Experimental Issues for Precision Electroweak Physics at a high luminosity Z factory

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Focus will be on the measurement of $sin^2\theta_W^{eff}$ by the A_{LR} technique, drawing on experience gained at the SLC.

Comments regarding other important observables, such as M_Z, Γ_Z, m_W, and m_{top} are possible as well, although these are covered in more detail elsewhere.

Our main conclusions in advance :

Along with **polarization, energy measurement** will play a central role.

There will likely be an interplay between machine parameters and the precision measurements - a **luminosity/precision trade-off**.

Systematic Effects for the Measurement of A_{LR}

$$\boldsymbol{A_{LR}} = \frac{\boldsymbol{A_m}}{\boldsymbol{P_e}} +$$

$$\frac{1}{P_e}\left[f_b(A_m - A_b) - A_L + A_m^2 A_P - E_{cm}\frac{\sigma'(E_{cm})}{\sigma(E_{cm})}A_E - A_\varepsilon \right] + P_p$$

• The dominant error is due to **electron polarimetry** (P_e)

•Smaller correction terms are due to backgrounds (f_b),
LR asymmetries (A_x, with $x = b,L,P,E,\varepsilon$) *of*
backgrounds,luminosity, polarization, center-of-mass energy,detection efficiency
and possible undetected positron polarization (P_p)

$$\boldsymbol{A_{LR}(E_{cm}) \rightarrow A^0_{LR}} \quad (\equiv \sin^2\theta_W^{eff} \text{ by definition})$$

•Conversion to the Z-pole value (and to the effective mixing angle)
requires **accurate and precise knowledge of E_{cm} :**
This introduces a systematic error only slightly smaller than polarimetry
Important rule of thumb : 80 MeV error → 1% A_{LR} error.

Polarization Measurements

Two Possibilities at NLC-90: Compton polarimetry and 'Blondel scheme'

1. Only the electron beam is polarized.

Use Compton Polarimetry:

Uncertainty	SLC-90 $\delta P/P$	NLC-90 Goal $\delta P/P$
Laser Pol.	0.1%	0.1%
Linearity	0.2%	0.1%
Electr. Noise	0.2%	0.05%
Anal. Pwr. Cal.	0.4%	0.2%
Total	0.50%	0.25%

Plausibly, a factor of two improvement

- use multichannel electron spectrometer (and if possible, Compton gamma detectors in dedicated electron-only runs as was done at the SLC)
- correct for any depolarization effect (expected to be <0.1%) by comparing polarization measurement with and without collisions

2. Both electron and positron beams are polarized.

$$P^- = 90\%, P^+ = 50\%$$

$$\frac{\delta P^-}{P^-} = 0.25\%, \frac{\delta P^+}{P^+} = 0.25\%$$

$$P_{eff} = \frac{P^- + P^+}{1 + P^- P^+} = 96.55\%$$

$$\frac{\delta P_{eff}}{P_{eff}} = 0.10\%$$

$$\frac{N_{LR} - N_{RL}}{N_{LR} + N_{RL}} = P_{eff} A_{LR}$$

One can also use the ‘Blondel scheme’ to determine beam polarizations directly:

$$\frac{N_{LL} + N_{LR} - N_{RL} - N_{RR}}{N_{LL} + N_{LR} + N_{RL} + N_{RR}} = P^- A_{LR}$$

$$\frac{N_{RR} + N_{LR} - N_{RL} - N_{LL}}{N_{RR} + N_{LR} + N_{RL} + N_{LL}} = P^+ A_{LR}$$

- Using the Blondel technique, one needs Compton polarimeters solely for measuring polarization *differences* between L,R states (A_P); and only needs to spend approx. 10% of the running time in N_{RR}, N_{LL} states.

- This technique directly measures lum-weighted polarizations (any depolarization effects are properly taken into account)

Polarized Positrons?

Need to understand relative detector efficiency for
'RL' and 'LR' modes at level of 10^{-4}
(probably not a problem)

Need to measure the polarization difference,
$P_R^+ - P_L^+$, at level of 10^{-3}
(demonstrated at the SLC for electrons)

But this will be difficult unless can measure these modes simultaneously, ie. can switch positron polarization randomly pulse-to-pulse, as is done for electrons. Even rapid (every few minutes) reversals might lead to lingering questions - this warrants more detailed study.

Note: Even if positrons are nominally unpolarized, one needs to verify this.

$$\boxed{\delta(A_{LR}) = P_p}$$

For $\delta(A_{LR})=4 \times 10^{-4}$, want $\delta(P^+)<2\times10^{-4}$. SLD's 'posipol' measurement achieved $\delta(P^+)=7\times10^{-4}$. (This is relevant for an A_{LR} measurement, without positron polarization, plausibly a factor 5 better than SLD's result.)

