OPAL's Luminosity

and

Z Lineshape Measurements

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Outline

I. LEP, LEP physics and OPAL

II. OPAL silicon-tungsten calorimeter

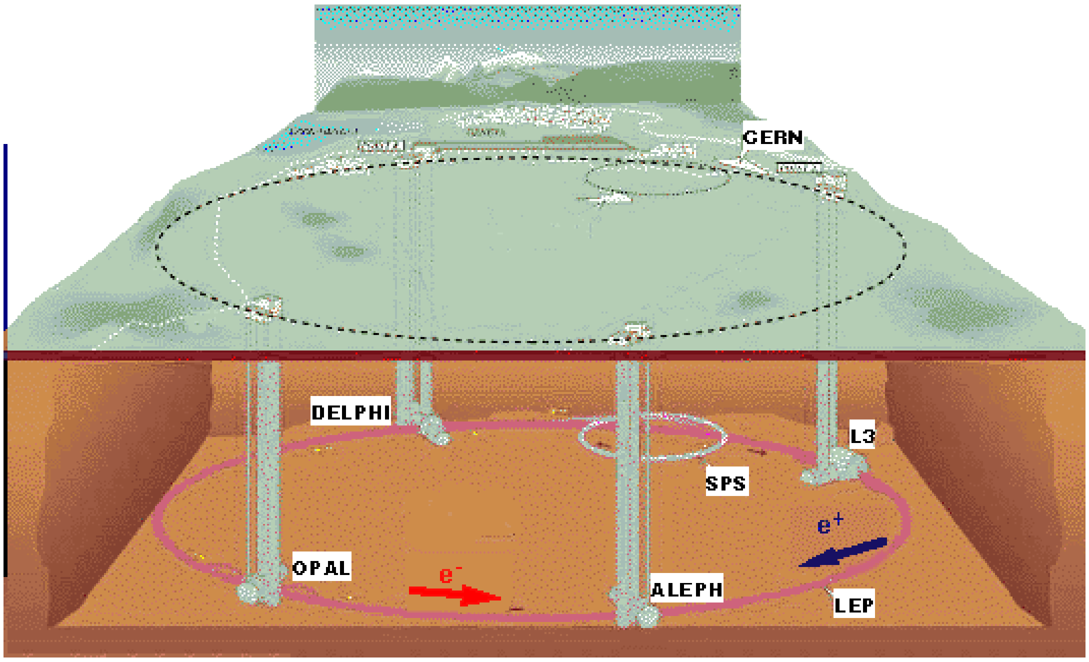
III. Detector performance

IV. Coordinate reconstruction

V. Luminosity results

VI. Z^0 Lineshape results

LEP



- LEP is the world's largest collider (27 km circumference)
- Its primary goal is to measure the properties of the Z^0 (mass, width, etc.)
- The four LEP experiments have collected over 1.5×10^7 Z^0 events

LEP Goals

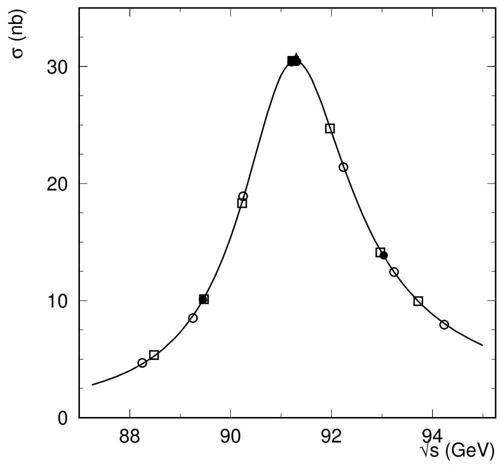
LEP was built to perform tests of the Standard Model. There is a rich program at LEP, including:

- Electroweak physics
- QCD physics
- b quark physics
- τ physics

This talk will concentrate on electroweak physics, particularly on the lineshape measurement, and even more particularly, on the measurement of
$\Gamma(\mathrm{Z}^0 \to \mathrm{invisible})/\Gamma(\mathrm{Z}^0 \to \ell^+\ell^-)$.

LEP Running Strategy

- LEP typically runs for $\sim$ 30 weeks each year
- performed energy scans near the Z^0 peak in 1990, 1991, 1993; ran on-peak in 1992 and 1994



- Originally ran with 4 e^- on 4 e^+ bunches; luminosity was doubled in 1993 with 8 on 8 running

Why Measure $\Gamma_{inv}/\Gamma_{\ell^+\ell^-}$?

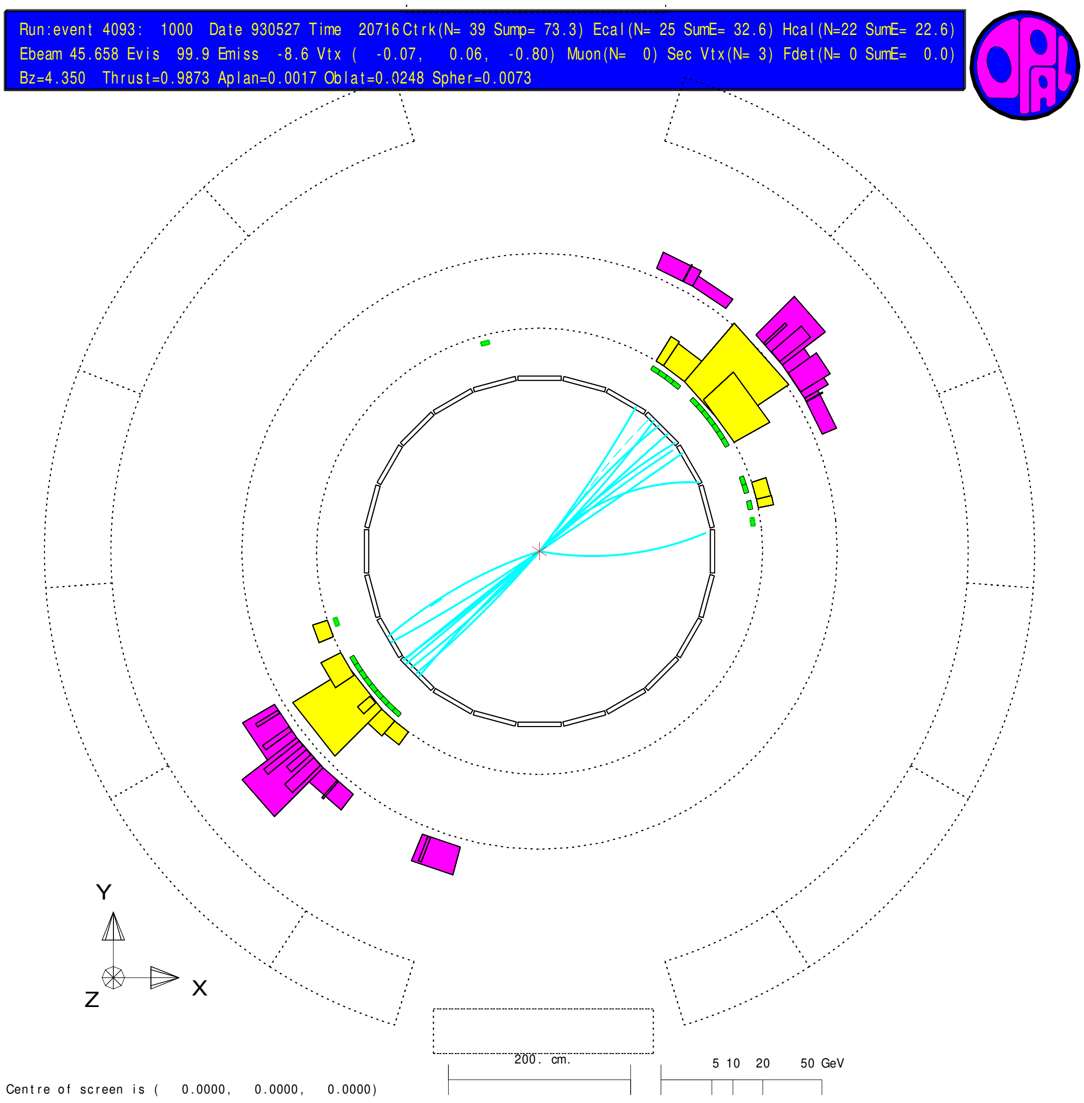
The Z width is

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_{\ell^+\ell^-} + \Gamma_{inv}$$

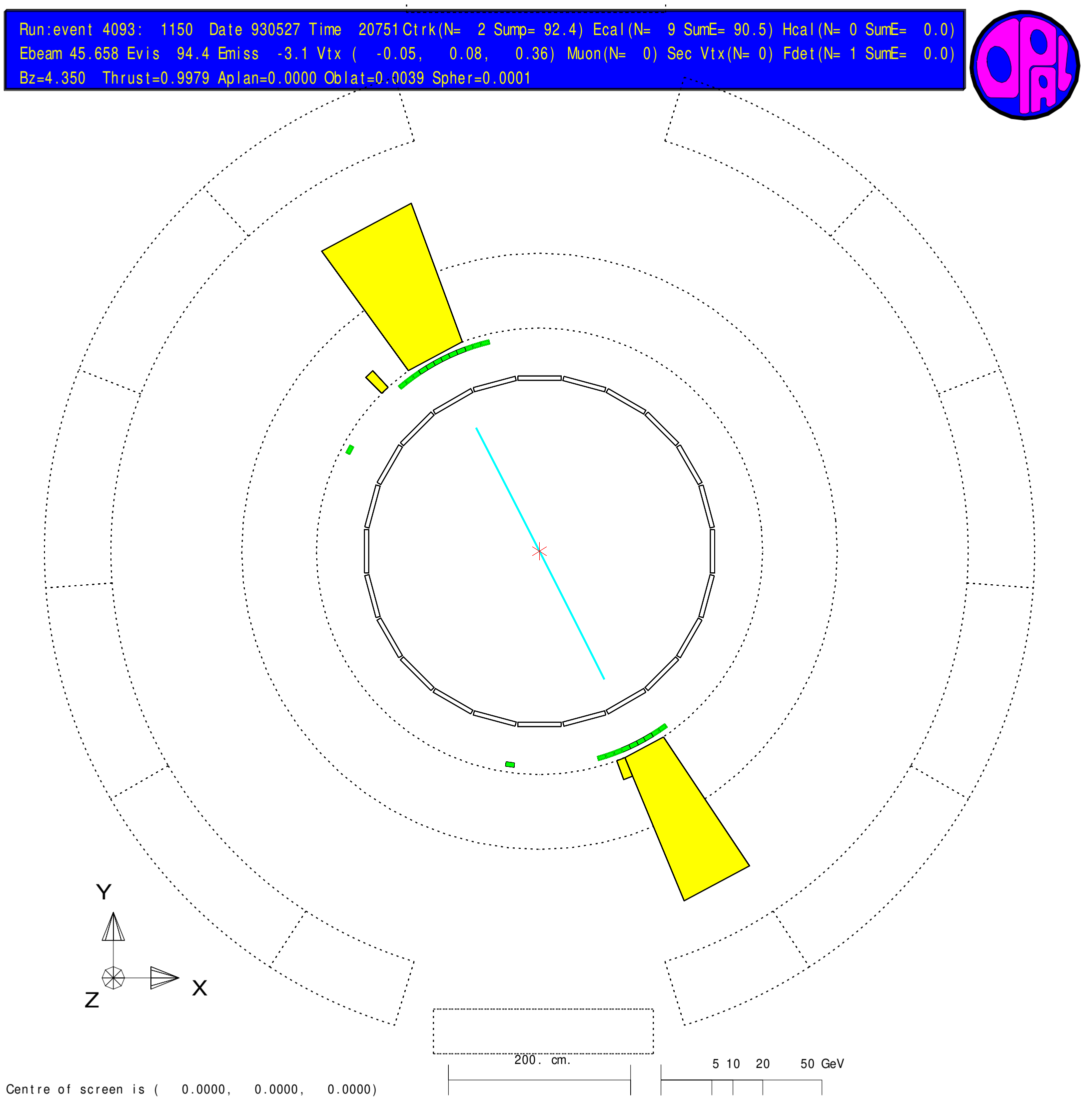
The ratio $\Gamma_{inv}/\Gamma_{\ell^+\ell^-}$ is:

