Exploring Measurements of m_{W}, B_{ℓ}, Γ_W at ILC250

Updates and new old ideas on m_{W} measurement etc

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Outline

Based partly on W section of arXiv:1908.11299

- Motivation etc
- Branching Fractions
- Lineshape sensitivity to m_W, Γ_W
- m_W overview including threshold
- m_W from leptons (I got intrigued by this)
- Systematics
- Summary

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Tests of the Standard Model at the

International Linear Collider

LCC Physics Working Group

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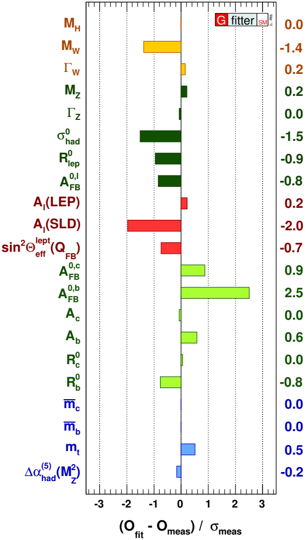
ABSTRACT

We present an overview of the capabilities that the International Linear Collider (ILC) offers for precision measurements that probe the Standard Model. First, we discuss the improvements that the ILC will make in precision electroweak observables, both from W boson production and radiative return to the Z at 250 GeV in the center of mass and from a dedicated GigaZ stage of running at the Z pole. We then present new results on precision measurements of fermion pair production, including the production of b and t quarks. We update the ILC projections for the determination of Higgs boson couplings through a Standard Model Effective Field Theory fit taking into account the new information on precision electroweak constraints. Finally, we review the capabilities of the ILC to measure the Higgs boson self-coupling.

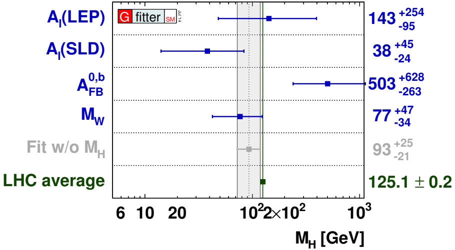
Physics Motivation

- Direct discovery of new physics beyond the Higgs would be wonderful. LHC is still searching and continues to have some discovery potential. Example: particles like electroweakinos.
- In the years before the direct discoveries of the top quark and the Higgs boson, precision measurements of the then observable Standard Model parameters pointed the way.
- If new physics continues to evade direct detection, ultra-precise measurements of the fundamental parameters of the Standard Model will become especially compelling. Can probe, albeit indirectly, potentially much higher energy scales and associated new physics.
- Comprehensive interpretation of Higgs properties using EFT needs input from the W sector. Two important inputs are m_W and $B(W \to e\nu)$, assumed to be measured to 2.5 MeV and 0.011% in the ILC Higgs boson couplings projections in arXiv:1908.11299. Is this reasonable?



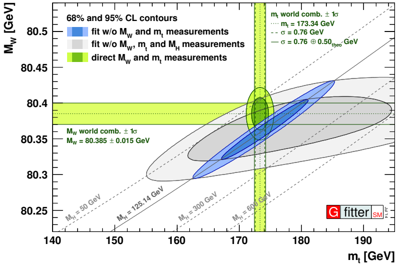
SM Tests

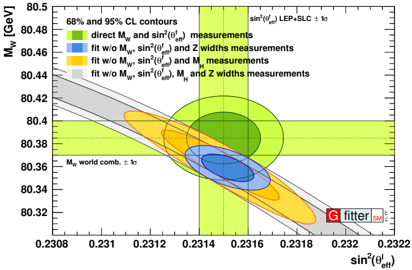
Are measurements consistent with the Standard Model?
Measurements mostly from LEP and SLD. Further significant improvement likely needs an e^+e^- collider.



Will focus on M_{W} and related measurement prospects at ILC.

SM parameters: $\alpha_{\rm em}$, $G_{\rm F}$, $M_{\rm Z}$, $M_{\rm W}$, $\sin^2\theta_{\rm W}$, $M_{\rm H}$.



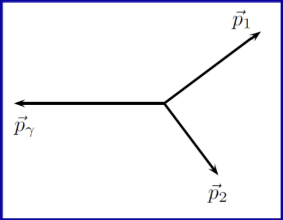


ILC can advance significantly these tests of the SM by measuring $M_{\rm W}$, $m_{\rm t}$, $\sin^2\theta_{\rm W}$ with much higher precision.

