Precision Electroweak Measurements with ILC250

Emphasis on Experimental Measurement Aspects Including $\sqrt{s}$, Polarization

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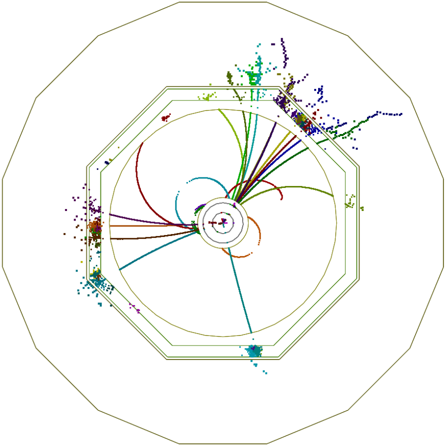
ILC is a unique and timely opportunity for understanding the electroweak scale

Many (physics, detector, and accelerator) opportunities [1] to make it better!

More information on EWPO estimates in [2]

Talk focus: Selected EW measurements with initial $\sqrt{s} \leq 250$ GeV stage

Outline



Physics Motivation

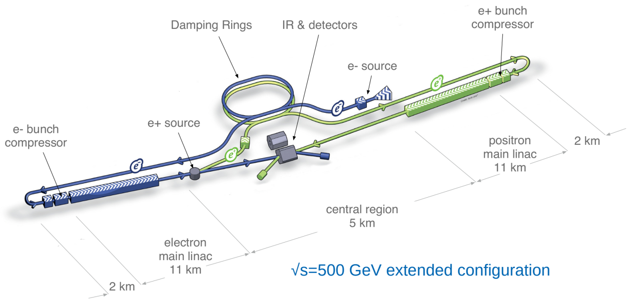
- Direct discovery of new physics would be wonderful
- Before the top and Higgs discoveries, precision measurements of then observable SM parameters pointed the way
- Newer physics may continue to evade direct collider detection
- Ultra-precise measurements of known physics can probe potentially much higher energy scales and associated new physics
- How best to do this?
    - Need flexible, broad and probing program of the underlying dynamics
    - Precision measurements at high energy: $\mathrm{W^+W^-}$, $\mathrm{f\bar{f}}$ full reconstruction
    - High precision measurements of other parameters at suitable $\sqrt{s}$ including top-pair threshold and Z-pole, and potentially WW threshold
    - **Polarized beams** (ILC strength - 4 colliders-in-1) give essential insight
- The physics case for a future $\mathrm{e^+e^-}$ collider is very well established. Let's seize this opportunity and explore the physics.

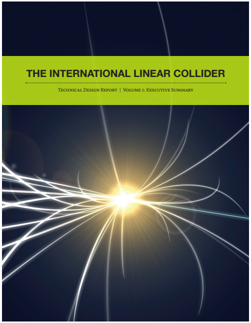
e^+e^- Linear Colliders

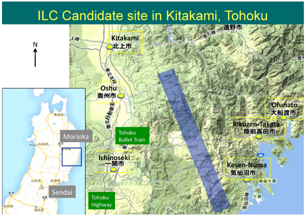
Linear colliders are the only practical way with e^+e^- to go significantly above the top-pair threshold (synchrotron radiation and real-world economics)

- ILC is based on superconducting RF (mature and power efficient)
  - Under study and development for many years
  - Fully international project with strong participation from US, Europe and Asia
  - Technology deployed in many facilities: XFEL, LCLS-II
- ILC TDR 2013 - engineered design capable of $\sqrt{s} = 200 - 500$ GeV upgradable to 1 TeV and potentially beyond
  - Longitudinally polarized e^- (80%) and e^+ (30%) beams
  - Japan is exploring hosting the ILC as a global project
  - With the Higgs discovery - guaranteed rich physics program
- Recent years → focus on starting at $\sqrt{s} = 250$ GeV with energy extendability
  - Optimized design for $\sqrt{s} = 250$ GeV with higher luminosity ($\mathcal{L}$)
  - Now have easily achievable running with polarized beams at lower energies, including $\sqrt{s} \approx M_Z$ with $\mathcal{L} = 4.2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - New appreciation in Japan of the longer-term opportunities with higher energy
- **International ILC project is transitioning toward realization in Japan**

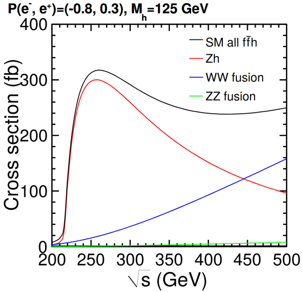
International Linear Collider Project







N of Tokyo (2hrs by train), between Sendai & Morioka



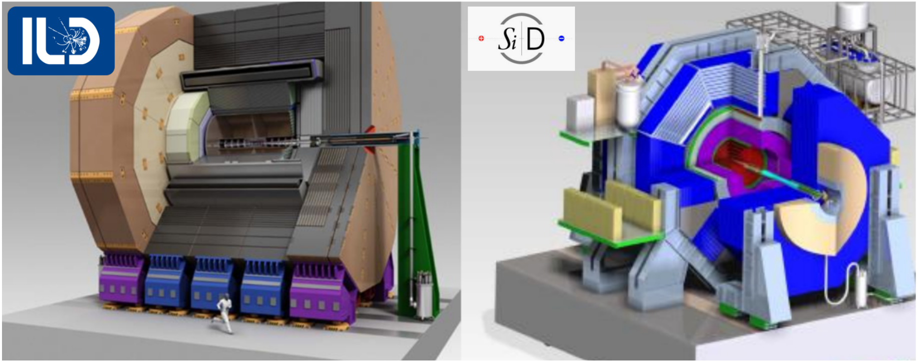
- TDR 2013 [3]
- 2019 update [4]
- 20.5 km footprint for initial 250 GeV stage

ILC Detectors

Modern detectors designed for ILC [5]

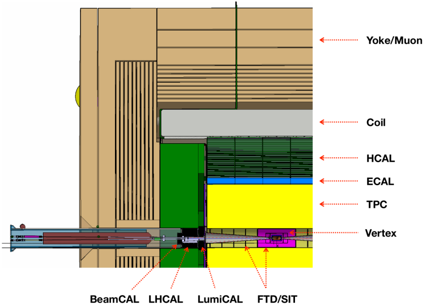
ILD = International Large Detector
(also ILD Interim Design Report (IDR) [6])

