Precision Electroweak Physics with a Future $e^+e^-$ Linear Collider
Emphasis on Experimental Measurement Aspects

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Outline

1. Physics Motivation
2. ILC Accelerator and Detectors
3. Experimental Issues
4. $W$ Mass
5. $A_{LR}$
6. Experimental Systematics
7. Synthesis
8. Summary
9. References
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: $\alpha_{\text{em}}$, $G_F$, $M_Z$, $M_W$, $\sin^2 \theta_W$, $M_H$.

ILC can advance significantly these tests of the SM by measuring $M_W$, $m_t$, $\sin^2 \theta_W$ 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.
- 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\(^{-1}\)).

6200 fb\(^{-1}\) total

200 fb\(^{-1}\) at \(\sqrt{s}\approx350\) GeV
Modern detectors designed for ILC. Particle-flow for jets. Similar size to CMS. ILD centered around a TPC. SiD – silicon tracking.

**ILD** = International Large Detector

**SiD** = Silicon Detector
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

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

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

Use muon momenta. Measure $E_1 + E_2 + |p_{12}|$ as an estimator of $\sqrt{s}$
Luminosity Spectrum

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

Luminosity spectrum 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.

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 ($\sigma_U, A_{LR}, P_{e^+}, P_{e^-}$). Assumes same $|P|$ for +ve and –ve helicity of same beam.
- Polarimeters to track relative polarization changes.
$M_W$ 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 $W^+W^-$ cross-section near threshold with longitudinally polarized beams.

2. **Constrained Reconstruction** Kinematically-constrained reconstruction of $W^+W^-$ 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 $W^+W^-$ 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.

See Snowmass document for more details

Bottom-line: 3 different methods with prospects to measure m_W with error < 5 MeV
$m_W$ from cross-section close to threshold

Key: $\sqrt{s}, \sigma$

Unpolarized No Beamstrahlung
- $m_W = 80.29$ GeV
- $m_W = 80.39$ GeV
- $m_W = 80.49$ GeV

GENTLE2.0

Stirling

$m_W = 80.23$ GeV

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

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

**Need 10 ppm error on \(\sqrt{s}\) to target 2 MeV on \(m_W\)**

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

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 \(\sqrt{s}\).

78\% \((-+)\), 17\% \((++)\)

2.5\% \((-\)), 2.5\% \((++)\)
### Example Polarized Threshold Scan

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<th>L (fb$^{-1}$)</th>
<th>$f$</th>
<th>$\lambda_{e^-} \lambda_{e^+}$</th>
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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)

<table>
<thead>
<tr>
<th>Fit parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
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<td>$m_W$ (GeV)</td>
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<td>$3.77 \times 10^{-3}$</td>
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<tr>
<td>$f_l$</td>
<td>1.0002</td>
<td>$0.924 \times 10^{-3}$</td>
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<tr>
<td>$\varepsilon$ (lvlv)</td>
<td>1.0004</td>
<td>$0.969 \times 10^{-3}$</td>
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<tr>
<td>$\varepsilon$ (qqlv)</td>
<td>0.99980</td>
<td>$0.929 \times 10^{-3}$</td>
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<tr>
<td>$\varepsilon$ (qqqq)</td>
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<td>$0.942 \times 10^{-3}$</td>
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<tr>
<td>$\sigma_B$ (lvlv) (fb)</td>
<td>10.28</td>
<td>0.92</td>
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<tr>
<td>$\sigma_B$ (qqlv) (fb)</td>
<td>40.48</td>
<td>2.26</td>
</tr>
<tr>
<td>$\sigma_B$ (qqqq) (fb)</td>
<td>196.37</td>
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<tr>
<td>$A_{LR}^B$ (lvlv)</td>
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<td>0.0247</td>
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<tr>
<td>$A_{LR}^B$ (qqlv)</td>
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<tr>
<td>$A_{LR}^B$ (qqqq)</td>
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<td>$4.72 \times 10^{-3}$</td>
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<td>$</td>
<td>P(e^-)</td>
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<td>$</td>
<td>P(e^+)</td>
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<td>$\sigma_Z$ (pb)</td>
<td>149.93</td>
<td>0.052</td>
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<tr>
<td>$A_{LR}^Z$</td>
<td>0.19062</td>
<td>$2.89 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

| $\sigma_Z$ (pb) | 149.93 | 0.052 |

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

| $\sigma_B$ (fb) | 10.28 | 0.92 |
| $\sigma_B$ (fb) | 40.48 | 2.26 |
| $\sigma_B$ (fb) | 196.37 | 3.62 |
| $A_{LR}^B$ (fb) | 0.15637 | 0.0247 |
| $A_{LR}^B$ (fb) | 0.29841 | 0.0119 |
| $A_{LR}^B$ (fb) | 0.48012 | $4.72 \times 10^{-3}$ |
| $|P(e^-)|$ | 0.89925 | $1.27 \times 10^{-3}$ |
| $|P(e^+)|$ | 0.60077 | $9.41 \times 10^{-4}$ |
| $\sigma_Z$ (pb) | 149.93 | 0.052 |
| $A_{LR}^Z$ | 0.19062 | $2.89 \times 10^{-4}$ |

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

$$\Delta M_W (\text{MeV}) = 2.4 \text{ (stat)} \oplus 3.1 \text{ (syst)} \oplus 0.8 \text{ (}\sqrt{s}\text{)} \oplus \text{theory}$$
\( A_{LR} \) at \( \sqrt{s} = M_Z \)

Studied by K. Mönig 1999

For \( Z \rightarrow f\bar{f} \), general cross-section formula simplifies to

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

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).

