ILD Calibration and Alignment - Z Running?

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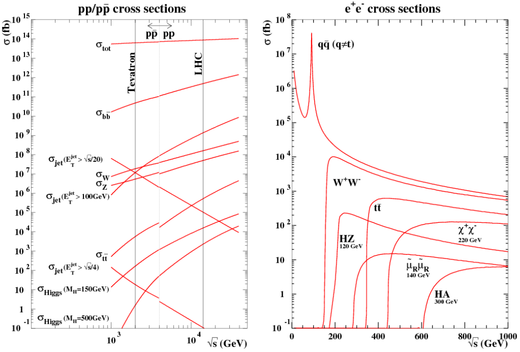


Introduction

Calibration and Alignment

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

ILD Response to Parameters Group Request

1. Overview of issues. Initial response. Focus on Z/no Z issue and generalities.
2. Sub-detector plans. Ask questions internally. Review existing work. Initiate studies.
3. Still awaiting input from critical detectors. Suspect TPC and SET are the main sub-detector drivers.
4. Also overall issues of systematic nature - precision global alignment - precision global p and energy scale calibration
5. ILD will have a mini-focus on these issues at the Morioka meeting.
6. "there is a huge work to do to see how we can live without ..."
7. We need actual alignment studies. This is a big task.

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 $\Longrightarrow$ 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.
- Only the basic $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$ process is considered. Ideal for calibration.
- Other processes will also be useful. For alignment, the generic particle rate will be more important than the rate of these events.

Time Evolution of Calibration Statistical Uncertainty

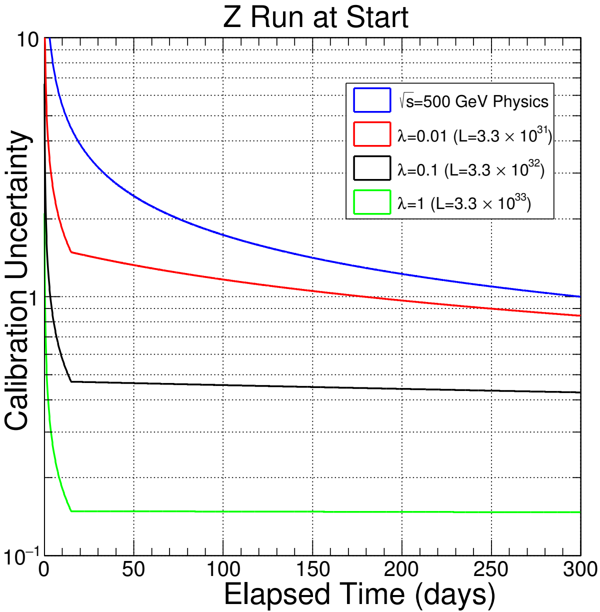
Assume 15-day Z run at start of year ($f = 0.05$).

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 $\lambda = 0.01$.

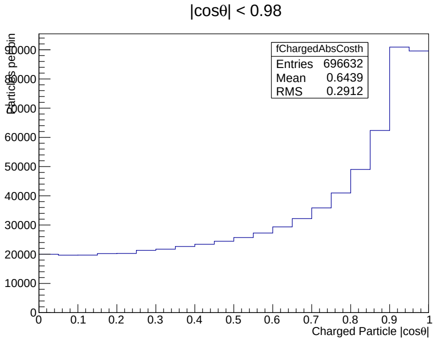
Normalized to value of 1.0 at t=300 days for no Z-running.

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



Calibratable Particles Definition?

Charged particles in $e^+e^- \to q\overline{q}(\gamma)$ at $\sqrt{s} = 500$ GeV.



Presumably, the most difficult part of the detector to do a track-based alignment will be the most central part at large radius. Particularly the outer silicon (SET). Have used $|\cos\theta| < 0.1$ as a measure of this calibratable acceptance issue.

Events at high $\sqrt{s}$ are more often forward than at the Z. But this is also compensated by the higher energy.
Higher momentum particles more useful for alignment (multiple scattering).