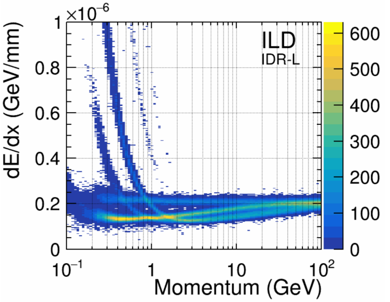
SiD = Silicon Detector

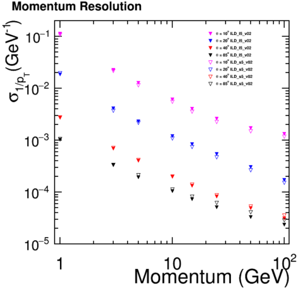


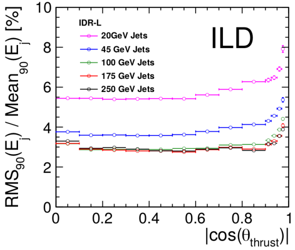
- B=3.5–5T. Particle-flow for jets. Very hermetic.
- Low material. Precision vertexing.
- ILD tracking centered around a Time Projection Chamber (TPC).

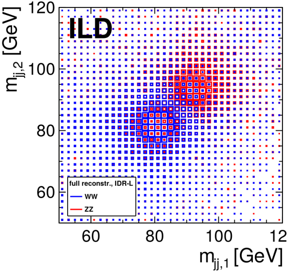
ILD Detector (See IDR and T. Tanabe talk)



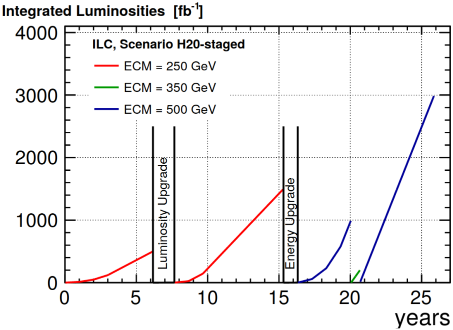








ILC Parameters / Run Scenarios



- Baseline scenario for study
- Run plan flexible - will evolve
- Future upgrade to 1 TeV ($8000\ \mathrm{fb}^{-1}$) and potentially beyond
- Options for dedicated running with polarized beams
  - Z-pole ($100\ \mathrm{fb}^{-1}$)
  - WW threshold ($500\ \mathrm{fb}^{-1}$)

- $6.2\ \mathrm{ab}^{-1}$ total at 250, 350, 500 GeV
- Dedicate $200\ \mathrm{fb}^{-1}$ to top-pair threshold
- See Ref. [4] for details

	int. luminosity with $\mathrm{sgn}(P(e^-),P(e^+))=$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]
250 GeV (update)	**900**	**900**	100	100
350 GeV	135	45	10	10
500 GeV	1600	1600	400	400

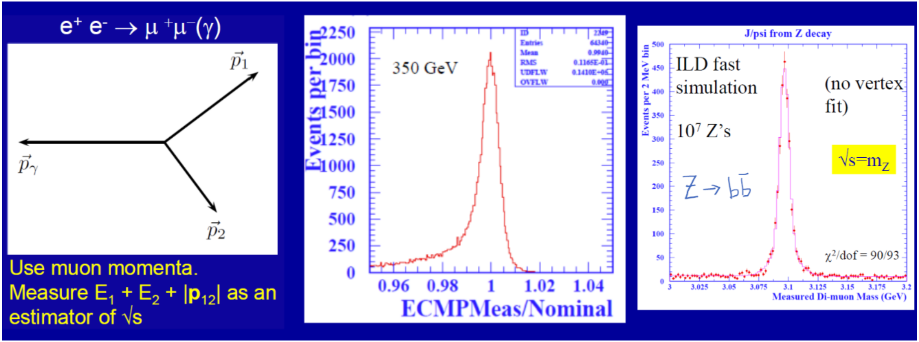
Assumes $(|P_{\mathrm{e}^-}|, |P_{\mathrm{e}^+}|) = (0.8, 0.3)$

Center-of-Mass Energy Measurement

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

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

Use di-muon momenta method, using $\sqrt{s}_p = E_+ + E_- + |\vec{p}_{+-}|$ estimator. Tie detector p-scale to the J/ψ mass scale (known to 1.9 ppm). See backup, [7].



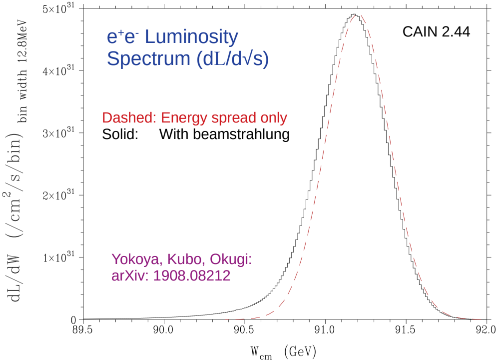
Use muon momenta. Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$

Measure $<\sqrt{s}>$ and luminosity spectrum with same events. Expect statistical uncertainty of 1.0 ppm on p-scale per 1.2M $J/\psi \to \mu^+\mu^-$ (4×10^9 hadronic Z's).

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
- New design with polarized beams at Z-pole with $\mathcal{L} = 4.2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ [8]
- Enables a broader program of electroweak measurements
- High Z statistics for detector calibration/alignment, physics modeling



Yokoya, Kubo, Okugi: arXiv: 1908.08212

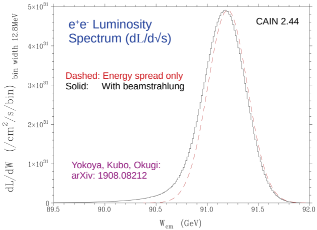
How well can one do with $100\ \mathrm{fb}^{-1}$ polarized at the Z?

- Control systematics?
- 4.2×10^{9} hadronic events
- 2.0×10^{8} dimuons
- 2.0×10^{7} J/ψ
- FWHM is about 500 MeV

Lots of fun questions to explore

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

- Use 200M $Z \to \mu^+\mu^-$ and $\sqrt{s}_p$ method
- With ILC $\Delta p/p$ of 0.15%, $\Delta\sqrt{s}_p \approx 230$ MeV per dimuon event
- $\Rightarrow$ stat. uncertainty of 0.18 ppm on average $\sqrt{s}_p$ with 100 fb^{-1} Z run



- In the same Z run, can measure p-scale with 1.0 ppm stat. uncertainty from $J/\psi \to \mu^+\mu^-$ ($<$ 1.9 ppm: $m_{J/\psi}$ PDG target)
- Collect Z events, and concurrently measure cross sections & asymmetries, C-o-M energy/lumi. spectrum, p-scale *in situ*.