- insensitive to M_t, M_H and QCD effects
- any deviation from the predicted value provides evidence for new physics

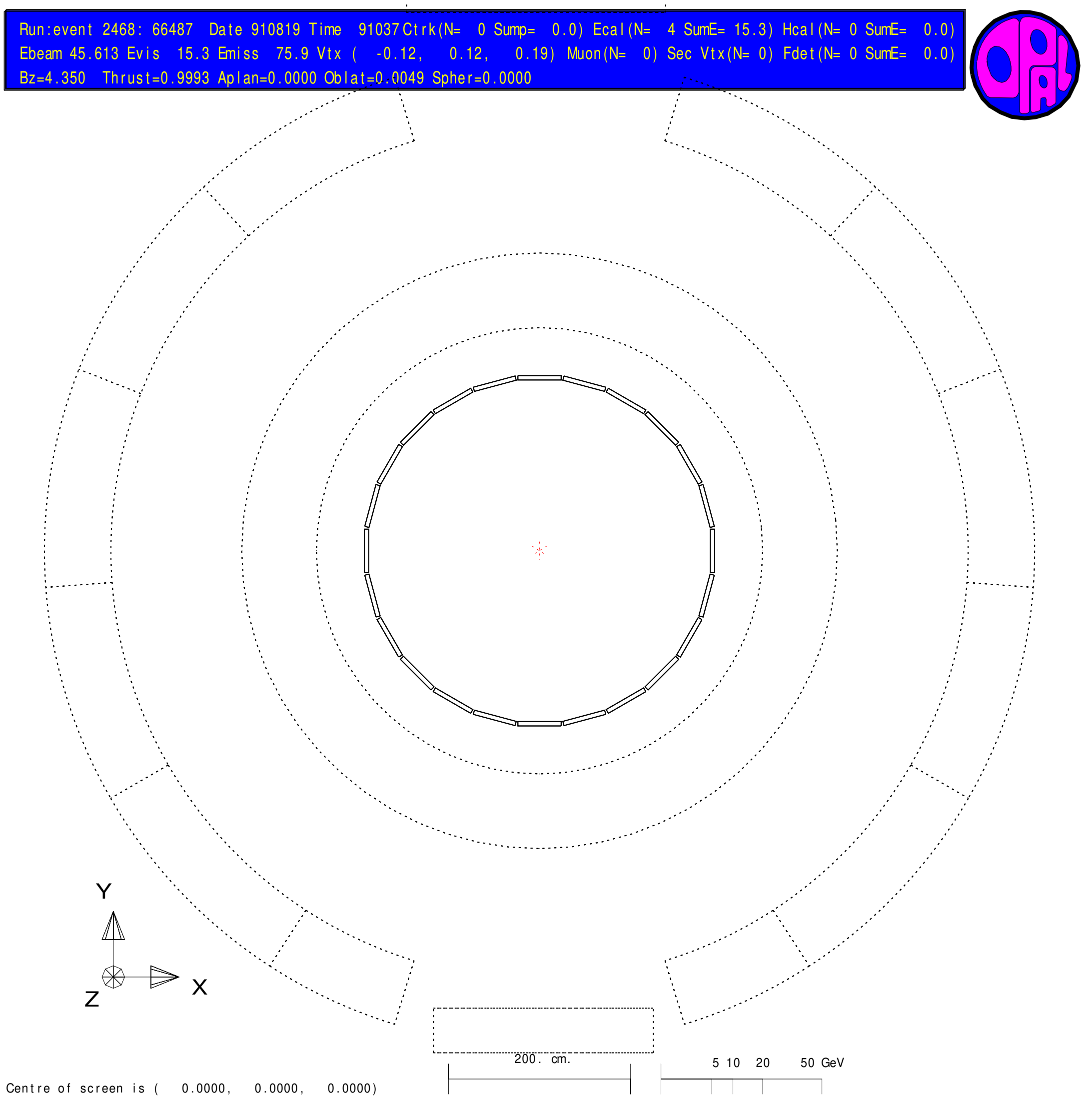
$Z^0 \to q\bar{q}$ **Event**



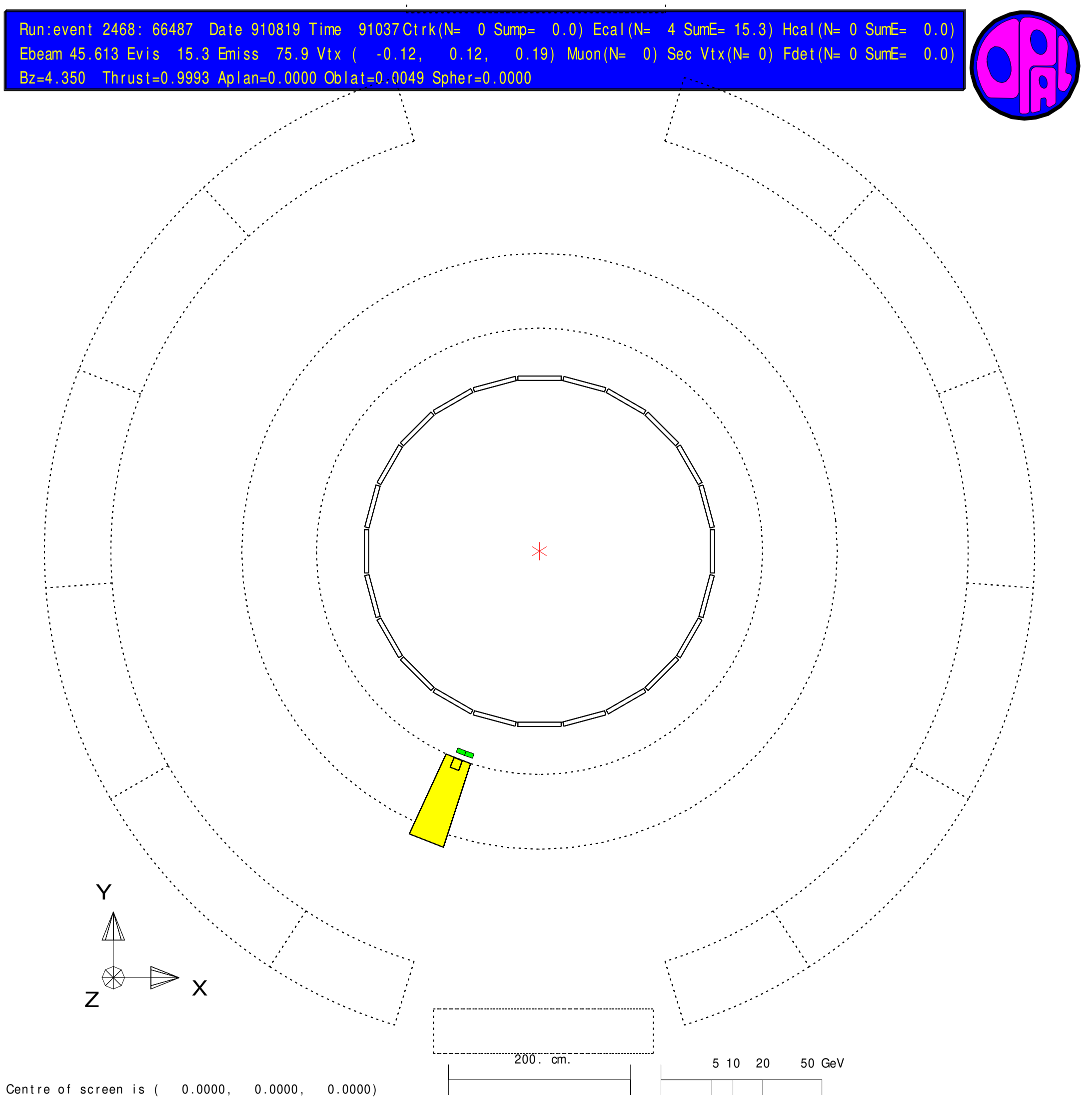
$Z^0 \to e^+e^-$ **Event**



$Z^0 \to \nu\bar{\nu}$ Event



$Z^0 \rightarrow \nu\bar{\nu}\gamma$ Event



Why Measure the Luminosity?

The search for $\mathrm{Z}^0 \rightarrow \nu\bar{\nu}\gamma$ has low statistics and large uncertainties.

However, prior to LEP, the best luminosity measurements were on the order of 5%. The luminosity detectors at LEP have achieved uncertainties of 0.5%.

But...

The measurements of the other channels are continually improving; for example, the current uncertainty on σ_{had} is 0.15%.

Why Build SiW?

$$\frac{\Gamma_{inv}}{\Gamma_{\ell^+\ell^-}} = \frac{\Gamma_Z - 3\Gamma_{\ell^+\ell^-} - \Gamma_{had}}{\Gamma_{\ell^+\ell^-}}$$

$$\Delta\left(\frac{\Gamma_{inv}}{\Gamma_{\ell^+\ell^-}}\right) \approx 15\frac{\Delta L}{L} \oplus 6\frac{\Delta N_{\ell^+\ell^-}}{N_{\ell^+\ell^-}} \oplus 21\frac{\Delta N_{had}}{N_{had}}$$

For $> 10^6$ $\mathrm{Z}^0 \rightarrow \mathrm{q\bar{q}}$ decays, we need to measure the luminosity with an uncertainty of $\sim 0.1\%$ to get comparable systematic uncertainties.

$\Rightarrow$ Need a detector with very high precision.

