Precision Electroweak Observables with ILC (the polarizable e^+e^- collider)

Emphasis on Experimental Measurement Aspects Including Polarization

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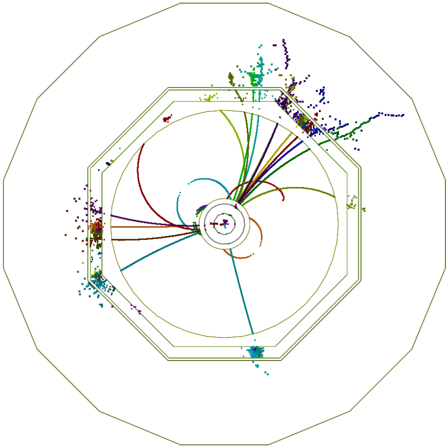
An overview of why many of us think ILC is a unique opportunity for understanding the electroweak scale.

Join us and make it even better! (physics, detector, and accelerator)

More information on EWPO estimates are in arXiv:1908.11299 (K. Fujii et al)

Outline



Physics Motivation & General Remarks

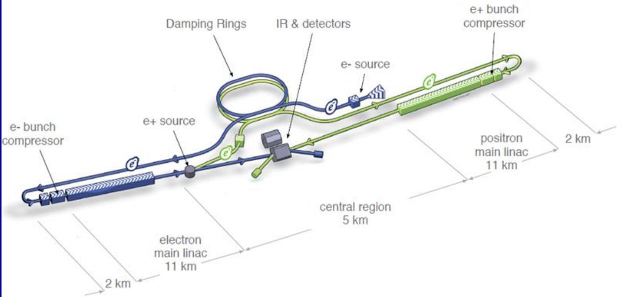
- Direct discovery of new physics would be wonderful. Many of us remain optimistic (also e^+e^- colliders have potential) and work on such searches with LHC.
- Before the direct discoveries of the top quark and the Higgs boson, precision measurements of the then observable SM parameters pointed the way.
- I have been working part-time on a future e^+e^- collider since 1995. I thought the Higgs should be discoverable at the Tevatron and would kick-start linear collider construction. With these two things in mind, I moved to the US in 2001 after LEP wrapped up.
- Newer physics may continue to evade direct collider detection. Ultra-precise measurements of the fundamental SM parameters including the Higgs sector are especially compelling and can probe potentially much higher energy scales and associated new physics.
- How best to do this? The program needs to be flexible, timely, broad and probing of the underlying dynamics. Precision measurements at high energy, with full reconstruction of processes such as W^+W^- and $f\bar{f}$. But also high precision measurements of other parameters at suitable $\sqrt{s}$ including top-threshold and Z-pole and potentially WW threshold with controlled systematics. **Polarized beams** (ILC strength - 4 colliders-in-1) give essential insight.
- The physics case for a future e^+e^- collider is very well established. Let's seize this opportunity and explore the physics (preferably in our lifetime).

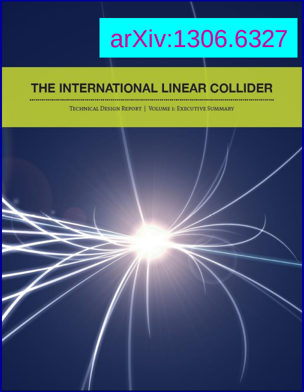
e^+e^- Linear Colliders

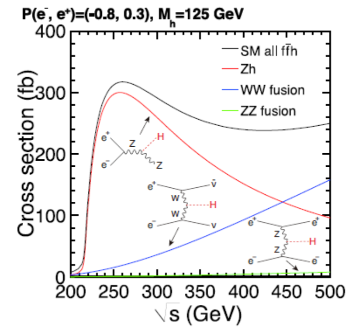
Linear colliders are the only practical way with e^+e^- to go significantly above the top pair threshold (synchrotron radiation and real-world economics)

- ILC is based on superconducting RF (mature and power efficient)
  - Under study and development for many years
  - World-wide consensus in 2001 as the next future collider
  - Fully international project with strong participation from US, Europe and Asia
  - Technology deployed in many facilities: XFEL, LCLS-II
- ILC TDR 2013 - focus on engineered design capable of $\sqrt{s} = 200 - 500$ GeV upgradable to 1 TeV and potentially beyond
  - longitudinally polarized electron (80%) and positron (30%) beams
  - Japan is exploring hosting the ILC as a global project
  - With the Higgs discovery - can guarantee a rich physics program
- In recent years → a focus on getting started as soon as possible at $\sqrt{s} = 250$ GeV while retaining energy extensibility
  - Optimized design for $\sqrt{s} = 250$ GeV with higher luminosity
  - Now also have easily achievable running with polarized beams at lower energies including $\sqrt{s} \approx M_Z$ with $L = 4.2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - New appreciation in Japan of the longer-term opportunities with higher energy

International Linear Collider Project





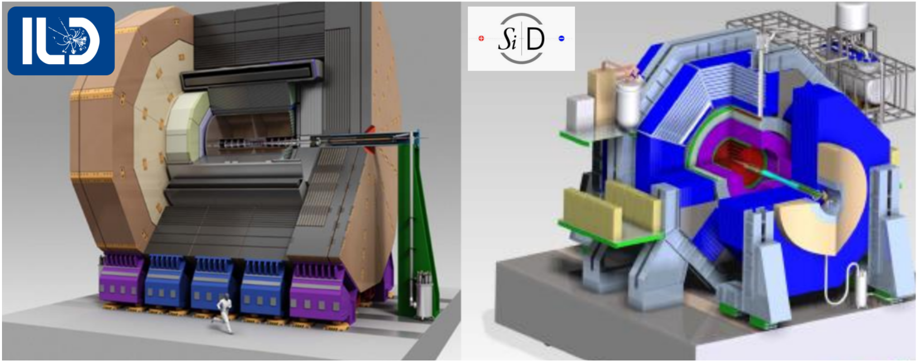


ILC Detectors

Described in arXiv:1306.6329.

ILD = International Large Detector
(also arXiv:2003.01116)

SiD = Silicon Detector

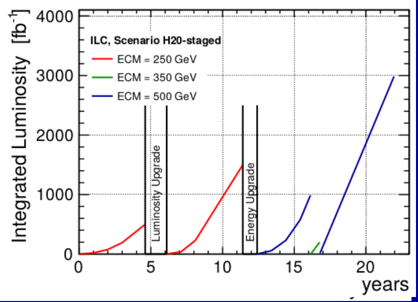


Modern detectors designed for ILC (B=3.5-5 T).
Particle-flow for jets. Very hermetic. Low material. Precision vertexing.
ILD centered around a TPC. SiD - all silicon tracking.