- Overall p-scale uncertainty of 2.5 ppm conceivable ($> 1.0 \oplus 1.9$) ppm
- Need further study of tracker design and $\sqrt{s}_p$ method
- Can envisage order-of-magnitude improvements on M_Z and Γ_Z
- 2.5 ppm on M_Z is 230 keV.

For now, estimate 5 ppm on $\sqrt{s}$-scale at $\sqrt{s} \approx M_\mathrm{Z}$ and 10 ppm at higher $\sqrt{s}$

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, is valuable, and may be feasible

Longitudinal polarization not expected to cost luminosity.

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

where σ_k ($k =$ LR, RL, LL and RR) are the fully polarized cross-sections [9]

Straightforward to measure the absolute polarization of both beams *in situ* when $\sigma_{LL} = \sigma_{RR} = 0$ (such as γ/Z exchange) using 4 σ measurements $(\sigma_{-+}, \sigma_{+-}, \sigma_{--}, \sigma_{++})$. Solve for 4 unknowns ($\sigma_U$, A_{LR}, $|P_{\mathrm{e}^-}|$, $|P_{\mathrm{e}^+}|$), where,

$$A_{LR} \equiv \frac{\sigma_{LR} - \sigma_{RL}}{(\sigma_{LR} + \sigma_{RL})}$$

Supplement with polarimeters to track relative polarization changes. See talk by J.List and backup slides for more details.

W Mass

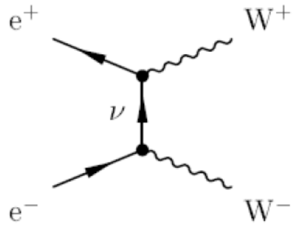
M_{W} is an experimental challenge. Especially for hadron colliders.

The four most promising approaches [2] to measure M_{W} at ILC are:

1. Polarized Threshold Scan Measurement of $\boldsymbol{\sigma}_{\mathbf{W^+W^-}}$ near **threshold** with longitudinally **polarized** beams. Unique ILC potential.
2. Constrained Reconstruction **Kinematically-constrained** reconstruction of $\mathrm{W^+W^-}$ using 4-momentum conservation and optionally mass-equality. (LEP2 main method)
3. Hadronic Mass Direct measurement of the **hadronic mass**. Can apply to hadronically decaying W's in semi-leptonic $\mathrm{W^+W^-}$ or single-W events.
4. Leptonic Observables Use lepton **endpoints** in semi-leptonic and fully leptonic $\mathrm{W^+W^-}$ events with either $\mathrm{W} \to \mathrm{e}\nu_e$ or $\mathrm{W} \to \mu\nu_\mu$. Use **pseudomasses** in dilepton events with no taus.

Method 1 needs dedicated running near $\sqrt{s} = 161$ GeV. Methods 2–4 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}.

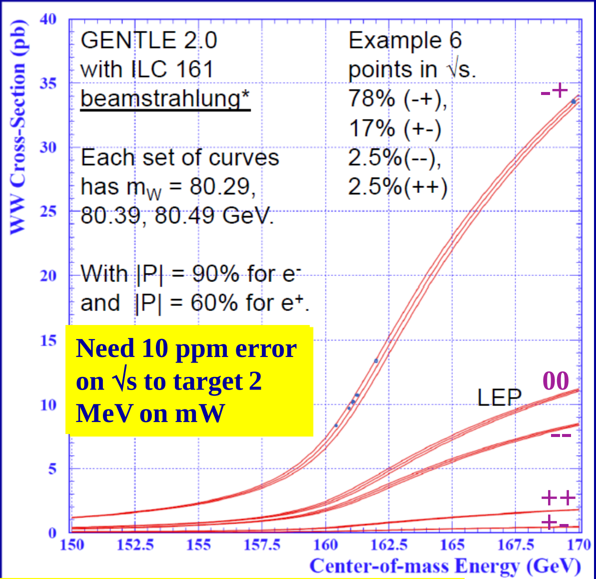
ILC Polarized Threshold Scan



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)



GENTLE 2.0
with ILC 161
beamstrahlung*

Each set of curves has m_W = 80.29, 80.39, 80.49 GeV.

With |P| = 90% for e^- and |P| = 60% for e^+.

Example 6 points in √s.
78% (-+),
17% (+-)
2.5%(--),
2.5%(++)

Need 10 ppm error on √s to target 2 MeV on mW

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

Results from updated ILC study [10]

Fit parameter	Value	Error
m_W (MeV)	80,388	3.8
f_l	1.0002	0.0009
ε (lvlv)	1.0004	0.001
ε (qqlv)	0.9998	0.001
ε (qqqq)	1.0000	0.001
σ_B (lvlv) (fb)	10.3	0.9
σ_B (qqlv) (fb)	40.5	2.3
σ_B (qqqq) (fb)	196	4
A^B_{LR} (lvlv)	0.156	0.025
A^B_{LR} (qqlv)	0.298	0.012
A^B_{LR} (qqqq)	0.480	0.005
$\lvert P(e^-)\rvert$	0.899	0.001
$\lvert P(e^+)\rvert$	0.601	0.001
σ_{Z} (pb)	149.92	0.05
A^Z_{LR}	0.1906	0.0003

← **Example fit:**

- 6-point scan as illustrated
- 100 fb^{-1}
- $(|P_{\mathrm{e}^-}|, |P_{\mathrm{e}^+}|) = (0.9, 0.6)$

$\lvert P(e^-)\rvert$	$\lvert P(e^+)\rvert$	100 fb^{-1}	500 fb^{-1}
80 %	30 %	6.0	2.9
90 %	30 %	5.2	2.6
80 %	60 %	4.0	2.2
90 %	60 %	3.8	2.1

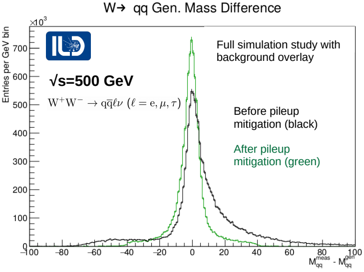
Total M_{W} experimental uncertainty (MeV)

10 ppm assumed uncertainty on $\sqrt{s}$
⇒ additional 0.8 MeV on M_{W}

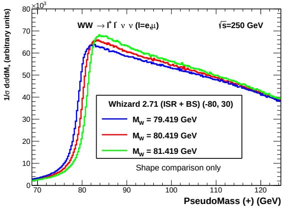
Fit essentially **includes** experimental systematics. Main one - **background** determination.