Luminosity Detector Design Goals

- Count low-angle Bhabha scattering events in the angular range from 30 to 55 mrad from the beam direction; Bhabha events follow a $1/\theta^3$ distribution, so the detector should be as close to the beam pipe as possible.

- The uncertainty on the luminosity is related to the uncertainty of the position of the acceptance cuts:

$$\frac{\Delta L}{L} \approx \frac{\Delta r_{inner}(\mu\mathrm{m})}{25} \times 10^{-3}$$

$$\frac{\Delta L}{L} \approx \frac{\Delta r_{outer}(\mu\mathrm{m})}{100} \times 10^{-3}$$

  For a 0.1% measurement, we need to know the absolute position of the acceptance cut to $20\ \mu\mathrm{m}$.

- To reject off-momentum background (mostly from beam-gas interactions), we need good energy resolution ($\Rightarrow$ good sampling and depth) and good azimuthal resolution.

OPAL Institutes

$\approx$ 300 collaborators from 32 institutions:

Birmingham
Cambridge
QMW
UCL
Manchester
Rutherford
Brunel

Carleton
CRPP
Montreal
Victoria
British Columbia
Alberta

Chicago
Riverside
Indiana
Maryland
Oregon
Duke

Bonn
Freiburg
Heidelburg
DESY
Aachen

Technion
Tel Aviv
Weizmann

Saclay

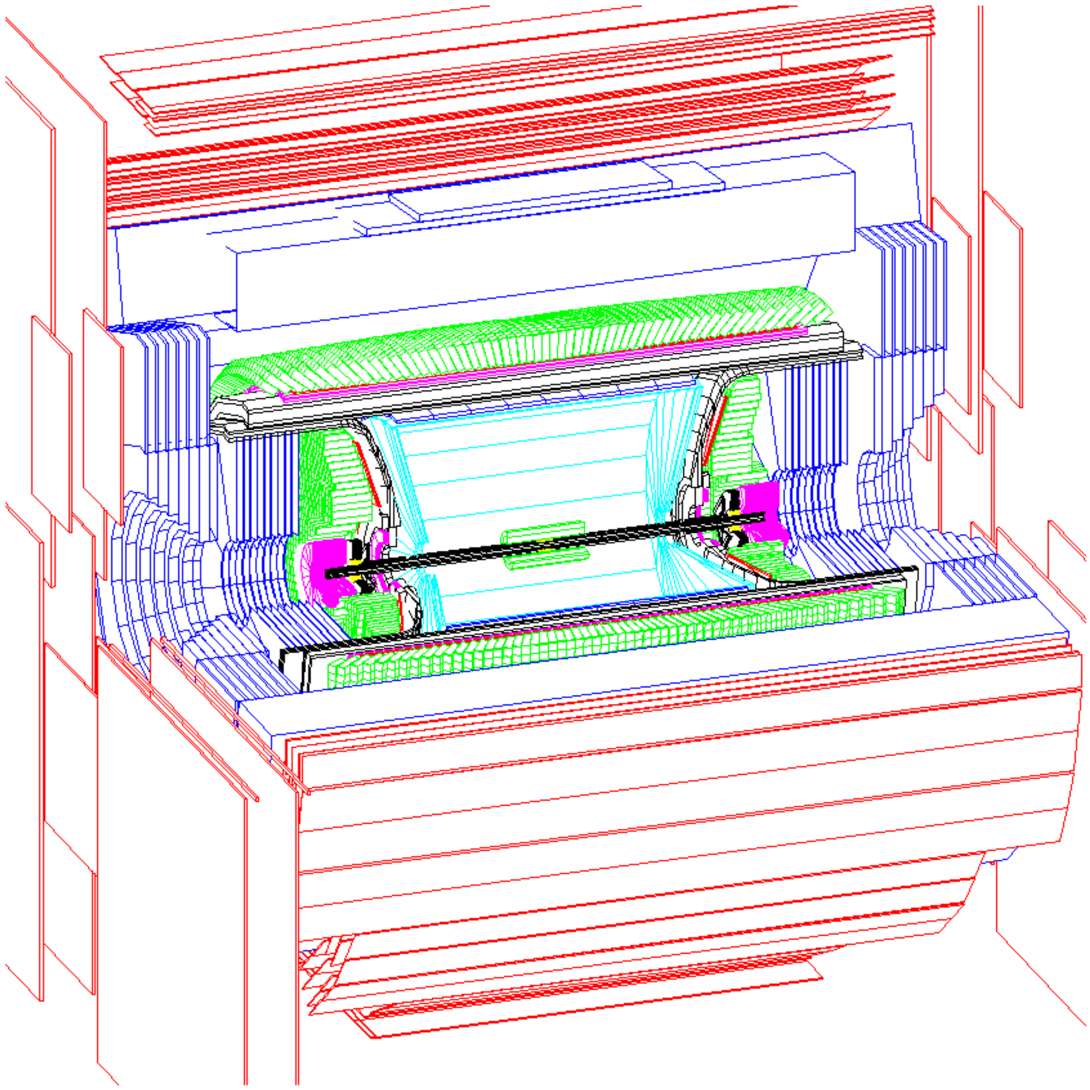
Budapest

Bologna

Tokyo

CERN

The OPAL Detector



The SiW Calorimeter

Two calorimeters, located at ± 240 cm from the interaction point. Each calorimeter consists of:

- 18 layers of tungsten
- 19 layers of silicon
  - 1 bare layer
  - 14 layers following $1\chi_0$ tungsten plates
  - 4 layers following $2\chi_0$ tungsten plates
- Even and odd layers are staggered in ϕ to reduce leakage between detector wedges.

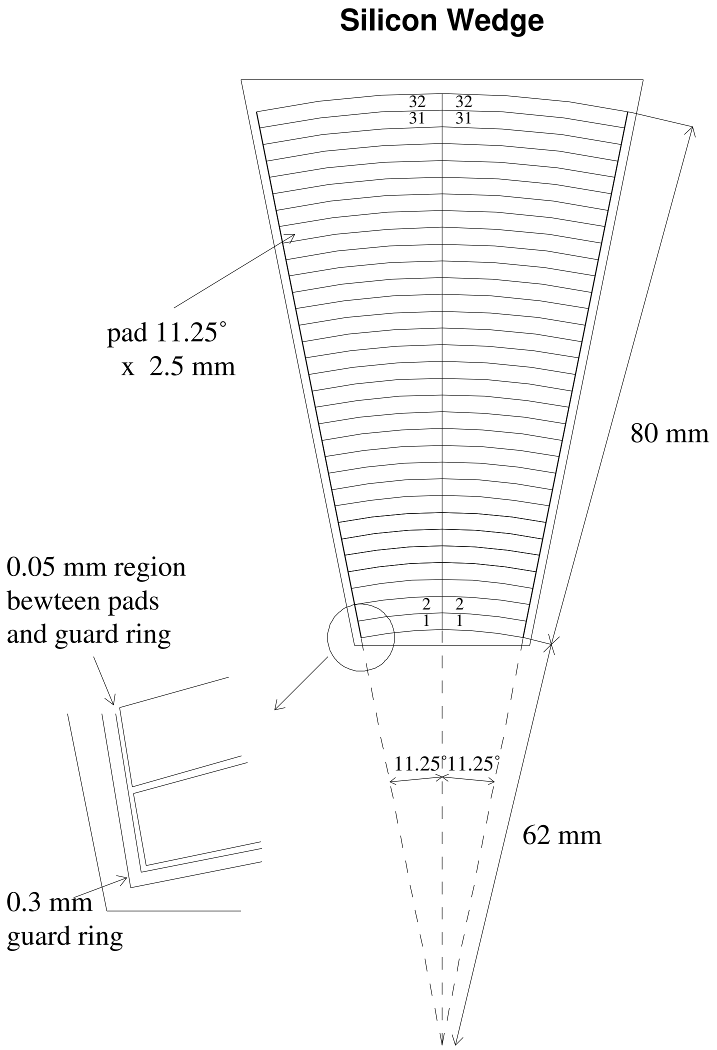
$\Rightarrow 2 \times 19 \times 32 \times 32 = 38912$ channels

Silicon Detector

Each layer contains 16 detector wedges. Each detector wedge:

- consists of a $300\mu\mathrm{m}$-thick wafer of silicon
- each wafer consists of 64 (32×2) pads
- each wedge covers an area of 8 cm (from 6.2 to 14.2 cm) in r by $22.5°$ in ϕ
- glued to each detector is a $250\mu\mathrm{m}$-thick ceramic with surface-mounted readout electronics
- each wedge is read out with 4 OPAL Amplex chips (based on the Aleph SICAL Amplex chips)