Luminosity Measurements and Backgrounds
(A_L and f_b)

SLD achieved luminosity asymmetries approx. 10^{-4}.
(SLAC E158 is working to achieve luminosity asymmetries << 10^{-6})

$$\delta(A_{LR}) = \frac{1}{P_e} \cdot A_L$$

Can measure luminosity asymmetries with small angle Bhabha detectors. For data samples of $>10^{8}$ Zs, need to understand luminosity asymmetries to better than 10^{-4}. This should be achievable (though could be difficult of different polarization modes are not taken simultaneously).

Need to understand non-Z backgrounds at level of 10^{-4}.
(SLD result was 3 x 10^{-4}.)

$$\delta(A_{LR}) = \frac{1}{P_e} f_b (A_m - A_b)$$

Other asymmetry corrections ($A_{P,}$ A_E) are much smaller.

And efficiency asymmetries (A_ε) are truly negligible
(In the limit of the very large statistics - 10^{9}- discussed by some, and if muon-pair final states are used, these may emerge as significant, depending on the detector design).

Beam Energy/Spectrum Measurements and Luminosity Spectra Measurements

The Lum-weighted E_{CM} needs to be accurately determined. This requires an accurate measurement of the undisrupted beam energy and a correction for beamstrahlung effects.

To correct for the beamstrahlung, there are 2 approaches:

Method 1 uses beam energy and beam spectrum diagnostics for measuring both the disrupted and undisrupted beam. (SLD approach)

Method 2 uses a beam energy measurement for the undisrupted beam, and a luminosity spectrum measurement -- ex. small angle Bhabhas. (proposed approach for top threshold scan)

1. Beam Energy/Spectrum Measurements

i) SLC-style Synchrotron Spectrometer (±20 MeV)
ii) LEP2-style BPM Spectrometer
iii) Moller/Bhabha Scattering from a hydrogen gas jet target (was proposed but not built for LEP2)
iv) wire scans at a high dispersion point

- *for absolute calibration of these devices, can cross-calibrate to Z Mass with a Z-peak scan*
(what will be time stability of these calibrations -- hours? days?)

2. Luminosity Spectra Measurements

- use small angle Bhabha event kinematics (energies, angles) to deduce beamstrahlung effect given undisrupted beam energy measurement and ISR calculations
- this has been studied for top threshold scans to determine energy uncertainty at level of 100 MeV - unclear if 10X greater precision is possible via this technique.

both Method 1 and Method 2 need a detailed study to determine if can reach desired energy-sensitivity for $\delta(E_{CM}^{\text{lum-wt}})$ of 1-10 MeV.

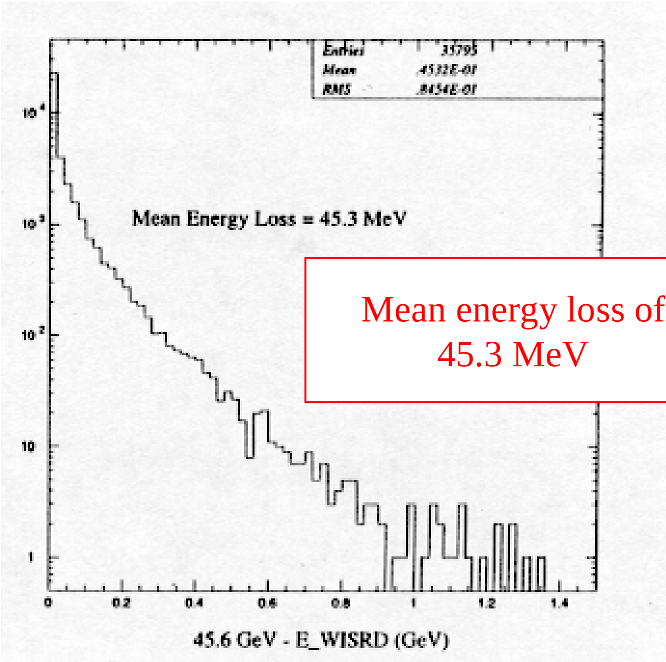
M.Woods has made GUINEAPIG simulations of beamstrahlung effects for

i) SLC-90
ii) NLC-90
iii) TESLA-90 (Nominal and Low)