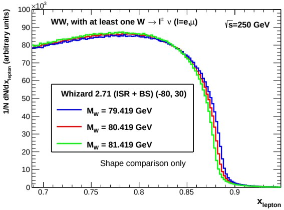
$$\Delta M_{\mathrm{W}}(\mathrm{MeV}) = 2.4\,(\mathrm{stat}) \oplus 3.1\,(\mathrm{syst}) \oplus 0.8\,(\sqrt{\mathrm{s}}) \oplus \mathrm{theory}$$

M_{W}, Γ_{W} from higher energy runs



- **Hadronic mass study**, J. Anguiano (KU).
- Stat. $\Delta M_{\mathrm{W}} = 2.4$ MeV for $1.6\ \mathrm{ab}^{-1}$ (-80%, +30%).
- Can be improved, but m_{had}-only measurement likely limited by JES systematic
- Expect improvements with **constrained fit** and $\sqrt{s} = 250$ GeV data set





Sensitivity to M_{W} with lepton distributions: **dilepton pseudomasses**, lepton **endpoints**

- Stat. $\Delta M_{\mathrm{W}} = 4.4$ MeV for $2\ \mathrm{ab}^{-1}$ (45,45,5,5) at $\sqrt{s} = 250$ GeV
- **Leptonic observables** (shape-only): x_ℓ, M_+, M_-. Exptl. systematics small.

A_{LR} at $\sqrt{s} \approx M_Z$ (Studied initially by K. Mönig [11])

For $\mathrm{Z} \to \mathrm{f}\bar{\mathrm{f}}$,
$\sigma = \sigma_u[1 - P^+P^- + A_{\mathrm{LR}}(P^+ - P^-)]$

With $(P_{\mathrm{e}^-}, P_{\mathrm{e}^+}) = (0.8, 0.6)$, $f_{\mathrm{SS}} = 0.08$:
$\Delta A_{LR}(\mathrm{stat}) = 1.7 \times 10^{-5}/\sqrt{\mathcal{L}(0.1\ \mathrm{ab}^{-1})}$

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 (relative to M_Z)

$dA_{LR}/d\sqrt{s} = 2.0 \times 10^{-2}\ \mathrm{GeV}^{-1}$. 5 ppm on $\sqrt{s} \Rightarrow 0.9 \times 10^{-5}$ on A_{LR}

Beamstrahlung (machine dependent)

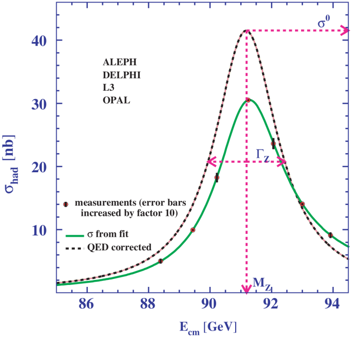
TESLA study ⇒ change in A_{LR} of 9×10^{-4}. Assume known to 1% ⇒ 0.9×10^{-5} on A_{LR}.

$$\Delta A_{LR}(10^{-5}) = 2.4/\sqrt{L(100\ \mathrm{fb}^{-1})}\ (\mathrm{stat}) \oplus 0.9\ (\sqrt{\mathrm{s}}) \oplus 0.9\ (\mathrm{BS})$$

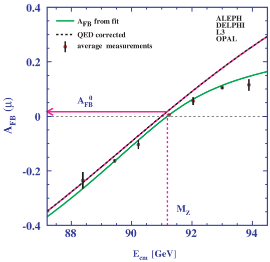
Can target experimental precision on A_{LR} of 3×10^{-5} with 100 fb^{-1}. Oft-cited 10^{-4} prospect (1.3×10^{-5} on $\sin^2\theta^{\ell}_{\mathrm{eff}}$) with 30 fb^{-1} well within reach (it was conservative).

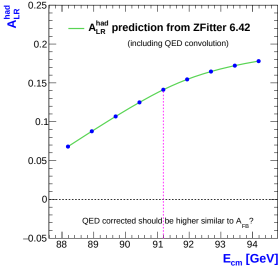
Polarized Beams Z Scan for Z LineShape and Asymmetries

Essentially, redo LEP/SLC-style measurements in all channels but also with $\sqrt{s}$ dependence of the polarized asymmetries, A_{LR} and $A^{f}_{FB,LR}$, in addition to A_{FB}.



LEP: $\Delta M_{\mathrm{Z}} = 2.1$ MeV, $\Delta\Gamma_{\mathrm{Z}} = 2.3$ MeV





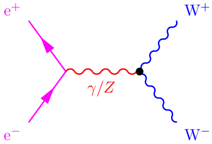
With 100 fb^{-1} polarized scan around M_{Z}, find **statistical** uncertainties of 35 keV on M_{Z}, and 80 keV on Γ_{Z}, from LEP-style fit to $(M_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}, \sigma^0_{\mathrm{had}}, R^0_e, R^0_\mu, R^0_\tau)$ using ZFITTER 6.42 [12] for QED convolution.

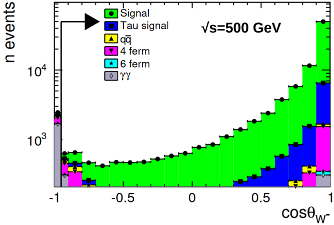
Exploiting this fully needs in-depth study of $\sqrt{s}$ calibration systematics + possibly smaller energy-spread. ILC $\mathcal{L}$ is sufficient for M_{Z}. Γ_{Z} systematic uncertainty depends on $(\sqrt{s}_+ - \sqrt{s}_-)$ uncertainty, so expect $\Delta\Gamma_{\mathrm{Z}} < \Delta M_{\mathrm{Z}}$.

