Measuring the Beam Energy with Radiative Return Events

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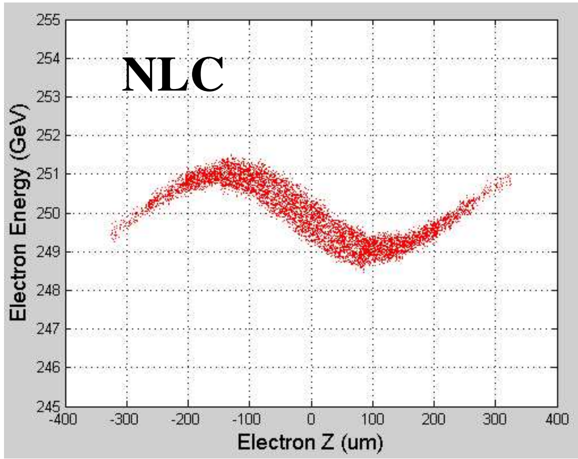
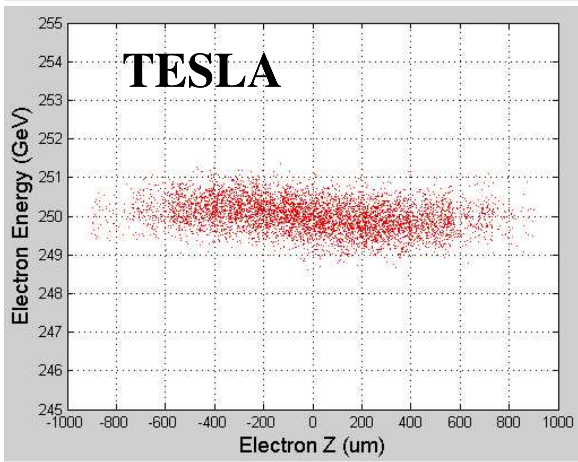
(Master thesis of Arnd Hinze)

Introduction

- The beam energy is needed on the 10^{-4} level for mass determinations at the ILC (Higgs, top, SUSY...)
- The beam-energy measurement will mainly come from a magnetic spectrometer
- The absolute calibration of the spectrometer is difficult
- In addition the average beam energy is not necessarily equal to the luminosity weighted centre of mass energy $\rightarrow$ next slide
- It would thus be useful to have a method to determine the beam energy from annihilation data
- Such a method exists: radiative return events $\mathrm{e^+e^-} \rightarrow Z\gamma \rightarrow \mathrm{f\bar{f}}\gamma$
- The validity of this method was already proven at LEP

