Searching for dark matter and electroweak symmetry breaking at OPAL

Outline:

- Measuring the invisible width of the Z Boson and other electroweak measurements

- Higgs searches at LEP
In December 1987, I found this in the Luxembourg airport and read it on the Icelandair 707 from Geneva to Chicago for my interview:

Still came to Chicago!

Jim helped me find an apartment here for the 1987-1988 academic year:

Spent a year at UC on building PB and its electronics (along with John Hobbs, Kelby and Waren Schappert). The following year we all moved to CERN. I stayed until 1991 when I started at Oregon.
LEP Lineshape and Lepton Asymmetry Measurements

\[ e^+e^- \rightarrow f\bar{f} \]

Lowest order differential cross section (ignoring masses and initial and final state QCD and QED corrections):

\[
\frac{2s}{\pi\alpha^2} \frac{1}{N_c} \frac{d\sigma}{d\cos \theta} = \\
q_f^2 (1 + \cos^2 \theta) \gamma \\
-8\text{Re}\{\chi(s)q_f(g_{Ve}g_{Vf}(1 + \cos^2 \theta) + 2g_{Ae}g_{Af} \cos \theta)\} \quad Z - \gamma \\
16|\chi(s)|^2[(g_{Ve}^2 + g_{Ae}^2)(g_{Vf}^2 + g_{Af}^2)(1 + \cos^2 \theta) + 8g_{Ve}g_{Ae}g_{Vf}g_{Af} \cos \theta] \quad Z
\]

Where:

- \( \chi(s) = \frac{G_F m_Z^2}{8\pi\alpha\sqrt{2} s - m_Z^2 + is\Gamma_Z/m_Z} \)

- \( g_{Vf} \) and \( g_{Af} \) are replaced with effective couplings in the Improved Born Approximation which we will use from now on.

- \( N_c \) is the number of “colors” for the final state fermions
Experimental results reported after unfolding for huge ($\simeq 25\%$) initial-state radiative corrections. Electrons are corrected for t-channel effects.

(These correction are known to third-order, see: Berends, Neerven, Burgers / Montagna, Nicrosini, and Piccinini / Skrzypek/ Jadach, Pietrzyk, and Skrzypek).
LEP Model “Independent” Parameter Set
(also called pseudo-observables)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Theory Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_Z )</td>
<td>0.3 MeV ((0.03 \times 10^{-4}))</td>
</tr>
<tr>
<td>( \Gamma_Z )</td>
<td>0.2 MeV ((0.8 \times 10^{-4}))</td>
</tr>
<tr>
<td>( \sigma^0_{\text{had}} )</td>
<td>( \equiv \frac{12\pi}{m_Z^2} \frac{\Gamma_{\gamma^+\gamma^-}}{\Gamma_Z^2} ) 0.022 nb ((5.3 \times 10^{-4}))</td>
</tr>
<tr>
<td>( R_\ell )</td>
<td>( \equiv \frac{\Gamma_{\text{had}}}{\Gamma_{\ell}} ) 0.004* ((1.9 \times 10^{-4}))</td>
</tr>
<tr>
<td>( A^0_{\text{FB}} )</td>
<td>( \equiv \frac{3}{4} A_e A_f ) 0.0001* ((0.6%)</td>
</tr>
</tbody>
</table>

\[
\Gamma_{ff} = \frac{G_F N_c m_Z^2}{6\pi \sqrt{2}} \left( R_v^f \Gamma_{\ell}^2 + R_A^f A_f^2 \right) + \Delta_{\text{QCD}}
\]
\[
A_f = 2 \frac{g_v^f g_A^f}{g_v^f + g_A^f}
\]

\((R_v^f \text{ and } R_A^f \text{ give corrections for final-state QED and QCD effects as well as quark masses, } \Delta_{\text{QCD}} \text{ for non-factorizable QCD effects.})\)

* Theory error for electrons is larger 0.024 \((R_e)\) and 0.0014 \((A^0_{\text{FB}})\)

Theory errors as of 2002
What can the Z lineshape tell us about possible dark matter: ratio of invisible width of Z to leptonic width

\[ R_{\text{inv}} = \frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = \left( \frac{\Gamma_Z}{\Gamma_{\ell\ell}} - \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}} - 3 \frac{\Gamma_{\ell\ell}}{\Gamma_{\ell\ell}} \right) / \Gamma_{\ell\ell} \]

\[ = \frac{\Gamma_Z}{\Gamma_{\ell\ell}} - \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}} - 3 \frac{\Gamma_{\ell\ell}}{\Gamma_{\ell\ell}} \]

\[ = \sqrt{\frac{12\pi R_{\ell}}{m_Z^2 \sigma_{\text{had}}^0}} - R_{\ell} - 3 \]

\[ \Delta R_{\text{inv}} \approx 6 \frac{\Delta n_{\ell\ell}}{n_{\ell\ell}} + 21 \frac{\Delta n_{\text{had}}}{n_{\text{had}}} + 15 \frac{\Delta \mathcal{L}}{\mathcal{L}} \]

