Questions about the Measurement of the e^+e^- Luminosity Spectrum.[a]

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Important analyses at a future linear collider, including top-quark and W-boson mass measurements will depend upon the precise determination of the luminosity spectrum. This can be done, in principle, in the planned detectors. We review the problems to be solved, both beam-related and detector-related.

1 First Order Optimism

Since the technique was suggested [1] at the first LCWS, a number of authors have confirmed [2,3,4] that the measurement of the acollinearity of the final state electron and positron in Bhabha scattering, in conjunction with suitable beam-line spectrometry, should enable the luminosity spectrum to be extracted with sufficient precision to allow the top quark mass to be determined with a precision of a few tens of MeV [5]. It may even allow the W boson mass to be measured to around 6 MeV [6]. Other analyses will require similar precision. But none of these studies has incorporated realistic modelling of the fluctuations which may occur in the collisions of the beam bunches, nor have they simulated the measurement of the outgoing particles in an actual detector design. In preparing to do a more detailed study we present here some of the issues and effects which may threaten the optimism of the previous studies, with the expectation that colleagues will persuade us that some of our doubts are ill-founded, or will draw attention to other potential difficulties that we have overlooked. (Inputs after the talks at LCWS are included.)

2 Sources of Energy Spread

Figure 1 shows an example of the three effects which cause the collision energy at a linear collider to be shifted from its nominal value. Initial State Radiation (ISR) is inescapable, and calculable to high precision. If it were the only effect present there would be no need to measure it. Beamstrahlung is essentially synchrotron radiation by individual particles in one bunch due to the high electromagnetic fields generated by the charge of the opposing bunch.

[a] Combined contribution to the Machine Detector Interface and Calorimeter sessions at LCWS2002.

In the planned colliders [6,7], between 30% and 50% of collisions have no beamstrahlung, even though the mean beamstrahlung loss is 1% to 3%, with a long tail of large losses. This lossless spike is what allows us to contemplate precise mass measurements from threshold scans. The linac itself will introduce a beam energy spread of between ~ 0.05 percent (TESLA [6]) and ~ 0.3 percent (X-band [7]). This is unlikely to be Gaussian and may vary from bunch to bunch. In TESLA at high energy the e^- beamspread is increased to $\sim 0.15\%$ in the helical undulator used to generate polarised positrons (the case shown in Fig. 1), though when running at the WW threshold this can be avoided.

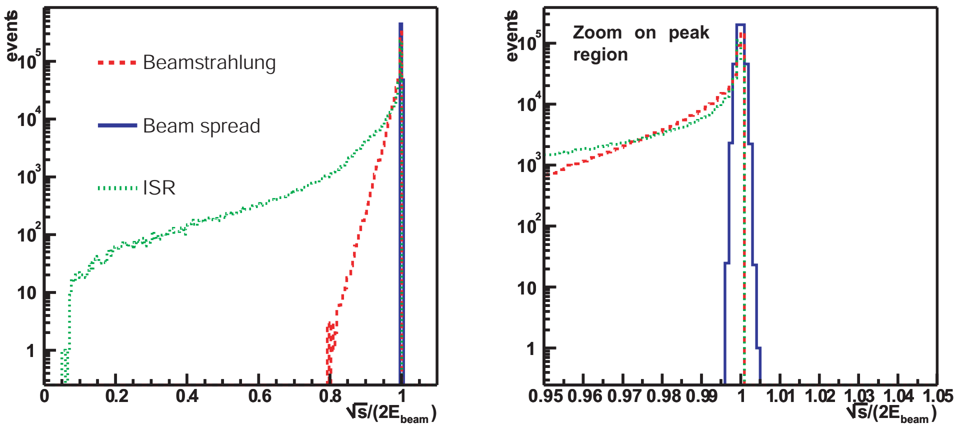

Figure 1: Sources of beam energy loss, for the TESLA design running at 350 GeV.

3 Measurement of the Absolute Beam Energy

The absolute incoming beam momenta can be measured in upstream spectrometers before the collision point, in a similar way to what has been done at LEP [9], or in downstream spectrometers like that used at Mark II [8]. To use a downstream spectrometer for precise measurements it would be necessary to include single electron and positron bunches in the trains without their opposing positron and electron bunches, to avoid the disruption, ISR and beamstrahlung from collisions. Such precise spectrometers (200 ppm is the goal, which should be enough to get M_W to 6 MeV) are essential to measure the absolute incoming energy and its spread. But there is no physics process which has good enough energy resolution and sufficiently high statistics to make direct event-based measurements of the luminosity spectrum $\partial L/\partial\sqrt{s}$ for individual data-taking runs.

