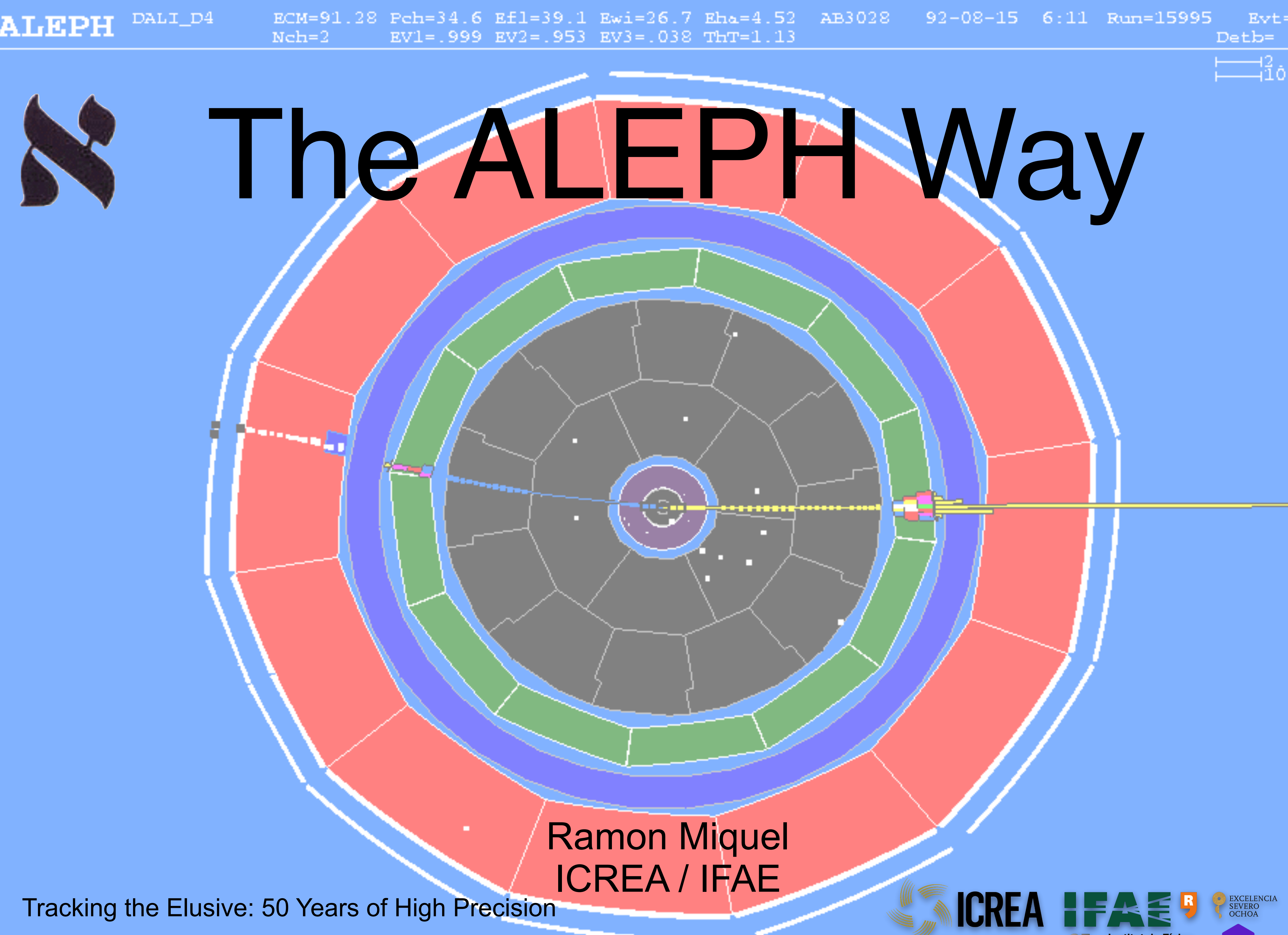


א The ALEPH Way

Ramon Miquel
ICREA / IFAE

Tracking the Elusive: 50 Years of High Precision Measurements with Luigi Rolandi, Pisa, Nov 7th 2025

ICREA IFAE Institut de Física d'Altes Energies EXCELENCIA SEVERO OCHOA BIST

The beginning (1986)

February 1986

The beginning (1986)

February 1986

The beginning (1986)

February 1986

The beginning (1986)

XIV International Winter Meeting on Fundamental Physics, St. Feliu de Guíxols, March 17-22, 1986

The beginning (1986)

XIV International Winter Meeting on Fundamental Physics, St. Feliu de Guíxols, March 17-22, 1986

The beginning (1986)

XIV International Winter Meeting on Fundamental Physics, St. Feliu de Guíxols, March 17-22, 1986

The beginning (1986)

XIV International Winter Meeting on Fundamental Physics, St. Feliu de Guíxols, March 17-22, 1986

The beginning (1986)

XIV International Winter Meeting on Fundamental Physics, St. Feliu de Guíxols, March 17-22, 1986

The beginning (1986)

XIV International Winter Meeting on Fundamental Physics, St. Feliu de Guíxols, March 17-22, 1986

The beginning (1986)

Luigi Rolandi
Dipartimento di Fisica and Sezione I.N.F.N.
Trieste, Italy

Talk given at the XIV International Winter Meeting on Fundamental Physics,
Sant Feliu de Giuxols, Catalonia, Spain
March 17-22 1986

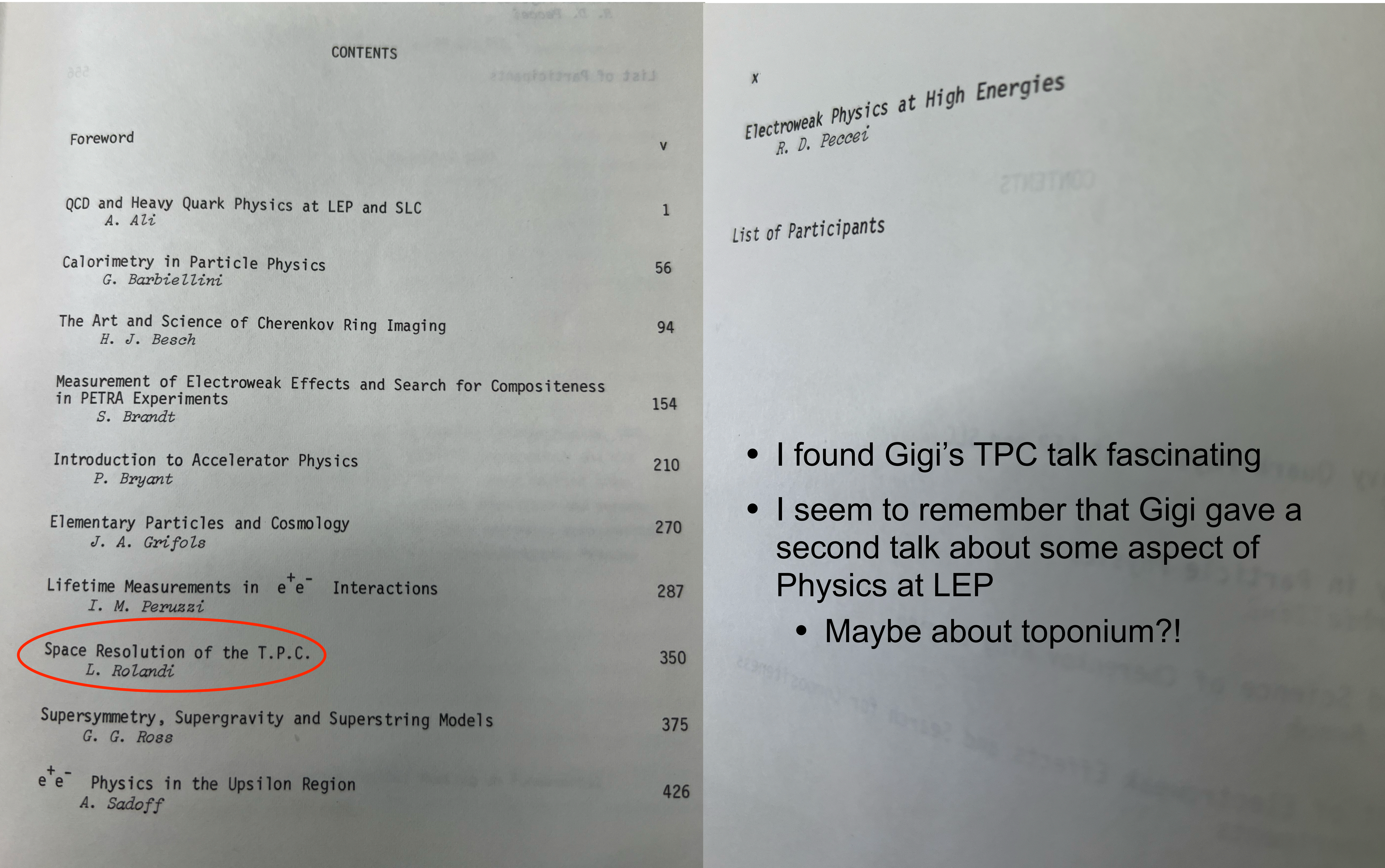
ABSTRACT

The principle of coordinate measurement of the Time Projection Chamber is discussed together with the various factors that influence the measuring accuracy in the sagitta direction. Some experimental results on the spatial resolution with different cathode geometry are presented and are compared with the theory.