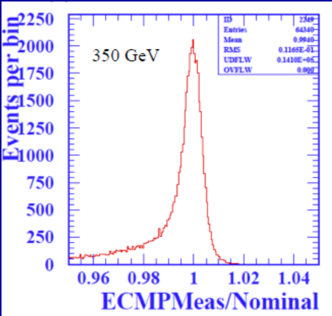
Beam Energy Measurement

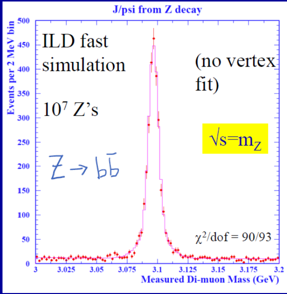
- Critical input to measurements of m_t, m_W, m_H, m_Z, m_X using threshold scans.
- Standard precision $O(10^{-4})$ for m_t straightforward.
- Targeting precision $O(10^{-5})$ for m_W, m_Z
  - Muon momenta based strategy looks feasible

$e^+ e^- \to \mu^+\mu^-(\gamma)$



Use muon momenta.
Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$





W Production and Decay Channels

Production:

1. "WW": pair production of W^+W^-
2. "single W": single production of $We\nu_e$

W decay to either $\ell\nu$ or to hadrons, leading to 10 4-fermion final states for WW.

Table 2. The luminosity-weighted average selection efficiencies for the CC03 processes for $\sqrt{s} = 161$–209 GeV. The efficiencies include corrections for detector occupancy and tracking inefficiencies as described in the text. In the $\ell\nu\ell\nu$ and $qq\ell\nu$ selections leptons from τ decays are separated from direct leptons from W-decay on the basis of momentum and/or kinematic variables

Event	Efficiencies [%] for $W^+W^- \to$									
selection	$e\nu e\nu$	$\mu\nu\mu\nu$	$\tau\nu\tau\nu$	$e\nu\mu\nu$	$e\nu\tau\nu$	$\mu\nu\tau\nu$	$qqe\nu$	$qq\mu\nu$	$qq\tau\nu$	$qqqq$
$e\nu e\nu$	74.1	0.0	0.8	0.4	6.6	0.1	0.0	0.0	0.0	0.0
$\mu\nu\mu\nu$	0.0	77.9	0.7	1.4	0.1	6.7	0.0	0.0	0.0	0.0
$\tau\nu\tau\nu$	0.7	0.7	48.1	0.7	4.9	5.6	0.0	0.0	0.0	0.0
$e\nu\mu\nu$	2.6	0.4	1.4	76.5	6.2	6.9	0.0	0.0	0.0	0.0
$e\nu\tau\nu$	10.3	0.0	11.5	5.6	64.2	1.2	0.0	0.0	0.0	0.0
$\mu\nu\tau\nu$	0.2	9.5	8.4	4.3	0.8	61.5	0.0	0.0	0.0	0.0
$qqe\nu$	0.0	0.0	0.0	0.0	0.2	0.0	84.3	0.1	4.0	0.0
$qq\mu\nu$	0.0	0.0	0.0	0.0	0.0	0.1	0.2	88.3	4.4	0.1
$qq\tau\nu$	0.0	0.0	0.2	0.0	0.0	0.0	4.3	4.4	61.5	0.5
$qqqq$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	85.9

Example efficiency matrix from OPAL (arXiv:1708.1311).

General Remarks

- Projecting performance for inverse ab data sets for measurements that are probably systematics limited, is not at all straightforward.
- ILC data sets benefit from much better detectors than at LEP2 so there is good reason to believe that the BR study is conservative in terms of performance.
- Measurements of W mass, were already quite complex at LEP2. Getting to a realistic estimate of the eventual performance at ILC is not straightforward.
- We can make educated guesses and identify salient issues, and in some simpler cases, like threshold scan and lepton observables, be relatively confident of projections.

W decay branching fractions study at 250 GeV

Project ILC prospects using LEP2 cross section and decay branching fractions measurements. These were mostly statistics limited.
Use OPAL efficiency matrix, and corresponding backgrounds. (250 GeV is not so far from 200 GeV).
Method is to fit the observed cross sections in each of the ten final states with four parameters (σ_{WW}, B_e, B_μ, B_τ) with the constraint that all branching fractions (including B_{had}) sum to one.

