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Results of Guinea-Pig Simulation for Energy Loss due to Beamstrahlung for 1997-98 SLD Run

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Abstract. Beamstrahlung in the collision process causes the beams to lose as much as 50 MeV energy during the 1997-98 SLD run. This note uses the Guinea-Pig simulation program written by Daniel Schulte to estimate this beam loss and to characterize it. These results can be compared with direct measurements using the WISRD energy spectrometer or using the BPMs at high dispersion points. Beamstrahlung energy loss and the WISRD algorithm may partially explain the observed error in the WISRD's determination of the Z^0 mass and the observed acollinearity in muon pair events. Uncertainties in applying a correction for beamsstrahlung energy loss contribute a signficant systematic error to the center-of-mass energy determination.

1. Introduction

The colliding charged particle beams at the Interaction Point (IP) emit radiation (beamstrahlung) due to the strong electromagnetic fields of the opposing beam. [1,2] This causes significant energy loss which must be accounted for to determine the luminosity-weighted center-of-mass energy. The standard procedure by SLD has been to use the WISRD energy spectrometers [3,4] to measure the beam energies with and without collisions. The energy difference due to collisions is attributed to the beamstrahlung process. We assume for beam electrons that make luminosity, that the effective beamstrahlung energy loss is one-half of the energy loss measured by the WISRD, since on average one expects one-half of the beamstrahlung to be emitted before the hard collision.

As part of the design work for the next generation of linear colliders, simulation programs have been developed to study in detail the collision process and to examine the beamstrahlung, pairs and minijets that are created. One of these simulation programs is Guinea-Pig (Generator of Unwanted Interactions for Numerical Experiment Analysis-Program Interfaced to Geant) written by Daniel Schulte, and described in Appendix A of his Ph.D. thesis. [5] This note describes the simulation results from this program for beam collision parameters representative of the 1997-98 SLD Run.

I examine the average energy loss for a variety of beam parameter sets with luminosities in the range of 55-230 Zs per hour. I note that the energy loss distribution is not a gaussian peaked about the average energy loss, but is instead an exponential distribution with the most probable energy loss being 0. The average number of beamstrahlung photons emitted per electron is roughly one. This has implications for the WISRD algorithm used to measure the beam energy, since an energy cutoff of typically 300 MeV is used and there are beam particles that radiate more than this amount. I also compare the luminosity-weighted energy loss to the total energy loss seen by the WISRD.

2. Simulation parameters and results at high luminosity.

The parameters for the nominal simulation at high luminosity are given in Table 1. Parameters for the Guinea-Pig simulation are given in Table 2. Some results for the simulation with this parameter set are plotted in Figures 1, 2 and 4.

Figure 1 indicates the beam energy loss distribution that would be measured with the WISRD. Plotted is a histogram of the incident beam energy (45.6 GeV) minus the disrupted electron energy after the collision process. The disrupted electron energy distribution is from the output file beam1.dat generated by Guinea-Pig. It does not take into account the initial beam energy spread distribution, but that does not affect the determination of the energy loss. Note that the most probable energy loss is zero and that the distribution is very broad, with some particles losing 1 GeV or more. The average energy loss is 45 MeV per electron.

Table 1. Beam parameters for high luminosity running.

Parameter	Value
Energy	45.6 GeV
Intensity	$4.0 \cdot 10^{10}$
σ_x	1550nm
σ_y	710nm
σ_z	920μm
σ_E/E	0.002
x emittance	60 mm-mrad
y emittance	12 mm-mrad

Table 2. Guinea-Pig simulation parameters.

Parameter	Value
n_x	32
n_y	64
n_z	24
n_t	5
n_m	40,000
cut_x	$3.0 \cdot \sigma_x$
cut_y	$6.0 \cdot \sigma_y$
cut_z	$3.0 \cdot \sigma_z$
do eloss	1
do photons	1
do isr	0
do lumi	1
num lumi	10000
lumi p	0.1
store beam	1
store photons	1
force symmetric	0
electron ratio	1.0
photon ratio	1.0
trav focus	1
charge sign	-1

