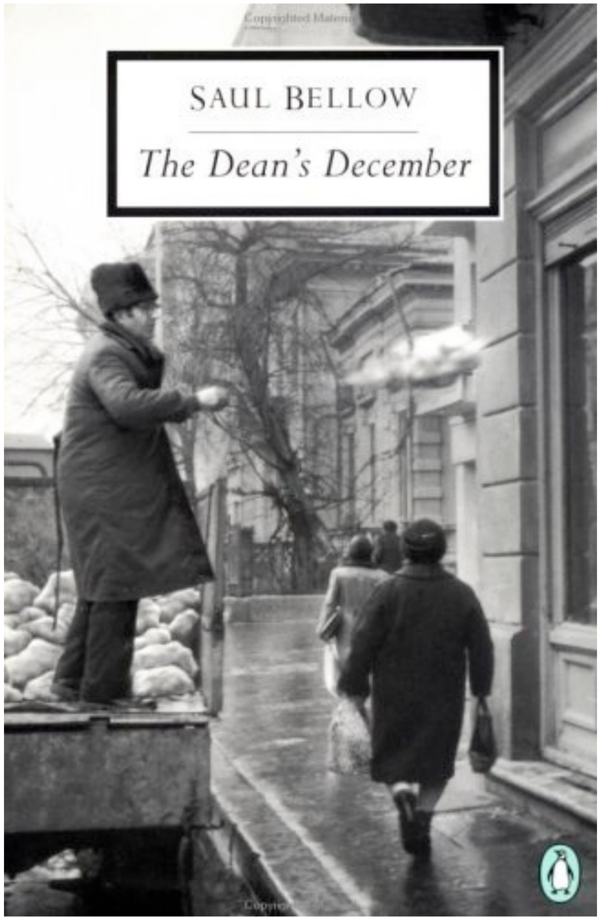
David Strom
University of Oregon

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:



SAUL BELLOW

The Dean's December

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

$$\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$$

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

$$\frac{2s}{\pi\alpha^2}\frac{1}{N_c}\frac{d\sigma}{d\cos\theta} =$$

$$q_f^2\left(1+\cos^2\theta\right) \qquad \gamma$$

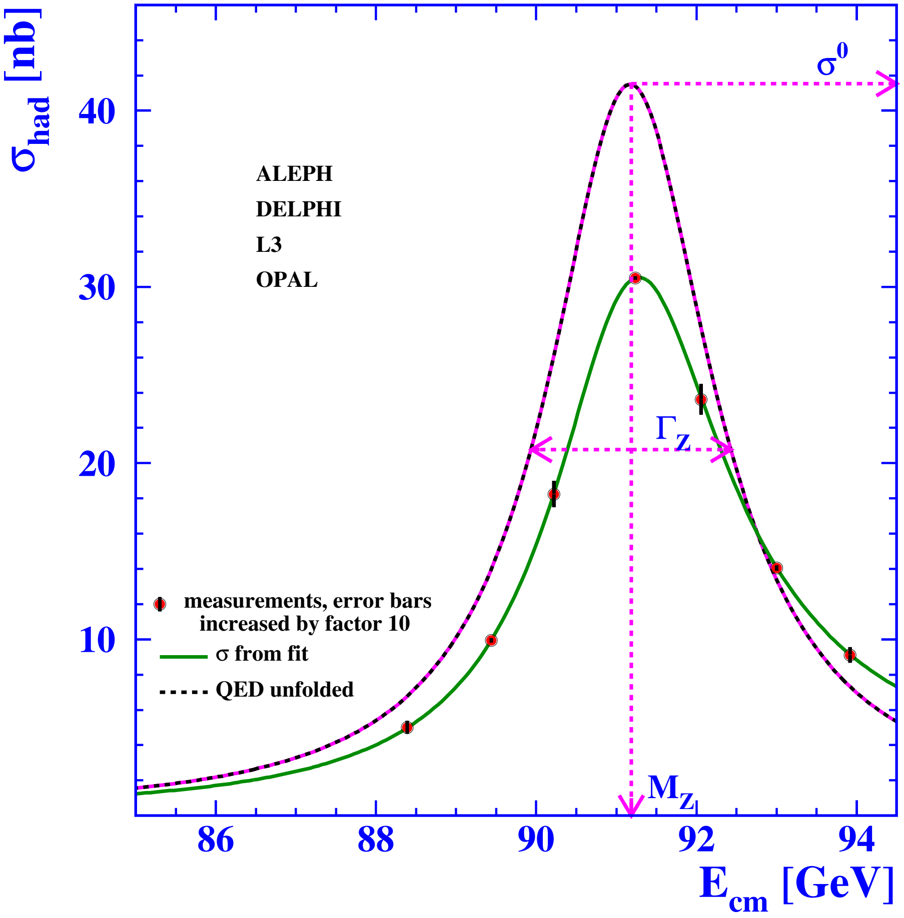
$$-8Re\{\chi(s)q_f(g_{\mathrm{Ve}}g_{\mathrm{Vf}}\left(1+\cos^2\theta\right) \qquad + 2g_{\mathrm{Ae}}g_{\mathrm{Af}}\cos\theta)\} \qquad \mathrm{Z}-\gamma$$

$$16|\chi(s)|^2[(g_{\mathrm{Ve}}^2+g_{\mathrm{Ae}}^2)(g_{\mathrm{Vf}}^2+g_{\mathrm{Af}}^2)\left(1+\cos^2\theta\right) \quad + 8g_{\mathrm{Ve}}g_{\mathrm{Ae}}g_{\mathrm{Vf}}g_{\mathrm{Af}}\cos\theta] \qquad \mathrm{Z}$$

Where:

- $\chi(s) \;=\; \frac{G_{\mathrm{F}}m_{\mathrm{Z}}^2}{8\pi\alpha\sqrt{2}}\frac{s}{s-m_{\mathrm{Z}}^2+is\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}}}$
- 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

OPAL measured cross sections



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)

Observable		Theory Error
m_{Z}		0.3 MeV (0.03×10^{-4})
Γ_{Z}		0.2 MeV (0.8×10^{-4})
σ^0_{had}	$\equiv \frac{12\pi}{m_{\mathrm{Z}}^2}\frac{\Gamma_{e^+e^-}\Gamma_{\mathrm{had}}}{{\Gamma_{\mathrm{Z}}}^2}$	0.022nb (5.3×10^{-4})
R_ℓ	$\equiv \frac{\Gamma_{\mathrm{had}}}{\Gamma_\ell}$	0.004* (1.9×10^{-4})
A^0_{FB}	$\equiv \frac{3}{4}A_{\mathrm{e}}A_{\mathrm{f}}$	0.0001* (0.6%)

$$\Gamma_{\mathrm{f\bar{f}}} = \frac{G_{\mathrm{F}}N_{\mathrm{c}}m_{\mathrm{Z}}^3}{6\pi\sqrt{2}}\left(R^{\mathrm{f}}_{\mathrm{V}}{g_{\mathrm{Vf}}}^2 + R^{\mathrm{f}}_{\mathrm{A}}{g_{\mathrm{Af}}}^2\right) + \Delta_{\mathrm{QCD}}$$

$$A_{\mathrm{f}} = 2\,\frac{g_{\mathrm{Vf}}g_{\mathrm{Af}}}{g_{\mathrm{Vf}}^2+g_{\mathrm{Af}}^2}$$

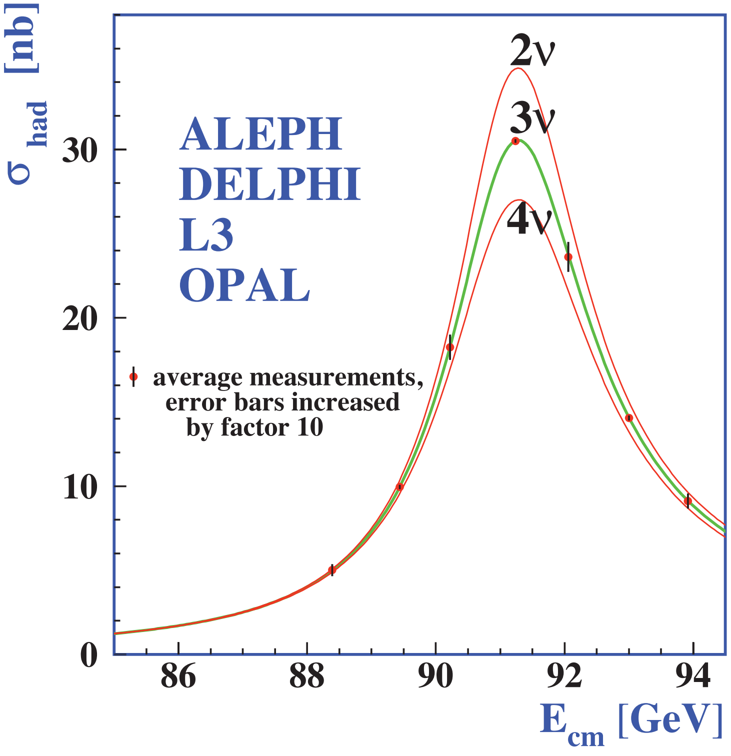
($R^{\mathrm{f}}_{\mathrm{V}}$ and $R^{\mathrm{f}}_{\mathrm{A}}$ give corrections for final-state QED and QCD effects as well as quark masses, Δ_{QCD} for non-factorizable QCD effects.)

* Theory error for electrons is larger 0.024 (R_{e}) and 0.0014 (A^0_{FB})

Theory errors as of 2002

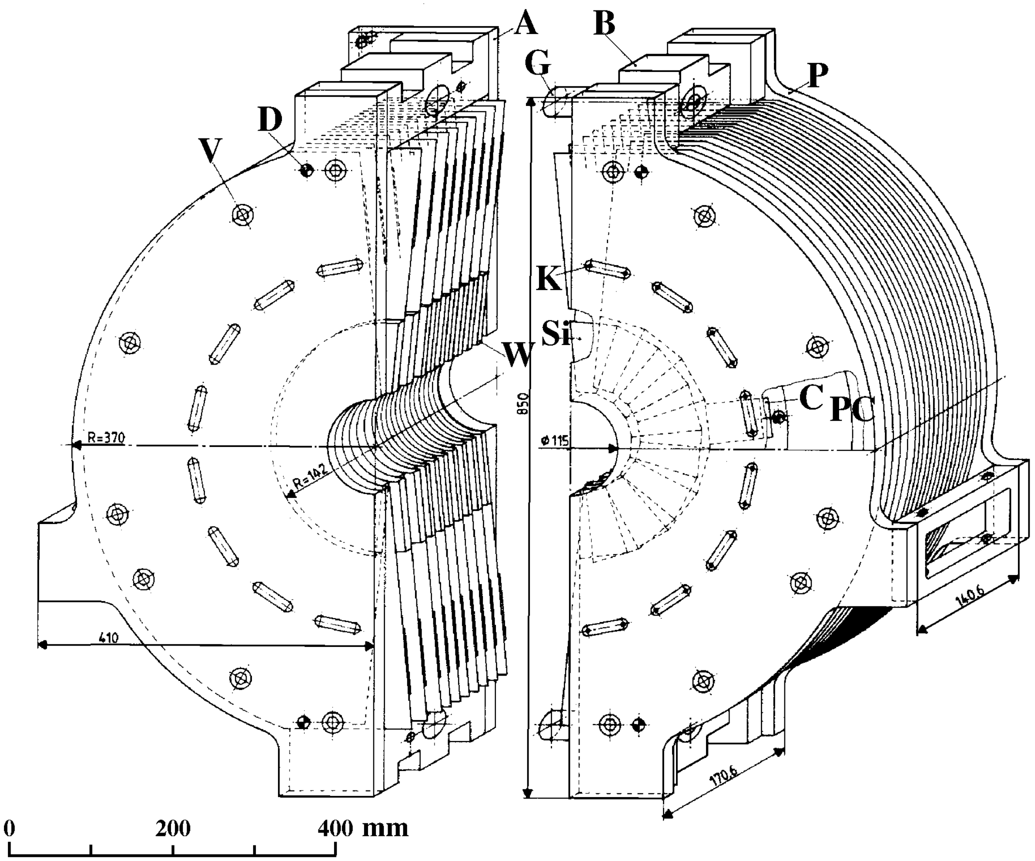
What can the Z lineshape tell us about possible dark matter: ratio of invisible width of Z to leptonic width

