Determination of the Number of Neutrino Species at LEP

(30 years after)

Monica Pepe Altarelli (CERN)

CERN, 28 November 2019

bulletin

WEEK MONDAY 21 AUGUST n° 34/89 SEMAINE DU LUNDI 21

Z^{0}s from the four LEP detectors

Announcement from the Director-General

I am pleased to announce to you that the LEP machine is operating at 45.5 GeV and that Z^0 particles have been observed.

This is a great achievement of which we can all be justly proud, especially the many of you who have made it all possible.

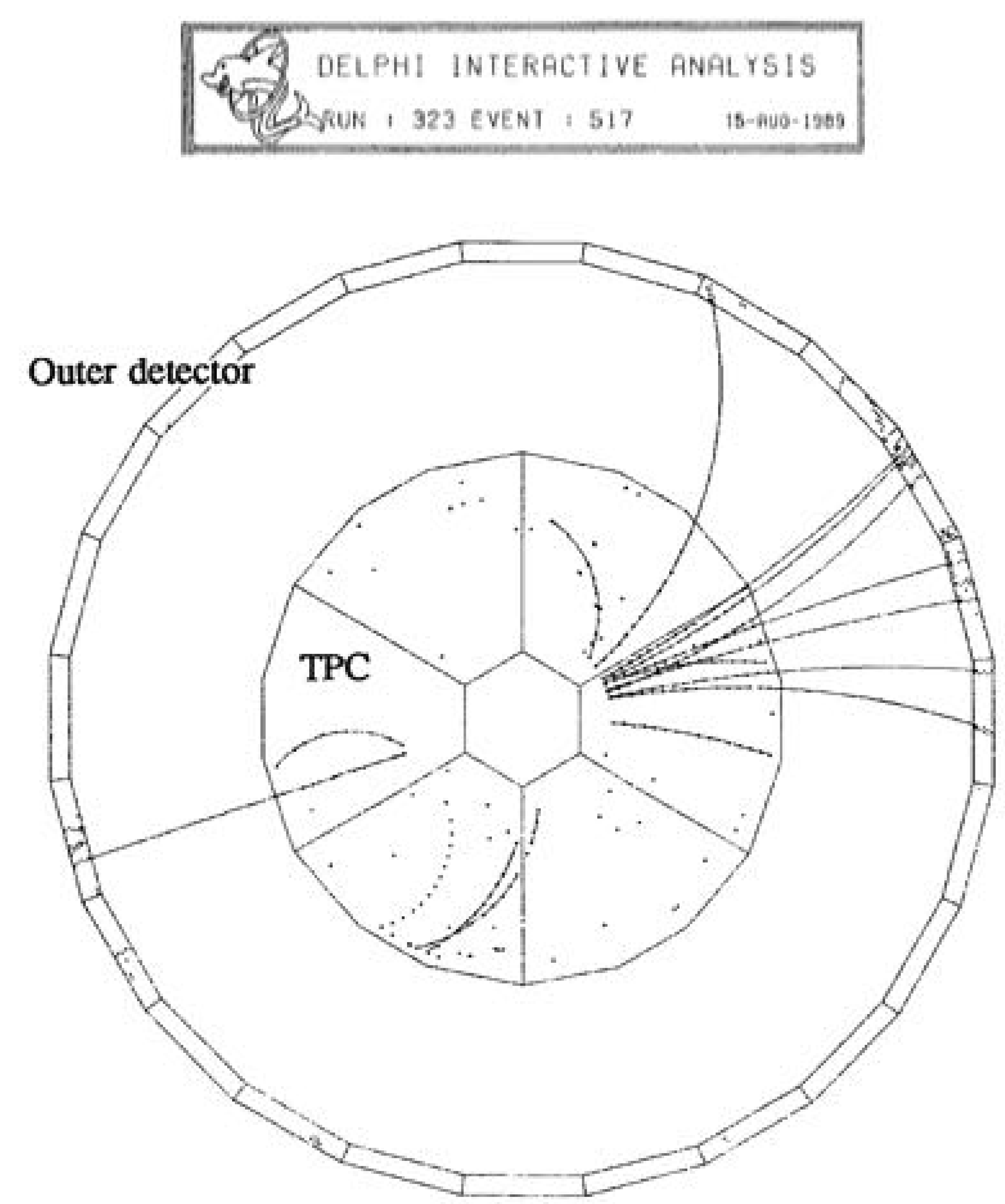
Carlo Rubbia
Director-General
14 August 1989

Communication du Directeur général

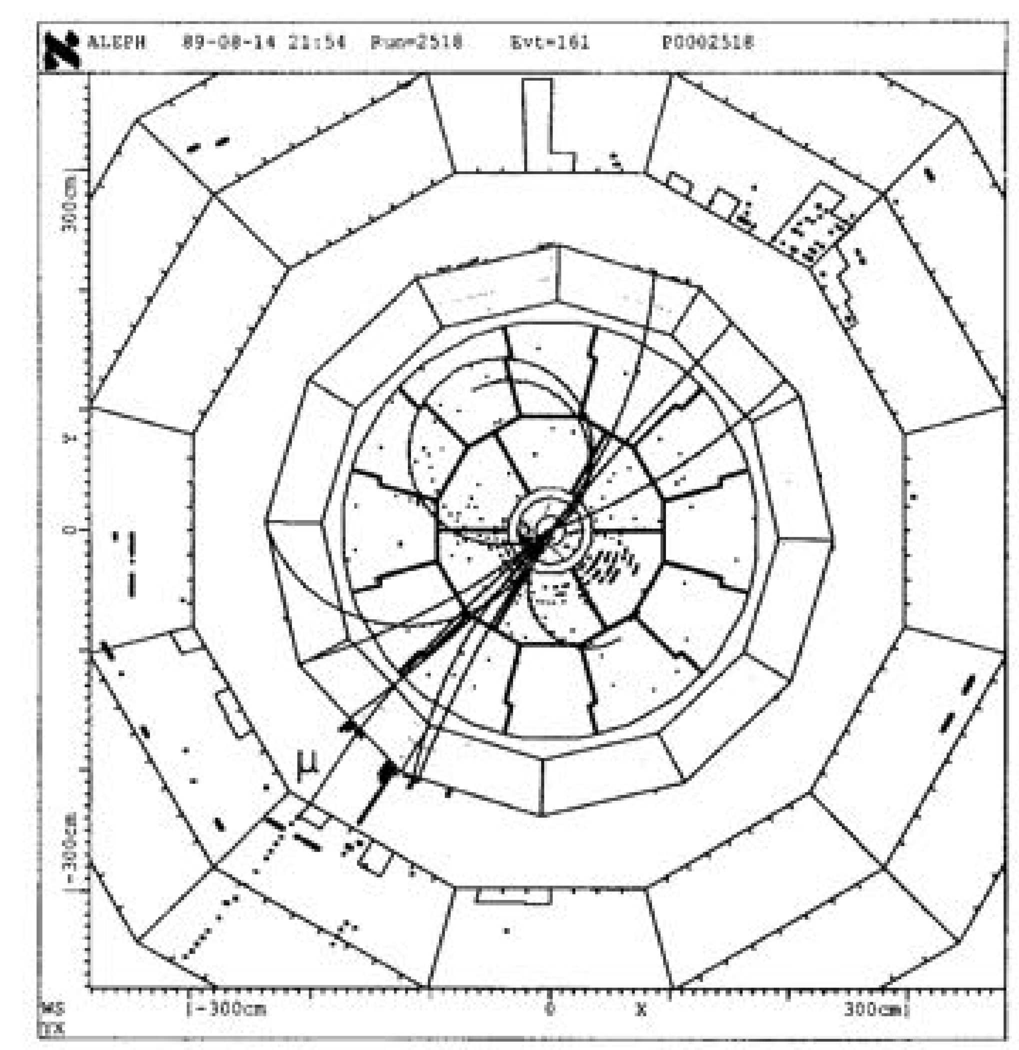
Je suis heureux de vous annoncer que la machine LEP fonctionne à 45,5 GeV et que des particules Z^0 y ont été observées.

C'est un grand succès dont nous pouvons tous être justement fiers, plus particulièrement les nombreuses personnes parmi vous qui l'ont rendu possible.

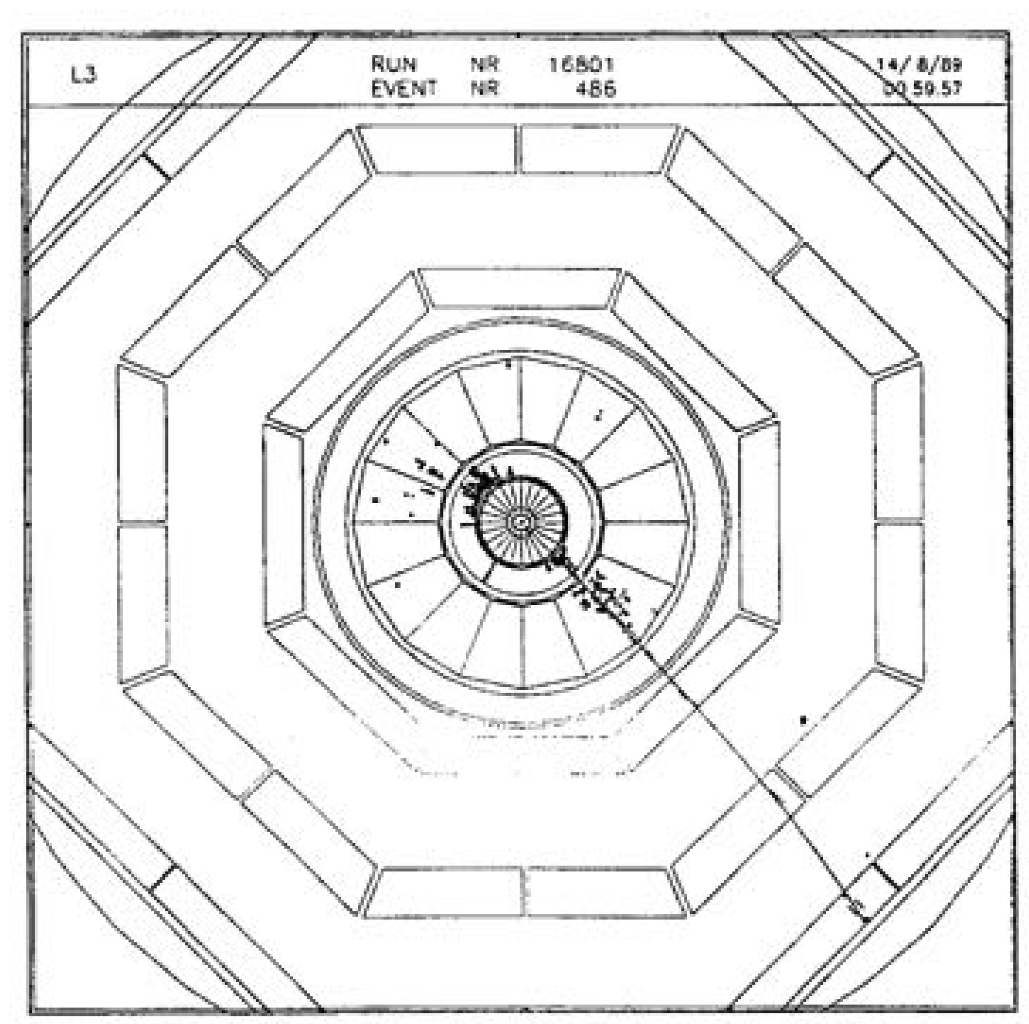
Carlo Rubbia
Directeur général
le 14 août 1989



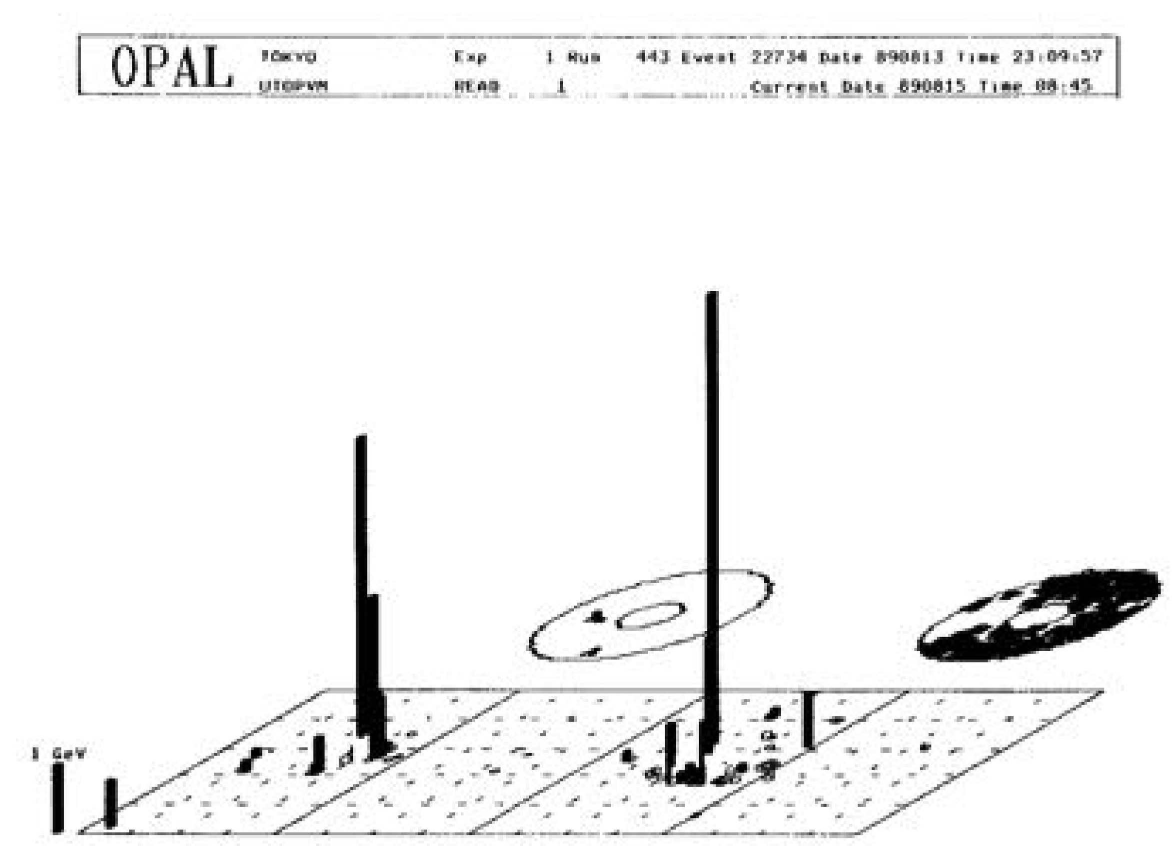
DELPHI



ALEPH



L3



OPAL

Z^0 marks the spot

Late on the night of Sunday 13 August, just one month after first beam circulated and a mere 16 minutes after the start of the pilot run, LEP's first Z^0 was recorded. By midnight a total of three had been observed, and on Monday there followed 13 more – a remarkable total of 16 between the four detectors ALEPH, DELPHI, OPAL and L3 in the first 24 hours of operation.

