Number of neutrino families from LEP1 measurements

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The number of light neutrino families can be determined at LEP1, either indirectly through the line shape method, or directly through the radiative process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. We discussed the results obtained, in both cases, by the four LEP experiments, using the data collected near the Z resonance.

1. Introduction

At the end of the eighties, just before LEP was giving its first beams, limits on the number of neutrino generations N_ν were obtained from several independant methods. Experiments at lower energy e^+e^- colliders (TRISTAN, PEP, PETRA) using the neutrino counting method, discussed below, set a limit of $N_\nu < 4.8$. This result was based on a total of 3.9 events observed above background [1].
Experiments at p$\overline{p}$ colliders placed limits on N_ν by measuring the ratio of $W \rightarrow l\nu$ to $Z \rightarrow l^+l^-$ events. Standard Model (SM) values for the W total width and the ratio of W to Z leptonic widths are assumed. Results could only be obtained as a function of the top mass m_t, unknown at the time. Precision was limited both by statistics and knowledge of production cross sections. Combined measurements of UA1 and UA2 gave, for $m_t = 44$ GeV, the direct lower limit on m_t in 1989, a value of $N_\nu < 6$ at 95 % $C.L$ [2].
Considerations on the global energy released by a star in a supernova explosion and the observed energy in detectors in the case of supernova SN1987A provide also a limitation of N_ν[3]. More stringent limits on N_ν were set by cosmological nucleosynthesis [4]. Big bang production of ^4He increases with the number of massless neutrino species. More ν generations means more density and an earlier decoupling time, the time when nuclear reactions are no longer efficient and neutrons only decay. Consequently, the number of neutrons is higher at nucleosynthesis time and so ^4He production is higher [5]. An upper limit to the estimated primeval ^4He abundance leads to an upper limit of N_ν. Measurements in 1989, with conservative assumptions, indicated than $N_\nu \leq 4$. In summary, taking into account the available information based on the completely independant methods coming from accelerator data, astrophysics and cosmology, at most one extra relativistic ν generation was allowed.
At LEP, two different methods have been used to determine N_ν, an indirect method through the analysis of the Z lineshape, subtracting the visible partial widths Γ_h, Γ_l from the total width Γ_z and a direct method based on the measurement of the cross section for the radiative process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ with events containing a single photon arising from initial state radiation.

2. The line shape method

Assuming lepton universality, one can write:

$$\Gamma_{inv} = \Gamma_z - \Gamma_h - 3\Gamma_l. \quad (1)$$

Using results from SM one can use one of the following equations to extract N_ν:

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu^{SM}} \quad \text{or} \quad N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_l}\left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{\rm SM} \quad (2)$$

The computation of $\frac{\Gamma_l}{\Gamma_\nu}$ is preferred as one gets a better precision ($0.5\,^o/_{oo}$ instead of $1.2\,^o/_{oo}$) due to some systematic error cancellations.

Hadronic and leptonic cross sections obtained around the Z resonance, allow to obtain the lineshape parameters M_z, Γ_z, σ_0^h, R_l, where σ_0^h is the hadronic cross section at the peak and $R_l = \frac{\Gamma_h}{\Gamma_l}$ the ratio of hadronic to leptonic width.

Introducing these parameters in (1) using (2), one gets:

$$N_\nu = \left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{SM} (\sqrt{\frac{12\pi R_l}{M_z^2\sigma_0^h}} - R_l - 3) \qquad (3)$$

In 1989, after a short run and only a few thousands of hadronic Z decays, LEP experiments were already able to exclude a fourth generation of neutrinos at 95 % C.L. In fact, the result was mainly a confirmation of the existence of the third neutrino ν_τ.

