Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

Number of Neutrino Types and Sum of Neutrino Masses

The neutrinos referred to in this section are those of the Standard SU(2)×U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m < m_Z/2$. The limits are on the number of neutrino mass eigenstates, including ν_1, ν_2, and ν_3.

THE NUMBER OF LIGHT NEUTRINO TYPES FROM COLLIDER EXPERIMENTS

Revised August 2001 by D. Karlen (Carleton University).

The most precise measurements of the number of light neutrino types, N_ν, come from studies of Z production in e^+e^- collisions. The invisible partial width, $\Gamma_{\rm inv}$, is determined by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{\rm SM} = 1.991\pm0.001$, is used instead of $(\Gamma_\nu)_{\rm SM}$ to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM} \quad . \tag{1}$$

The combined result from the four LEP experiments is $N_\nu = 2.984 \pm 0.008$ [1].

In the past, when only small samples of Z decays had been recorded by the LEP experiments and by the Mark II at SLC, the uncertainty in N_ν was reduced by using Standard Model fits to the measured hadronic cross sections at several center-of-mass energies near the Z resonance. Since this method is much more dependent on the Standard Model, the approach described above is favored.

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy e^+e^- colliders by measuring the cross section of the process $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. The ASP, CELLO, MAC, MARK J, and VENUS experiments observed a total of 3.9 events above background [2], leading to a 95% CL limit of $N_\nu < 4.8$. This process has a much larger cross section at center-of-mass energies near the Z mass and has been measured at LEP by the ALEPH, DELPHI, L3, and OPAL experiments [3]. These experiments have observed several thousand such events, and the combined result is $N_\nu = 3.00 \pm 0.08$. The same process has also been measured by the LEP experiments at much higher center-of-mass energies, between 130 and 208 GeV, in searches for new physics [4]. Combined, the measured cross section is 0.982 ± 0.012 (stat) of that expected for three light neutrino generations [5].

Experiments at $p\overline{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \rightarrow \ell^\pm\nu$ to $Z \rightarrow \ell^+\ell^-$ events [6]. This involved a calculation that assumed Standard Model values for the total W width and the ratio of W and Z leptonic partial widths, and used an estimate of the ratio of Z to W production cross sections. Now that the Z width is very precisely known from the LEP experiments, the approach is now one of those used to determine the W width.

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Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value $\Gamma_\nu/\Gamma_\ell = 1.9908 \pm 0.0015$.

VALUE	DOCUMENT ID	TECN
2.994±0.012 OUR EVALUATION	Combined fit to all LEP data.	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.00 ±0.05	[1] LEP 92	RVUE

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–209 GeV.

VALUE	DOCUMENT ID	TECN	COMMENT
2.92±0.07 OUR AVERAGE			
2.86 ± 0.09	HEISTER 03C	ALEP	$\sqrt{s}$=189–209 GeV
2.69±0.13±0.11	ABBIENDI,G 00D	OPAL	1998 LEP run
2.84±0.15±0.14	ABREU 00Z	DLPH	1997–1998 LEP runs
3.01±0.08	ACCIARRI 99R	L3	1991–1998 LEP runs
2.89±0.32±0.19	ABREU 97J	DLPH	1993–1994 LEP runs
2.68±0.20±0.20	BUSKULIC 93L	ALEP	1990–1991 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.1 ±0.6 ±0.1	ADAM 96C	DLPH	$\sqrt{s}$ = 130, 136 GeV

Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means $<$ about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3.3	[2] BARGER	03C	COSM	
$1.4 < N_\nu < 6.8$	[3] CROTTY	03	COSM	
< 3.6	[4] CYBURT	03	COSM	
$1.9 < N_\nu < 7.0$	[5] HANNESTAD	03B	COSM	
$1.9 < N_\nu < 6.6$	[3] PIERPAOLI	03	COSM	
$2 < N_\nu < 4$	LISI	99		BBN
< 4.3	OLIVE	99		BBN
< 4.9	COPI	97		Cosmology
< 3.6	HATA	97B		High D/H quasar abs.
< 4.0	OLIVE	97		BBN; high ^{4}He and ^{7}Li
< 4.7	CARDALL	96B		Cosmology, High D/H quasar abs.
< 3.9	FIELDS	96		Cosmology, BBN; high ^{4}He and ^{7}Li
< 4.5	KERNAN	96		Cosmology, High D/H quasar abs.
< 3.6	OLIVE	95		BBN; ≥ 3 massless ν
< 3.3	WALKER	91		Cosmology
< 3.4	OLIVE	90		Cosmology
< 4	YANG	84		Cosmology
< 4	YANG	79		Cosmology
< 7	STEIGMAN	77		Cosmology
	PEEBLES	71		Cosmology
< 16	[6] SHVARTSMAN	69		Cosmology
	HOYLE	64		Cosmology

[2] Limit on the number of neutrino types based on combination of WMAP data and big-bang nucleosynthesis. The limit from WMAP data alone is 8.3. See also KNELLER 01. $N_\nu \geq 3$ is assumed to compute the limit.

