Z Running for Calibration (Draft 1.0)

ILD Detector Concept

Abstract

Extracting the most science from the high energy running of the ILC relies on proper calibration and alignment of the detector. A key tool for achieving satisfactory calibration is high statistics of particles from collision events. The capability to operate the ILC with high luminosity at the Z pole is the most statistically effective way to calibrate the detector and can be essential to fully exploiting the ILC. Such a capability would ideally be an integral part of the design of the initial accelerator facility.

Introduction

The request document [1] dated March 2^{nd}, 2016 from the ILC Parameters Joint Working Group asked ILD to clarify its needs in terms of Z pole running for "calibration". As outlined in that document the request was mostly focused on "detector calibration" involving issues such as tracker alignment, calorimeter calibration and jet energy scale. Recent overviews of some of the issues for ILD are given in [2, 3].

Extracting the most science from the high energy running of the ILC relies on proper calibration and alignment of the detector. It is known that running at the Z pole with high luminosity is the most effective way of producing particles from collision events for calibration and alignment. With relatively low cross-sections in collisions at high energy at ILC, it is important that the detector be commissioned quickly to achieve its ultimate performance. The Z also provides high statistics that can be used to reduce systematic effects.

More detailed studies to evaluate and assess the needs in terms of calibration and alignment are an on-going component of designing ILD, and we plan to address the request in detail as resources permit in the near future.

Here we make some general remarks relevant to the discussion, and convey our overall assessment that the detectors will be able to benefit greatly from the availability of reasonably high luminosity running at the Z ($L > 3 \times 10^{32}$ cm^{-2}s^{-1}) for calibration from the very beginning of the program. It is of course not our wish to spend more time than absolutely necessary doing such calibration runs. For it to make sense the accelerator design needs to build in capability for a high instantaneous luminosity at the Z. In order for the benefits to impact the whole ILC program, it would be important that such capability is available from the start.

The ILC experiments are in many aspects an order of magnitude more demanding in precision than the LHC experiments, but they will operate in an environment where the rate of potentially useful calibration events is much, much lower. There are also six likely aspects of ILC running and the ILC detectors that make calibration and alignment much more challenging than would be imagined from straightforward extrapolations of prior experience:

1. the alignment of the detector needs to be carried out relatively frequently given the current push-pull scenario, where the detectors are mounted on platforms that move back and forth onto the beam line.

2. expected seismic activity.

3. the power pulsing used in the electronics is expected to limit the live-time available for cosmic-ray based calibration and alignment.

4. in addition to duty cycle issues, the ILC detectors (for good reasons) are currently envisaged with no hardware triggers - making substantial cosmic data-taking even less pragmatic. An over-burden of around 100 m is envisaged.

5. in contrast to lower energy circular e^+e^- machines, it is of course not feasible at ILC to use resonant depolarization for a precision measurement of the absolute beam energy.

6. it is expected that we aim to avoid relying on radionuclide based calibration strategies.

Finally, there is precedent. When the LEP experiments operated at centre-of-mass energies well above the Z, it was found by consensus by the four experiments to be reasonable to devote a couple of days per year for calibration at the Z. Those data-sets were collected at the start of annual data-taking and represented about 1% of the annual integrated luminosity. Z running was also undertaken after particular incidents to recover the calibration.

Rate Considerations

The usefulness of Z running compared with high energy running for calibration depends on a number of factors.

There is a likely unavoidable reduction in instantaneous luminosity that scales with $\gamma = \sqrt{s}/m_Z$. Compared with $\sqrt{s} = 500$ GeV, this gives a factor of 0.182. There can also be further modification of the luminosity that we define using a multiplicative factor, λ.

Therefore the instantaneous luminosity at the Z, L_Z, will be related to the instantaneous luminosity at high energy, $L_{\sqrt{s}}$, by

$$L_Z = \lambda(L_{\sqrt{s}}/\gamma)$$

The cross-sections at the various centre-of-mass energies differ by up to a factor of almost 10,000. Table 1 shows the cross-sections vs centre-of-mass energy and the ratios with respect to Z running for three processes, $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-$, $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q\bar{q}}$, $\mathrm{e}^+\mathrm{e}^- \to \mathrm{b\bar{b}}$. We define

$$\rho_Z(\sqrt{s}) = \sigma(m_Z)/\sigma(\sqrt{s})$$

as the enhancement factor for Z running compared to high energy running.

