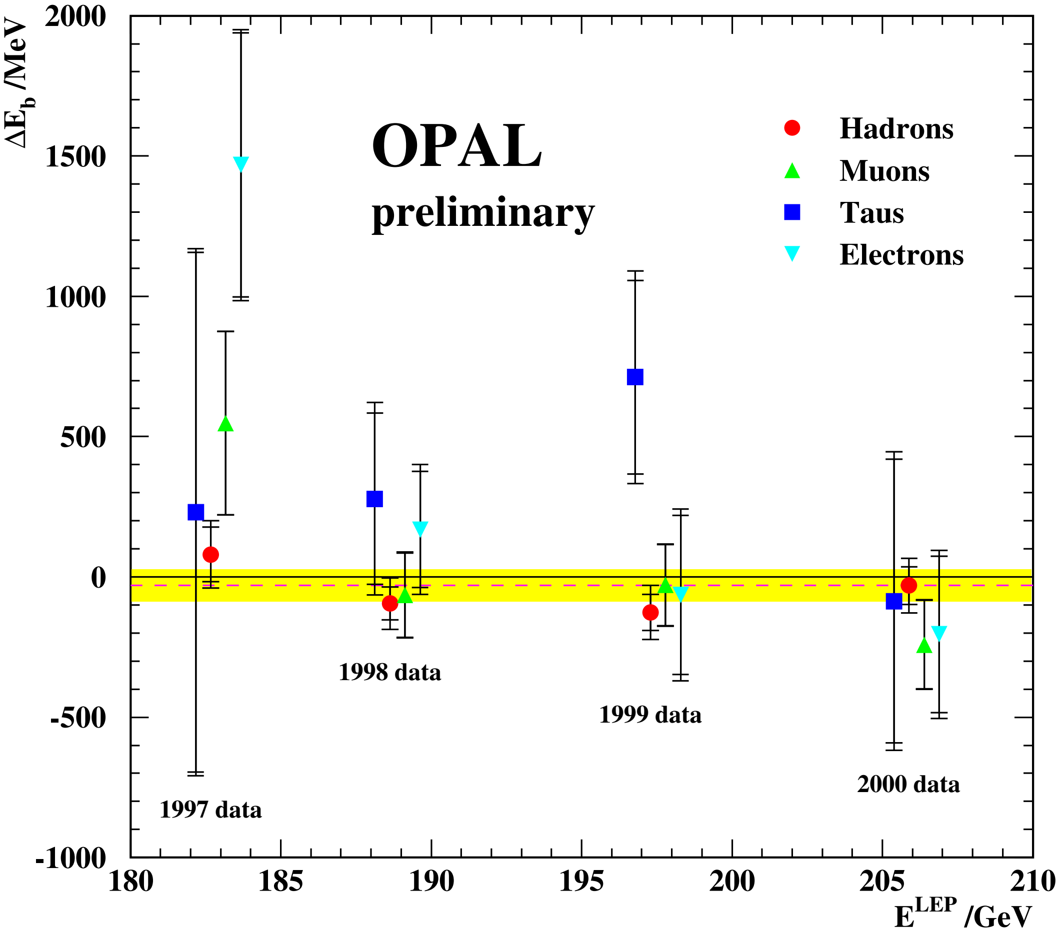
Channel	Result
$e^+e^- \to \mu^+\mu^-\gamma$	$+113 \pm 75 \pm 27$ MeV
$e^+e^- \to q\bar{q}\gamma$	$-\ 55 \pm 53 \pm 65$ MeV
Combined	$+33 \pm 37 \pm 47$ MeV