Other processes

500 GeV unpolarized cross-section (pb)

Process	Cross-section (pb)	$p > 10$ GeV, $|\cos\theta| < 0.1$ (pb)
($Z \to qq$ 91.2)	30500	2258
(Other Z decays 91.2)	4400	632
qq	12.6	2.17
ll		0.22
ee		0.12
single W (SL)	2.3	?
WW (hadronic)	1.9	0.30
WW (SL)	2.4	0.21
Zee (Z to qq)	1.8	?
4q (ZZ/WW)	1.6	0.27
$\gamma\gamma \to \mathrm{q\overline{q}}$	big	0.20
$\gamma\gamma \to \ell\overline{\ell}$ ($\ell = \mu, \tau$)	big	4.12
$\gamma\gamma \to \mathrm{q\overline{q}}$ (lowpt)	big	(3.7 ± 2.6)
Total (non 91.2GeV)		7.6 (11.3)

Ratios to Z of 380. (Not $2420/0.49 = 4940$).

ILD Momentum Resolution - requires precision alignment

Measure curvature of charged particle trajectory in $\mathrm{B} = 3.5$ T solenoid field over 1.83 m radius.

Tracker: VXD (3μm), SIT (7μm), TPC (100μm), SET (7μm).

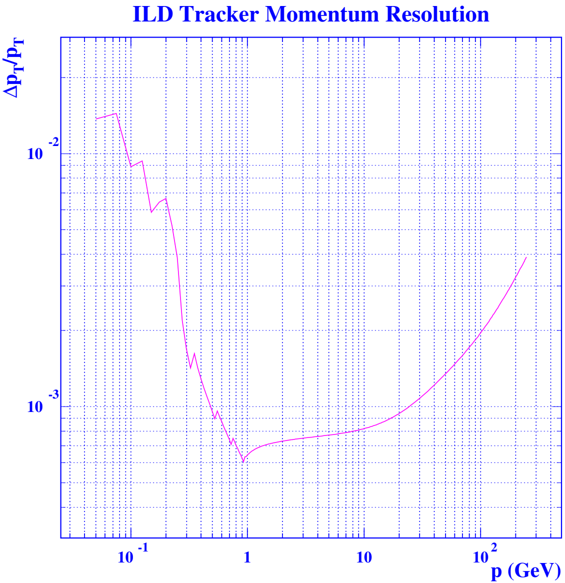
$\sigma^2 = \sigma^2_{MS} + \sigma^2_{\mathrm{point}} + \sigma^2_{\mathrm{align}}$

Need $\sigma_{\mathrm{align}} << \sigma_{\mathrm{point}}$

Best to measure in region where multiple-scattering is small. $p > 25$ GeV.

Primary issue - aligning the SET. What track momenta are useful?

SGV simulation $\theta = 90^\circ$



ILD Momentum Resolution - SET requirement?

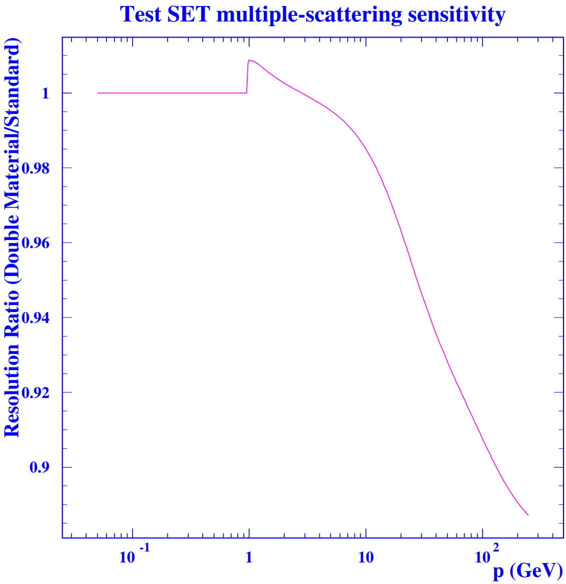
Estimate p at which $\sigma_{MS} = \sigma_{\text{point}}$ for SET by comparing the nominal model with a model with double the material in the TPC outer field cage (4% X_0 cf 2% X_0) and perfect SET point resolution.