Energy Bias from the Kink-Instability



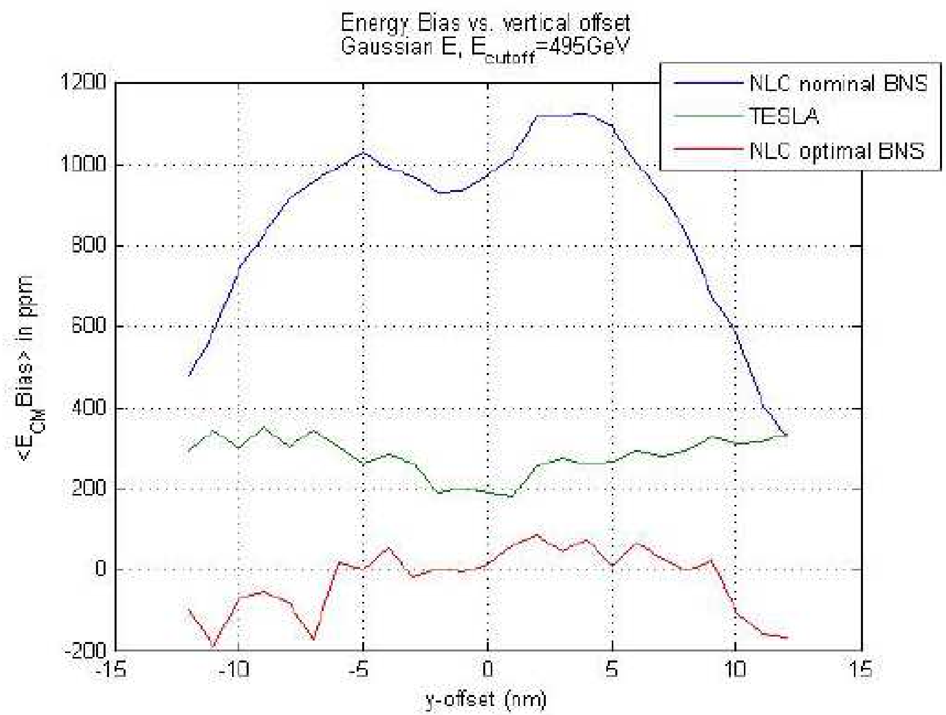


500 GeV TESLA	
mean	150 ppm
spread	30 ppm
max	350 ppm

A. Florimonte, M. Woods, IPBI TN-2005-1

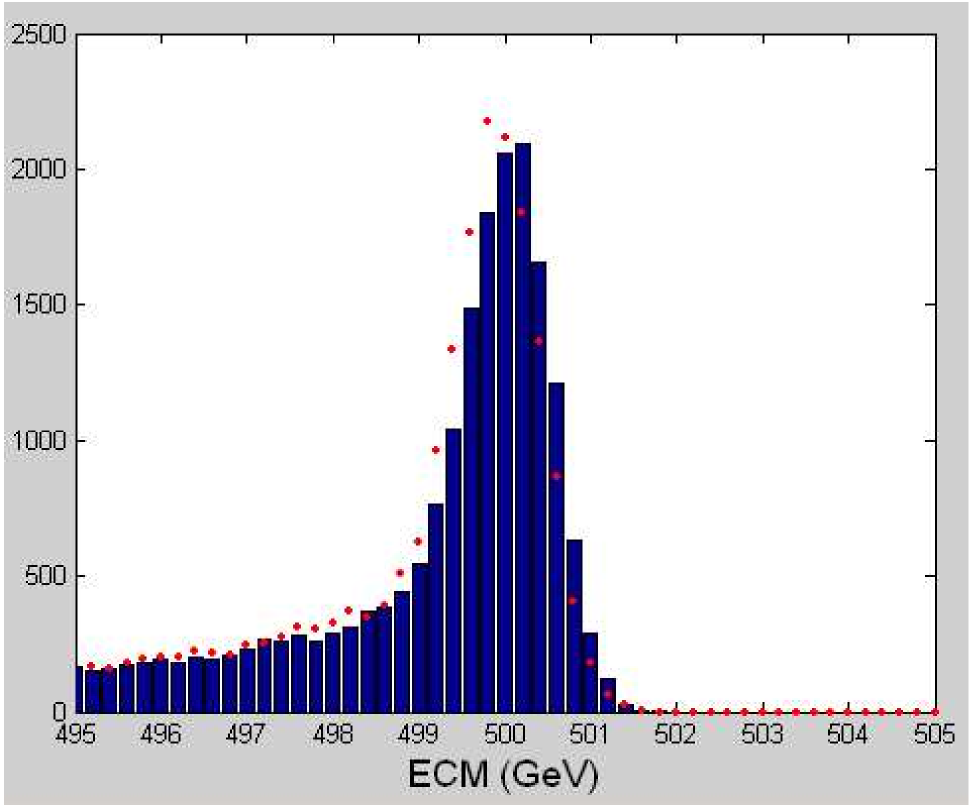
- Wakefields introduce a correlation $z - E$
- Disruption give a different weight to different parts of the bunch

➠ These effects make the luminosity weighted cms energy different from twice the beam energy