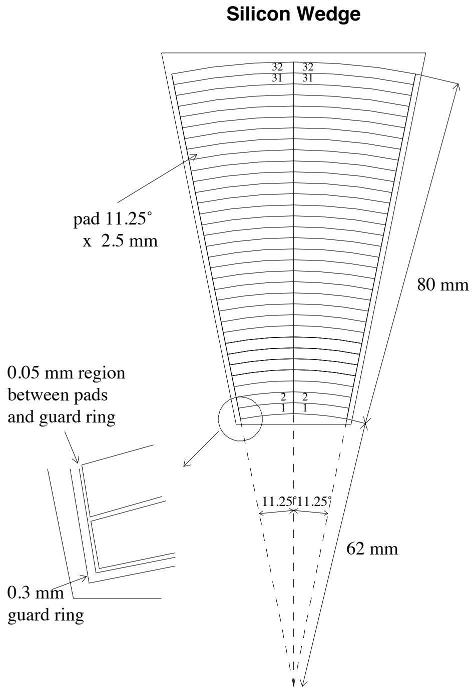
$$
\begin{aligned}
R_{inv} = \frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} &= (\Gamma_{\text{Z}} - \Gamma_{\text{had}} - 3\Gamma_{\ell\ell})/\Gamma_{\ell\ell} \\
&= \frac{\Gamma_{\text{Z}}}{\Gamma_{\ell\ell}} - \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}} - 3\frac{\Gamma_{\ell\ell}}{\Gamma_{\ell\ell}} \\
&= \sqrt{\frac{12\pi}{m_{\text{Z}}^2}\frac{R_\ell}{\sigma^0_{\text{had}}}} - R_\ell - 3 \\
&\simeq \sqrt{\frac{12\pi}{m_{\text{Z}}^2}\frac{n_{\ell\ell}}{\mathcal{L}}} - \frac{n_{\ell\ell}}{n_{had}} - 3 \\
\frac{\Delta R_{inv}}{R_{inv}} &\simeq 6\frac{\Delta n_{\ell\ell}}{n_{\ell\ell}} + 21\frac{\Delta n_{had}}{n_{had}} + 15\frac{\Delta\mathcal{L}}{\mathcal{L}}
\end{aligned}
$$



Need to measure $\mathcal{L}$ (luminoisty), $n_{\ell\ell}$ and n_{had} to determine coupling of Z to dark matter candidates.
Expect n_{had} to be $> 10^6$, need to measure $\mathcal{L}$ to better than 1/1000 .

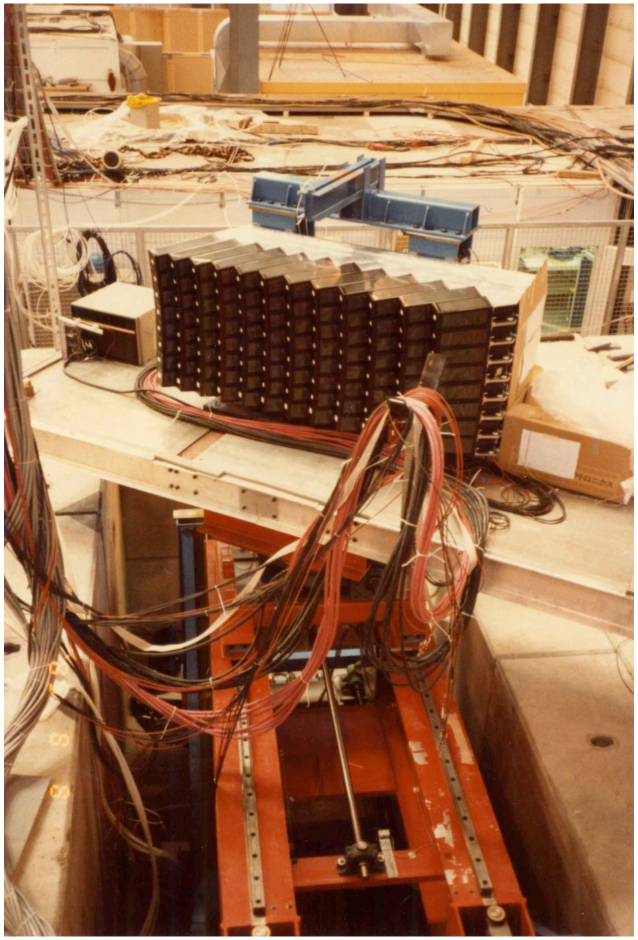
- Starting in 1991 the Chicago (DS later Oregon) group, Maryland, CERN (Marcello Mannelli originally Chicago) and others started to design a silicon tungsten detector capable of measuring small angle Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) to 1/1000 ($\sim$ 20 micron precision on radius) or better:



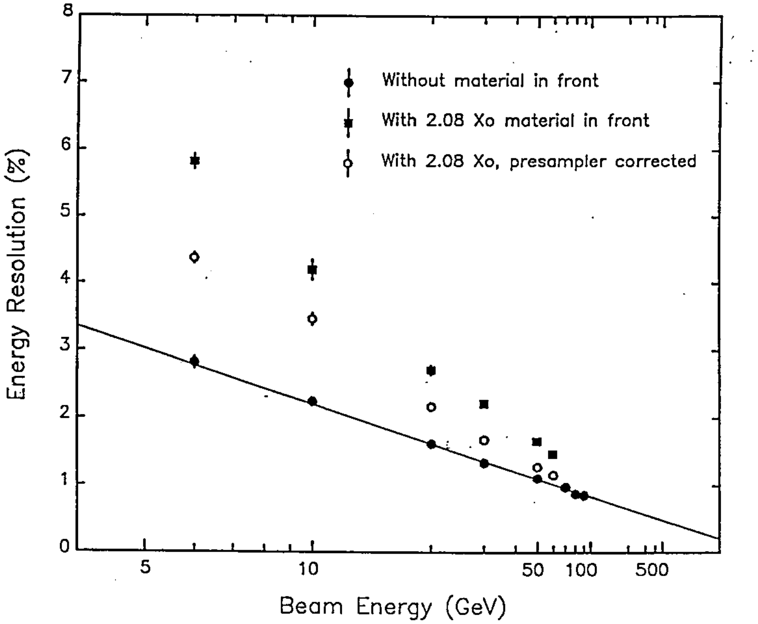


- Chicago had the lead role on the digitization electronics, similar to those used for Presampler Barrel.

The Chicago Stage was revived for the first OPAL SiW test beam:

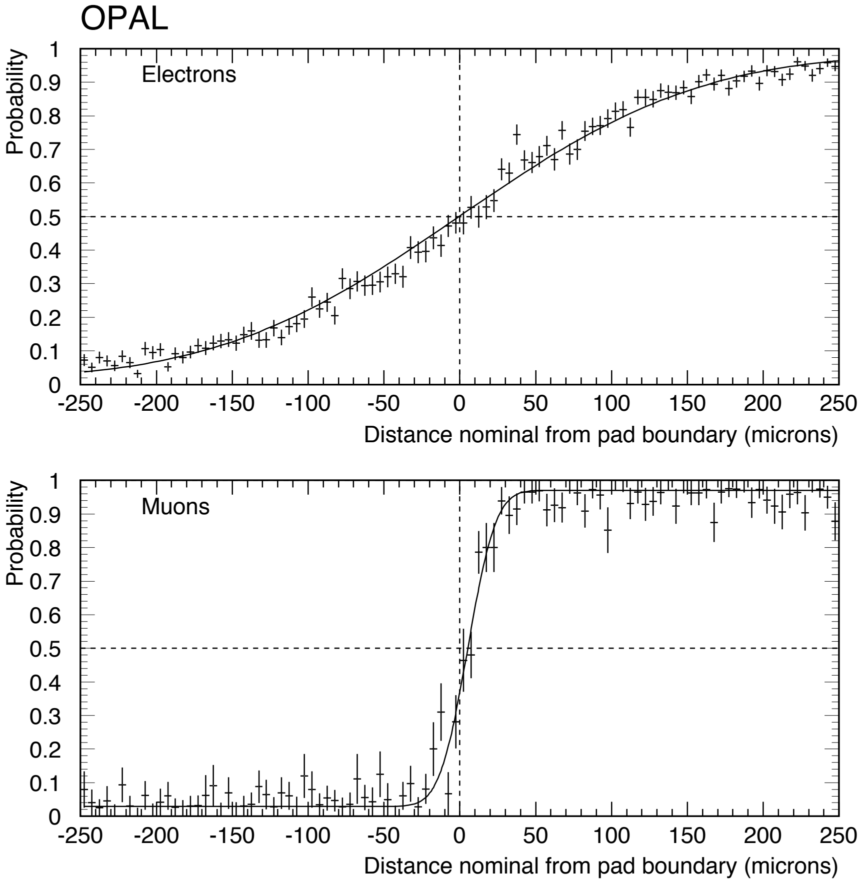


Combined Beam Test with “Chicago Stage” in X5 Beam Line

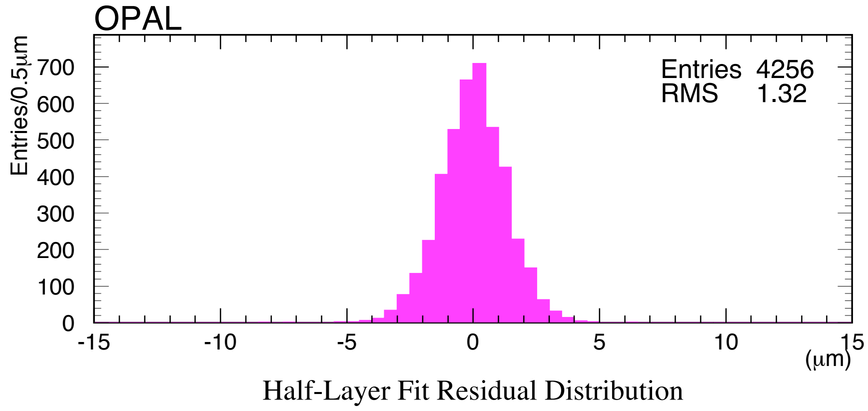


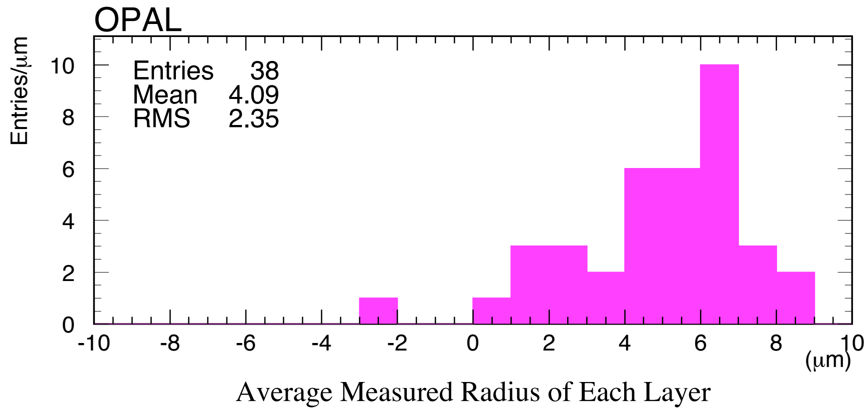
Slide from Tomio Kobayashi, OPAL reunion

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 3.4×10^{-4}, significantly below the theoretical error of 5.4×10^{-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.”