A downstream spectrometer in the spent beam after collision may also be able to monitor the effects of beamstrahlung and ISR but it is not clear how this can be done precisely enough for physics analysis. Fortunately, as explained below, the acollinearity of Bhabha scattering in the endcap region of the detector gives a high statistics event-based technique which is sensitive to the relative beamspread from all three sources. This note is not primarily concerned with the spectrometer measurements of absolute energy and spread, but we here list a number of crucial questions about them which are being addressed elsewhere [10]:

- Can we get both mean energy and beamspread shape on a bunch-by-bunch basis or just train-by-train?
- Since all the bunches in a train do not collide optimally, how do we calculate luminosity-weighted energies and spreads for each physics run? This may be posible with input from a high-rate small angle Bhabha detector like the TESLA LCAL [6].
- How is TESLA different from X-band? The zero crossing angle, followed by an extraction kicker, makes a downstream spectrometer much less effective, but the hundreds of nanoseconds between separate bunches may allow an upstream spectrometer to resolve them in a way which cannot be done for X-band, and allow the LCAL to luminosity-weight each bunch.
- How much will the incoming energy wander from train to train or from bunch to bunch?
- How much will the nongaussian beamspread shape vary between bunches and between trains?

4 Basic Principles of the Acollinearity Method

The acollinearity angle θ_A is defined in Figure 2. For $\theta_A << \theta$ we have $\theta_A = (\Delta p/p_b)\sin\theta$, where $\Delta p = p_+ - p_-$, i.e. the missmatch between the two beam momenta at collision. The quantity needed for physics is $\sqrt{s} \simeq p_+ + p_-$. For small θ_A and Gaussian errors, $\sigma_{\sqrt{s}} \simeq \sigma_{\Delta p} \simeq \sigma_{\theta_A} p_b/\sin\theta \simeq \sqrt{2}\sigma_{p_b}$. So with a given angular resolution σ_{θ_A} the error on $\sqrt{s}$ blows up at small values of the scattering angle θ. This means that the best sensitivity to $\sqrt{s}$ will be in the endcap region ($100 \le \theta \le 450$ milliradians) of the detector. In this region there is a large t-channel contribution to Bhabha scattering, giving a rate about 400 times the pointlike s-channel rate which governs $\mu^+\mu^-$, $t\bar{t}$ and many of the other interesting SM or SUSY processes. As discussed in 6 below, the detector angular resolutions in this region are expected to be as good as is needed not only for the top mass measurement but also for M_W.

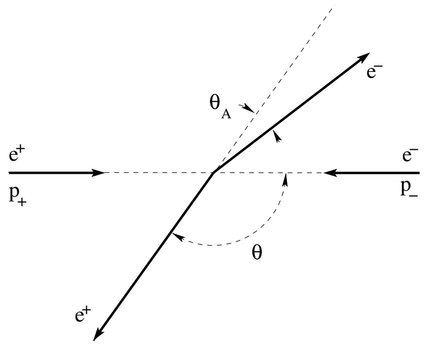

Figure 2: Definition of acolinearity angle θ_A

5 Beam-related Questions about the Acollinearity Method

Positive correlations between the event-to-event shifts in the momenta p_+ and p_- can give rise to reduced values of Δp and of the acollinearity, even when the shifts in $\sqrt{s}$ are large. At least three sources of such correlations have been suggested.

- Dispersion effects. If there were dispersion at the final focus then each beam might (see Fig. 4a) have slightly higher momenta on one edge of the bunch and slightly lower momenta on the other edge [11]. But disruption, as sketched (see Fig. 4b), actually causes particles from one beam to oscillate violently as they pass through the opposing bunch, and this may obliterate the effect of dispersion.

- Early-late Correlation. Evidence has already been reported [4] for a correlation in simulated events between the collision energies of e^+ and e^- which meet early in the crossing of two bunches and those which meet late in the crossing, when particles in both bunches are more likely to

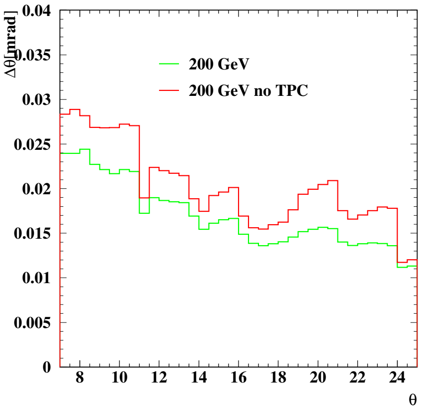

Figure 3: Angular resolution of the forward tracking detectors at TESLA

have had beamstrahlung losses. Coarse information from small angle detectors on the bunch-by-bunch luminosity may be useful in correcting for this effect.

- Bananas. If beams become misaligned in the LINAC then the bunches may develop 'banana-shaped' tails which are expected to have slightly different energy from the main part of the bunch.

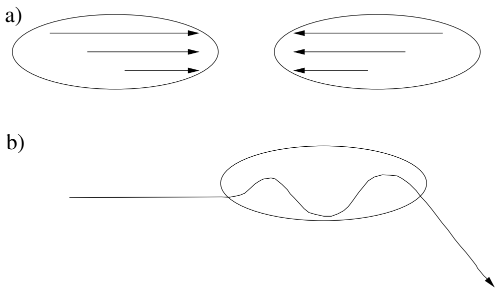

Figure 4: How the effects of dispersion could be removed by disruption

It may also be possible (see discussion of angular precision below) to observe an azimuthal variation in the spread of acollinearity due to the much greater disruption in the horizontal plane compared with the vertical [13]. All of these effects will be studied with the full Guinea Pig [13] beam-beam interaction simulation program.