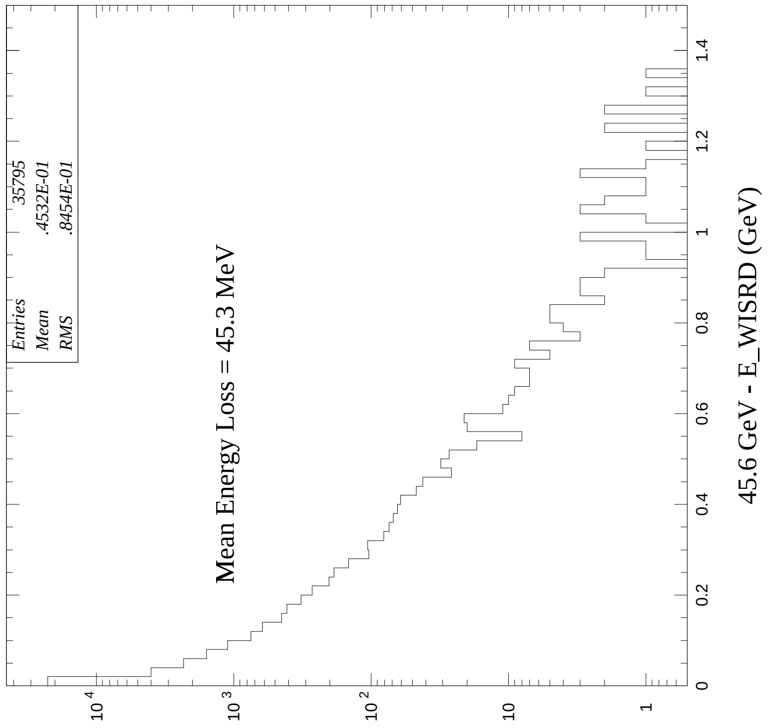

Figure 1: Beamstrahlung energy loss measured by WISRD.

Figure 2 is similar to Figure 1, except that the output file lumi.dat is used instead of beam1.dat. This file has the energies of the colliding particles that make luminosity. In this case the file does include the initial beam energy distribution that has an rms of 0.2%. Initial state radiation has been turned off for this simulation to simplify the analysis, but this has no effect on the determination of the luminosity-weighted energy loss due to beamstrahlung. We observe that the mean luminosity-weighted energy loss is 26 MeV. This is roughly one-half of the mean total beamstrahlung energy loss, which is the naive expectation.

The algorithm used by the WISRD effectively places a low energy cut on the detected electrons, which can introduce a bias in the energy measurement. The WISRD energy spectrometer detector observes synchrotron radiation on an array of 96 wires, with wire spacing of 100 microns (approximately 16.5 MeV spacing for the wire array at the dispersive location). The algorithm used is to locate the wire with the highest signal (peak wire) and then to place a low marker at the first wire below the peak with 0 or negative adc counts relative to pedestal. Similarly, a high marker is placed at the first wire above the peak with zero or negative adc counts relative to pedestal. A mean energy is then calculated using all channels between the markers. The typical noise on a wire corresponds to 2 adc counts, with some wires having as much as 10 adc counts noise. A peak wire will have typically 100 adc counts at the dispersive array. Thus the noise is an important effect setting where the markers are. A typical WISRD measurement online display is shown in Figure 3. For the