Eur.Phys.J. C14 (2000) 373-425

LEP average of ratio of invisible to leptonic widths:

$$\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = \frac{Br(\text{Z} \to \text{inv})}{Br(\text{Z} \to \ell^{+}\ell^{-})} = 5.943 \pm 0.016$$

$$(\text{SM } \frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = 5.9736 \pm 0.0048)$$

or

$$N_{\nu} = 2.9840 \pm 0.0082$$

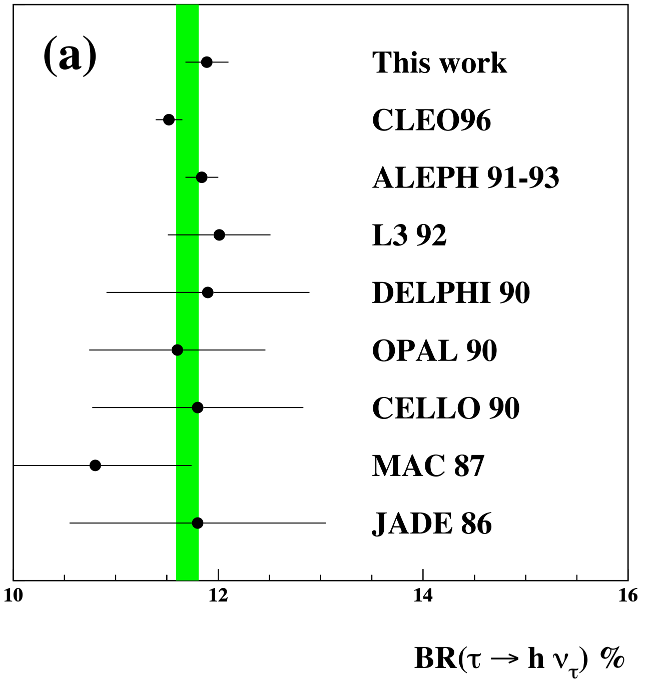
or

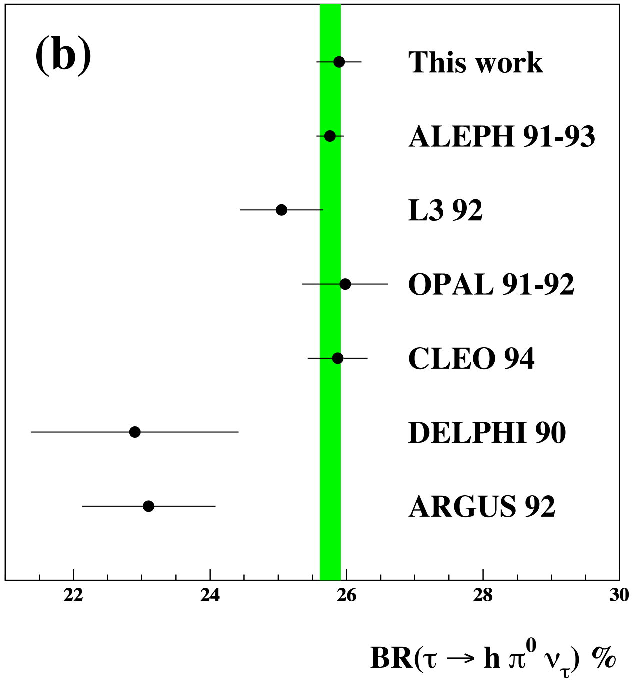
$$\Delta\Gamma_{\text{inv}} < 2.0\text{MeV} \quad (95\%\text{C.L.})$$

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):





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

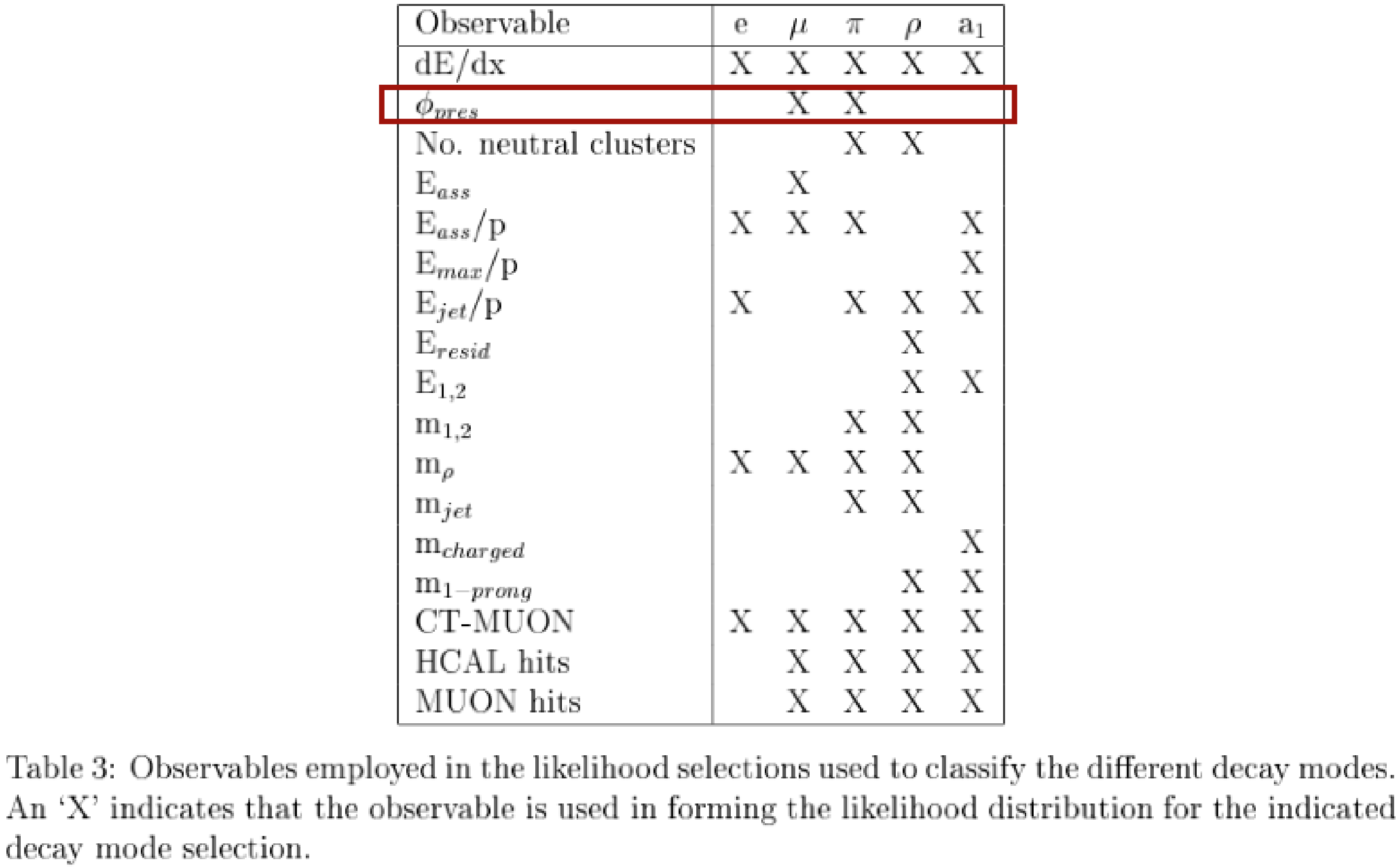
At Born level

$$P_\tau(\cos\theta_{\tau^-}) = \frac{\langle P_\tau\rangle\ (1+\cos^2\theta_{\tau^-}) + \frac{8}{3}\mathrm{A}^{\mathrm{FB}}_{\mathrm{pol}}\ \cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}\mathrm{A}_{\mathrm{FB}}\ \cos\theta_{\tau^-}}$$

with $\langle P_\tau\rangle\ = -A_\tau$ and $\mathrm{A}^{\mathrm{FB}}_{\mathrm{pol}}\ = -\frac{3}{4}A_{\mathrm{e}}$

Recall $A_{\mathrm{f}} = 2\,\frac{g_{\mathrm{Vf}}g_{\mathrm{Af}}}{g^2_{\mathrm{Vf}}+g^2_{\mathrm{Af}}}$

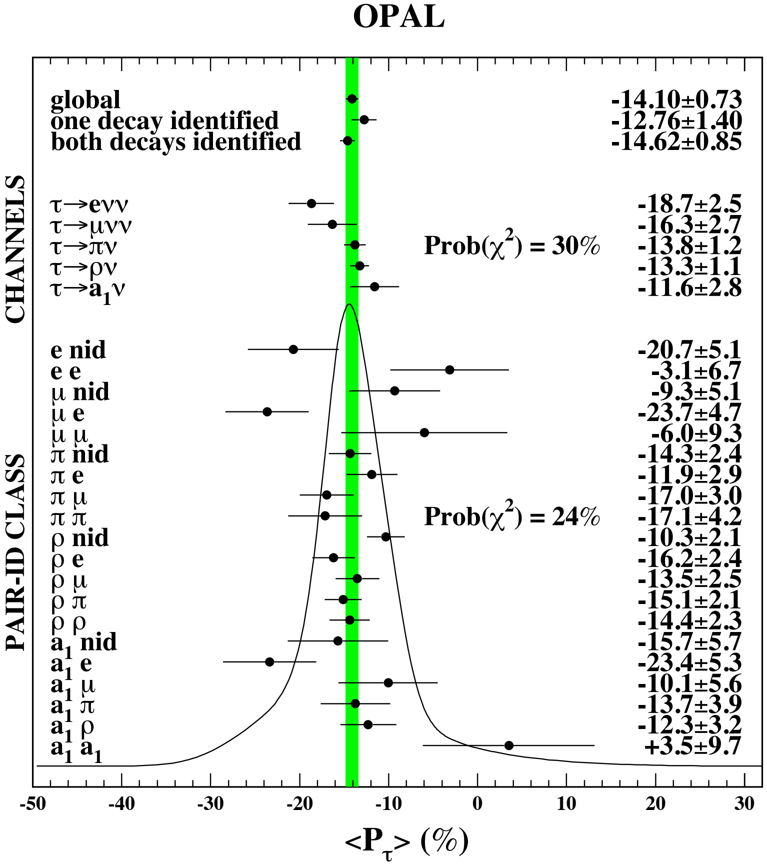
Final OPAL analysis led by M. Roney, former UC post-doc, *Precision Neutral Current Asymmetry Parameter Measurements from the Tau Polarization at LEP*
March 8, 2001, Eur. Phys. J.C21 (2001) 1-21.

