Z Running for Calibration?

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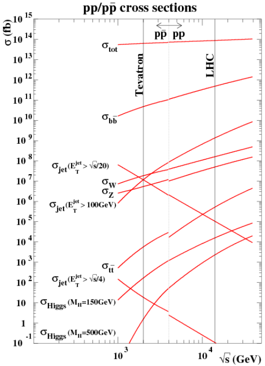
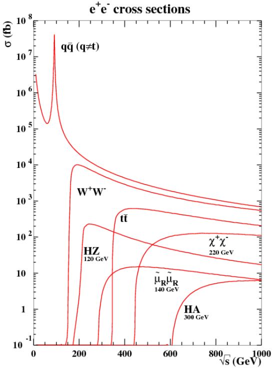




Basics

Unpolarized cross-sections from DBD samples. Define $\rho_Z(\sqrt{s}) = \sigma(m_Z)/\sigma(\sqrt{s})$.

Cross-sections and ratios

$\sqrt{s}$	$\sigma(\mu\mu)$ (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

- Event rate, $dN/dt = \sigma\mathcal{L}$.
- Luminosity at $\sqrt{s} = m_Z$ will be lower. Beam dynamics $\implies$ at least a factor of $\gamma = \sqrt{s}/m_Z = 500/91 = 5.5$ lower compared to 500 GeV.
- Event rate advantage at Z cf 500 GeV of up to a factor of 440. (2420/5.5)
- In practice, the luminosity at the Z will likely be reduced compared to the "gamma-scaling" limit. $L_Z = \lambda(L_{\sqrt{s}}/\gamma)$ where λ is a further multiplicative scale-factor.
- Here only the basic $\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$ process is considered

Time Evolution of Calibration Statistical Uncertainty

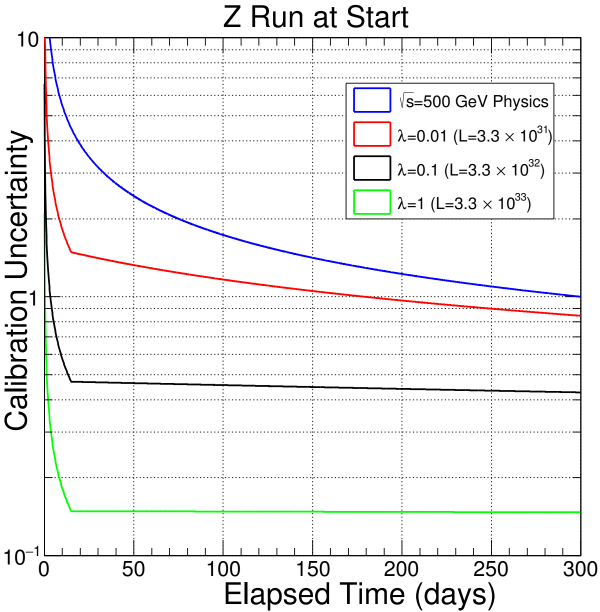
Assume 15-day Z run at start of year ($f = 0.05$).

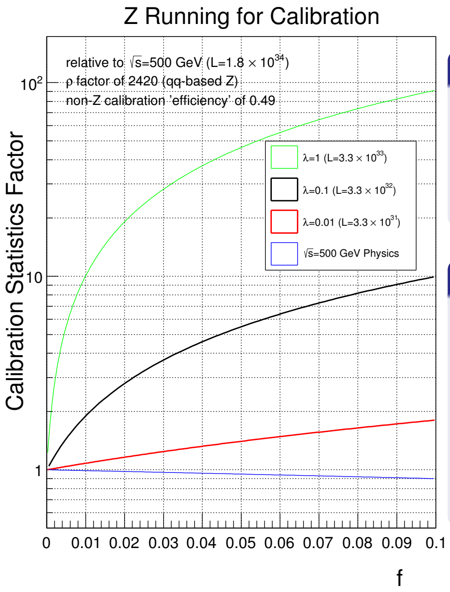
Baseline $L_{500} = 1.8 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Shown are three machine possibilities for Z running, $\lambda = 1$ (ideal), $\lambda = 0.1$ and $\lambda = 0.01$.