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

TGCs: $(g_1^Z, \kappa_\gamma, \lambda_\gamma)$

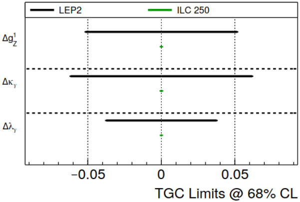
Example with
$W^+W^- \to q\bar{q}\ell\nu$





$\sqrt{s}$ (GeV)	g_1^Z	κ_γ	λ_γ
250	6.2	9.6	7.7
500	2.5	3.4	3.7
1000	0.88	1.1	0.90

Uncertainties (10^{-4}) from 3 TGC parameters fit with 0.5 ab^{-1} equally shared between (-80, 30)% and (80, -30)%



- Based on full simulation studies (ILD) and their extrapolation [2, 4, 13]
- Higher energy better given s/M_W^2 dependence of TGCs (and γ scaling of $\mathcal{L}$)
- Already with ILC250 (2 ab^{-1}), expect 0.05% precision cf 5% at LEP2 (ALEPH)

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

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

$$\Delta A_{LR}(10^{-5}) = 2.4/\sqrt{L(100\ \mathrm{fb}^{-1})}\,(\mathrm{stat})\ \oplus 0.9\,(\sqrt{\mathrm{s}})\ \oplus 0.9(\mathrm{BS})$$

- 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}, etc
- More study on expt./acc. systematics + tracker design work necessary.
- An accelerator is needed! On-going very 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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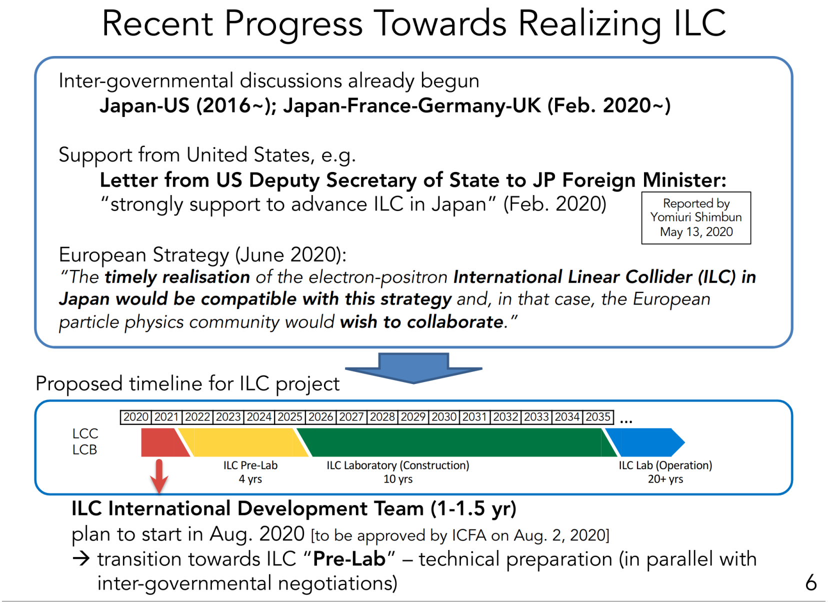
Acknowledgments

Backup Slides

ILC Project Timelines



Recent Progress Towards Realizing ILC

Inter-governmental discussions already begun

Japan-US (2016~); Japan-France-Germany-UK (Feb. 2020~)

Support from United States, e.g.

Letter from US Deputy Secretary of State to JP Foreign Minister:
"strongly support to advance ILC in Japan" (Feb. 2020)

Reported by
Yomiuri Shimbun
May 13, 2020

European Strategy (June 2020):
*"The **timely realisation** of the electron-positron **International Linear Collider (ILC) in Japan would be compatible with this strategy** and, in that case, the European particle physics community would **wish to collaborate**."*

Proposed timeline for ILC project

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	…

LCC
LCB

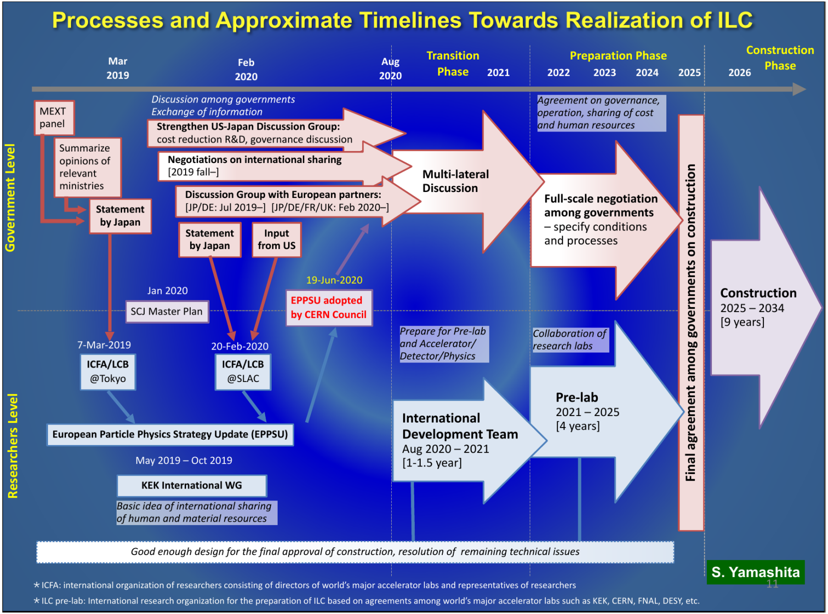
ILC Pre-Lab
4 yrs

ILC Laboratory (Construction)
10 yrs

ILC Lab (Operation)
20+ yrs

ILC International Development Team (1-1.5 yr)
plan to start in Aug. 2020 [to be approved by ICFA on Aug. 2, 2020]
→ transition towards ILC "**Pre-Lab**" – technical preparation (in parallel with inter-governmental negotiations)

ILC Project Timeline Details



Processes and Approximate Timelines Towards Realization of ILC

Mar 2019 | Feb 2020 | Aug 2020 | Transition Phase | 2021 | Preparation Phase 2022 2023 2024 2025 | 2026 | Construction Phase

Government Level

MEXT panel

Summarize opinions of relevant ministries

Statement by Japan

Discussion among governments
Exchange of information

Strengthen US-Japan Discussion Group: cost reduction R&D, governance discussion

Negotiations on international sharing [2019 fall–]

Discussion Group with European partners: [JP/DE: Jul 2019–] [JP/DE/FR/UK: Feb 2020–]