The total number of events collected that are useful for calibration (at 91 GeV and high energy), N, given running time T, and time-fraction f, devoted to Z running is:

$$N(\sqrt{s}; f) = \sigma_{\sqrt{s}} L_{\sqrt{s}} T \left[(1-f) + \rho_Z(\sqrt{s})(\lambda/\gamma)f\right] \quad (1)$$

Given that the angular distribution of calibratable particles is more forward-peaked at high energy compared to the $1 + \cos^2\theta$ distribution at the Z, we have included an additional factor, ε. This is estimated from the relative number of particles expected with $|\cos\theta| < 0.1$ that takes into account the effective calibratable particle rate at the most central polar angles. This amounts to a factor of about 0.49 at $\sqrt{s} = 500$ GeV.

$$N'(\sqrt{s}; f) \sim \sigma_{\sqrt{s}} L_{\sqrt{s}} T \left[\varepsilon(1-f) + \rho_Z(\sqrt{s})(\lambda/\gamma)f\right] \quad (2)$$

Graphs using equation (2) are presented in Figures 1-3 for $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-$, $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q\bar{q}}$, and $\mathrm{e}^+\mathrm{e}^- \to \mathrm{b\bar{b}}$. These illustrate the integrated statistical enhancement factor for Z running for various assumptions on λ and f. The ε factors are given in Table 2 and are based on the angular distributions in di-muon events which are seen in Figures 4 and 5 to have a substantial component from radiative-return to the Z events, and a correspondingly more forward angular distribution at high energy.

Z calibration is most useful when the second term in equation (2) dominates. However f can not be allowed to be much greater than several %. The baseline $L(500)$ is 1.8×10^{34} cm^{-2}s^{-1}. For $\lambda = 1$, corresponding to L(Z) of 3.3×10^{33} cm^{-2}s^{-1}, $f = 0.05$, and $\varepsilon = 0.49$, one obtains integrated statistical enhancement factors of 24, 46, and 51 for the three channels ($\mu\mu$, qq, bb). In some cases, it may be important to establish or recover the calibration as quickly as possible. For the same amount of elapsed time, Z running can give instantaneous statistical enhancement factors of 453, 906 and 1000 for the three channels (assuming the same value of L(Z)). The relative statistical advantage of Z running is even greater when compared with running at $\sqrt{s} = 1000$ GeV instead of $\sqrt{s} = 500$ GeV. Correspondingly it is less at $\sqrt{s} = 250$ GeV and $\sqrt{s} = 350$ GeV.

$\sqrt{s}$ (GeV)	$\sigma(\mu\mu)$ (pb)	$\sigma(q\bar{q})$ (pb)	$\rho_Z(\mu\mu)$	$\rho_Z(q\bar{q})$	$\rho_Z(b\bar{b})$
91.2	1580	30500	1.0	1.0	1.0
250	4.99	50.1	316	609	662
350	2.57	24.8	614	1230	1350
500	1.30	12.6	1210	2420	2670
1000	0.386	3.64	4080	8370	9250

Table 1: Unpolarized cross-sections and the cross-section enhancement factor for Z running, $\rho_Z(\sqrt{s}) = \sigma(m_Z)/\sigma(\sqrt{s})$, compared with high energy running

$\sqrt{s}$	Central muons per event	ε
91.2	0.150	1.00
250	0.104	0.69
350	0.092	0.61
500	0.073	0.49
1000	0.067	0.45

Table 2: Muon event numbers in $e^+e^- \to \mu^+\mu^-$ events in the very central region, $|\cos\theta| < 0.1$, and the fraction of very central muons, ε, normalized to those expected in events collected at the Z.

Calibration Types

There are a number of issues that belong under "calibration".

- Inter-calibration. Channel-to-channel relative calibration. Example scintillator cells in the AHCAL. Primarily a statistical issue.
- Alignment
- Absolute energy and momentum scales
- B-field measurements
- E, B-field effects / distortions
- Gas parameters (mixture, T, P, dE/dx, drift velocity, t_0)
- Monitoring of long-term calibration/alignment
- Fragmentation tuning

General Considerations

- We are trying to design the detector in such a way that it is as far as possible already very well calibrated - but it will be necessary to improve the calibration further with a variety of in situ data including collisions, cosmics, and zero-field data. The sooner this can be done, the sooner the experiments will be able to reach their ultimate performance. In this sense, there is a premium on accumulating significant statistics for calibration as soon as possible. Z running can confer significant statistical advantages in this respect. CMS [1] did its tracker alignment (more than 200,000 alignment parameters) based on 3.6 M high quality cosmics, 16 M high pT muons and 3 M $p > 8$ GeV tracks. Such a sample is likely out of reach of ILC. Yet the ILC requirements entail a factor of 10 more precision in the momentum measurement.
- As a specific example, a data sample of 1000 pb^{-1} at the Z would provide a total of 3 M muons (from $e^+e^- \rightarrow \mu^+\mu^-$) with a close to isotropic angular distribution ($1 + \cos^2\theta$). However, a similar sample of 1000 pb^{-1} at $\sqrt{s} = 500$ GeV, would provide a total of just 6000 muons - many of these would be highly boosted (Zγ events) - and not so useful.