Find cross-over point at 2.8 GeV.

So estimated MS component for the SET alignment is $20\mu\text{m}/p$.

Still need to check this directly using extrapolated track error matrix and full simulation.

$\theta = 90^\circ$



Calibratable Particle Take-away

At least for the SET, the alignment precision per particle in μm, appears to be about

$7 \oplus 20/p(\mathrm{GeV})$

So for minimal degradation of the intrinsic resolution (increase by at most 10%), the track momentum should exceed 9 GeV.
Counting raw particle flux above this momentum threshold is reasonable for this application.
Lower momentum particles will still be very useful, but need to be deweighted appropriately.

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?

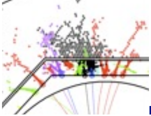
- What constitutes a useful calibration particle?
- Tracking: charged particle with $p > 5$ GeV?
- High energy muon. But maybe not too high ? $10 < p < 100$ GeV ??
- Maybe - whatever we can get, but multiple scattering $\sim 1/p$

Experimental 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. Needed for monitoring. 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?

Section on Detector Questions and Issues

The following questions were posed to all ILD subdetectors.
Meeting Oct 27th to discuss.



Outline

QUESTIONS

1. Outline the strategy for alignment and calibration of your subdetector.
2. What calibration and alignment parameters need to be measured with particles (either from collisions or cosmics) for your subdetector?
3. What precision is needed on the calibration and alignment parameters for your subdetector? What is the basis for this assessment?
4. How many usable particles per sub-detector element are needed to establish the calibration and alignment constants at the above level of precision?
5. What particles and kinematic criteria are needed?
6. What is the smallest solid-angle subtended by an individual sub-detector element?
7. Does your subdetector plan to use power-pulsing?
8. Are cosmics useful for the alignment/calibration of your sub-detector?
9. Are beam halo muons useful for the alignment/calibration of your sub-detector?
10. If power-pulsing is used, what is the effective live-time percentage?
11. Is data with the magnetic field off needed for your sub-detector?
12. On which time-scales do you anticipate that the alignment and/or calibration of your sub-detector will be stable? In particular would it be reasonable to assume that data collected over multiple running periods in multiple years can be used collectively to refine the overall calibration or alignment?
13. Do you foresee particular challenges in the alignment and calibration of your subdetector?

ILD Meeting focussed on Calibration/Alignment

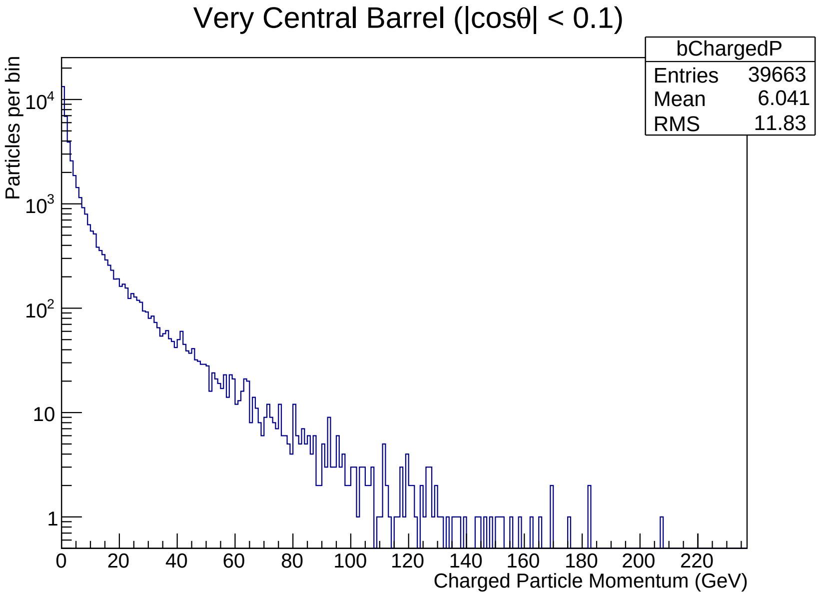
- On October 27th. See https://agenda.linearcollider.org/event/7393/
- Many sub-detectors have now provided detailed answers to these questions.
- So far my take-away is that the subdetectors we understood to be in good shape are in good shape. For example calibration procedures underlie calorimetry and experience gained from multiple prototypes gives a lot of confidence.
- But for those sub-detectors facing more complex challenges - and in particular the overall tracking system "it is tempting to have this possibility of Z pole running ... but there is a huge work to do to see how we can live without"