Le règne du Z^0

Tard dans la nuit du dimanche 13 août, u exactement après les premières révolutic faisceaux dans l'anneau et 16 minutes se après le début de la période d'essai, le premie LEP a été enregistré. A minuit leur nombre à trois et lundi 13 autres ont suivi, soit u remarquable de 16 Z^0 pour l'ensemble des détecteurs ALEPH, DELPHI, OPAL et L3 a des 24 premières heures d'exploitation.

Let us turn our clock back

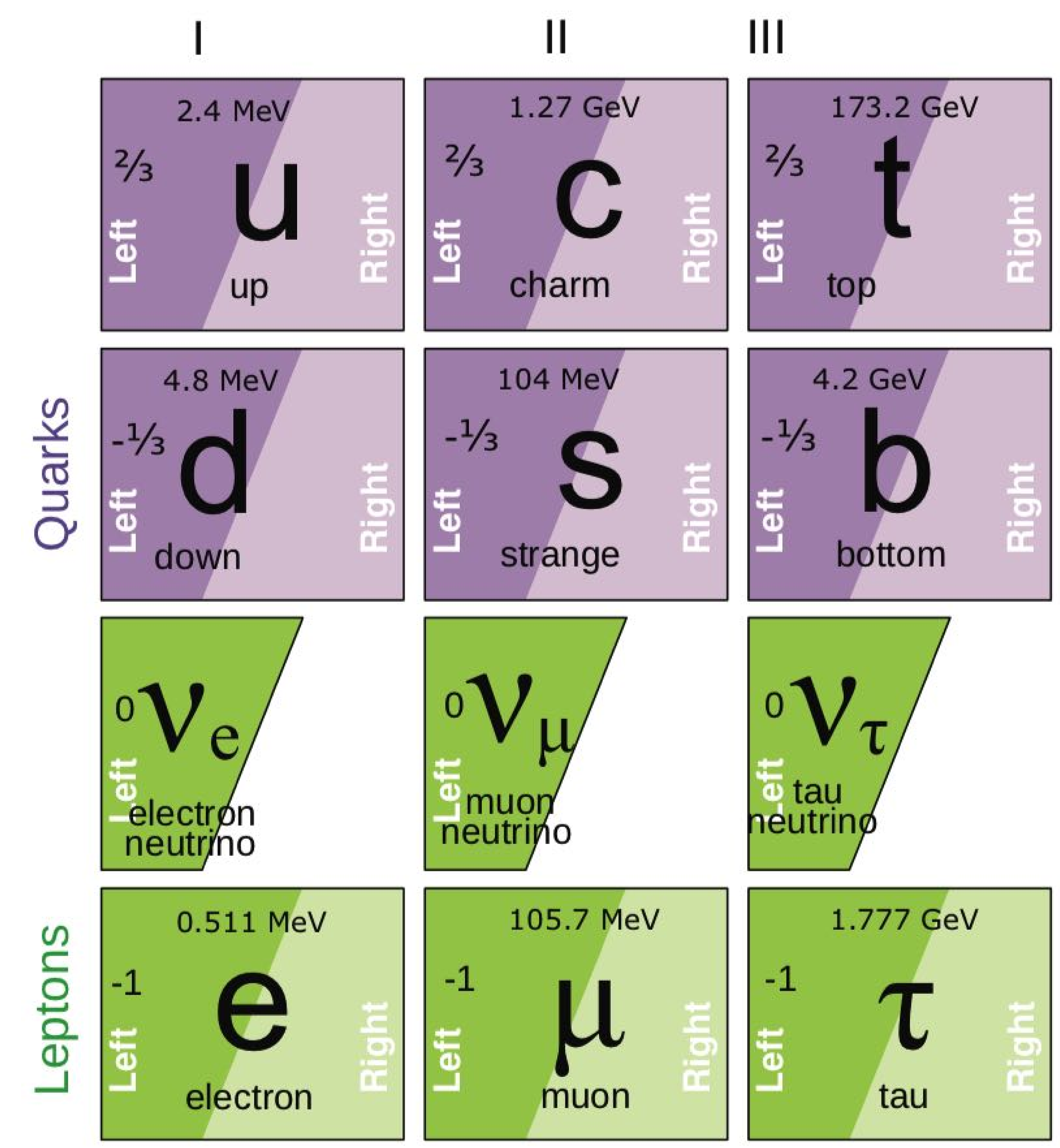
What was known on N_ν at the time?

- SM of electroweak interactions well established with the W and Z discovery in 1983 and the measurement of their properties

- SM however does not predict the number of fermion generations or their masses

- Quarks and leptons organised into three families →

  Why did nature provide three replications of the same pattern of matter? Could there be more than three families?



- Given the regularity of the pattern, counting the number of neutrino species N_ν may also mean counting the number of fundamental fermion generations (including higher-mass families with neutrinos lighter than $M_Z/2$)

What was known at the time? (II)

Info on N_ν from cosmology, astrophysics & particle physics

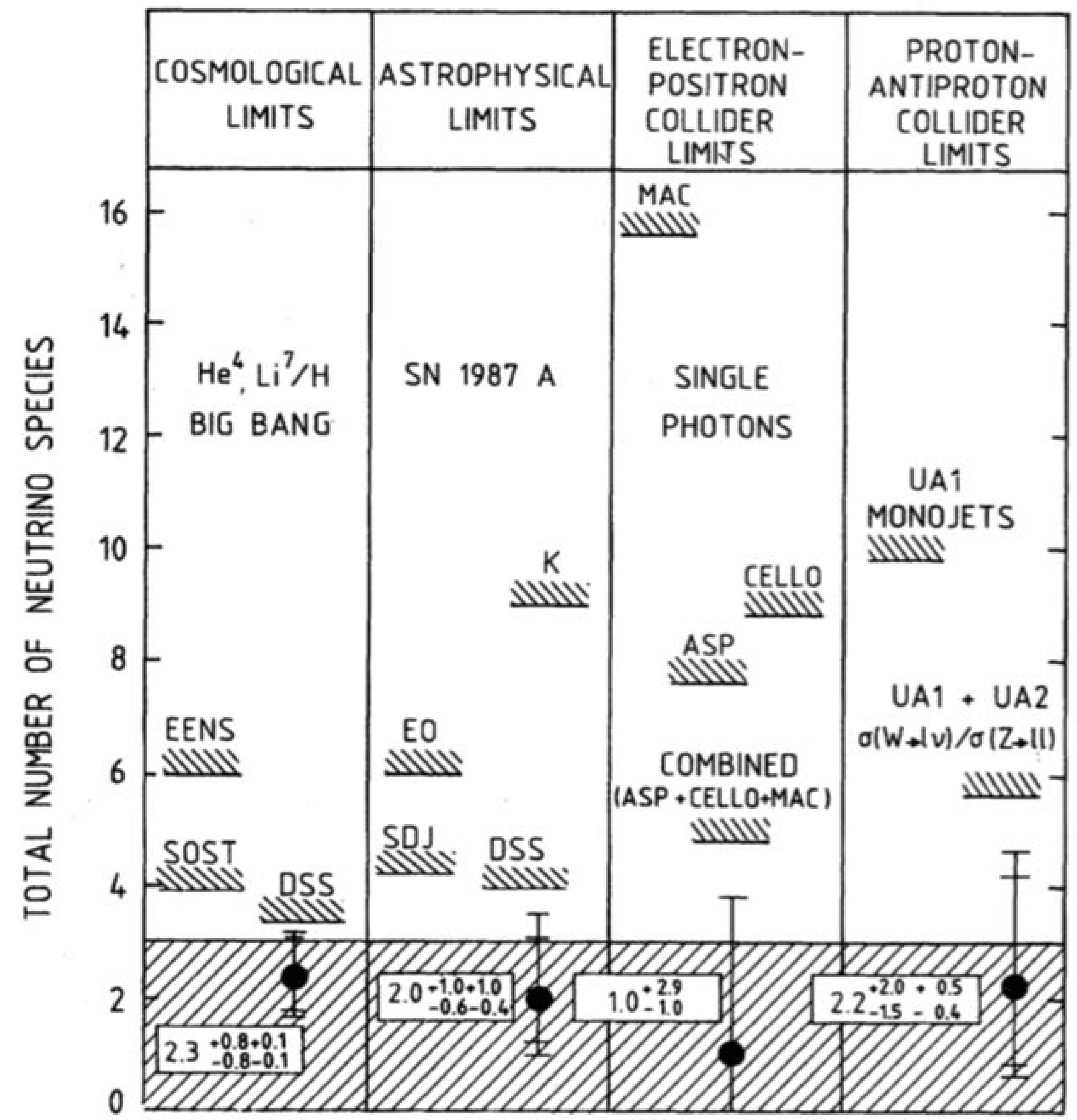
- Cosmology, from primordial nucleosynthesis: formation of light elements and their relative abundances (He/H) is a function of the neutron-proton ratio at the time light elements were forming. This is turn depends on the expansion rate of the Universe, which is a function of the number of neutrino species N_ν

- Astrophysics, based on observation of $\bar{\nu}$ emitted by the collapse of SN 1987A in 1987, relying on theory and based on assumption that total gravitational energy release shared equally by all neutrino species

- Particle physics: indications from direct search from the process $e^+e^- \to \nu\bar{\nu}\gamma$ and from Z/W properties at CERN and FERMILAB $p\bar{p}$ experiments, e.g. $\sigma(W \to \ell\nu)/\sigma(Z \to \ell\bar{\ell})$

What was known at the time? (III)

Denegri, Sadoulet & Spiro
[Rev. Mod. Phys, 1989]



← 3

- Remarkable agreement between values derived from the analysis of such widely different phenomena
- Putting everything together, Denegri, Sadoulet & Spiro obtained $N_\nu = 2.0^{+0.6}_{-0.4}$
- "Results perfectly compatible with the a priori knowledge that at least three neutrino families should exist … Although the consistency is significantly worse, four families still provide a reasonable fit"

First Z detected at SLC!

12 April 1989

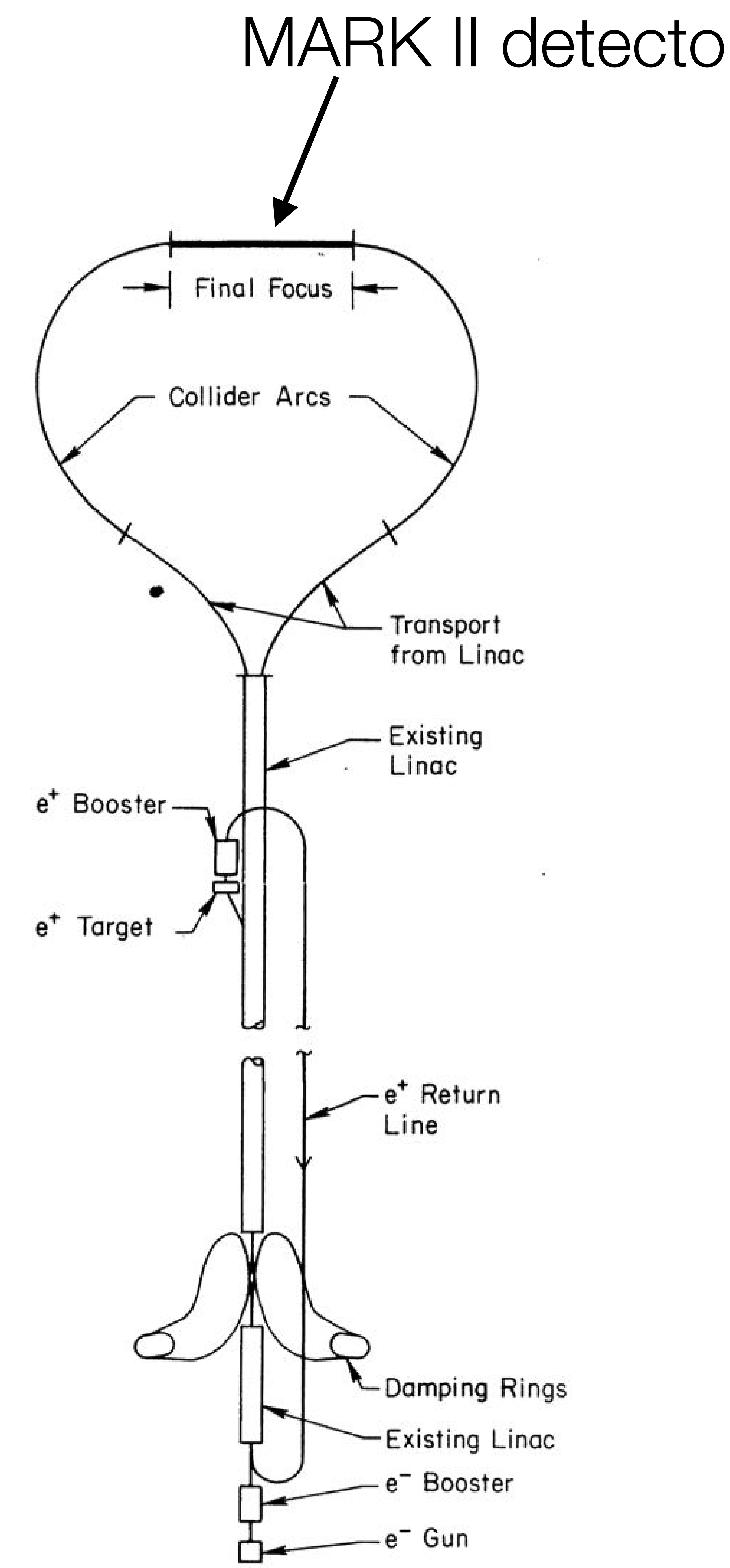
ed maintenance is 4/19 and
Added by ROGER at 89/04/12 15:52:25
2, 1989 !!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

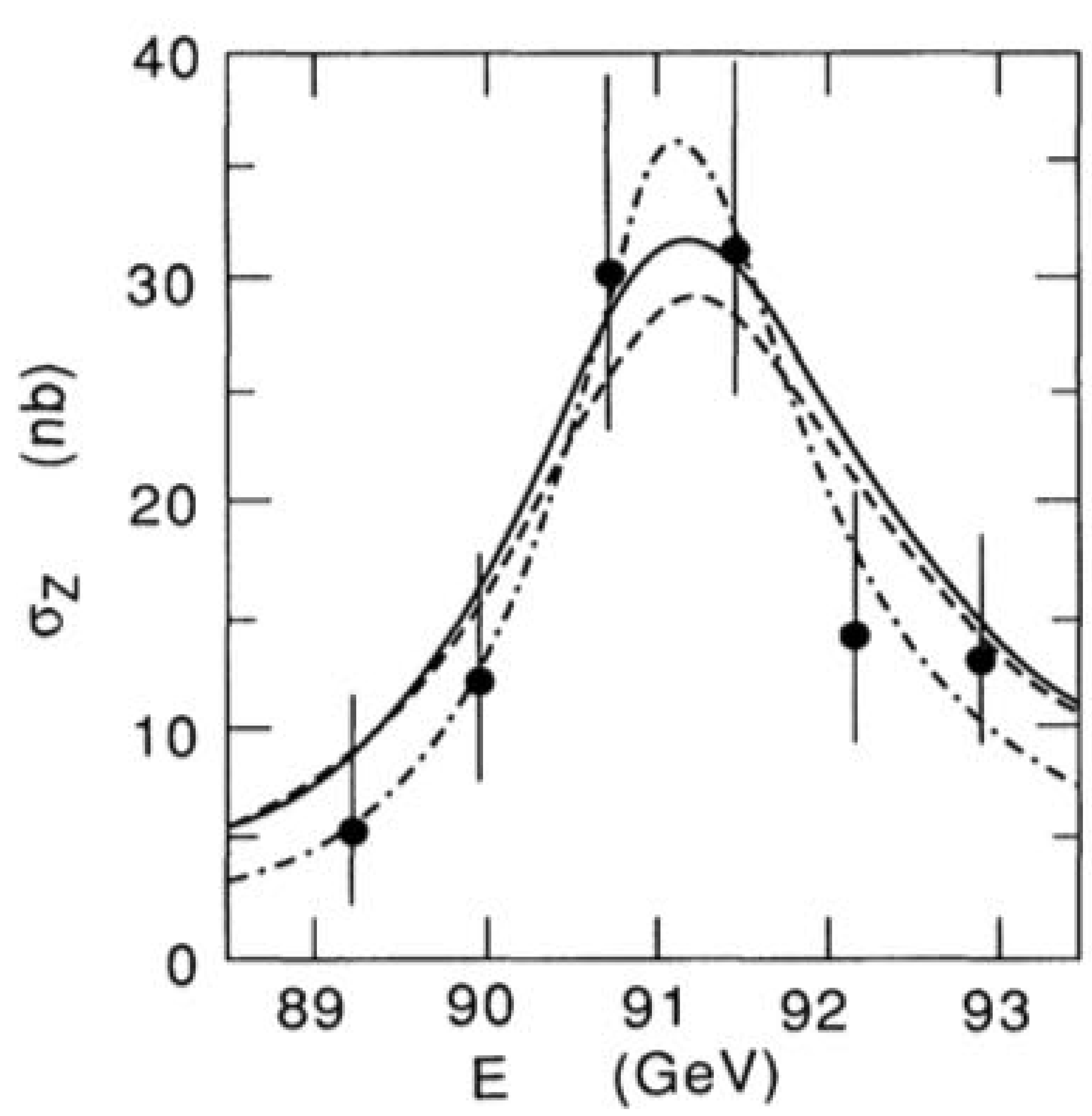
FIRST Z DETECTED AT SLC.