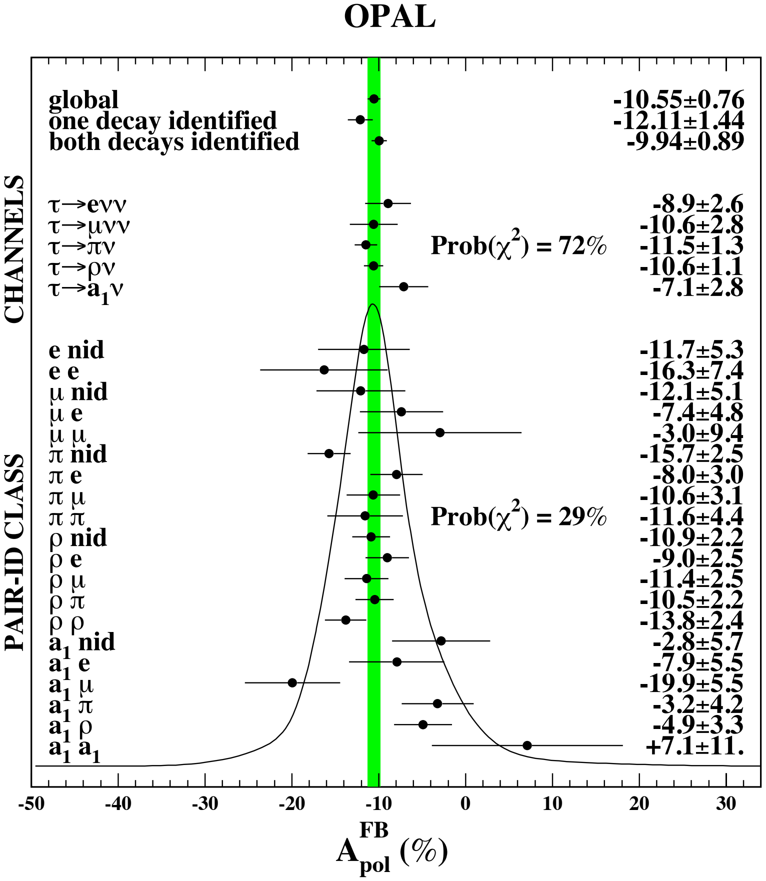


Observable	e	μ	π	ρ	a_1
dE/dx	X	X	X	X	X
ϕ_{pres}		X	X		
No. neutral clusters			X	X	
E_{ass}		X			
E_{ass}/p	X	X	X		X
E_{max}/p					X
E_{jet}/p	X		X	X	X
E_{resid}				X	
$E_{1,2}$				X	X
$m_{1,2}$			X	X	
m_ρ	X	X	X	X	
m_{jet}			X	X	
$m_{charged}$					X
$m_{1-prong}$				X	X
CT-MUON	X	X	X	X	X
HCAL hits		X	X	X	X
MUON hits		X	X	X	X

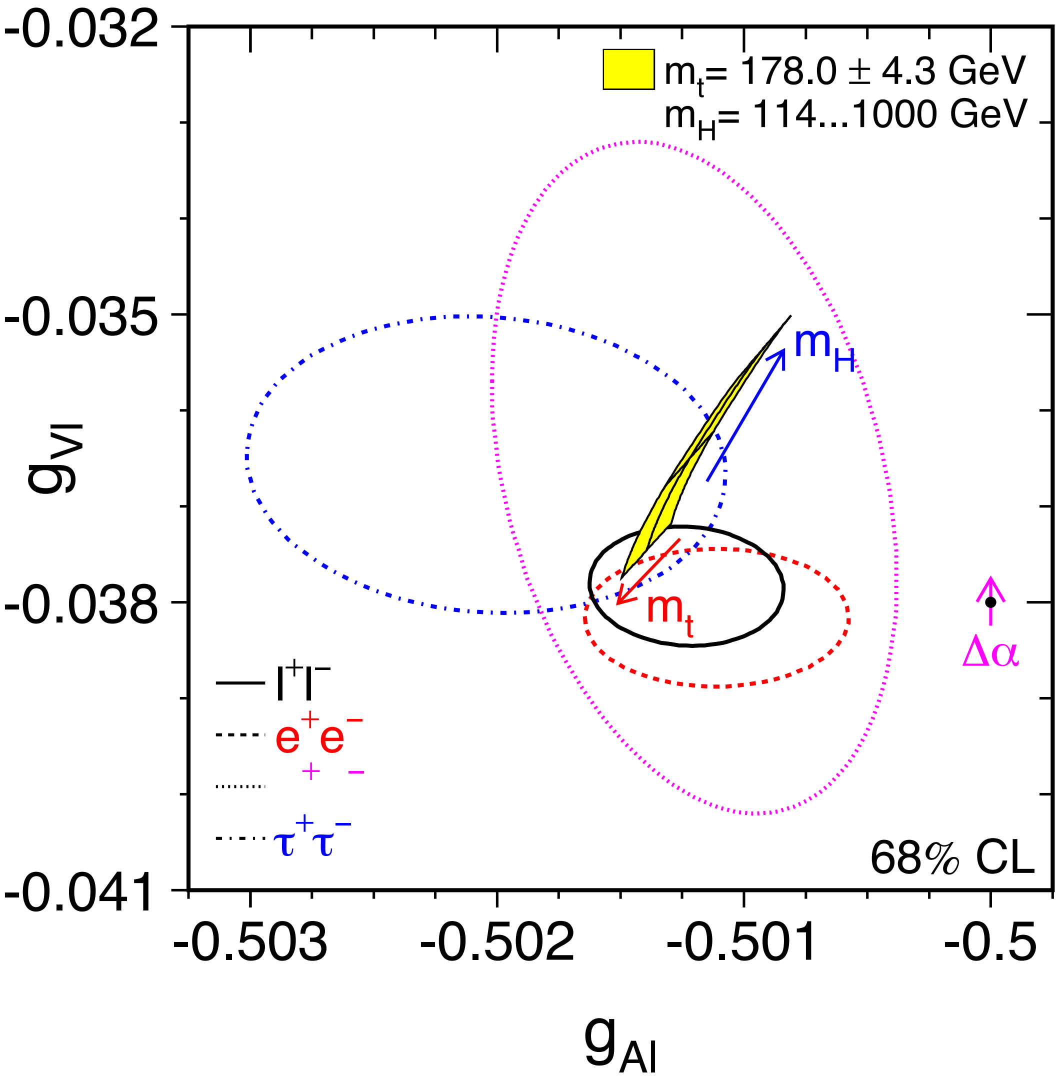
Table 3: Observables employed in the likelihood selections used to classify the different decay modes. An 'X' indicates that the observable is used in forming the likelihood distribution for the indicated decay mode selection.

After much work final polarization and forward-backward asymmetry of polarization:





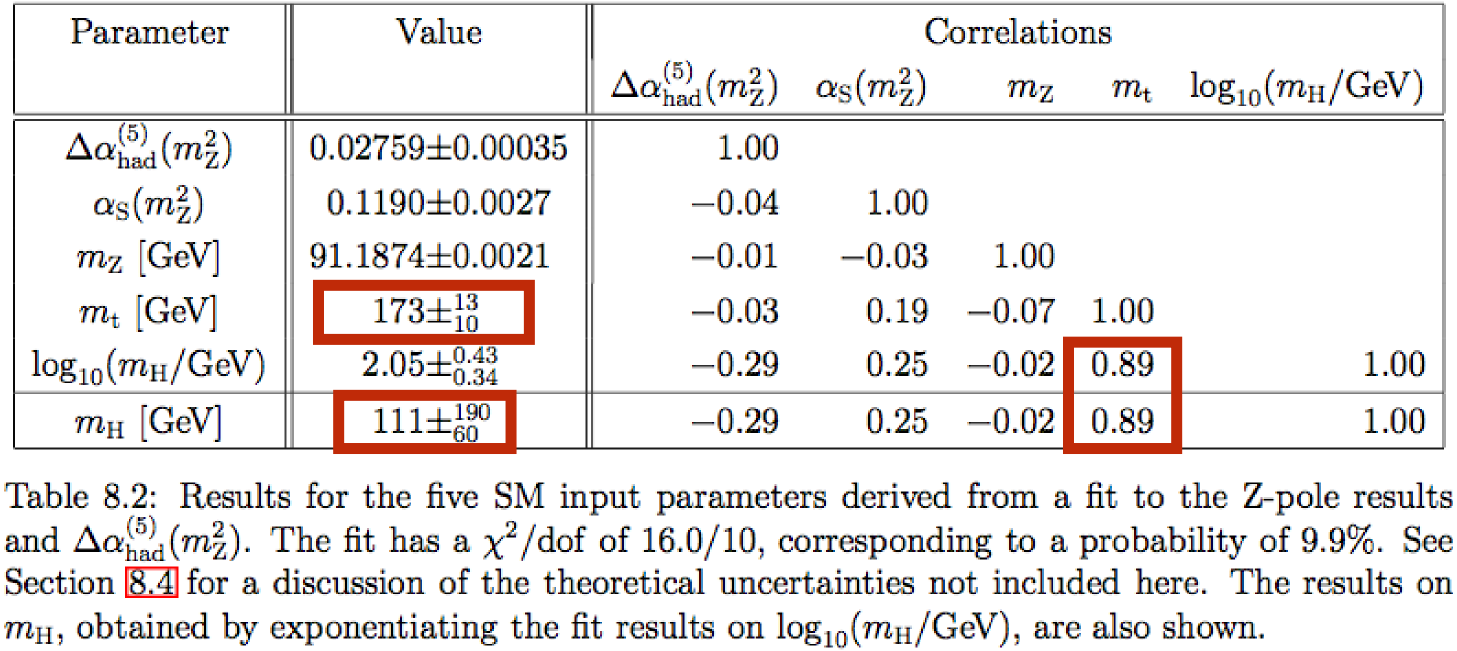
Final LEP results on Z couplings to leptons:



In general the LEP Z pole results greatly exceeded expectations:

	Expectation	Result
Z Decays/experiment	5 - 10 $\times 10^6$	5 $\times 10^6$
Systematic on energy	10 MeV	< 2.0 MeV
Systematic on luminosity	$\sim 1\%$	$\sim 0.05\%$ (Exp) 0.054% (Th)

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))



Parameter	Value	Correlations				
		$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$	$\alpha_{\mathrm{S}}(m^2_{\mathrm{Z}})$	m_{Z}	m_{t}	$\log_{10}(m_{\mathrm{H}}/\mathrm{GeV})$
$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$	0.02759 ± 0.00035	1.00				
$\alpha_{\mathrm{S}}(m^2_{\mathrm{Z}})$	0.1190 ± 0.0027	−0.04	1.00			
m_{Z} [GeV]	91.1874 ± 0.0021	−0.01	−0.03	1.00		
m_{t} [GeV]	$173\pm^{13}_{10}$	−0.03	0.19	−0.07	1.00	
$\log_{10}(m_{\mathrm{H}}/\mathrm{GeV})$	$2.05\pm^{0.43}_{0.34}$	−0.29	0.25	−0.02	0.89	1.00
m_{H} [GeV]	$111\pm^{190}_{60}$	−0.29	0.25	−0.02	0.89	1.00

Table 8.2: Results for the five SM input parameters derived from a fit to the Z-pole results and $\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$. The fit has a χ^2/dof of 16.0/10, corresponding to a probability of 9.9%. See Section 8.4 for a discussion of the theoretical uncertainties not included here. The results on m_{H}, obtained by exponentiating the fit results on $\log_{10}(m_{\mathrm{H}}/\mathrm{GeV})$, are also shown.