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

For \( P^- = 0.8, \ P^+ = 0.6, \ f_{SS} = 0.08, \ \sigma_{vis}^U = 33 \text{ nb} \):

\[
\Delta A_{LR} \text{(stat)} = 1.7 \times 10^{-5} / \sqrt{L(100 \text{ fb}^{-1})}
\]
**Statistical Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>Multiplicative Factor</th>
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<tr>
<td>Bhabha Statistics</td>
<td>1.09</td>
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<tr>
<td>Compton Statistics</td>
<td>1.34</td>
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</table>

**Center-of-mass Energy**

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

**Beamstrahlung**

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

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

Can target experimental precision of \(4 \times 10^{-5}\) with 100 fb\(^{-1}\). Oft-cited \(10^{-4}\) prospect (\(1.3 \times 10^{-5}\) on \(\sin^2 \theta^\ell \text{ eff}\)) with 30 fb\(^{-1}\) is well within reach (ie is conservative).

Note that \(\sin^2 \theta^\ell \text{ eff}\) interpretation depends amongst others on improved knowledge of \(\Delta \alpha_{\text{had}}\).
“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!
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.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$n_{Z\text{had}}$</th>
<th>Decay</th>
<th>BR (%)</th>
<th>$n_{Z\text{had}} \cdot BR$</th>
<th>$\Gamma/M$</th>
<th>PDG ($\Delta M/M$)</th>
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<tr>
<td>$J/\psi$</td>
<td>0.0052</td>
<td>$\mu^+ \mu^-$</td>
<td>5.93</td>
<td>0.00031</td>
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<td>$3.6 \times 10^{-6}$</td>
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<tr>
<td>$K_S^0$</td>
<td>1.02</td>
<td>$\pi^+ \pi^-$</td>
<td>69.2</td>
<td>0.71</td>
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Candidate particles for momentum scale calibration and abundances in $Z$ decay

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

$$m_{12}^2 = m_1^2 + m_2^2 + 2p_1 p_2 \left[ (\beta_1 \beta_2)^{-1} - \cos \psi_{12} \right]$$

<table>
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<tr>
<th>Particle</th>
<th>Decay</th>
<th>$&lt;\alpha&gt;$</th>
<th>max $\alpha$</th>
<th>$\sigma M/M$</th>
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Estimated momentum scale statistical errors ($p = 20$ GeV)

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

Opens up possibility of improved $M_Z$ measurements.
ILC can indeed measure $M_W$, $m_t$, $\sin^2 \theta_W$ with much higher precision.
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

\[
\Delta M_W (\text{MeV}) = 2.4 \, (\text{stat}) \oplus 3.1 \, (\text{syst}) \oplus 0.8 \, (\sqrt{s}) \oplus \text{theory}
\]