DRONIC EVENT HAS BEEN IDENTIFIED IN
LLISION ENERGY OF 92.2 GEV. NINE CHA
TED WITH THE EVENT, AND 70 GEV IS ACC

SLAC Linear Collider

- SLC was the prototype of a new accelerator concept, the linear collider
- Scheduled to take first data in Jan.'87, but new and difficult technology → First reasonable Lumi only in March '89 (few $10^{27} cm^{-2}s^{-1}$)
- First results based on 106 Z events collected at 6 different energies around the Z peak





$$M_Z = 91.11 \pm 0.23\,\mathrm{GeV}/c^2$$

$$\Gamma_Z = 1.61^{+0.60}_{-0.43}\,\mathrm{GeV}$$

$$\Gamma_{inv} = 0.62 \pm 0.23\,\mathrm{GeV} \;\rightarrow N_\nu = 3.8 \pm 1.4$$

[PRL 63, 724 (1989)]

LEP

- LEP start-up advertised for 14 July 1989
  - July 14, First turn
  - August 13, First Collision
  - August 13-18, Physics pilot run
  - August 21-Sept.11, Machine studies
  - Sept. 20-Nov. 5, Physics

- The Economist August 19, 1989 :

The results from California are impressive, especially since they come from a new and unique type of machine. They may provide a sure answer to the generation problem before LEP does. That explains the haste with which the finishing touches have been put to LEP. The 27km-long device, six years in the making, was transformed from inert hardware to working machine in just four weeks —a prodigious feat, unthinkable anywhere but CERN. Even so, it was still not as quick as Dr Carlo Rubbia, CERN's domineering director-general, might have liked.

[S.Myers, CERN's 50th anniversary]

13 November 1989
F.Mitterand visits ALEPH

SPECIAL SEMINAR

Friday 13 October

at 15.00 hrs - Auditorium

Results from the first physics run at LEP

Reports from each of the LEP experiments

Closed-circuit transmission to : Council Chamber, LEP Auditorium, SPS Auditorium

- After only three weeks of data-taking, in a packed Auditorium the four experiments presented their results based on ~3000 Z each (J.Lefrancois, U.Amaldi, S.Ting, A.Wagner) & MARKII update

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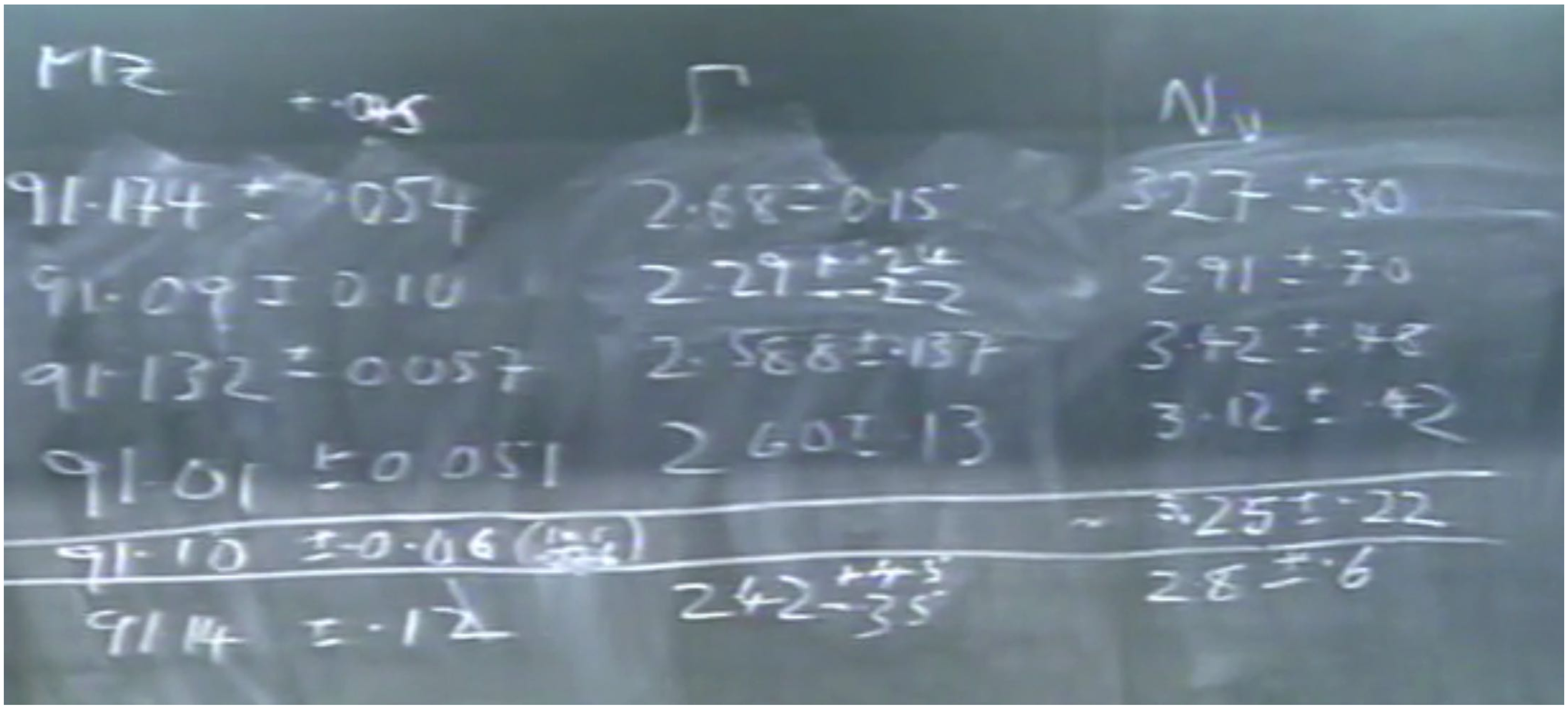
First results

13 October 1989

- Results written on a blackboard by John Thresher, CERN research director with responsibility for the new LEP experimental programme



http://cds.cern.ch/record/423005?ln=en

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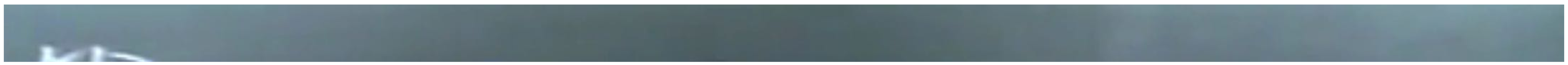
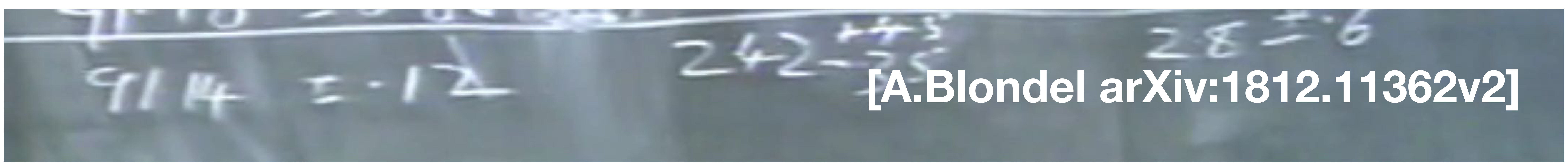


Experiment	Hadronic Zs	Z mass (GeV)			N_ν		
MARKII	450	91.14	±	0.12	2.8	±	0.60
L3	2538	91.13	±	0.06	3.42	±	0.48
ALEPH	3112	91.17	±	0.05	3.27	±	0.30
OPAL	4350	91.01	±	0.05	3.10	±	0.40
DELPHI	1066	91.06	±	0.05	2.4	±	0.64
Average		91.10	±	0.05	3.12	±	0.19



[A.Blondel arXiv:1812.11362v2]

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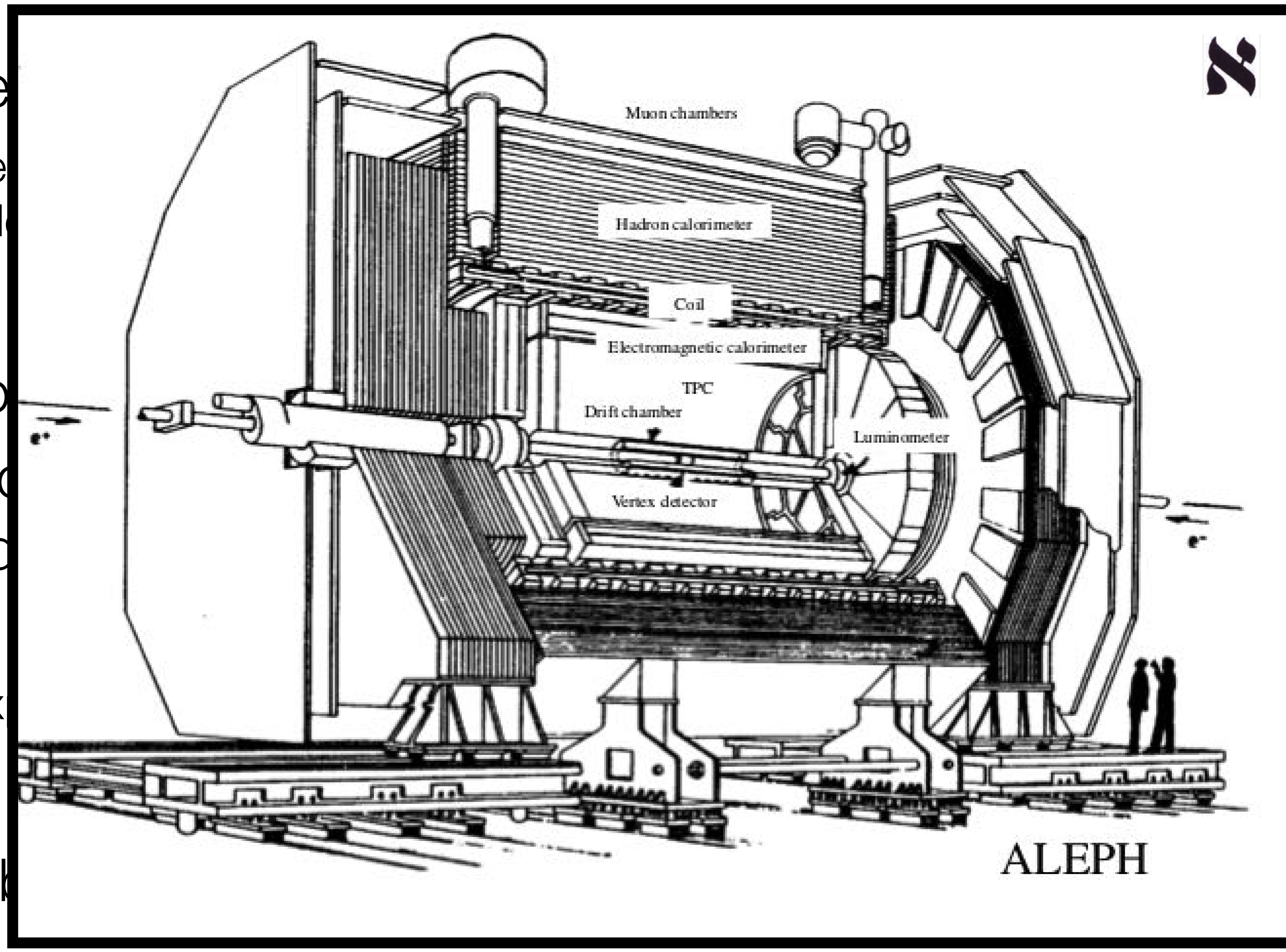
DELPHI	1066	91.06	±	0.05	2.4	±	0.64
Average		91.10	±	0.05	3.12	±	0.19

The number of light neutrino species is three!

http://cds.cern.ch/record/423005?ln=en

The four LEP experiments

- **ALEPH**: main emphasis on momentum measurement via accurate tracking in high magnetic field (1.5 Tesla); high granularity ECAL
  - Vertex detector installed in '91 (Silicon strips), Inner Tracking Chamber, Time Projection Chamber (main tracking detector) → $\Delta p/p \simeq 2.7\,\%$ for 45 GeV muons
- **DELPHI**: pione
  - PID via RICH dete d as electromagnetic calorimeter (excell stalled in '90
- **L3**: emphasis o n the largest magnet in the wo smuth Germanium Oxid $E/E \simeq 1.4\,\%$ for 45 GeV electrons)
  - About twice as ex



- **OPAL**: design b hat had to work!
  - Excellent tracking achieved by means of a "jet-type" drift chamber; Silicon Vertex detector installed in 1992