6 Calorimeter-related Questions about the Acollinearity Method

The first question is; which detectors to use to measure the luminosity spectrum? As mentioned in 4 above, the error on $\sqrt{s}$ for a given angular error on the outgoing tracks is proportional to $1/\sin\theta$. In the TESLA detector (Fig. 5), the best available angular resolution ($\sim 20-30\,\mu$radian) will come from the Forward Tracking discs and the TPC central tracker, so the acollinearity method will give the best results in this angular region. If this precision can be exploited [4] there would be no trouble in measuring the top quark mass to the desired precision, and the W mass should not be too difficult. But a luminosity measurement requires high efficiency, and the track finding efficiency is unlikely to be much above 90%, especially in the forward region where background tracks spiral around field lines and give extra hits. Fortunately the whole of the region is backed by the CALICE electromagnetic calorimeter [15] with fine granularity, both laterally and longitudinally. This should have 100% efficiency for high energy electrons, so it can be used to map the efficiency of the tracker.

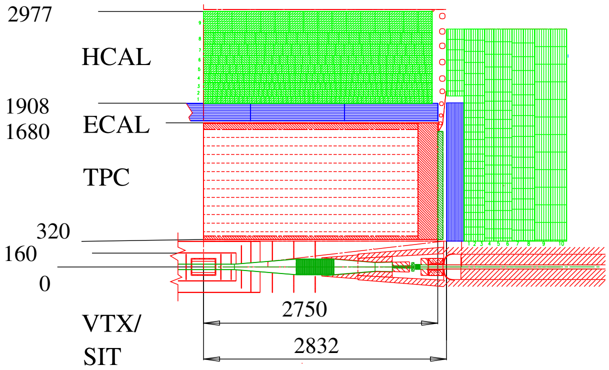

Figure 5: A Quadrant of the TESLA detector

In addition, CALICE will have an angular resolution for high energy electrons of about 0.5 milliradians, so it might by itself provide an adequate acollinearity measurement for the top quark mass measurement, if it can be surveyed to sufficient precision. Experience from OPAL [14] shows that a precision tracker in front of a calorimeter can provide such a survey. We are beginning a study of the performance of CALICE in this region, with special attention to the degradation of the angle measurement in CALICE which will come from scattering and delta-ray production in the field cage and end plates of the TPC. This produces soft electrons which run along magnetic field lines to hit the calorimeter at lower radius than the main shower.

The LAT calorimeter at TESLA covers the range $30 < \theta < 87$ milliradians, similar to the coverage of the LEP and SLC luminosity monitors. Like them it will have a high enough Bhabha scattering rate to exceed interesting physics channels even at the peak of the Z^0 resonance. It is therefore an important absolute luminosity monitor. Its angular resolution will be similar to CALICE and it will have less dead material in front of it. But this angular region is not so good for measuring the luminosity spectrum by the acollinearity method because of the $1/\sin\theta$ factor mentioned above. It has pointed out [12] that the summed energies of the two showers in LCAL Bhabha events will give a measure of $\sqrt{s}$ with a precision of 1-2%. Although this is not precise enough to resolve the spike in the luminosity spectrum (Fig 1) which is needed for measurements of the top mass or the W mass, it is sufficient to constrain a large part of the ISR and beamstrahlung tail.

The TESLA design also includes a very small angle calorimeter, the LCAL, spanning 5 to 27 milliradians. Even with a 4T magnetic field this detector will be hit on every beam crossing by an intense background flux of soft photons and electrons from the beamstrahlung and pair production processes. This will make it a poor device for absolute luminosity measurement because the efficiency for the Bhabha signal will be badly measured, especially close to the lower angle cutoff. But its background rate may be high enough to give a rough bunch-by-bunch measure of the luminosity which can be used to weight the spectrometer output (see 3 above). It may also be useful in correcting for the early-late correlation (see 5 above).

7 Unfolding Variables

It has been suggested [12], that the best approach to the determination of $\partial L/\partial\sqrt{s}$ for any event sample will be to unfold the spectrum from measurements of the distributions of all available sensitive variables. These would include: a) the sums of Bhabha shower energies from LAT, LCAL and CALICE (to constrain the ISR + beamstrahlung tail); b) results from the beam spectrometers on both absolute energy and spread, with luminosity weighting; c) an appropriate variable derived from the acollinearity of Bhabha scatters in the endcap region. Two such variables have been discussed: Δp, as defined in

4 above[1], or s', the invariant mass of the final e^+e^- on the assumption that a single radiated gamma has been lost along the beam direction[4].

8 Plans

Guinea Pig[13] and other simulations of the collision process are being set up to produce samples which contain all of the possible beam-based effects that could bias measurements of the luminosity spectrum. These events will be passed through a realistic model of the forward regions of TESLA detector, including CALICE, and reconstructed to extract the relevant variables. The reconstructed or unfolded luminosity spectrum will be compared with the Monte Carlo truth. The consequences for physics of any disagreement between truth and measurement will be investigated, especially for the top and W mass measurements.

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