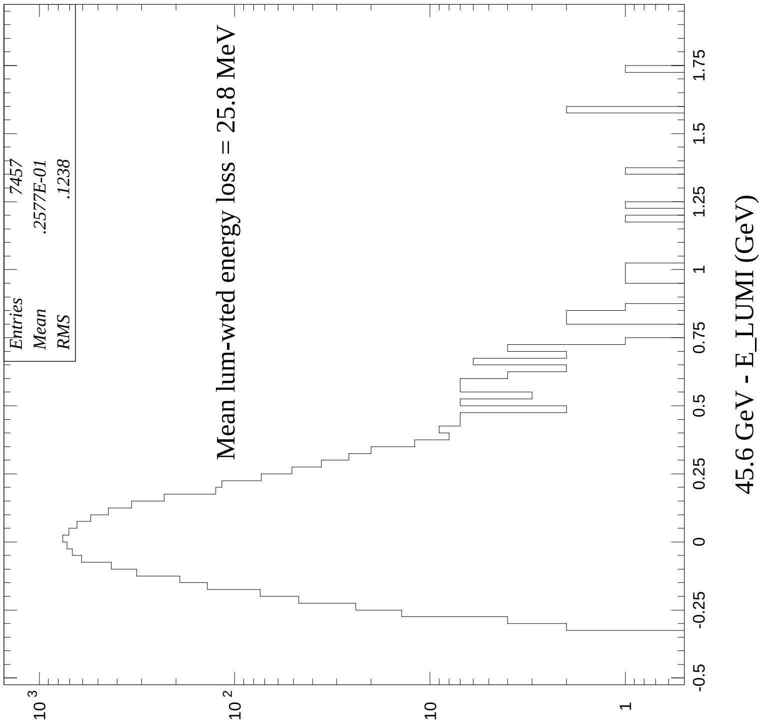

Figure 2: Beamstrahlung energy loss for luminosity.

wire array at the dispersive location (broader peak), the high and low markers are typically 15-20 wires from the peak (250-330 MeV). Real beam tails, especially low energy tails due to disruption, therefore get truncated.

To estimate the bias introduced by the WISRD algorithm that truncates the tails on the beam energy distribution, we plot in Figure 4 the energy loss that would be measured by the WISRD as a function of a low energy cut for the Guinea-Pig simulation that produced the energy distributions shown in Figures 1 and 2. With no low energy cut, the WISRD would measure a beam energy loss of 45 MeV as in the result from Figure 1. However, with a low energy cut 300 MeV below the peak an energy loss of 27 MeV would be measured. This would lead to a bias in the center-of-mass energy determination, such that the WISRD would report a center-of-mass energy approximately 18 MeV TOO HIGH. Note that there are 2 effects that enter here: i) the WISRD with an energy truncation cut measures a beam energy that is too high with respect to a perfect WISRD with no energy cut, and ii) the WISRD with an energy truncation cut measures a beamstrahlung energy loss that is too low with respect to a perfect WISRD with no energy cut. The net effect is that the real (imperfect) WISRD measures a center-of-mass energy that is too high. This effect can partially explain the observed error by the WISRD in the peak scan, where the WISRD measured the Z^0 mass to be TOO HIGH with respect to the precise measurement by LEP, by approximately 50 MeV.

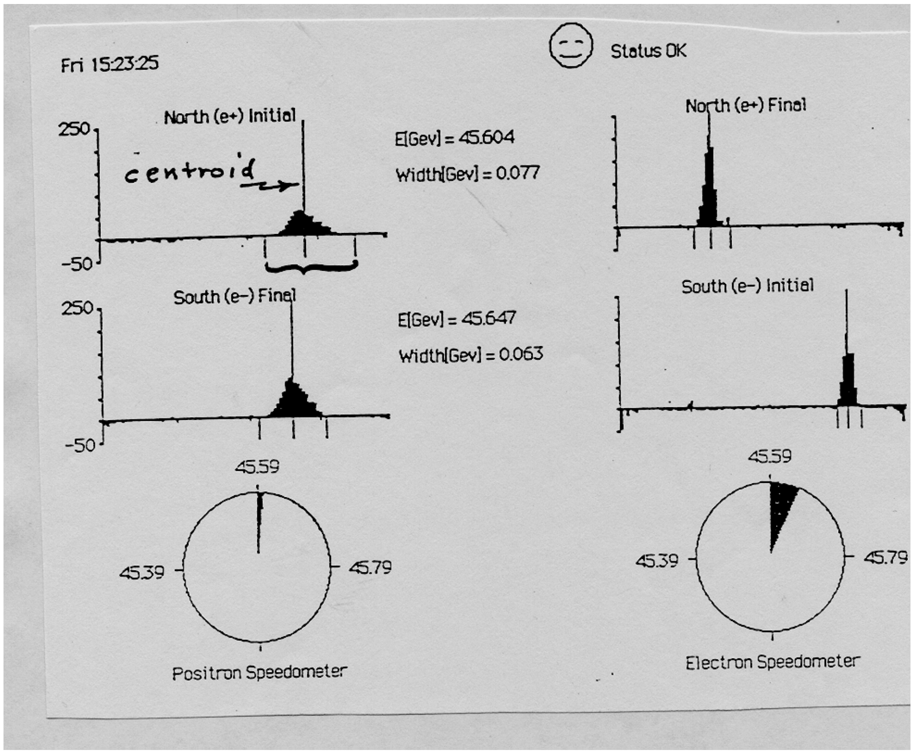

Figure 3: WISRD online display.

