Precision Electroweak Physics with a Future e^+e^- Linear Collider

Emphasis on Experimental Measurement Aspects

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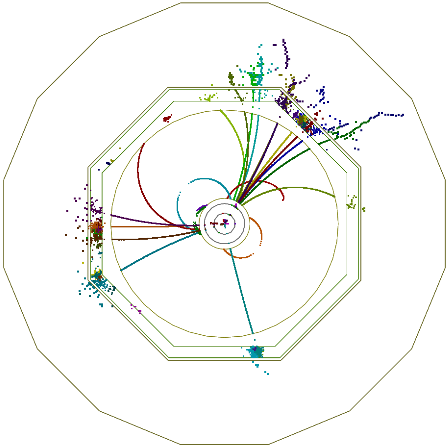
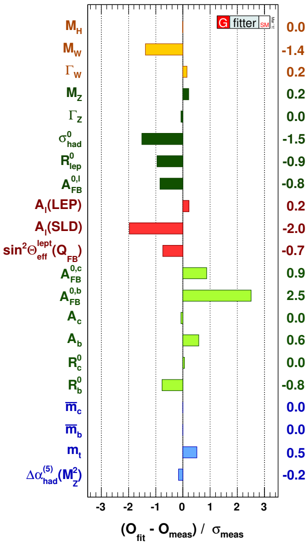
August 5th 2016

Outline



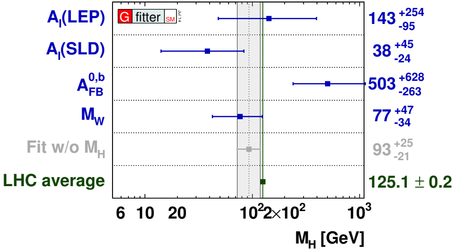
Physics Motivation

- Direct discovery of new physics would be wonderful. Looking forward to new results from LHC Run II.
- 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.



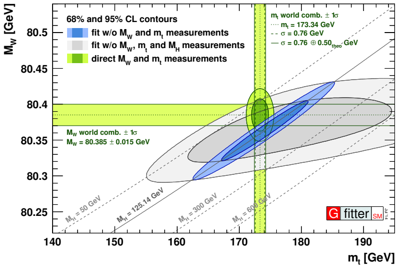
SM Tests

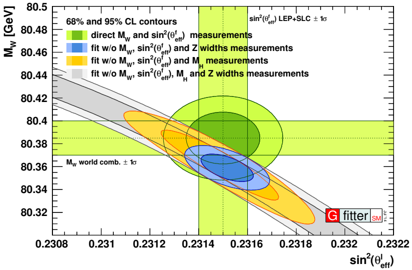
Are measurements consistent with the Standard Model?
Measurements mostly from LEP and SLD. Further significant improvement likely needs an e^+e^- collider.



Will focus on M_W and A_{LR} prospects at ILC. Emphasis on experimental issues.

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



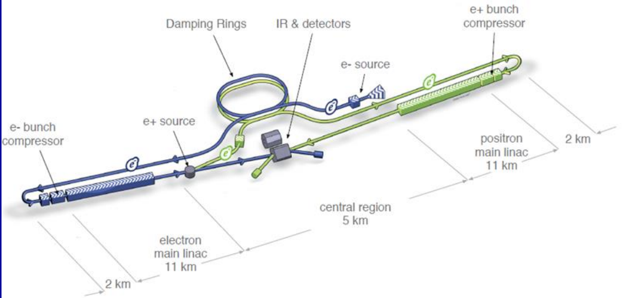


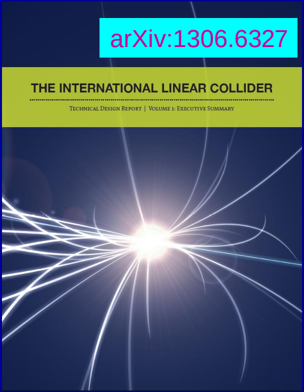
ILC can advance significantly these tests of the SM by measuring $M_{\rm W}$, $m_{\rm t}$, $\sin^2\theta_{\rm W}$ with much higher precision.