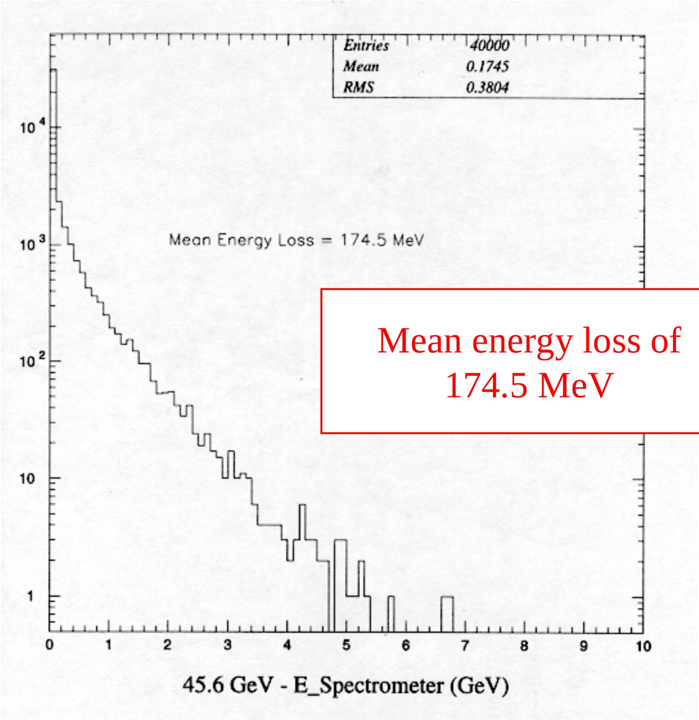
These will illustrate the size of the beamstrahlung corrections needed.
(Our feeling is it will be hard, but perhaps possible, to understand such corrections with 10% accuracy -- We are skeptical of achieving 1% accuracy in these corrections; ***The SLD estimate was 33%*** *)*

Compare Beamstrahlung Energy Losses at SLC-90 and NLC-90

'GUINEAPIG' Simulation



Mean energy loss of 45.3 MeV



Mean energy loss of 174.5 MeV

SLC: $L = 2.0 \cdot 10^{30} cm^{-2} s^{-1}$

NLC: $L = 1.3 \cdot 10^{33} cm^{-2} s^{-1}$

These are single beam energy losses, as measured SLC-style with spectrometers. (At the SLC - the total E_{cm} correction was about 1/2 the sum of the single beam losses, a hypothesis that was verified using GINEAPIG simulation)

NLC-90, 250 and Tesla-90 Parameters

	Preliminary! IP Parameters for low energy IR						TESLA-90	
	90 GeV			250 GeV				
	Nominal	Semi-High	Round	Nominal	Semi-High	Round	Nominal	Low
Luminosity (10^{33})	1.3	1.7	4.1	2.7	4.4	7.7	6.5	2.0
Pinch Enhancement	1.3	1.4	4.4	1.4	1.4	3.9		
Repetition Rate (Hz)	60	60	60	60	60	60	5	5
Bunch Charge (10^{10})	1	0.75	0.7	1	0.75	0.7	2.	1.2
Bunches/RF Pulse	95	190	190	95	190	190	2820	2820
Bunch Separation (ns)	2.8	1.4	1.4	2.8	1.4	1.4	337	337
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 3	300 / 2	300 / 3	300 / 3	300 / 2	300 / 3		
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	400	360	360	400	360	360	1000	1000
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	6	3.5	5	7	4	5	3	3
Tolerances	10	10	13	9	9	10		
β_x / β_y at IP (mm)	10 / 0.10	10 / 0.10	1 / 1	10 / 0.12	10 / 0.10	1.3 / 1.3	15/0.4	15/0.4
σ_x / σ_y at IP (nm)	670 / 8	632 / 6	200 / 24	400 / 6	384 / 4	140 / 16	1300/12	1300/12
σ_z at IP (um)	125	100	125	125	100	125	400	400
L0 / Ltotal (%)	55	62	13	40	48	9		
Yave	0.01	0.01	0.03	0.06	0.06	0.12		
Beamstrahlung δB (%)	0.28	0.22	4.2	1.7	1.3	13.9	0.10	0.03
Photons per e+/e-	0.6	0.5	2.5	1	0.8	3.1		
Polarization loss (%) ??	0.1	0.1	0.6	0.3	0.2	1.7		

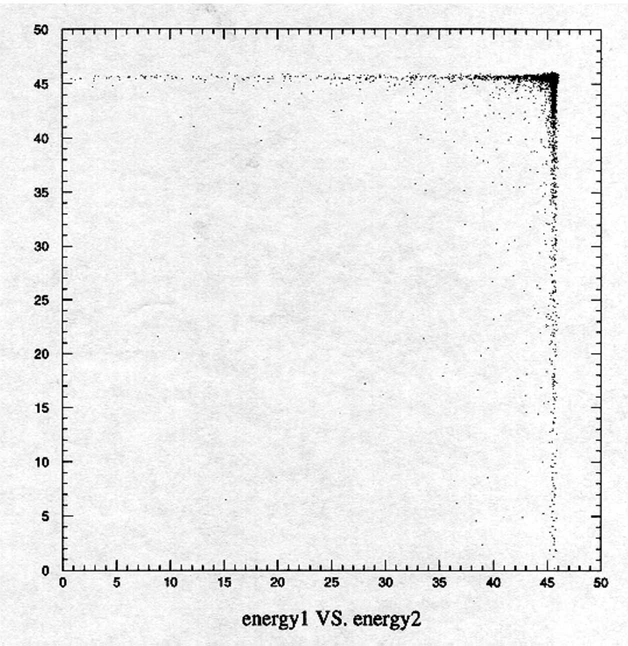
The beamstrahlung effect is highlighted. *Note also that the NLC numbers assume 60 Hz rep.rate in this table - scale to 120 or 180 Hz as needed.*