A Detector Wedge



SiW Milestones

June 1991

Discussion

November 1991

Proposal and LEPC approval

July 1992

Testbeam with partially instrumented prototype calorimeter

June 1993

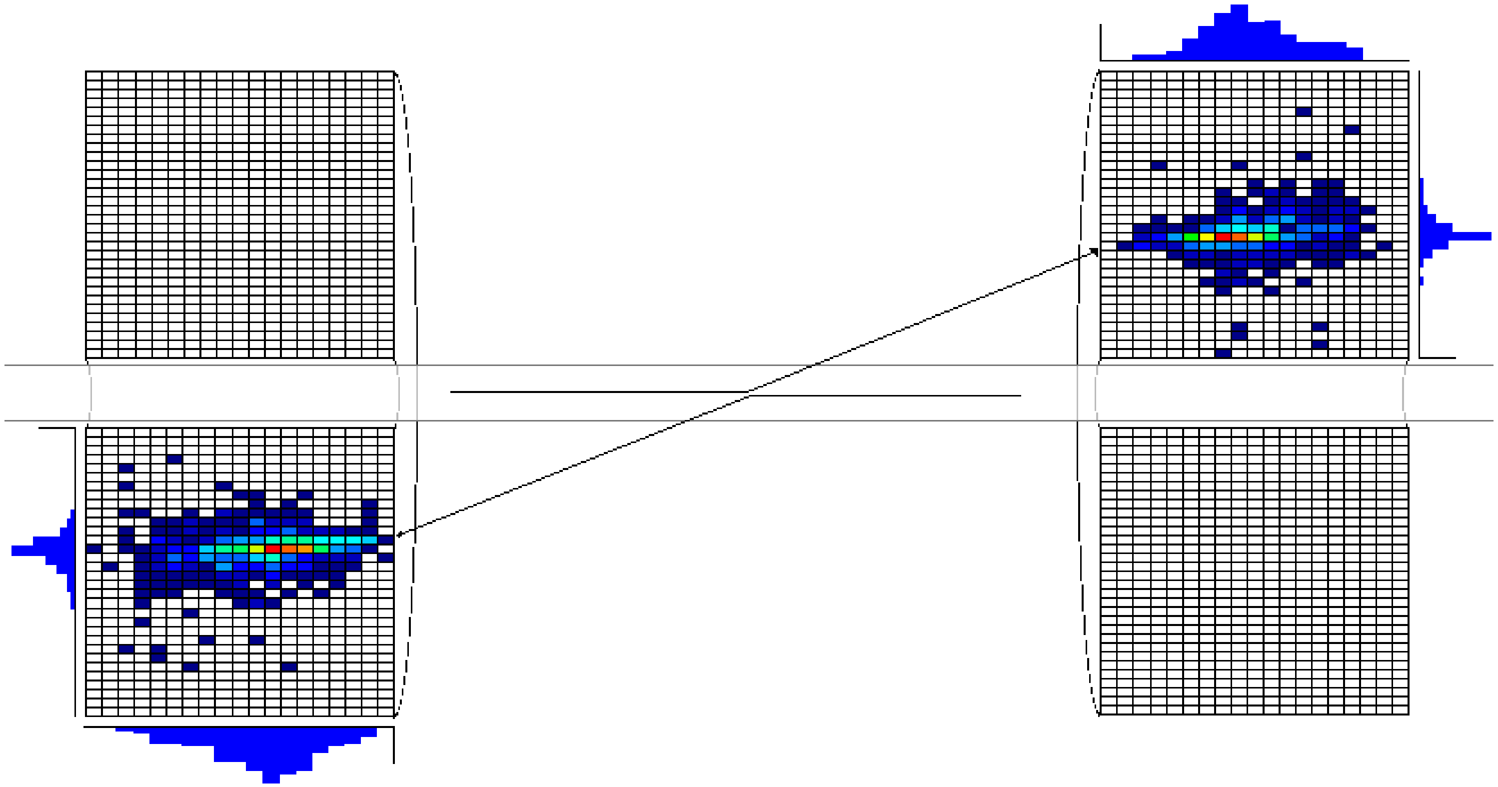
First data

June 1994

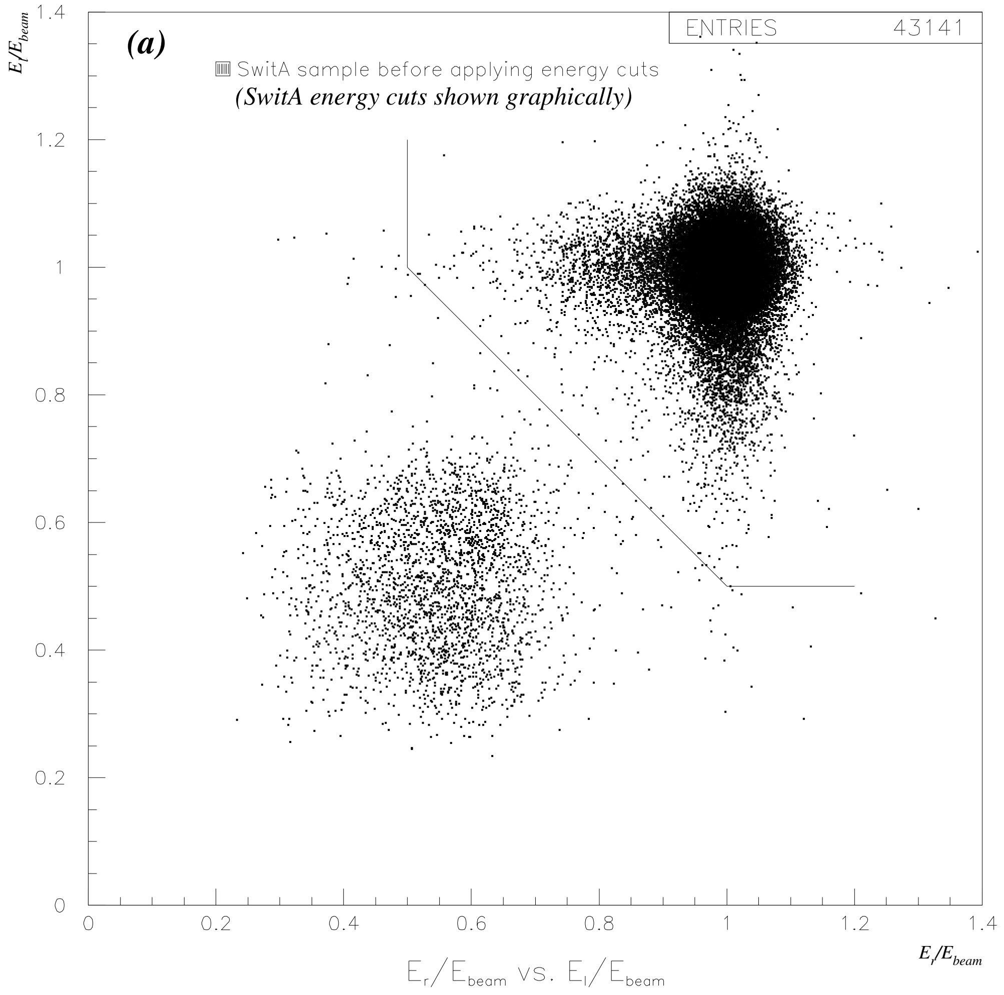
Presentation of luminosity results with experimental error of $\leq 10^{-3}$

A Bhabha Scattering Event

A typical Bhabha event in the calorimeter (not to scale):

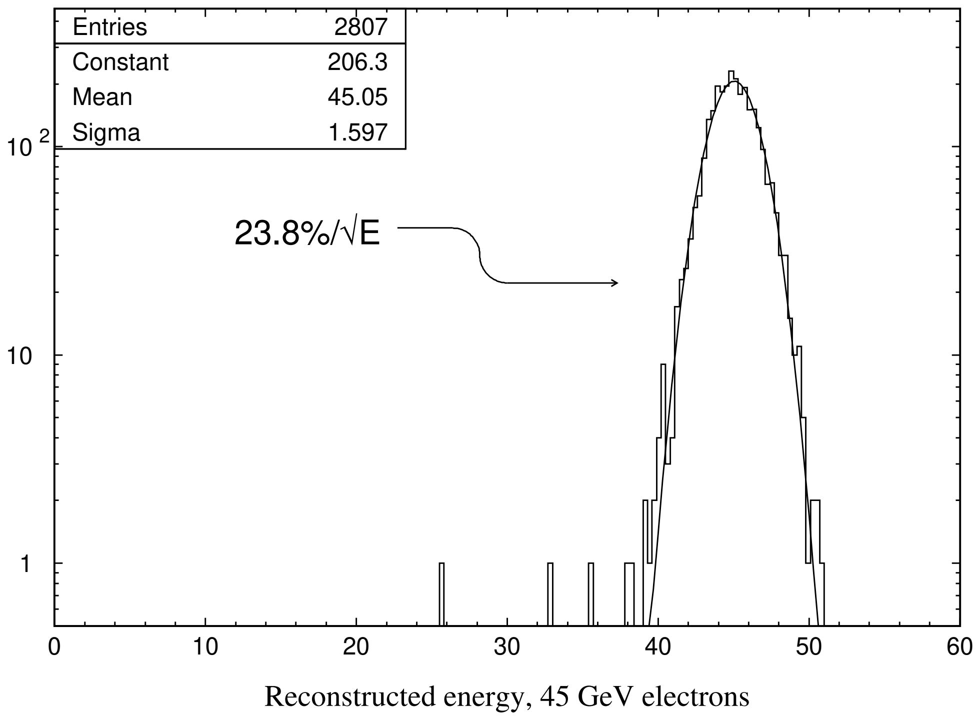


Energy Response



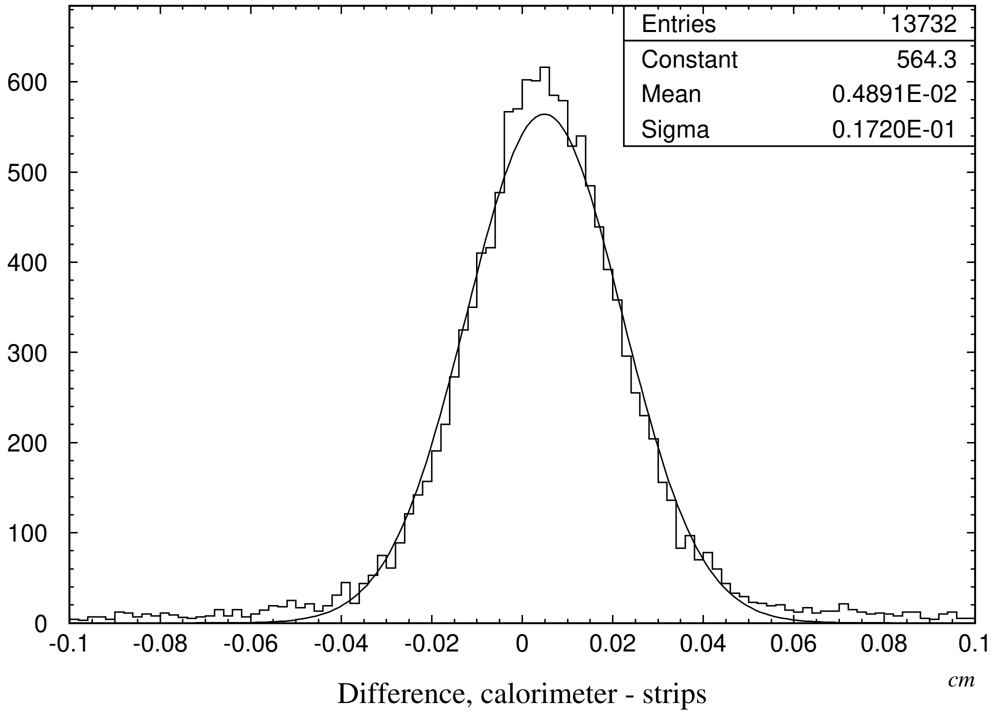
Energy Resolution

The energy resolution for monochromatic 45 GeV electrons:



Position Resolution

We can measure the position resolution using testbeam information:

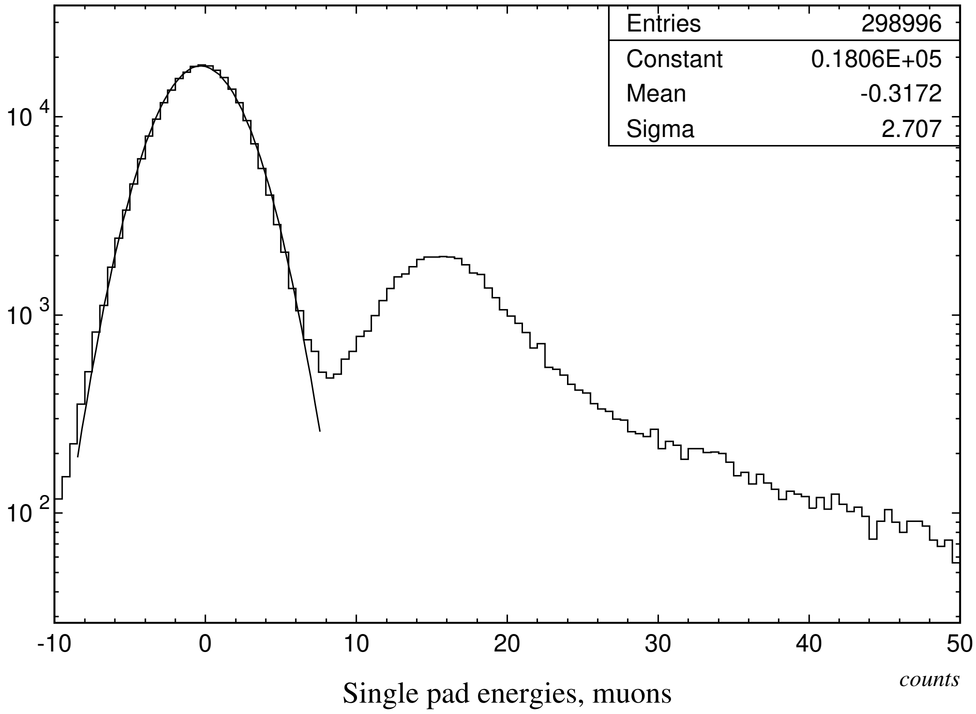


Note: For the luminosity measurement, it is not the resolution which is important, but the uncertainty on the mean.