The beginning (1986)

CONTENTS

The beginning (1986)

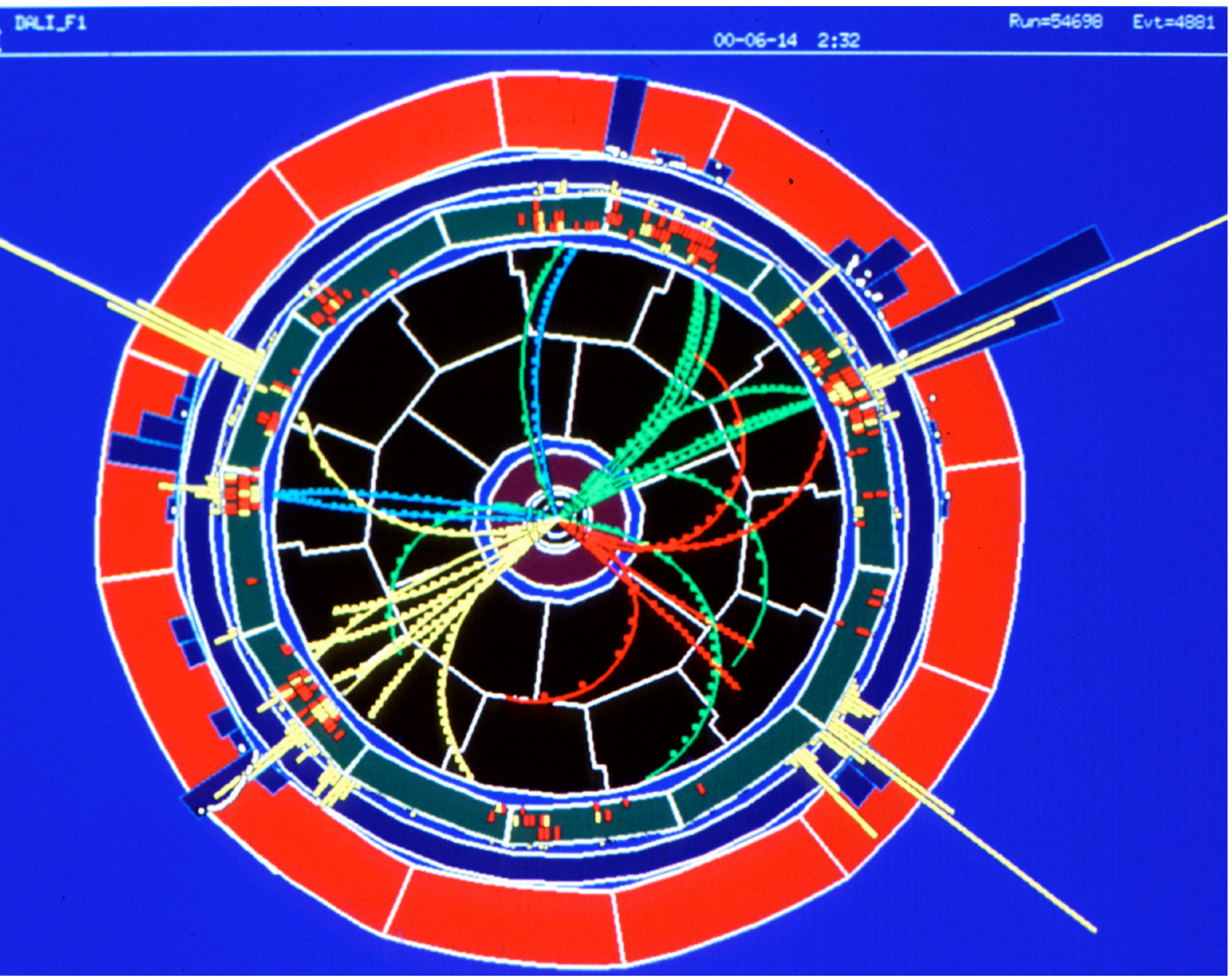


CONTENTS

- I found Gigi's TPC talk fascinating
- I seem to remember that Gigi gave a second talk about some aspect of Physics at LEP
  - Maybe about toponium?!

The Detector

Key insight: **granularity** and hermeticity are more important than energy resolution in detectors for e^+e^- collisions. Also, favor simplicity.



- Only gas detectors (no scintillators, Cherenkov, etc.). Eventually, silicon.
- End-caps like barrels, LCAL like ECAL, muon chambers like hadron calorimeter
- ECAL with 220k channels (3cm^2 pads).
- Tracking HCAL using digital readout.
- No aligned cracks anywhere.
- And, of course, TPC with 180 cm radius in 1.5 T field.

All this allowed energy flow algorithms and use of beam-energy constraints.

The First Paper

- In mid October 1989, just a few days (!) after the first LEP run finished, the four LEP experiments presented their first results:

Measurement of the Mass and Width of the Z^0-Particle from Multihadronic Final States Produced in e^+e^- Annihilations

DELPHI collaboration

A DETERMINATION OF THE PROPERTIES OF THE NEUTRAL INTERMEDIATE VECTOR BOSON Z^0

by

THE L3 COLLABORATION

Measurement of the Z^0 Mass and Width with the OPAL Detector at LEP

The OPAL Collaboration

The First Paper

- In mid October 1989, just a few days (!) after the first LEP run finished, the four LEP experiments presented their first results:

Determination of the Number of Light Neutrino Species

12 October 1989

The ALEPH Collaboration

Measurement of the Mass and Width of the Z^0-Particle from Multihadronic Final States Produced in e^+e^- Annihilations

DELPHI collaboration

A DETERMINATION OF THE PROPERTIES OF THE NEUTRAL INTERMEDIATE VECTOR BOSON Z°

by

THE L3 COLLABORATION

Measurement of the Z^0 Mass and Width with the OPAL Detector at LEP

The OPAL Collaboration

The First Paper

- In mid October 1989, just a few days (!) after the first LEP run finished, the four LEP experiments presented their first results:

Determination of the Number of Light Neutrino Species

12 October 1989

The ALEPH Collaboration

Measurement of the Mass and Width of the Z^0-Particle from Multihadronic Final States Produced in e^+e^- Annihilations

$N_\nu = 2.40 \pm 0.64$

DELPHI collaboration

A DETERMINATION OF THE PROPERTIES OF THE NEUTRAL INTERMEDIATE VECTOR BOSON Z°

$N_\nu = 3.42 \pm 0.48$

by

THE L3 COLLABORATION

Measurement of the Z^0 Mass and Width with the OPAL Detector at LEP

$N_\nu = 3.12 \pm 0.42$

The OPAL Collaboration

The First Paper

- In mid October 1989, just a few days (!) after the first LEP run finished, the four LEP experiments presented their first results:

Determination of the Number of Light Neutrino Species

12 October 1989

The ALEPH Collaboration

$N_\nu = 3.27 \pm 0.30$

Measurement of the Mass and Width of the Z^0-Particle from Multihadronic Final States Produced in e^+e^- Annihilations

DELPHI collaboration

$N_\nu = 2.40 \pm 0.64$

A DETERMINATION OF THE PROPERTIES OF THE NEUTRAL INTERMEDIATE VECTOR BOSON Z°

by

THE L3 COLLABORATION

$N_\nu = 3.42 \pm 0.48$

Measurement of the Z^0 Mass and Width with the OPAL Detector at LEP

The OPAL Collaboration

$N_\nu = 3.12 \pm 0.42$

How Was That Possible?

- By 1987, it had become clear that the best way to determine N_ν was, perhaps surprisingly, to measure the cross section to hadrons at the Z peak:

$$\sigma^0_{\mathrm{had}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_{\mathrm{had}}}{\Gamma_Z^2} \quad \text{with} \quad \Gamma_Z = \Gamma_{\mathrm{had}} + 3\Gamma_e + N_\nu\Gamma_\nu$$

- From which:

$$N_\nu = \frac{\Gamma_e}{\Gamma_\nu}\left(\sqrt{\frac{12\pi R_e}{M_Z^2\sigma^0_{\mathrm{had}}}} - R_e - 3\right)$$

where $R_e = \Gamma_{\mathrm{had}}/\Gamma_e$ and Γ_e/Γ_ν were taken from the Standard Model. (Since they are ratios of widths, their sensitivity to the then unknown top and Higgs masses was rather small.)

- The key was to measure σ^0_{had} precisely, for which one needed to determine the luminosity precisely:

$$\sigma_i = \frac{N_i - N^i_{bk}}{\epsilon_i L} \quad \text{and} \quad L = \frac{N_{bh} - N^{bh}_{bk}}{\epsilon_{bh}\sigma^{th}_{bh}}$$

for which Bhabha scattering ($e^+e^- \to e^+e^-$) at low angles was used.

How Was That Possible?

- By 1987, it had become clear that the best way to determine N_ν was, perhaps surprisingly, to measure the cross section to hadrons at the Z peak: $$\sigma^0_{\rm had} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_{\rm had}}{\Gamma_Z^2} \quad \text{with} \quad \Gamma_Z = \Gamma_{\rm had} + 3\Gamma_e + N_\nu\Gamma_\nu$$

- From which: $$N_\nu = \frac{\Gamma_e}{\Gamma_\nu}\left(\sqrt{\frac{12\pi R_e}{M_Z^2\sigma^0_{\rm had}}} - R_e - 3\right)$$

  where $R_e = \Gamma_{\rm had}/\Gamma_e$ and Γ_e/Γ_ν were taken from the Standard Model. (Since they are ratios of widths, their sensitivity to the then unknown top and Higgs masses was rather small.)

- The key was to measure $\sigma^0_{\rm had}$ precisely, for which one needed to determine the luminosity precisely:

  $$\sigma_i = \frac{N_i - N^i_{bk}}{\epsilon_i L} \quad \text{and} \quad L = \frac{N_{bh} - N^{bh}_{bk}}{\epsilon_{bh}\sigma^{th}_{bh}}$$

  for which Bhabha scattering ($e^+e^- \to e^+e^-$) at low angles was used.

How Was That Possible?