Event selections	B_e	B_μ	B_τ	R_μ	R_τ
All 10	4.2	4.1	5.2	6.1	7.5
9 (not fully-hadronic)	5.9	5.7	6.4	6.1	7.5
9 (not tau-semileptonic)	4.6	4.6	7.8	6.1	10.8
8 (not f-h and not τ-semileptonic)	8.3	8.4	7.8	6.1	12.8
7 (not f-h and not τ-sl and not di-τ)	9.0	9.1	10.6	6.1	16.7

Relative uncertainties in units of 10^{-4} at $\sqrt{s} = 250$ GeV using the 45% of the 2 ab^{-1} integrated luminosity with enhanced $e_L^- e_R^+$ collisions.

Example: $B_e = 10.8032 \pm 0.0045\%$. Would lead to $\Gamma_W = \Gamma_e / B_e$ with statistical uncertainty of 0.9 MeV (assuming Γ_e perfectly calculable).

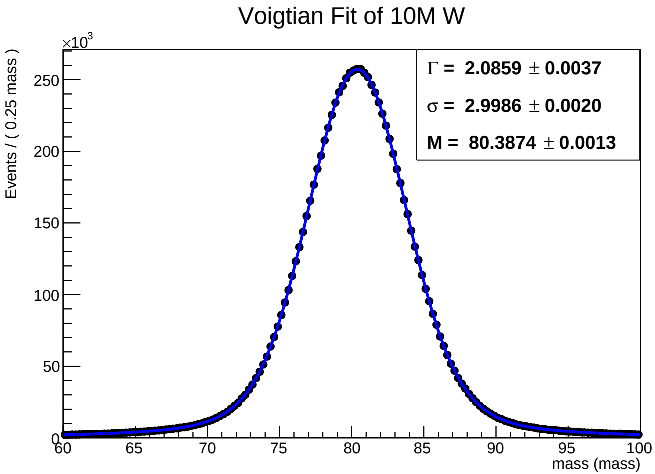
Fits to W Lineshape (M, Γ, σ_M)

Higgs factory machines like ILC likely systematics dominated for m_W and Γ_W. Statistical uncertainties for m_W and Γ_W for 10^7 W bosons.

σ_M (GeV)	Δm_W (MeV)	$\Delta\Gamma_W^a$ (MeV)	$\Delta\Gamma_W^b$ (MeV)
1.0	0.67	1.3	2.0
2.0	0.98	1.7	2.7
2.5	1.1	2.0	3.2
3.0	1.3	2.3	3.7
4.0	1.6	2.8	5.0

Estimated from a simple parametric fit of the Breit-Wigner lineshape convolved with a range of constant Gaussian experimental mass resolutions, σ_M. The m_W uncertainty is evaluated with a one parameter fit with the width and mass resolution fixed. The corresponding uncertainties on the Γ_W width are evaluated either with the mass resolution fixed and known perfectly from a 2-parameter fit (Γ_W^a), or more realistically, from a 3-parameter fit (Γ_W^b) that also fits for the mass resolution.

Toy MC Example. (Has $\chi^2/\text{ndf} = 152/157.$)



I had wrongly assumed that one needed to know σ very well to extract Γ, but this is not the case. Of course with no constraint on σ, the uncertainty on Γ is larger. In reality, σ varies from W to W. So for a similar approach to work, one needs well understood event by event errors. Use by categorizing events with varying quality levels.

W Mass

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

The three most promising approaches to measuring the W mass at an e^+e^- collider are:

1. Polarized Threshold Scan Measurement of the $\mathrm{W^+W^-}$ cross-section near **threshold** with longitudinally polarized beams. Requires dedicated luminosity well below Higgs threshold; so can it not be done well enough in other ways?
2. Constrained Reconstruction Kinematically-constrained reconstruction of $\mathrm{W^+W^-}$ using constraints from **four-momentum conservation** and optionally mass-equality as was done at LEP2. Primarily using semileptonic events. Color reconnection assumed to dog fully hadronic - really?
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 $\mathrm{W^+W^-}$ events.

Methods 2 and 3 can exploit the standard $\sqrt{s} \geq 250$ GeV ILC program.