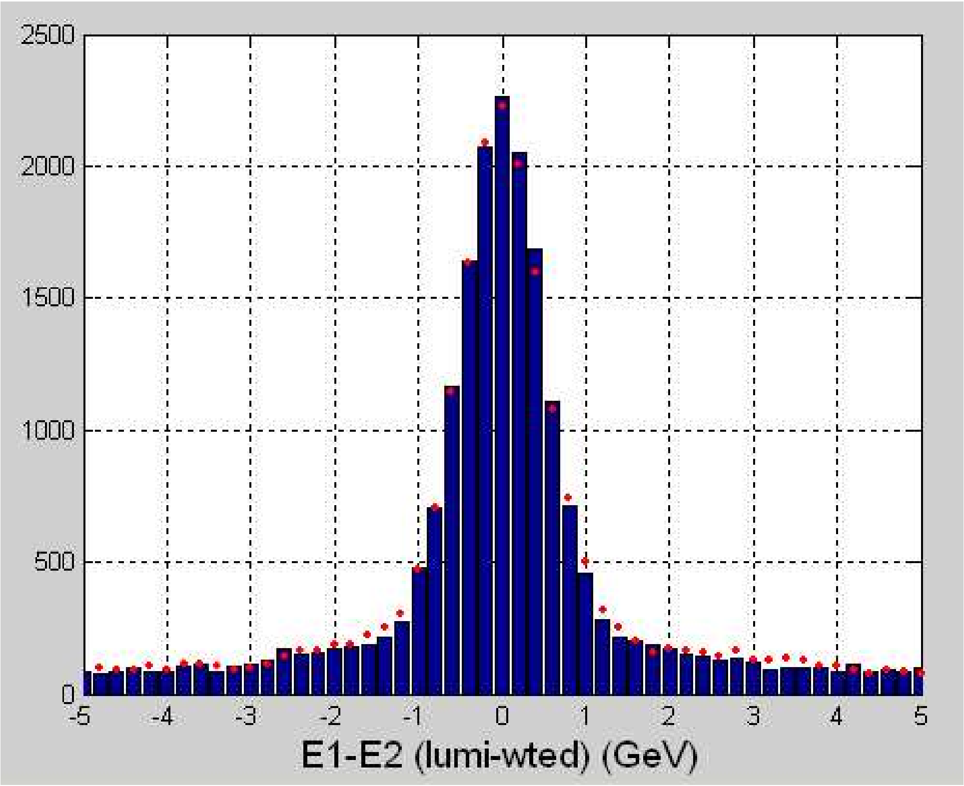


This effect is not visible in the Bhabha acolinearity!

$E_1 + E_2$



$E_1 - E_2$



TESLA

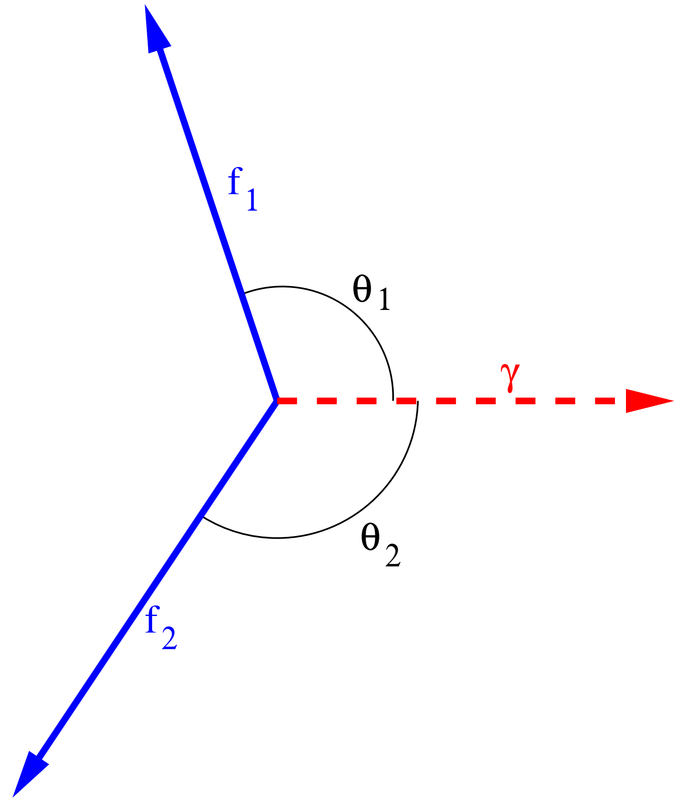
TESLA with random ordered E

Basic Idea of the Radiative Return Analysis

- The Z-mass is known with very high precision from LEP
- assume only one photon is radiated
  ➠ $\sqrt{s'}$ can be calculated from fermion angles only