My personal conclusion

1. Need to more thoroughly evaluate track-based alignment possibilities at high $\sqrt{s}$. (Not just $\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$)
2. Need actual alignment studies. (also using not just pristine high-pT tracks.)

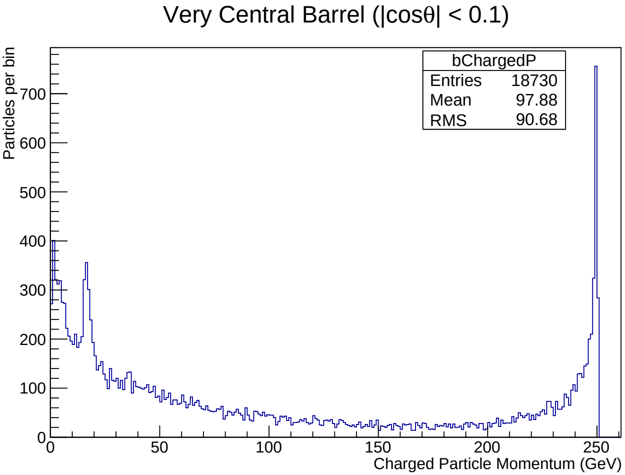
Charged Particle Momentum Distributions

$e^+e^- \rightarrow q\overline{q}(\gamma)$ at $\sqrt{s} = 500$ GeV



Charged Particle Momentum Distributions II

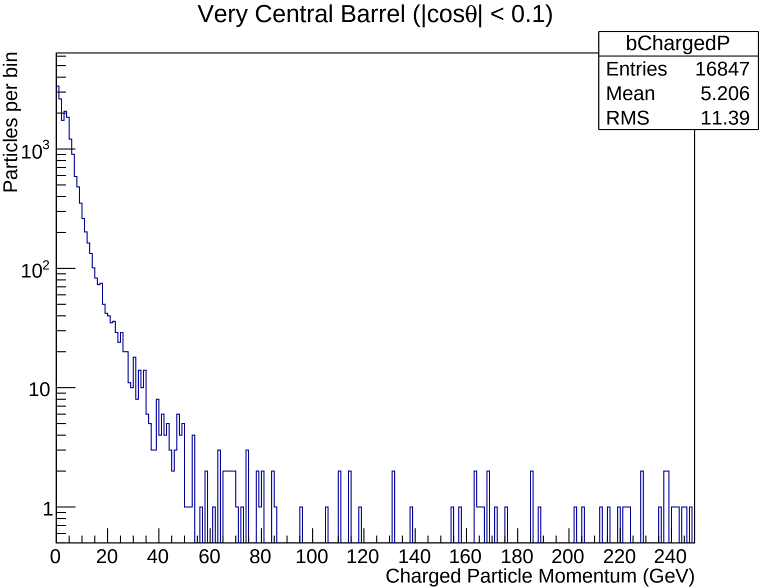
$e^+e^- \to \ell\bar{\ell}(\gamma)$ at $\sqrt{s} = 500$ GeV $(\ell = \mu, \tau)$



Peak at 18 GeV is due to the lower energy muon from $Z \to \mu\mu$ in radiative-return $(Z\gamma)$ events.

Charged Particle Momentum Distributions III

$e^+e^- \rightarrow e^+e^-\ell\bar{\ell}$ at $\sqrt{s} = 500$ GeV $(\ell = \mu, \tau)$



Absolute Jet Energy Scale Calibration

Some topics blur the lines between subdetector calibration and overall "physics" calibration. Good example: jet energy. Would like to target better than 20 ppm ....