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

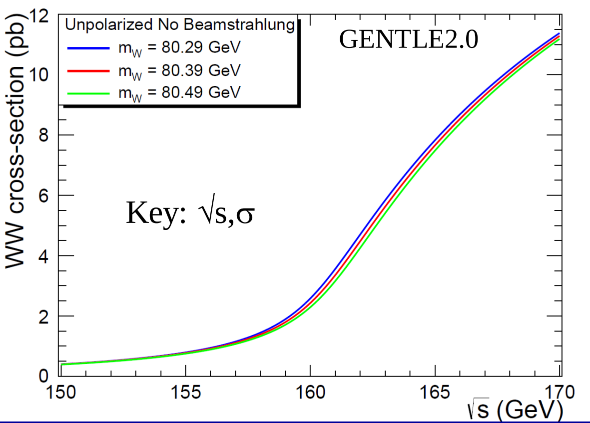
3

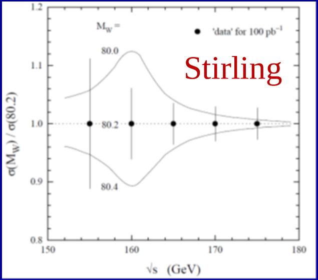
ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5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

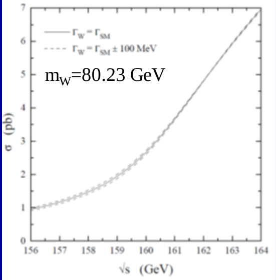
See Snowmass document for more details

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

m_W from cross-section close to threshold



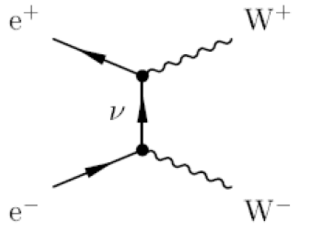




$\sigma_t \sim \beta$ $\sigma_s \sim \beta^3$

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

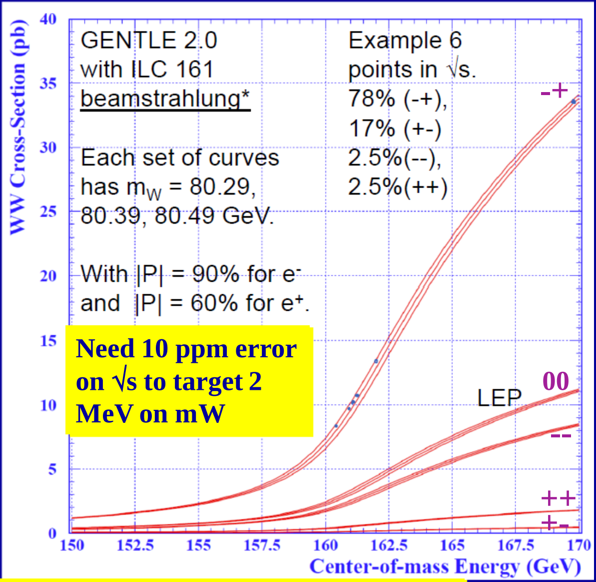
ILC Polarized Threshold Scan



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}

Note 125 inv fb/yr now feasible! (1908.08212, Yokoya, Kubo, Okogi).

$\lvert P(e^-) \rvert$	$\lvert P(e^+) \rvert$	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.

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

$\mathrm{M_W}$ Measurement Using Leptons

One complementary method to the main methods for measuring $\mathrm{M_W}$ at LEP was the measurement by OPAL (hep-ex/020326) using the fully leptonic channel. Results were modest at best. Limited by the integrated luminosity of 0.67 fb^{-1} (unpolarized), and the poor momentum resolution. ILC will be much better for L, P and dp/p. Cons: beamstrahlung. Also higher $\sqrt{s}$?
Method uses lepton $\vec{\mathbf{p}}$ measurement:

- The prompt (e, μ)-lepton energy spectrum in ee, $\mu\mu$, eμ, eτ, $\mu\tau$ events with endpoints at $E_\pm = \frac{1}{2} E_\mathrm{b}(1 \pm \beta)$. Can also apply to qqe$\nu$ and qq$\mu\nu$.
- The positive pseudo-mass (M_+) solution in ee, $\mu\mu$, eμ events.

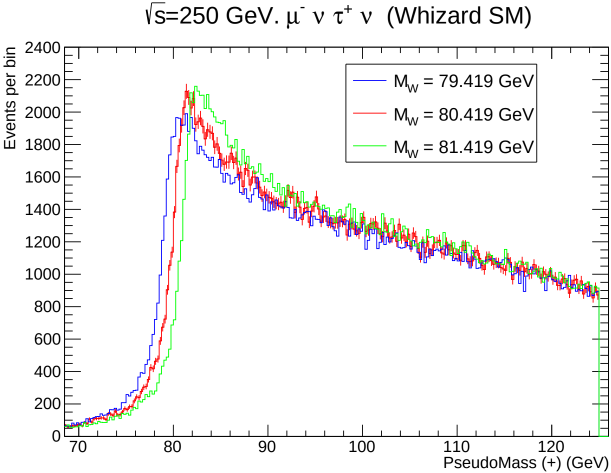
Latter assumes 4-momentum conservation, equal (l-ν) masses, and guesses that the neutrinos are in the same plane as the di-lepton.