- We certainly would like to be able to calibrate the detector with sufficient precision using physics events collected at simply the physics production collision energy. This has the dual advantages of tracking in real-time any variations of the calibration and avoids the allocation of dedicated accelerator time to calibration. But the rate of useful calibration events during high energy running is limited. There are possibilities of exploiting other types of events such as gamma-gamma collisions and Bhabhas, but the corresponding angular distributions are not very favourable. One advantage is access to higher momentum particles.

- The hadronic cross-section at the Z (91 GeV) is about 2500 times higher than the comparable cross-section at $\sqrt{s} = 500$ GeV. So **IF** it is feasible to collect significant integrated luminosity at the Z this can be very attractive. As discussed earlier one can envisage collecting a total data-set with up to 50 times the statistics for calibration by dedicating some running time to the Z. Furthermore, with up to a factor of 1000 in instantaneous calibratable particle rate, Z running can be extremely effective in quickly establishing/recovering the calibration and in checking its validity.

- Frequency of Z running for detector calibration. Given that we would expect to be able to check to a reasonable extent the quality of the established calibration with detector running at high energy, it would only normally be necessary to redo Z running if there was some major change.

- There are some unique things where the Z is something that gives more than just more statistics. The Z is effectively the well known mass scale (known to 23 ppm from LEP) in the ILC energy range. A mini-scan of the hadronic lineshape with the same statistics as LEP would yield an absolute calibration of the centre-of-mass energy of the machine that can then be leveraged in measurements of absolute energy and momentum scales.

- In the current push-pull scheme, it is expected that we need to be able to re-align the detector especially the tracking detectors after each push-pull cycle. It would be important that this can be done fast. Preferably this could be done without needing to rely on Z running - but it is an open question.

- From the calibration point of view polarized beams are not necessary for Z running for calibration. The main figure-of-merit is the event rate.

- In [2], it is stated that the track based alignment precision needed to degrade the momentum resolution by less than 5% is 2μm (VTX), 4–6 μm (Si), 20 μm (TPC). This (if the alignment errors are random) primarily affects the resolution. Ultimately the needed precisions are even more stringent for control of systematics.

- Systematics. For example, fragmentation systematics. Best done with highest statistics. Data primarily from LEP at $\sqrt{s} = m_Z$ is the current benchmark, and would almost certainly need to be revisited with better detectors and higher statistics.

- The Z likely provides the most abundant source of known mass particles such as J/ψ, Λ, K^0_S etc for absolute calibration of the momentum/mass scales and the refinement of the material model.

- The absolute centre-of-mass energy in ILC high energy running can be best determined using the "$\sqrt{s}_P$" method with $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ events, where the momenta of the muons are used to reconstruct with high precision an estimator of the center-of-mass energy. This method relies on a calibrated muon momentum scale. The momentum scale can be tied down with the best systematic precision using J/$\psi \rightarrow \mu^+\mu^-$ events where the mass is known to 3.6 ppm. Achieving sufficient statistical samples of high momentum J/$\psi \rightarrow \mu^+\mu^-$ likely necessitates running at the Z as the main production mechanism is through B meson decay.

Subdetector Considerations

We are in the process of surveying the needs of each individual subdetector in terms of overall minimal calibration and alignment requirements. From discussions it appears that the most critical element in terms of statistics is likely to be the alignment of the outermost part of the tracker especially the silicon envelope tracker (SET) which underpins the momentum resolution. In this region[1], it would take 8 years to collect 1000 high momentum muons

[1] R=1.84 m, $\theta = 90^\circ$

incident on a 100 cm^2 detector element at nominal $\sqrt{s} = 500$ GeV instantaneous luminosity. We would like the time-scale for establishing calibrations to be measured in weeks not years.

Physics Considerations

There is considerable interest in precision measurements of the Higgs mass, top mass and W mass. Key elements in such absolute measurements are the systematic uncertainties on the absolute centre-of-mass energy, the absolute momentum scale and the absolute jet energy scale.

In order to target a precision on the W mass of a few MeV comparable to our current knowledge of the Z mass, it is envisaged that the absolute momentum scale and the corresponding measurement of the absolute center-of-mass energy target precisions at the 10 ppm level. Such precision requires high statistics from Z events (40M hadronic Z's or 1.3 fb^{-1} of Z running) for calibrating the momentum scale.