Normalized to value of 1.0 at t=300 days for no Z-running.

Graphs use $e^+e^- \to q\bar{q}$ and $\varepsilon_{500} = 0.49$ factor.





Note

$\alpha = 1$. Curves are for 1, 0.1 and 0.01 of the γ-scaling assumption. Blue curve - linear decrease in statistics for physics measurements at $\sqrt{s} = 500$ GeV.

Take-away

Z data at γ scaled luminosity gives 1000 times the instantaneous rate. VERY useful for fast commissioning. Overall effect on long-term calibration, need to spend at least a few to several %, potentially gaining up to a factor of around 100 in statistics.

Figure of Merit

- $N'(\sqrt{s}; f) \sim \sigma_{\sqrt{s}} L_{\sqrt{s}} T \; [\varepsilon_{\sqrt{s}}(1-f) + \rho_Z(\sqrt{s})(\lambda/\gamma)f]$
- Relative utility depends on the various factors. Essentially the statistical advantage goes as
- $\rho_Z(\sqrt{s})(\lambda/\gamma)f/(\varepsilon_{\sqrt{s}}(1-f))$
- Obviously the more easily adjustable parts are $\lambda f/(1-f) \approx \lambda f$.
- Either improve the luminosity at the Z (λ) or increase the running fraction (f).

Other processes

Focus for now on hadronic events

500 GeV unpolarized cross-section (pb)

Process	Cross-section (pb)
($Z \to qq$ 91.2)	30500
qq	12.6
single W (SL)	2.3
WW (hadronic)	1.9
WW (SL)	2.4
Zee (Z to qq)	1.8
ZZ (hadronic)	0.24
ZZ (SL)	0.22
4q (ZZ/WW)	1.6
Z nunu	0.25
Total (non-qq)	10.7

Expect acceptance for other events to be more forward peaked (less useful).

More processes

Focus for now on hadronic events. Here are γ induced processes. (both virtual and beamstrahlung ones). Are the eγ and $\gamma\gamma$ luminosities correct in the DBD files? Whizard files have cut of m(hadronic) $>$ 10 GeV.

500 GeV unpolarized cross-section (pb)

Process	Cross-section (pb)
$(Z \to qq$ 91.2)	30500
qq	12.6
e$\gamma \to qq$	55.6
e$\gamma \to \nu qq$	5.0
$\gamma\gamma \to qq$	557
$\gamma\gamma \to 4q$	0.05

Cross-sections are big but central acceptance and high pT acceptance expected to be small.

In contrast to the case at CLIC (more beamstrahlung photons and much higher potential $\sqrt{s}$), it appears unlikely that other processes can increase the effective high energy calibration cross-section at 500 GeV by any more than a factor of two.

Today's Theme

- The preceding slides should have convinced you that if ILC is able to provide reasonable L at the Z then this can be a big statistical advantage for the calibration and alignment of the detector.
- The real question for all of us is how well do we need/want to calibrate/align the individual elements of the detector, and how are we going to do the global alignment.
- At this stage in the project we should be careful about sending a message that we are not interested in Z running based on not having done any serious studies.

Backup Slides

Introduction

See J. Timmermans talk at Oshu re Z calibration running (in references).

Calibration

A detector for ILC like ILD needs a plan for calibration and alignment. We assume that the ultimate detector precision will make extensive use of collision data. Data taking at the Z pole may be the most efficient for calibrating the detector. Needs to also be feasible for the accelerator.

Request from ILC parameters WG to ILD & SiD (March 2nd, 2016)

"The TDR version of the ILC is not easily operated at the Z and would likely need modification. Quantify and justify your needs.
Please specify your needs for Z pole calibration.
For which subdetectors is Z pole calibration essential and why? Which precision could be achieved without Z pole running?
If Z pole running is required, specify how often (once for commissioning, every year, every push-pull?) they are needed and with which integrated luminosity."