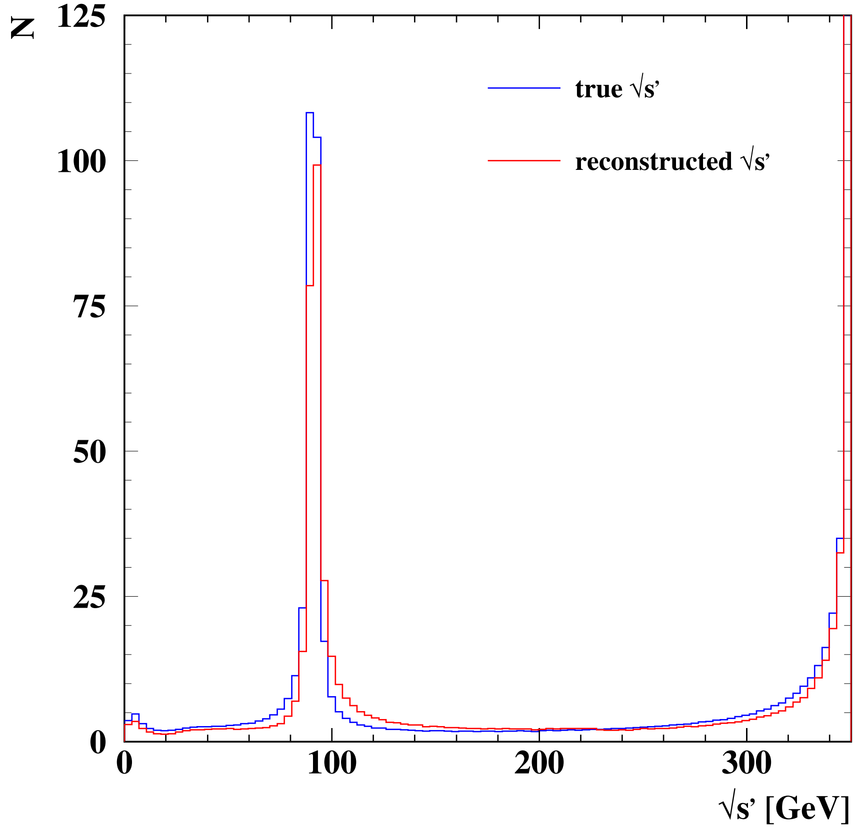
$$\frac{\sqrt{s'}}{\sqrt{s}} = \sqrt{\frac{\sin\theta_1 + \sin\theta_2 + \sin(\theta_1+\theta_2)}{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1+\theta_2)}}$$

  - γ either along the beampipe or angle is measured
  - this formula assumes that the fermion mass can be neglected