Statement by Japan

Input from US

Multi-lateral Discussion

Agreement on governance, operation, sharing of cost and human resources

Full-scale negotiation among governments – specify conditions and processes

Final agreement among governments on construction

Construction 2025 – 2034 [9 years]

Researchers Level

Jan 2020
SCJ Master Plan

19-Jun-2020
EPPSU adopted by CERN Council

7-Mar-2019
ICFA/LCB @Tokyo

20-Feb-2020
ICFA/LCB @SLAC

European Particle Physics Strategy Update (EPPSU)

May 2019 – Oct 2019

KEK International WG

Basic idea of international sharing of human and material resources

Prepare for Pre-lab and Accelerator/ Detector/Physics

International Development Team Aug 2020 – 2021 [1-1.5 year]

Collaboration of research labs

Pre-lab 2021 – 2025 [4 years]

Good enough design for the final approval of construction, resolution of remaining technical issues

S. Yamashita

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⋆ICFA: international organization of researchers consisting of directors of world's major accelerator labs and representatives of researchers

⋆ILC pre-lab: International research organization for the preparation of ILC based on agreements among world's major accelerator labs such as KEK, CERN, FNAL, DESY, etc.

Ubiquity of $\mu^+\mu^-/\mathrm{Z}$ in $\sqrt{s}$ scale discussion

"$\mu^+\mu^-$" or "Z" appears in many places - for varied, but 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 angle-based 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).

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}	**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	$\pi^-\mathrm{p}$	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

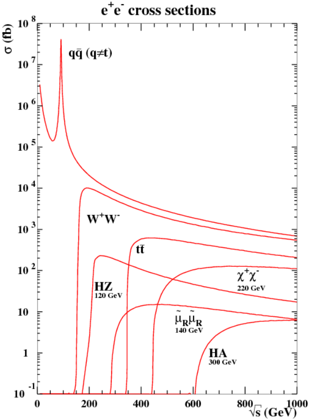
Estimated momentum scale statistical errors ($p_X = 20$ GeV)

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.)

Detector Calibration and Alignment

Clean $\mathrm{e^+e^-}$ 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. May be essential to fully exploiting the ILC at all $\sqrt{s}$. Design this capability in!

Now done!

Polarized Observables with Radiative Return Events

See 1908.11299 for details. Use jet polar angles to infer longitudinal boost, β.

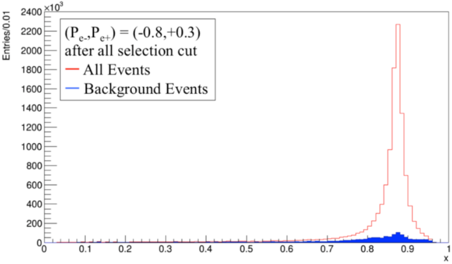


Figure 2: Reconstructed distribution of $x \equiv \frac{2|\beta|}{1+|\beta|}$ for the signal $e^+e^- \to \gamma Z$, $Z \to q\bar{q}$ and from background events that mimic this signal, at $\sqrt{s} = 250$ GeV with an integrated luminosity of 250 fb^{-1}.

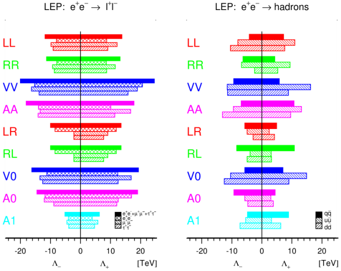
Study indicates statistical uncertainty on A_e of 14×10^{-5} with full 2 ab^{-1} of ILC250 running.

Very different systematics to Z-pole based A_{LR} measurement and accessible with data collected synergystically with Higgs production. Nevertheless, Z-pole running precision expected to be superior.

Two-Fermions and Four-Fermion Contact Interactions

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

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



LEP2

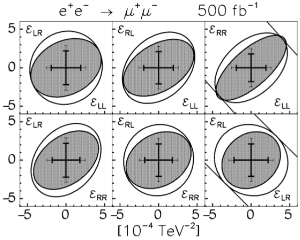
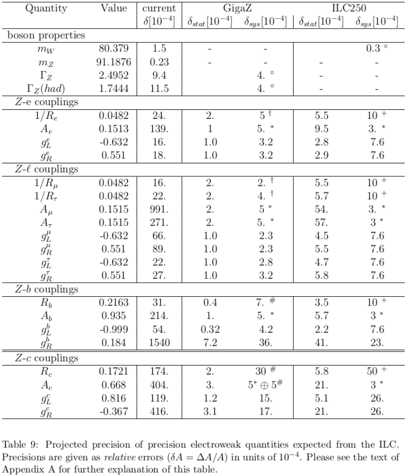


Fig. 1. Two-dimensional projections of the 95% C.L. allowed region (27) for $e^+e^- \to \mu^+\mu^-$ at $\mathcal{L}_{\text{int}} = 50$ fb^{-1} and $\mathcal{L}_{\text{int}} = 500$ fb^{-1}. Note that the scales are different. $|P_e| = 0.8$, $|P_{\bar{e}}| = 0.0$ (outer ellipse) and $|P_{\bar{e}}| = 0.6$ (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. [14]. Polarization gives access to full 4-parameter space (LR,RL,LL,RR).

Current ILC projections - see [2] extend to 151 to 478 TeV for Λ in various models (driven by 8 ab^{-1} at 1 TeV).

Table of EWPO from arXiv:1908.11299

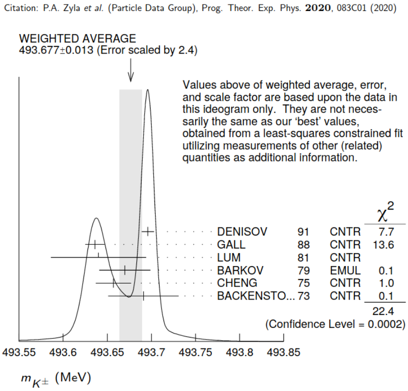


Quantity	Value	current	GigaZ		ILC250	
		$\delta[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$
boson properties						
m_W	80.379	1.5	-	-		0.3 °
m_Z	91.1876	0.23	-	-	-	-
Γ_Z	2.4952	9.4		4. °	-	-
$\Gamma_Z(had)$	1.7444	11.5		4. °	-	-
Z-e couplings						
$1/R_e$	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)

WEIGHTED AVERAGE
493.677±0.013 (Error scaled by 2.4)

Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

			χ^2
DENISOV	91	CNTR	7.7
GALL	88	CNTR	13.6
LUM	81	CNTR	
BARKOV	79	EMUL	0.1
CHENG	75	CNTR	1.0
BACKENSTO...	73	CNTR	0.1
			22.4

(Confidence Level = 0.0002)

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.