One method for measuring the Higgs mass and the W mass is by direct reconstruction of the hadronic mass. This method is directly exposed to uncertainties on the jet energy scale which would have to be measured/calibrated to unprecedented precision (in the 10 - 100 ppm) range. In this high precision regime, it is hard to see how such demands can be met without considerable assistance from high statistics Z running for jet energy scale calibration.

Summary

We are revisiting the issue of Z running for calibration and will provide updated quantitative numbers in due course. At this point we would like to make it clear that Z running for calibration makes the most sense if there is a plan for reasonable luminosity at the Z that provides a much larger statistical sample per unit time than is accumulated in nominal physics running conditions. We therefore recommend that Z running for calibration should be aiming at $L > 3 \times 10^{32}$ $cm^{-2}s^{-1}$ and should be available from day one.

We primarily consider Z running as an efficient method to establish calibrations and would hopefully not need it to be done repetitively. If the detectors were stable, it would likely make sense to envisage doing this once a year.

We reserve the right to revisit these statements as informed by ongoing studies.

In summary, precision alignment of the ILD detector is challenging given the relatively low event rate and the low cosmic-ray live-time associated with power-pulsing. Running at the Z for high statistics calibration data can be essential to fully exploiting the ILC and should be planned for appropriately.

References

[1] ILC Parameters Joint Working Group (T. Barklow, J. Brau, K. Fujii, J.List, N.Walker, K. Yokoya), "Request to ILD and SiD to specify their need for Z pole calibration", March 2, 2016.

[2] J. Timmermans, Talk at ILD meeting in Oshu, 2014. https://agenda.linearcollider.org/event/6360/contributions/30251/attachments/25016/38564/JanT-calibration_v3.pdf

[3] G.W. Wilson, Talk at ILD meeting in Santander, 2016. https://agenda.linearcollider.org/event/7014/contributions/34676/attachments/30220/45166/ZPole_ForCalibration.pdf

[4] CMS Collab., "Alignment of the CMS tracker with LHC and cosmic ray data", JINST 9 (2014) P06009