Results from L3



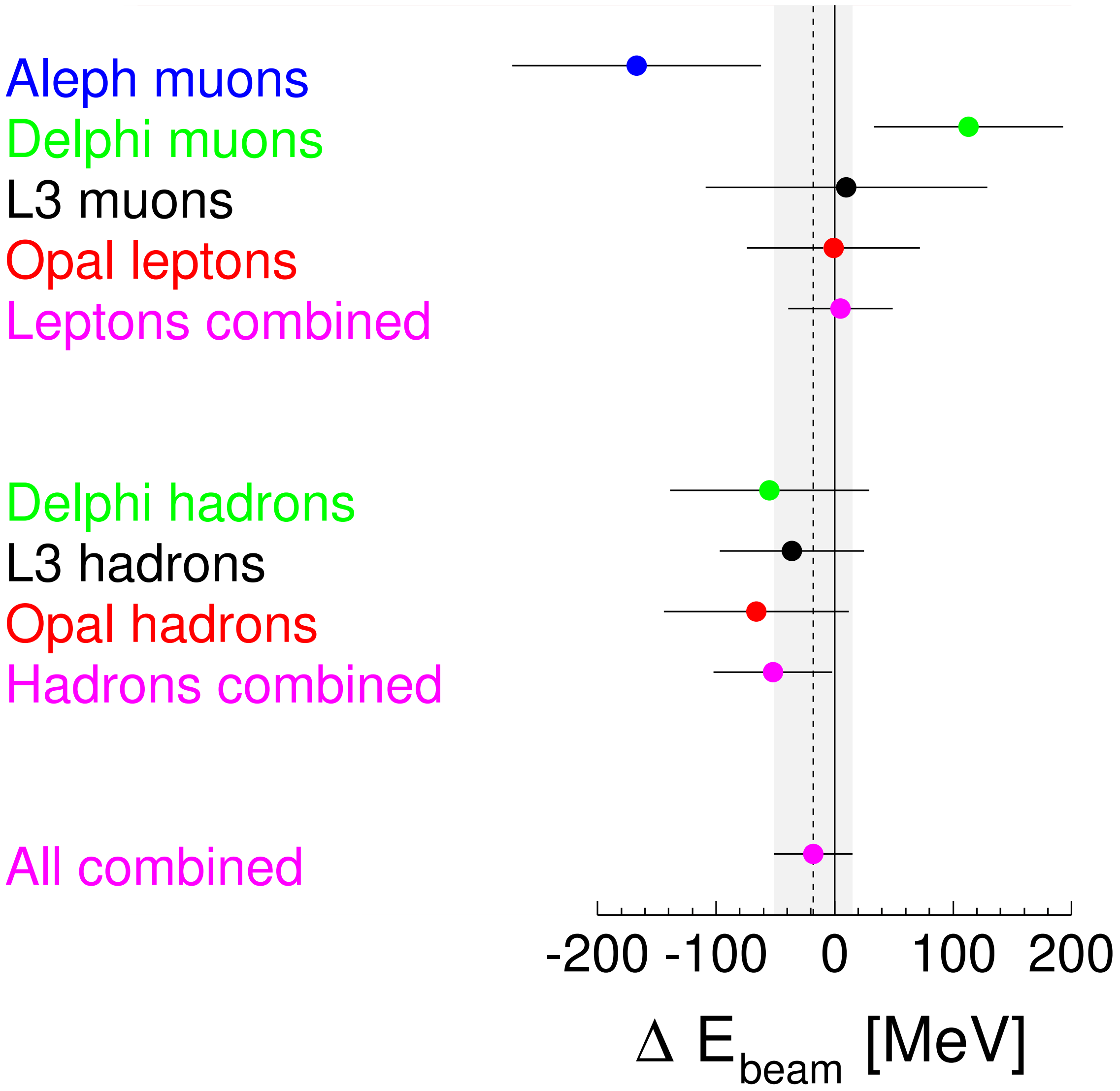
Channel	Result
$e^+e^- \to \mu^+\mu^-\gamma$	$+\ 10 \pm 115 \pm 22$ MeV
$e^+e^- \to q\bar{q}\gamma$	$-\ 46 \pm 33 \pm 51$ MeV
Combined	$-\ 34 \pm 36 \pm 41$ MeV

Results from Opal



Channel	Result
$e^+e^- \to e^+e^-\gamma$	$+40 \pm 136 \pm 78$ MeV
$e^+e^- \to \mu^+\mu^-\gamma$	$-51 \pm 84 \pm 22$ MeV
$e^+e^- \to \tau^+\tau^-\gamma$	$+301 \pm 199 \pm 148$ MeV
$e^+e^- \to q\bar{q}\gamma$	$-66 \pm 34 \pm 70$ MeV
Combined	$-31 \pm 40 \pm 36$ MeV

Combining ADLO...