- In the PFA paradigm. $E_{\mathrm{jet}} = E_{\mathrm{charged}} + E_{\mathrm{photons}} + E_{\mathrm{neutral\ hadrons}}$
- Bottom-up calibration:
- Momentum scale for E_{charged}
- Photon energy scale for E_{photons}
- Neutral hadron energy scale (??) for $E_{\mathrm{neutral\ hadrons}}$
- Or top-down with Z or W. (want to also measure Z and W ...) - at least as a check.
- "Confusion" - likely demands both a bottom-up and top-down approach .

Need serious study.

Summary So Far

- 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 on-going question for ILD 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 need to get serious about calibration and alignment. We should make sure that the Z running possibility and the plan for high energy calibration/monitoring is investigated in sufficient depth.
- Relative advantage/disadvantage of Z running depends on application and λ factor.
- Lousy luminosity at the Z is not very useful. Recent studies also suggest that higher luminosity needed to be interesting for all applications.

Conclusions So Far

- ILD is revisiting the issue of Z running for calibration. We will provide updated quantitative numbers in due course.
- 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. We envisage that Z running for calibration should be aiming at least at $L > 2 \times 10^{32}$ cm^{-2}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, then 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.

Backup Slides

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

$\sqrt{s}$	$\sigma(\mu\mu)$ (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, $dN/dt = \sigma\mathcal{L}$. 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

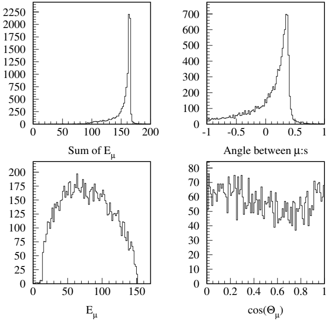
Angular distribution of Z in ZH events. Very central.

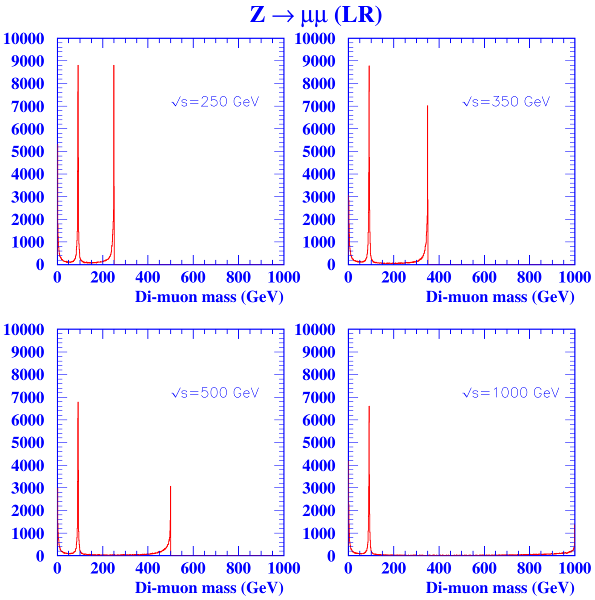
$$d\sigma/d\cos\theta_Z \sim \beta^2 \sin^2\theta_Z + 8{M_Z}^2/s$$

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

Higgs recoil-mass @ 350 GeV: mesurables

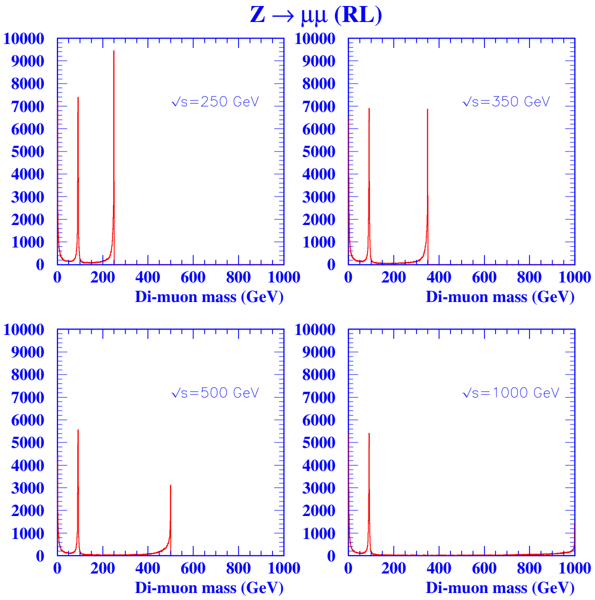
- Look at $e^+e^- \rightarrow ZH$, $Z \rightarrow \mu^+\mu^-$, $H \rightarrow X$.
- Signal only, perfect μ finding, SGV.
- Recoil-mass = $\sqrt{(E_Z - E_{CMS})^2 - \bar{p}_Z^2}$, where $E_Z = E_{\mu^+} + E_{\mu^-}$,$\bar{p}_Z = \bar{p}_{\mu^+} + \bar{p}_{\mu^-}$, E_{CMS} =nominal=350.
- So,it's all about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