Response to Muons

The calorimeter was designed to be sensitive to ionizing particles. This extremely important feature will be used in the analysis.

The response of the calorimeter to ionizing particles (digitizer counts for a single pad):



[On this scale, an electron deposits $\sim$ 2000 counts per pad.]

Trigger

A typical Bhabha event will be two back-to-back electrons, each carrying half the beam energy. We use three triggers:

1. A segment trigger requiring significant energy in both ends ($E_R, E_L > 18$ GeV) and a ϕ correlation ($||\phi_R - \phi_L| - \pi| < 500$ mrad)

2. As a check of the efficiency, a "high-low" trigger with a low threshold on one end (> 10 GeV) and high threshold on the other (> 40 GeV), no phi correlation

3. To measure the background (mostly beam-gas interactions), an accidental trigger (the segment trigger with one end in-time and one end using information from 8 bunch crossings earlier).

Shower Reconstruction

The shower reconstruction performs the following steps:

1. project all pad information into the $r - \phi$ plane and perform a quick search for areas of activity
2. search for "peaks" in energy in the central layers, and require that these peaks be correlated among several layers (i.e. look for something shaped like a shower)
3. calculate the basic quantities: E, r and ϕ
4. any energy left over is also recorded (in case of inefficiencies in the shower finder)

Note: This shower reconstruction method can separate showers that are within several millimeters of each other; this may be useful for future studies of the angular distribution of final-state photons.

Isolation Cuts

To select good Bhabha events, select good back-to-back electrons that are well-contained in the calorimeters:

Radius $67\ \mathrm{mm} < \mathrm{R_{R,L}} < 137\ \mathrm{mm}$

containment in calorimeter

Energy $E_{R,L} > 0.5\ E_{beam}$

Average energy $\frac{E_R+E_L}{2} > 0.75\ E_{beam}$

Acoplanarity $||\phi_R - \phi_L| - \pi| < 200\ \mathrm{mrad}$

reject off-momentum background

Acollinearity $|R_R - R_L| < 25\ \mathrm{mm}$

explicit cut on single-radiative events

Definition Cuts

Define three counters:

SWITR	$77\ \mathrm{mm} < \mathrm{R_R} < 127\ \mathrm{mm}$
SWITL	$77\ \mathrm{mm} < \mathrm{R_L} < 127\ \mathrm{mm}$

and

SWITA	$77\ \mathrm{mm} < \frac{\mathrm{R_R}+\mathrm{R_L}}{2} < 127\ \mathrm{mm}$

Advantages: This counter is independent of beam spot shifts.

Disadvantages: The cut is not in the same place each event.

We measure the luminosity with

$$\frac{1}{2}\left(N_{SWITR} + N_{SWITL}\right)$$

and check with N_{SWITA}.

Radial Coordinate Reconstruction

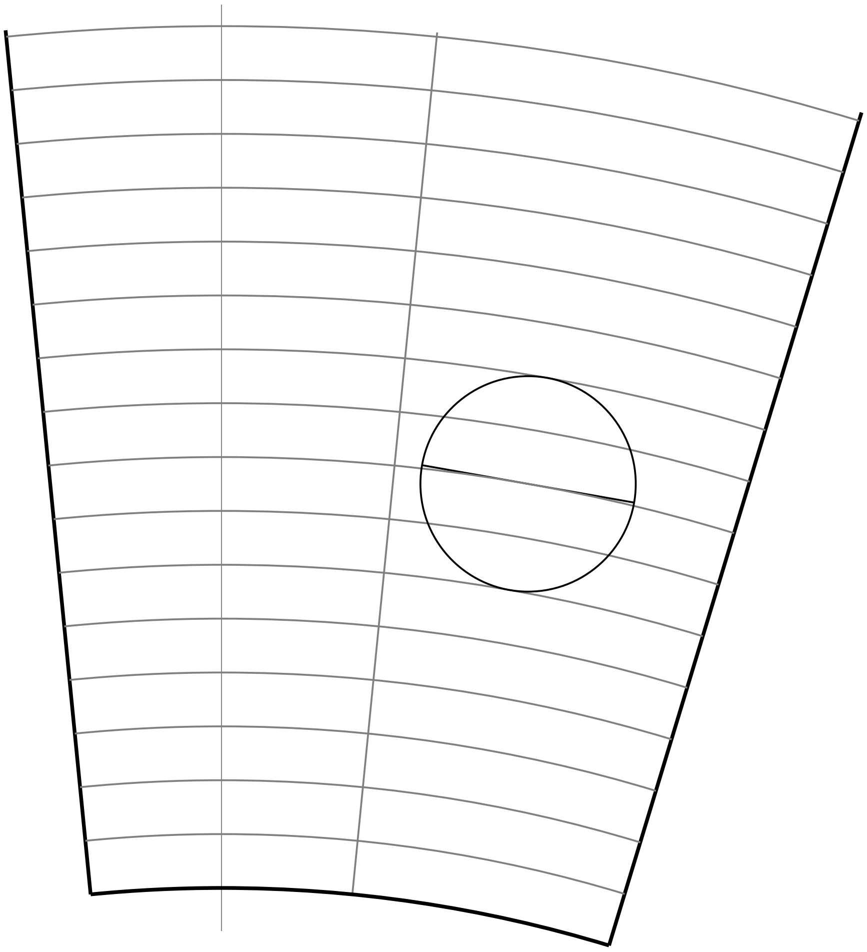
This is the luminosity measurement! We need to understand the absolute position of the acceptance cut to 20 μm.

In this talk, we look at:

- Potential systematic biases
- Naïve (“padmax”) method
- Reconstruction using a fit to several layers

Potential Biases

The curved pads introduce a bias due to the different pad sizes. This bias depends on the radial position and the size of the shower:



"Padmax" Coordinate

The simple method for calculating the radial coordinate is to simply look at the energy sharing between two pads in a single layer; for example:

$$f \equiv \frac{E_{in} - E_{out}}{E_{in} + E_{out}}$$

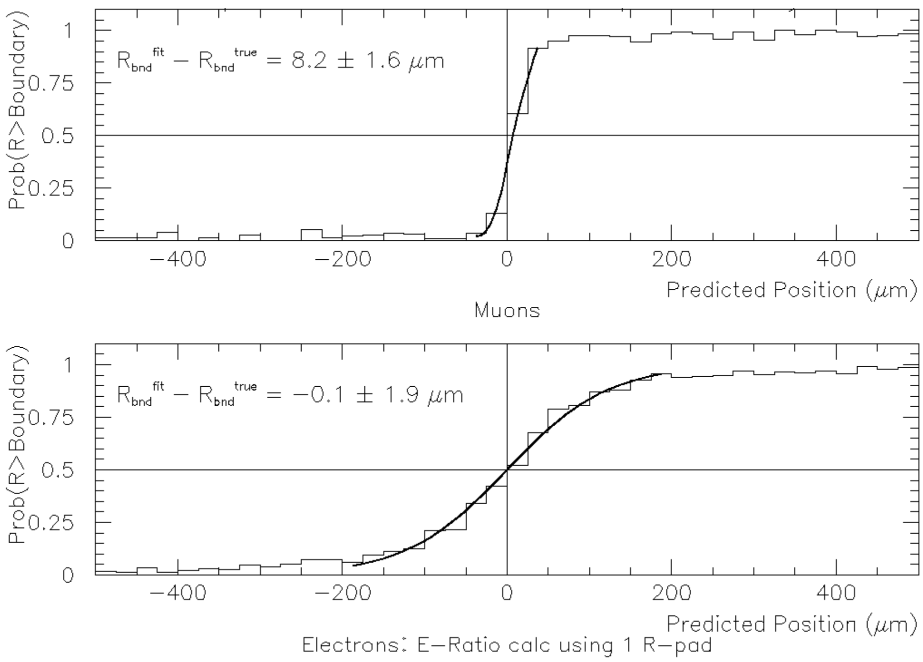
and discriminate between $f < 0$ and $f > 0$.

Note:

- This does not exploit the full capabilities of the calorimeter
- In a testbeam we did use this method to find reconstruction bias by comparing electrons and muons

Coordinate Bias of Padmax Method

Testbeam data, using microstrips to determine the absolute position of the particles entering the calorimeter. Muons do not shower, so they can be used to "survey" the calorimeter:

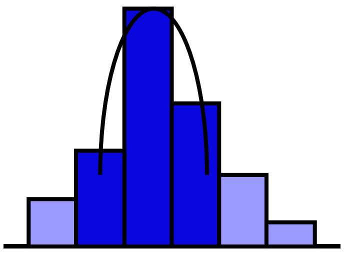


Comparing muons to electrons yields a bias of $8 \pm 6\mu m$.