Recent update from T. Raubenheimer - 180 Hz, and low beamstrahlung options shown.

Luminosity Estimates

	Preliminary! IP Parameters for low energy IR					
	90 GeV		250 GeV		350 GeV	
	1.4 ns	**Low δB**	**1.4 ns**	**Low δB**	**1.4 ns**	**Low δB**
Luminosity (10^{33})	**4.1**	**2**	**10.4**	**5.1**	**14.1**	**7**
Pinch Enhancement	1.4	1.3	1.4	1.3	1.4	1.3
Repetition Rate (Hz)	**180**	**180**	**180**	**180**	**180**	**180**
Bunch Charge (10^{10})	**0.75**	**0.75**	**0.75**	**0.75**	**0.75**	**0.75**
Bunches/RF Pulse	190	190	190	190	190	190
Bunch Separation (ns)	1.4	1.4	1.4	1.4	1.4	1.4
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 3	300 / 3	300 / 3	300 / 3	300 / 3	300 / 3
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	400	400	400	400	400	400
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	**4.6**	**4.6**	**5.2**	**5.2**	**5.5**	**5.2**
Tolerances	**10**	**10**	**10**	**10**	**10**	**10**
β_x / β_y at IP (mm)	10 / 0.12	35 / 0.12	10 / 0.12	35 / 0.12	10 / 0.12	35 / 0.12
σ_x / σ_y at IP (nm)	**670 / 7.8**	**1250 / 7.8**	**404 / 5.1**	**760 / 5.1**	**340 / 4.4**	**640 / 4.4**
σ_z at IP (um)	125	125	125	125	125	125
L0 / Ltotal (%)	62	78	49	67	44	63
Υave	0.007	0.004	0.033	0.017	0.081	0.043
Beamstrahlung δB (%)	0.16	0.05	1	0.31	1.8	0.57
Photons per e+/e-	0.47	0.25	0.75	0.41	0.88	0.48
Polarization loss (%) ??	0.07	0.02	0.2	0.06	0.31	0.09

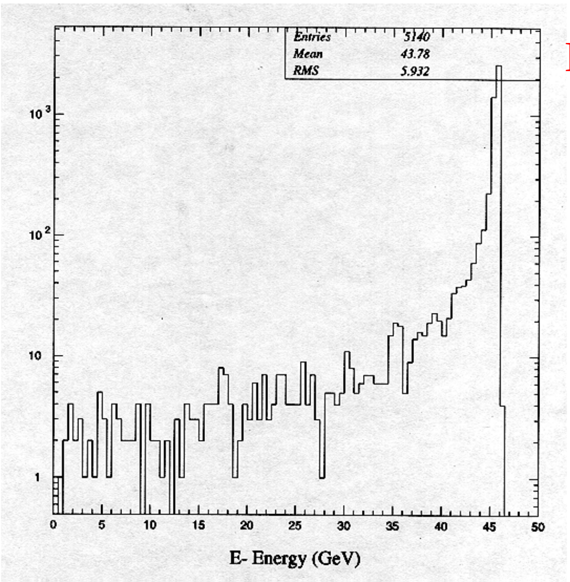
Luminosity Spectra with and without ISR



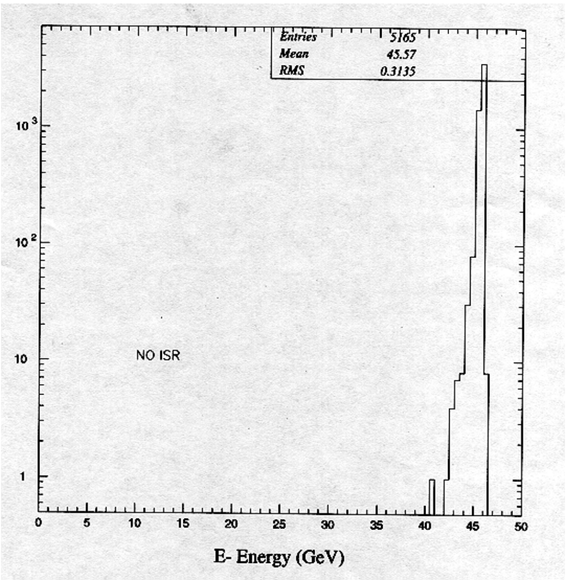
GINEAPIG allows one to separate ISR and beamstrahlung contributions. Beam particles that contribute to luminosity can be separately studied, as done here.