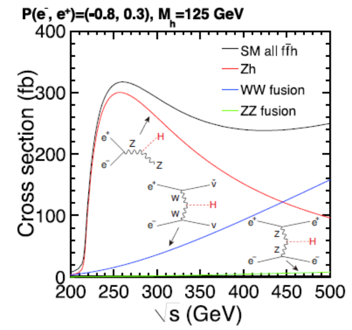
e^+e^- Linear Colliders (ILC/CLIC)

- Only practical way to go significantly above the top pair threshold.
- ILC is based on superconducting RF.
  - ILC under study and development for many years
  - World-wide consensus in 2001 as the next future collider
- ILC initial stage - $\sqrt{s}$ up to 500 GeV, upgradable to 1 TeV
  - Now we have the discovery of the Higgs in 2012
  - ILC technology is mature
  - Japan is deciding whether to host the ILC as a global project
- CLIC: R&D project at CERN. 2-beam accelerator. Post-LHC option with potential of reaching 3 TeV.

International Linear Collider Project

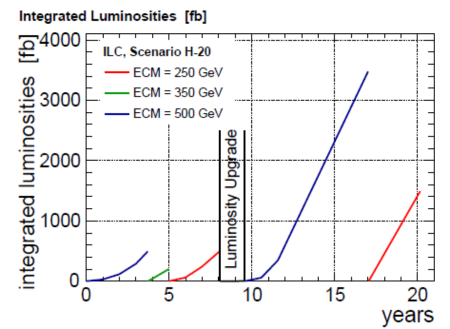






ILC Parameters / Running Scenarios

J. Brau et al., arXiv: 1506.07830



- 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}).

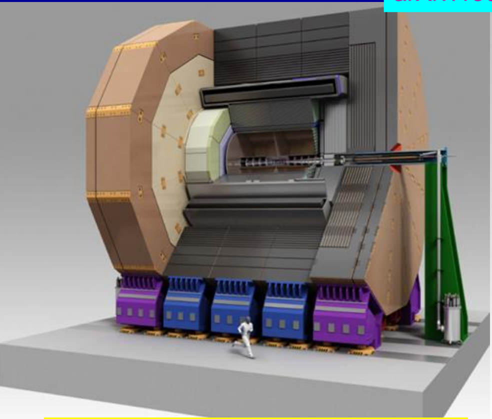
	integrated luminosity with $\mathrm{sgn}(P(e^-), P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]
250 GeV	1350	450	100	100
350 GeV	135	45	10	10
500 GeV	1600	1600	400	400

6200 fb^{-1} total

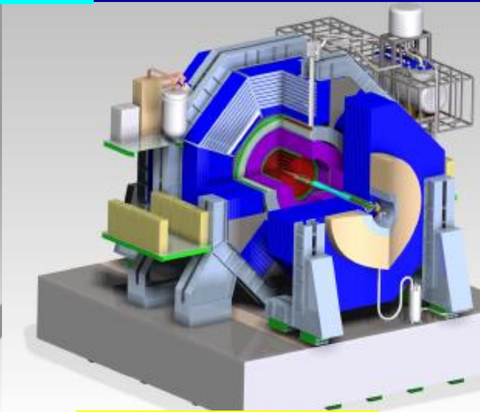
200 fb^{-1} at $\sqrt{s} \approx 350$ GeV

ILC Detectors

arXiv:1306.6329



ILD = International Large Detector



SiD = Silicon Detector

Modern detectors designed for ILC. Particle-flow for jets.
Similar size to CMS.
ILD centered around a TPC. SiD – silicon tracking.