ILC Parameters / Running Scenarios

J. Brau et al., arXiv: 1506.07830

Updated in 1903.01629



- Baseline scenario for study
- Run plan flexible - will evolve informed by future developments
- Future upgrade to 1 TeV and potentially beyond
- Options for dedicated running with polarized beams at Z-pole (100 fb^{-1}) and WW threshold (500 fb^{-1}).

	integrated luminosity with sgn$(P(e^-), P(e^+))$ =			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]
250 GeV	1350	450	100	100
350 GeV	135	45	10	10
500 GeV	1600	1600	400	400

6200 fb^{-1} total

200 fb^{-1} at $\sqrt{s} \approx 350$ GeV

ILC Physics

- Physics studies at future e^+e^- colliders.
- Seeds were planted in the mid-80's.
- Now a vast literature.
- 3 recent publications.
  - K. Fujii et al
    - arXiv:1506.05992
  - G. Moortgat-Pick et al.,
    - arXiv:1504.01726
  - H. Baer et al,
    - arXiv:1306.6352

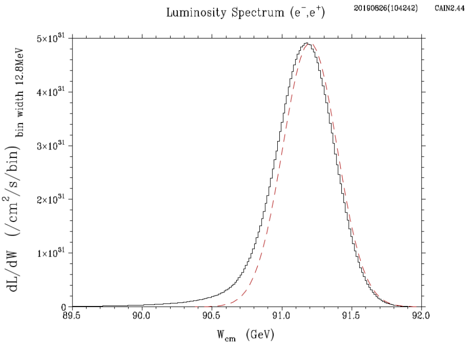
See references slide 28 containing more recent documents with consistent assumptions

Topic	Parameter	Initial Phase	Full Data Set	units
Higgs	m_h	25	15	MeV
	$g(hZZ)$	0.58	0.31	%
	$g(hWW)$	0.81	0.42	%
	$g(hb\bar{b})$	1.5	0.7	%
	$g(hgg)$	2.3	1.0	%
	$g(h\gamma\gamma)$	7.8	3.4	%
		1.2	1.0	%, w. LHC results
	$g(h\tau\tau)$	1.9	0.9	%
	$g(hc\bar{c})$	2.7	1.2	%
	$g(ht\bar{t})$	18	6.3	%, direct
		20	20	%, $t\bar{t}$ threshold
	$g(h\mu\mu)$	20	9.2	%
	$g(hhh)$	77	27	%
	Γ_{tot}	3.8	1.8	%
	Γ_{invis}	0.54	0.29	%, 95% conf. limit
Top	m_t	50	50	MeV (m_t(1S))
	Γ_t	60	60	MeV
	g_L^γ	0.8	0.6	%
	g_R^γ	0.8	0.6	%
	g_L^Z	1.0	0.6	%
	g_R^Z	2.5	1.0	%
	F_2^γ	0.001	0.001	absolute
	F_2^Z	0.002	0.002	absolute
W	m_W	2.8	2.4	MeV
	g_1^Z	8.5×10^{-4}	6×10^{-4}	absolute
	κ_γ	9.2×10^{-4}	7×10^{-4}	absolute
	λ_γ	7×10^{-4}	2.5×10^{-4}	absolute
Dark Matter	EFT Λ: D5	2.3	3.0	TeV, 90% conf. limit
	EFT Λ: D8	2.2	2.8	TeV, 90% conf. limit

ILC running below $\sqrt{s} = 250$ GeV ?

Always foreseen as an "option" that should be justifiable by the physics du jour

- ILC TDR design focused on $\sqrt{s} > 200$ GeV
- Luminosity naturally scales with γ at a linear collider
- Now have a design that leads to $L = 4.2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s} = 91$ GeV with polarized beams (see arXiv:1908.08212 by Yokoya, Kubo and Okugi [3])
- Enables a broader program of electroweak measurements
- High statistics Z samples for detector calibration and alignment, and hadronization modeling



How well can we make use of this? Control systematics? $100\ \mathrm{fb}^{-1}$ polarized corresponds to 4.2×10^9 hadronic events and 2.0×10^8 dimuons. FWHM is about 500 MeV (beam momentum spread + beamstrahlung). Lots of fun questions to explore.

$\mu^+\mu^-/Z$ ubiquity (in $\sqrt{s}$ scale discussion)

These slides have $\mu^+\mu^-$ or Z in many places, from different sources, and for varied, but usually related purposes.

1. Full energy $\mu^+\mu^-$: $\mathrm{e^+e^-} \to \mu^+\mu^-$ with little ISR ($s' \approx s \gg M_{\mathrm{Z}}^2$)
2. Radiative return $\mu^+\mu^-$: $\mathrm{e^+e^-} \to \mu^+\mu^-\gamma(\gamma)$ with lots of ISR ($s \gg s' \approx M_{\mathrm{Z}}^2$). The photon(s) may or may not be detected.
3. Z-pole $\mu^+\mu^-$: $\mathrm{e^+e^-} \to \mu^+\mu^-$ with $\sqrt{s}$ near M_{Z}
4. $J/\psi \to \mu^+\mu^-$: A common source of J/ψ is from $\mathrm{Z} \to \mathrm{b\bar{b}}$.

Why?

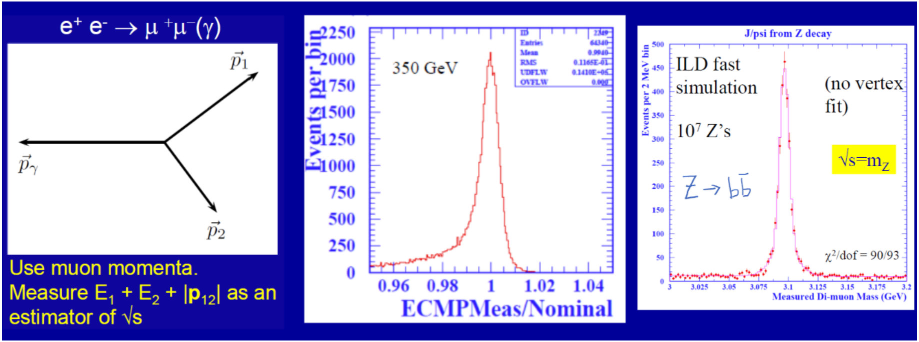
- The old method of choice for $\sqrt{s}$ estimation at ILC was to use radiative return $\mu^+\mu^-$ and rely only on the angle reconstruction. Robust - but suffers statistically due to $\Gamma_{\mathrm{Z}}/M_{\mathrm{Z}}$ and relies on M_{Z} (23 ppm)
- New method for $\sqrt{s}$ estimation uses all $\mu^+\mu^-$ (both full energy, intermediate energy, radiative return) to form a muon-momentum based estimator, $\sqrt{s}_{\mathrm{P}}$.
- In turn $\sqrt{s}_{\mathrm{P}}$ needs the tracker momentum-scale to be calibrated to high precision. Principally use $J/\psi \to \mu^+\mu^-$ for this. Z running is very helpful.
- Given the 0.15% tracker momentum resolution, Z-pole $\mu^+\mu^-$, can also be used to measure $\sqrt{s}$ for Z-pole runs (limited by 1.9 ppm $m_{J/\psi}$ knowledge).