$$M_\pm^2 = \frac{2}{(\mathbf{p}_{\ell'} + \mathbf{p}_\ell)^2}\Big((P\ \mathbf{p}_{\ell'} - Q\ \mathbf{p}_\ell)(\mathbf{p}_{\ell'} + \mathbf{p}_\ell) \pm\sqrt{(\mathbf{p}_\ell \times \mathbf{p}_{\ell'})^2[(\mathbf{p}_{\ell'} + \mathbf{p}_\ell)^2(E_\mathrm{b} - E_\ell)^2 - (P+Q)^2]}\Big), \quad (1)$$

where

$$P = E_\mathrm{b} E_\ell - E_\ell^2 + \frac{1}{2} m_\ell^2, \qquad Q = -E_\mathrm{b} E_{\ell'} - \mathbf{p}_{\ell'} \cdot \mathbf{p}_\ell + \frac{1}{2} m_{\ell'}^2,$$

Positive PseudoMass (250k events per sample) (-80,+30)

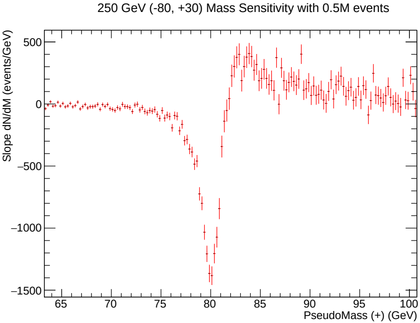


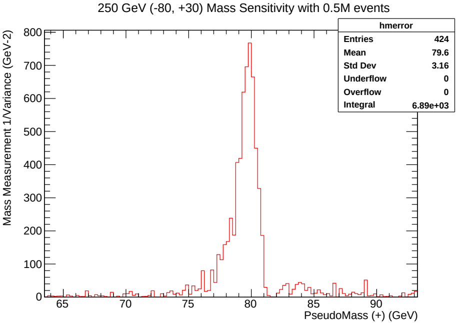
This study just uses changes in the shape. The absolute cross sections should be relatively insensitive to m_W well above threshold (depends on SM parameter scheme implementation ....). Plots are at generator level (no detector smearing).

Positive PseudoMass (500k events sensitivity) (-80,+30)

Estimate mass sensitivity bin-by-bin by using

$$\Delta m_W = |\frac{d\sigma}{dm_W}|^{-1}\Delta\sigma \text{ or } \Delta m_W = |\frac{dN}{dm_W}|^{-1}\Delta N$$



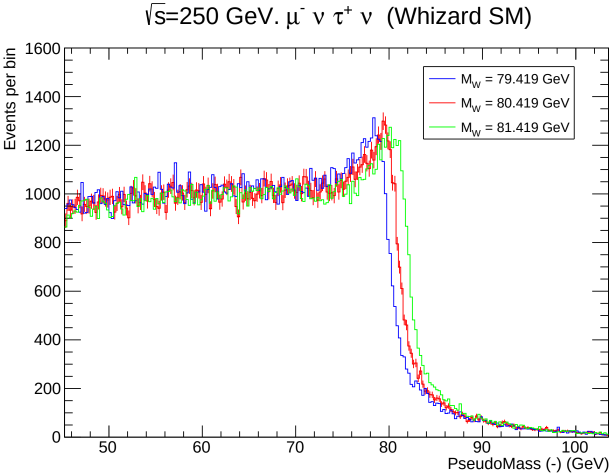


Then, can estimate overall statistical uncertainty on m_W from

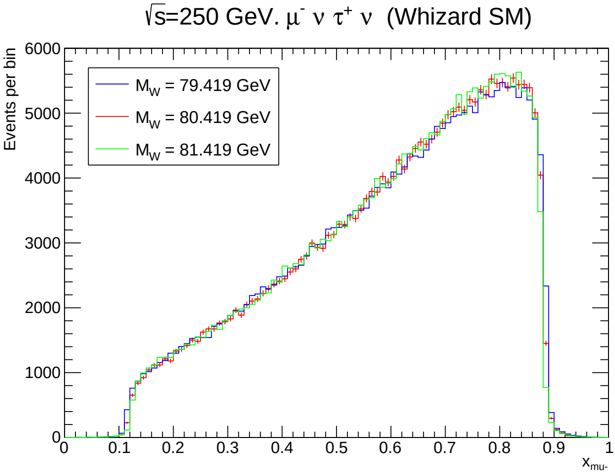
$$\Delta m_W = \sqrt{1/\sum \frac{1}{\sigma_i^2}}$$