Full Reconstruction

The following is the method we use for the calculation of the radial coordinate for real OPAL data:

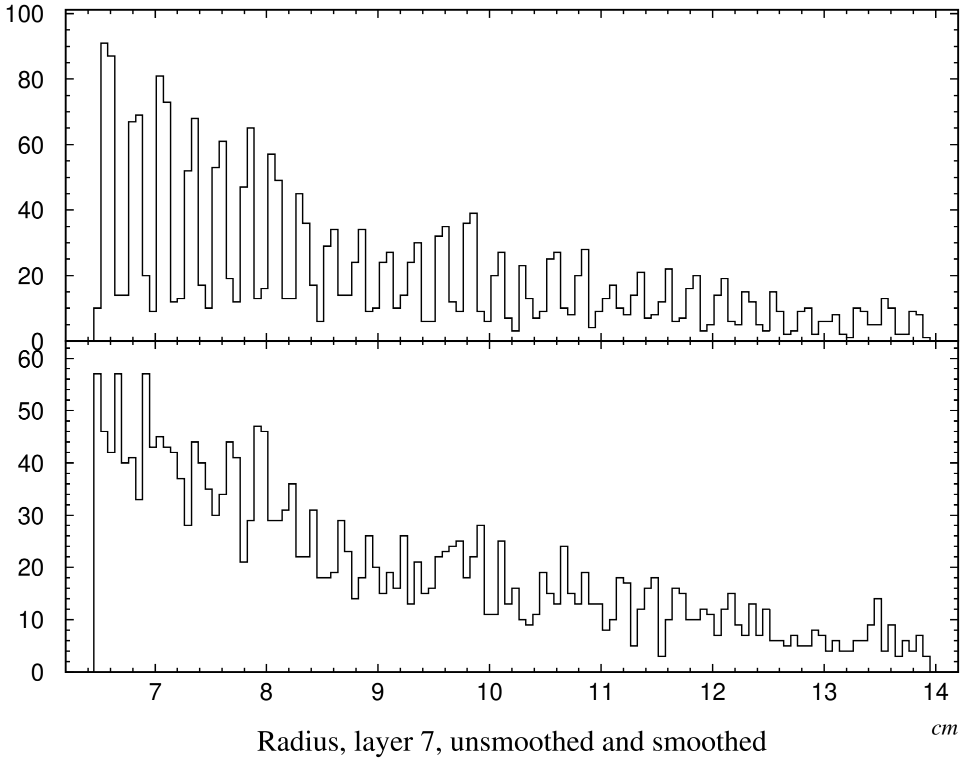
1. Calculate r coordinate from 3 pads in one layer using parabolic fit ($f = \frac{E_3 - E_1}{2E_2 - E_3 - E_1}$)



Note that this function has nice symmetry properties near pad boundaries.

Smoothing a Single Layer

2. Since the shower shape is not a parabola, the coordinate tends to be pulled towards pad centers. We smooth this coordinate using shower shape information:



Radius, layer 7, unsmoothed and smoothed

Full Reconstruction (2)

3. Fit to the layers with the maximum energy deposition ($\sim$ 6 layers) and beam position, and project to layer 7.

   Note: despite the fact that coordinate in individual layers is smooth, the resolution is position dependent $\Rightarrow$ fit is pulled towards pad boundaries

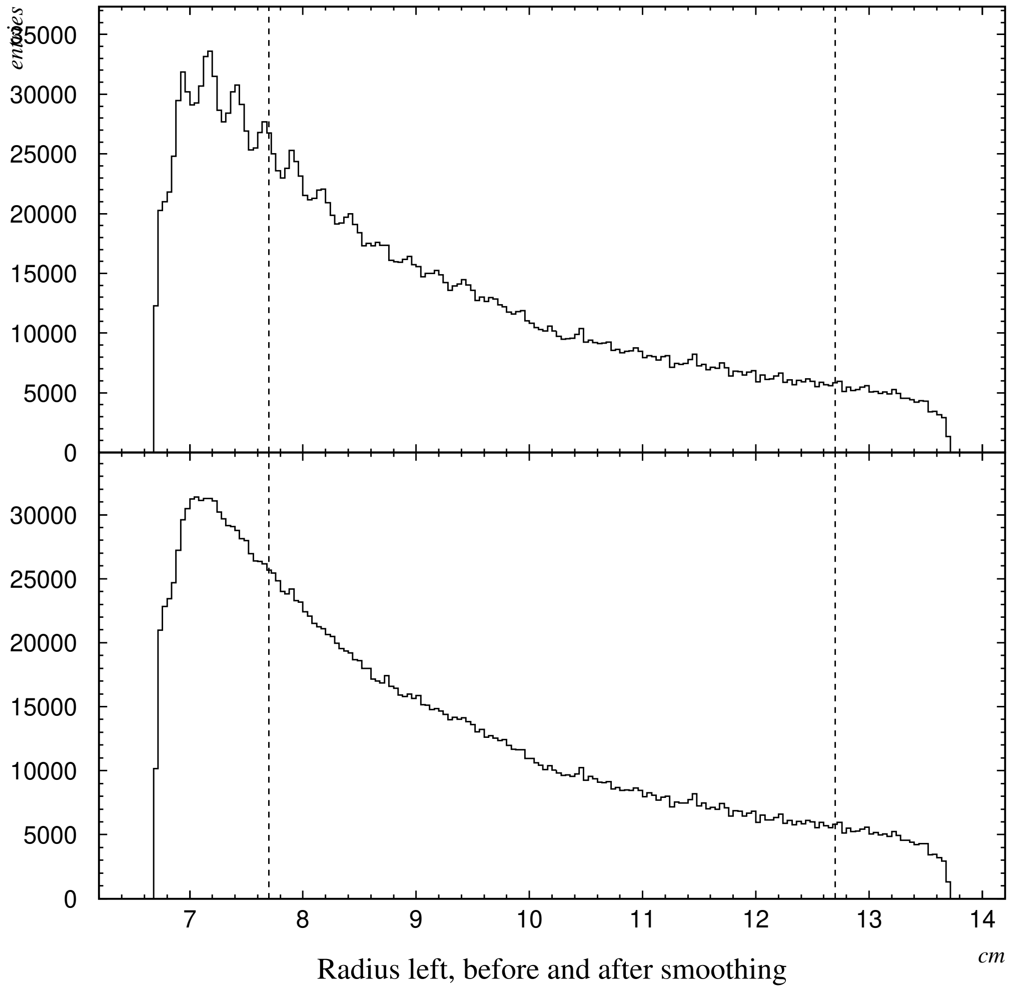
4. Apply a smoothing function to the data

   choosing the cut at any radius gives the same answer

   potential biases?

Smoothing

Before and after applying a smoothing function:



Radius left, before and after smoothing

“Anchoring” the Coordinate

From testbeam studies, we know:

1. the true electron trajectory (from microstrips)
2. the coordinate reconstructed with the maximum pad method

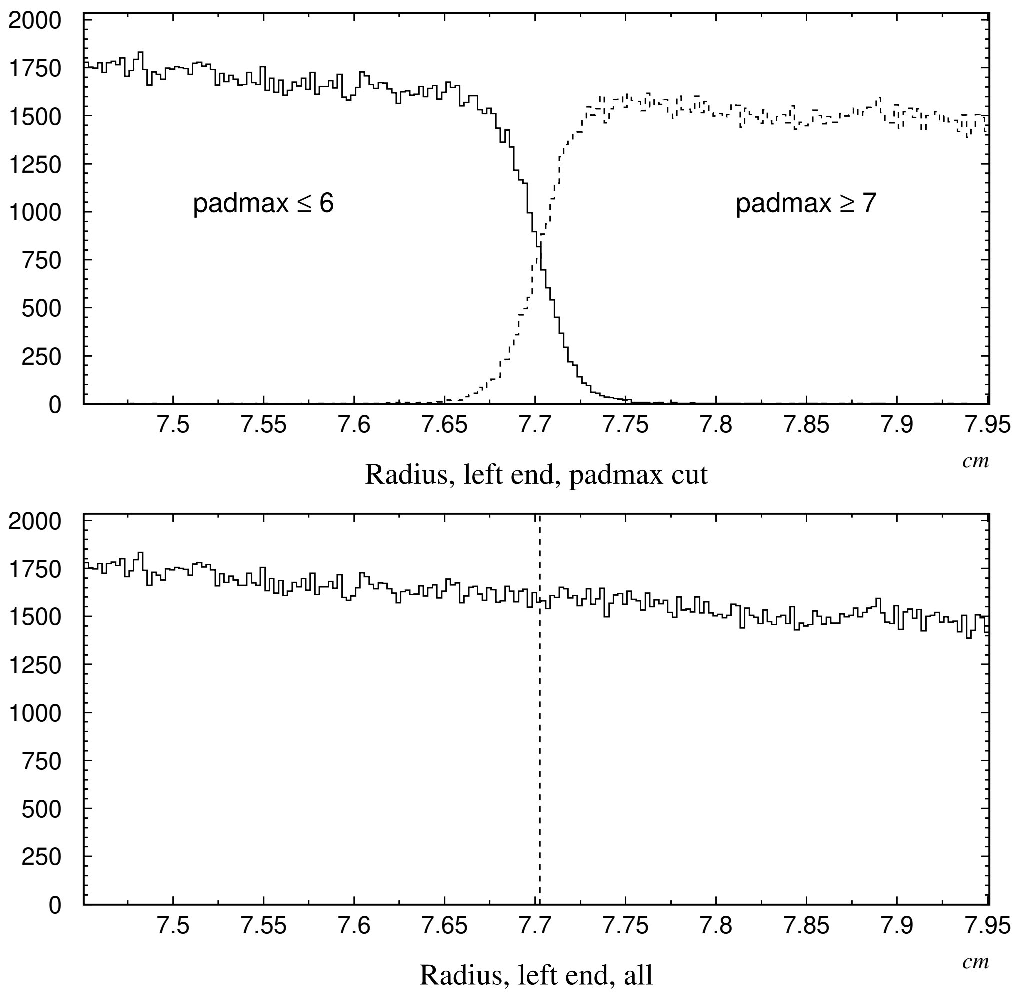
We don’t know the true trajectory of the particle in OPAL, but we do know:

2. the coordinate reconstructed with the maximum pad method
3. the fully reconstructed shower position

To “anchor” the coordinate, we find the radial coordinate where the acceptance of the radial cut is exactly the same as the acceptance of the padmax method.

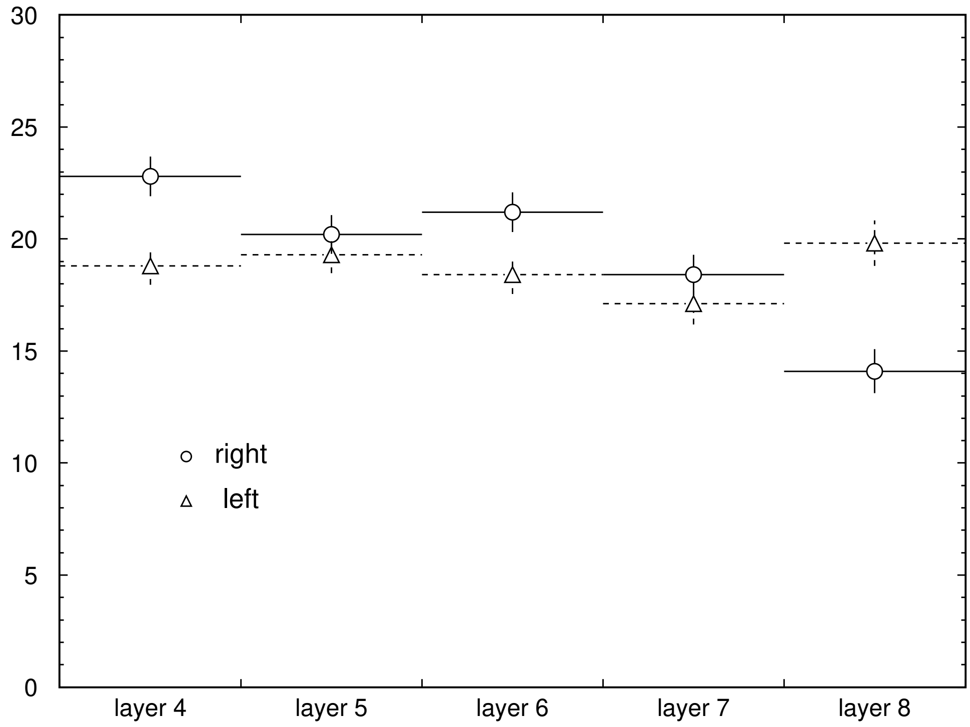
Anchoring the Coordinate

Find the radial coordinate where the acceptance of the radial cut is exactly the same as the acceptance of the padmax method.