The present data totalizes more than 15.10^6 hadronic Z decays. Figure 1 shows the combined results for the invisible to leptonic width ratio from the LEP Electroweak Working Group[6]: $\frac{\Gamma_{inv}}{\Gamma_l} = 5.941 \pm 0.016$, around 2 standard deviations below the expected SM value. From there : $\mathrm{N}_\nu^{LEP} = 2.9835 \pm 0.0083(exp) \pm 0.002(m_t, m_H)$ and $\Delta\Gamma_{inv} < 2.0$ MeV. Contributions outside the Standart Model is now restricted to less than 1.2 % of a ν generation (95% C.L), an outstanding result to be put on the LEP accelerator credit. From (3) systematic errors can be expressed as :

$$\Delta N_\nu = 7.5 \ \frac{\Delta\sigma_0}{\sigma_0} + 0.145 \ \Delta R_l + 0.16 \ \Delta M_z \qquad (4)$$

The main contribution comes from the first term, the error on the hadronic cross section which is of the order of 1.4 $^o\!/_{oo}$. This can be traced back to the uncertainty on the luminosity measurement. In the LEP proposals, the original goal was a 2 % measurement, but in 1991 a systematic error of 0.5 % was achieved. Thanks to a second generation of luminometers based on Si technology, precisions well below 1 $^o\!/_{oo}$ were obtained in the following years. This was mainly the result of a precise determination of the inner edge of the acceptance in the luminosity calculation. Remaining major contribution (1.1$^o\!/_{oo}$) was coming from the theoretical prediction for small angle Bhabha cross section. Recently a factor of two improvement has been gained using new calculations with better photonic corrections [7]. This is taken into account in the above mentionned result, so the given value must not be very far from the final LEP result on N_ν based on this method.

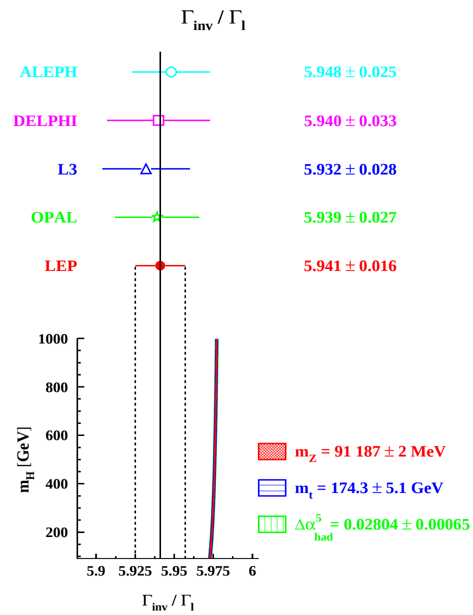

Figure 1. Invisible over leptonic width obtained by combining the results of the 4 LEP experiments.

3. The neutrino counting method

The neutrino counting or direct method measures the cross section of the reaction $e^+e^- \to \gamma + nothing$, which, in the SM, is dominated by the decay amplitude of the Z resonance into light neutrino pairs. Another contribution, involving only ν_e neutrinos, is coming from the W exchange amplitudes.

The differential cross section can be written as

$$\frac{d^2\sigma}{dE_\gamma d\cos\theta_\gamma} = H(E_\gamma, \cos\theta_\gamma, s)\sigma_0(s') \qquad (5)$$

where H is a radiator function for a photon of energy E_γ at angle θ_γ with respect to the beam axis, s is the square of the center of mass energy and $s' = s(1 - 2E_\gamma/\sqrt{s})$. In lowest order, σ_0 is given by:

$$\sigma_0(s) = \frac{12\pi}{M_Z^2} \frac{s\Gamma_e \mathrm{N}_\nu \Gamma_\nu}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} + W\ terms (6)$$

Table 1
LEP1 results on N_ν with the neutrino counting method

	Acceptance E_γ *in GeV*	*Year*	$\int \mathcal{L}$ dt pb^{-1}	N_{data}	N_{back}	Γ_{inv} *in MeV*	N_ν	ΔN_ν
Aleph	$\|cos\theta\| < 0.74$	$90-91$	15.7	400	140.1	450.	2.68	0.28
	$E_\gamma > 1.5$					$\pm 34 \pm 34$	$\pm 0.20 \pm 0.20$	
Delphi	$\|cos\theta\| < 0.70$	$93-94$	67.6	106	14.3		2.89	0.37
	$E_\gamma > 3.$						$\pm 0.32 \pm 0.19$	
L3	$\|cos\theta\| < 0.71$	$91-94$	99.9	2091	297.0	498.	2.98	0.10
	$E_\gamma > 1.$					$\pm 12 \pm 12$	$\pm 0.07 \pm 0.07$	
Opal	$\|cos\theta\| < 0.70$	$90-92$	40.5	447	37.1	539.	3.23	0.19
	$E_\gamma > 1.75$					$\pm 26 \pm 17$	$\pm 0.16 \pm 0.10$	

At $\sqrt{s} = M_Z$, the W contribution is only a few %, the first term is dominant and the cross section is proportional to N_ν.