Here $\Delta m_W = 1.0/\sqrt{6890}\,\mathrm{GeV} = 12.0$ MeV

Negative PseudoMass (250k events per sample) (-80,+30)

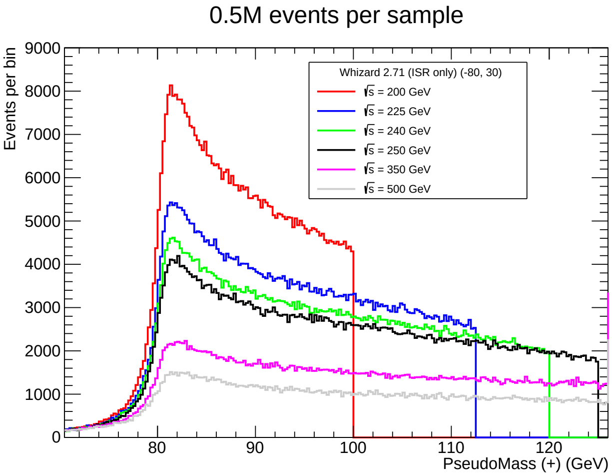


This distribution DOES have sensitivity (in contrast to it being neglected at LEP2). Relatively more important at higher $\sqrt{s}$.



Most of the sensitivity is at the high energy end.

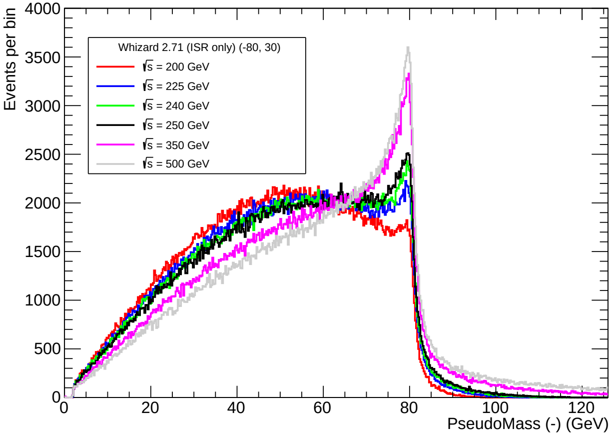
Positive PseudoMass $\sqrt{s}$ dependence



Factor of 2 more events near the edge at 200 GeV compared to 250 GeV. Translates to roughly a factor of $\sqrt{2}$ in better mass sensitivity at 200 GeV for equal overall event numbers.

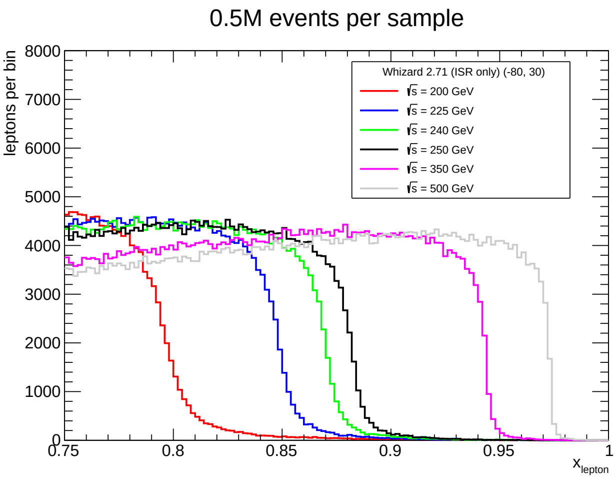
Negative PseudoMass $\sqrt{s}$ dependence

0.5M events per sample



Opposite trend to positive pseudomass, but overall sensitivity weaker.