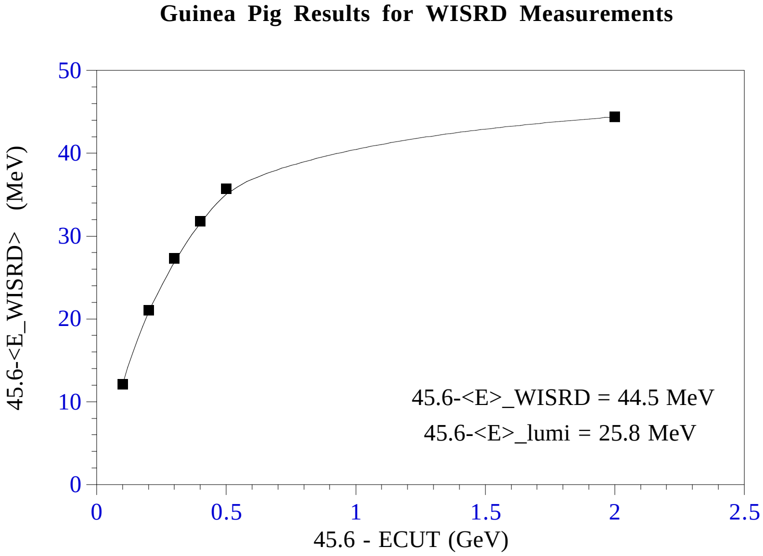

Figure 4: Beamstrahlung energy loss measured by WISRD as a function of a low energy cut on the measured energy distribution.

Table 3. Beamstrahlung energy losses at different luminosities.

I ($\cdot 10^{10}$)	σ_x (nm)	σ_y (nm)	Luminosity (Z/hr)	ΔE_{WISRD} (MeV)	$\Delta E_{lumi-wt}$ (MeV)
4.0	1550	710	230	44.5	25.8
3.5	1550	710	160	35.4	13.9
3.0	1550	710	105	25.6	8.9
4.0	1550	900	170	38.6	17.3
3.5	1550	900	120	28.6	12.3
3.0	1550	900	80	22.4	7.4
3.0	2000	900	55	14.2	4.4

3. Results as a function of luminosity.

To study some of the results for beamstrahlung energy loss as a function of luminosity, I varied the beam parameters as shown in Table 3 to obtain luminosities in the range 55-230 Z/hour. I also tabulate here the average beamstrahlung energy loss for one beam and the average luminosity-weighted beamstrahlung energy loss for one beam, assuming a perfect WISRD with no low energy cutoff. The beam emittance and bunch length parameters are not changed and are left at the values indicated in Table 1. While the beamstrahlung losses tabulated here are similar for different values of spotsizes and intensities that give the same luminosity, I note that the same is not true if I were to vary the bunch length. The beamstrahlung energy loss is roughly inversely proportional to the bunch length, while the luminosity is a weak function of the bunch length. For the simulations described here, I've chosen symmetric bunch lengths for the electron and positron beams that give the observed convoluted bunch length (about 650 μm) as measured by SLD's vertex detector. However, it is possible that the bunch lengths are rather asymmetric and this would have a significant effect. In fact, the WISRD measurements do tend to indicate asymmetric energy losses and hence asymmetric bunch lengths. [6]

Figure 5 plots the luminosity-dependence of the average beamstrahlung energy loss for one beam, as well as the average luminosity-weighted beamstrahlung energy loss.

4. Example Results.

Let me consider an example where the WISRD with its imperfect algorithm measures the electron beamstrahlung energy loss to be 30 MeV and the positron beamstrahlung energy loss to be 24 MeV. In this example, I consider that if the WISRD did not have a low energy truncation it would have measured 44 MeV electron beamstrahlung energy loss and 30 MeV positron beamstrahlung energy loss (ie. the TRUE losses). I tabulate in Table 4 some results for energy determinations by the WISRD with its imperfect algorithm and also what the TRUE energies are. I note that in this example the WISRD overestimates the luminosity-weighted center-of-mass