→ **Luminosity weighted corrections**

NLC-90 simultation

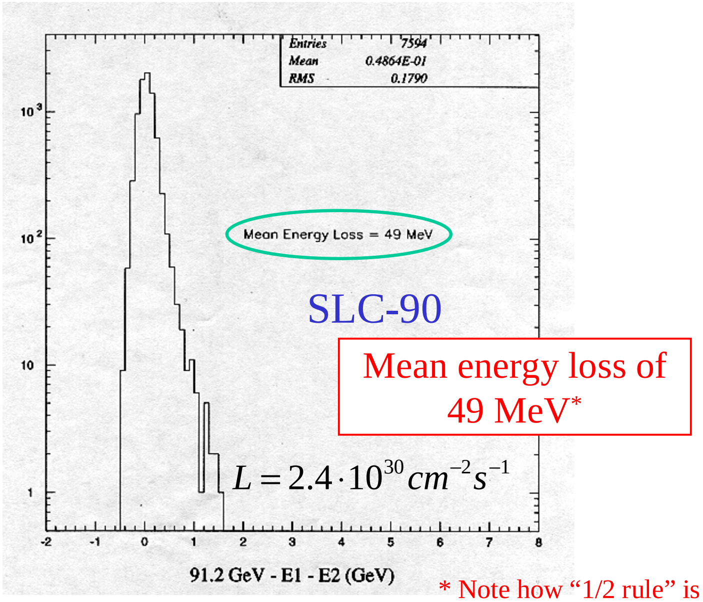


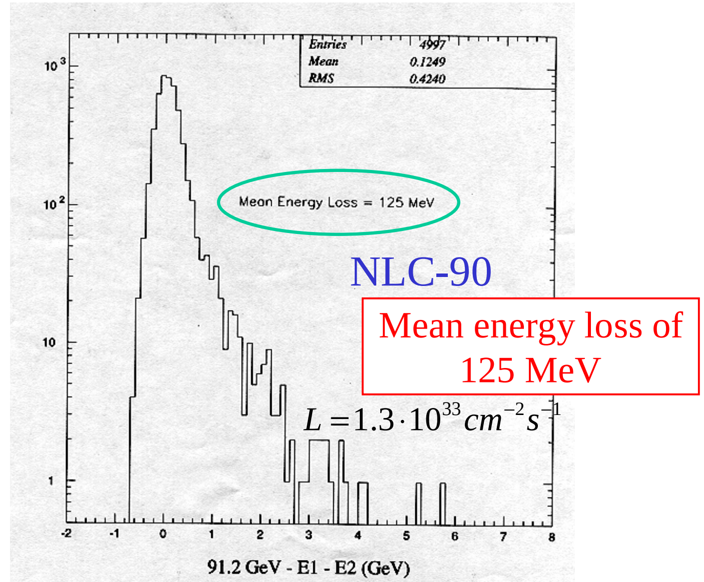
ISR + Beamstrahlung



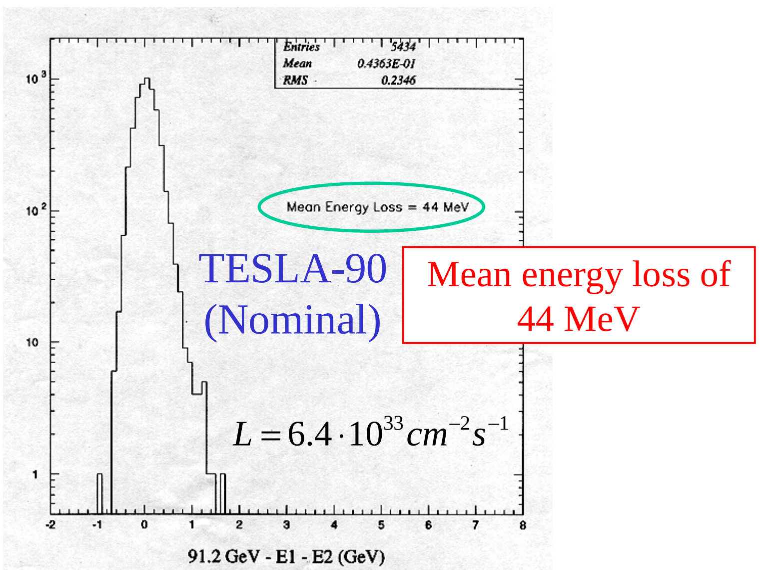
Beamstrahlung Only

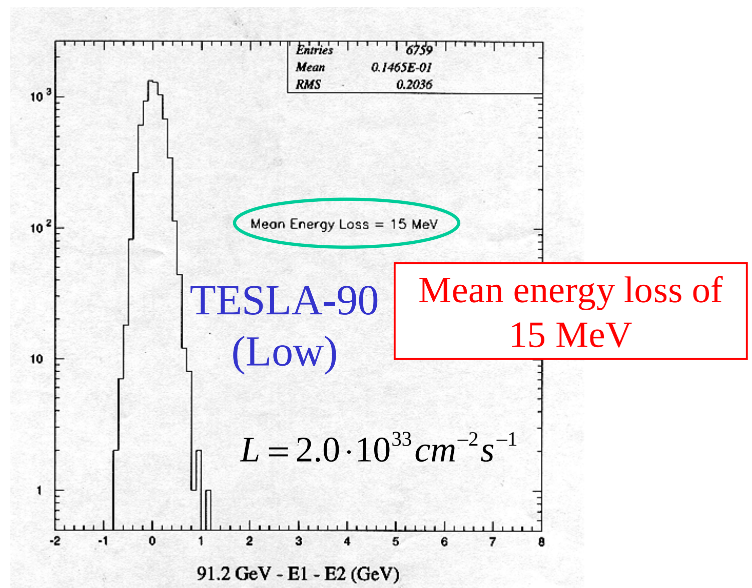