3.1. Why two methods to measure N_ν?

Systematic errors in direct and indirect methods are different and the first one is statistically limited due to the need of a radiative photon. If no new physics appears, the 2 methods measure, with different uncertainties, the same quantity. In general, the sensitivity to new physics will be different. New physics will lead to a non integer value of N_ν. Some exotic mechanisms can decrease N_ν to less than 3, even with 3 neutrinos [8]. Multiple scenarios can be constructed with different contributions in both methods. For instance, a forth unstable neutrino, decaying in the detector will not change the value of N_ν in neutrino counting. In the line shape method, if decays are not accounted as hadronic or leptonic decays, the apparent Γ_{inv} will increase. The indirect method measures the *non seen* width. Any exotic Z decay, not seen as hadron or lepton decay will be counted as invisible, but generally, events will not be selected in the direct method. In addition, the latter gives two specific observables which are of great interest in the search for possible new physics:

- the photon energy spectrum,
- the cross section versus $\sqrt{s}$

New physics can generate peaks in the energy spectrum or increase the cross section outside (below) the Z resonance. In both cases, this will go unnoticed in the indirect method.

3.2. Experimental conditions

The measurement is optimally carried out at energies a few GeV above the Z mass, where initial state photon radiation brings the e^+e^- center of mass energy down to the Z resonance. So, contrary to most other processes, the cross section does not peak at the resonance, but slightly above, depending on the photon energy. However the cross section can still be substantial at the Z peak and allows a meaningful measure of the number of neutrino families. In these conditions, the photons have low energies with a rapidly falling spectrum, requiring the two following experimental conditions to be realized:

- the capacity to trigger the detector on low energy single photons,
- a good hermiticity at very low angles for the rejection of background.

Main background comes from the radiative low Q^2 Bhabha scattering when both electrons escape detection in the beam pipe or in some inactive region if any. It increases quickly in the forward direction and, consequently, only the central part of the electromagnetic calorimeter is used for the photon detection. Decreasing the energy threshold gives access to higher statistics for the signal but this is valid only if, at the same time, hermiticity is assured down to lower angle. The detection of scattered electrons down to very small angle, in the luminosity detector is then particularly important.

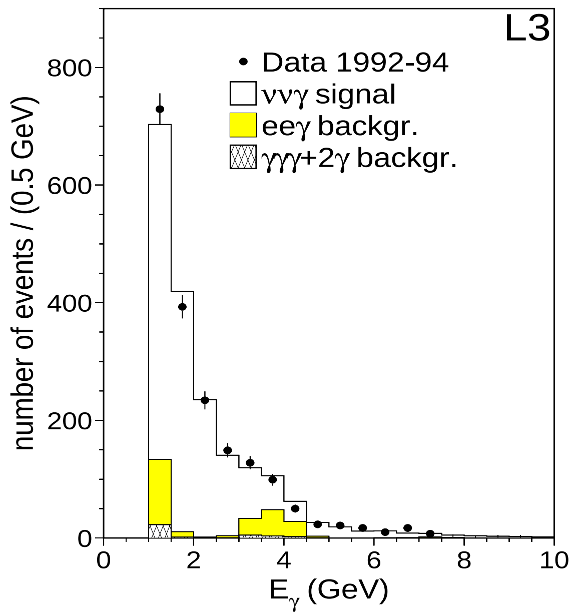

Figure 2. Energy spectrum of the single photons for data and Monte Carlo predictions [9,10] obtained by L3