Need to measure \( \mathcal{L} \) (luminoisty ), \( n_{\ell\ell} \) and \( n_{\text{had}} \) to determine coupling of Z to dark matter candidates. Expect \( n_{\text{had}} \) to be \( > 10^6 \), need to measure \( \mathcal{L} \) to better than \( 1/1000 \).
• Starting in 1991 the Chicago (DS later Oregon) group, Maryland, CERN (Marcello Mannelli originally Chicago) and others started to design a silicon tungsten detector capable of measuring small angle Bhabha scattering \((e^+e^- \rightarrow e^+e^-)\) to 1/1000 (\(\sim 20\) micron precision on radius) or better:

• Chicago had the lead role on the digitization electronics, similar to those used for Presampler Barrel.
The Chicago Stage was revived for the first OPAL SiW test beam:

Slide from Tomio Kobayashi, OPAL reunion
Test beam was used to measure the response of the detector. This was coupled with careful metrology.

Measurement of response at radial boundary only possible because of the MIP sensitivity of the detector. Testbeam in 92 and 94.

Lab metrology
Almost 10 years later luminosity paper published:

“The total systematic measurement uncertainty is $3.4 \times 10^{-4}$, significantly below the theoretical error of $5.4 \times 10^{-4}$ currently assigned to the QED calculation of the Bhabha acceptance, and contributes negligibly to the total uncertainty in the OPAL measurement of $\Gamma_{inv}/\Gamma_{\ell\ell}$, a quantity of basic physical interest which depends crucially on the luminosity measurement.”

LEP average of ratio of invisible to leptonic widths:

\[
\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = \frac{Br(Z \rightarrow \text{inv})}{Br(Z \rightarrow \ell^+ \ell^-)} = 5.943 \pm 0.016
\]

\[\begin{align*}
\text{(SM } \frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = 5.9736 \pm 0.0048)\end{align*}\]

or

\[N_\nu = 2.9840 \pm 0.0082\]

or

\[\Delta \Gamma_{\text{inv}} < 2.0\text{MeV (95\% C.L.)}\]

This result benefits from the improved Bhabha theory error (Jadach, Placzek, Richter-Was, Ward, Z. Was/ Montagna, Moretti, Nicrosini, Pallavicini, Piccinini) and from the improved initial-state radiative corrections.
Interlude

The Chicago group had a big role in OPAL tau physics. Mike Roney and Hal Evans both served as tau group leaders. Here are measurement of one-prong rates from Hal’s tenure (Eur. Phys. J. C4 (1998) 193-206):

![Graph (a)](image1)

![Graph (b)](image2)

Gives constraints on r-parity violating couplings.
See http://hep.physics.indiana.edu/~hgevans/papers/rpv.ps
Tau Polarization

\[ P_\tau \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

where \( \sigma_+(-) \) is for positive(negative) helicity

At Born level

\[ P_\tau(\cos \theta_\tau^-) = \langle P_\tau \rangle \left( 1 + \cos^2 \theta_\tau^- \right) + \frac{8}{3} A_{\text{pol}}^{FB} \cos \theta_\tau^- \]

with \( \langle P_\tau \rangle = -A_\tau \) and \( A_{\text{pol}}^{FB} = -\frac{3}{4} A_e \)

Recall \( A_f = 2 \frac{g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} \)
Final OPAL analysis led by M. Roney, former UC post-doc, *Precision Neutral Current Asymmetry Parameter Measurements from the Tau Polarization at LEP*

<table>
<thead>
<tr>
<th>Observable</th>
<th>e</th>
<th>μ</th>
<th>π</th>
<th>ρ</th>
<th>a₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>dE/dx</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>φ_mecs</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>No. neutral clusters</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>E_{ass}</td>
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<tr>
<td>E_{ass}/p</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>E_{max}/p</td>
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<tr>
<td>E_{jet}/p</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>E_{resid}</td>
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</tr>
<tr>
<td>E_{1,2}</td>
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<td>X</td>
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</tr>
<tr>
<td>m_{ρ}</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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</tr>
<tr>
<td>m_{jet}</td>
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<td>m_{charged}</td>
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<tr>
<td>HCAL hits</td>
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<td>X</td>
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<tr>
<td>MUON hits</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Observables employed in the likelihood selections used to classify the different decay modes. An ‘X’ indicates that the observable is used in forming the likelihood distribution for the indicated decay mode selection.
After much work final polarization and forward-backward asymmetry of polarization:
Final LEP results on $Z$ couplings to leptons:

$$m_t = 178.0 \pm 4.3 \text{ GeV}$$
$$m_H = 114 \ldots 1000 \text{ GeV}$$
In general the LEP Z pole results greatly exceeded expectations:

<table>
<thead>
<tr>
<th></th>
<th>Expectation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z Decays/experiment</td>
<td>5 - 10 ×10^6</td>
<td>5 ×10^6</td>
</tr>
<tr>
<td>Systematic on energy</td>
<td>10 MeV</td>
<td>&lt; 2.0 MeV</td>
</tr>
<tr>
<td>Systematic on luminosity</td>
<td>~ 1%</td>
<td>~ 0.05% (Exp)</td>
</tr>
</tbody>
</table>
<pre><code>                                      |             | 0.054% (Th) |
</code></pre>
Results of full fit for LEP and SLC Z pole observables (including radiative corrections from $m_t$ and $m_h$) gave (Physics Reports, Volume 427, Issues 56, Pages 257-456 (May 2006))

In retrospect, results too good to believe:

Current Tevatron: $m_t = 173.18 \pm 0.94$ GeV  Pull: +0.01

ATLAS: $m_h = 126.0 \pm 0.4 (\text{stat}) \pm 0.4 (\text{sys})$ GeV  Pull: +0.08

Tevatron top mass at time of 2006 publication: 178.0 ± 4.3 GeV

Present PDB $\alpha_s$ world average (dominated by lattice results) is

$$\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$$
Higgs and Top mass constraints from the 2006 Z pole Physics Reports

![Graph showing Higgs and Top mass constraints from the 2006 Z pole Physics Reports. The graph includes data from LEP1, SLD, LEP2 (prel.), pp data, and current CDF mW + Tevatron top. The exclusion regions are marked with 68% CL.](image)

PilcherFest 18 22 September 2012
First OPAL paper on Higgs Production


- look for $e^+e^- \rightarrow Z^*H$

- Result is based on 825 nb$^{-1}$ from first run of LEP

- Use $Z^*$ decays to electrons, muons and neutrinos

- No limit below $m_{\tau\tau}$!

Background is four-fermion events

PilcherFest 22 September 2012
The Wisconsin group at ALEPH my alma mater was sure we were hiding something:

Charged Particle Pair Production
Associated with a Lepton Pair in Z Decays: Indication of an Excess in the Tau Channel

The ALEPH Collaboration*
Closing the Loopholes


Decay Mode Independent Search for a Light Higgs Boson and New Scalars (24 July 1991)


Mike Roney, D.S., ...

Hogan Nguyen, Frank, Mark ...

PilcherFest

22 September 2012
• No Higgs found at LEP I

• Result at right is from Hogan Nguyen’s thesis
Fermion-Pair Production at LEP II

OPAL $e^+e^-\rightarrow$ hadrons

Cross-section / pb

$\sqrt{s} / \text{GeV}$

$\Lambda / \text{TeV}$

Contact Interaction

PilcherFest 23 September 2012
Luminosity production and center-of-mass energy at LEP 2 very much exceeded expectations:

Possible to look at processes with cross section of \( \sim 10 fb^{-1} \)

PilcherFest 22 September 2012
Energy and luminosity were not enough to find a 125 GeV Higgs

Higgs-strahlung dominates

Possibility of looking for Higgs in circular machines is being revived:

Accelerators for a Higgs Factory:

Linear vs Circular

https://indico.fnal.gov/

conferenceDisplay.py?confId=5775

Janot, arxiv, 1208.1662

Callot and Tulley, Annual Reviews
Final LEP Standard Model Higgs Limits

Decay modes used:

\[ h \rightarrow b\bar{b} \quad Z \rightarrow \nu\nu \]
\[ h \rightarrow b\bar{b} \quad Z \rightarrow e^+e^- \]
\[ h \rightarrow b\bar{b} \quad Z \rightarrow \mu^+\mu^- \]
\[ h \rightarrow b\bar{b} \quad Z \rightarrow \tau^+\tau^- \]
\[ h \rightarrow b\bar{b} \quad Z \rightarrow \text{hadrons} \]
\[ h \rightarrow \tau^+\tau^- \quad Z \rightarrow \text{hadrons} \]

OPAL (LEP) limit 112.7 (114.4) GeV
Model Independent Searches at LEP II

Decay-mode independent searches for new scalar bosons with the OPAL detector at LEP

The OPAL Collaboration

- “sensitive to all decays of $S^0$ into an arbitrary combination of hadrons, leptons, photons and invisible particles ..”

- Use recoil mass of visible $Z$ decay products to get mass for the $S^0$ limit

Used both LEP 1 and LEP 2 data. Still useful today to constrain extensions to the Standard Model.
Many other non-Standard Higgs searches made, for example for the flavor-independent decay of scalar and psuedo-scalar Higgs:

**Flavor Independent** $h^0 Z^0$

$$e^+ e^- \rightarrow h^0 Z^0; \sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{SM}$$

$$e^+ e^- \rightarrow h^0 A^0; \sigma_{hA} = \cos^2(\beta - \alpha) \sigma_{SM}$$

---

OPAL found neither dark matter nor Higgs bosons, but:

- Precise $Z$ lineshape measurements are the basis of all precision tests of the Standard Model
- Limits on the invisible width are important for constraining dark matter models
- Many model independent Higgs searches are important for restricting extensions to the Standard Model