In retrospect, results too good to believe:

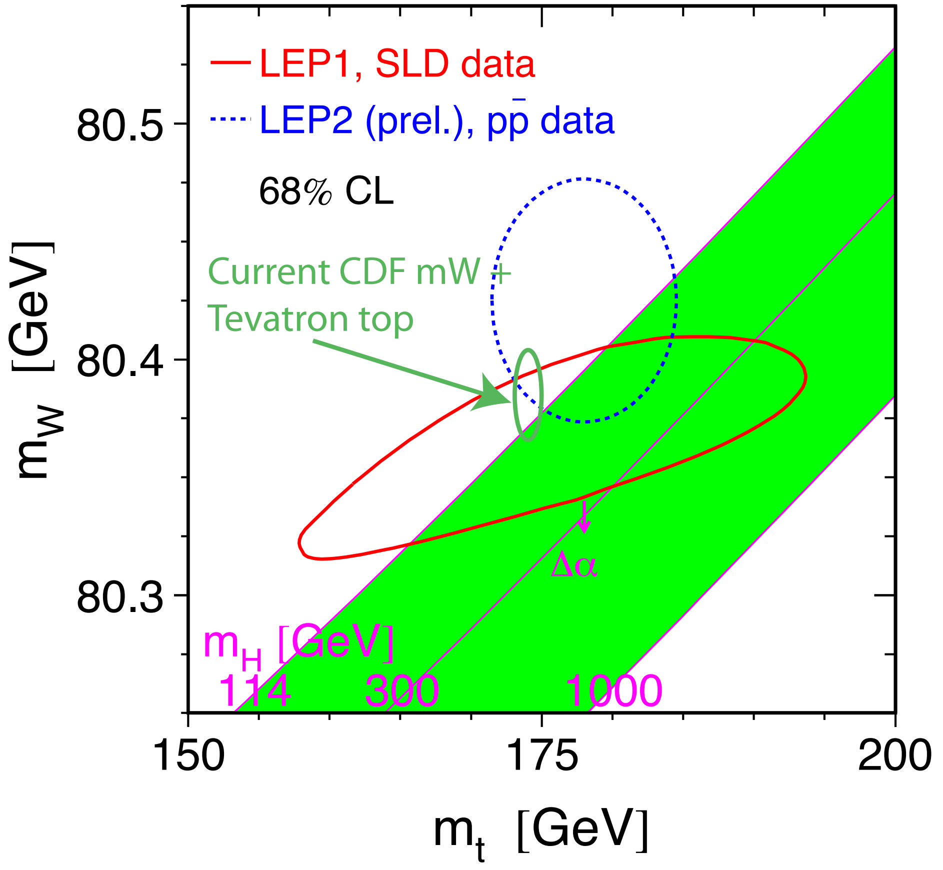
Current Tevatron:	$m_t = 173.18 \pm 0.94$	GeV	Pull: +0.01
ATLAS :	$m_h = 126.0 \pm 0.4(stat) \pm 0.4(sys)$	GeV	Pull: +0.08

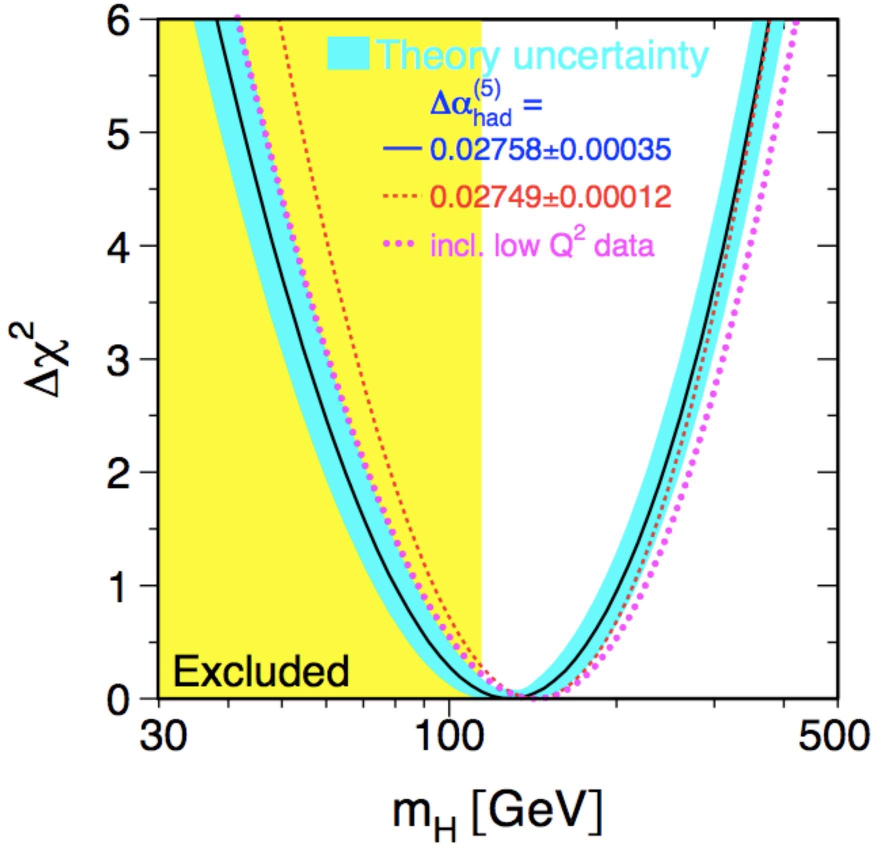
Tevatron top mass at time of 2006 publication: 178.0 ± 4.3 GeV

Present PDB α_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

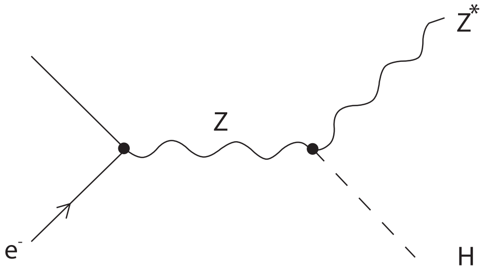




First OPAL paper on Higgs Production

Mass Limits for a Standard Model HIggs Boson in e^+e^- *Collisions at LEP* (December 22, 1989) Phys. Lett. B 236 (1990) 224-232

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

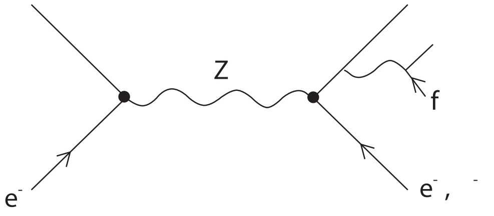


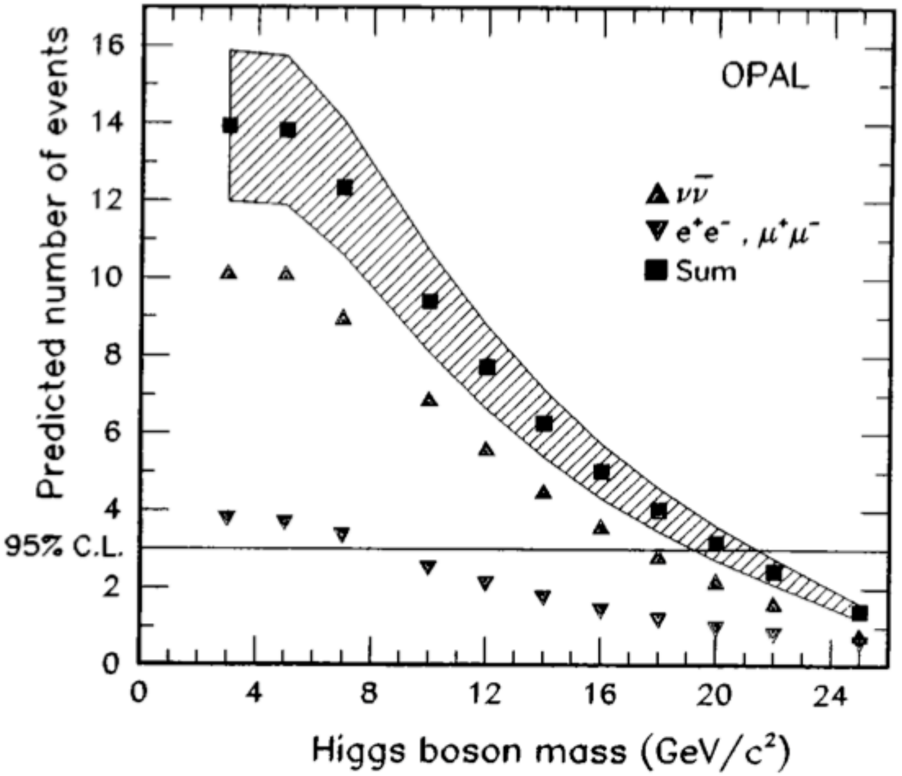
- Result is based on $825\,\mathrm{nb}^{-1}$ from first run of LEP