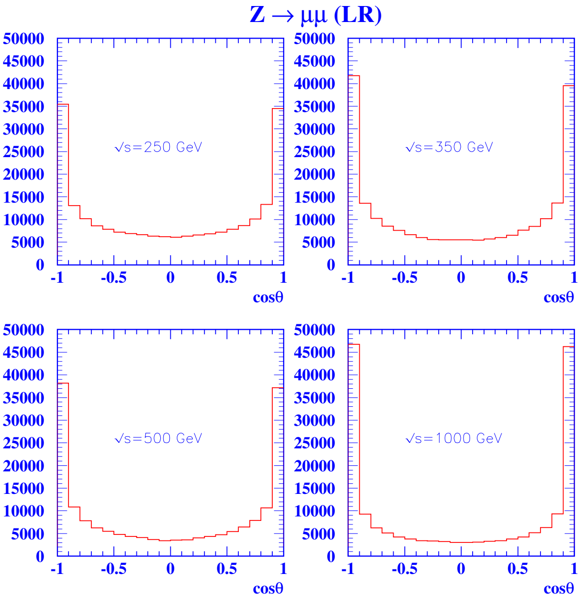
Di-muon events are a mix of full-energy events with mass close to the nominal $\sqrt{s}$ and the radiative return events, Z (γ), where the Z is boosted.

Calibrate at high $\sqrt{s}$? $M_{\mu\mu}$ distributions for $e^+e^- \to \mu^+\mu^-$



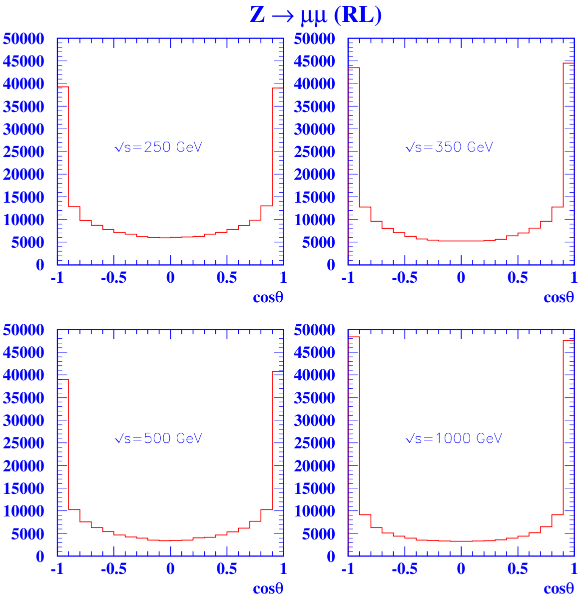
Di-muon events are a mix of full-energy events with mass close to the nominal $\sqrt{s}$ and the radiative return events, Z (γ), where the Z is boosted.