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

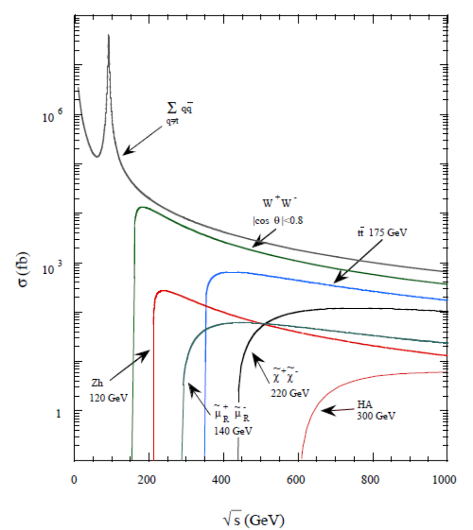
Topic	Parameter	Initial Phase	Full Data Set	units
Higgs	m_h	25	15	MeV
	$g(hZZ)$	0.58	0.31	%
	$g(hWW)$	0.81	0.42	%
	$g(hb\bar{b})$	1.5	0.7	%
	$g(hgg)$	2.3	1.0	%
	$g(h\gamma\gamma)$	7.8	3.4	%
		1.2	1.0	%, w. LHC results
	$g(h\tau\tau)$	1.9	0.9	%
	$g(hc\bar{c})$	2.7	1.2	%
	$g(ht\bar{t})$	18	6.3	%, direct
		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

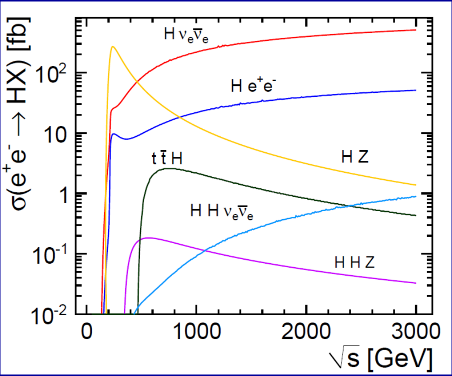
Refer you to these references for more comprehensive picture

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



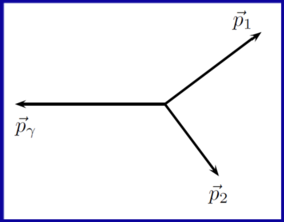


Cross-sections are typically at the pb level.

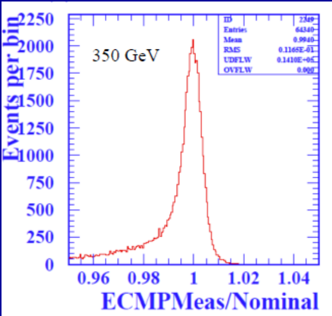
Beam Energy Measurement

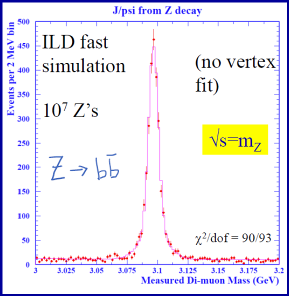
- Critical input to measurements of m_t, m_W, m_H, m_Z, m_X using threshold scans.
- Standard precision $O(10^{-4})$ for m_t straightforward.
- Targeting precision $O(10^{-5})$ for m_W, m_Z
  - Muon momenta based strategy looks feasible

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



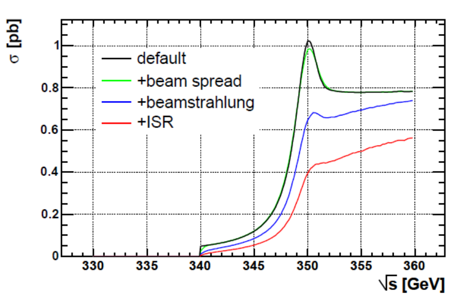
Use muon momenta.
Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$

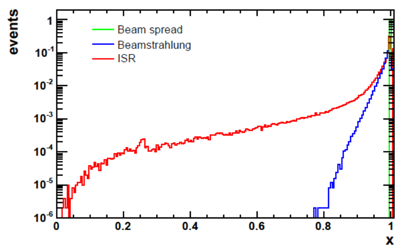


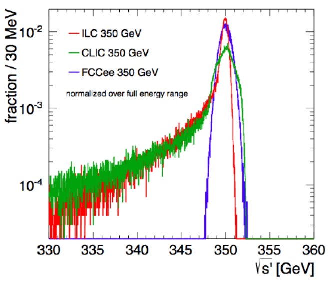


Luminosity Spectrum

- 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)