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

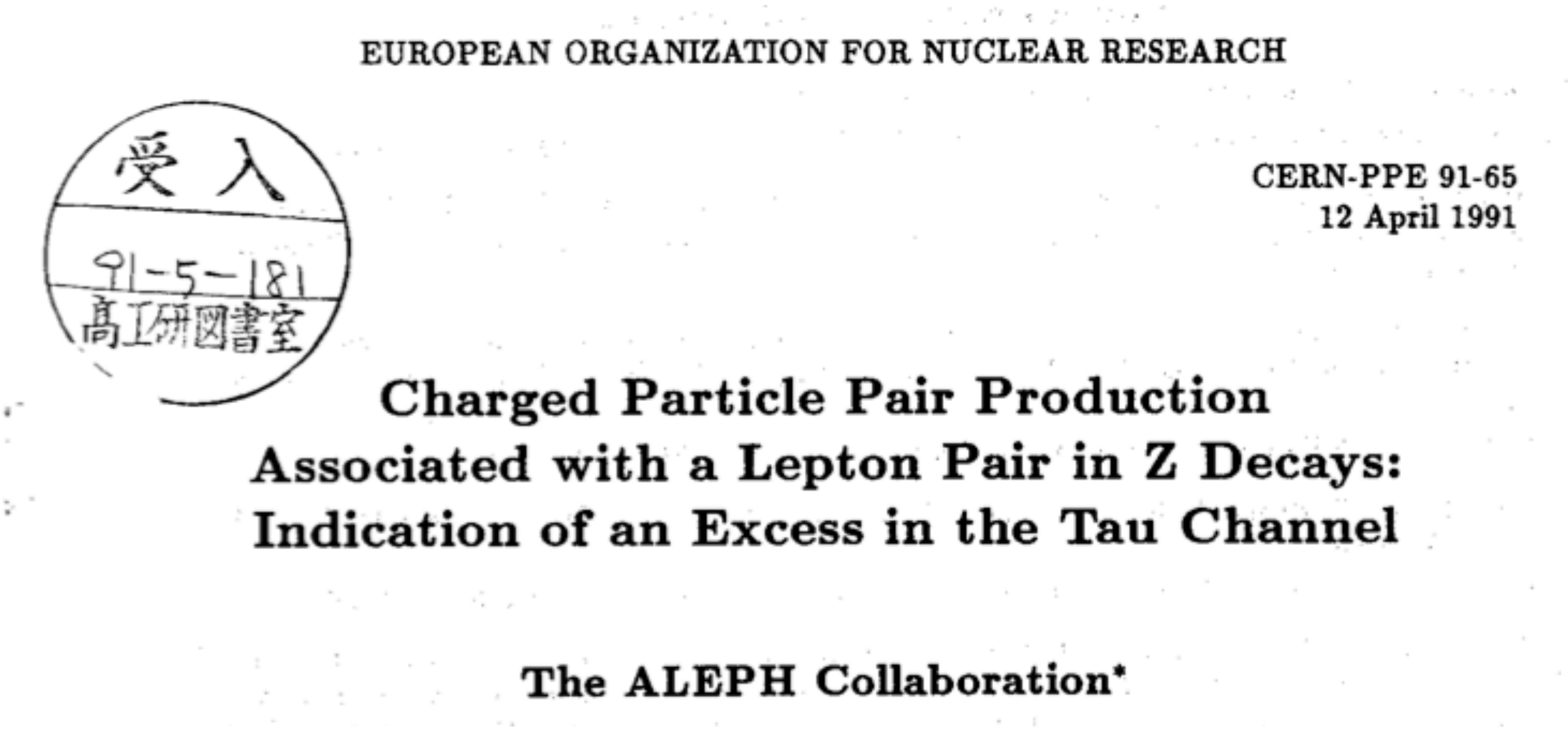
- No limit below $m_{\tau\tau}$!

Background is four-fermion events





The Wisconsin group at ALEPH *my alma mater* was sure we were hiding something:



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE 91-65
12 April 1991

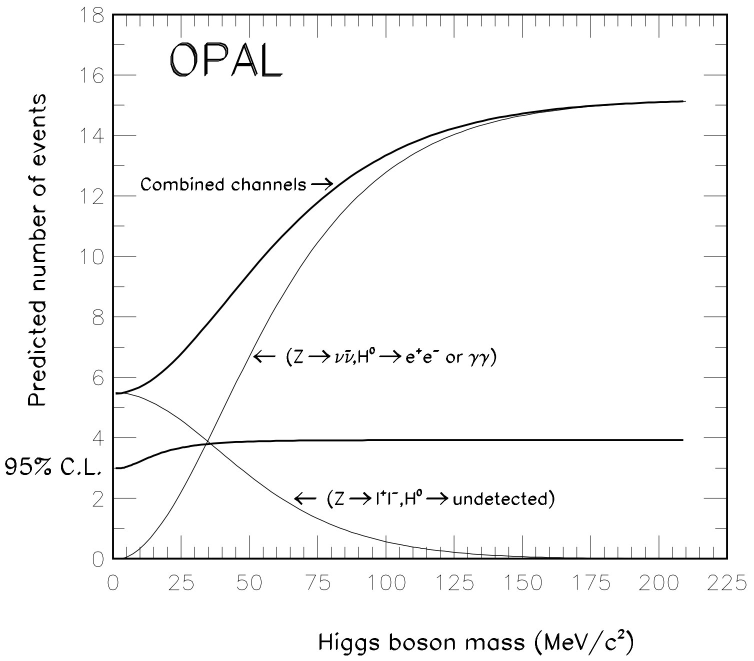
Charged Particle Pair Production Associated with a Lepton Pair in Z Decays: Indication of an Excess in the Tau Channel

The ALEPH Collaboration*

Closing the Loopholes

Limits on a Light Higgs Boson in e^+e^- Collisions at LEP (14 August 1990),

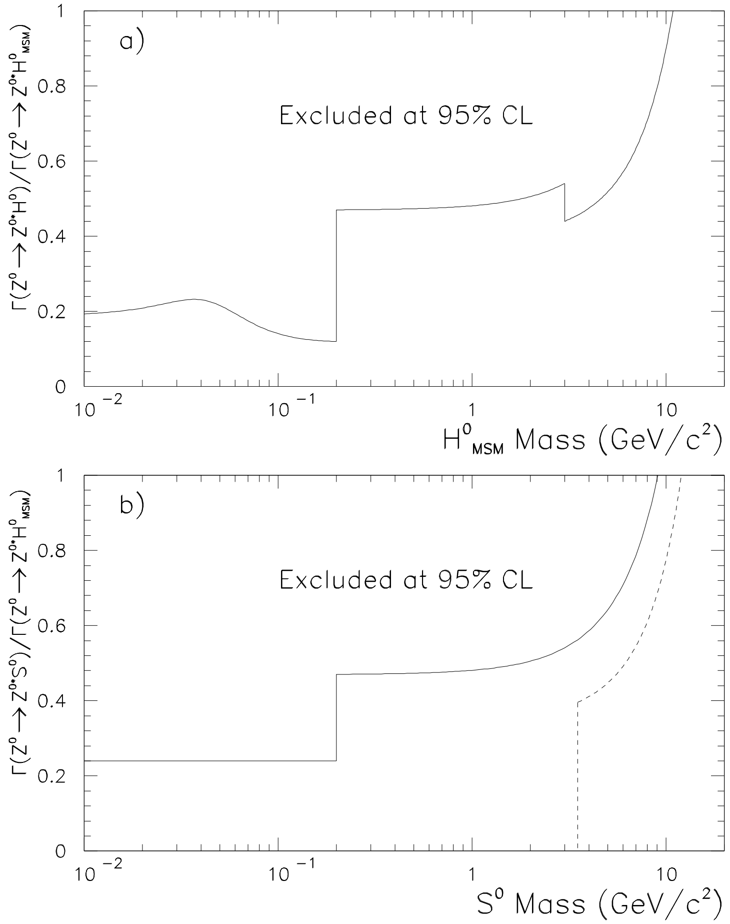
Phys.Lett. B251 (1990) 211-222.



Mike Roney, D.S., ...

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

Phys. Lett. B268 (1991) 122-136.



Hogan Nguyen, Frank, Mark ...

- No Higgs found at LEP I

- Result at right is from Hogan Nguyen's thesis

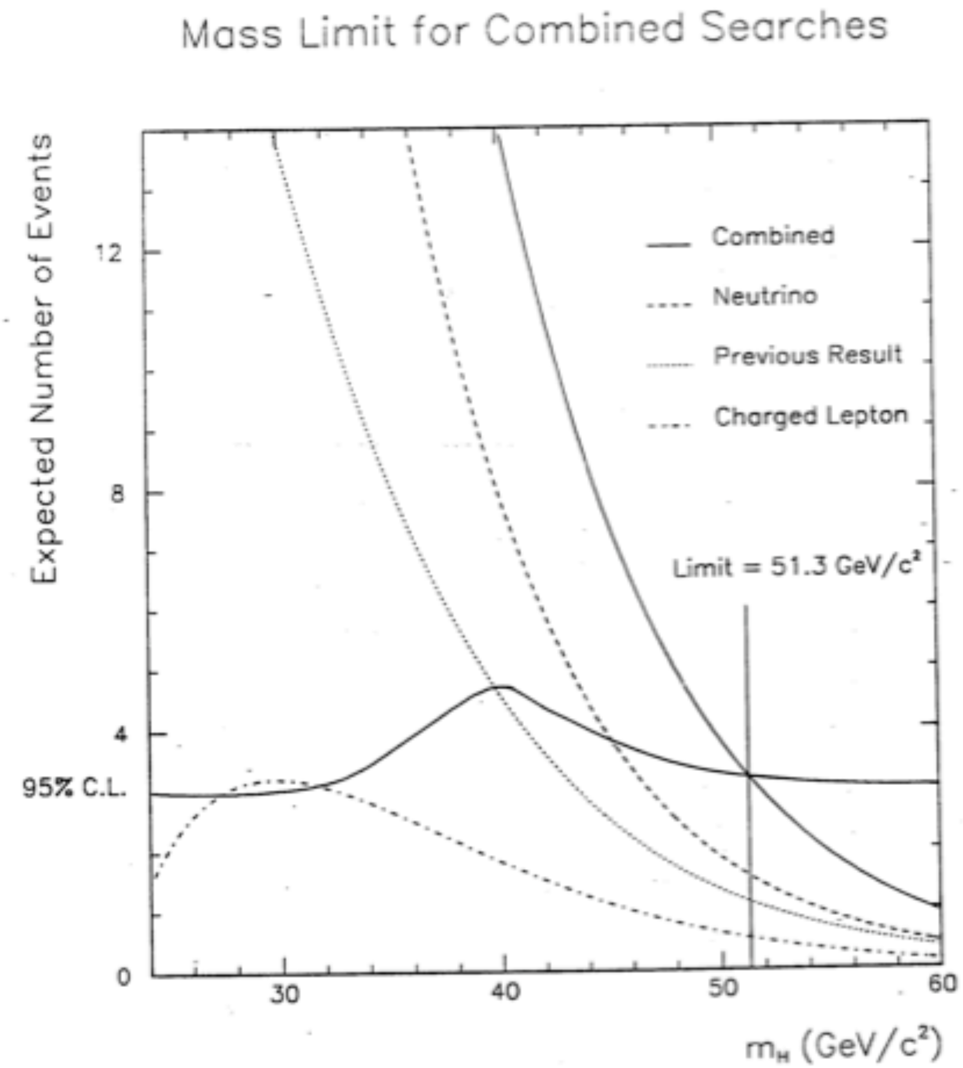


Figure 73. The number of events expected to be seen in the charged lepton channel (dotdashed), the neutrino channel (dashed), a previously published result (dotted) [52], and the sum total (solid). The upper limit accounts for one event remaining in the neutrino channel. The combined result excludes an H^0 of mass less than 51.3 GeV/c^2 at the 95 confidence level.