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,

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

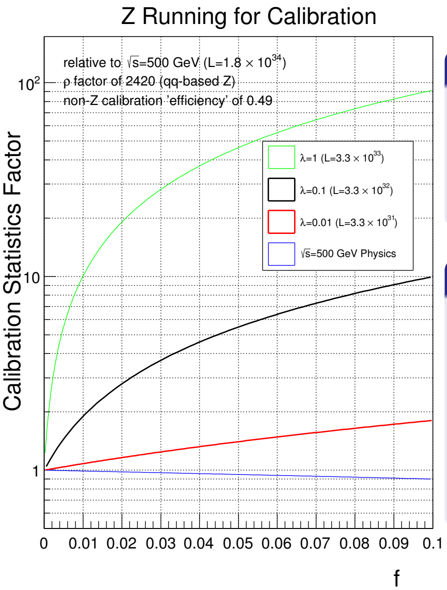
and $\alpha = 1$ corresponds to gamma-scaling.
Total number of events for calibration (at 91 GeV and high energy), given running time T, and time-fraction f, devoted to Z.

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

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.



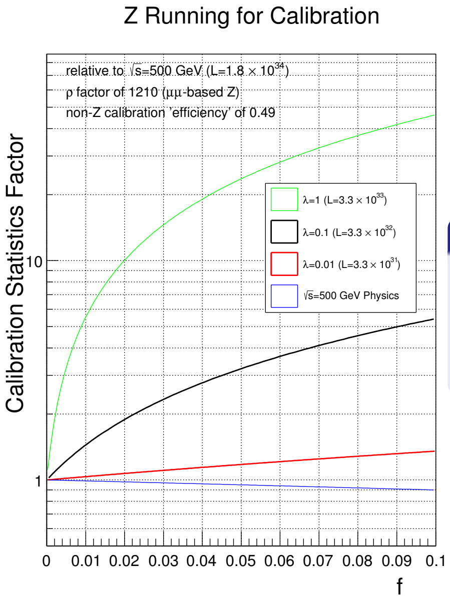
Note

$\alpha = 1$. 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.

$\mu\mu$ Plot



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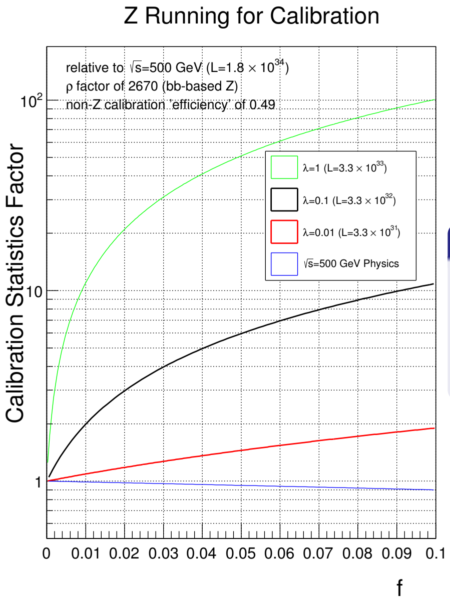


Important for J/ψ statistics.

Note

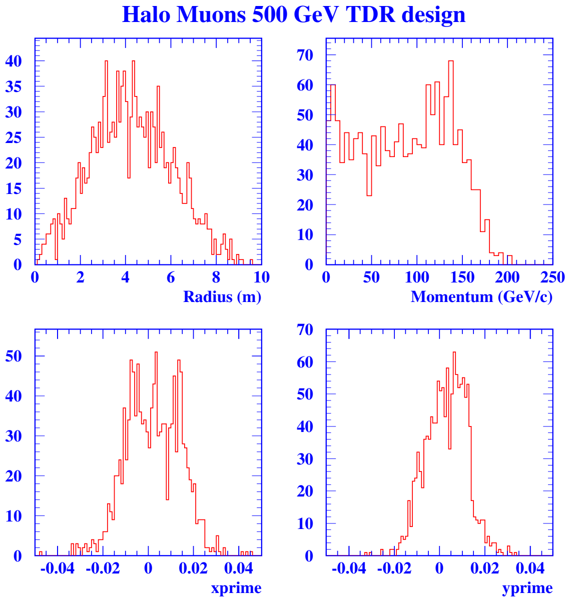
$\alpha = 1$. Curves are for 1, 0.1 and 0.01 of the γ-scaling assumption. Blue curve - linear decrease in statistics for physics measurements at $\sqrt{s} = 500$ GeV.

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 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

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.