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- **DELPHI**: pioneering new techniques
  - PID via RICH detectors (with liquid and gas radiators), Heavy Projection Chamber used as electromagnetic calorimeter (excellent spatial resolution but complex to operate), Silicon Microvertex installed in '90
- **L3**: emphasis on precise trac … magnet in the world (5kG field, Δ… Germanium Oxide (BGO) cryst … r 45 GeV electrons)
  - About twice as expensive as the othe…
- **OPAL**: design based on well- … ork!
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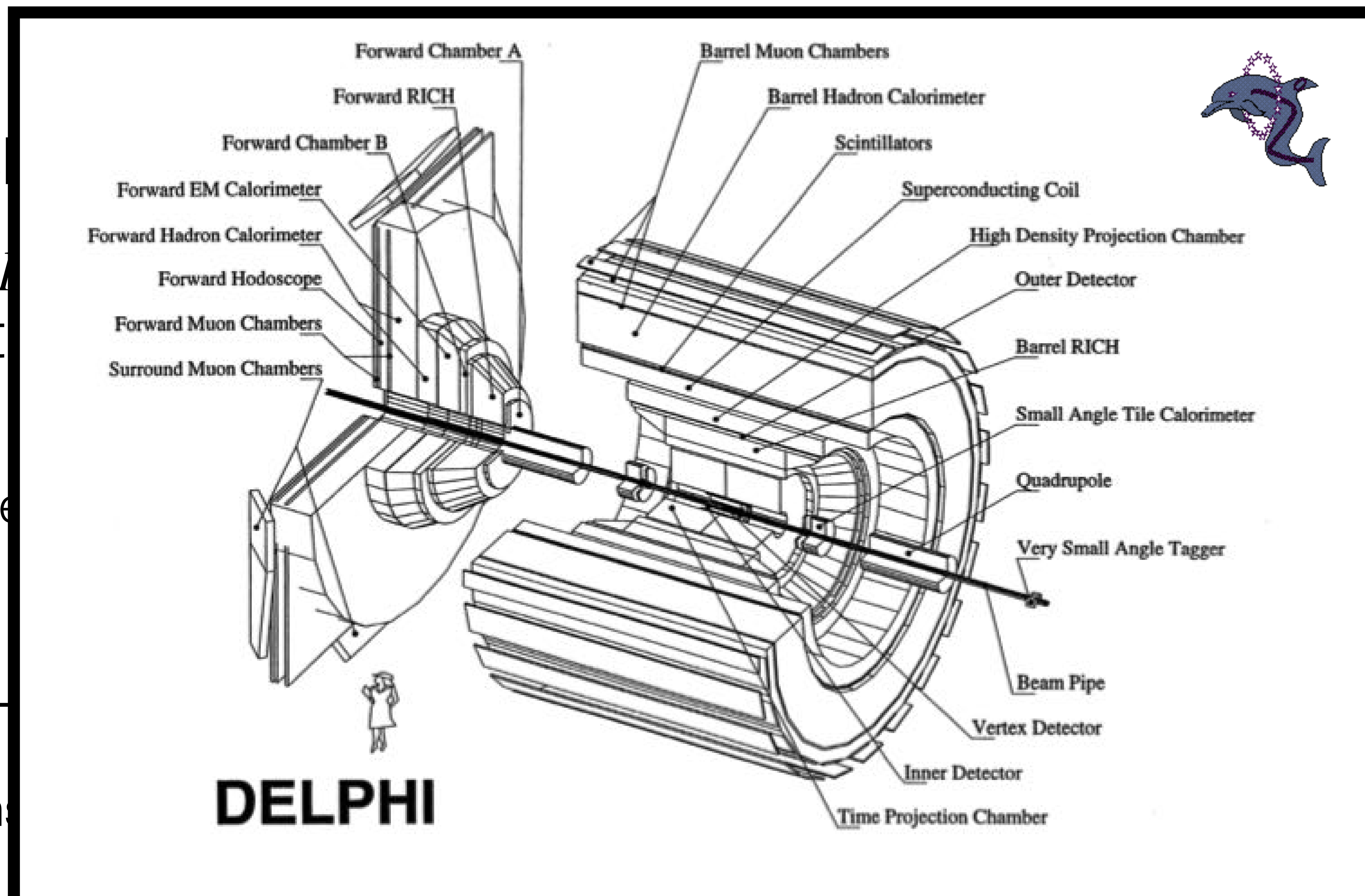
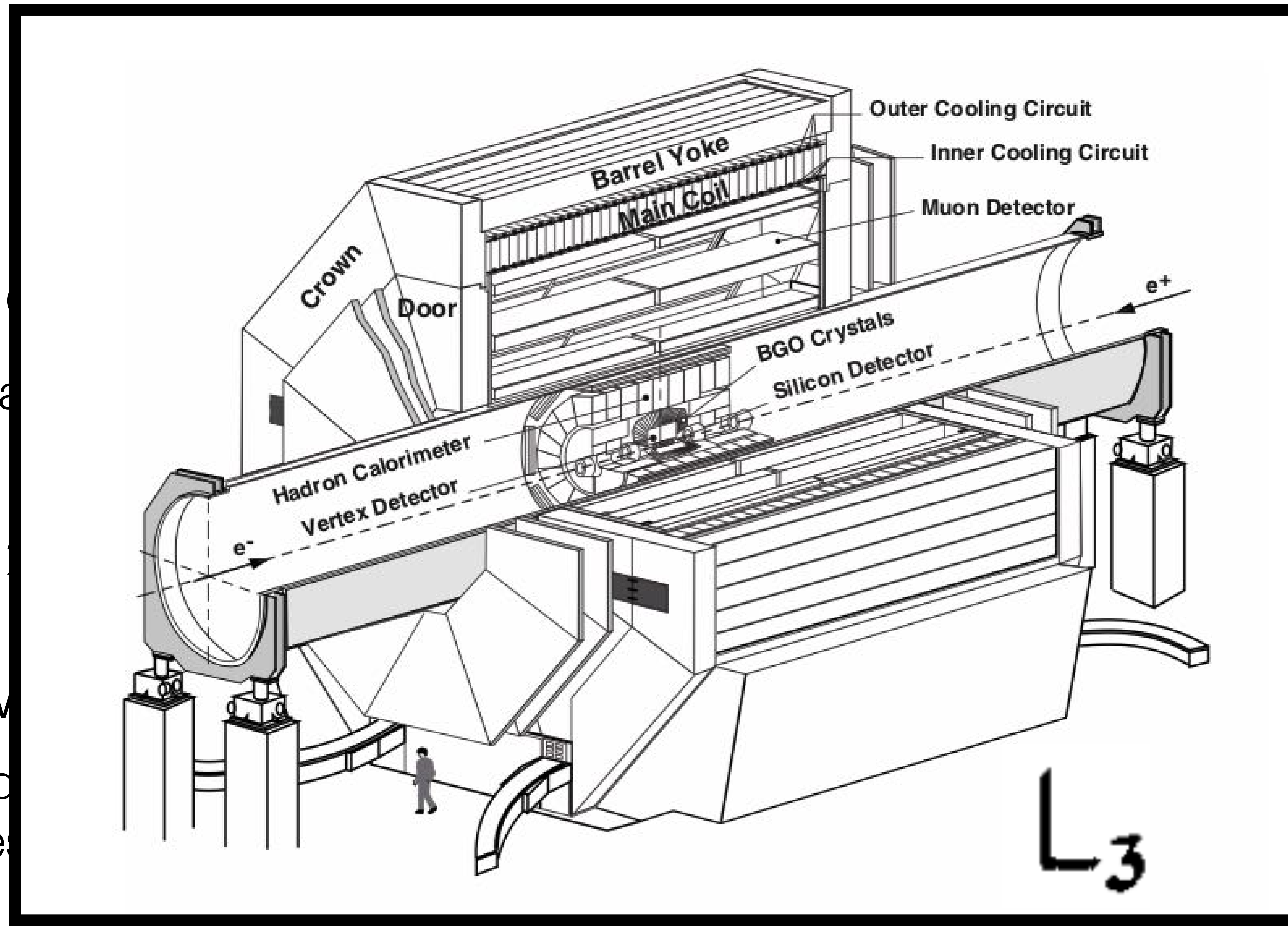


The four … nts



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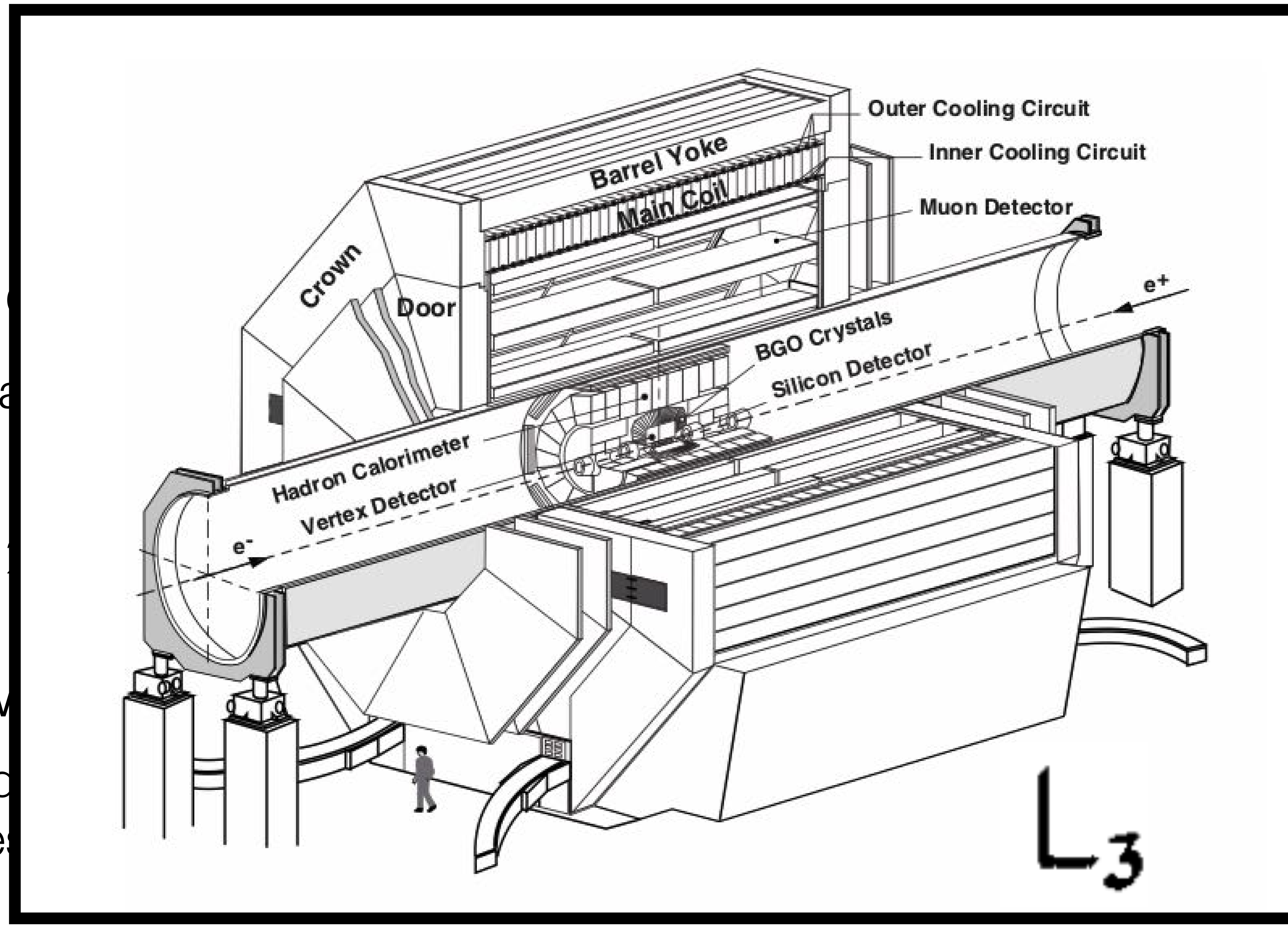
- **L3**: emphasis on precise tracking for muons utilising what was then the largest magnet in the world (5kG field, $\Delta p/p \simeq 2.5\,\%$ for 45 GeV muons); layer of Bismuth Germanium Oxide (BGO) crystals as electromagnetic calorimeter ($\Delta E/E \simeq 1.4\,\%$ for 45 GeV electrons)
  - About twice as expensive as the other detectors!
- **OPAL**: design based on well-tested technologies→ the detector that had to work!
  - Excellent tracking achieved by means of a "jet-type" drift chamber; Silicon Vertex detector installed in 1992

The four ... nts



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The Economist: The BGO was made in China. The iron (and uranium) came from the Soviet Union, which makes L3 the largest Soviet-Chinese collaboration since Mao and Stalin went their separate ways. Getting that sort of co-operation to work is one reason L3 has kept Dr Ting busy for the best part of a decade

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The four LEP experiments

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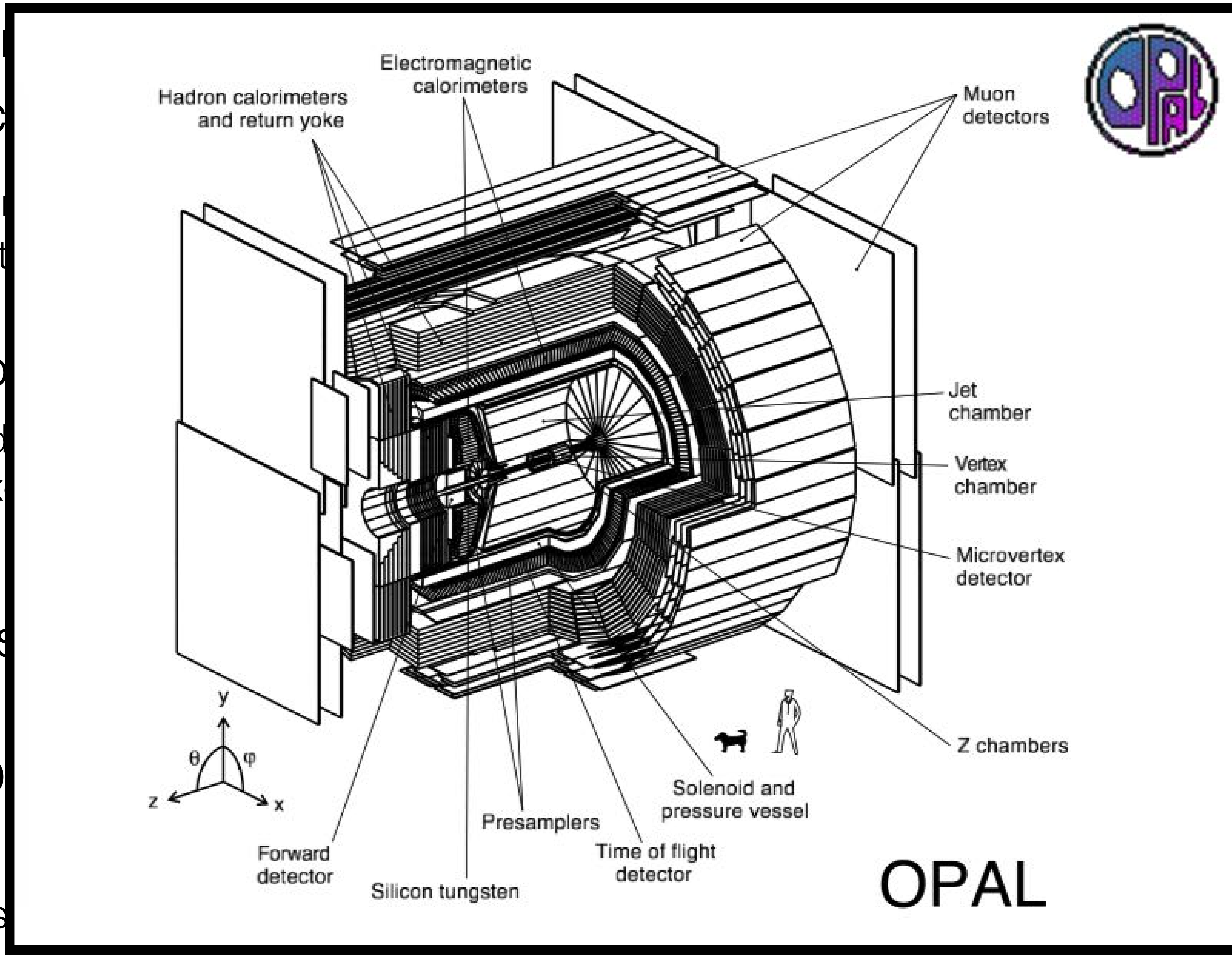