Center-of-Mass Energy Measurement

Critical input for M_{t}, M_{W}, M_{H}, M_{Z}, M_{X} measurements

1. Standard precision of $\mathcal{O}(10^{-4})$ in $\sqrt{s}$ for M_{t} straightforward
2. Targeting precision of $\mathcal{O}(10^{-5})$ in $\sqrt{s}$ for M_{W} given likely systematics
3. For M_{Z} - helps to do even better

Use muon momenta method. Tie p to the J/ψ mass scale (1.9 ppm uncertainty).



Measure $<\sqrt{s}>$ and lumi. spectrum simultaneously. Expect stat. uncertainty of 2.0 ppm on p-scale per 300k $J/\psi \to \mu^+\mu^-$ (10^9 hadronic Z's).

Longitudinally Polarized Beams

ILC baseline design has e^- polarized to 80%, e^+ to 30%

- $P_{\mathrm{e}^-} = 90\%$ is not out of the question
- $P_{\mathrm{e}^+} = 60\%$ is under study and may be feasible

In contrast to circular colliders, longitudinal polarization is easier and not expected to cost luminosity.

$$\sigma(P_{\mathrm{e}^-}, P_{\mathrm{e}^+}) = \frac{1}{4}\{(1 - P_{\mathrm{e}^-})(1 + P_{\mathrm{e}^+})\sigma_{LR} + (1 + P_{\mathrm{e}^-})(1 - P_{\mathrm{e}^+})\sigma_{RL} + (1 - P_{\mathrm{e}^-})(1 - P_{\mathrm{e}^+})\sigma_{LL} + (1 + P_{\mathrm{e}^-})(1 + P_{\mathrm{e}^+})\sigma_{RR}\}$$

where σ_k ($k =$ LR, RL, LL and RR) are the fully polarized cross-sections.

With both beams polarized it is **straightforward** to measure accurately the absolute polarization of both beams *in situ* for processes like s-channel vector exchange with $\sigma_{LL} = \sigma_{RR} = 0$. Using 4 cross-section measurements from the $(-+, +-, --, ++)$ helicity combinations, solve for 4 unknowns (σ_U, A_{LR}, P_{e^-}, P_{e^+}). Assumes same $|P|$ for $+$ and $-$ helicity of same beam.

Supplement with polarimeters to track relative polarization changes. (Also can use $\mathrm{W}^+\mathrm{W}^-$ etc at high $\sqrt{s}$)

W Mass

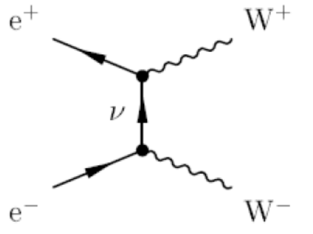
M_{W} is an experimental challenge. Especially so for hadron colliders.

The four most promising approaches to measure M_{W} at an e^+e^- collider are:

1. Polarized Threshold Scan Measurement of the $\mathrm{W}^+\mathrm{W}^-$ cross-section near **threshold** with longitudinally polarized beams.
2. Constrained Reconstruction Kinematically-constrained reconstruction of $\mathrm{W}^+\mathrm{W}^-$ using constraints from **four-momentum conservation** and optionally mass-equality as was done at LEP2.
3. Hadronic Mass Direct measurement of the **hadronic mass**. This can be applied particularly to single-W events decaying hadronically or to the hadronic system in semi-leptonic $\mathrm{W}^+\mathrm{W}^-$ events.
4. Leptonic Observables Use lepton endpoints in semi-leptonic and fully leptonic $\mathrm{W}^+\mathrm{W}^-$ events with either $\mathrm{W} \to \mathrm{e}\nu_e$ or $\mathrm{W} \to \mu\nu_\mu$. Use pseudomasses in dileptons.

Method 1 needs dedicated running near $\sqrt{s} = 161$ GeV. Methods 2, 3, and 4 can exploit the standard $\sqrt{s} \geq 250$ GeV ILC program (deserve more study). Methods 1, 2, and 4 rely on $\sqrt{s}$ scale systematic control. Target 2 MeV uncertainty on M_{W}.

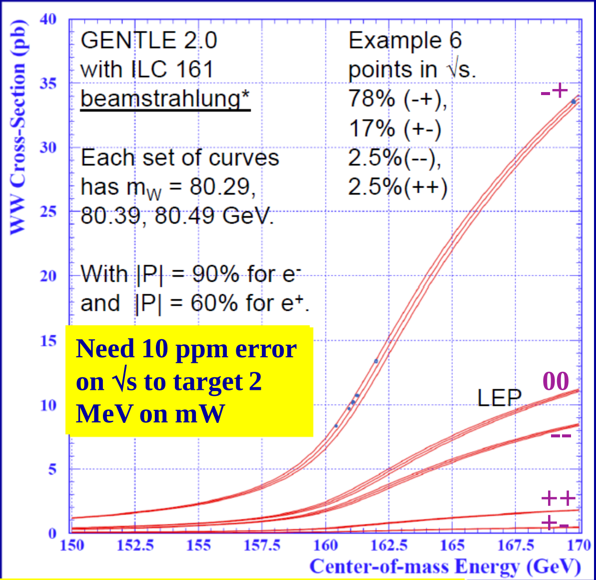
ILC Polarized Threshold Scan



Use (-+) helicity combination of e⁻ and e⁺ to enhance WW.

Use (+-) helicity to suppress WW and measure background.

Use (--) and (++) to control polarization (also use 150 pb Z-like events)



Experimentally very robust. Measure pol., bkg. in situ

Results from updated ILC study (arXiv:1603.06016)

Fit parameter	Value	Error
m_W (GeV)	80.388	3.77×10^{-3}
f_l	1.0002	0.924×10^{-3}
ε (lvlv)	1.0004	0.969×10^{-3}
ε (qqlv)	0.99980	0.929×10^{-3}
ε (qqqq)	1.0000	0.942×10^{-3}
σ_B (lvlv) (fb)	10.28	0.92
σ_B (qqlv) (fb)	40.48	2.26
σ_B (qqqq) (fb)	196.37	3.62
A^B_{LR} (lvlv)	0.15637	0.0247
A^B_{LR} (qqlv)	0.29841	0.0119
A^B_{LR} (qqqq)	0.48012	4.72×10^{-3}
$\lvert P(e^-)\rvert$	0.89925	1.27×10^{-3}
$\lvert P(e^+)\rvert$	0.60077	9.41×10^{-4}
σ_{Z} (pb)	149.93	0.052
A^{Z}_{LR}	0.19062	2.89×10^{-4}