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

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.
M. Baak et al. [Gfitter Group Collaboration],
The global electroweak fit at NNLO and prospects for the LHC and ILC
### SM Fit (GFitter)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Free in fit</th>
<th>Fit Result</th>
<th>w/o exp. input in line</th>
<th>w/o exp. input in line, no theo. unc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_H$ [GeV]$^{(\circ)}$</td>
<td>$125.14 \pm 0.24$</td>
<td>yes</td>
<td>$125.14 \pm 0.24$</td>
<td>$93^{+25}_{-21}$</td>
<td>$93^{+24}_{-20}$</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>$80.385 \pm 0.015$</td>
<td>–</td>
<td>$80.364 \pm 0.007$</td>
<td>$80.358 \pm 0.008$</td>
<td>$80.358 \pm 0.006$</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.085 \pm 0.042$</td>
<td>–</td>
<td>$2.091 \pm 0.001$</td>
<td>$2.091 \pm 0.001$</td>
<td>$2.091 \pm 0.001$</td>
</tr>
<tr>
<td>$M_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
<td>yes</td>
<td>$91.1880 \pm 0.0021$</td>
<td>$91.200 \pm 0.011$</td>
<td>$91.2000 \pm 0.0010$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>–</td>
<td>$2.4950 \pm 0.0014$</td>
<td>$2.4946 \pm 0.0016$</td>
<td>$2.4945 \pm 0.0016$</td>
</tr>
<tr>
<td>$\sigma^{0}_{\text{had}}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
<td>–</td>
<td>$41.484 \pm 0.015$</td>
<td>$41.475 \pm 0.016$</td>
<td>$41.474 \pm 0.015$</td>
</tr>
<tr>
<td>$R^{0}_{\ell}$</td>
<td>$20.767 \pm 0.025$</td>
<td>–</td>
<td>$20.743 \pm 0.017$</td>
<td>$20.722 \pm 0.026$</td>
<td>$20.721 \pm 0.026$</td>
</tr>
<tr>
<td>$A^{0}_{FB}$</td>
<td>$0.0171 \pm 0.0010$</td>
<td>–</td>
<td>$0.01626 \pm 0.00001$</td>
<td>$0.01625 \pm 0.00001$</td>
<td>$0.01625 \pm 0.00001$</td>
</tr>
<tr>
<td>$A^{\ell}(\ast)$</td>
<td>$0.1499 \pm 0.0018$</td>
<td>–</td>
<td>$0.1472 \pm 0.00005$</td>
<td>$0.1472 \pm 0.00005$</td>
<td>$0.1472 \pm 0.00004$</td>
</tr>
<tr>
<td>$\sin^{\ast}<em>{\text{eff}}(Q</em>{FB})$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>–</td>
<td>$0.23150 \pm 0.00006$</td>
<td>$0.23149 \pm 0.00007$</td>
<td>$0.23150 \pm 0.00005$</td>
</tr>
<tr>
<td>$A_{c}$</td>
<td>$0.670 \pm 0.027$</td>
<td>–</td>
<td>$0.6680 \pm 0.00022$</td>
<td>$0.6680 \pm 0.00022$</td>
<td>$0.6680 \pm 0.00016$</td>
</tr>
<tr>
<td>$A_{b}$</td>
<td>$0.923 \pm 0.020$</td>
<td>–</td>
<td>$0.93463 \pm 0.00004$</td>
<td>$0.93463 \pm 0.00004$</td>
<td>$0.93463 \pm 0.00003$</td>
</tr>
<tr>
<td>$A^{0}_{c}$</td>
<td>$0.0707 \pm 0.0035$</td>
<td>–</td>
<td>$0.0738 \pm 0.0003$</td>
<td>$0.0738 \pm 0.0003$</td>
<td>$0.0738 \pm 0.0002$</td>
</tr>
<tr>
<td>$A^{0}_{b}$</td>
<td>$0.0992 \pm 0.0016$</td>
<td>–</td>
<td>$0.1032 \pm 0.0004$</td>
<td>$0.1034 \pm 0.0004$</td>
<td>$0.1033 \pm 0.0003$</td>
</tr>
<tr>
<td>$R^{0}_{c}$</td>
<td>$0.1721 \pm 0.0030$</td>
<td>–</td>
<td>$0.17226 \pm 0.00009_{-0.00008}$</td>
<td>$0.17226 \pm 0.00008$</td>
<td>$0.17226 \pm 0.00006$</td>
</tr>
<tr>
<td>$R^{0}_{b}$</td>
<td>$0.21629 \pm 0.00066$</td>
<td>–</td>
<td>$0.21578 \pm 0.00011$</td>
<td>$0.21577 \pm 0.00011$</td>
<td>$0.21577 \pm 0.00004$</td>
</tr>
<tr>
<td>$m_c$ [GeV]</td>
<td>$1.27^{+0.07}_{-0.11}$</td>
<td>yes</td>
<td>$1.27^{+0.07}_{-0.11}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$m_b$ [GeV]</td>
<td>$4.20^{+0.17}_{-0.07}$</td>
<td>yes</td>
<td>$4.20^{+0.17}_{-0.07}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.34 \pm 0.76$</td>
<td>yes</td>
<td>$173.81 \pm 0.85_{\text{\tiny (\vee)}}$</td>
<td>$177.0 \pm 2.3_{\text{\tiny (\vee)}}$</td>
<td>$177.0 \pm 2.3$</td>
</tr>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(M_Z^2)^{(\ast\ast)}$</td>
<td>$2757 \pm 10$</td>
<td>yes</td>
<td>$2756 \pm 10$</td>
<td>$2723 \pm 44$</td>
<td>$2722 \pm 42$</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>$0.1196 \pm 0.0030$</td>
<td>–</td>
<td>$0.1196 \pm 0.0030$</td>
<td>$0.1196 \pm 0.0028$</td>
<td></td>
</tr>
</tbody>
</table>

$^{(\circ)}$ Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties.

$^{(\ast)}$ Average of the LEP and SLD $A_\ell$ measurements, used as two measurements in the fit.

$^{(\vee)}$ The theoretical top mass uncertainty of 0.5 GeV is excluded.

$^{(\ast\ast)}$ In units of $10^{-5}$.

$^{(\ast\ast)}$ Rescaled due to $\alpha_s$ dependence.
Full Simulation + Kalman Filter

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 

\[ 1.8 \text{ MeV} / \sqrt{N} \]

With N in millions.

ILC TDR design focused on $\sqrt{s} > 200$ GeV.
Luminosity naturally scales with $\gamma$ 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 $3.3 \times 10^{33}$.
Need modification to the $e^+$ production scheme.
Details need detailed design - but no obvious technical show-stoppers.