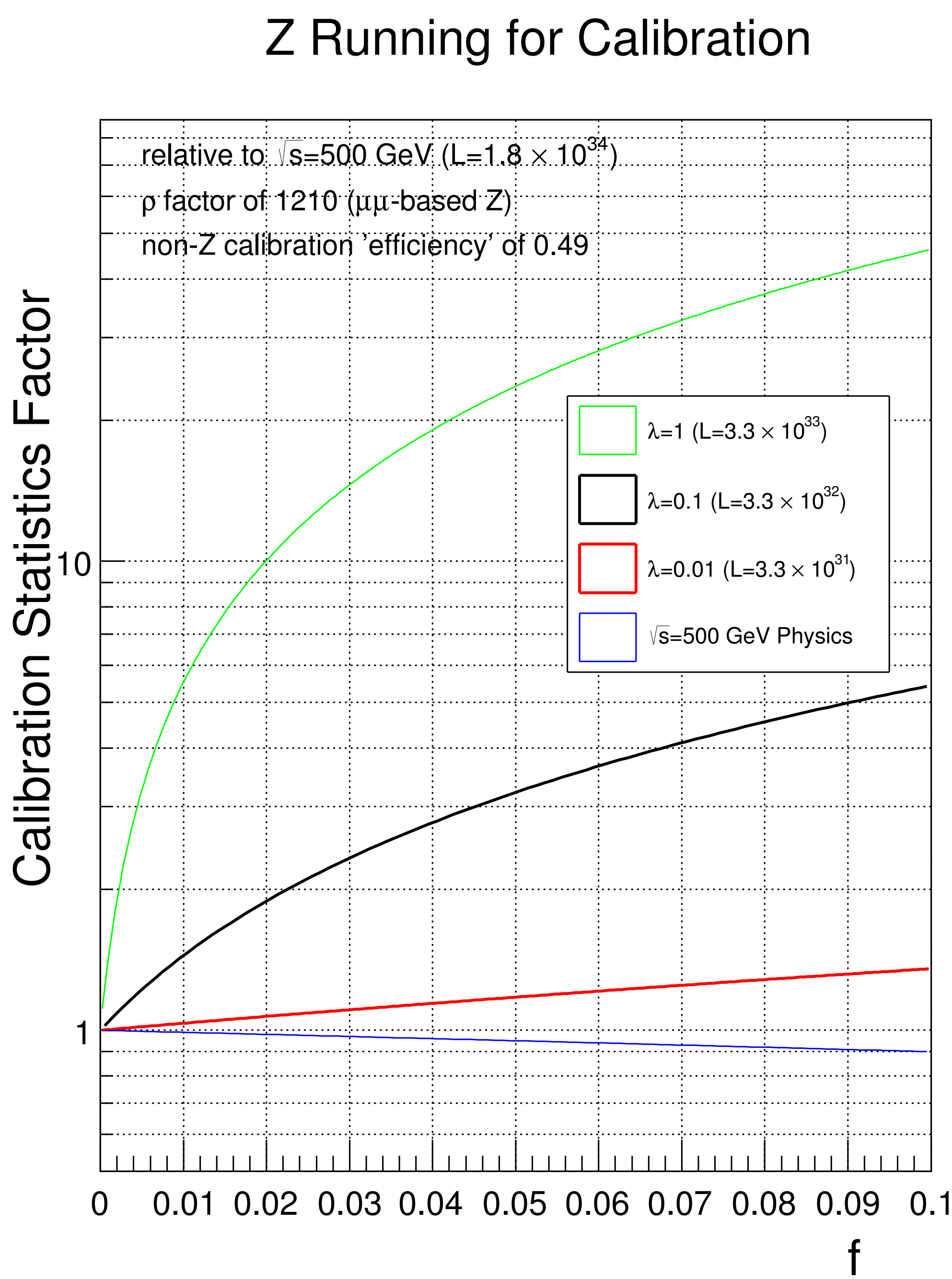

Figure 1: Integrated statistical enhancement factor of Z-Running for calibration and alignment with di-muon events ($e^+e^- \rightarrow \mu^+\mu^-$) versus fraction of running time devoted to Z running (f). Comparison is made with running at $\sqrt{s} = 500$ GeV at baseline ILC luminosity. Z-Running scenarios are shown for three assumptions on the achievable instantaneous luminosity. Also shown in blue is the corresponding linear reduction in $\sqrt{s} = 500$ GeV physics statistics. Graph includes ε factor of 0.49.