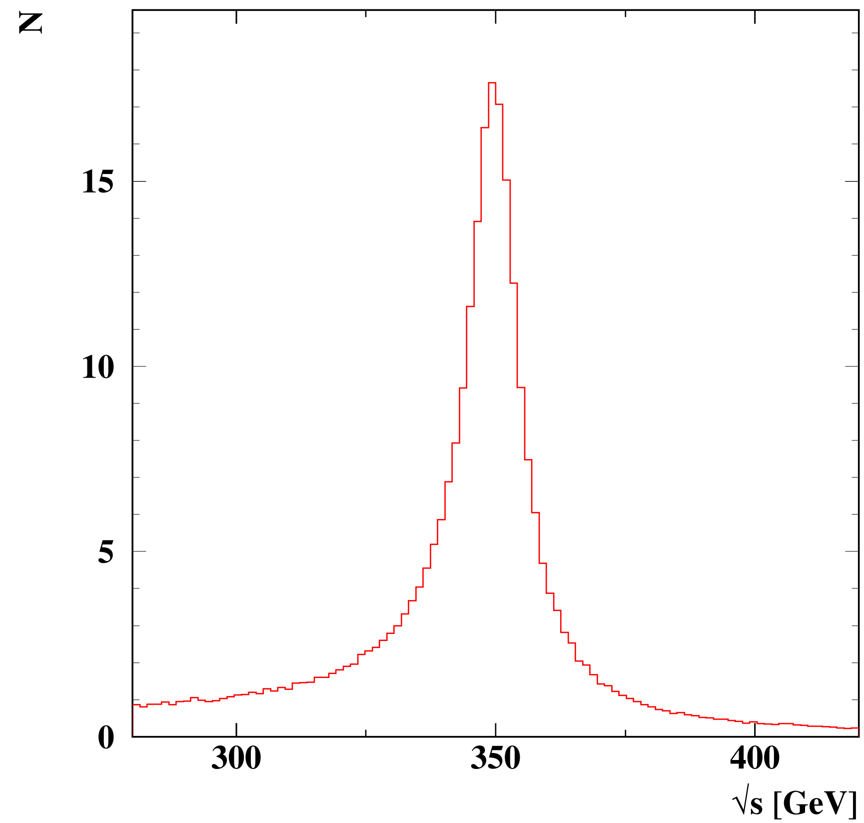


- Assume $\sqrt{s'} = m_Z \Rightarrow \sqrt{s} = m_Z \sqrt{\frac{\sin\theta_1+\sin\theta_2-\sin(\theta_1+\theta_2)}{\sin\theta_1+\sin\theta_2+\sin(\theta_1+\theta_2)}}$

$\sqrt{s'}$ spectrum



Reconstructed $\sqrt{s}$



First analysis with $e^+e^- \to \mu^+\mu^-$: 100 fb^{-1} at $\sqrt{s} = 350\,\text{GeV}$

- $\sigma(\text{rad. ret.}) \sim 0.5\,\text{pb}$ scales approx. with $1/s$
- detector efficiency (7° cut) $\approx 90\%$
- ideal beam with beamstrahlung and 0.2% Gaussian energy spread

Fit method:

- χ^2 fit of data to MC prediction with free normalisation
- MC prediction from linearisation around a default value:
  - two MC samples $\mathrm{MC_{def}}$ at $\sqrt{s}_{\mathrm{def}}$ and MC_{Δ} at $\sqrt{s}_{\mathrm{def}} + \Delta\sqrt{s}$
  - $N_{\mathrm{pred}}(\sqrt{s}) = \frac{\sqrt{s}-\sqrt{s}_{\mathrm{def}}}{\Delta\sqrt{s}} (\mathrm{MC}_{\Delta} - \mathrm{MC_{def}})$
- easy to include all effects into fit
- fit tested to be bias free in region $\sqrt{s}_{\mathrm{def}} \pm \Delta\sqrt{s}$

Cuts:

- $7^\circ < \theta_{1,2} < 183^\circ$ (detector acceptance)
- $m_Z - 5\,\mathrm{GeV} < m(\mu^+\mu^-) < m_Z + 5\,\mathrm{GeV}$

Backgrounds

$\gamma\gamma$ background ($e^+e^- \rightarrow e^+e^-\mu^+\mu^-$)

- very large cross section without cuts
- less than 10% background in fit range after $m(\mu^+\mu^-)$ cut

Zee:

- cross section similar to signal
- after cut on visible electrons $\sim 25\%$ background remains
- however kinematics similar to signal, so no problem

WW,ZZ:

- ZZ already small, WW reduced by $m(\mu^+\mu^-)$ cut
- in the end $\sim 1\%$ background

Results

Fit to 100 fb^{-1} including beam effects and background:

$$\Delta\sqrt{s} = 47\,\mathrm{MeV} \qquad \left(\frac{\Delta\sqrt{s}}{\sqrt{s}} = 1.3 \cdot 10^{-4}\right)$$