Example 6-point ILC scan with 100 fb^{-1}

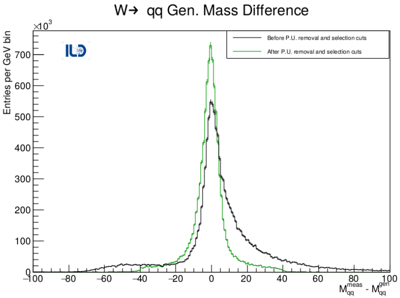
$\lvert P(e^-)\rvert$	$\lvert P(e^+)\rvert$	100 fb^{-1}	500 fb^{-1}
80 %	30 %	6.02	2.88
90 %	30 %	5.24	2.60
80 %	60 %	4.05	2.21
90 %	60 %	3.77	2.12

Total M_{W} experimental uncertainty (MeV)

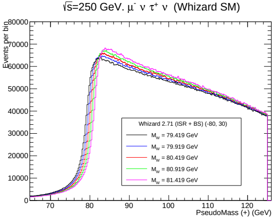
Fit essentially includes experimental systematics. Main one - background determination.

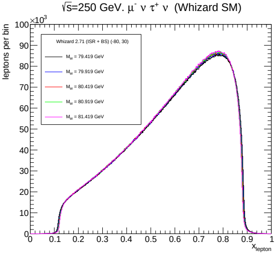
$$\Delta M_{\mathrm{W}}(\mathrm{MeV}) = 2.4\,(\mathrm{stat}) \oplus 3.1\,(\mathrm{syst}) \oplus 0.8\,(\sqrt{\mathrm{s}}) \oplus \mathrm{theory}$$

$M_{\rm W}$ from higher energy runs (work in progress)



$\mathrm{W^+W^-} \to \mathrm{q\bar{q}}\ell\nu$ $(\ell = \mathrm{e}, \mu, \tau)$ study (J. Anguiano (KU)), using **hadronic mass**. Statistical sensitivity of 2.4 MeV on $M_{\rm W}$ for 1.6 ab^{-1} (-80%, +30%) at $\sqrt{s} = 500$ GeV based on full simulation including overlay. Likely can be improved but $m_{\rm had}$-only measurement will be limited by systematics like JES.





Stat. uncertainty of 4.4 MeV on $M_{\rm W}$ for 2.0 ab^{-1} (45,45,5,5) at $\sqrt{s} = 250$ GeV. **Leptonic observables** (shape-only), x_ℓ, M_+, M_- (GWW) Exptl. systematics should be small.

Polarization Observables

At a polarized e^+e^- collider, A_e is given by the left-right asymmetry in the total rate for Z production,

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)} \ ,$$

where σ_L and σ_R are the cross section for 100% polarized $e^-_L e^+_R$ and $e^-_R e^+_L$ initial states. For other asymmetries, beam polarization can also play a role. These quantities are measured from the left-right forward-backward asymmetry

$$A^f_{FB,LR} \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \ ,$$

where, again, L and R refer to states of 100% polarization. At the tree level,

$$A^f_{FB,LR} = \frac{3}{4} A_f \ .$$

For unpolarized/polarized collider, the A_f values can again be obtained from quantities such as the forward-backward asymmetry using charge-identified fermion $\frac{d\sigma}{d\cos\theta}$

$$A^f_{FB} \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{[(\sigma_F)_L + (\sigma_F)_R] - [(\sigma_B)_L + (\sigma_B)_R]}{[(\sigma_F)_L + (\sigma_F)_R] + [(\sigma_B)_L + (\sigma_B)_R]} = \frac{3}{4} A_e A_f \ ,$$

A_{LR} at $\sqrt{s} = M_{\mathrm{Z}}$

Studied by K. Mönig 1999
For $\mathrm{Z} \to \mathrm{f\bar{f}}$, general cross-section formula simplifies to

$$\sigma = \sigma_u[1 - P^+ P^- + A_{\mathrm{LR}}(P^+ - P^-)]$$

With four combinations of helicities, 4 equations in 4 unknowns. Can solve for A_{LR} in terms of the four measured cross-sections (assumes helicity reversal for each beam maintains identical absolute polarization).

$$\begin{aligned}
\sigma_{++} &= \sigma_u[1 - P^+ P^- + A_{\mathrm{LR}}(P^+ - P^-)] \\
\sigma_{-+} &= \sigma_u[1 + P^+ P^- + A_{\mathrm{LR}}(-P^+ - P^-)] \\
\sigma_{+-} &= \sigma_u[1 + P^+ P^- + A_{\mathrm{LR}}(P^+ + P^-)] \\
\sigma_{--} &= \sigma_u[1 - P^+ P^- + A_{\mathrm{LR}}(-P^+ + P^-)]
\end{aligned}$$

For $P^- = 0.8$, $P^+ = 0.6$, $f_{\mathrm{SS}} = 0.08$, $\sigma_U^{vis} = 33$ nb:

$$\Delta A_{\mathrm{LR}}(\mathrm{stat}) = 1.7 \times 10^{-5} / \sqrt{\mathrm{L}(100\ \mathrm{fb}^{-1})}$$

A_{LR} Systematics

Statistical Systematics

Source		Multiplicative Factor
Bhabha Statistics	relative L ($\sigma_{\mathrm{Bhabha}} = 250$ nb)	1.09
Compton Statistics	relative P of opposite helicity	1.34

Center-of-mass Energy

$dA_{\mathrm{LR}}/d\sqrt{s} = 2.0 \times 10^{-2}\ \mathrm{GeV}^{-1}$. 10 ppm on $\sqrt{s} \Rightarrow 1.8 \times 10^{-5}$ on A_{LR}

Beamstrahlung

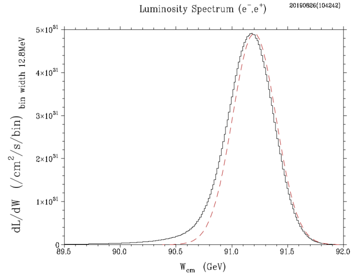
Depends on machine. Previous study (TESLA) estimated a change in A_{LR} of 9×10^{-4}. Assume known to 2% $\Rightarrow 1.8 \times 10^{-5}$ on A_{LR}

$$\Delta A_{\mathrm{LR}}(10^{-5}) = 2.4/\sqrt{L(100\ \mathrm{fb}^{-1})}\,(\mathrm{stat}) \oplus 1.8\,(\sqrt{\mathrm{s}}) \oplus 1.8(\mathrm{BS})$$

Can target experimental precision of 4×10^{-5} with 100 fb^{-1}. Oft-cited 10^{-4} prospect (1.3×10^{-5} on $\sin^2\theta^{\ell}_{\mathrm{eff}}$) with 30 fb^{-1} is well within reach (ie is conservative).
Note that $\sin^2\theta^{\ell}_{\mathrm{eff}}$ interpretation depends amongst others on improved knowledge of $\Delta\alpha_{\mathrm{had}}$.