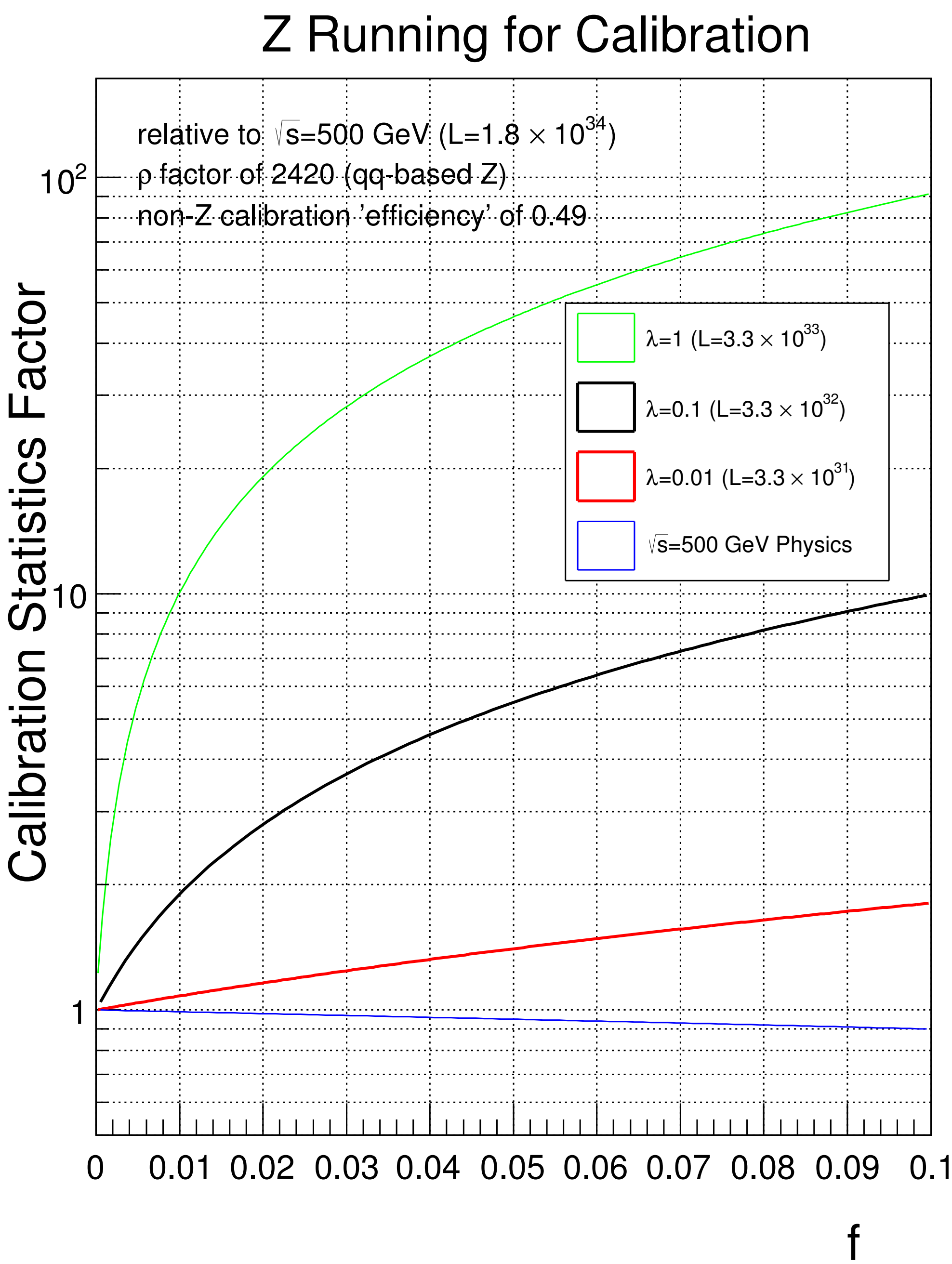

Figure 2: Integrated statistical enhancement factor of Z-Running for calibration and alignment with multi-hadronic events ($e^+e^- \to q\overline{q}$) versus fraction of running time devoted to Z running (f). Comparison is made with running at $\sqrt{s} = 500$ GeV at baseline ILC luminosity. Z-Running scenarios are shown for three assumptions on the achievable instantaneous luminosity. Also shown in blue is the corresponding linear reduction in $\sqrt{s} = 500$ GeV physics statistics. Graph includes ε factor of 0.49.