- The Bhabha cross-section has a strong dependence on the inner acceptance of the detector

$$\sigma_{bh}^{th} \sim \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right)$$

  so that $\Delta\sigma/\sigma \simeq 2\Delta\theta_{min}/\theta_{min} \simeq 2\Delta R_{min}/R_{min}$: It becomes mandatory to know the inner acceptance very precisely.

- The Copenhagen group (Dines Hansen et el.) built the ALEPH luminosity calorimeter (LCAL), and also came up with a very ingenious way to define the inner acceptance and, overall, determine the luminosity very precisely.

Luminosity Measurement

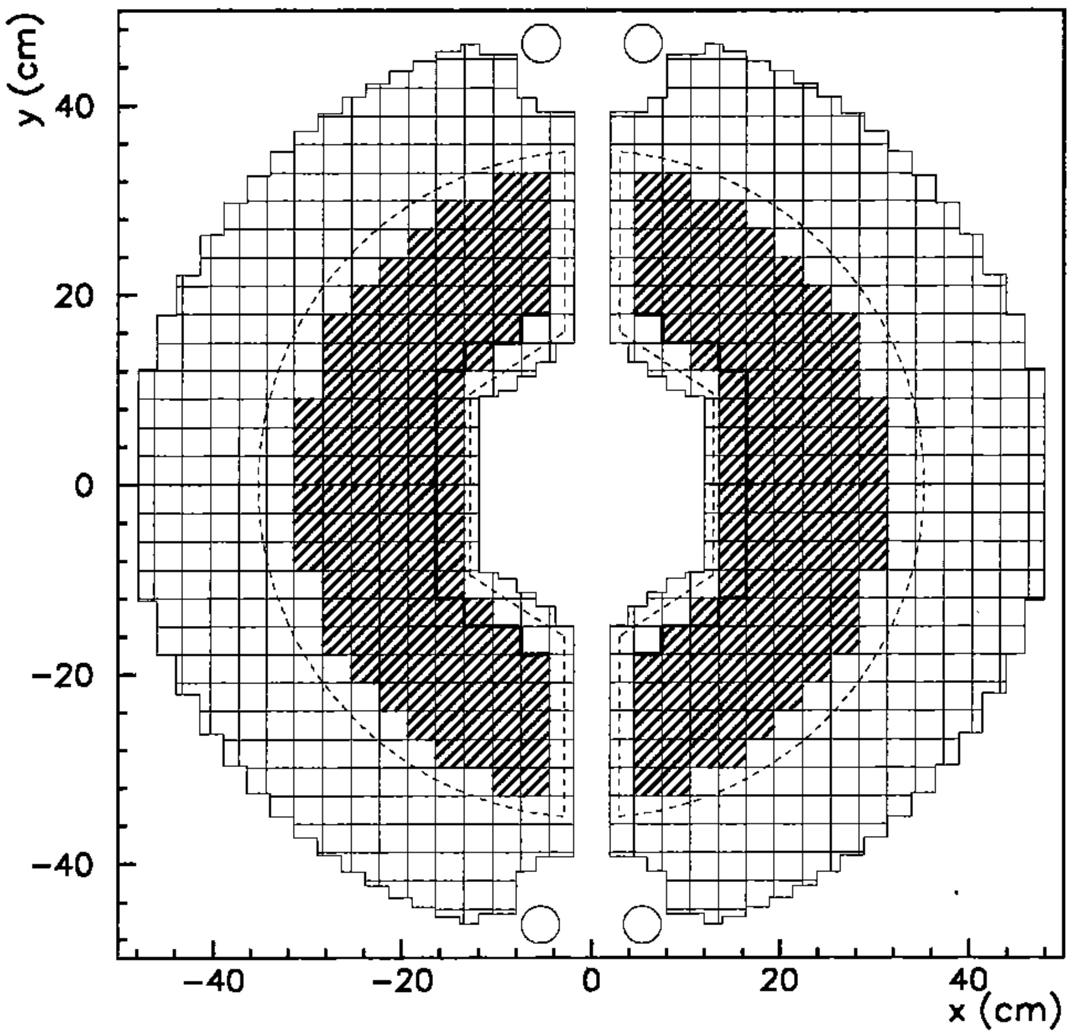


Figure 2: The active area of an LCAL module showing the fiducial (hatched) and non-fiducial (dashed outline) regions. The squares represent the PCB pads; they are shown at $z = 280$ cm, the average position of maximum energy deposition. The bold line shows the inner boundary of a more restrictive fiducial area which is used for systematic studies. The support dowels are also shown.

D. Decamp et al., Z. Phys. C 53 (1992) 375

1. A fiducial side was defined with a tighter boundary than the non-fiducial side.
2. Difference has to be at least twice the expected transverse beam displacement.
3. Shower position in fiducial side was not defined as centroid but using difference in energy deposition across pads.
4. Role of fiducial and non-fiducial side was alternated with each beam crossing.

- With this, the effective acceptance was insensitive, in first order, to transverse and longitudinal beam displacements.
- The luminosity was measured with 2% uncertainty in Oct 1989 (vs. 5% for the other LEP experiments), 0.6% in 1990 and 0.3% (0.09% experimental!) in 1992, with the new luminometer SiCAL, resulting in $N_\nu = 2.983 \pm 0.034$.

Electroweak Results (Oct 1989)

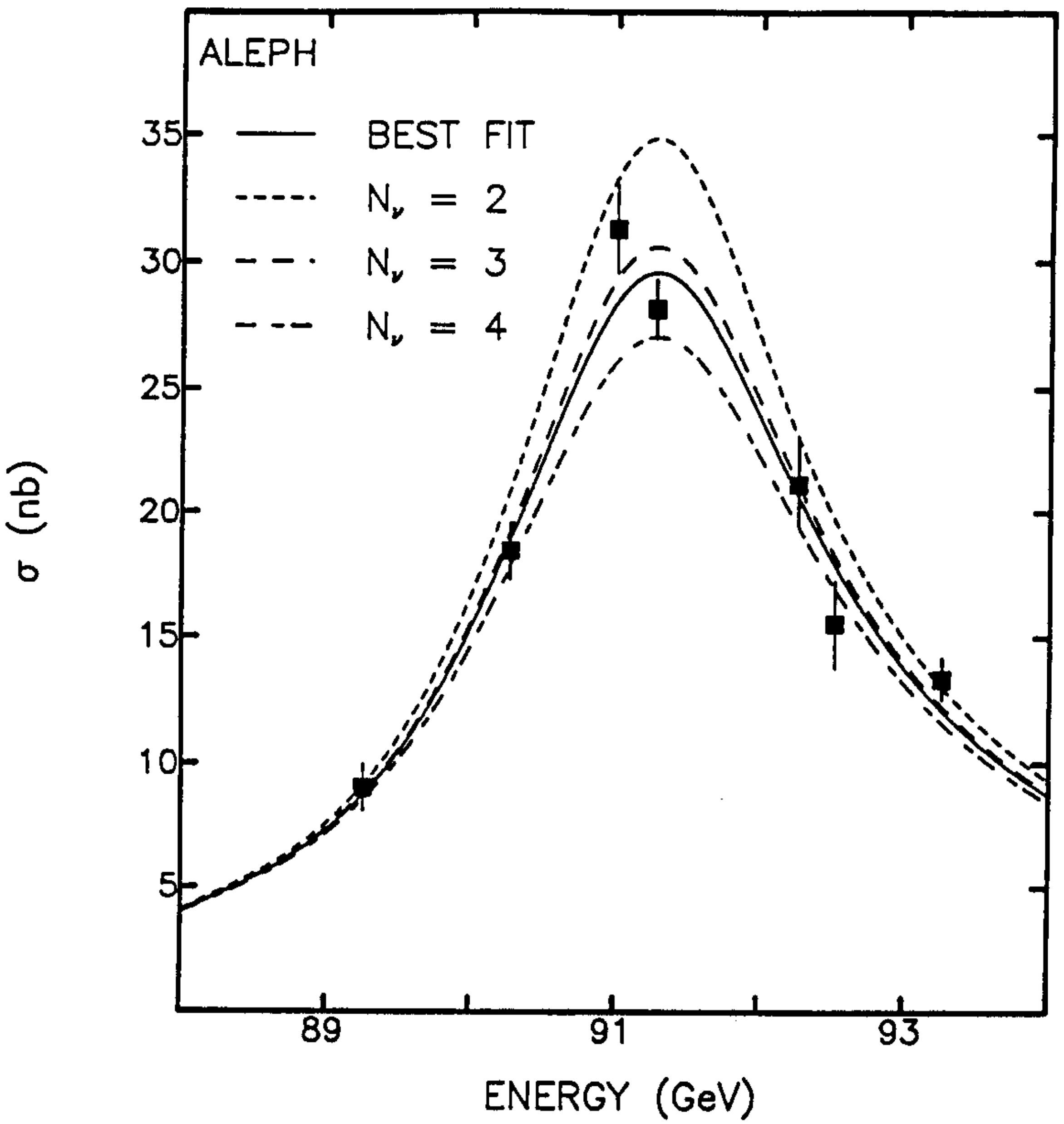


Figure 5: The cross-section for $e^+e^- \rightarrow$ hadrons as a function of centre-of-mass energy and result of the three parameter fit.