Luminosity weighted E_{CM} Corrections





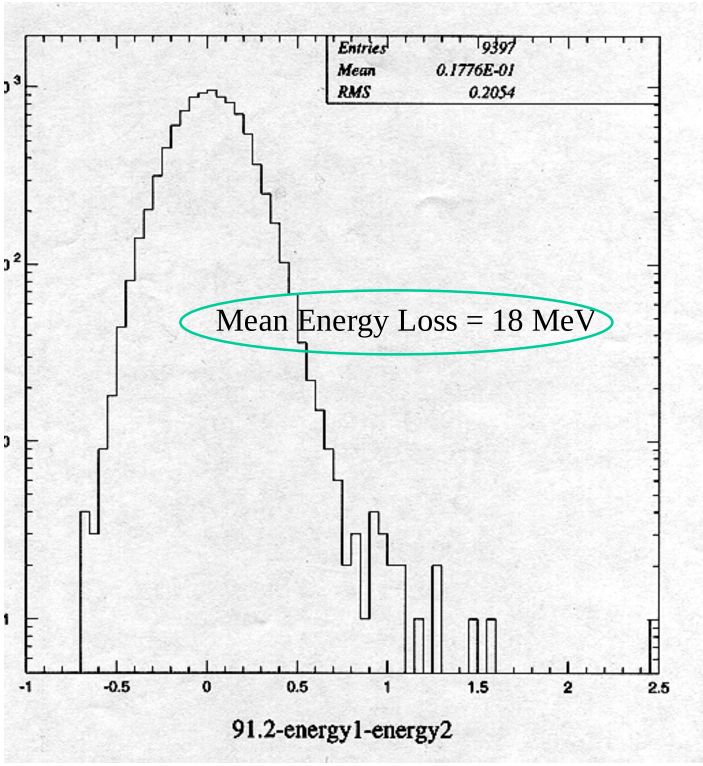
* Note how "1/2 rule" is satisfied





Using NLC-90 Nominal and Tesla-90 Nominal, but increasing β_x by x9.

Significant reduction of the beamstrahlung is possible, at the expense of some luminosity.