Longitudinally Polarized Beams

- ILC baseline design has e^- polarized to 80%, e^+ to 30%.
- e^- polarization to 90% is not out of the question.
- e^+ polarization to 60% is under study and possible.
- In contrast to circular colliders, longitudinal polarization is not expected to cost luminosity.

$$
\begin{aligned}
\sigma(P_{\mathrm{e}^-}, P_{\mathrm{e}^+}) \;\; &= \;\; \frac{1}{4}\{(1 - P_{\mathrm{e}^-})(1 + P_{\mathrm{e}^+})\sigma_{LR} + (1 + P_{\mathrm{e}^-})(1 - P_{\mathrm{e}^+})\sigma_{RL} + \\
&\qquad (1 - P_{\mathrm{e}^-})(1 - P_{\mathrm{e}^+})\sigma_{LL} + (1 + P_{\mathrm{e}^-})(1 + P_{\mathrm{e}^+})\sigma_{RR}\}
\end{aligned}
$$

With both beams polarized it is straightforward to measure accurately the absolute polarization in-situ for processes where $\sigma_{LL}=\sigma_{RR}=0$.

  - Using the 4 cross-section measurements from the (-+. +-, --, ++) helicity combinations, and the 4 unknowns (σ_U, A_{LR}, P_{e+}, P_{e-}). Assumes same |P| for +ve and –ve helicity of same beam.

- Polarimeters to track relative polarization changes.

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 $\mathrm{W}^+\mathrm{W}^-$ 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.

Method 1 needs dedicated running near $\sqrt{s} = 161$ GeV. 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

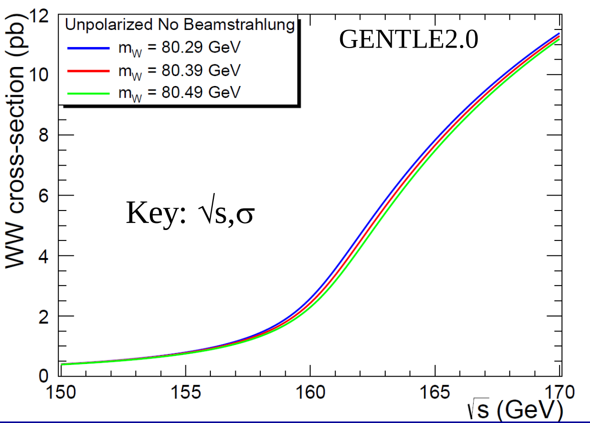
3

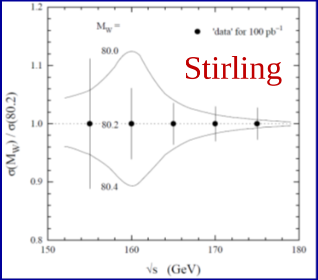
ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5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