Center-of-mass Energy Calibration around the Z-Pole

Expected lumi. spectrum at the Z, has a FWHM of about 500 MeV ($\sigma \approx 215$ MeV). Tracker momentum resolution per muon is 0.15% (88 MeV on $\sqrt{s}$). Leads to an average stat. uncertainty per di-muon event of ≈ 232 MeV. So one can measure the average $\sqrt{s}$ with a stat. uncertainty of 0.18 ppm with the 100 fb^{-1} A_{LR} optimized run at M_{Z} (2×10^8 $\mathrm{e}^+\mathrm{e}^- \rightarrow Z \rightarrow \mu^+\mu^-$).



In the same data taking, one can measure the tracker momentum scale with 1.0 ppm stat. uncertainty using $J/\psi \rightarrow \mu^+\mu^-$, more than saturating the 1.9 ppm syst. uncertainty from the known J/ψ mass. Note that the idea is to collect Z events and use these to measure cross sections, center-of-mass energy/lumi spectrum and momentum scale simultaneously. Potentially even bunch-by-bunch under the exact same conditions.

If one really can target an overall momentum scale uncertainty at the 2.5 ppm level (previously, I had assumed conservatively? 10 ppm motivated by the M_{W} target), one will want to use whatever is achievable to improve on the current 23 ppm uncertainty on M_{Z}. Presumably uncertainties on M_{Z} as low as 230 keV are thinkable (2.5 ppm).

Higher Energy: Triple Gauge Couplings ($WW\gamma$, WWZ)

A key observation is that there are many 4f processes in addition to simply W^+W^-. Of particular importance are "single-W" processes, $e^+e^- \to W^-e^+\nu_e$ and $e^+e^- \to W^+e^-\overline{\nu_e}$. These are very helpful in experimentally disentangling the beam polarizations, P_{e^-} and P_{e^+}, and constraining residual non-ideal spin-flip issues, especially in processes like these where the LL or RR cross sections are non-zero.

	250 GeV W^+W^-	350 GeV W^+W^-	500 GeV W^+W^-	1000 GeV W^+W^-
g_{1Z}	0 .062	0.033	0.025	0.0088
κ_A	0.096	0.049	0.034	0.011
λ_A	0.077	0.047	0.037	0.0090
$\rho(g_{1Z}, \kappa_A)$	63.4	63.4	63.4	63.4
$\rho(g_{1Z}, \lambda_A)$	47.7	47.7	47.7	47.7
$\rho(\kappa_A, \lambda_A)$	35.4	35.4	35.4	35.4

Table 13: Projected statistical errors, in %, for $e^+e^- \to W^+W^-$ measurements input to our fits. The errors are quoted for luminosity samples of 500 fb^{-1} divided equally between beams with -80% electron polarisation and +30% positron polarisation and brams with +80% electron polarisation and -30% positron polarisation. Please see the text of Appendix B for further explanation of this table.

Table based on full simulation studies and their extrapolation with ILD. Clearly higher energy is better especially given the γ scaling of luminosity.
See thesis by Robert Karl (DESY) with work on a multi-channel global fit including correlations. Now being extended by Jakob Beyer who is interested in giving a talk in future EF04 venues.

Global TGC Fit Appetizer (Jakob Beyer)

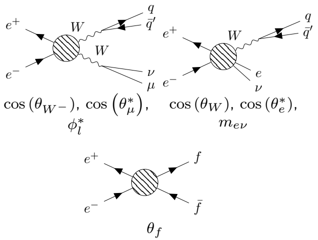
Global fit including (WIP):

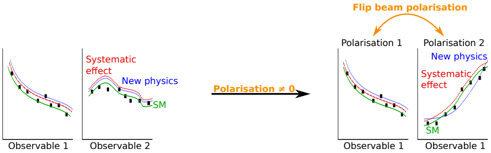
Processes:

- $e^+e^- \to q\bar{q}\mu\nu$
- $e^+e^- \to q\bar{q}e\nu$
- $e^+e^- \to q\bar{q}$

Parameters:

- cTGCs (LEP-parametrisation)
- chiral asymmetries (A_e, A_f)
- Polarisations
- Luminosity
- **Systematics** (μ-efficiency)





- How do systematic effects influence cTGC+Polarisation fit?
- Can polarisation isolate and eliminate them?

DESY. | cTGCs @ e^+e^- | Jakob Beyer | Hamburg, 15.06.2020

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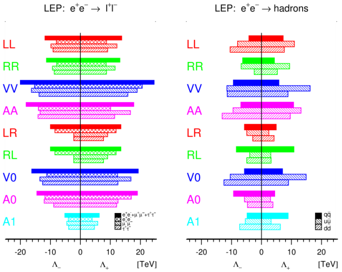
See LEP2 studies with cross-sections and A_{FB} / (ILC adds $A_{LR}, A^{f}_{FB,LR}$)

$$\mathcal{L}_{\rm eff} = \frac{g^2}{(1+\delta)\Lambda_{\pm}^2} \sum_{i,j=L,R} \eta_{ij} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j,$$



LEP2

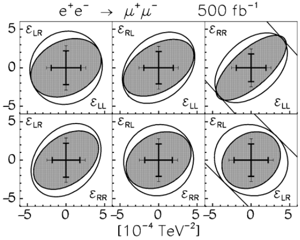


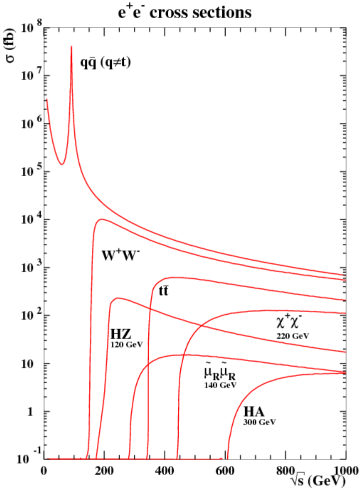
Fig. 1. Two-dimensional projections of the 95% C.L. allowed region (27) for $e^+e^- \to \mu^+\mu^-$ at $\mathcal{L}_{\rm int} = 50$ fb^{-1} and $\mathcal{L}_{\rm int} = 500$ fb^{-1}. Note that the scales are different. $|P_e| = 0.8$, $|P_{\bar{e}}| = 0.0$ (outer ellipse) and $|P_{\bar{e}}| = 0.6$ (inner ellipse). The solid crosses represent the 'one-parameter' bounds under the same conditions.

At ILC, can follow a more model independent approach. Example Ref. 2. Polarization gives access to full 4-parameter space (LR,RL,LL,RR).

Current ILC projections - see arXiv:1908.11299 extend to 151 to 478 TeV for Λ in various models (driven by 8 ab^{-1} at 1 TeV).