Channel	Result
$e^+e^- \to l^+l^-\gamma$	$+\ \ 5 \pm 41 \pm 16$ MeV
$e^+e^- \to q\bar{q}\gamma$	$-\ 52 \pm 24 \pm 43$ MeV
Combined	$-\ 20 \pm 25 \pm 22$ MeV

Main systematic uncertainty for combined result:
Hadronisation (15 MeV)

Conclusions

- The beam energy obtained by using $e^+e^- \rightarrow f\bar{f}\gamma$ events is in good agreement with the value given by the LEP Energy Group.

- This ansatz can only measure the mean beam energy and depends on the overall LEP model (tide, TGV, etc.)

- Impose $\Delta E_{beam} = 0 \rightarrow$ measure M_Z as cross check for M_W measurement (detector effects, hadronisation, ...)

- This method can also be used at future linear colliders where the resonant depolarisation method can't work

Hadron error table

Source	Effect [MeV]
Fragmentation	34
ISR modelling	6
MC Statistics	5
4-fermion backgrounds	2
LEP parameters	1
Delphi - Data/MC disagreement	18
L3 - Jet energies	13
L3 - fit method	9
Delphi - Angular bias	6
L3 - Jet angles	5
Opal - Energies/Angles	5
L3 - Backgrounds	2
Opal - $\sqrt{s'}$ determination	2
Opal - Other Backgrounds	1
Total	43
Statistical Uncertainty	24

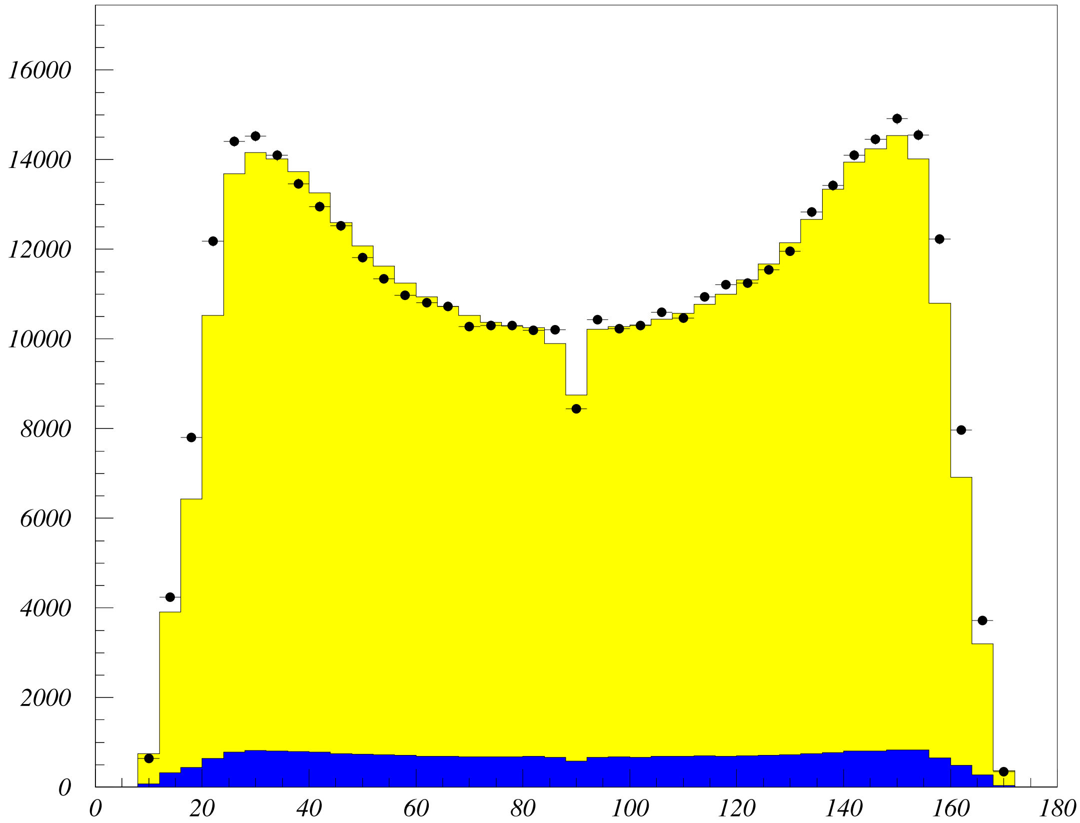
Lepton error table

MC Statistics	9
LEP parameters	4
ISR modelling (KK2f)	3
ISR modelling (electron channel)	2
4-fermion background	2
Delphi - Angular measurement	7
Aleph - Angular measurement	5
Opal - Angular meas. ($\mu^+\mu^-\gamma$)	5
Opal - Angular meas. ($\tau^+\tau^-\gamma$)	5
Opal - Angular meas. ($e^+e^-\gamma$)	4
Aleph - Fit method	3
Aleph - Momentum measurement	2
L3 - Angular measurement	2
Opal - Fit parameters	1
Total	16
Statistics	41