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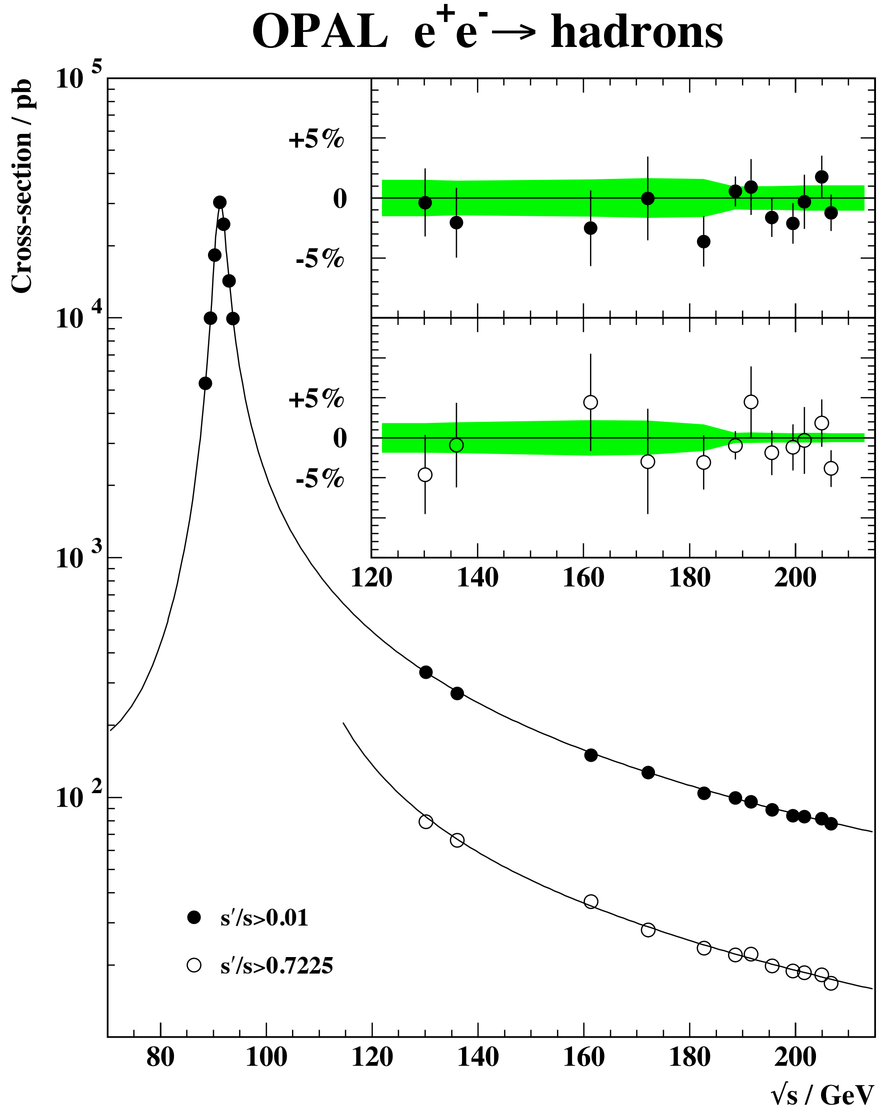
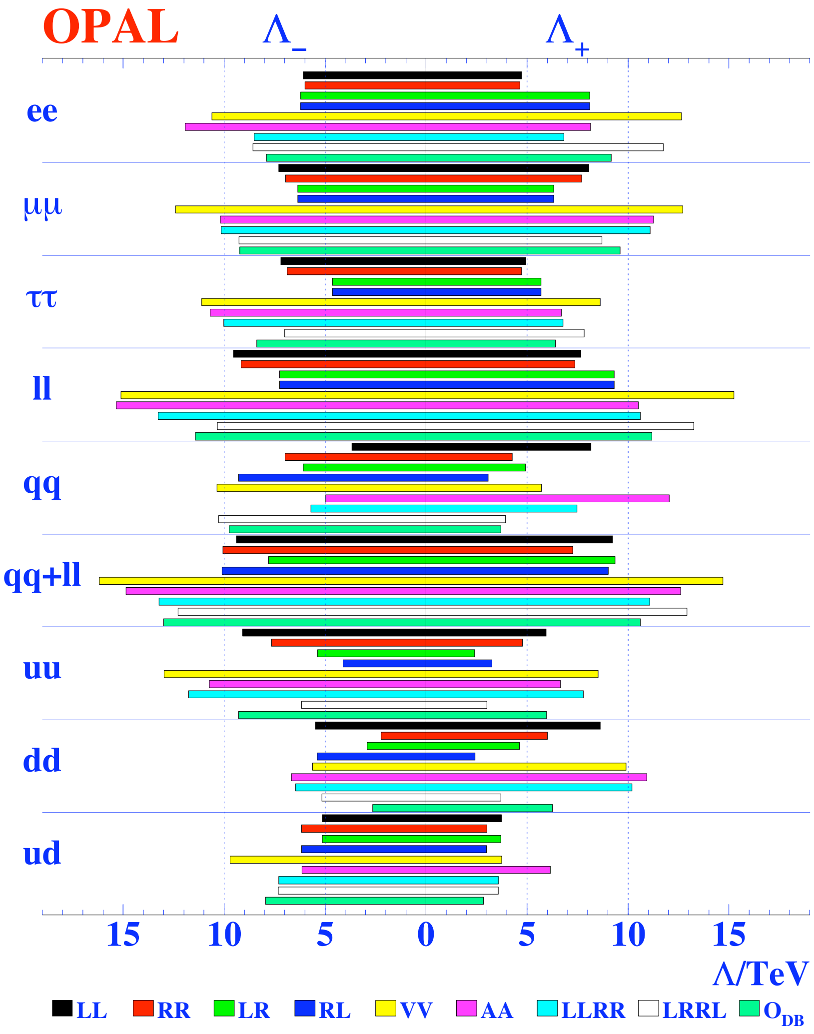
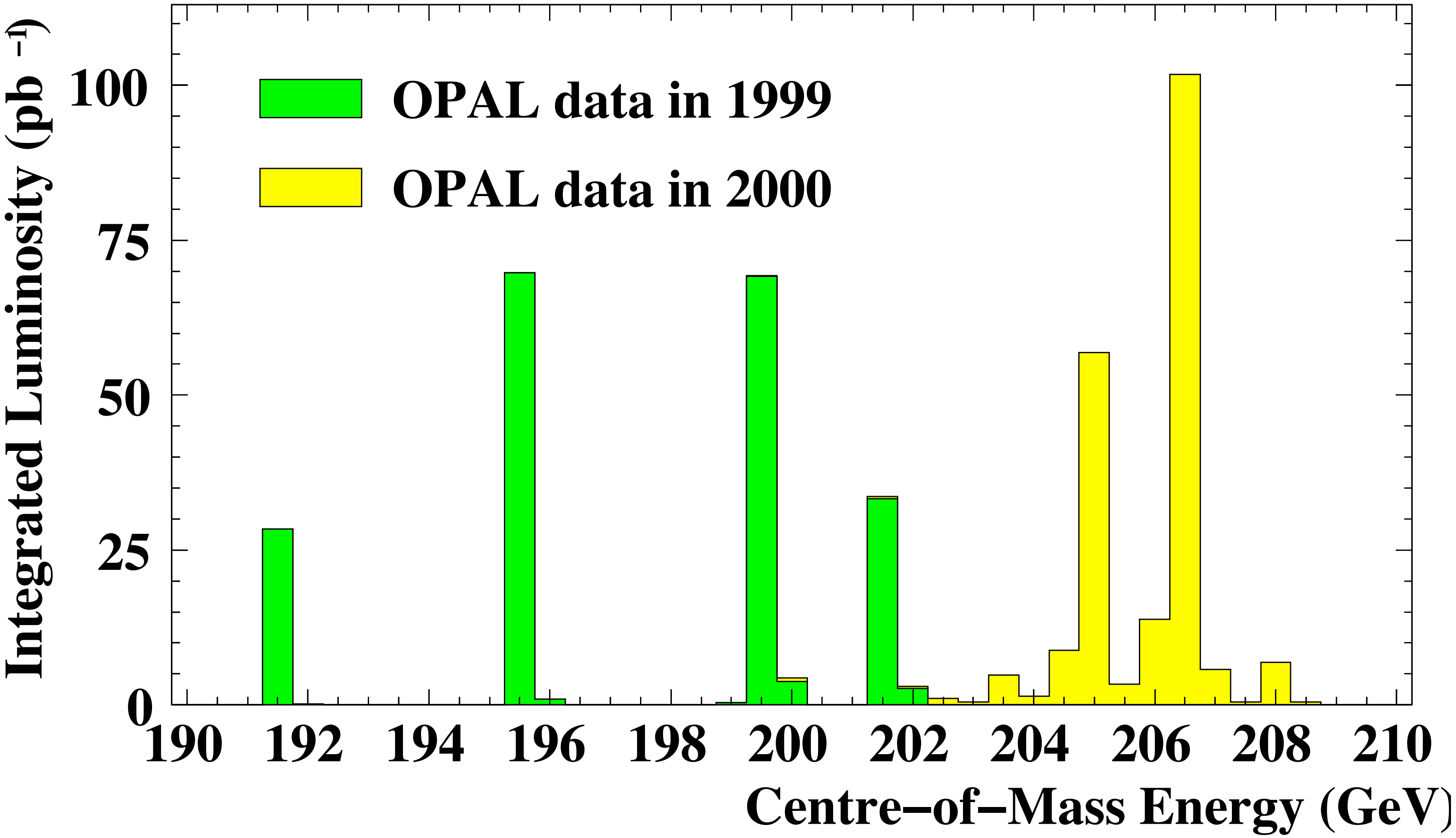
Fermion-Pair Production at LEP II