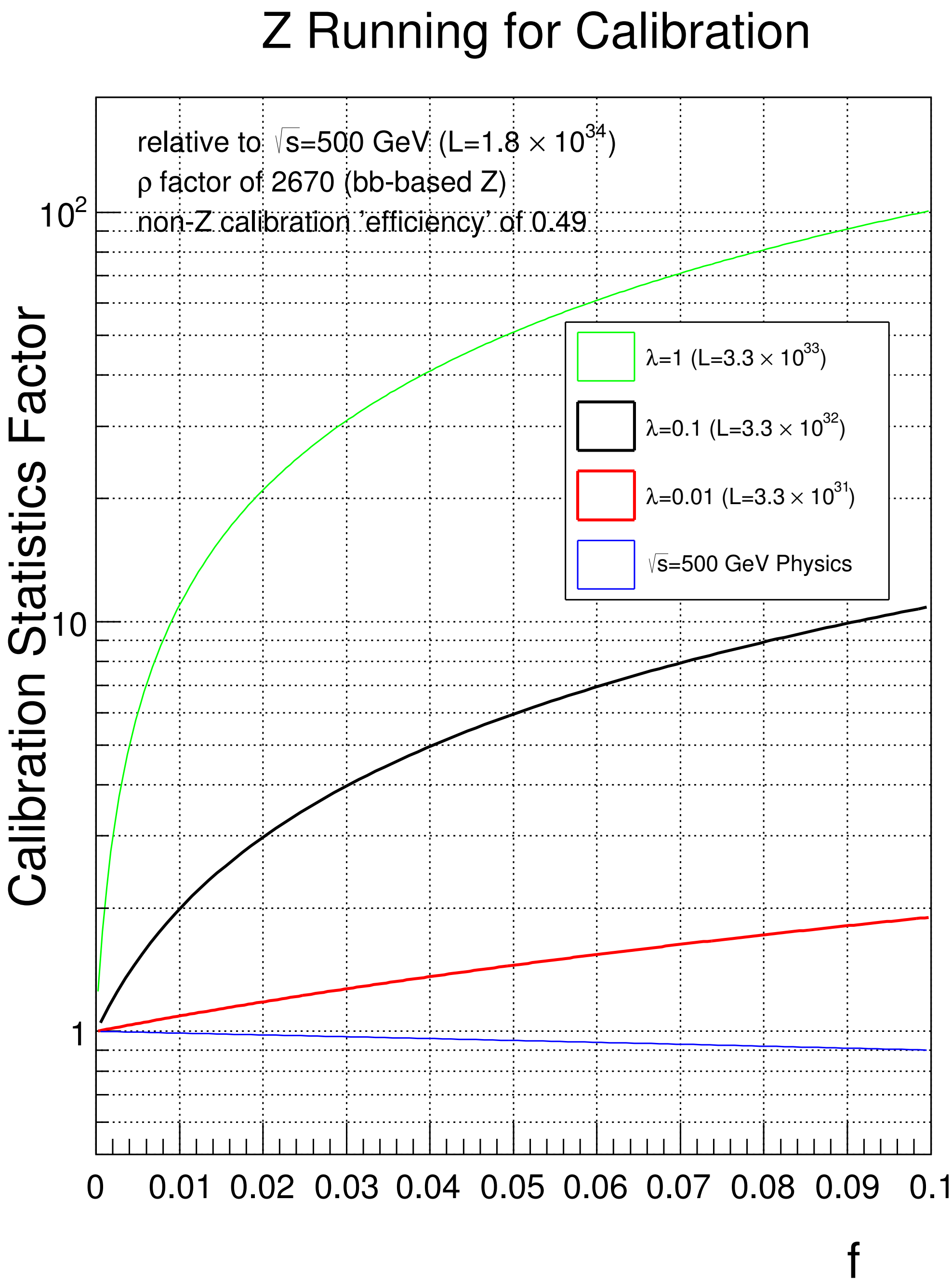

Figure 3: Integrated statistical enhancement factor of Z-Running for calibration and alignment with $e^+e^- \rightarrow b\bar{b}$ events versus fraction of running time devoted to Z running (f). Comparison is made with running at $\sqrt{s} = 500$ GeV at baseline ILC luminosity. Z-Running scenarios are shown for three assumptions on the achievable instantaneous luminosity. Also shown in blue is the corresponding linear reduction in $\sqrt{s} = 500$ GeV physics statistics. Graph includes ε factor of 0.49.