Detector Calibration and Alignment

"clean" e^+e^- environment. But particle-based calibration at high $\sqrt{s}$ has



Challenges

- cross-sections
- duty-cycle (power-pulsing)
- "push-pull"
- seismic tolerance
- thermal issues
- unprecedented precision goals

Part of the solution

Accelerator capable of "calibration runs" at the Z with reasonable luminosity. Z running is the most statistically effective way to calibrate the detector - can be essential to fully exploiting the ILC at all $\sqrt{s}$. Design this in!

Done!

Hadronization Systematics

How does a W, Z, H, t decay hadronically?

Models like PYTHIA, HERWIG etc have been tuned extensively to data. Not expected to be a complete picture.

Inclusive measurements of **identified particle rates** and **momenta spectra** are an essential ingredient to describing hadronic decays of massive particles.

ILC could provide comprehensive measurements with up to 1000 times the published LEP statistics and with a much better detector with Z running.

High statistics with W events.

Why?

Measurements based on hadronic decays, such as hadronic mass, jet directions underlie much of what we do in energy frontier experiments.

Key component of understanding jet energy scales and resolution.

Important to also understand flavor dependence: u-jets, d-jets, s-jets, c-jets, b-jets, g-jets.

Momentum Scale Calibration (essential for $\sqrt{s}$)

Most obvious is to use $J/\psi \to \mu^+\mu^-$. But event rate is limited.

Particle	$n_{Z\text{had}}$	Decay	BR (%)	$n_{Z\text{had}} \cdot$ BR	Γ/M	PDG $(\Delta M/M)$
J/ψ	0.0052	$\mu^+\mu^-$	5.93	0.00031	3.0×10^{-5}	**1.9** $\times 10^{-6}$
K^0_S	1.02	$\pi^+\pi^-$	69.2	0.71	1.5×10^{-14}	2.6×10^{-5}
Λ	0.39	$\pi^- p$	63.9	0.25	2.2×10^{-15}	5.4×10^{-6}
D^0	0.45	$K^-\pi^+$	3.88	0.0175	8.6×10^{-13}	2.7×10^{-5}
K^+	2.05	various	-	-	1.1×10^{-16}	3.2×10^{-5}
π^+	17.0	$\mu^+\nu_\mu$	100	-	1.8×10^{-16}	2.5×10^{-6}

Candidate particles for momentum scale calibration and abundances in Z decay

Sensitivity of mass-measurement to p-scale (α) depends on daughter masses and decay

$$m_{12}^2 = m_1^2 + m_2^2 + 2p_1p_2\left[(\beta_1\beta_2)^{-1} - \cos\psi_{12}\right]$$

Particle	Decay	$<\alpha>$	max α	σ_M/M	$\Delta p/p$ (10 MZ)	$\Delta p/p$ (GZ)	PDG limit
J/ψ	$\mu^+\mu^-$	0.99	0.995	7.4×10^{-4}	13 ppm	1.3 ppm	1.9 ppm
K^0_S	$\pi^+\pi^-$	0.55	0.685	1.7×10^{-3}	1.2 ppm	0.12 ppm	38 ppm
Λ	$\pi^- p$	0.044	0.067	2.6×10^{-4}	3.7 ppm	0.37 ppm	80 ppm
D^0	$K^-\pi^+$	0.77	0.885	7.6×10^{-4}	2.4 ppm	0.24 ppm	30 ppm

Estimated momentum scale statistical errors ($p = 20$ GeV)

Use of J/ψ would decouple $\sqrt{s}$ determination from M_Z knowledge.

Opens up improved M_Z and Γ_Z measurements. (B-field map, alignment, material etc.)

Summary

- ILC can advance greatly our knowledge of electroweak precision physics.
- Polarized electron and **positron** beams are a unique asset.
- Can deliver much more rigorous test of the SM which explores new physics. Highlighted by top mass measurement and

$$\Delta M_{\mathrm{W}} = 2 - 3\,\mathrm{MeV}$$

$$\Delta A_{\mathrm{LR}}(10^{-5}) = 2.4/\sqrt{L(100\ \mathrm{fb}^{-1})}\,(\mathrm{stat})\ \oplus 1.8\,(\sqrt{\mathrm{s}})\ \oplus 1.8(\mathrm{BS})$$

- Scope for best M_{W} measurements from standard ILC running.
- Experimental strategies for controlling systematics associated with $\sqrt{s}$, polarization, luminosity spectrum are worked out.
- Momentum scale is a key. Enabled by precision low material tracker. Promises to also open up precision measurement advances for M_{Z}, Γ_{Z}.
- Generally need more study on experimental/accelerator systematics
- An accelerator is needed! On-going encouraging developments in Japan.
- The physics discussed here benefits greatly given that the accelerator is now designed to include efficient running at lower $\sqrt{s}$.

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arXiv:1908.11299 [hep-ex]

[2] A. Babich, P. Osland, A. Pankov and N. Paver,
New physics signatures at a linear collider: Model independent analysis from 'conventional' polarized observables, Phys. Lett. B **518**, 128-136 (2001)

[3] K. Yokoya, K. Kubo and T. Okugi,
Operation of ILC250 at the Z-pole [arXiv:1908.08212 [physics.acc-ph]].

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The role of positron polarization for the initial 250 GeV stage of the International Linear Collider, [arXiv:1801.02840 [hep-ph]].

[5] P. Bambade et al.
The International Linear Collider: A Global Project, [arXiv:1903.01629 [hep-ex]].

[6] G. W. Wilson, Precision Electroweak Measurements at a Future e^+e^- Linear Collider, PoS **ICHEP2016**, 688 (2016)