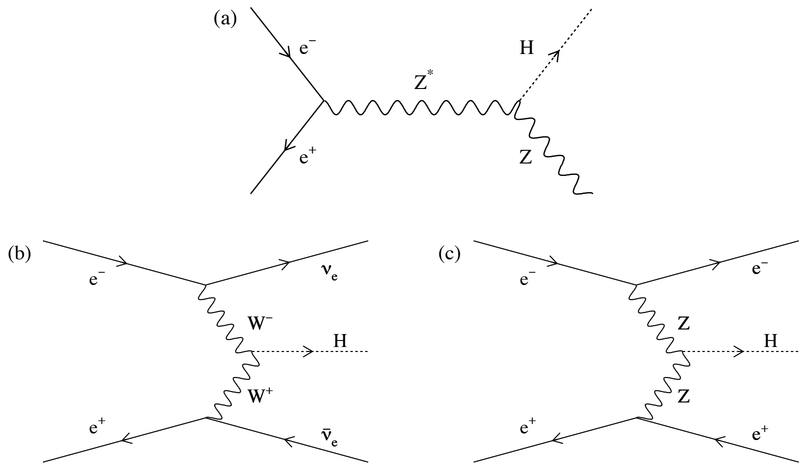
Contact Interaction

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

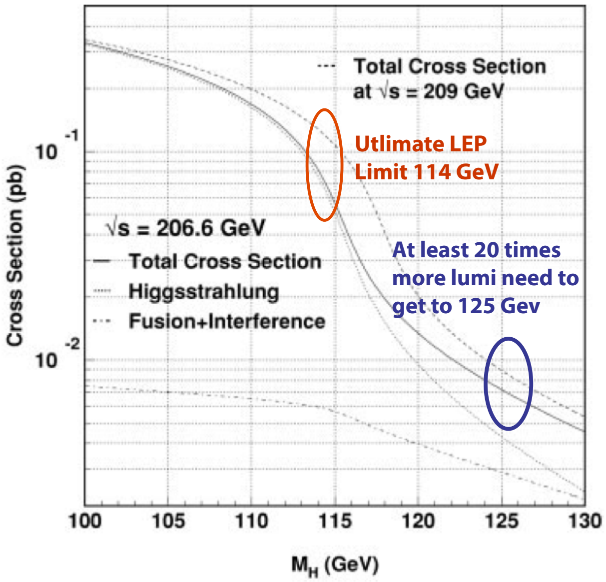


Possible to look at processes with cross section of $\sim 10 fb^{-1}$

Energy and luminosity were not enough to find a 125 GeV Higgs



Higgs-strahlung dominates



Utlimate LEP Limit 114 GeV

At least 20 times more lumi need to get to 125 Gev

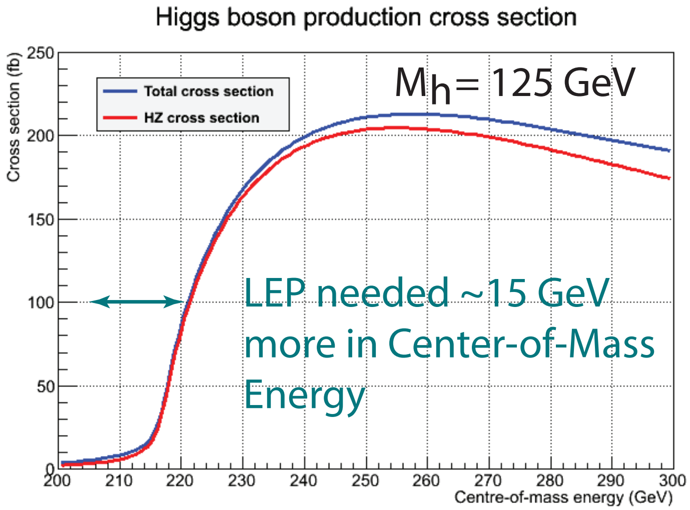
Callot and Tulley, Annual Reviews

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



M_h= 125 GeV

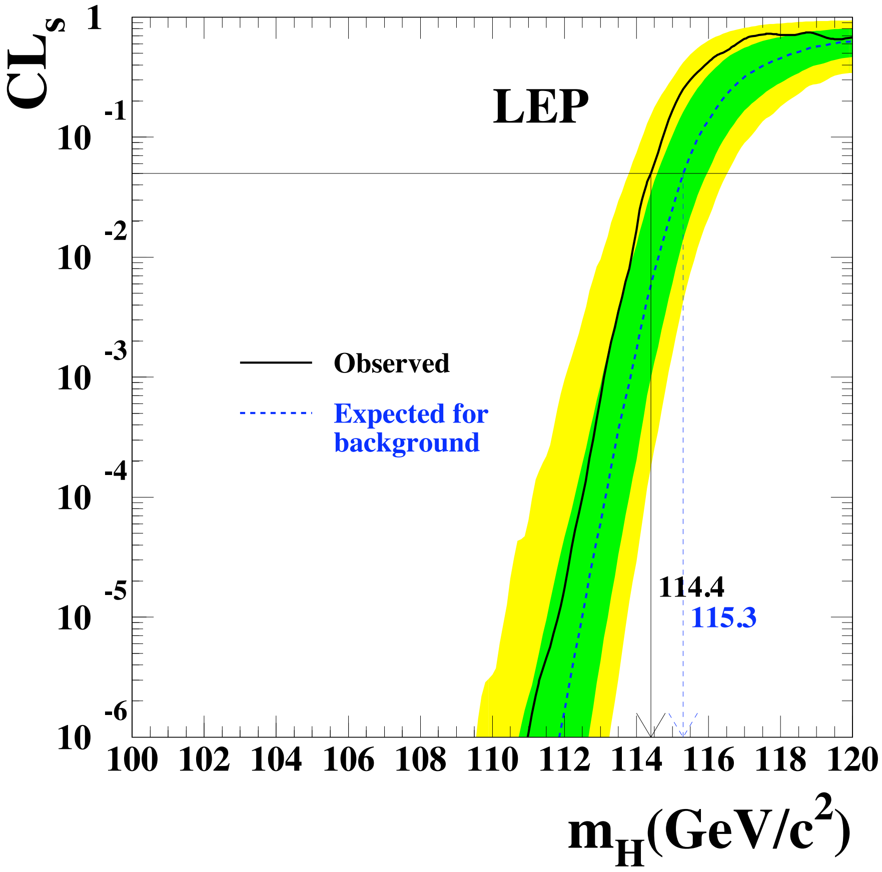
LEP needed ~15 GeV more in Center-of-Mass Energy

Janot, arxiv, 1208.1662

Final LEP Standard Model Higgs Limits

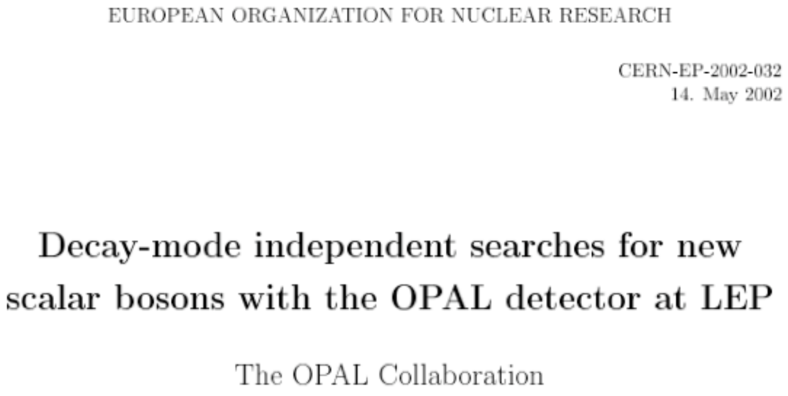
Decay modes used:

$$\begin{array}{ll} h \longrightarrow b\bar{b} & Z \longrightarrow \nu\nu \\ h \longrightarrow b\bar{b} & Z \longrightarrow e^+e^- \\ h \longrightarrow b\bar{b} & Z \longrightarrow \mu^+\mu^- \\ h \longrightarrow b\bar{b} & Z \longrightarrow \tau^+\tau^- \\ h \longrightarrow b\bar{b} & Z \longrightarrow hadrons \\ h \longrightarrow \tau^+\tau^- & Z \longrightarrow hadrons \end{array}$$



OPAL (LEP) limit 112.7 (114.4) GeV

Model Independent Searches at LEP II



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

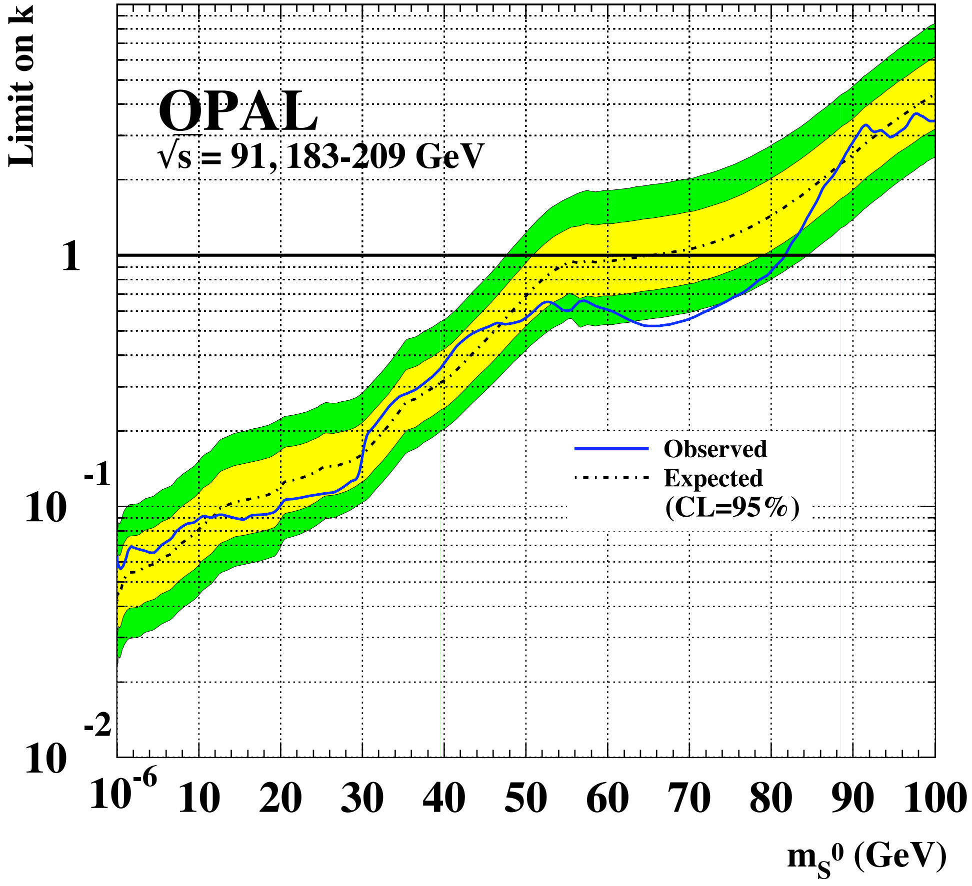
CERN-EP-2002-032
14. May 2002

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



Eur. Phys. J C27 (2003) 311-329

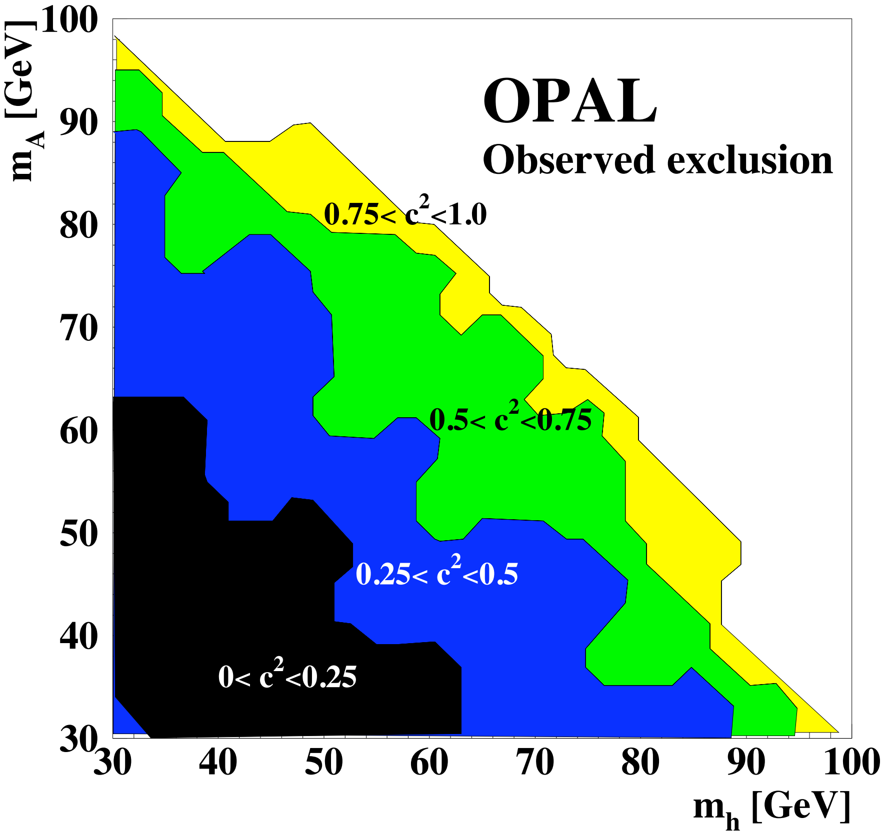
Used both LEP 1 and LEP 2 data. Still useful today to constrain extensions to the Standard Model.

Many other non-Standard Higgs searches made, for example for the flavor-independent decay of scalar and psuedo-scalar Higgs:

Flavor Independent $h^0 Z^0$

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

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



Eur. Phys. J. C40 (2005) 317 - 332.

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