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.

Full Simulation + Kalman Filter

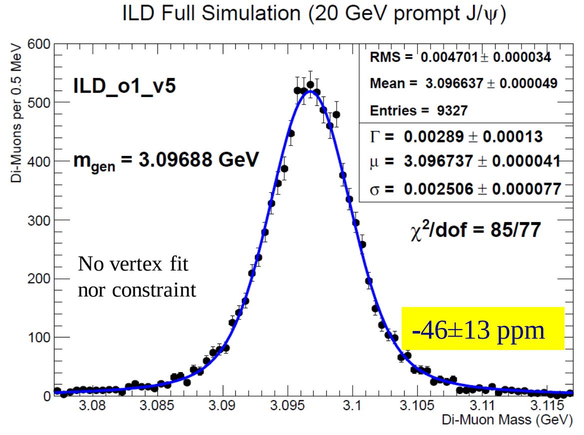
$\sqrt{s}=m_Z$

10k “single particle events”

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

Preliminary statistical precision similar.

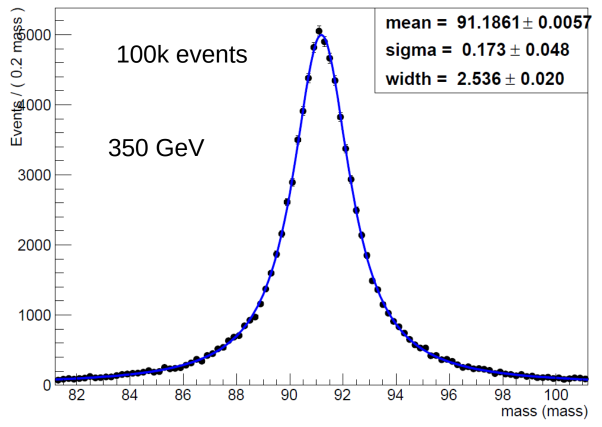
More realistic material, energy loss and multiple scattering.



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.

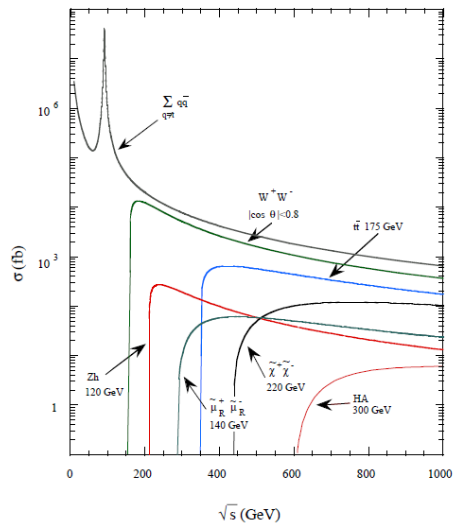
Alignment ?
B-field ?
Push-pull ?
Etc …

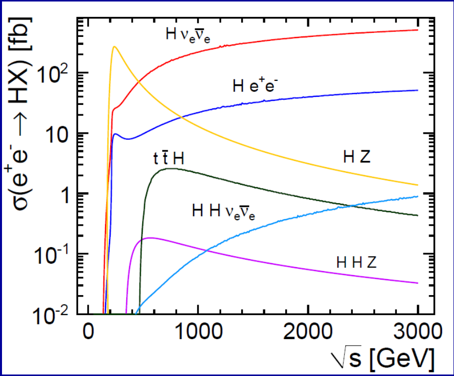
XFEL at DESY

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→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

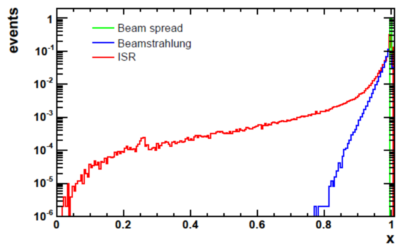


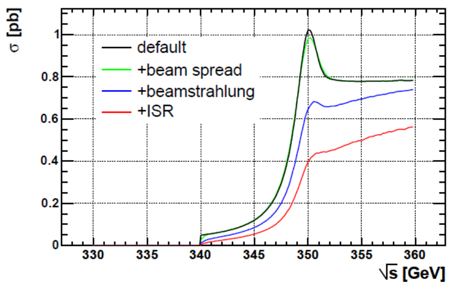


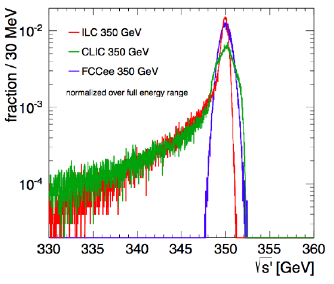
Cross-sections are typically at the pb level.

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

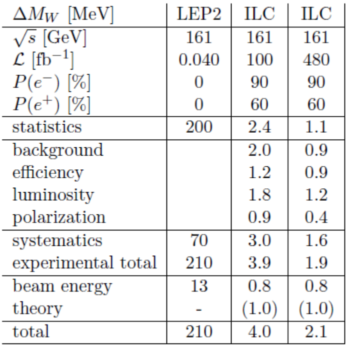
1. Polarized Threshold Scan
2. Kinematic Reconstruction
3. Hadronic Mass

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.

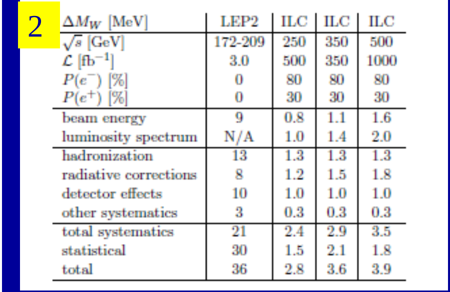
Method 3: Depends on di-jet mass scale. Plenty Z's for 3 MeV.