Some arguments related to Z calibration running

General

- Quick commissioning with Z
- Z provides high statistics for reducing systematic effects
- Reasonably high luminosity needed to make Z running time efficient. Likely 10^{32} or higher.
- ILC experiments order of magnitude more demanding in precision than LHC - but rate of calibration events is much, much smaller.
- Precedent. Was considered a reasonable use of beam time at LEP.

ILC Specifics

- Push-pull. Need more frequent alignment.
- Power-pulsing. Only 0.5% live-time needed. Not good for cosmics. Increase?
- Precision beam energy not available from machine (in contrast to LEP).
- No hardware trigger. Also issue for cosmics. Rate? Overburden - 100m?
- Halo muons. Shallow angles - useful for endcaps.
- Potential seismic activity.
- Prefer not to use radionuclide based calibration strategies.

What do we mean by calibration

Calibration Types

- Inter-calibration. Channel-to-channel relative calibration. Eg AHCAL cells.
- Alignment (example, CMS 200,000 parameters ...)
- Absolute energy and momentum scales
- B-field measurements
- E, B-field effects / distortions
- Gas parameters (mixture, T, P, dE/dx)
- Monitoring of long-term calibration/alignment
- Fragmentation tuning
- Others ?

What Particles?

- What constitutes a useful calibration particle?
- Tracking: charged particle with $p > 5$ GeV?
- High energy muon. But maybe not too high ? $10 < p < 100$ GeV ??
- Maybe - whatever we can get, but multiple scattering $\sim 1/p$

Principles

- We try to design the detector to be already well calibrated.
- But - expect that this will need to be refined with in situ data.
- Ability to establish calibration quickly (commissioning) - very important.
- We prefer to be able to do the calibration at the physics collision energy. But rates are limited.
- Ability to take quick snapshot - for example at beginning and end of run - potentially very helpful.
- Z running well suited to efficient $B = 0$ special runs for alignment / TPC systematics.
- Need to restablish alignment after each push-pull. Hopefully don't need Z's for this - but not excluded ...
- Polarization for calibration events not needed - but would be acceptable. Figure of merit is event rate.
- Some issues where the Z may give more than just statistics. Obvious one is the known Z mass that can be leveraged for absolute energy and momentum scales. Anything else?

CMS tracker alignment as example

It seems that tracker calibration (B-field, alignment, systematics) is most critical for ILD. Will need cosmics, B-field off, particles from collisions, field-mapping, momentum-scale.

CMS tracker. Over 200,000 alignment parameters. Essentially each module with 9 alignment parameters (translation, rotation, sensor curvature). Including scattering effects, track model has $5 + 2n$ parameters.

Based on 15 million isolated muons - mainly from W. 375,000 muon pairs from Z. 3 million tracks $p > 8$ GeV from minimum bias. 3.6 million tracks from cosmics. ($p > 4$ GeV/c.)

CMS was very fortunate (in this sense) to have accumulated a lot of cosmics prior to prime-time data-taking.

Note that CMS performance goals are an order of magnitude less precise compared to ILD goal.

Quantify

Unpolarized cross-sections from DBD samples. Define $\rho_Z(\sqrt{s}) = \sigma(m_Z)/\sigma(\sqrt{s})$.

Cross-sections and ratios

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Event rate, $dN/dt = \sigma\mathcal{L}$. For $\sqrt{s} = 500$ GeV, nominally, 0.047 Hz of muons ($L = 1.8 \times 10^{34}$). For the SET, this leads to a muon rate of 5.6 μHz per 100 cm^2 area at R=1.84 m and $\theta = 90^\circ$. (5.7 years for 1000 muons)

Assuming γ scaling of the luminosity, the hadronic event rate at the Z can be 440 times higher than at $\sqrt{s} = 500$ GeV.

A calibration that may need more than one year at $\sqrt{s} = 500$ GeV for statistics can be done in one day at $\sqrt{s} = m_Z$ **IF** the machine is designed properly.