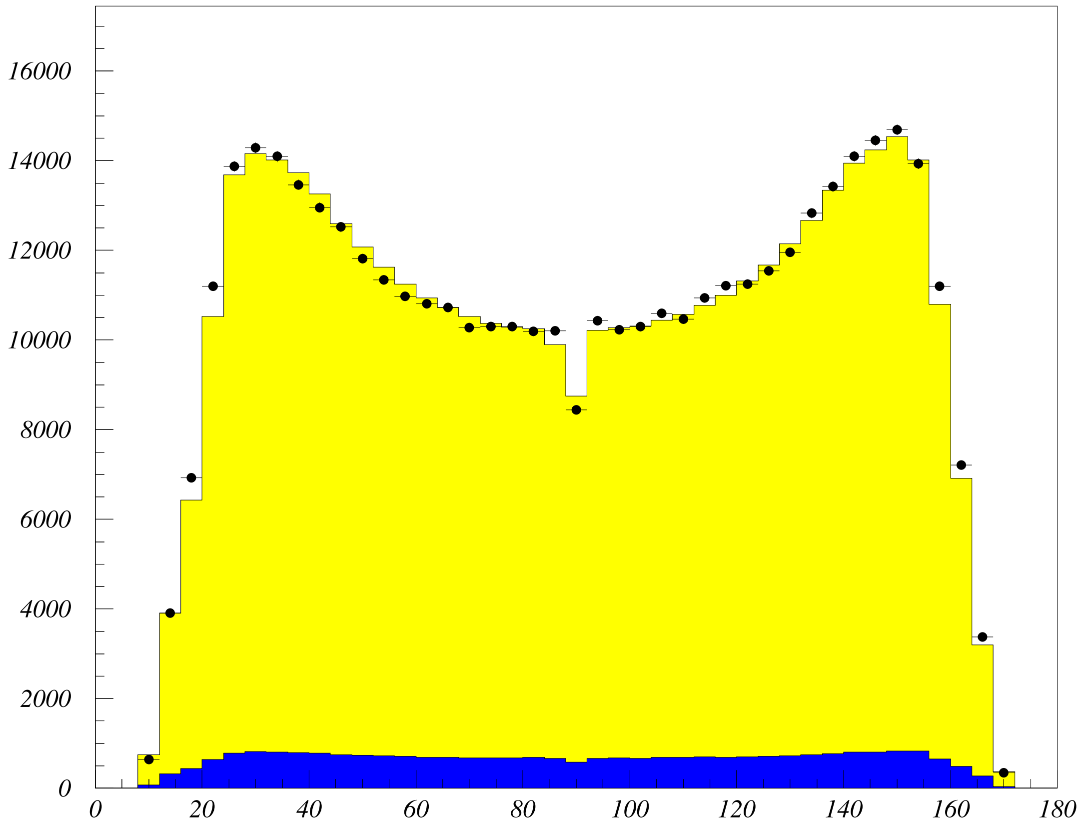
Combined error table

Fragmentation	15
MC Statistics	5
ISR modelling (KK2f)	4
LEP parameters	2
4-fermion background	2
ISR modelling (electron channel)	1
Delphi - Data/MC disagreement	7
Delphi - Angular measurement ($q\bar{q}\gamma$)	6
L3 - Jet energies	6
L3 - Fit method	4
Opal - Angular meas. ($\mu^+\mu^-\gamma$)	3
Opal - Angular meas. ($\tau^+\tau^-\gamma$)	3
Aleph - Angular measurement	3
Opal - Angular meas. ($e^+e^-\gamma$)	2
Aleph - Fit method	2
L3 - Jet angles	2
Opal - Energies and Angles	2
L3 - Muon angles	1
Opal - $\sqrt{s'}$determination	1
L3 - Background ($q\bar{q}\gamma$)	1
Total	22
Statistical uncertainty	25

Delphi Data/MC disagreement



a) before corrections



b) after corrections