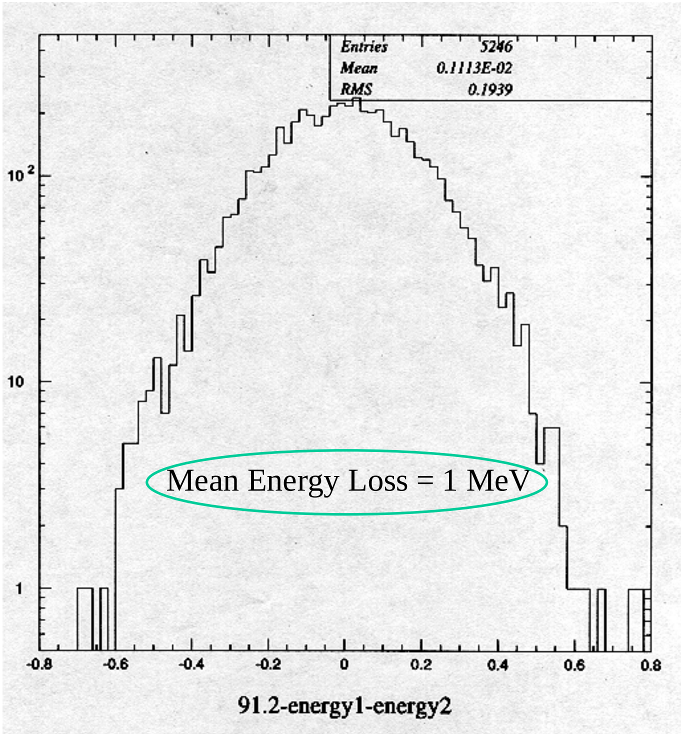


NLC-90

Factor of 4.5 reduction

$L = 2.9 \cdot 10^{32} cm^{-2} s^{-1}$ @60Hz

$L = 8.6 \cdot 10^{32} cm^{-2} s^{-1}$ @180Hz



TESLA-90

Factor of 1.3 reduction

$L = 1.5 \cdot 10^{33} cm^{-2} s^{-1}$

Extraction Line Design

For precise NLC-90 measurements, the extraction line design may not be compatible with high luminosity running of the low energy IR.

May need to reconfigure some aspects of the extraction line between different running modes.

Note *: Extraction line E-losses at the SLC were of order 40 MeV/beam, and known to a few MeV. Losses very much higher than this would become an issue.*

Z-Rate Effects

(Multiple Zs per train)

Z Cross-section: $\sigma^Z = 30.5$ nb,

NLC-90 Luminosity: $L = 1.3 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Z Rate: $R = \sigma^Z \times L = 40$ Z/s

Rep rate = 60Hz, so Z Rate = 0.65 Z/train

=> **52% probability for 0 Zs in a given train**

34% probability for 1 Z in a given train

14% probability for 2 or more Zs in a given train!!

With a data sample of $>10^8$ Zs, need to understand Z multiplicity distribution with better than 0.02% accuracy

TESLA-90 (Low) , R= 60 Z/s = 0.0043Z/bunch

=> **99.57% probability for 0 Zs in a given bunch**

0.43% probability for 1 Z in a given bunch

9.2e-6 probability for 2 or more Zs in a given bunch

With data sample of $>10^8$ Zs, need to understand Z multiplicity distribution with better than 5% accuracy

Z Linewidth Measurement

LEP1 Result: 5M Z peak scan gives $\delta(\Gamma_Z)$ = 2.1 MeV (stat); $\delta(\Gamma_Z)$ = 2.4 MeV (stat+syst)

Systematic errors:

i) Beam Energy measurement: 1.2 MeV

ii) Uncertainty in center-of-mass energy spread

$$\delta(E_{CM}^{rms}) = 1MeV \Rightarrow \delta(\Gamma_Z) = 0.2MeV$$

(At LEP1, beam energy spread = 37 MeV; 0.08%)

Could NLC-90 or TESLA-90 achieve $\delta(\Gamma_Z)$ = 1.0 MeV (stat+syst)??