Including a factor of around 2 related to the angular distributions (see later), the effective instantaneous rate of calibratable events can be 1000 times higher at the Z than at $\sqrt{s} = 500$ GeV.

Physics Guidance

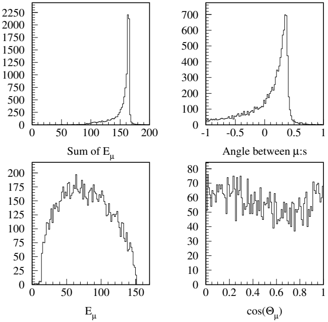
Angular distribution of Z in ZH events. Very central.

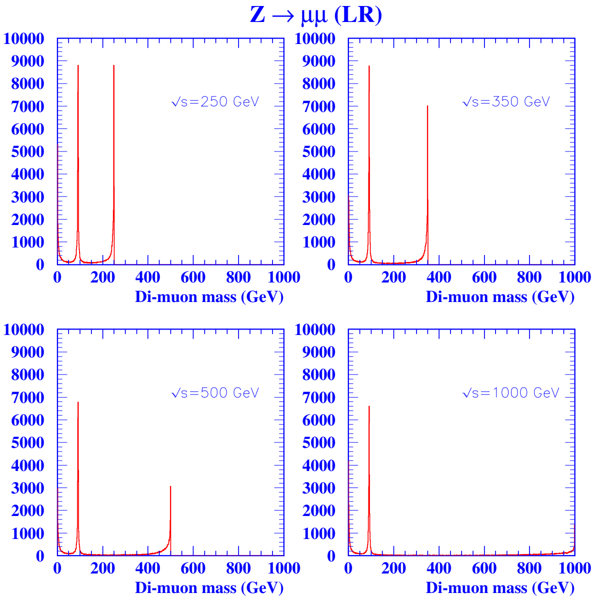
$$d\sigma/d\cos\theta_Z \sim \beta^2 \sin^2\theta_Z + 8{M_Z}^2/s$$

We care very much about momentum resolution for central tracks..

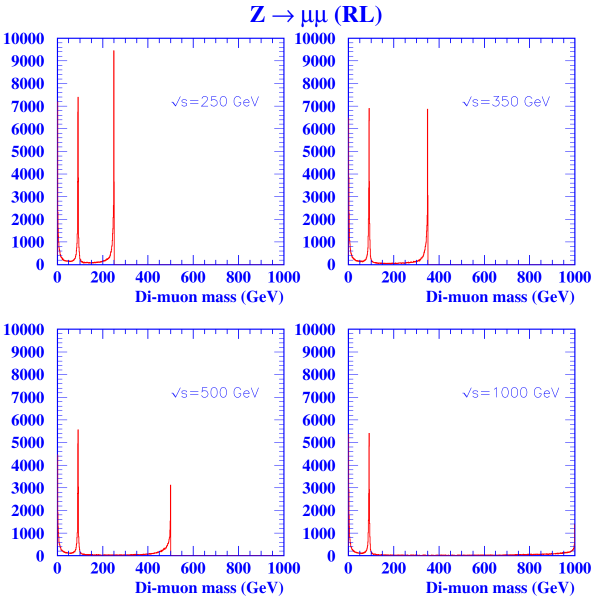
Higgs recoil-mass @ 350 GeV: mesurables

- Look at $e^+e^- \rightarrow ZH$, $Z \rightarrow \mu^+\mu^-$, $H \rightarrow X$.
- Signal only, perfect μ finding, SGV.
- Recoil-mass = $\sqrt{(E_Z - E_{CMS})^2 - \bar{p}_Z^2}$, where $E_Z = E_{\mu^+} + E_{\mu^-}$,$\bar{p}_Z = \bar{p}_{\mu^+} + \bar{p}_{\mu^-}$, E_{CMS} =nominal=350.
- So,it's all about measuring the μ:s !
- Note: E range 20 to 150, θ in barrel.