	TPC selection Hadronic events	Calo. selection Hadronic $+\tau$ events	Combined
M_Z (GeV)	91.178±0.055	91.170 ± 0.054	91.174 ± 0.054
Γ_Z (GeV)	2.66 ± 0.16	2.70 ± 0.15	2.68 ± 0.15
σ^0(nb)	39.1 ± 1.6	40.9 ± 1.7	–
σ^{peak}(nb)	29.3 ± 1.2	30.5 ± 1.3	–

$N_\nu = 3.27 \pm 0.24_{stat} \pm 0.16_{sys} \pm 0.05_{th}$

D. Decamp et al., Phys. Lett. B 231 (1989) 519

Electroweak Results (Dec 1989)

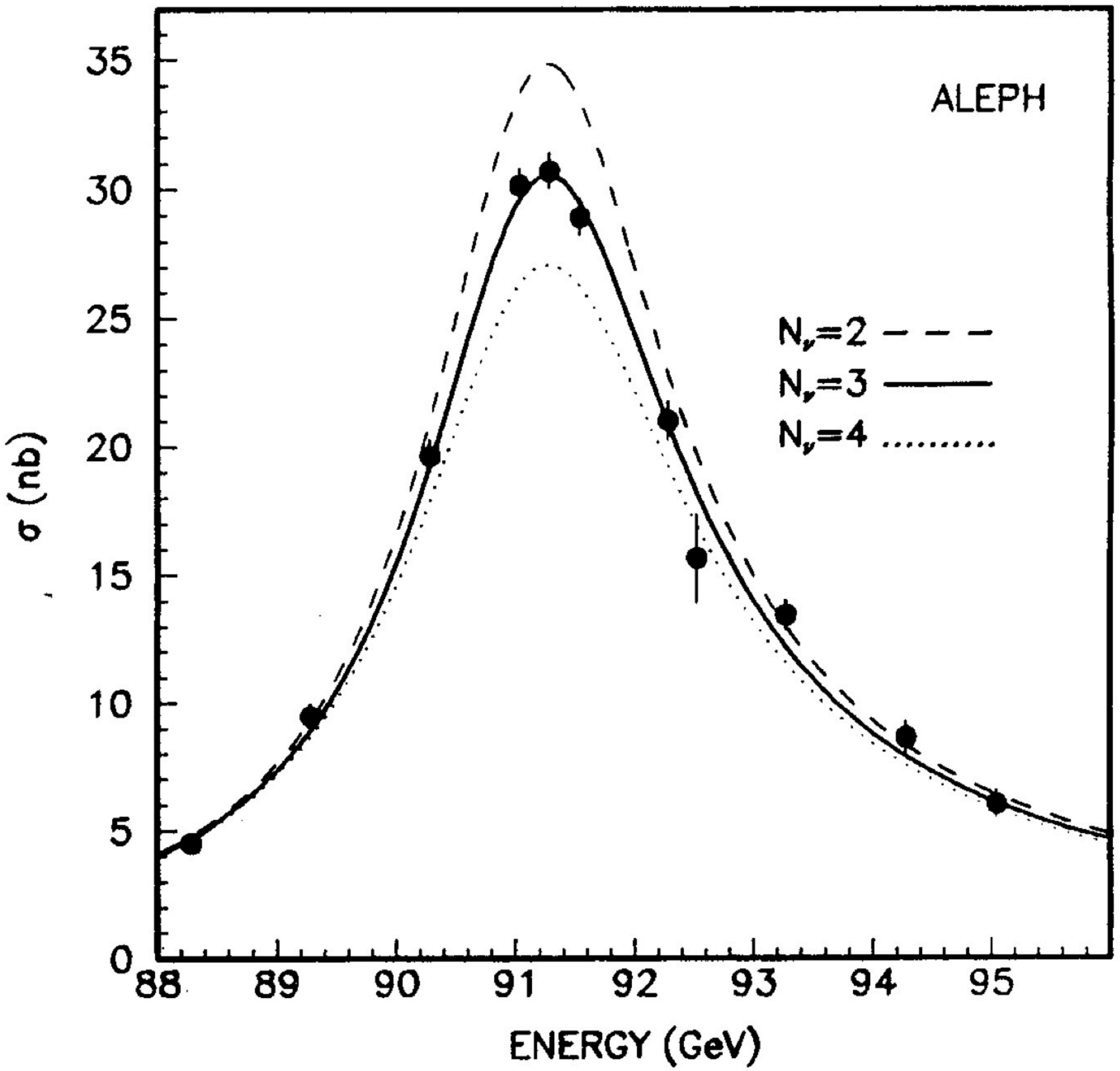


Fig. 4

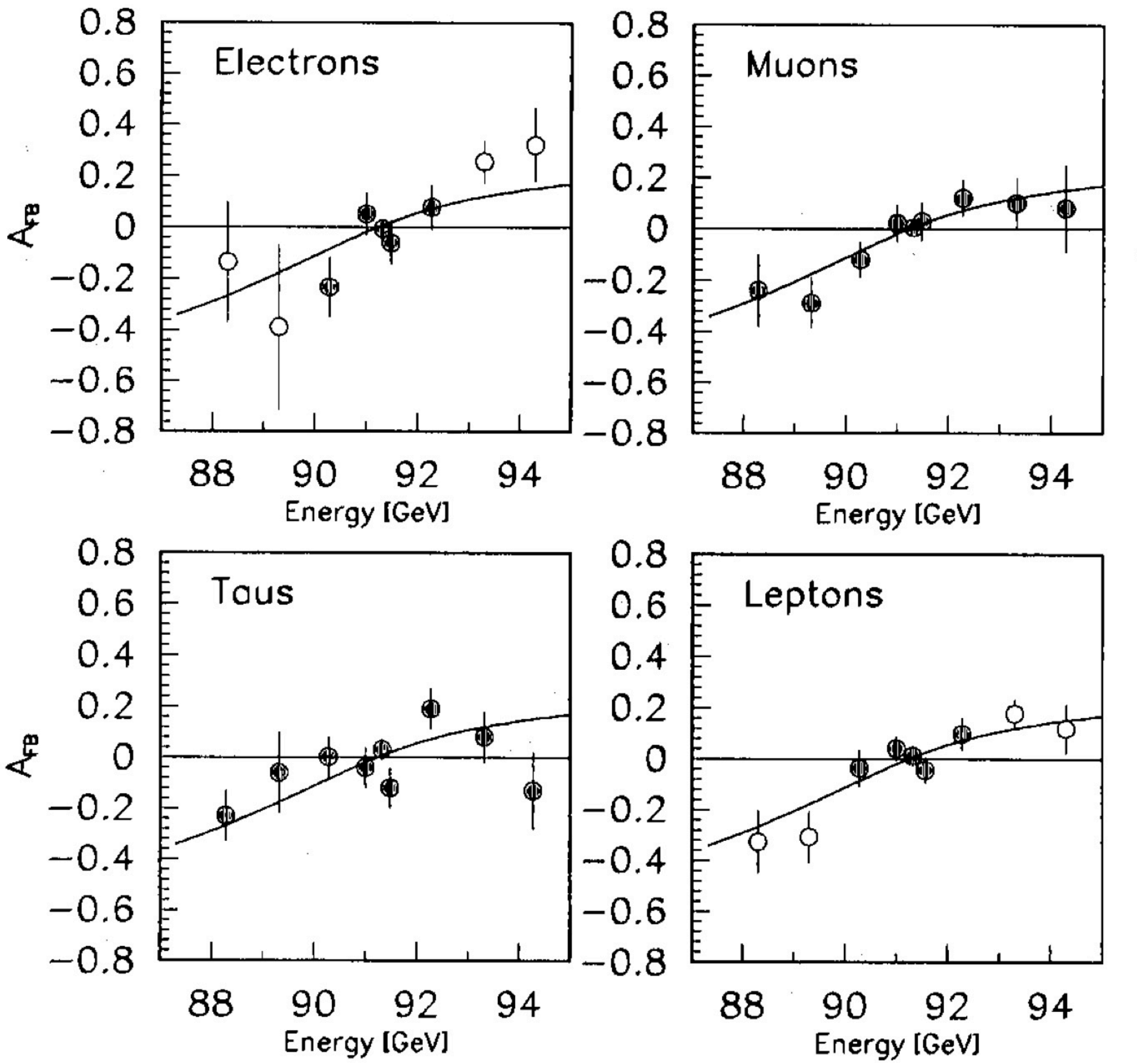
$N_{\nu} = 3.01 \pm 0.15_{exp} \pm 0.05_{th}$

(with luminosity measured with 1.3% precision)