1



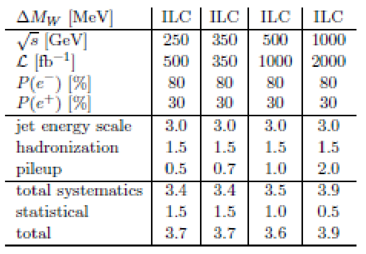
ΔM_W [MeV]	LEP2	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480
$P(e^-)$ [%]	0	90	90
$P(e^+)$ [%]	0	60	60
statistics	200	2.4	1.1
background		2.0	0.9
efficiency		1.2	0.9
luminosity		1.8	1.2
polarization		0.9	0.4
systematics	70	3.0	1.6
experimental total	210	3.9	1.9
beam energy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

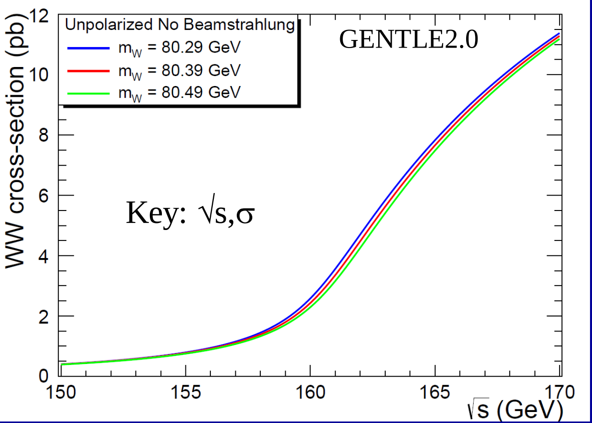


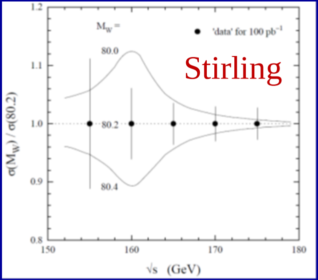
ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5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

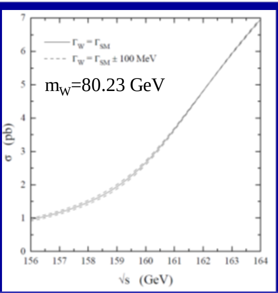
See Snowmass document for more details

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

m_W from cross-section close to threshold







$\sigma_t \sim \beta$

$\sigma_s \sim \beta^3$

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

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 $\mathrm{m}(W^+) = \mathrm{m}(W^-)$.
- a specified value for M_{W}

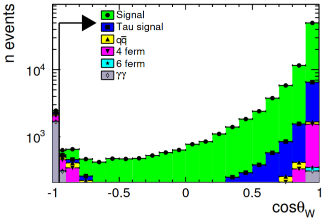
$$\mathbf{p}_{\vec{\overline{\nu}}} = a\,\vec{\mathbf{l}} + b\,\vec{\mathbf{l}'} + c\,\vec{\mathbf{l}} \times \vec{\mathbf{l}'}$$

By specifying, M_{W}, one can find a, b and c^2, so there are two solutions.

The alternative pseudomass technique is more appropriate for a M_{W} measurement. It does not assume M_{W}, but sets $c = 0$, similarly yielding two solutions, $(a_+,\, b_+)$ and $(a_-,\, b_-)$, leading to PseudoMass(+) and PseudoMass(−) estimators per event.

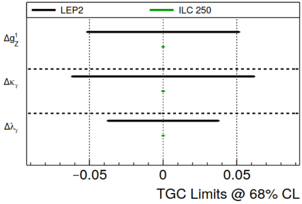
Higher Energy: Triple Gauge Couplings (WWγ, WWZ)

Many 4f processes besides $\mathrm{W^+W^-}$. “Single-W” processes, $\mathrm{e^+e^-} \to \mathrm{W\ e}\ \nu_e$, very important. Can disentangle the beam polarizations, P_{e^-} and P_{e^+}, and constrain residual imperfect spin-flip, using such processes where σ_{LL} or $\sigma_{RR} \neq 0$.



	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.



3-parameter fits based on full simulation studies and their extrapolation with ILD. Clearly higher energy is better especially given the γ scaling of luminosity. Already with ILC250 (2 ab^{-1}), expect 0.05% precision, compared to 5% precision for a LEP2 experiment. No comparable hadron collider results available. See thesis by Robert Karl (DESY) with work on a multi-channel global fit including correlations.

Polarization Observables

At a polarized $\mathrm{e^+e^-}$ 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

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

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

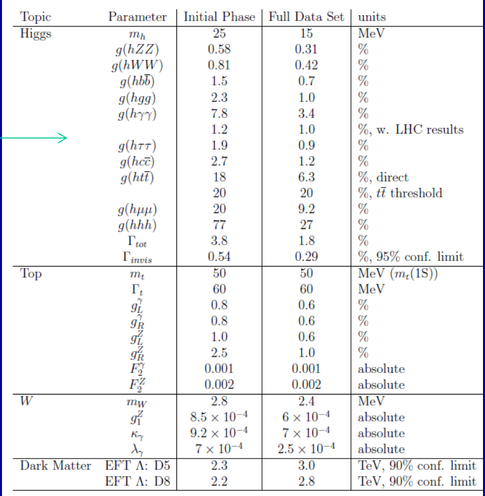
$$A_{FB,LR}^{f} = \frac{3}{4} A_f \ .$$

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

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

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



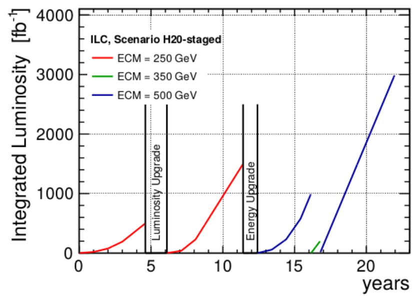
Topic	Parameter	Initial Phase	Full Data Set	units
Higgs	m_h	25	15	MeV
	$g(hZZ)$	0.58	0.31	%
	$g(hWW)$	0.81	0.42	%
	$g(hb\bar{b})$	1.5	0.7	%
	$g(hgg)$	2.3	1.0	%
	$g(h\gamma\gamma)$	7.8	3.4	%
		1.2	1.0	%, w. LHC results
	$g(h\tau\tau)$	1.9	0.9	%
	$g(hc\bar{c})$	2.7	1.2	%
	$g(ht\bar{t})$	18	6.3	%, direct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

See references slide containing more recent documents with consistent assumptions

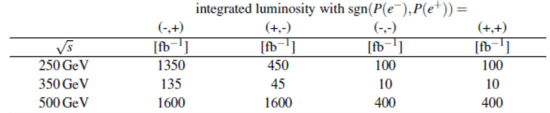
ILC Parameters / Running Scenarios

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