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Z line shape

- Cornerstone of LEP physics programme, studied by measuring the visible cross-section at several centre-of-mass energies near the Z mass
- For $e^+e^- \to Z \to f\bar{f}$, $\sigma_f(s) = \sigma_f^0 \dfrac{s\Gamma_Z^2}{(s - M_Z^2)^2 + s^2 \frac{\Gamma_Z^2}{M_Z^2}} (1 + \delta_{\mathrm{rad}}(s))$

  with the peak cross-section $\sigma_f^0(s = M_Z^2) = 12\pi \dfrac{\Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2}$

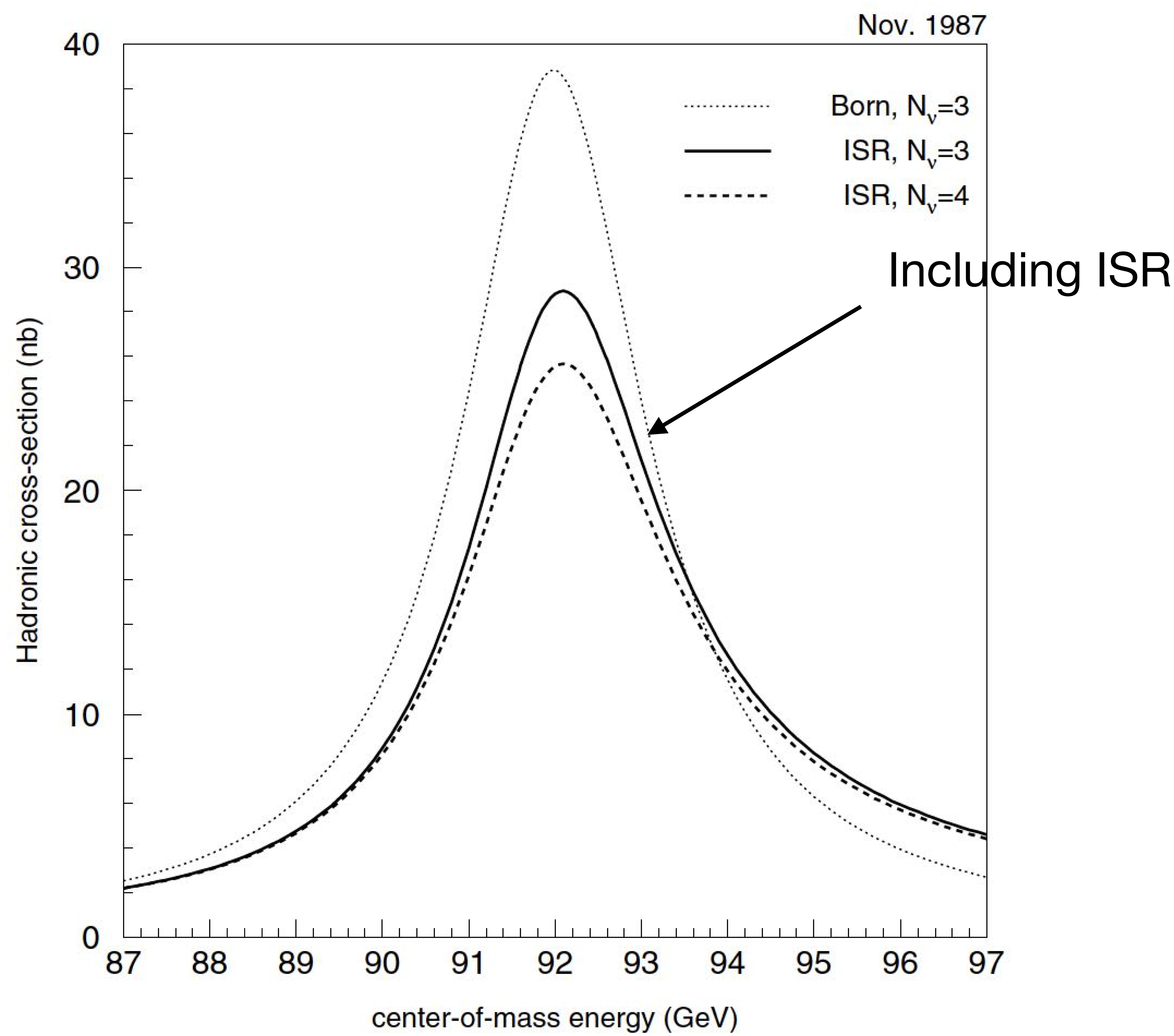
- From measured cross-sections, EW parameters extracted after correcting for QED effects (ISR), which are large (~30% at the peak) but precisely known (few 10^{-4})
- Dependence on N_ν through $\Gamma_Z = 3\Gamma_\ell + \Gamma_{\mathrm{had}} + N_\nu \Gamma_\nu$
- In the SM, $\Gamma_{\mathrm{had}} \sim 70\,\%$, $3\Gamma_\ell \sim 10\,\%$ and $\Gamma_{\mathrm{inv}} = N_\nu \Gamma_\nu \sim 20\,\%$

$\sigma(e^+e^- \to \text{hadrons})$ as a function of $\sqrt{s}$

[A.Blondel, arXiv:1812.11362]

- Drawn in 1987 before the start of LEP
- One additional ν species would increase Γ_z by 6.6% and decrease the peak cross-section σ^0_{had} by 13% :

$$\frac{\mathrm{d}\sigma^0_{\text{had}}/\mathrm{d}N_\nu}{\sigma^0_{\text{had}}} = -13\%$$



The method

- Primary quantities measured : $\sigma(\sqrt{s})$ for hadrons, $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ (but first N_ν measurement only based on hadrons)
- From $\sigma(\sqrt{s})$ to a final state $f\bar{f}$ one can extract peak position, width and overall normalisation, best obtained from the peak cross-section σ_f^0
- Fit for M_Z, Γ_Z, σ^0_{had} and $R_{e,\mu,\tau} \equiv \sigma^0_{\mathrm{had}}/\sigma^0_{e,\mu,\tau} = \Gamma_{\mathrm{had}}/\Gamma_{e,\mu,\tau}$ (choice that minimizes experimental correlations)
- Parameter set reduces to four: $M_Z, \Gamma_Z, \sigma^0_{\mathrm{had}}, R_\ell$ assuming lepton universality

$$N_\nu = \left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\mathrm{SM}} \cdot \left(\sqrt{\frac{12\pi R_\ell}{M_z^2 \sigma^0_{\mathrm{had}}}} - R_\ell - 3\right)$$

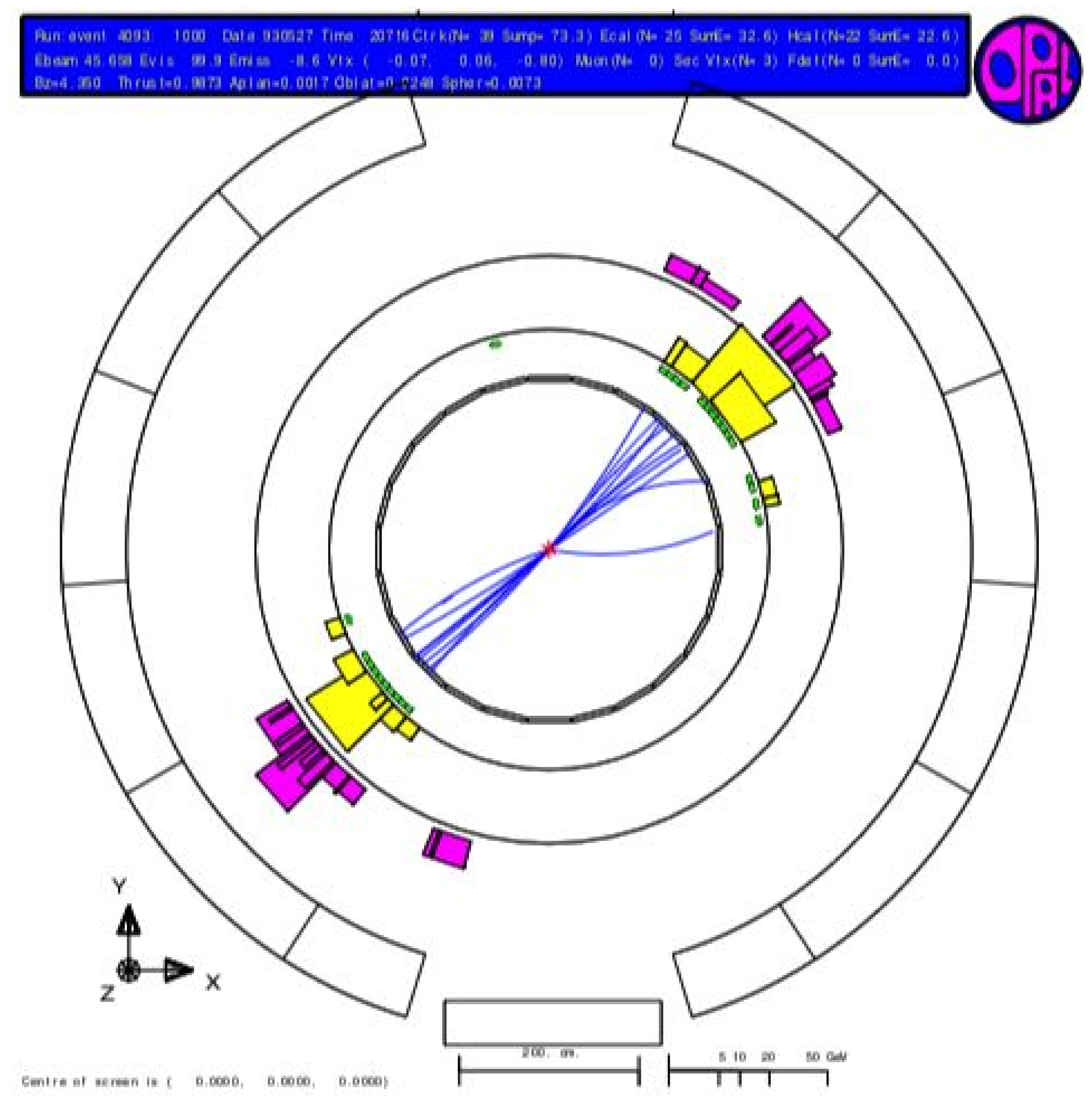
- Dominant sensitivity in N_ν determination through hadronic peak cross-section [G.Feldman, '87]

Principles of the analysis

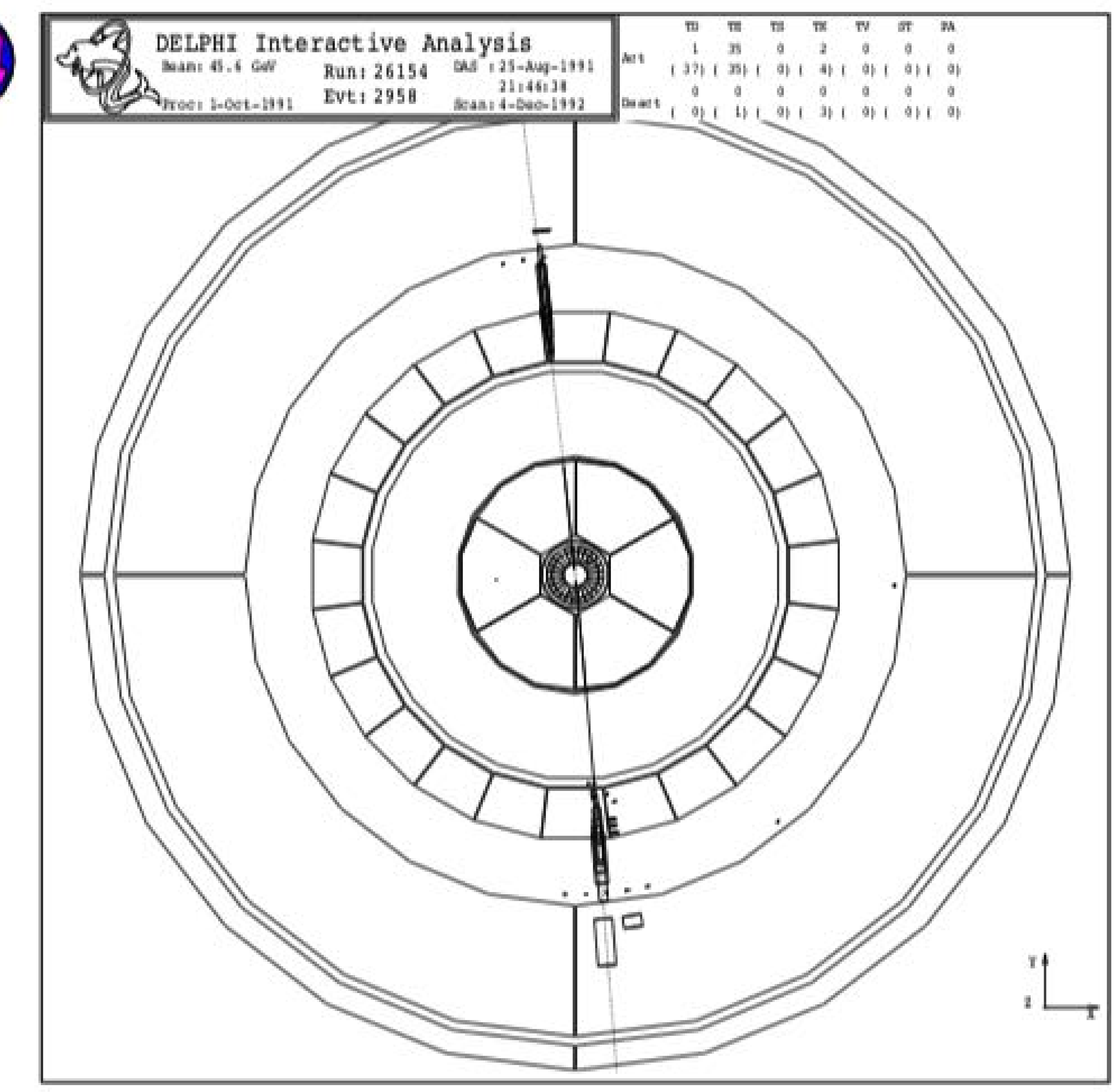
- All visible Z decays detected and classified according to the four categories: hadrons, $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