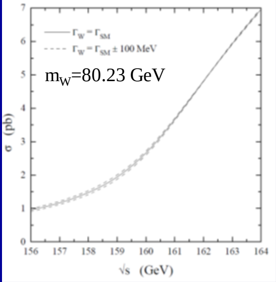
See Snowmass document for more details

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

m_W from cross-section close to threshold



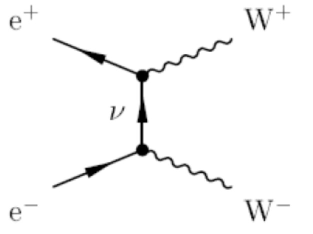




$\sigma_t \sim \beta$ $\quad$ $\sigma_s \sim \beta^3$

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

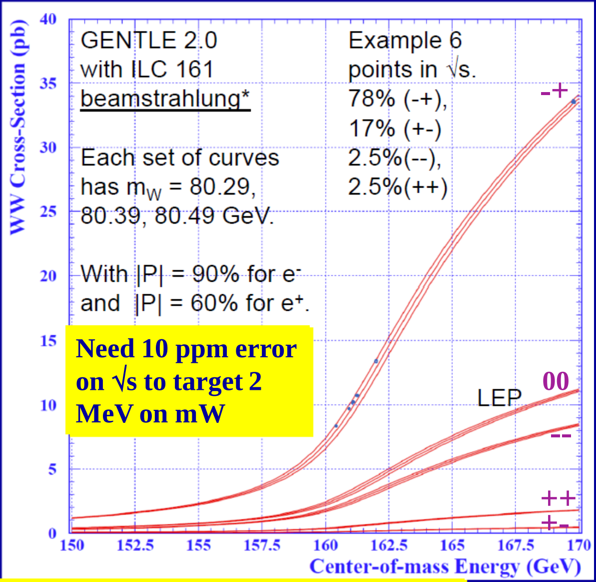
ILC Polarized Threshold Scan



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

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

Results from updated ILC study (arXiv:1603.06016)

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

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.

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

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

Studied by K. Mönig 1999
For $\mathrm{Z} \rightarrow \mathrm{f\bar{f}}$, 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

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

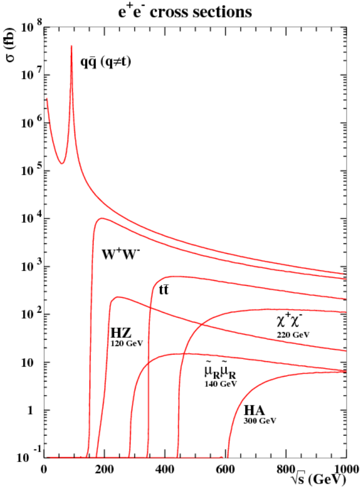
Beamstrahlung

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 $\Delta\alpha_{\mathrm{had}}$.

Detector Calibration and Alignment



"clean" e^+e^- experimental environment but particle-based calibration has

Challenges

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

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!

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	$n_{Z\mathrm{had}}$	Decay	BR (%)	$n_{Z\mathrm{had}} \cdot$ BR	Γ/M	PDG ($\Delta M/M$)
J/ψ	0.0052	$\mu^+\mu^-$	5.93	0.00031	3.0×10^{-5}	3.6×10^{-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

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

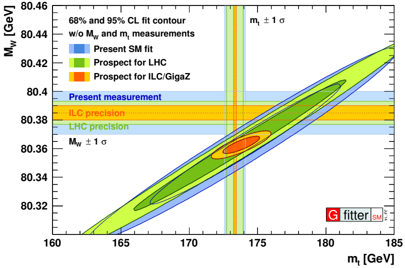
Particle	Decay	$<\alpha>$	max α	σ_M/M	$\Delta p/p$ (10 MZ)	$\Delta p/p$ (GZ)	PDG limit
J/ψ	$\mu^+\mu^-$	0.99	0.995	7.4×10^{-4}	13 ppm	1.3 ppm	3.6 ppm
K^0_S	$\pi^+\pi^-$	0.55	0.685	1.7×10^{-3}	1.2 ppm	0.12 ppm	38 ppm
Λ	$\pi^-\mathrm{p}$	0.044	0.067	2.6×10^{-4}	3.7 ppm	0.37 ppm	80 ppm
D^0	$\mathrm{K}^-\pi^+$	0.77	0.885	7.6×10^{-4}	2.4 ppm	0.24 ppm	30 ppm

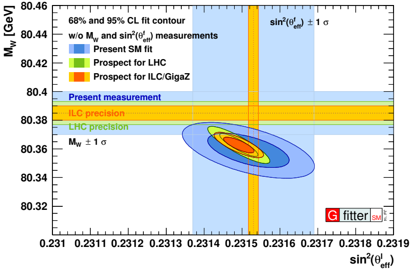
Estimated momentum scale statistical errors ($p = 20$ GeV)

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

Opens up possibility of improved M_Z measurements.

