Exploring Precision Electroweak Measurement Potential of e^+e^- Colliders

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See previous report to EF04 on ILC EW potential, talk at ICHEP2020, and references in LOI for more details.

LOI = SNOWMASS21-EF4_EF0-AF3_AF0-IF3_IF5_GrahamWilson-119

LOI Abstract

Abstract

The ILC linear e^+e^- collider has been designed with an emphasis on an initial-stage Higgs factory that starts at $\sqrt{s}$ = 250 GeV and is expandable in energy to run at higher energies for pair production of top quarks and Higgs bosons, and potentially to 1 TeV and more. The unique feature of longitudinally polarized electron and positron beams and the higher energies open up many new measurement possibilities that are very complementary to those feasible with e^+e^- circular colliders. An overarching very timely question is how well can ILC running at lower center-of-mass energies, particularly near the Z-pole, perform statistically and systematically for measurements of precision electroweak observables including those already explored at SLC and LEP? Would this offer significant advantages over only running at energies above ZH threshold? A related question is how such running with ILC compares statistically and systematically with the various circular e^+e^- collider proposals? On the one hand, the circular approach now claims enormous luminosity at low energy, but on the other hand, is therefore enormous and expensive, and if ever realized for e^+e^- would likely be on a much longer time horizon than ILC. Whether one can exploit the very large statistics and not be dominated by systematics is at the heart of these questions. A follow-up question is whether, with advances in accelerator designs, there could ever be a physics niche for a SuperLEP? Namely, a high-luminosity circular e^+e^- collider Z-factory of modest size (eg. Tevatron tunnel) that is likely incompatible with use as a Higgs factory. Studies are being undertaken: i) to understand ILC capabilities for a precision measurement of the Z lineshape observables with a scan using polarized beams, ii) to further explore an experimental strategy for $\sqrt{s}$ determination, and iii) to further explore M_W capabilities synergistic with a concurrent Higgs program.

Will go through this in a more readable way in next slides.

LOI Abstract Intro

The ILC linear e^+e^- collider has been designed with an emphasis on an **initial-stage Higgs factory** that starts at $\sqrt{s} = 250$ GeV and is **expandable in energy** to run at higher energies for pair production of top quarks and Higgs bosons, and potentially to 1 TeV and more.

The **unique feature** of **longitudinally polarized electron and positron beams** and the **higher energies** open up many new measurement possibilities that are very complementary to those feasible with e^+e^- circular colliders.

(The ILC is designed primarily to explore the 200 – 1000 GeV energy frontier regime. This has been the primary focus in making the case for the project. It is also capable of running at the Z and WW threshold.)

LOI Abstract Questions

1. An overarching question is how well can ILC running at lower $\sqrt{s}$, particularly near the Z-pole, perform **statistically** and **systematically** for measurements of PEW observables including those already explored at SLC/LEP?
2. Would this offer significant advantages over only running at energies above ZH threshold?
3. A related question is how such running with ILC compares statistically and systematically with the various circular $\mathrm{e}^+\mathrm{e}^-$ collider proposals?

On the one hand, the circular approach now targets enormous luminosity at low energy, but on the other hand, is therefore enormous and expensive, and if ever realized for $\mathrm{e}^+\mathrm{e}^-$ would likely be on a much longer time horizon than ILC. Whether one can exploit the very large statistics and not be dominated by systematics is at the heart of these questions.

A follow-up question is whether

- With advances in accelerator designs, could there be a physics niche for a SuperLEP? Namely, a high-lumi circular $\mathrm{e}^+\mathrm{e}^-$ collider Z-factory of modest size (eg. Tevatron tunnel) that is incompatible with use as a Higgs factory.

LOI Abstract Studies

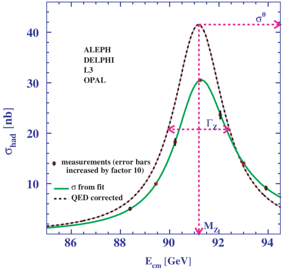
Studies are being undertaken:

1. to understand ILC capabilities for a precision measurement of the Z lineshape observables with a scan using polarized beams,
2. to further explore an experimental strategy for $\sqrt{s}$ determination using di-leptons, and
3. to further explore M_{W} capabilities synergistic with a concurrent Higgs program.

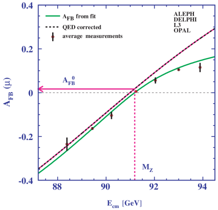
Next - 1 slide on each of these areas.

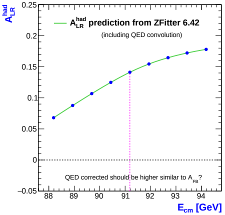
Polarized Beams Z Scan for Z LineShape and Asymmetries

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}. (Also polarized $\nu\overline{\nu}\gamma$ scan.) Not constrained to LEP-style scan points.