- High and well-known efficiency, e.g. $\epsilon_{\mathrm{had}} > 99\ \%$

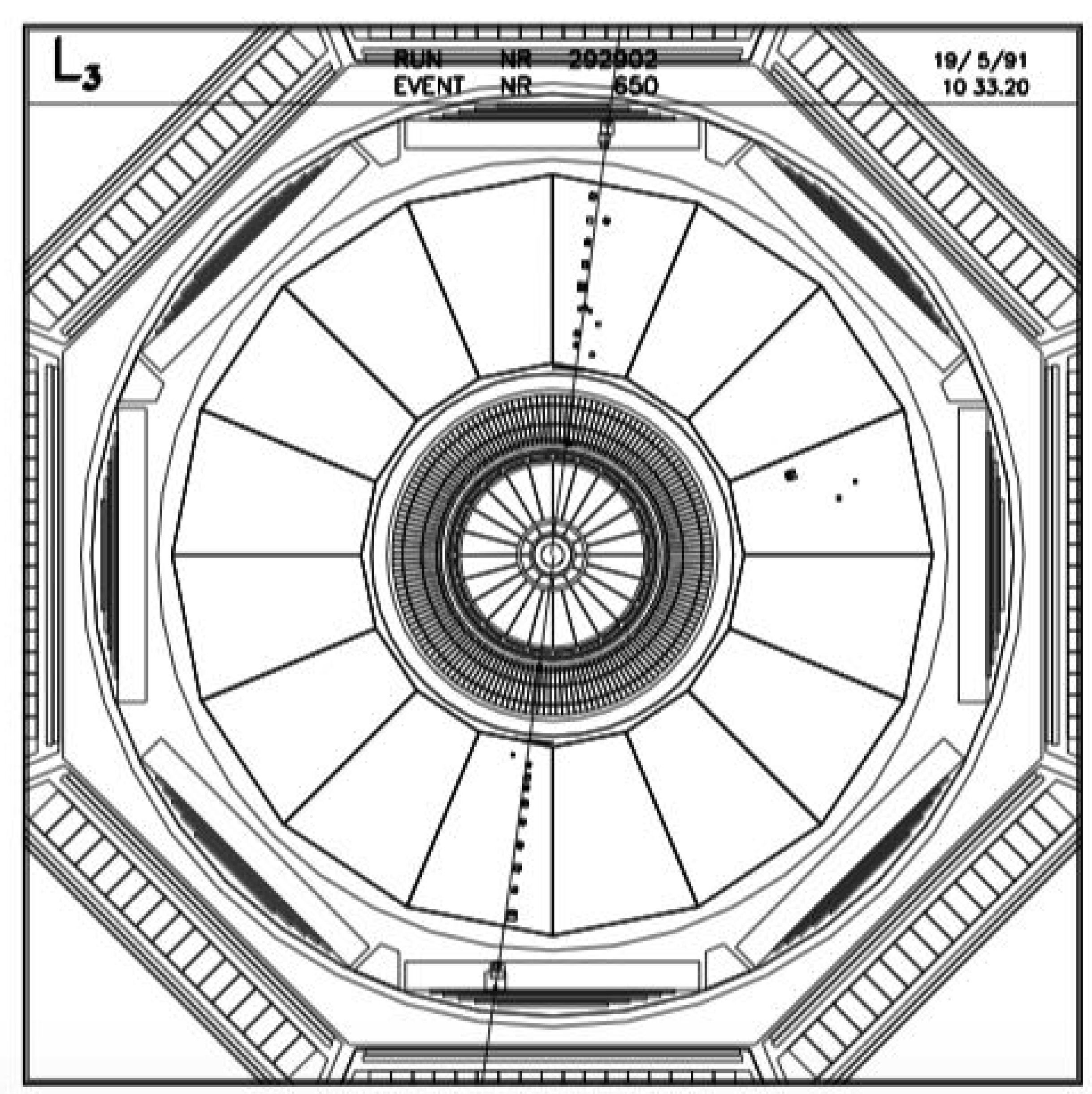
$e^+e^- \to q\bar{q}$



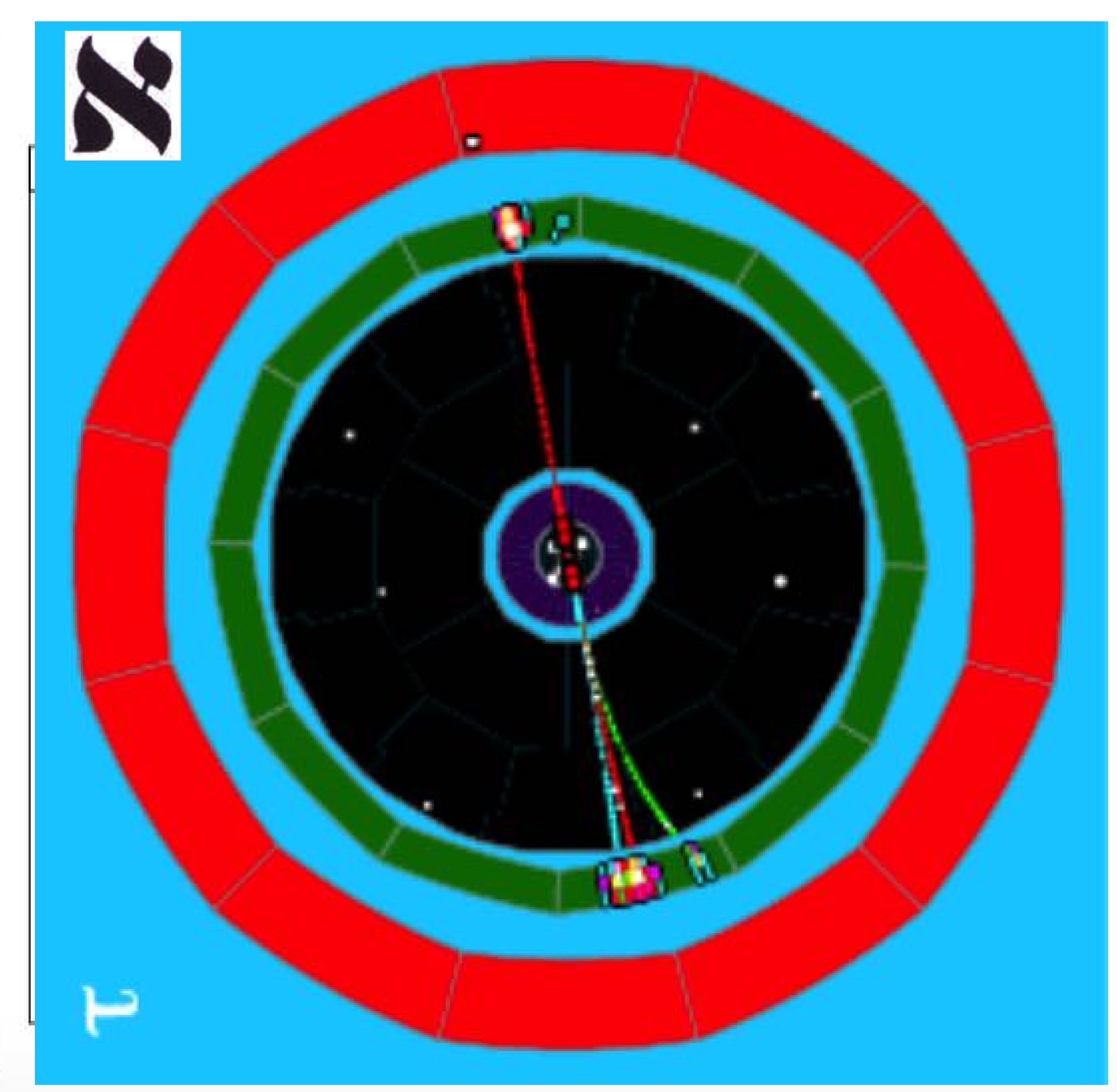
$e^+e^- \to e^+e^-$



$e^+e^- \to \mu^+\mu^-$

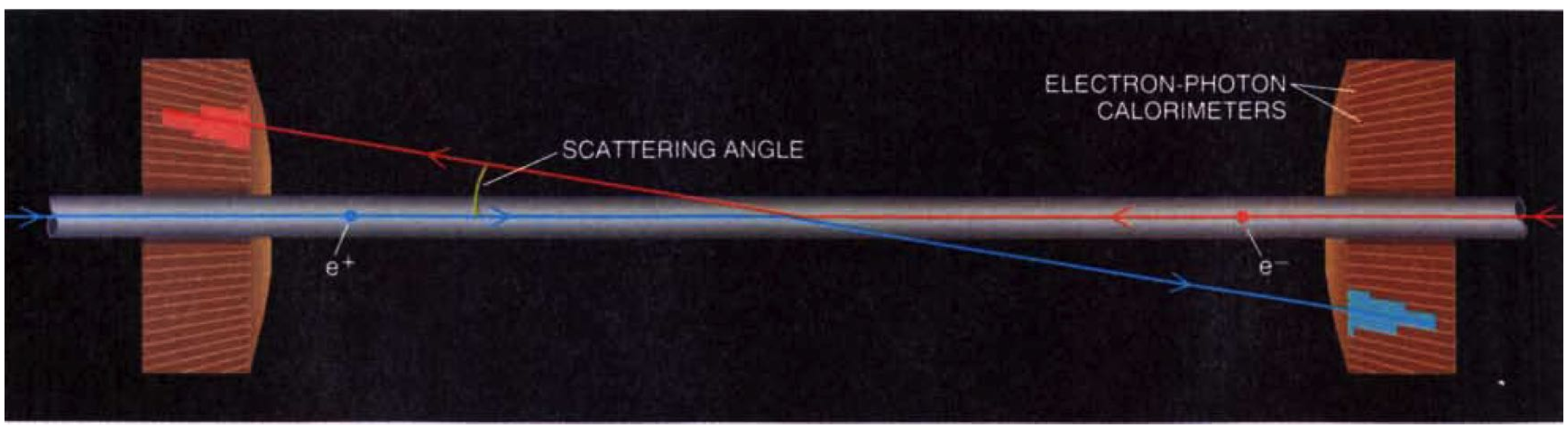


$e^+e^- \to \tau^+\tau^-$



Luminosity measurement

- Uncertainty on Luminosity has direct impact on N_ν : $\Delta N_\nu \sim 7.5 \frac{\Delta \mathscr{L}}{\mathscr{L}}$
- Luminosity determined by measuring at the same time another process with known cross-section, low-angle $e^+e^- \to e^+e^-$ (Bhabha scattering, dominated by QED t-channel γ-exchange) through dedicated detectors for the scattered electrons



- Method: compare measured rate of Bhabha scattering with cross-section predicted by theory

$$\mathcal{L} = \frac{N_{\mathrm{Bhabha}}}{\sigma_{\mathrm{ref}}}$$

events in data passing selection cuts

Calculated from MC events using same cuts as for data

Luminosity measurement (II)

- Experimental challenge was to define the geometrical acceptance with high accuracy, especially at the lowest θ bound:

$$\frac{d\sigma}{d\theta} \sim \frac{1}{\theta^3} \ \rightarrow \ \sigma^{\rm acc} \sim \frac{1}{\theta^2_{\rm min}} - \frac{1}{\theta^2_{\rm max}} \ \rightarrow$$

$$\frac{\delta\sigma^{\rm acc}}{\sigma^{\rm acc}} \simeq \frac{2\delta\theta_{\rm min}}{\theta_{\rm min}} = 2\left(\frac{\delta R_{\rm min}}{R_{\rm min}} \oplus \frac{\delta z}{z}\right) \qquad \theta \simeq R/z$$

- ALEPH: Already in first paper, sensitivity to possible displacements with respect to beam position reduced with asymmetrical event selection: tight fiducial cut on one side (e.g. e^+) and loose on the other (e^-) with fiducial role alternating from one event to the next (plus other clever tricks → experimental systematics ~1%)

- Experimental precision decreased to well below 10^{-3} at the end of LEP after progressive replacement with more precise calorimeters, e.g. silicon-tungsten

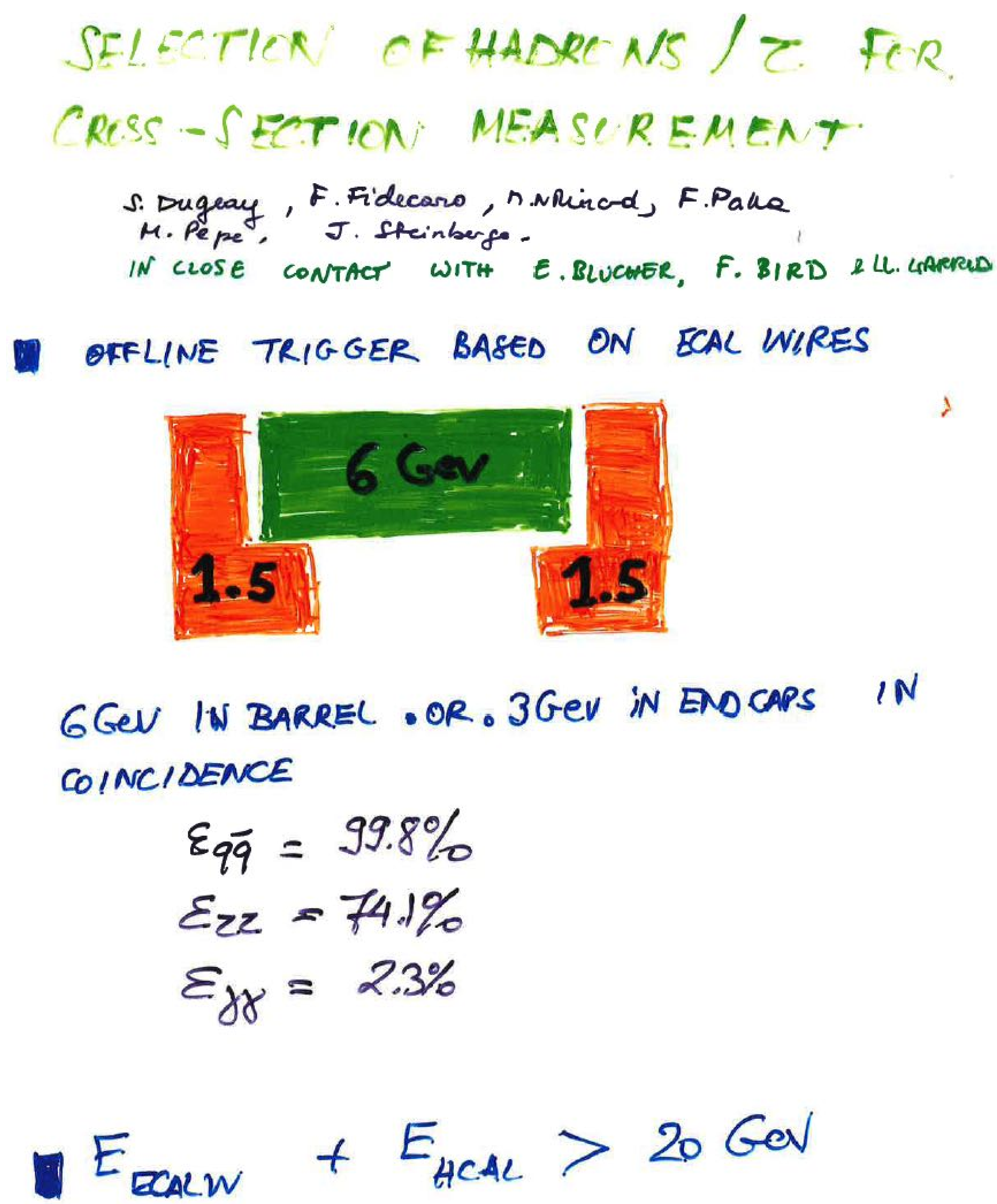
- After a lot of hard work final precision on theory estimate of cross-section within acceptance reached 0.06% (from Monte Carlo program for small-angle Bhabha scattering BHLUMI 4.04) matching experimental uncertainty