Backup Slides

Table of EWPO from arXiv:1908.11299

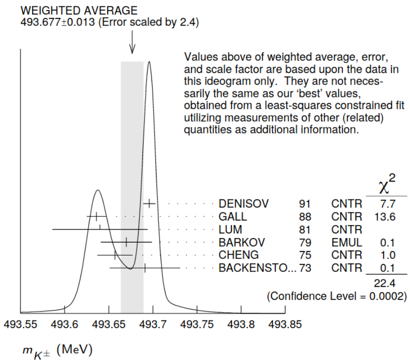
Quantity	Value	current	GigaZ		ILC250	
		$\delta[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$
boson properties						
m_W	80.379	1.5	-	-		0.3°
m_Z	91.1876	0.23	-	-	-	-
Γ_Z	2.4952	9.4		$4.^{\circ}$	-	-
$\Gamma_Z(had)$	1.7444	11.5		$4.^{\circ}$	-	-
Z-e couplings						
$1/R_e$	0.0482	24.	2.	$5^{\dagger}$	5.5	10^{+}
A_e	0.1513	139.	1	$5.^{*}$	9.5	$3.^{*}$
g_L^e	-0.632	16.	1.0	3.2	2.8	7.6
g_R^e	0.551	18.	1.0	3.2	2.9	7.6
Z-ℓ couplings						
$1/R_\mu$	0.0482	16.	2.	$2.^{\dagger}$	5.5	10^{+}
$1/R_\tau$	0.0482	22.	2.	$4.^{\dagger}$	5.7	10^{+}
A_μ	0.1515	991.	2.	5^{*}	54.	$3.^{*}$
A_τ	0.1515	271.	2.	$5.^{*}$	57.	3^{*}
g_L^μ	-0.632	66.	1.0	2.3	4.5	7.6
g_R^μ	0.551	89.	1.0	2.3	5.5	7.6
g_L^τ	-0.632	22.	1.0	2.8	4.7	7.6
g_R^τ	0.551	27.	1.0	3.2	5.8	7.6
Z-b couplings						
R_b	0.2163	31.	0.4	$7.^{\#}$	3.5	10^{+}
A_b	0.935	214.	1.	$5.^{*}$	5.7	3^{*}
g_L^b	-0.999	54.	0.32	4.2	2.2	7.6
g_R^b	0.184	1540	7.2	36.	41.	23.
Z-c couplings						
R_c	0.1721	174.	2.	$30^{\#}$	5.8	50^{+}
A_c	0.668	404.	3.	$5^{*} \oplus 5^{\#}$	21.	3^{*}
g_L^c	0.816	119.	1.2	15.	5.1	26.
g_R^c	-0.367	416.	3.1	17.	21.	26.

Table 9: Projected precision of precision electroweak quantities expected from the ILC. Precisions are given as *relative* errors ($\delta A = \Delta A/A$) in units of 10^{-4}. Please see the text of Appendix A for further explanation of this table.

Charged Kaon Mass

A long-standing example of inconsistent precision measurements. As yet not resolved.

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)



An example of something, not so far from being fundamental with a big inconsistency. Accuracy is as important as precision. Important to measure particles with different methods if there are actually residual misunderstood systematics (examples top, W, Higgs, Z).

With ILC detectors and precision momentum-scale calibration, ILC should be able to help resolve this! This would also help lots of D, B masses etc.

Maybe worth doing a careful study of how to improve this with colliders.

Full Simulation + Kalman Filter

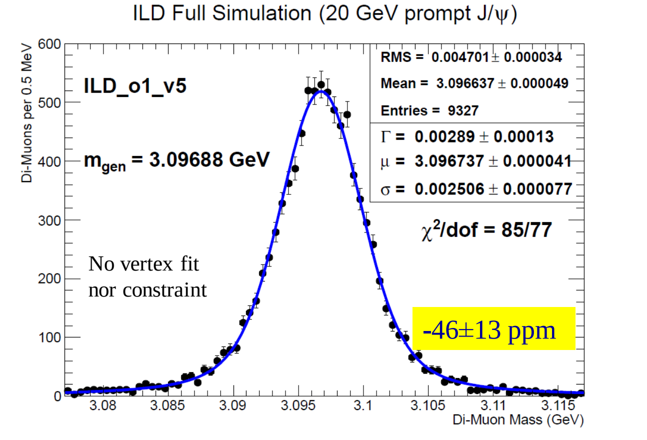
$\sqrt{s}=m_Z$

10k "single particle events"

Work in progress – likely need to pay attention to issues like energy loss model and FSR.

Preliminary statistical precision similar.

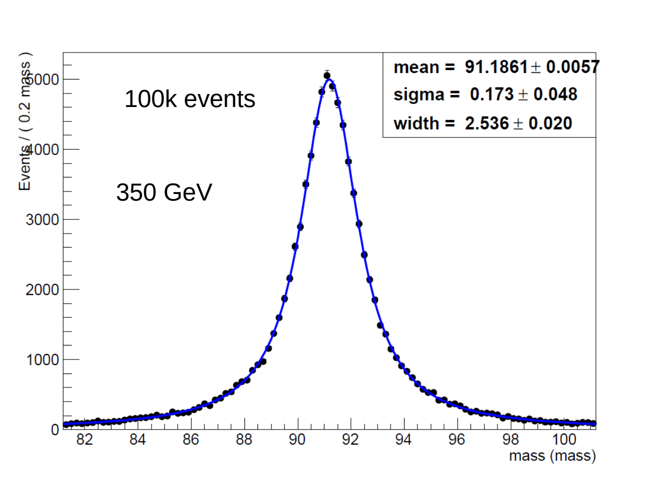
More realistic material, energy loss and multiple scattering.



Empirical Voigtian fit.

Need consistent material model in simulation AND reconstruction

Can control for p-scale using measured di-lepton mass



This is about 100 fb^{-1} at ECM=350 GeV.

Statistical sensitivity if one turns this into a Z mass measurement (if p-scale is determined by other means) is

1.8 MeV / √N

With N in millions.

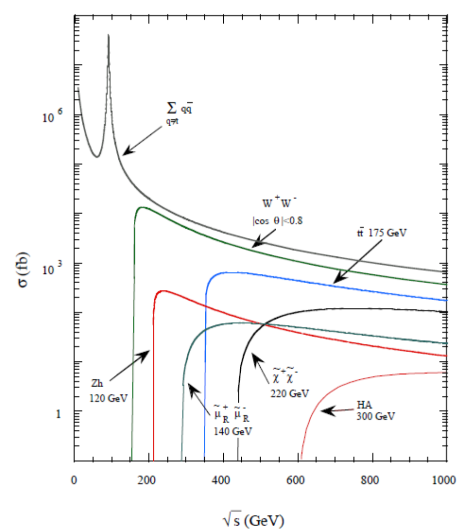
Alignment ?
B-field ?
Push-pull ?
Etc …

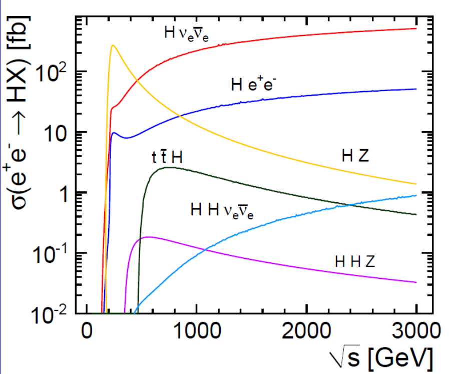
XFEL at DESY

Experimentation with ILC

- Physics experiments with e^+e^- colliders are **very different** from a hadron collider.
- Experiments and detectors can be **designed without the constraints** imposed by triggering, radiation damage, pileup.
- **All decay channels** can often be used (not only $H \rightarrow 4l$ etc)
- **Can adjust the initial conditions**, the beam energy, polarize the electrons and the positrons, and measure precisely the absolute integrated luminosity.
- **No trigger** needed.
- Last – but not least – **theoretical predictions** can be brought under very good control.