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





With 0.1 ab^{-1} polarized scan around $M_{\rm Z}$, find **statistical** uncertainties of 35 keV on $M_{\rm Z}$, and 80 keV on $\Gamma_{\rm Z}$, from LEP-style fit to $(M_{\rm Z}, \Gamma_{\rm Z}, \sigma^0_{\rm had}, R^0_e, R^0_\mu, R^0_\tau)$ using ZFITTER for QED convolution. Started using SMATASY (model-independent S-matrix approach). Likely need to follow up with Ayres/Tord Riemann.

Exploiting this fully needs in-depth study of $\sqrt{s}$ calibration systematics

ILC $\mathcal{L}$ is sufficient for $M_{\rm Z}$

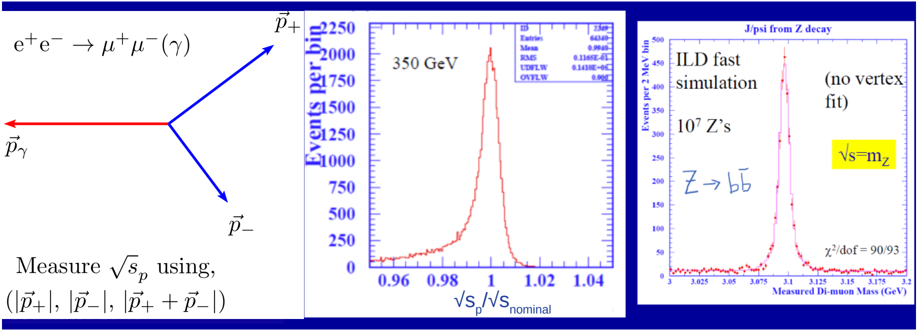
$\Gamma_{\rm Z}$ systematic uncertainty depends on $\Delta(\sqrt{s}_+ - \sqrt{s}_-)$, so expect $\Delta\Gamma_{\rm Z} < \Delta M_{\rm Z}$

Center-of-Mass Energy Measurement (*)

Critical input for M_t, M_W, M_H, M_Z, M_X measurements

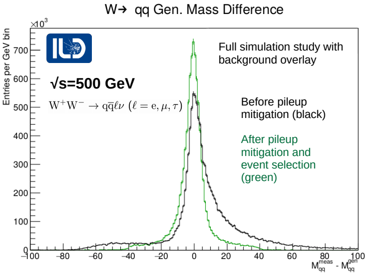
1. Standard precision of $\mathcal{O}(10^{-4})$ in $\sqrt{s}$ for M_t straightforward
2. Targeting precision of $\mathcal{O}(10^{-5})$ in $\sqrt{s}$ for M_W given likely systematics
3. For M_Z - helps to do even better

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

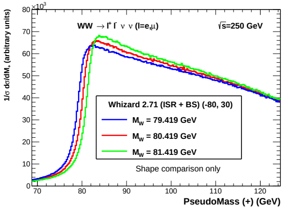


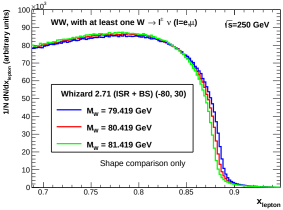
Measure $<\sqrt{s}>$ and luminosity spectrum with same events. Expect statistical uncertainty of 1.0 ppm on p-scale per 1.2M $J/\psi \to \mu^+\mu^-$ (4×10^9 hadronic Z's).

M_W, Γ_W measurements concurrent with Higgs program



- **Hadronic mass study**, J. Anguiano (KU).
- Stat. $\Delta M_W = 2.4$ 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. $\Delta M_W = 4.4$ MeV for $2\ \mathrm{ab}^{-1}$ (45,45,5,5) at $\sqrt{s} = 250$ GeV
- **Leptonic observables** (shape-only): M_+, M_-, $x_\ell \equiv E_\ell / E_\mathrm{b}$. Exptl. systematics small.

Concluding Remarks

LOI has 3 main thrusts

1. New study on polarized Z-scan. While anchored in old studies of "Giga-Z" – much broader in scope and ambition. Very much welcome collaboration.
2. Further exploration based on existing studies of center-of-mass energy calibration using di-leptons.
3. Further exploration based on existing studies and LEP2-style W mass measurements using WW production. Much room for additional work and collaboration.

In all cases welcome further collaboration.

- KU student, Justin Anguiano, worked on some of the WW aspects of M_{W} (preprint to appear soon).
- Collaborating with others including Jenny List and Michael Peskin.