Radial Coordinate Bias

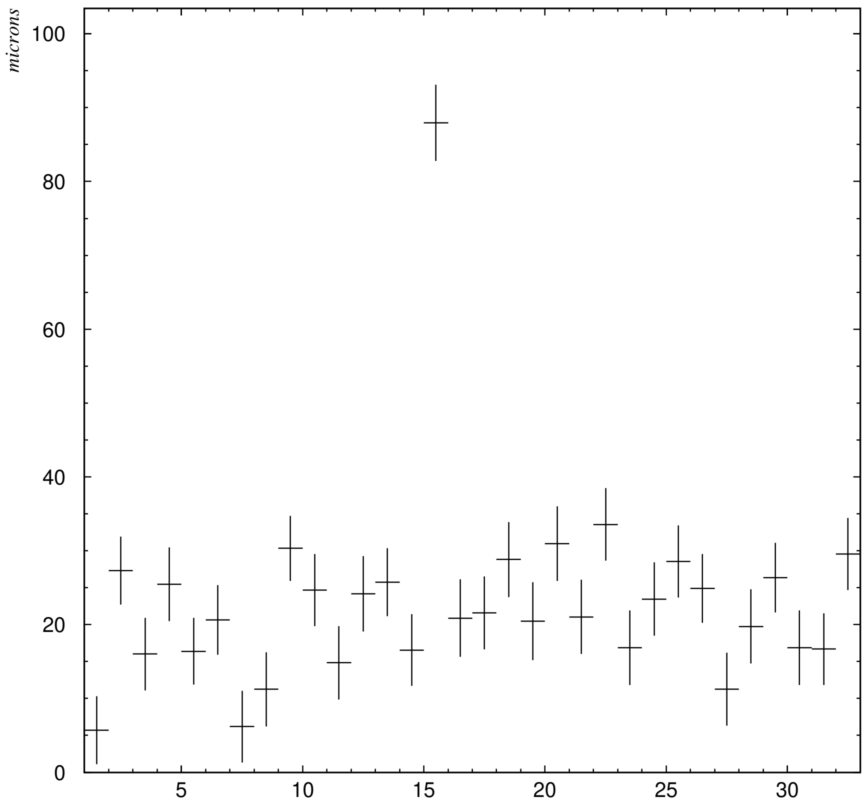
We can only perform the anchoring for certain specific points in the detector. For the point where we make the cut (layer 7) the bias is $\sim 18\mu\mathrm{m}$. As a check, we can perform the check for several layers:



Bias versus layer of cut

Reconstruction Biases vs ϕ

We can even perform the anchoring for every ϕ segment in the calorimeter:



Biases, layer 6

(Note that we can "survey" the calorimeter with this method, which is an advantage over maximum-pad!)

Testbeam studies

In the summer of 1994, we performed another testbeam; this time with four microstrip modules for determining the trajectories and a calorimeter which was fully instrumented with 19 layers of silicon detector.

⇒ When this analysis is done, we will be able to determine the reconstruction biases directly (and at any point in the detector) without the intermediate step of anchoring certain places in the detector.

Work is still in progress.

Luminosity Systematic Errors

Effect on L_{RL}	Correction $\times 10^{-4}$		Systematic $\times 10^{-4}$	
	1993	1994	1993	1994
SiW radial dimensions ($\pm 9\mu$m)	—	—	$3.6 \oplus 0.0$	$3.6 \oplus 2.0$
Radial coordinate bias	—	—	$3.3 \oplus 0.8$	$3.3 \oplus 0.5$
Monte Carlo, detector response	-7.3	-7.3	$3.8 \oplus 0.3$	$3.8 \oplus 0.3$
Monte Carlo, statistics	—	—	$3.7 \oplus 0.0$	$3.7 \oplus 0.0$
Detector instability (mech. + response)	—	—	$0.5 \oplus 0.0$	$0.5 \oplus 0.0$
Trigger inefficiency	0	0	< 0.01	< 0.01
LEP Beam parameters (average)	$+3.1$	$+4.4$	$1.9 \oplus 0.5$	$1.9 \oplus 0.4$
Fluctuations in LEP beam parameters	—	—	$0.0 \oplus 0.5$	$0.0 \oplus 0.5$
Accidental coincidence background	$+1.0$	$+0.1$	$0.0 \oplus 0.1$	$0.0 \oplus 1.0$
$\gamma\gamma$ background	$+2.0$	$+2.0$	$0.1 \oplus 0.0$	$0.1 \oplus 0.0$
Total experimental error	-1.2	-0.8	$7.5 \oplus 1.1$	$7.5 \oplus 2.4$
Total theoretical error			16.	

Acceptance: Calculation

The acceptance is calculated using BHLUMI 2 as the Monte Carlo generator, convoluting with:

- geometrical acceptance
- parameterized energy response of the calorimeters
- LEP beam parameters (offsets, tilts)

Important: we do not rely on detailed simulations of showers in order to calculate the acceptance!

Acceptance: BHLUMI

Calculate acceptance using BHLUMI 2:

- multiphoton exponentiated $O(\alpha)$ generator for small-angle Bhabha scattering
- pure t-channel (use BHAGEN and ALIBABA to account for $\gamma - \mathrm{Z}$ interference)
- overall theoretical uncertainty of 2.5×10^{-3}

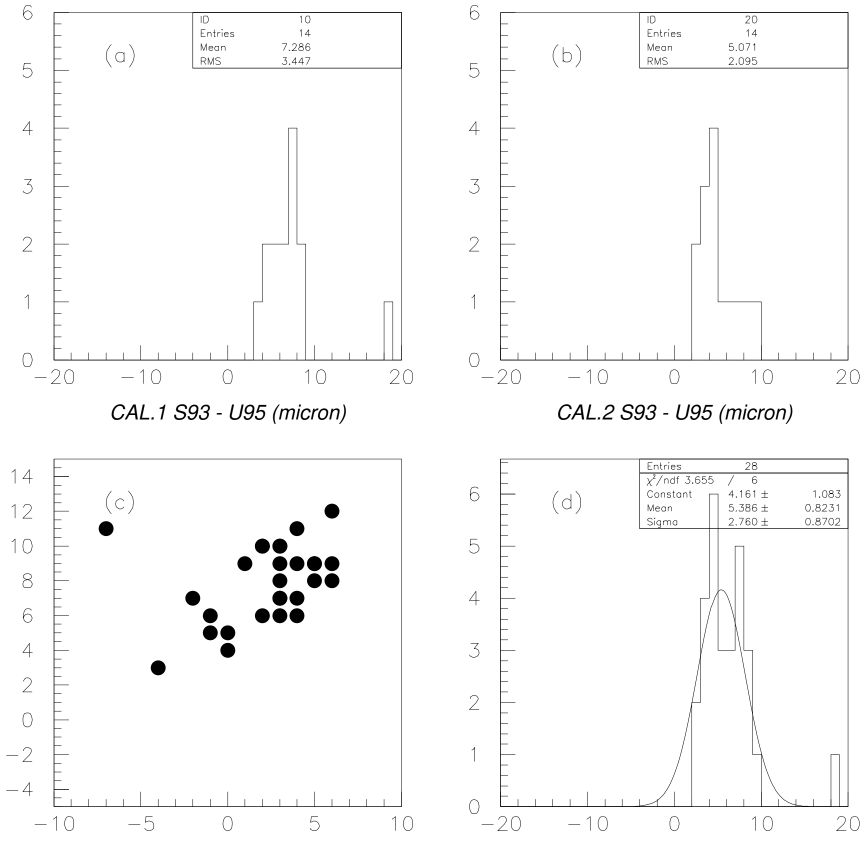
Recently, BHLUMI 4 has been released:

- includes additional next to leading logarithmic terms of $O(\alpha^2)$
- total theoretical error at or below 1.6×10^{-3}
- for OPAL, the difference in acceptance between the two versions is 1.5×10^{-4}

Metrology

Compare the radial positions of each layer between 1993 and 1995:

AVERAGE R comparison (full layer): Stack 93 - Unstack 95

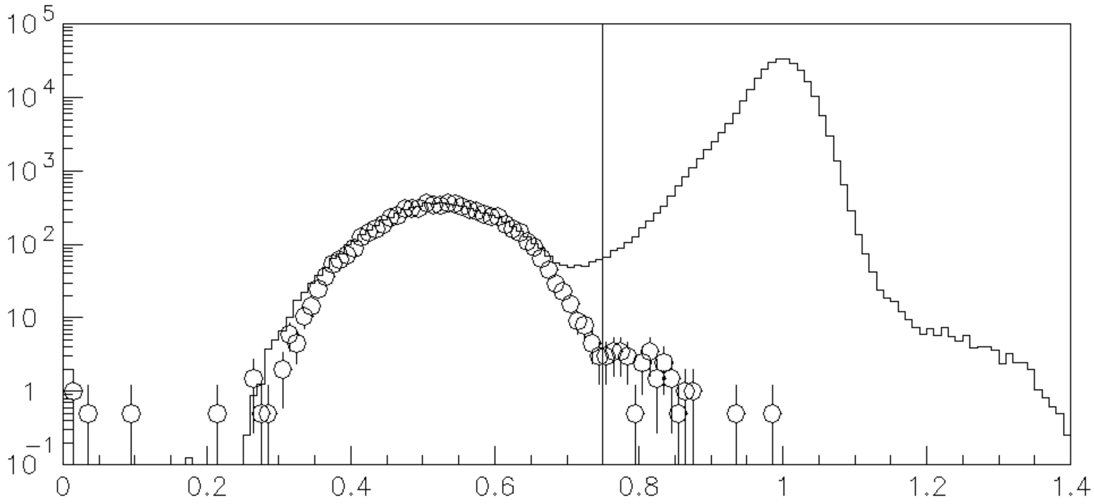


Trigger and shower finder efficiencies

- Trigger efficiency:
  - Verify the efficiency of the "high-low" trigger against the old forward detector
  - For "high-low" triggered events, verify that those which should have also been triggered by the segment trigger did
  - Inefficiency of $< 1.0 \times 10^{-6}$
- Shower finder efficiency:
  - For all events with a trigger, check that there is a shower
  - Uncertainty of $\approx 2.4 \times 10^{-4}$