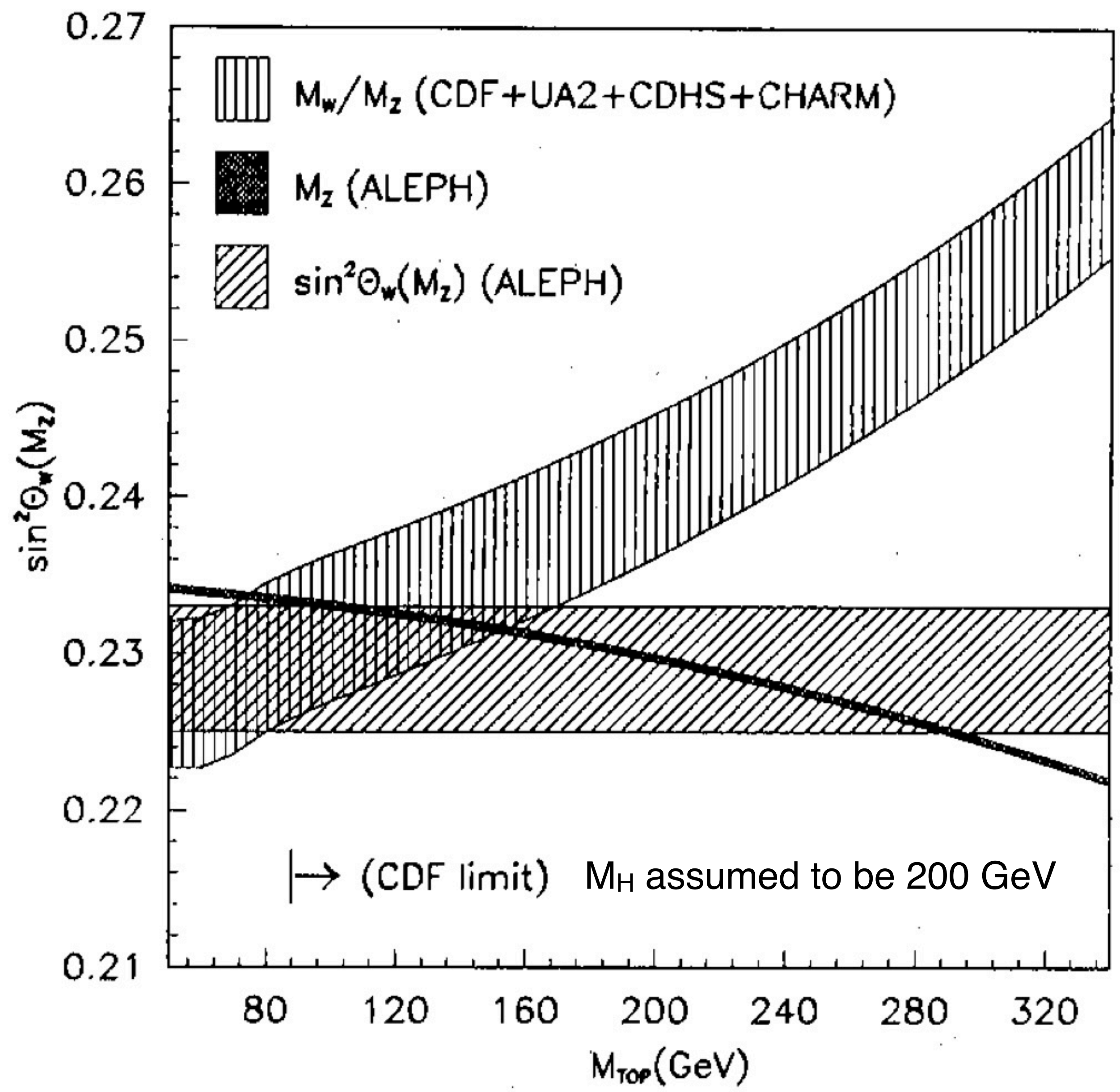
D. Decamp et al., Phys. Lett. B 235 (1990) 399

Electroweak Results (Jul 1990)

Lepton forward-backward asymmetries



First attempt to determine the top mass



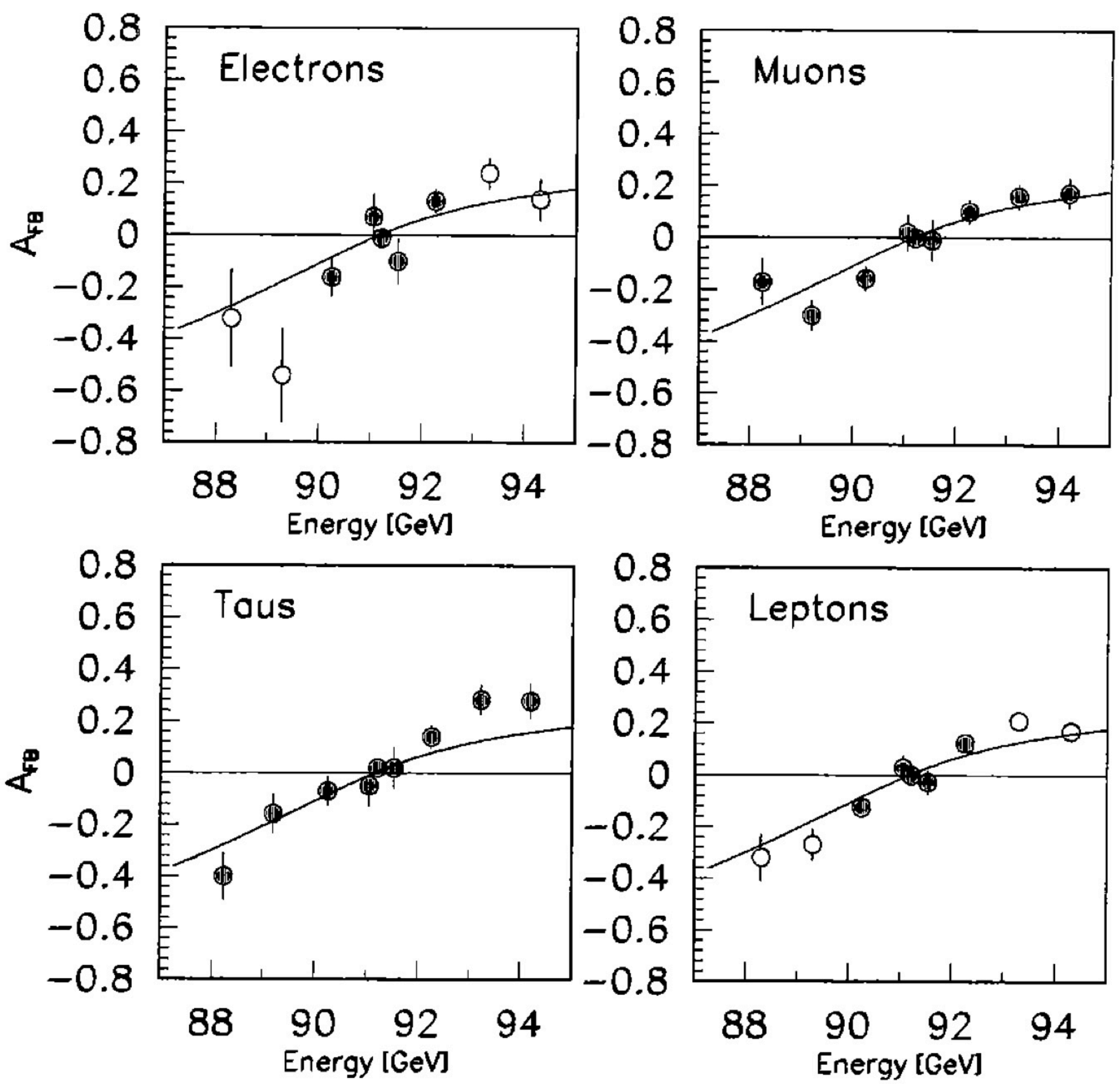
$M_{top} = (120 \pm 40 \pm 20_{Higgs})$ GeV

The external measurements of M_W drive the top mass to lower values.

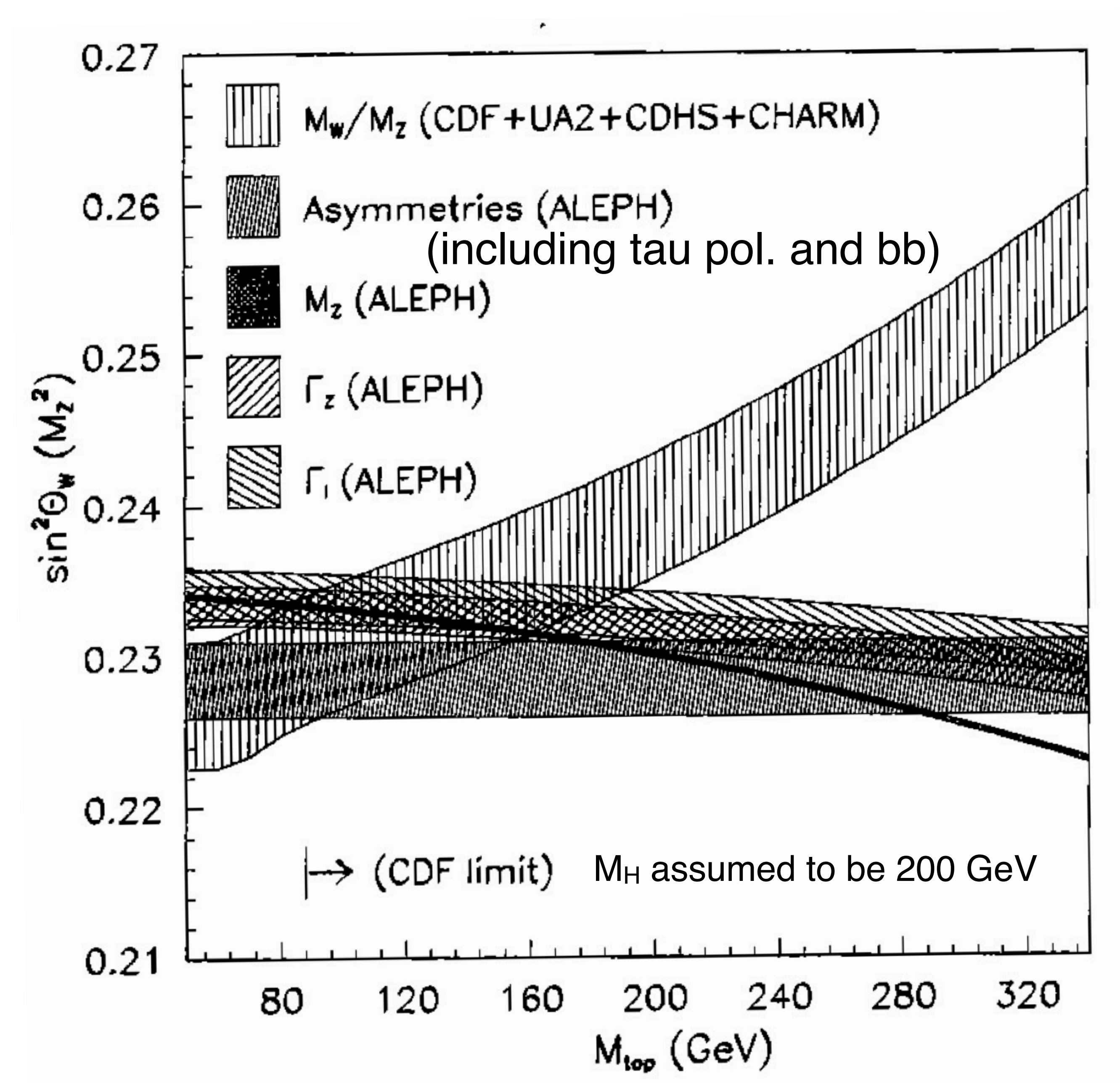
D. Decamp et al., Z. Phys. C 48 (1990) 365

Electroweak Results (Jul 1991)

Lepton forward-backward asymmetries



Stand-alone determination of the top mass



$M_{top} = (170\ ^{+42}_{-55}\ ^{+21}_{-14\,Higgs})$ GeV

First ALEPH-only measurement

D. Decamp et al., Z. Phys. C 53 (1992) 1

Electroweak Results (Feb 1994)

Extremely precise luminosity with SiCAL

Background estimation:	
– Off-momentum beam particles	0.018%
– Physics sources	0.010%
Trigger efficiency	0.010%
Radial fiducial cuts:	
– mechanical precision and z position	0.068%
– beam-module relative tilt and alignments	0.035%
– energy sharing cuts	0.044%
– shower parametrization and simulation	0.023%
Energy cuts	0.015%
Acoplanarity cut	0.005%
Simulation statistics	0.120%
TOTAL experimental uncertainty	0.153%

} 0.095%

Table 1: Summary of SiCAL luminosity systematic errors.