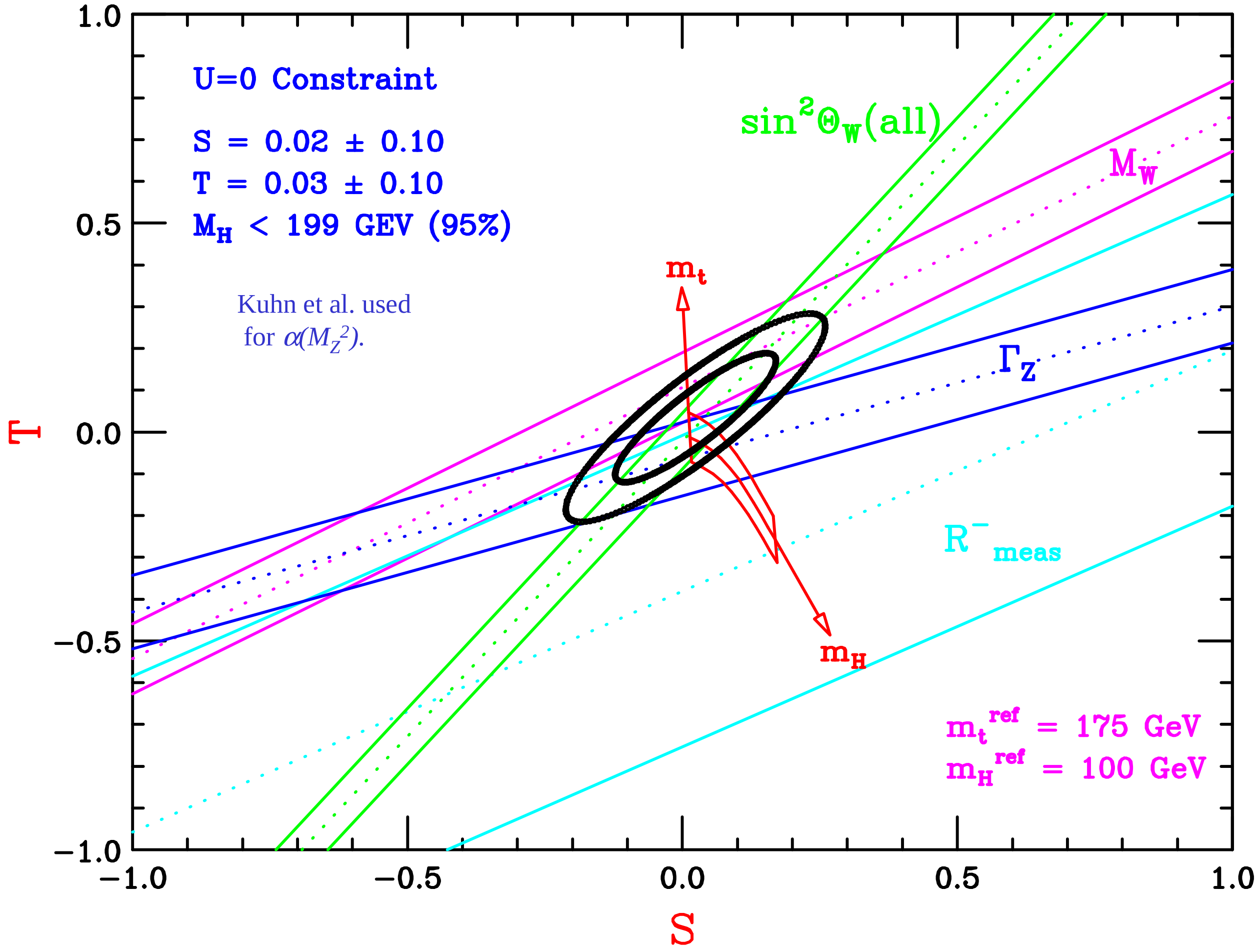
Very unlikely (though easier at TESLA)

- don't have resonant depolarization; need very detailed study to demonstrate feasibility of alternate technique achieving < 1MeV
- want beamsstrahlung correction on $E_{CM}^{lum\text{-}wt}$ < 10 MeV so only need to know correction to 5-10%; but want luminosity high so scan can be done quickly
- need to understand E_{CM} energy spread to < 3-5 MeV
  (NLC-90 0.3% beam energy spread gives E_{CM} energy spread = 190 MeV)

A better electroweak measurement is to improve W mass msmt to $\delta(M_W)$=5-10 MeV

- current uncertainty is 38 MeV (expected to improve to 25 MeV with LEP2 and Tevatron Run 2)
- 5-10 MeV should be achievable at NLC-180, TESLA-180

The utility of the combination of precision mixing angle and M_W results is clear from the ST plot. Although the Z width is more orthogonal, the greater relative improvement possible for the W mass measurement compensates for this fact.



SUMMARY

With only the electron beam polarized, 90%,

→ can improve SLD's A_{LR} measurement by a factor of 5

With 0.25% polarimetry (plausible SLC extrapolation) and with modest luminosity (use $L = 4 \times 10^{32}\ cm^{-2}\ s^{-1}$) to accumulate 50M Zs in 0.4 Snowmass-years. Beamstrahlung correction for $E_{CM}^{lum\text{-}wt}$ should only be about 40 MeV and one needs to know this with 10 MeV accuracy. But still need to study problem of understanding the Z multiplicity (to approx 0.2%). (This measurement is much easier at TESLA-90.)

With $P^- = 90\%$ and $P^+ = 50\%$,

→ to improve SLD's A_{LR} measurement by a factor of 10 or more,

Need to understand $E_{CM}^{lum\text{-}wt}$ at 5 MeV level and to understand Z multiplicity at level of 0.02% at NLC (5% at TESLA-90). This measurement probably only makes sense at TESLA-90, or perhaps the new low beamstrahlung NLC configuration from T. Raubenheimer (@180 Hz rep.rate).

SUMMARY (con't)

To measure Z mass/width to 1 MeV, W mass to 5-10 MeV, top mass to 200 MeV.

Z mass and width : Too hard at NLC-90. Possible, but unlikely, at TESLA-90.

W mass : Should be achievable at NLC-180, TESLA-180, but 5-10 MeV absolute energy calibration of threshold will not be trivial, as some high beamstrahlung scenarios, and the extra extrapolation from Z-pole, will introduce challenges. In addition, the statistical requirements for a W threshold measurement are more of an issue here (than at the Z-pole) - 100 fb^{-1} is required for a 6 MeV precision (K. Mönig's talk).

Top mass : Energy calibration is not the dominant problem.