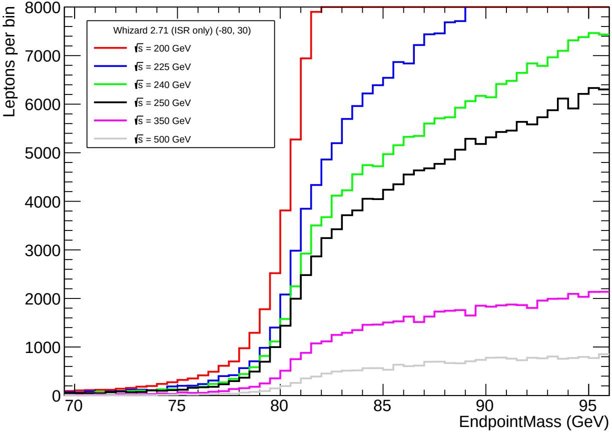
Lepton Endpoint $\sqrt{s}$ dependence



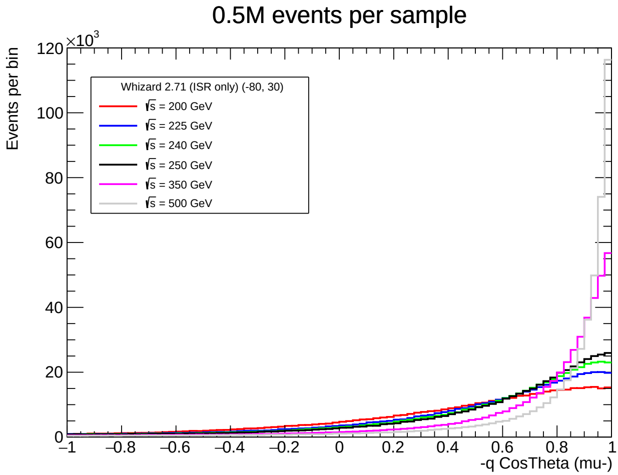
Lepton Endpoint Mass $\sqrt{s}$ dependence

$$m_W^2 = 4E_l(E_\mathrm{b} - E_l)$$

0.5M events per sample



Again lower center-of-mass energy is better.



Leptons very forward at higher $\sqrt{s}$. But at 250 GeV not so different to LEP2.

Estimated m_W statistical uncertainties from leptons

Based on 0.9 ab^{-1} with (-80%,+30%) beam polarization at generator level at $\sqrt{s} = 250$ GeV. Currently neglects detector resolution: generally $\ll \Gamma_W / m_W$.

1. M_+: 1.25M prompt dilepton events = 7.6 MeV
2. M_-: 1.25M prompt dilepton events = 9.7 MeV
3. Combined: 1.25M prompt dilepton events = 6.0 MeV (assuming uncorrelated)
4. x_+: 1.875M positive leptons = 14.0 MeV
5. x_-: 1.875M negative leptons = 14.0 MeV
6. Combined: 3.75M leptons = 9.9 MeV
7. (x_{low}: 1.875M leptons, 23.2 MeV)
8. (x_{high}: 1.875M leptons, 11.0 MeV)
9. Combined: Fully leptonic (M and endpoints) = 5.1 MeV (neglects probable correlation (+11% in OPAL case))
10. Semi-leptonic endpoints (10.5M leptons) = 5.9 MeV
11. Grand total = 3.9 MeV

Other Methods

Fully hadronic channel has huge statistical power, but thought plagued by color reconnection (CR) systematics.

Recent study, Christiansen and Sjostrand, arXiv:1506.09085 shows that CR effects could be diagnosed using W mass measurements at various $\sqrt{s}$.

Table 2 Systematic W mass shifts at center-of-mass energies of 240 and 350 GeV, respectively. The $\langle \delta \overline{m}_{\mathrm{W}} \rangle$ is the mass shift in the CR models relative to the no-CR result. The Monte Carlo statistical uncertainty is 5 MeV

Method	$\langle \delta \overline{m}_{\mathrm{W}} \rangle$ (MeV) ($E_{\mathrm{cm}} = 240$ GeV)						
	SK-I	SK-II	SK-II′	GM-I	GM-II	GM-III	CS
1	+95	+29	+25	−74	+400	+104	+9
2	+87	+26	+24	−68	+369	+93	+8
3	+95	+30	+26	−72	+402	+105	+10
Method	$\langle \delta \overline{m}_{\mathrm{W}} \rangle$ (MeV) ($E_{\mathrm{cm}} = 350$ GeV)						
	SK-I	SK-II	SK-II′	GM-I	GM-II	GM-III	CS
1	+72	+18	+16	−50	+369	+60	+4
2	+70	+18	+15	−50	+369	+60	+4
3	+71	+18	+16	−50	+369	+60	+3

But this is not really at all well established.

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: use $J/\psi \to \mu^+\mu^-$. Event rate limited unless sizeable Z running.