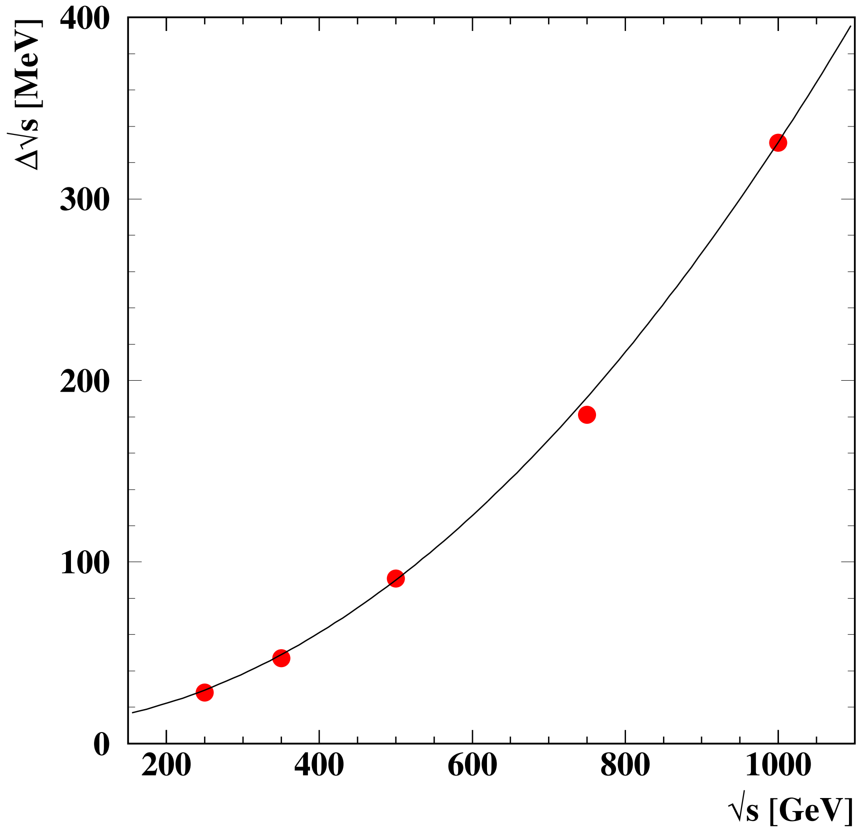
- without beamstrahlung and energy spread $\sim 10\%$ better
- little effect from background
- slight improvement possible if 2D fit $(\sqrt{s}, \theta)$

Energy dependence

Result strongly energy dependent:

- cross section $\propto 1/s$
- resolution deteriorates with s
- background rises with s
- acceptance worse at larger s
- parameterisation:

$\Delta\sqrt{s}$ for $\mathcal{L} = 100\ \text{fb}^{-1}$



$$\Delta\sqrt{s} = \left(8.8 + 0.0026\sqrt{s}/\,\text{GeV} + 0.0032s/GeV^2\right)\ \text{MeV}$$

(However $\Delta\sqrt{s}/\sqrt{s}$ constant if $\mathcal{L} \propto s$)

Systematics

- Background: no effect for 20-30% background uncertainty
- Energy spread: $\Delta\sqrt{s} = 10\,\mathrm{MeV}$ if Gaussian energy spread is replaced by rectangular, no effect if 0.1% instead of 0.2%
- Beamstrahlung: method largely cancels errors from beamstrahlung determination
- Aspect ratio: LEP error $\Delta\left(\frac{\delta R}{\delta L}\right) = \delta\tan\theta = 5\cdot 10^{-4}$

  $\Rightarrow \Delta\sqrt{s} = 160\,\mathrm{MeV}$

  ➟ need about one order of magnitude better

Work to be done

- Possible larger statistics:
  - Bhabha scattering: clean, however diluted by t-channel contribution
  - $e^+e^- \to \tau^+\tau^-$: slight dilution from τ decay angle, $m(\tau^+\tau^-)$ against $\gamma\gamma$ does not work because of missing neutrinos
  - $e^+e^- \to q\bar{q}$: mass effects significant (e.g. 5 GeV jet mass gives a 2.5 GeV shift in reconstructed $\sqrt{s}$) $\Rightarrow$ large sensitivity to fragmentation and particle losses
- Global analysis:
  - beamstrahlung is correlated for the two beams (e.g. from z-position)
  - also the kink instability is correlated for the two beams
  - both effects modify the acolinearity used in the beam spectrum and in the radiative return analysis
  - to understand the interplay of those effects a common analysis taking into account realistic beam effects is needed

Conclusions

- The centre of mass energy can be measured on the 10^{-4} level from radiative return events.

- This is a high luminosity analysis, so relative measurements e.g. in a scan are needed from spectrometers.

- The length to radius ratio of the detector needs to be known to better than 10^{-4} not to be limited by this effect.

- A global analysis of Bhabha acolinearity for beamstrahlung and radiative return events for the beam energy is needed to understand effects from beam-beam correlations.