Some
archeology

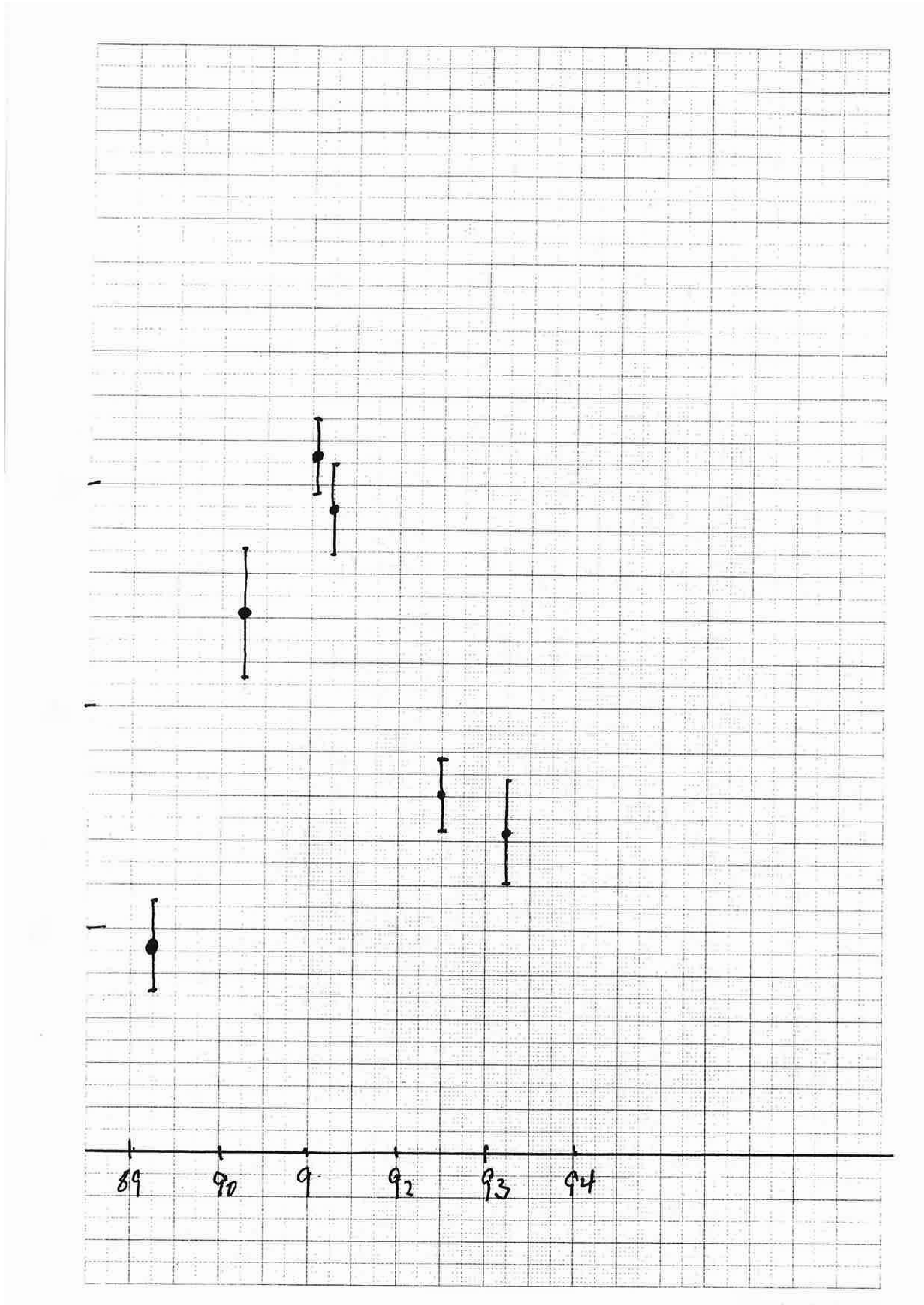
First ALEPH analysis approval

Early October 1989

- Hadronic event selection based on energy deposited in calorimeters (while an independent group counted hadrons using the TPC)
- Immense effort with many sleepless nights as we were at the same time validating the data, removing the noise and calibrating them and running the reconstruction
- By Sunday 2 October 1989, both groups had a measurement of the hadronic cross-sections. The two results were perfectly consistent, which gave us confidence in the results. (We had no idea what the other collaborations were doing as nothing filtered out!)

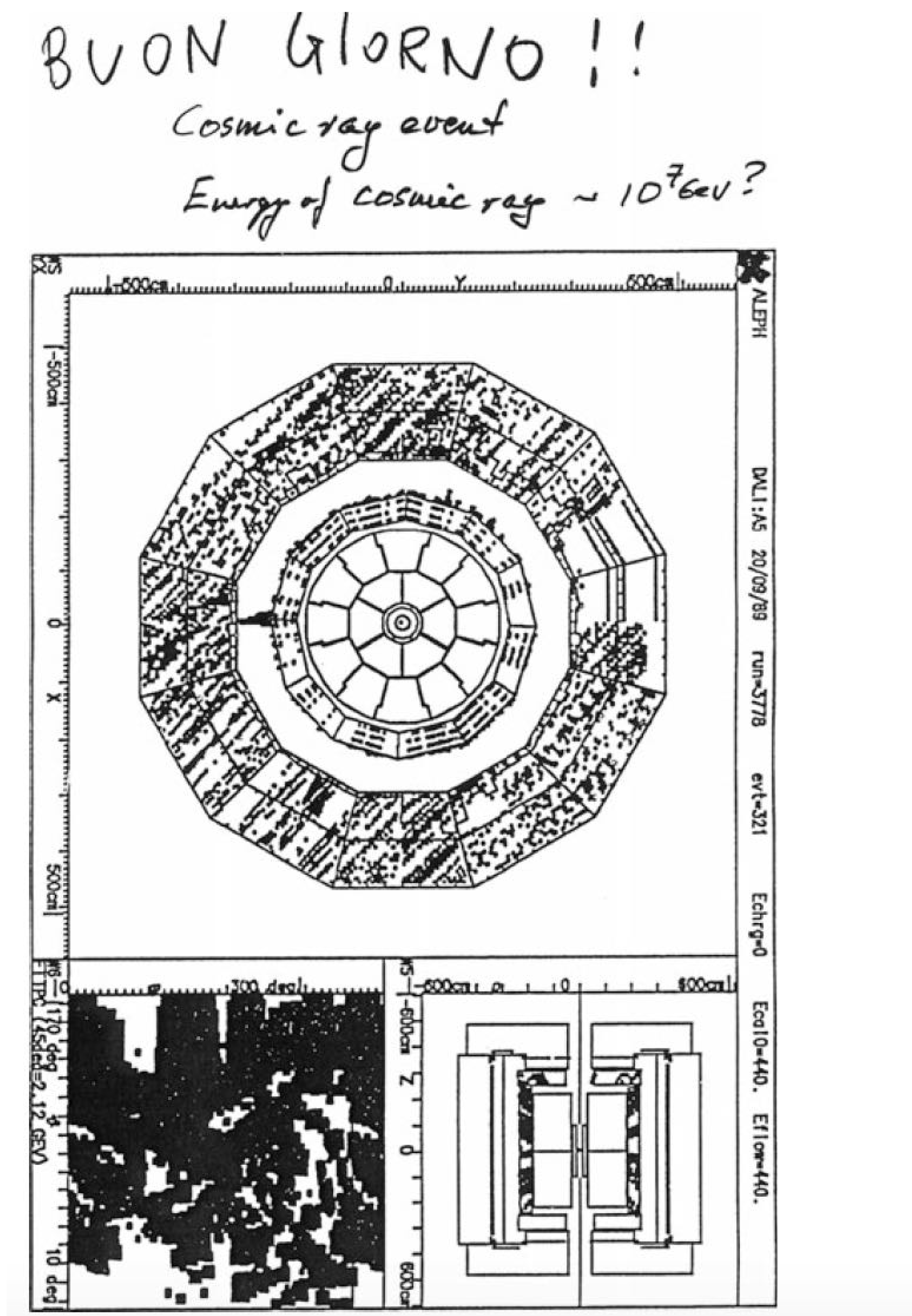


First ALEPH Z line shape



Some events had an incredibly high energy!

- Such at this one, which we found during the night of Sept. 20th



[J. Steinberger, 60 Years of CERN Experiments and Discoveries]

CERN Theory Christmas play 1989

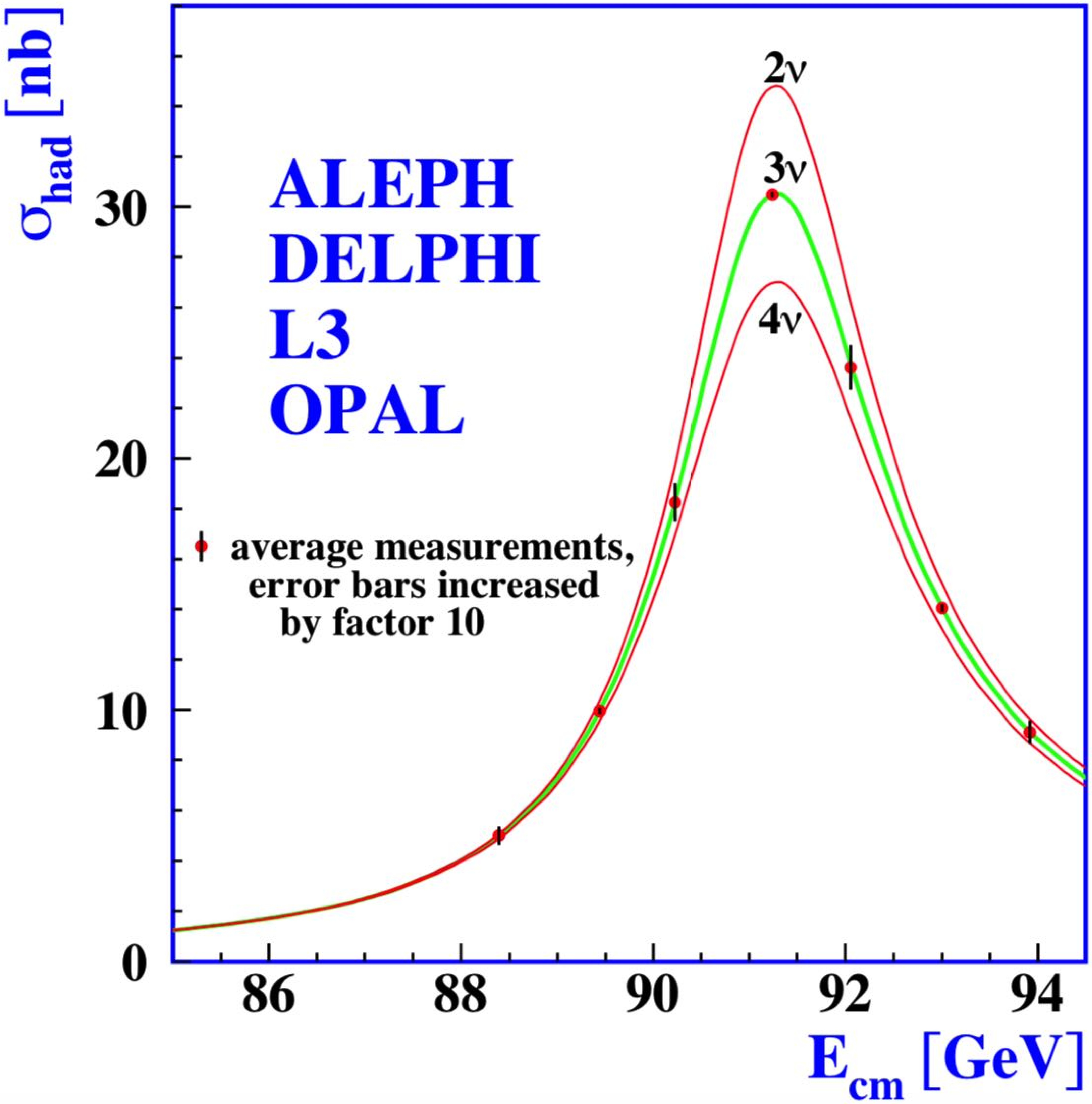
https://videos.cern.ch/record/1337777

Foundation of the LEP ElectroWeak Working Group

- Originally, a group with members of the four LEP experiments, led by Jack Steinberger, investigated the combination of the Z line shape parameters [Phys. Lett. B 276 (1992) 247]
  - Jack insisted that the combination was a job for the experimentalists from the four collaborations who should discuss together, rather than for the PDG or the theorists! [J.Lefrancois reminded me of Jack's role in this!]
- This led to the establishment of the LEP ElectroWeak Working Group, an unprecedented, collaborative effort across the experiments
- Mandate: to combine the measurements of the four LEP experiments on electroweak observables, e.g. cross sections, masses and various couplings, properly taking into account the common systematic uncertainties and producing the ``best'' LEP averages

http://lepewwg.web.cern.ch/LEPEWWG/

Final combined result



$N_\nu = 2.9840 \pm 0.0082$

- Based on 17 million Z decays
- Consistent within 2σ with three families of fundamental fermions
- Less than 3 per mille uncertainty ~ half of it (0.0046) from theoretical uncertainty on low-angle Bhabha scattering cross-section

[LEP EW WG:
Phys. Rept. 427 (2006)]

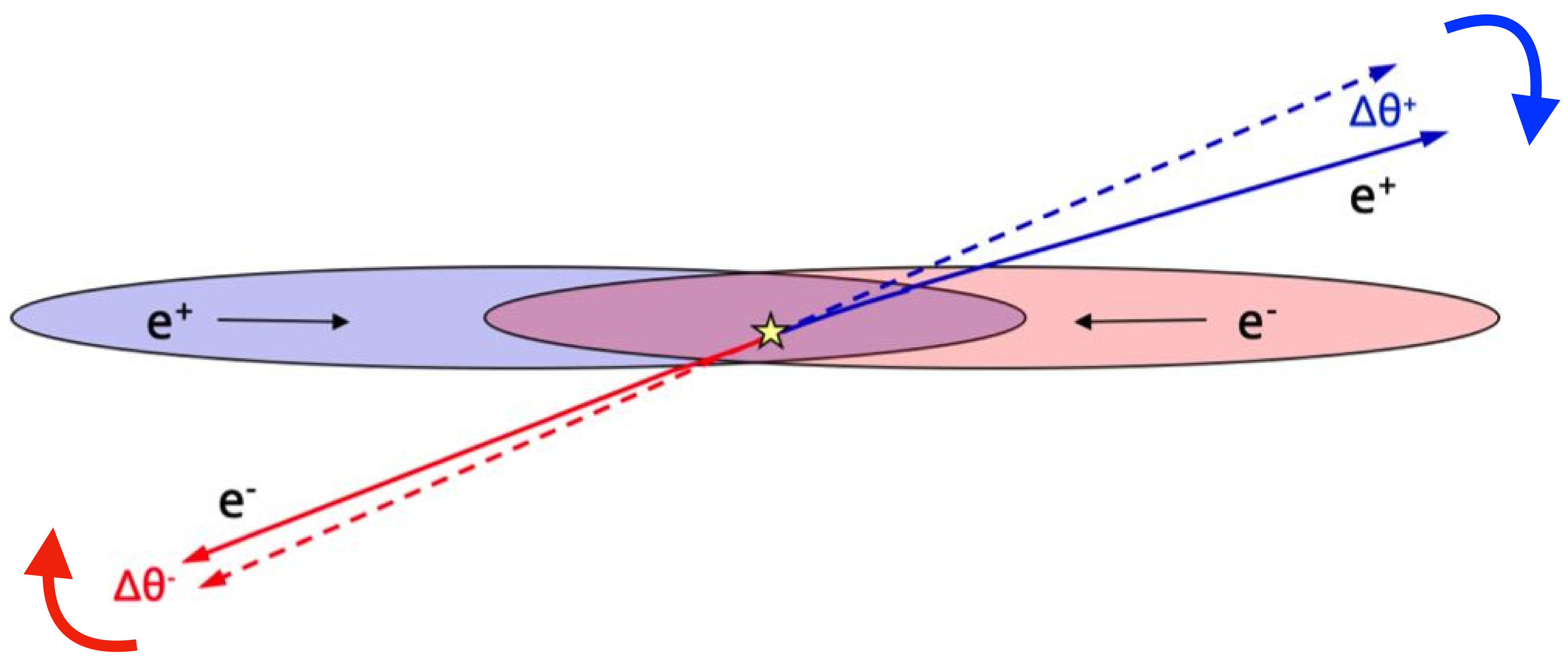
- First paper ever signed by over 2500 authors !