Plots from Gfitter group (with their more conservative benchmark scenario)





ILC can indeed measure M_{W}, m_{t}, $\sin^2\theta_{\mathrm{W}}$ with much higher precision.

Summary

- ILC can advance our knowledge of electroweak precision physics
- Can deliver much more rigorous test of the SM which explores new physics. Highlighted by top mass measurement (see AF Zarnecki talk) and

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

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

- Scope for complementary M_{W} measurements with similar precision 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. Can also open up a measurement of M_{Z}.
- An accelerator is needed! On-going encouraging developments in Japan.
- The physics discussed here benefits greatly when the accelerator is designed to include efficient running at lower center-of-mass energies.

References

M. Baak *et al.* [Gfitter Group Collaboration],
The global electroweak fit at NNLO and prospects for the LHC and ILC
Eur. Phys. J. C **74**, 3046 (2014)

Backup Slides

SM Fit (GFitter)

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}	93^{+24}_{-20}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008	80.358 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011	91.2000 ± 0.010
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016	2.4945 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026	20.721 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004	0.93463 ± 0.00003
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003	0.0738 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011	0.21577 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\triangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\triangledown)}$	177.0 ± 2.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44	2722 ± 42
$\alpha_s(M_Z^2)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030	0.1196 ± 0.0028

$^{(\circ)}$Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties.
$^{(\star)}$Average of the LEP and SLD A_ℓ measurements, used as two measurements in the fit.
$^{(\triangledown)}$The theoretical top mass uncertainty of 0.5 GeV is excluded.
$^{(\dagger)}$In units of 10^{-5}.
$^{(\triangle)}$Rescaled due to α_s dependence.

Full Simulation + Kalman Filter

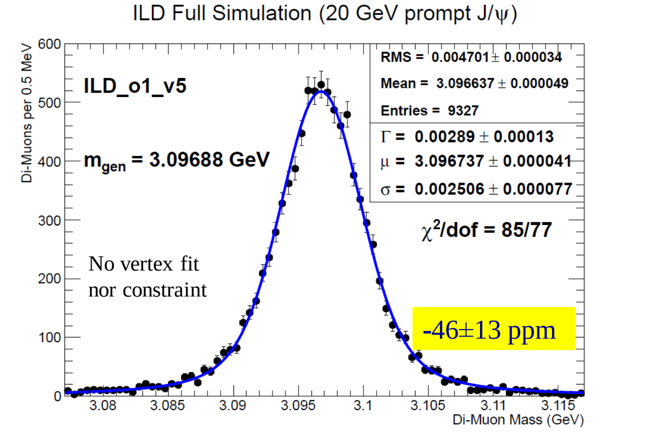
$\sqrt{s}=m_Z$

10k "single particle events"

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

Preliminary statistical precision similar.

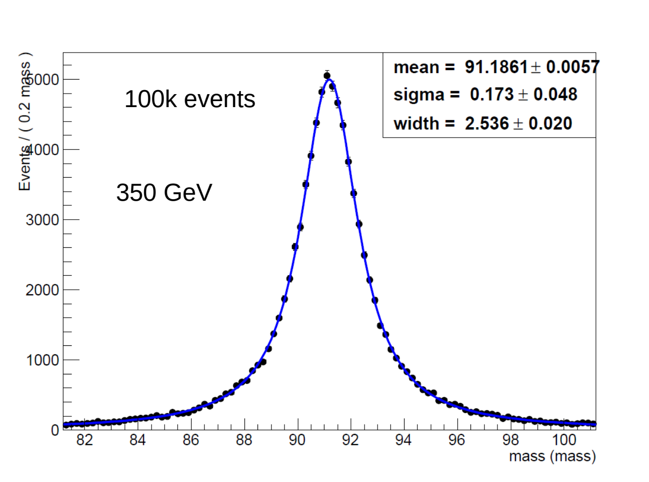
More realistic material, energy loss and multiple scattering.



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

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.