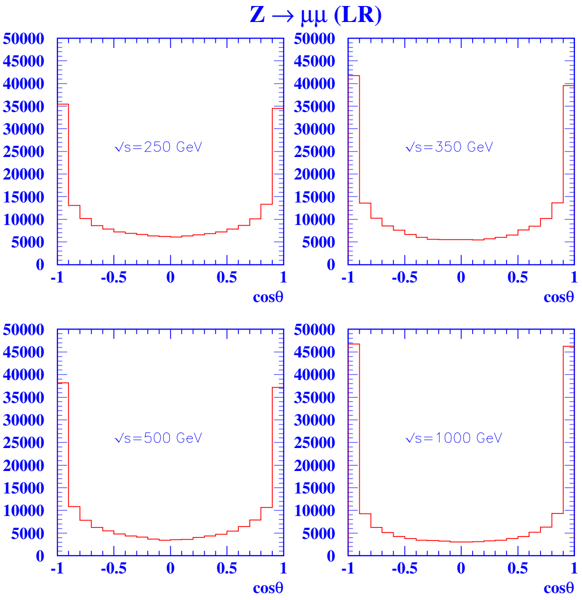


Di-muon events are a mix of full-energy events with mass close to the nominal $\sqrt{s}$ and the radiative return events, Z (γ), where the Z is boosted.



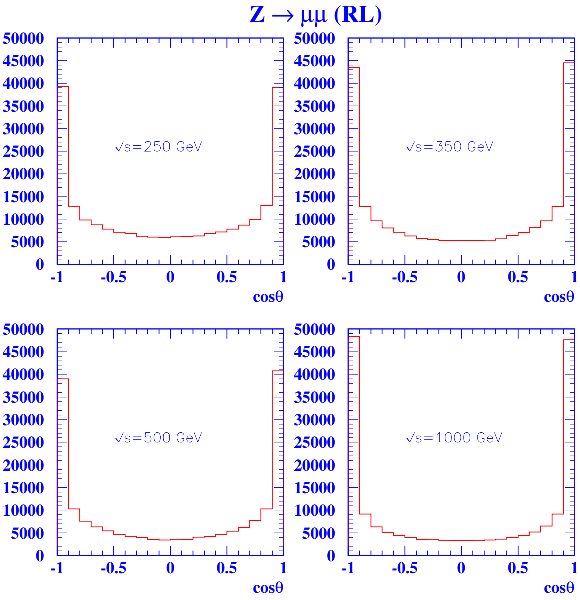
Di-muon events are a mix of full-energy events with mass close to the nominal $\sqrt{s}$ and the radiative return events, Z (γ), where the Z is boosted.

Angular distributions of muons in $e^+e^- \to \mu^+\mu^-$



Require $p > 20$ GeV. For $e^+e^- \to \mu^+\mu^-$ events at $\sqrt{s} >> m_Z$, the angular distribution is much more forward-peaked than the $1 + \cos^2\theta$ of Z's produced at rest (like at $\sqrt{s} = 91$ GeV).

Angular distributions of muons in $e^+e^- \to \mu^+\mu^-$



Assess an effective high energy calibration "efficiency" (ε) related to relative fraction of muons in $|\cos\theta| < 0.1$.

Effective Central Angular Efficiency

Relative Acceptances

$\sqrt{s}$	Muons per event ($\lvert \cos\theta \rvert < 0.1$)	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

Presumably, the most difficult part of the detector to do a track-based alignment will be the most central part at large radius.

Given the above numbers, data taken at $\sqrt{s} = 500$ GeV is a factor of two less effective for aligning the hardest to align part than data at $\sqrt{s} = 91$ GeV.

This factor has been assessed for now with $\mu\mu$ (4-vectors at hand). It should be checked for $q\overline{q}$ - expected to be similar. For now assume the same.