Stand-alone determination of the top mass

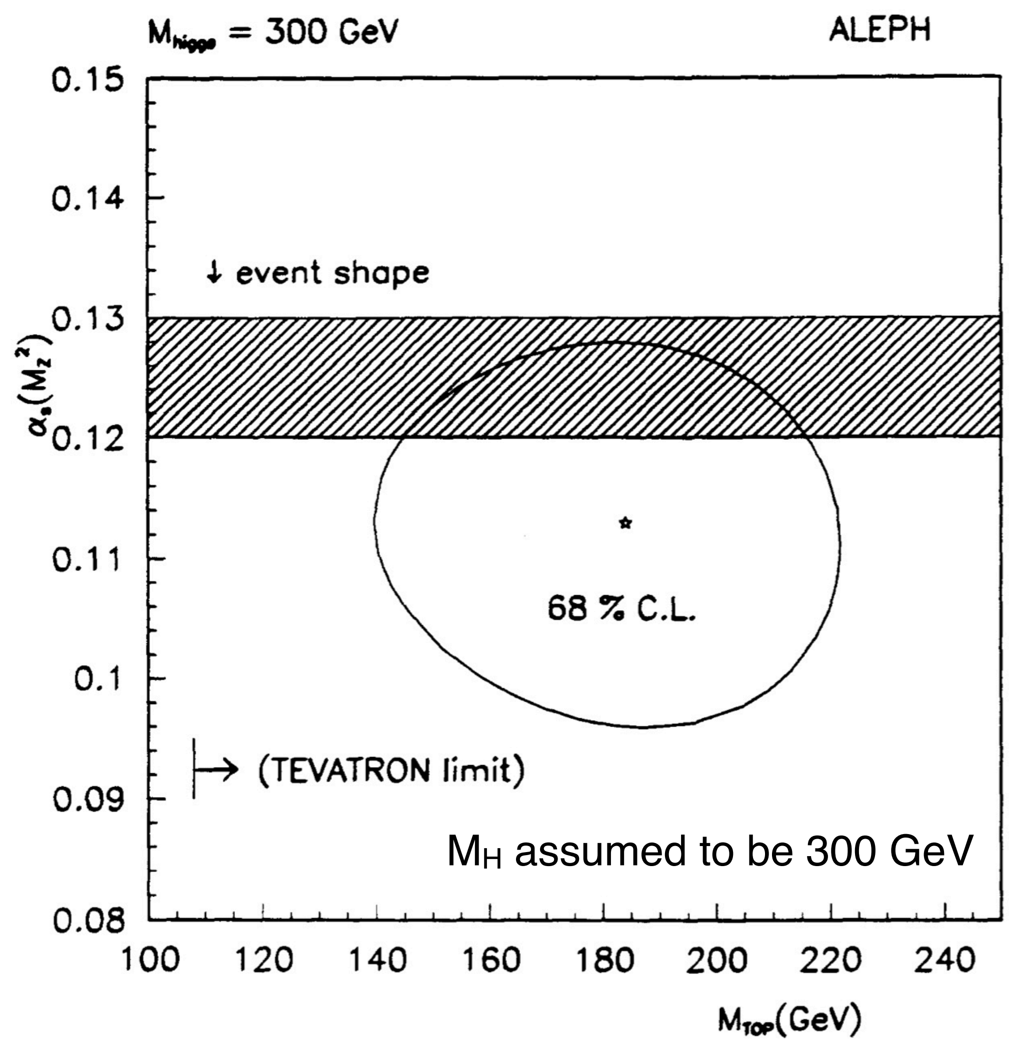


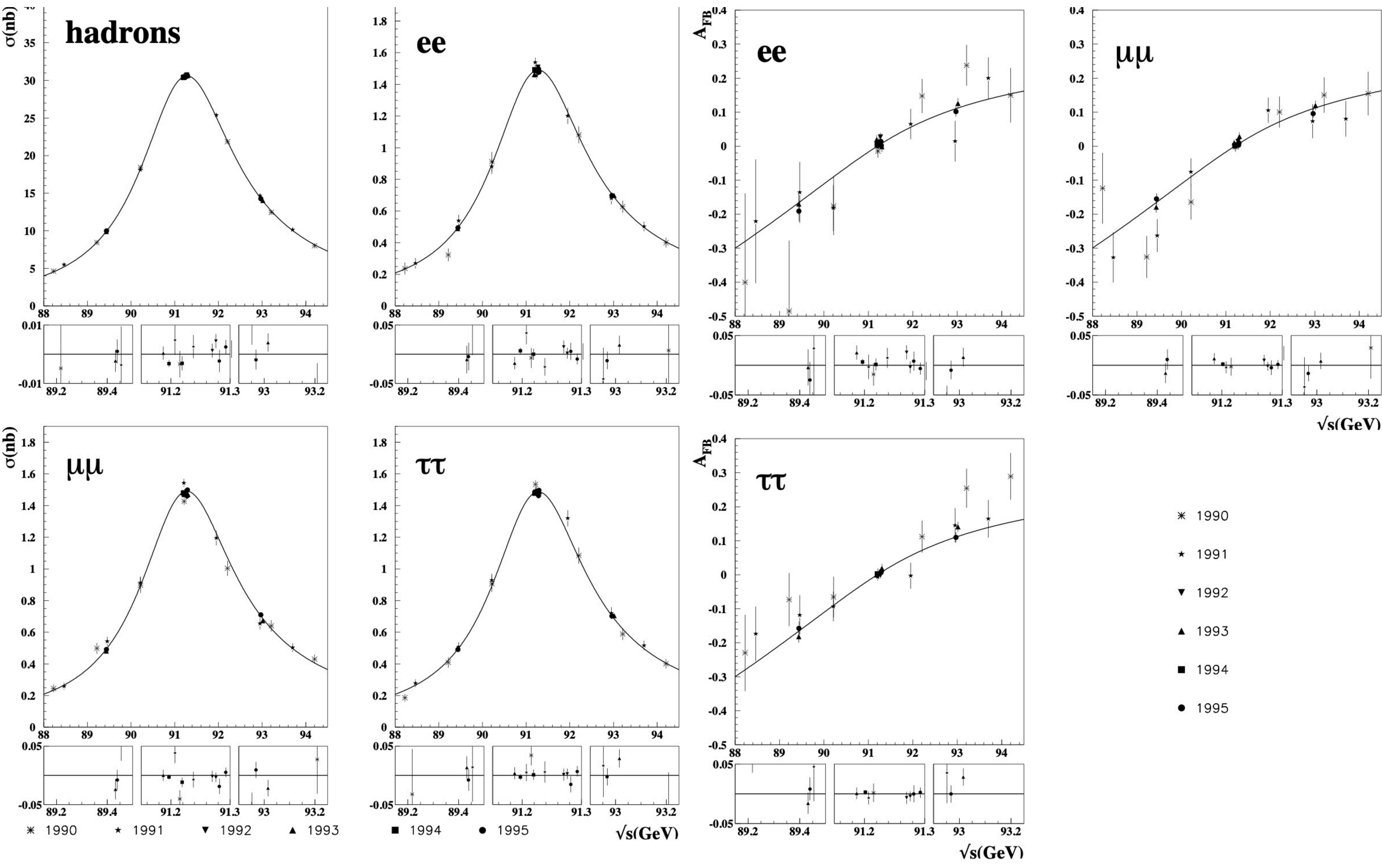
Figure 5: Contours of constant probability for the fit to the top quark mass, m_t, and the strong coupling constant, α_s. The results of the event shape analysis [21] for α_s are shown by the hashed band. The Tevatron limit refers to the result of [23].