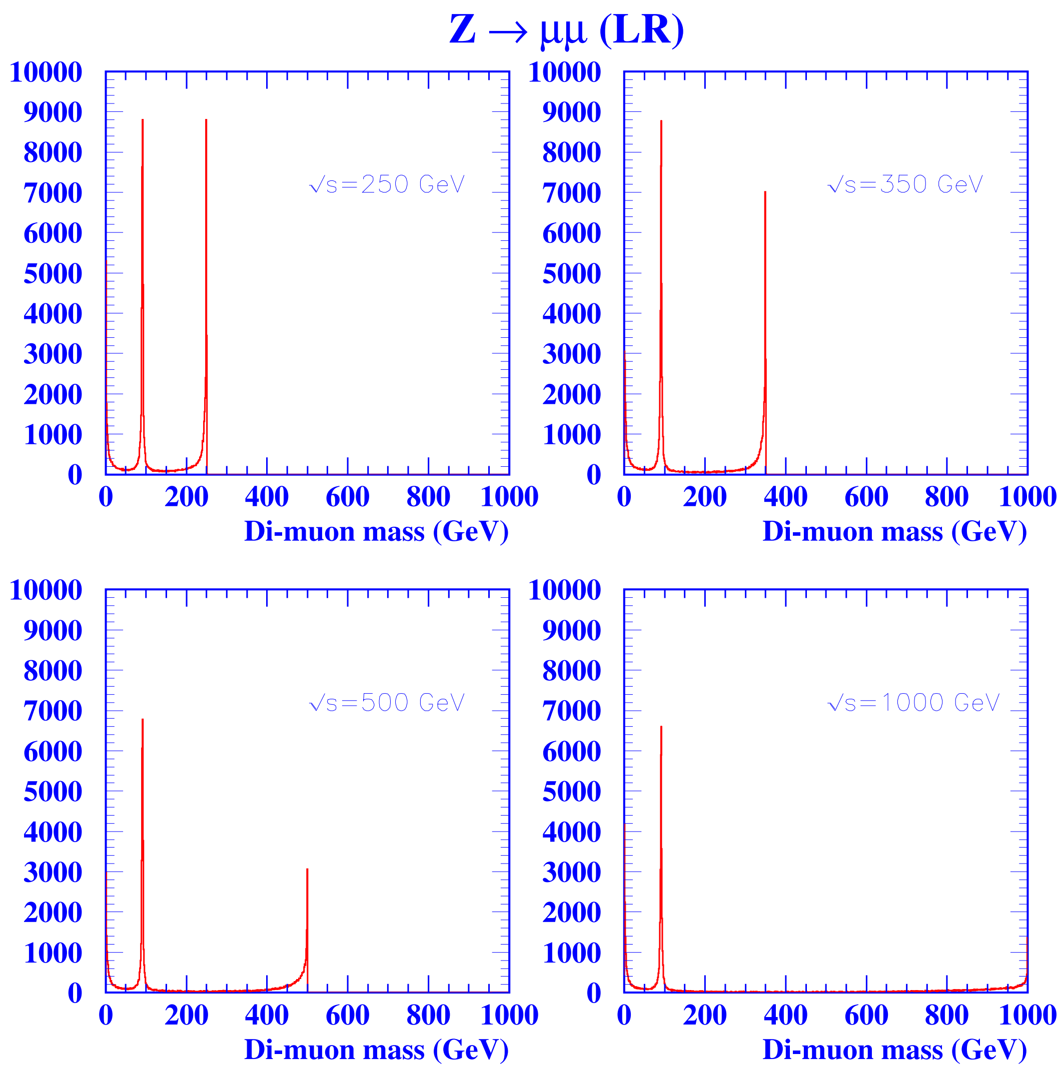

Figure 4: Di-muon invariant mass distributions (arbitrary normalization) for $e^+e^- \to \mu^+\mu^-$ at various centre of mass energies illustrating the mix of full-energy and radiative return to the Z events.

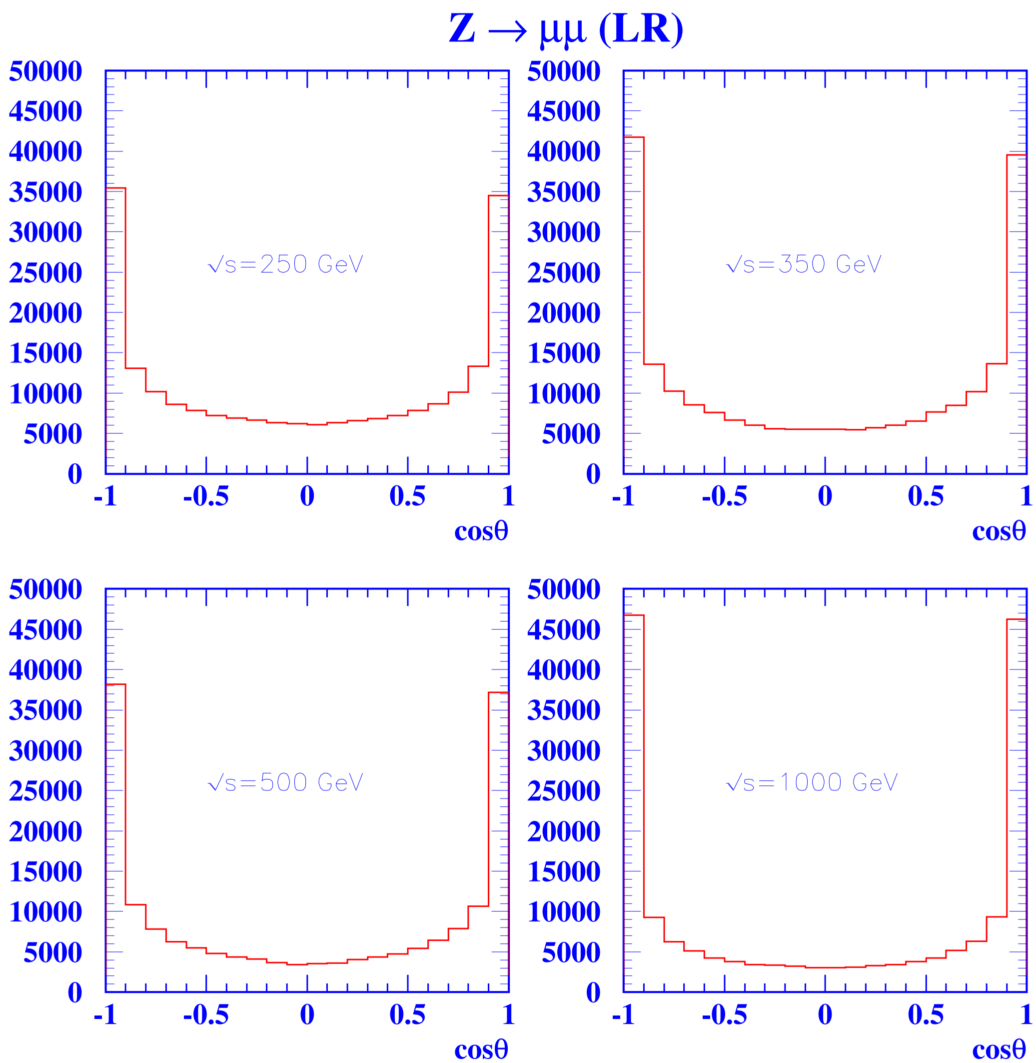

Figure 5: Distributions (arbitrary normalization) for the cosine of the polar angle of muons from $e^+e^- \to \mu^+\mu^-$.