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}	1.9×10^{-6}
K^0_S	1.02	$\pi^+\pi^-$	69.2	0.71	1.5×10^{-14}	2.6×10^{-5}
Λ	0.39	$\pi^-\mathrm{p}$	63.9	0.25	2.2×10^{-15}	5.4×10^{-6}
D^0	0.45	$\mathrm{K}^-\pi^+$	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	$\pi^-\mathrm{p}$	0.044	0.067	2.6×10^{-4}	3.7 ppm	0.37 ppm	80 ppm
D^0	$\mathrm{K}^-\pi^+$	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 possibility of improved M_Z measurements.

Summary

- ILC can advance our knowledge of electroweak precision physics
- Several methods to measure the W mass with precisions in the few MeV range. Systematics are to some extent complementary. Estimate overall experimental uncertainty of 2.5 MeV.
- The W width can be determined either directly, or by interpreting measurements related to branching fractions. The latter promises higher precision: $< 0.1\%$ on Γ_W.

- Scope for complementary M_{W} measurements with similar precision from standard ILC running. Fully leptonic events statistical estimate is 5.1 MeV.
- 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. Can also open up a measurement of M_{Z}.
- An accelerator is needed. Let's make this happen!
- The physics discussed here benefits greatly when the accelerator is designed to include efficient running at lower center-of-mass energies.

Backup Slides

Full Simulation + Kalman Filter

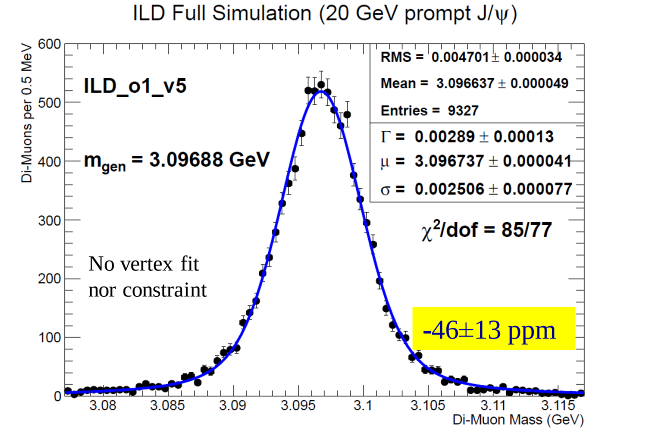
$\sqrt{s}=m_Z$

10k "single particle events"

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

Preliminary statistical precision similar.

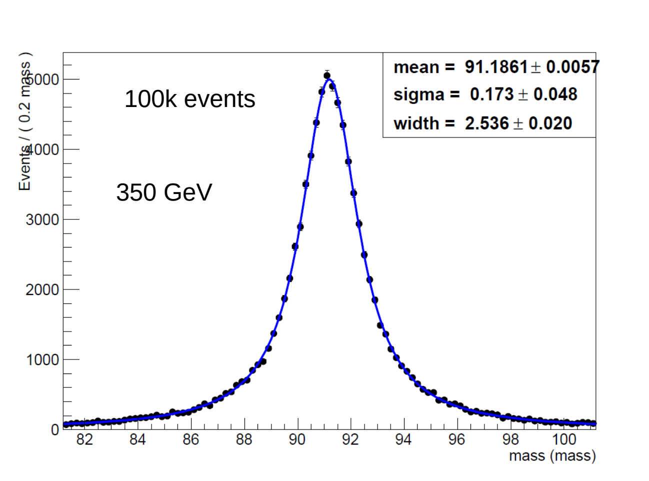
More realistic material, energy loss and multiple scattering.



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 …

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 mW

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

By specifying, mW, one can find a, b and c^2, so there are two solutions.

The alternative pseudomass technique, does not assume mW, but sets $c = 0$, and similarly has two solutions (a_+, b_+) and (a_-, b_-).

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

- ILC TDR design focused on $\sqrt{s} > 200$ GeV.
- Luminosity naturally scales with γ at a linear collider.
- For nominal $L = 1.8 \times 10^{34}$ at $\sqrt{s} = 500$ GeV corresponding L at $\sqrt{s} = 91$ GeV is 3.3×10^{33}.
- Need modification to the e^{+} production scheme.
- Details need detailed design - but no obvious technical show-stoppers.
- Zpole running for ILC250 revisited recently. See Yokoya, Kubo, Okogi, arXiv:1908.08212. Parameters for $L = 2.05 \times 10^{33}$ at 91.2 GeV.

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