Others backgrounds include annihilation into three photons $e^+e^- \rightarrow \gamma\gamma\gamma$, and cosmic ray contributions. To reduce sensitivity to cosmic muons, experiments use timing information (signal must be in coincidence with the beam crossing) or shape of the electromagnetic shower (which must be electromagnetic and coming from the vertex region).
Single electron events, coming from inverse Compton scattering, are very useful data. Topology is the same as the signal (except for a charged track) but the cross section is a factor 10 higher. So, the applied cuts can be studied on this reaction, and the trigger efficiency, one of the main contribution to the systematic error of the method, measured (thanks to an independant trigger using the tracking information). Moreover, the same generator [9] is describing, both the single electron channel and the radiative low Q^2 Bhabha scattering, the main background. The prediction of the generator can then be checked on the large sample of single electrons events.

3.3. Results

The experimental signature of $Z \rightarrow \nu\bar{\nu}\gamma$ events is a single electromagnetic shower and no other activity except the one which is consistent with noise. The obtained energy spectrum of the single photon candidates is shown in Figure 2, in case of L3, together with the Monte Carlo prediction for the signal expected from 3 light neutrino families and the backgrounds.
Data published by the 4 LEP experiments [11] are summarized in Table 1. The selected event sample, together with the integrated luminosity, the expected number of background events and the extracted results are shown. Notice that only L3 has made full use of the whole available luminosity. Figure 3 shows the corrected L3 cross sections for the $\nu\bar{\nu}\gamma$ (γ) process as a function of the center of mass energy, together with expectations corresponding to N_ν equal to two, three and four respectively. The number of light neutrino families is extracted by performing a maximum likelihood fit to the number of candidates using equation (5) to get the expected numbers. The L3 result is :
$N_\nu = 2.98 \pm 0.07(stat) \pm 0.07(syst)$
Any increase in statistics would imply further work to reduce the systematic errors. Contrary to the line shape method, luminosity or theoretical predictions are not the main sources of errors. Those are mainly due to the uncertainties to the trigger efficiency, the background subtraction, the absolute energy scale calibration and the cosmic ray contamination.

4. Conclusions

Both direct and indirect methods have been used at LEP1 and have produced valuable measurements of the number of neutrino families. Definitely, they have shown that there are only 3 light neutrinos. The 2 methods are different, the indirect method measures the *non seen* width (non hadrons, non leptons), the direct method measures directly the *invisible* cross section, proportional to N_ν. Systematic errors are different in

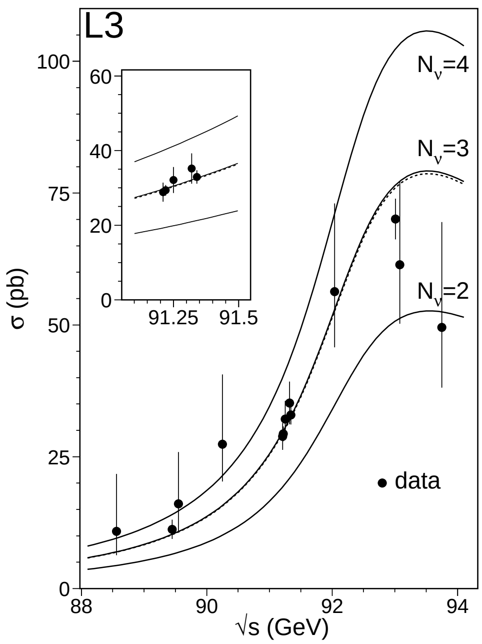

Figure 3. Corrected experimental cross section for the $\nu\bar{\nu}\gamma$ (γ) process as a function of center of mass energy for $E_\gamma > 1.$ GeV and $|\cos\theta < 0.71$.

both methods. The first one is essentially limited be the luminosity measurement and by the precision on the theoretical calculations of low angle Bhabha scattering. The second method comes up against both statistical and systematic problems. However, single photon measurement has given specific observables of interest for tagging possible new physics and it continues to be widely used at LEP2. Also, with the increased statistics at high energy, the number of neutrino families can also be extracted from the single photon energy spectrum, this time with a different systematics. Combining with the results of LEP1 would significantly improve the final result of the neutrino counting method.

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