The e^+e^- Landscape

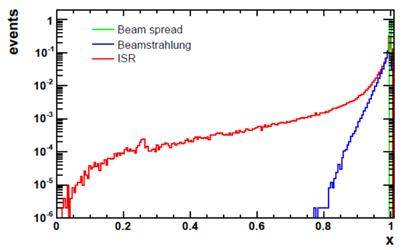


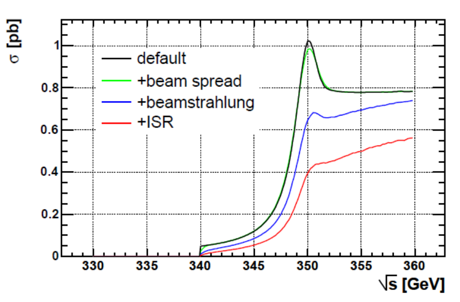


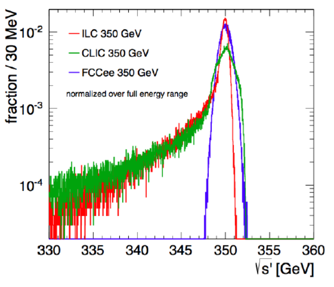
Cross-sections are typically at the pb level.

Luminosity Spectrum

- Experimentally accessible measurements are convolved with effects of ISR, beam spread and beamstrahlung







Luminosity sprectrum should be controlled well at ILC (to < 0.2% differentially using Bhabhas)

m_W Prospects

1. Polarized Threshold Scan
2. Kinematic Reconstruction
3. Hadronic Mass

Method 1: Statistics limited.

Method 2: With up to 1000 the LEP statistics and much better detectors. Can target factor of 10 reduction in systematics.

Method 3: Depends on di-jet mass scale. Plenty Z's for 3 MeV.

1

ΔM_W [MeV]	LEP2	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480
$P(e^-)$ [%]	0	90	90
$P(e^+)$ [%]	0	60	60
statistics	200	2.4	1.1
background		2.0	0.9
efficiency		1.2	0.9
luminosity		1.8	1.2
polarization		0.9	0.4
systematics	70	3.0	1.6
experimental total	210	3.9	1.9
beam energy	13	0.8	0.8
theory	-	(1.0)	(1.0)
total	210	4.0	2.1

2

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.8	1.1	1.6
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.4	2.9	3.5
statistical	30	1.5	2.1	1.8
total	36	2.8	3.6	3.9

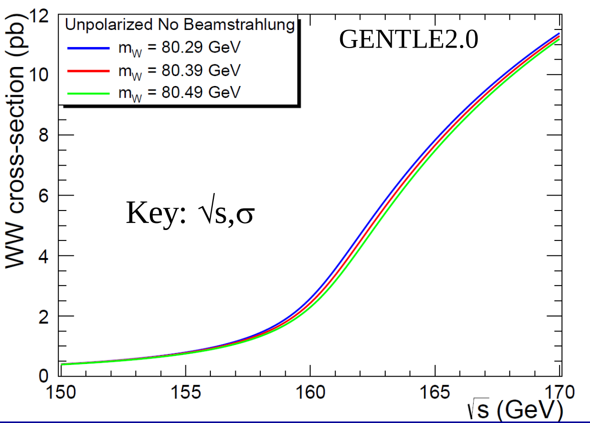
3

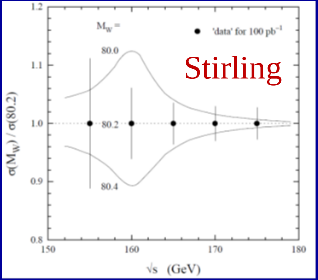
ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

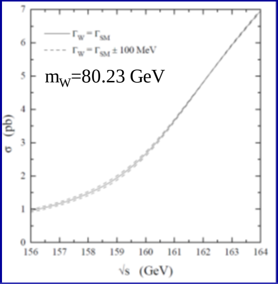
See Snowmass document for more details

Bottom-line: 3 different methods with prospects to measure mW with error < 5 MeV

m_W from cross-section close to threshold







$\sigma_t \sim \beta$ $\sigma_s \sim \beta^3$

$$\Delta M_{\rm sys}^{\rm bkgd} = 470\ \text{MeV} \left[\frac{\Delta\sigma}{1\ \text{pb}}\right]$$

Example Polarized Threshold Scan

$\sqrt{s}$ (GeV)	L (fb^{-1})	f	$\lambda_{e^-}\lambda_{e^+}$	N_{ll}	N_{lh}	N_{hh}	N_{RR}
160.6	4.348	0.7789	$-+$	2752	11279	12321	926968
		0.1704	$+-$	20	67	158	139932
		0.0254	$++$	2	19	27	6661
		0.0254	$--$	21	100	102	8455
161.2	21.739	0.7789	$-+$	16096	67610	73538	4635245
		0.1704	$+-$	98	354	820	697141
		0.0254	$++$	37	134	130	33202
		0.0254	$--$	145	574	622	42832
161.4	21.739	0.7789	$-+$	17334	72012	77991	4639495
		0.1704	$+-$	100	376	770	697459
		0.0254	$++$	28	104	133	33556
		0.0254	$--$	135	553	661	42979
161.6	21.739	0.7789	$-+$	18364	76393	82169	4636591
		0.1704	$+-$	81	369	803	697851
		0.0254	$++$	43	135	174	33271
		0.0254	$--$	146	618	681	42689
162.2	4.348	0.7789	$-+$	4159	17814	19145	927793
		0.1704	$+-$	16	62	173	138837
		0.0254	$++$	10	28	43	6633
		0.0254	$--$	46	135	141	8463
170.0	26.087	0.7789	$-+$	63621	264869	270577	5560286
		0.1704	$+-$	244	957	1447	838233
		0.0254	$++$	106	451	466	40196
		0.0254	$--$	508	2215	2282	50979

Illustrative example of the numbers of events in each channel for a 100 fb^{-1} 6-point ILC scan with 4 helicity configurations

Kinematic Reconstruction in Fully Leptonic Events

See Appendix B of Hagiwara et al., Nucl. Phys. B. 282 (1987) 253 for full production and decay 5-angle reconstruction in fully leptonic decays as motivated by TGC analyses.

The technique applies energy and momentum conservation. One solves for the anti-neutrino 3-momentum, decomposed into its components in the dilepton plane, and out of it. Additional assumptions are:

- the energies of the two W's are equal to E_{beam}, so m(W+) = m(W-).
- a specified value for M_{W}

$$\vec{\mathbf{p}_{\bar{\nu}}} = a\,\vec{\mathbf{l}} + b\,\vec{\mathbf{l'}} + c\,\vec{\mathbf{l}} \times \vec{\mathbf{l'}}$$

By specifying, M_{W}, one can find a, b and c^2, so there are two solutions.
The alternative pseudomass technique, does not assume M_{W}, but sets $c = 0$, and similarly has two solutions $(a_+,\, b_+)$ and $(a_-,\, b_-)$.