$M_{top} = (184\ ^{+25}_{-29}\ ^{+17}_{-18\,Higgs})$ GeV

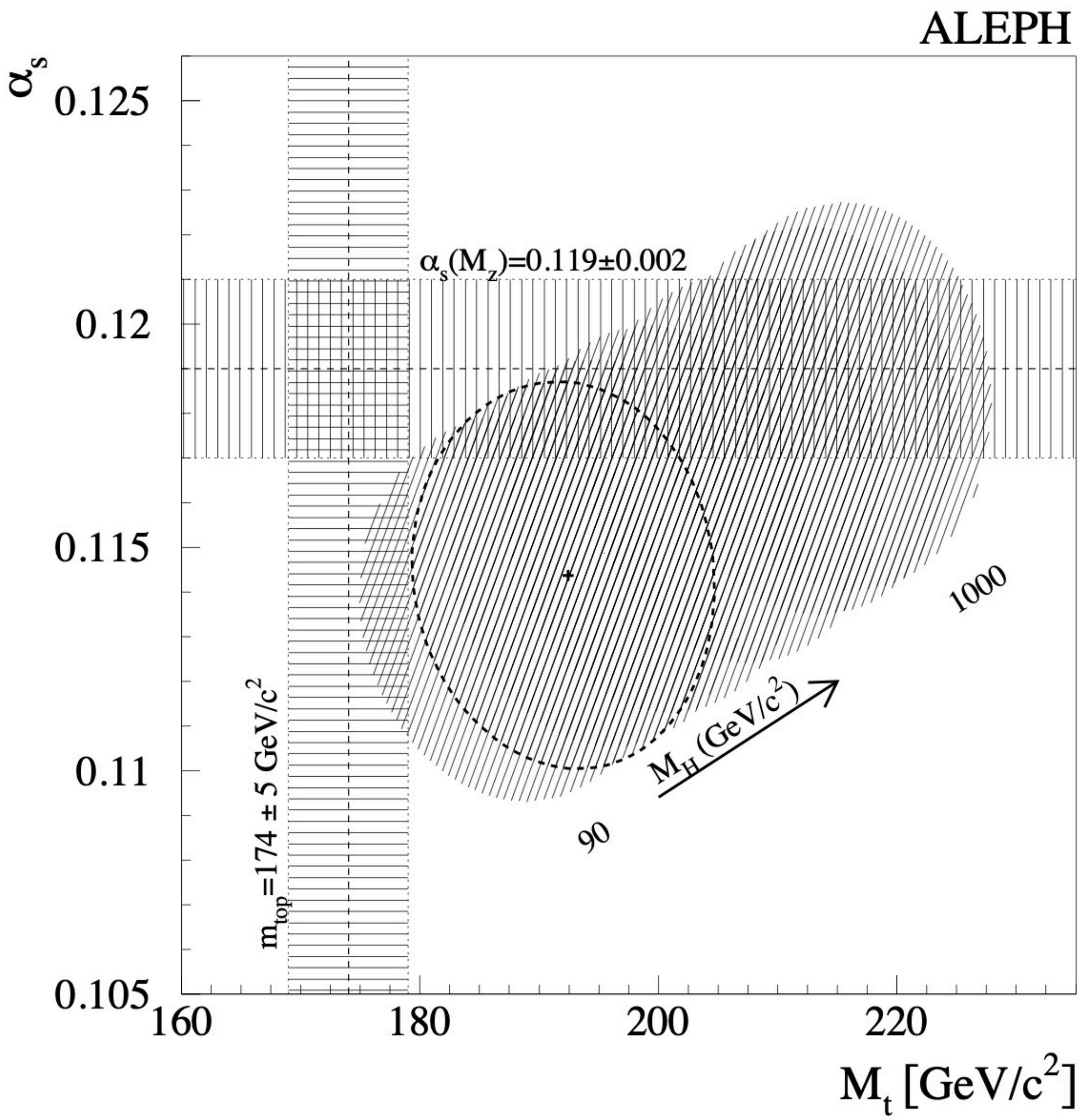
Last ALEPH result before CDF "evidence" paper in Apr 1994: $M_{top} = (174 \pm 10\ ^{+13}_{-12})$ GeV

D. Buskulic et al., Z. Phys. C 62 (1994) 539

Electroweak Results (Jul 1999)



Electroweak Results (Jul 1999)



- The **final ALEPH LEP1 electroweak fit result** for the top mass was

$$M_t(\text{GeV}/c^2) \;=\; 192^{+12}_{-13} + 23\,\log_{10}\left[\frac{M_H}{150\,\text{GeV}/c^2}\right]$$

in slight tension with the direct measurement by CDF and D0.

- Combining the ALEPH electroweak measurements with the external constraints on M_t and α_s, ALEPH obtained

$$M_H = \left(52^{+140}_{-38}\right)\,\text{GeV}$$

not taking into account the direct lower limit, which at the time was ~95 GeV.

Figure 25: One-σ contour lines in the plane of the top quark mass versus the strong coupling constant, for $M_H = 150$ GeV/c^2. The horizontal and vertical bands represent the world averages of other measurements. The shaded area indicates variations of the Higgs boson mass between 90 GeV/c^2 and 1000 GeV/c^2.

R. Barate et al., Eur. Phys. J. C 14 (2000) 1

Electroweak Results (Sep 2005)

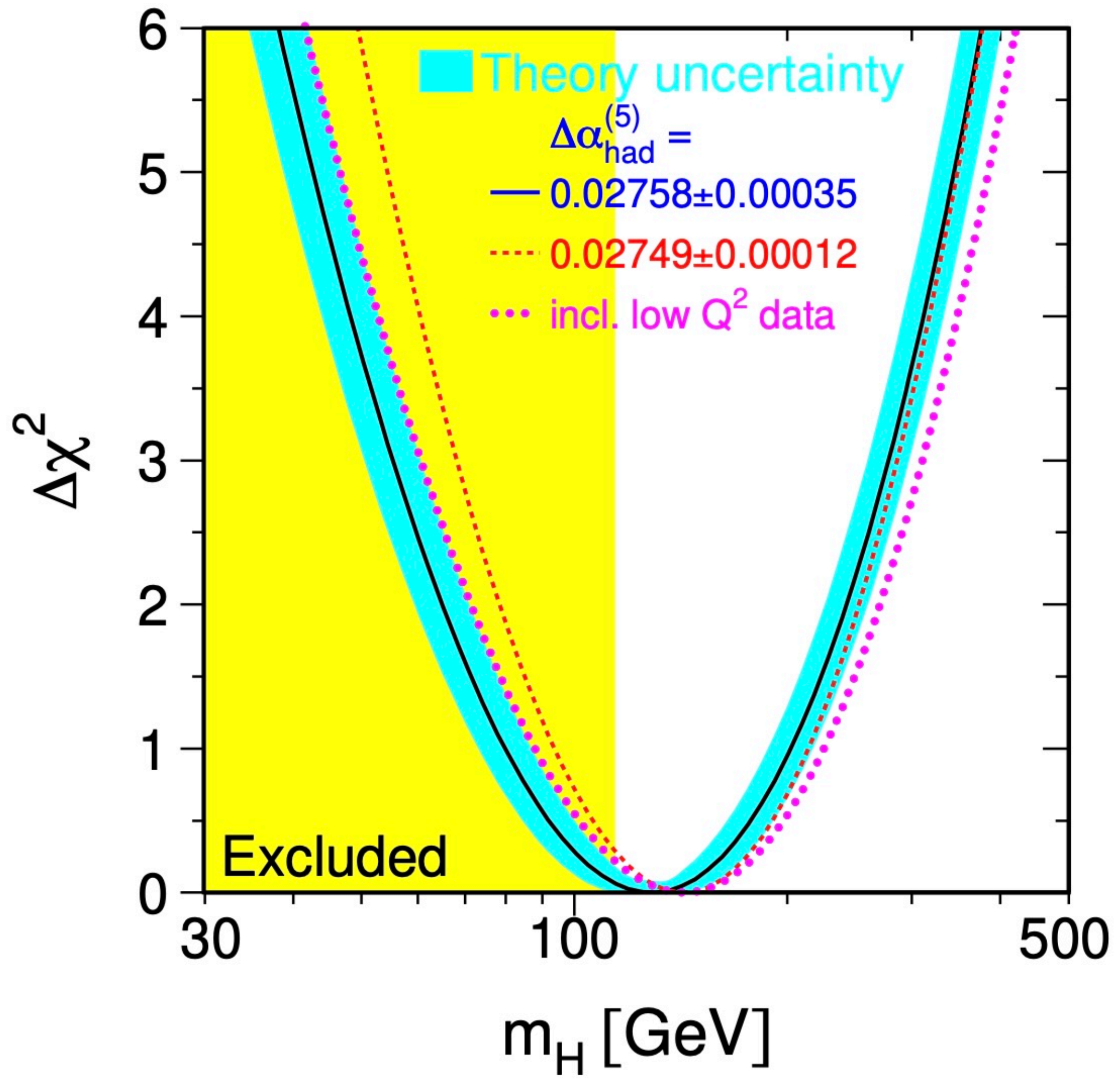


Figure 8.13: $\Delta\chi^2(m_H) = \chi^2_{min}(m_H) - \chi^2_{min}$ as a function of m_H. The line is the result of the fit using all 18 results. The associated band represents the estimate of the theoretical uncertainty due to missing higher-order corrections as discussed in Section . The vertical band shows the 95% confidence level exclusion limit on m_H of 114.4 GeV derived from the direct search at LEP-II [ ]. The dashed curve is the result obtained using the theory-driven $\Delta\alpha^{(5)}_{had}(m_Z^2)$ determination of Equation . The direct measurements of m_W and Γ_W used here are preliminary.