Details

Define $\lambda g_Z = L_Z / L_{\sqrt{s}}$, where the gamma related scaling factor,

$$g_Z(\sqrt{s}; \alpha) = (m_Z / \sqrt{s})^{\alpha}$$

and $\alpha = 1$ corresponds to gamma-scaling.
Total number of events for calibration (at 91 GeV and high energy), given running time T, and time-fraction f, devoted to Z.

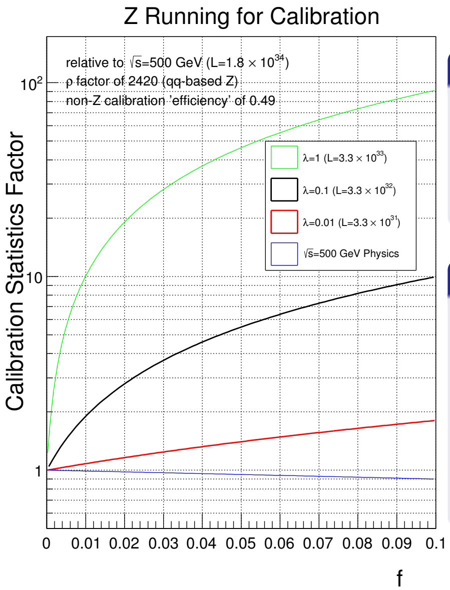
$$N(\sqrt{s}; f) = \sigma_{\sqrt{s}} L_{\sqrt{s}} T \left[\varepsilon(1 - f) + \rho_Z(\sqrt{s})(\lambda g_Z) f\right]$$

where ε is to account for the effective calibration efficiency of high energy running. Z calibration only makes sense when the second term is big, but f had better not be much greater than a few %. Note baseline $L(500)$ is 1.8×10^{34}.

Note

1. 91 GeV Z data angular distribution explores the full solid angle more efficiently than high energy data. 2. Other processes like gamma-gamma collisions may be quite effective for high-energy calibration. 3. Very high momentum tracks at high $\sqrt{s}$ have very low multiple scattering. Relative benefit not quantified currently.

qq Plot



Note

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Take-away

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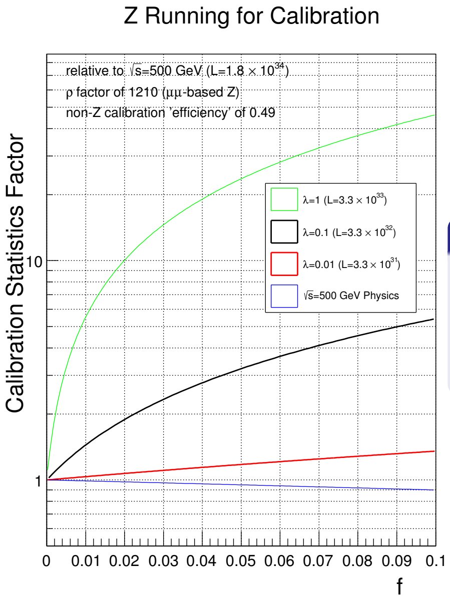

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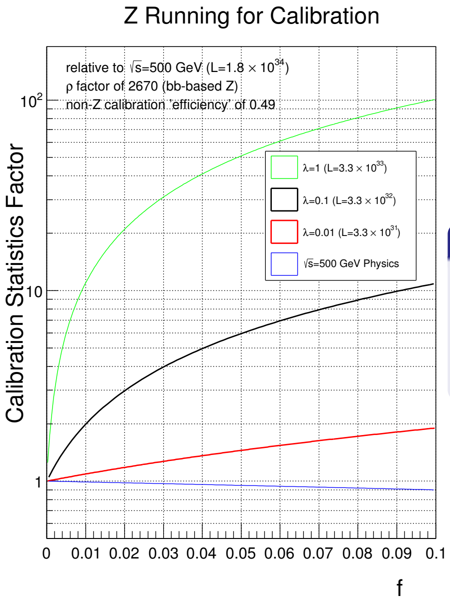


Important for J/ψ statistics.