This is not the end of the story….

New insights on precision measurements emerging in context of studies for future e^+e^- colliders

“New” beam-beam effect

- Caused by large charge density bunches, which modify effective acceptance of luminosity calorimeters, biasing the luminosity
- Particle focused to lower polar angles by field of opposite-charge bunch
  → Number of e^+, e^- in acceptance is reduced



- Its impact first studied for a precise Luminosity measurement at the ILC
  [C.Rimbaud et al., JINST2(2007) P09001]

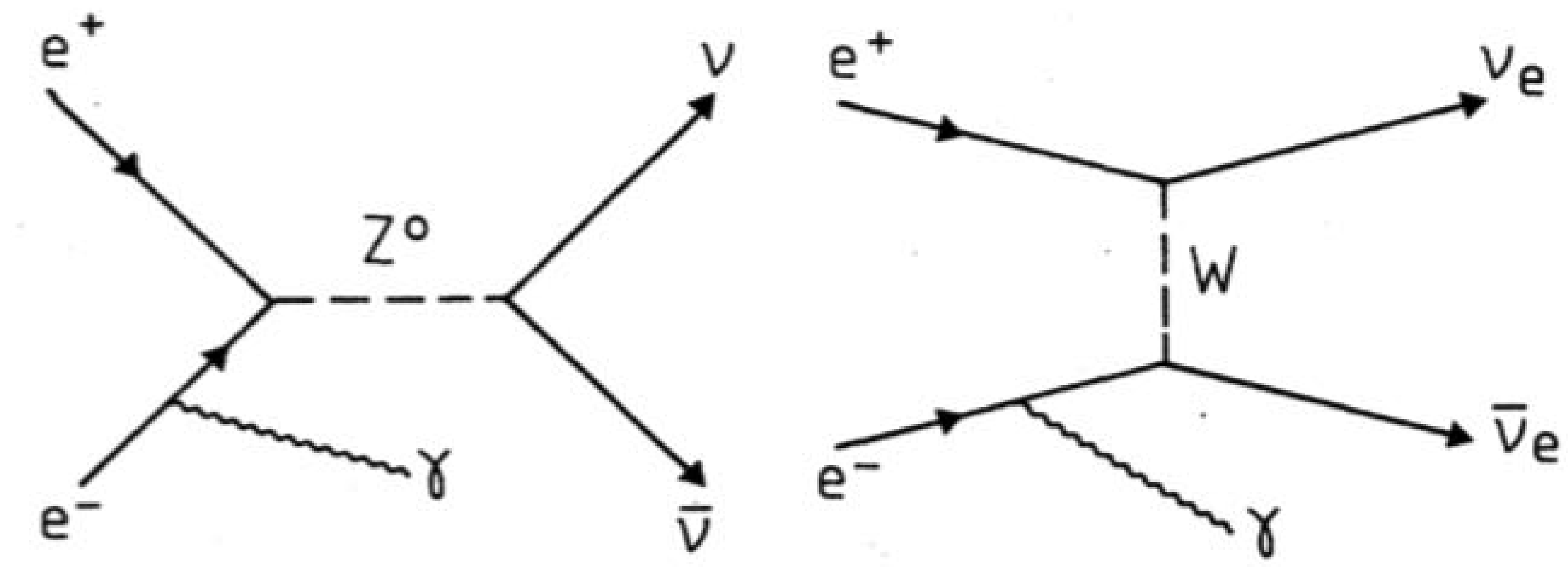
- Effect significant at LEP!

[PLB 800 (2020) 135068, arXiv:1908.01704
Voutsinas, Perez, Dam & Janot]

- Integrated luminosity underestimated by about 0.1%, which increases N_ν by ~1σ $(\delta N_\nu = +0.0078 \pm 0.0004)$
- $N_\nu = 2.9918 \pm 0.0081$ Long-standing 2σ deficit reduced to 1σ!
- Ongoing work on evaluating improved Bhabha cross-section @LEP profiting from new theory insights (from 0.061% to 0.037%)

An alternative method: $e^+e^- \to \nu\bar{\nu}\gamma$

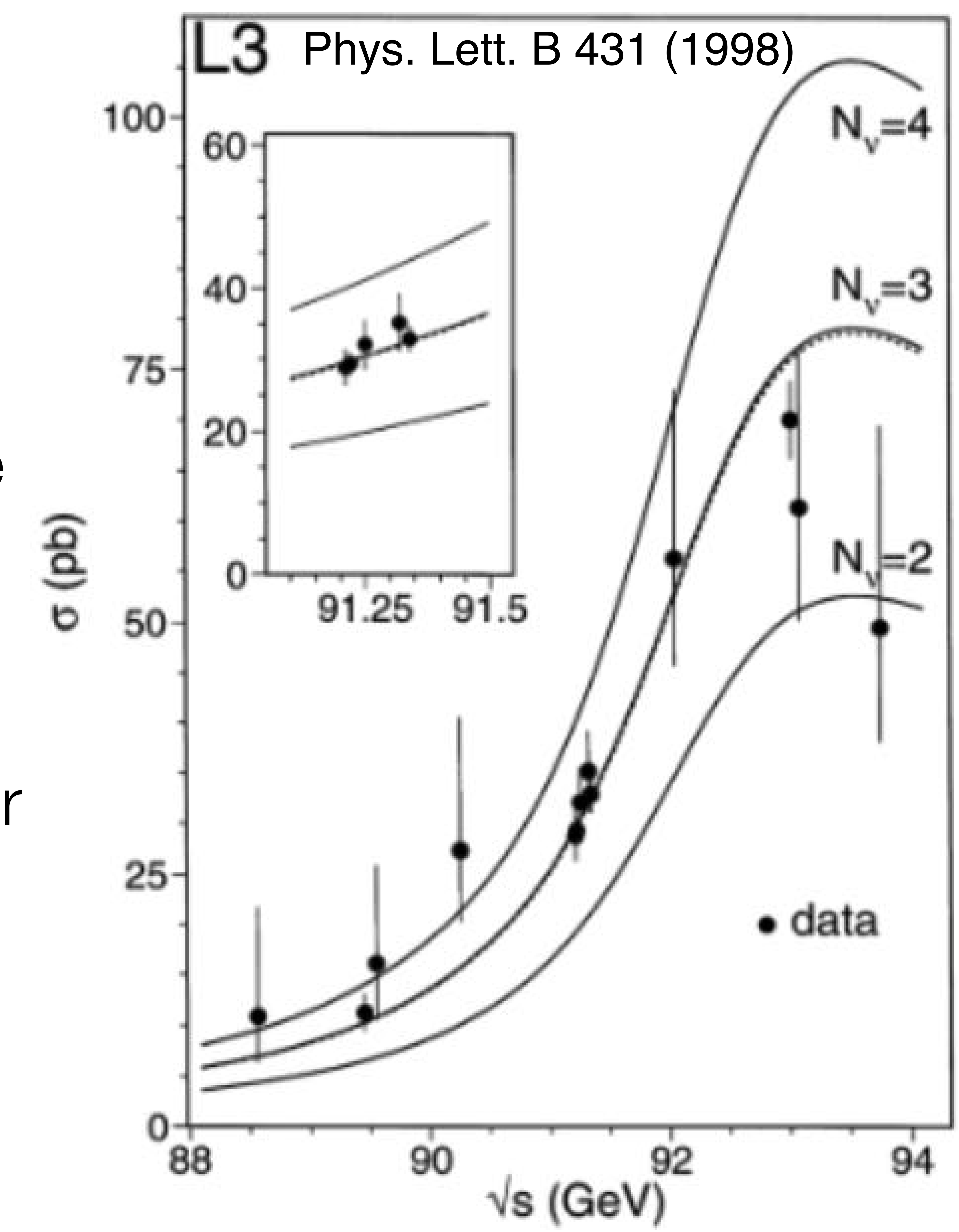
- Method originally advocated for neutrino counting: detect events with a single photon and nothing else at center-of-mass energies above the Z mass with radiative return to the Z



- Cross-section approximately proportional to N_ν (contribution from t-channel W-exchange is small)

- Around 2500 single-photon events collected by the four LEP experiments, giving $N_\nu = 3.00 \pm 0.08$

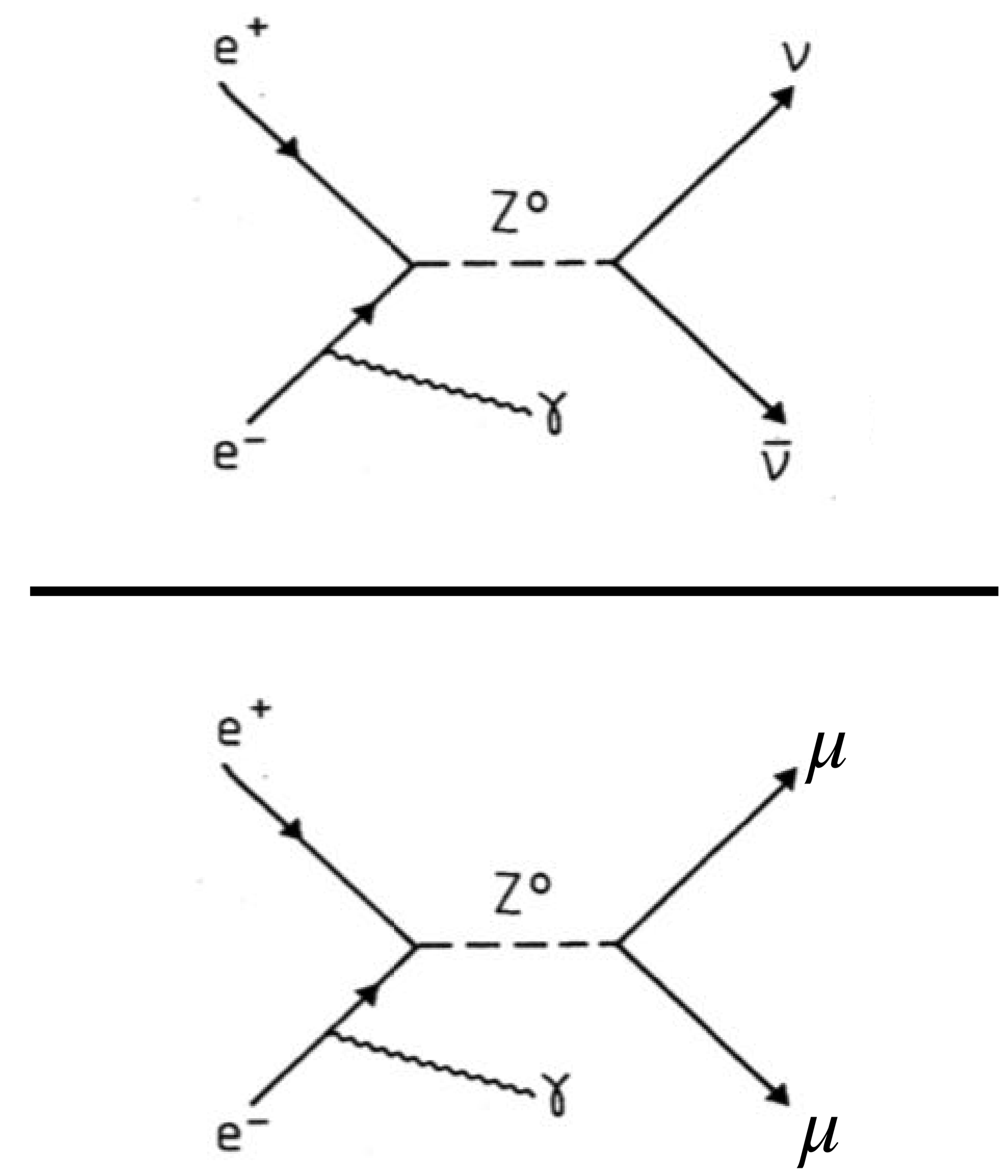
- By also including data at $130 < \sqrt{s}\,[\mathrm{GeV}] < 209$ for new physics searches, the LEP experiments collectively detected ~6200 single-photon events, giving $N_\nu = 2.92 \pm 0.05$



$e^+e^- \to \nu\bar{\nu}\gamma$ (The revival)

- Method advocated in FCC-ee studies for a high precision measurement of invisible partial width (sensitive to invisible particles, e.g. a neutralino, or to the mixing of heavy right-handed 'sterile' neutrinos with active ones)

- $$N_\nu = \frac{\gamma\,\Gamma_Z^{\rm inv}}{\gamma\,\Gamma_Z^{\rm lept}} \Big/ \left(\frac{\Gamma_\nu}{\Gamma_\ell}\right)_{\rm SM}$$



arXiv:1308.6176

- Ratio with common γ tag cancels many systematic uncertainties (e.g. luminosity, photon detection efficiency)

- Gain of a factor ~10 in precision on N_ν seems possible

Conclusions

- The measurement of the number of neutrino generations stands out as one of the legacies of the LEP physics programme. It ruled out for the first time the existence of a fourth generation, posing stringent limits on theoretical models relevant in astrophysics and cosmology

- The overall determination of the Standard Model parameters by the LEP experiments, with precision exceeding the initial expectations, and the proof of its unexpected consistency, marked a turning point in our field

- The story of success of the Standard Model continues with the results from the LHC, demonstrating its validity up to the multi-TeV range and possibly even beyond

- Still many questions remain unanswered: Why are there just three families of fundamental particles? What determines the pattern of their masses? These questions still lie at the centre of particle physics today