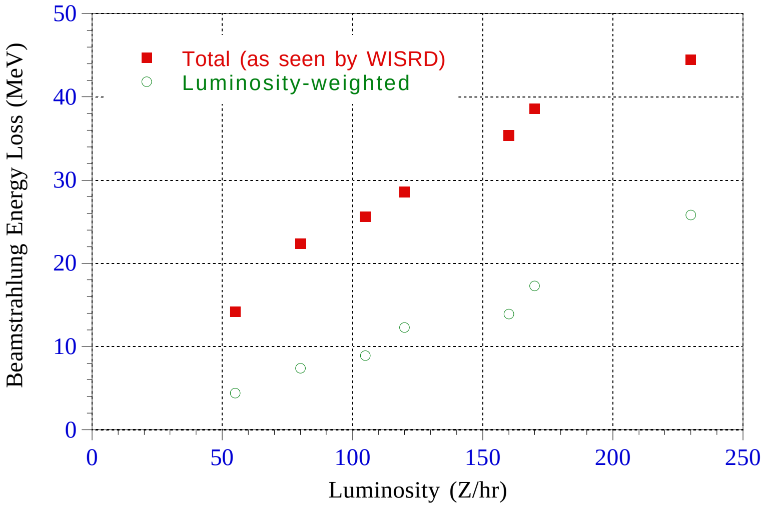

Figure 5: Luminosity dependence of the Beamstrahlung energy loss.

Table 4. Example Comparison of WISRD results vs true results

Algorithm	E_-^{WISRD} (GeV)	E_+^{WISRD} (GeV)	E_-^{lum-wt} (GeV)	E_+^{lum-wt} (GeV)	E_{CM}^{lum-wt} (GeV)	$E_-^{lum-wt} - E_+^{lum-wt}$ (GeV)
WISRD	45.590	45.590	45.605	45.602	91.207	0.003
True	45.576	45.584	45.598	45.599	91.197	-0.001

energy by 10 MeV, and overestimates the luminosity-weighted electron-positron energy difference by 4 MeV. While these are fairly small effects in this example, they should not be considered negligibly small. These effects can be appreciably larger in the case of even shorter bunch lengths (with perhaps more asymmetry between electrons and positrons) and for more severe low energy truncation problems in the WISRD algorithm. This example also illustrates a possible contribution to the observed acollinearity in the muon pair data that would result from an energy asymmetry between the electron and positron beams. [6] I note that the bunch lengths of the beams are not well measured near the SLD, and that the bunches can undergo significant longitudinal compression in the SLC Arcs. [7,8] This compression could be significantly different for the electron and positron beams.

5. Conclusions

We have presented simulation results for the energy loss due to beamstrahlung, using the Guinea-Pig program. We find that beamstrahlung produces an energy loss of 45 MeV to the outgoing beam, for a set of colliding beam parameters that give a luminosity of 230 Z/hr. The corresponding effect on the center-of-mass energy is to reduce it by 50 MeV, or roughly one-half of the sum of the beamstrahlung energy losses experienced by the two beams. We also find that the WISRD algorithm introduces a bias in the determination of the center-of-mass energy because it truncates the low energy disrupted tail. This causes the WISRD to overestimate the center-of-mass energy and may partly explain the discrepancy in the Z^0 mass determination from the peak scan performed in May 1998. For the parameter set giving a luminosity of 230 Z/hr studied here, the WISRD overestimates the center-of-mass energy by about 18 MeV. We also note that the energy loss determination is very dependent on the many beam parameters that influence the luminosity and is not a function of just the luminosity. In particular, the energy loss is inversely proportional to the bunch length. If there is an asymmetry in the bunch lengths between the electron and positron beams, this will lead to an asymmetry in the beamstrahlung energy losses of the two beams. Such an asymmetry, together with the WISRD algorithm bias, may partially account for the observed acollinearity in the muon pair data.

The results presented here can be used to estimate the bias in the WISRD energy determination as well as the systematic errors associated with applying a beamsstrahlung energy loss correction. The bias and the uncertainty vary with the luminosity and the bunch length, with the bias being approximately 5 MeV/beam and the uncertainty approximately 10 MeV/beam averaged over the 1997/98 run. This correction gets calibrated out at some level by using the peak scan calibration, but the cancellation is not perfect due to the variable luminosity running conditions.

6. References

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