- The **final LEP1 + SLD electroweak fit result** for the Higgs mass was

$$M_H = \left(111^{+190}_{-60}\right)\,\text{GeV}$$

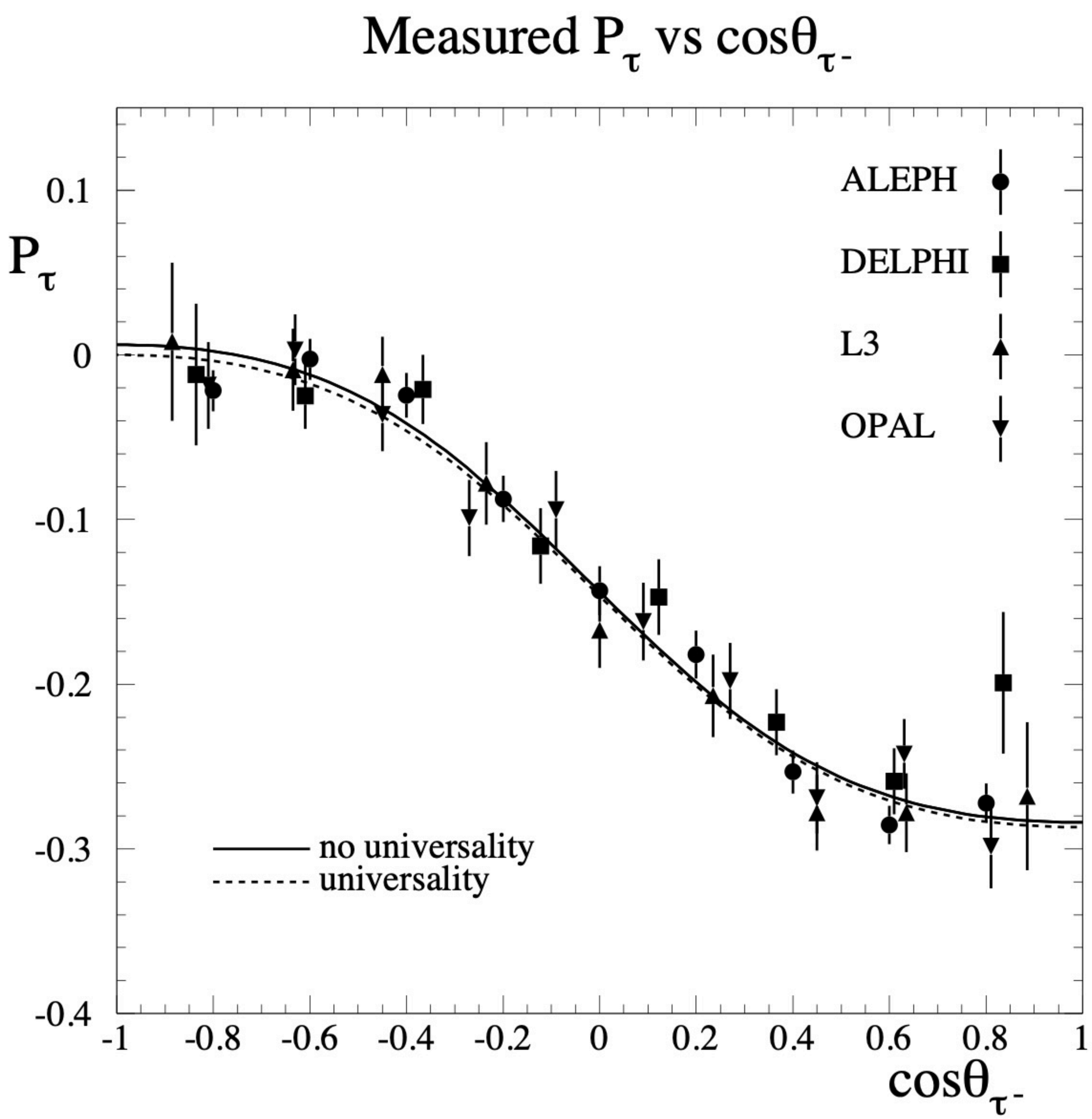
- Combining these data with external M_t, M_W, and Γ_W, resulted in

$$M_H = \left(129^{+74}_{-49}\right)\,\text{GeV}$$

A culmination of a long journey that started in 1980, when the first ideas about the ALEPH detector were discussed.

S. Schael et al., Phys. Rept. 427 (2006) 257

Electroweak Results (Sep 2005)



I can't resist showing one not-so-random example of the comparison between the final results of the four LEP experiments: **tau polarization**.

Figure 4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP experiments. Only the statistical errors are shown. The values are not corrected for radiation, interference or pure photon exchange. The solid curve overlays Equation [?] for the LEP values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation [?] under the assumption of lepton universality for the LEP value of $\mathcal{A}_\ell$.

Electroweak Results (Sep 2005)

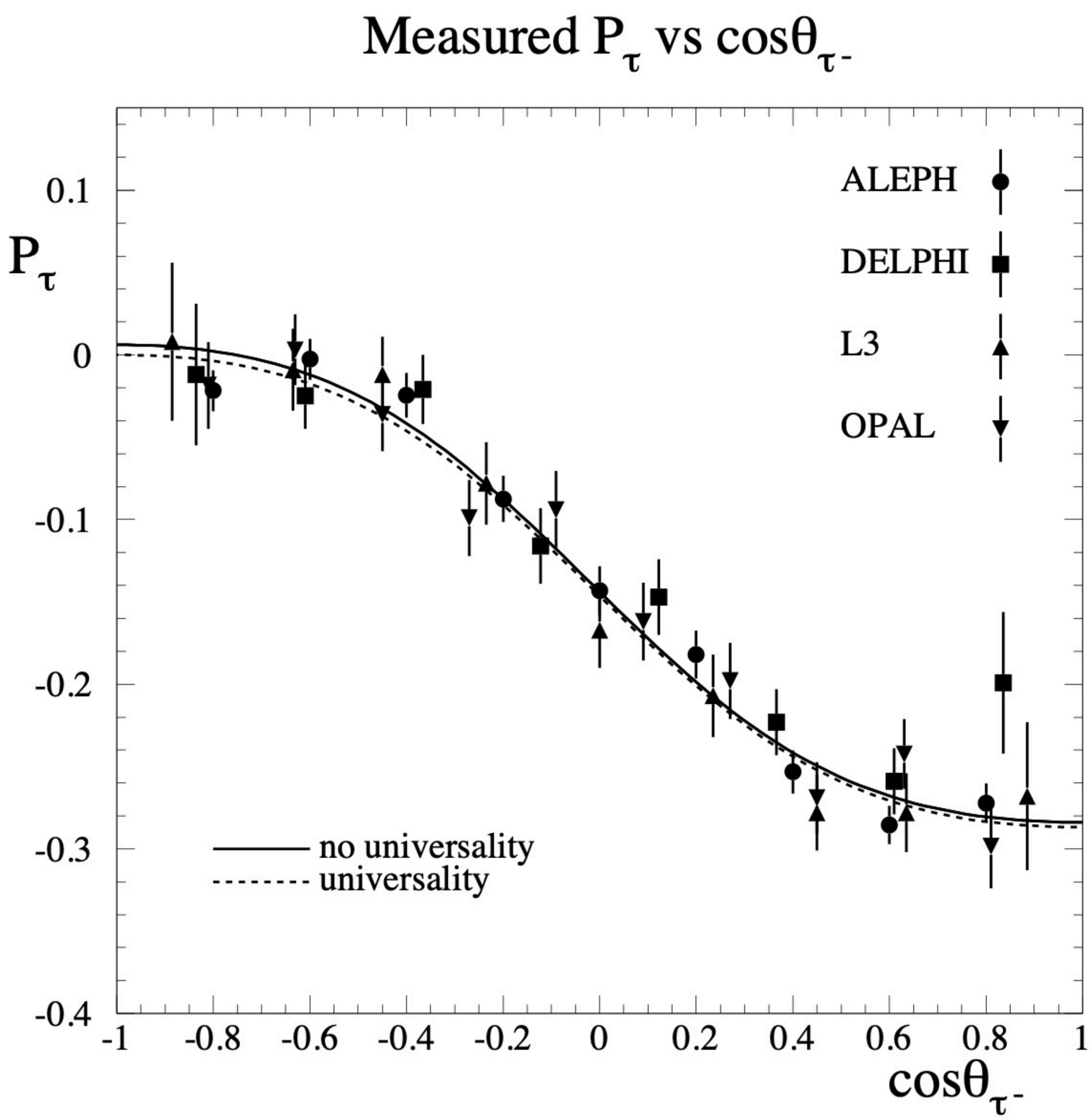


Figure 4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP experiments. Only the statistical errors are shown. The values are not corrected for radiation, interference or pure photon exchange. The solid curve overlays Equation [–] for the LEP values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation [–] under the assumption of lepton universality for the LEP value of $\mathcal{A}_\ell$.

I can't resist showing one not-so-random example of the comparison between the final results of the four LEP experiments: **tau polarization**.

There's just no comparison!

The ALEPH Way (I)

- I have never been in a collaboration with the level of scientific rigor that ALEPH had, and I have been in many (9!).
- This was probably due to a combination of the tone that was set by the most senior leaders (Jack Steinberger, Jacques Lefrançois, Lorenzo Foà), and the spirit of the younger leaders that played crucial roles in the collaboration (Alain Blondel, Gigi Rolandi, etc.)
- **Gigi was Physics Coordinator of ALEPH from 1989 to 1994…and then he became Spokesperson until 1997. So he held the scientific leadership of the collaboration during the whole of LEP1 and LEP1.5, and the first year of LEP2!**
- Those “Tuesday meetings”, which Gigi chaired, where results were approved before papers could be written, became the stuff of legend:
  - I have never seen the same level of scrutiny of results and subsequent papers.
  - On the other hand, young people were scared to present…

The ALEPH Way (II)

- There were many fights within ALEPH, some of them even vicious fights:
  - TPC vs Calorimeter hadronic selection in 1989
  - Energy flow algorithms (Orsay / Marseille / Annecy)
  - Tau physics (Orsay / Ecôle Polytechnique / Wisconsin / Gigi et al.)
  - Searches in general and, in particular Higgs searchers (Orsay / Wisconsin)
  - Several others…
- Was this a consequence of having so many alpha-type individuals within the collaboration? Could have this been handled better? Was it consubstantial with the ALEPH Way?
- Even with its obvious shortcomings, I would still not change ALEPH for any other collaboration I have ever been in.

The Spokespersons (2009)

The Spokespersons (2009)

Thank you!