Note

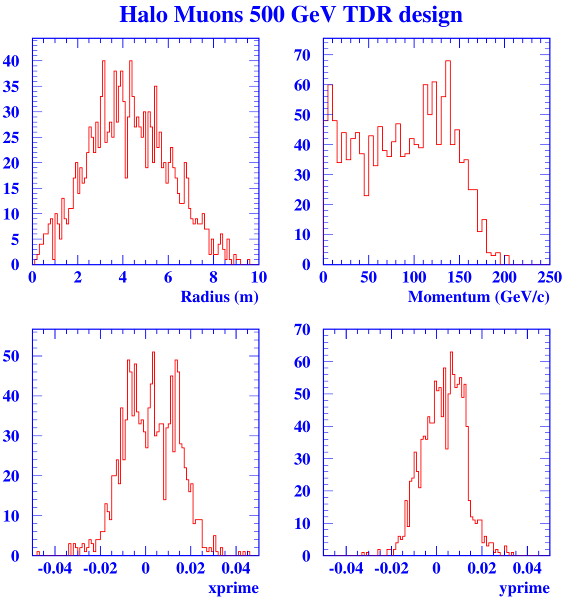
$\alpha = 1$. Curves are for 1, 0.1 and 0.01 of the γ-scaling assumption. Blue curve - linear decrease in statistics for physics measurements at $\sqrt{s} = 500$ GeV.

Important Systematics Addressable with Z's

Z's are good for calibrating the whole detector. Energy limited to 45 GeV.

- Precision absolute center-of-mass energy determination using $\mathrm{e^+e^-} \to \mu^+\mu^-$ at high $\sqrt{s}$ relies on precision momentum scale. Needs high statistics of $\mathrm{J}/\psi \to \mu\mu$. Best source is Z's. If done early - applicable to whole ILC program.
- b-tagging systematics. High statistics available with Z's.
- neutral hadron energy scale. Best chance of high statistics: identified neutral hadrons in Z events.
- jet energy scale. Best statistics from Z. Target < 0.01 %.
- fragmentation. Will need to understand the particle content of jets for ultimate particle flow performance. For hadronic Z recoil in ZH, Z's at 91 GeV very relevant.

Halo Muons. File from Glen White.



TDR design. Estimate 0.5 muons/BX in 6.5m radius detector. x' and y' distributions for $p > 20$ GeV/c. See Glen White talk earlier this week.

At startup, with an alignment hat on, we may want more. There are of course possibilities in that direction. I assume that we want to minimize the halo muon background for longer term physics running.

How to proceed

Propose Two-Track Response

1. Reply soon.
   - Make the case for efficent Z pole calibration data-taking being essential given our current understanding.
   - Encourage work on the accelerator design.
2. Initiate more mature and longer term quantitative studies of calibration and alignment in coordination with detector and physics studies.

Steps so far

1. Draft reply document being worked on.
2. Assembles various arguments.
3. Some estimates exist and need to be reviewed/revisited.

Input welcome

1. Your input on this is very welcome

Concluding remarks

... draft summary

- ILD is revisiting the issue of Z running for calibration. We will provide updated quantitative numbers in due course.
- 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 running interval than is accumulated in nominal physics running conditions. In this sense, we envisage that Z running for calibration should be aiming at $L > 3 \times 10^{32}$ $\text{cm}^{-2}\text{s}^{-1}$ and should be available from day one.
- We primarily envisage 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 I

- 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.
- CMS Collab., "Alignment of the CMS tracker with LHC and cosmic ray data", JINST 9 (2014) P06009
- J. Timmermans, Talk at ILD meeting in Oshu, 2014. https://agenda.linearcollider.org/event/6360

Old Backup Slides

Machine Issues

There has been some recent thought put into how to deliver high luminosity at low energy "for physics". The summary from Nick Walker is "the ILC baseline machine can in principle operate at the Z pole with luminosities in the range $1 - 2 \times 10^{33}$" with polarized positrons. This capability can be implemented from 'day one' if we ask for it.