Background

Compare the spectrum of accidental triggers (in-time on one end, information from 8 bunch crossings earlier on the other end):

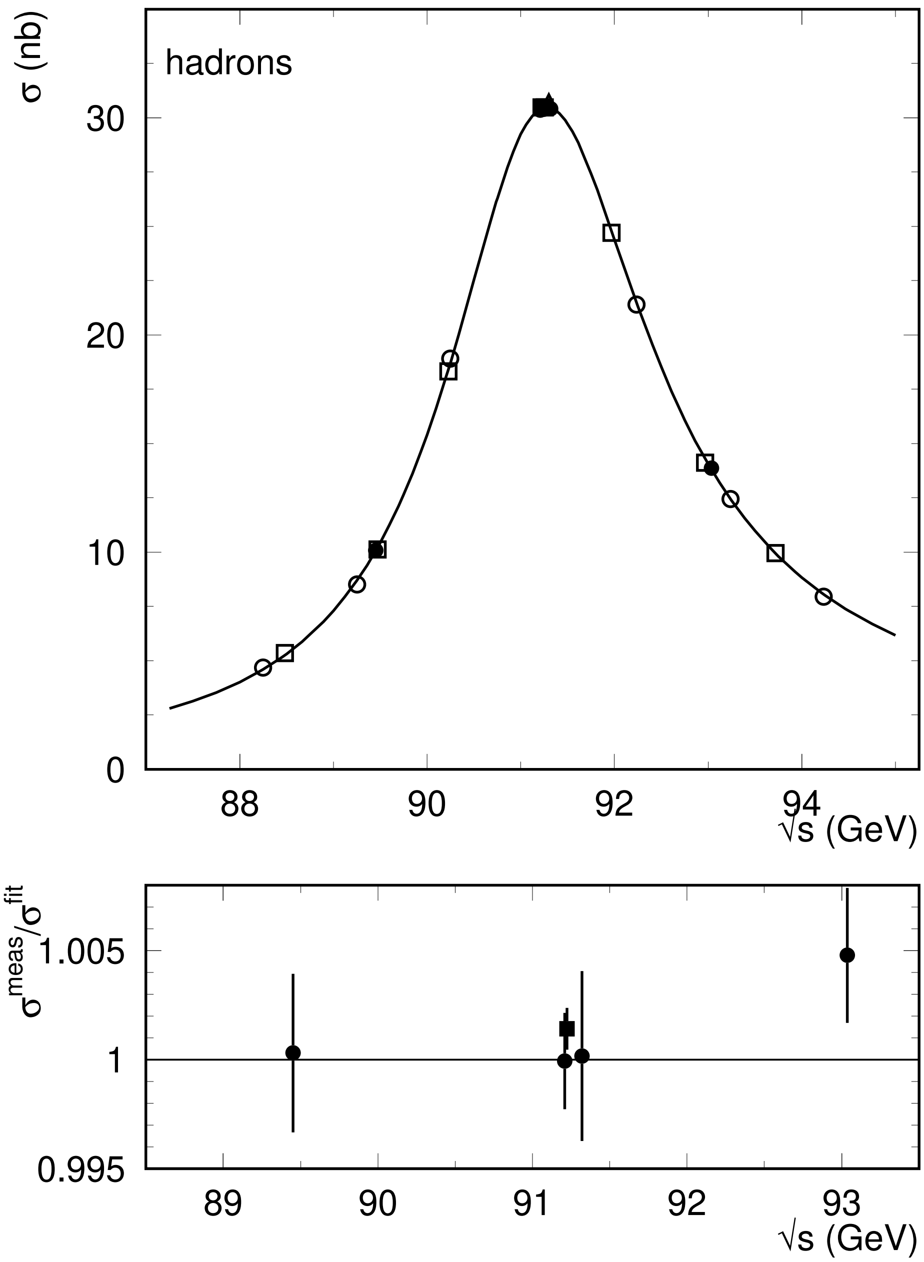


The expected effect on the luminosity is 9.5×10^{-5}

Position and Temperature Stability

- SiW is mounted on the central detector pressure vessel, which can "breathe." We monitor the z position of the calorimeter to within 2 $\mu\mathrm{m}$. The shifts were negligible (2×10^{-5}).
- A $3^\circ\mathrm{C}$ shift in temperature produces a radial shift of 6 $\mu\mathrm{m}$. We controlled the temperature of the calorimeters to within $0.1^\circ\mathrm{C}$ (1×10^{-5}).

Z Lineshape


hadrons
σ (nb)
30
20
10
0
88
90
92
94
√s (GeV)
σmeas/σfit
1.005
1
0.995
89
90
91
92
93
√s (GeV)

OPAL Preliminary Lineshape Results, 1990-1994

	Without Lepton Universality	With Lepton Universality	SM Prediction
R_e	20.90±0.10		
R_μ	20.796±0.073		
R_τ	21.00±0.11		
R_ℓ		20.851±0.059	$20.75^{+0.03}_{-0.04}$
$A_{FB}^{pole}(e^+e^-)$	0.0081±0.0051		
$A_{FB}^{pole}(\mu^+\mu^-)$	0.0137±0.0027		
$A_{FB}^{pole}(\tau^+\tau^-)$	0.0183±0.0035		
A_{FB}^{pole}		0.0142±0.0020	$0.014^{+0.006}_{-0.004}$
M_Z [GeV]	91.1852±0.0036	91.1846±0.0035	input
Γ_Z [GeV]	2.4960±0.0052±0.001	2.4959±0.0052±0.001	$2.489^{+0.027}_{-0.020}$
σ_{had}^{pole} [nb]	41.47±0.10	41.47±0.10	$41.46^{+0.07}_{-0.04}$
$\chi^2/d.o.f.$	10.0/6	14.5/10	

LEP Energy Calibration

- Due to emission of synchrotron radiation, transverse polarization builds up over time
- Beam energies can be measured using resonant depolarization
- The model of LEP energy includes hysteresis effects, magnet temperatures, tides, horizontal orbit position, etc.
- The accuracy of the energy measurement is $O(1\ \mathrm{MeV})$

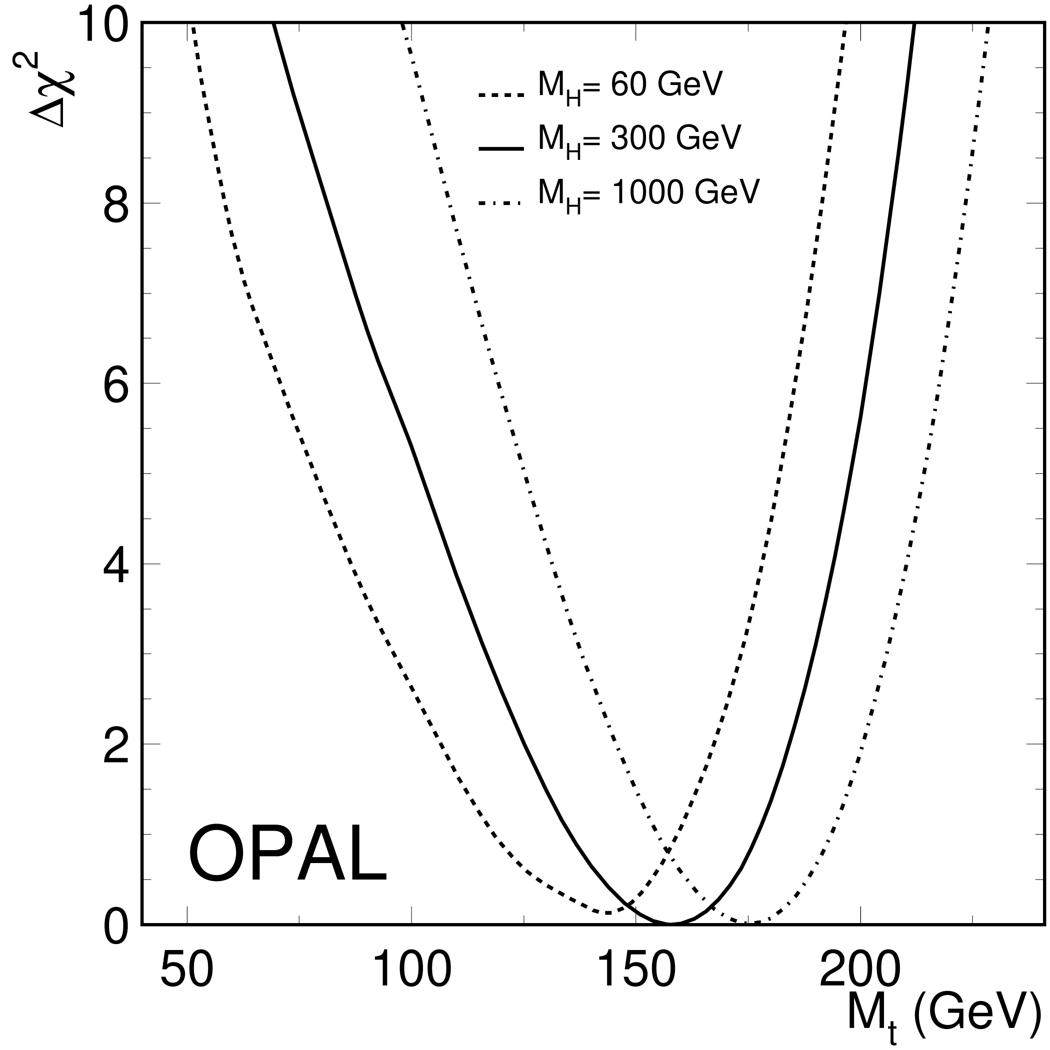
Standard Model Results

- $\Gamma_{inv}/\Gamma_{\ell^+\ell^-}$:
  - results: 5.944 ± 0.047
  - prediction: 5.977 ± 0.010
- N_ν:
  - results: $2.984 \pm 0.024(\mathrm{exp}) \pm 0.005(\mathrm{M_t}, \mathrm{M_H})$
  - prediction: 3

$\Rightarrow$ The Standard Model is still intact!

Top Mass

The results can even be used to constrain the top quark mass:



The Future

- Starting in 1995, LEP will be running in *bunch train* mode (4 trains containing ~ 4 bunchlets). This requires hardware modification to SiW so that it will trigger itself for the appropriate bunchlet.
- 1995 will be the last lineshape scan at LEP I.
- LEP II (W pairs) begins in 1996!