[3] 95% confidence level range on the number of neutrino flavors from WMAP data combined with other CMB measurements, the 2dfGRS data, and HST data.

[4] Limit on the number of neutrino types based on ^{4}He abundance assuming a baryon density fixed by the WMAP data. Limit relaxes to 5.2 if D/H is used instead of ^{4}He. See also CYBURT 01. $N_\nu \geq 3$ is assumed to compute the limit.

[5] 95% confidence level range on the number of neutrino flavors from WMAP data combined with other CMB measurements, the 2dfGRS data, HST data, and SN1a data.

[6] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*DOCUMENT ID*		*TECN*
< 20	[7] OLIVE	81C	COSM
< 20	[7] STEIGMAN	79	COSM

[7] Limit varies with strength of coupling. See also WALKER 91.

Revised April 1998 by K.A. Olive (University of Minnesota).

The limits on low mass ($m_\nu \lesssim 1$ MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu \ ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. Stable neutrinos in this mass range make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu = m_{\rm tot}(3/11) n_\gamma \ ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where ρ_c is the critical energy density of the Universe, and using $n_\gamma = 412\ {\rm cm}^{-3}$, we have

$$\Omega_\nu h^2 = m_{\rm tot}/(94\ {\rm eV}) \ .$$

Therefore, a limit on $\Omega_\nu h^2$ such as $\Omega_\nu h^2 < 0.25$ gives the limit

$$m_{\rm tot} < 24\ {\rm eV} \ .$$

The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, $m_{\rm tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\rm tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 1.0	[8] HANNESTAD	03B	COSM	
< 0.7	[9] SPERGEL	03	COSM	WMAP

$<$ 1.8	[10] ELGAROY	02	ASTR	2dF Galaxy Redshift Survey
$<$ 0.9	[11] LEWIS	02	COSM	
$<$ 4.2	[12] WANG	02	COSM	CMB
$<$ 2.7	[13] FUKUGITA	00	COSM	
$<$ 5.5	[14] CROFT	99	ASTR	Ly α power spec
$<$180	SZALAY	74	COSM	
$<$132	COWSIK	72	COSM	
$<$280	MARX	72	COSM	
$<$400	GERSHTEIN	66	COSM	

[8] Constrains the fractional contribution of neutrinos to the total matter density in the Universe from WMAP data combined with other CMB measurements, the 2dfGRS data, HST data, and SN1a data.

[9] Constrains the fractional contribution of neutrinos to the total matter density in the Universe from WMAP data combined with other CMB measurements, the 2dfGRS data, and Lyman α data. The limit does not noticeably change if the Lyman α data are not used.

[10] ELGAROY 02 constrains the fractional contribution of neutrinos to the total matter density in the Universe from the power spectrum of fluctuations derived from the 2 Degree Field Galaxy Redshift Survey. Assumes $\Omega_{\text{matter}} < 0.5$ and a spectral index of 1.0. Limit softens to $m_\nu < 2.2$ eV for n=1.0 ± 0.1.

[11] LEWIS 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB, HST Key project, 2dF galaxy redshift survey, supernovae type Ia, and BBN.

[12] WANG 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB and other cosmological data sets such as galaxy clustering and the Lyman α forest.

[13] FUKUGITA 00 is a limit on neutrino masses from structure formation. The constraint is based on the clustering scale σ_8 and the COBE normalization and leads to a conservative limit of 0.9 eV assuming 3 nearly degenerate neutrinos. The quoted limit is on the sum of the light neutrino masses.

[14] CROFT 99 result based on the power spectrum of the Ly α forest. If $\Omega_{\text{matter}} < 0.5$, the limit is improved to $m_\nu < 2.4\ (\Omega_{\text{matter}}/0.17\text{–}1)$ eV.

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$100–200	[15] OLIVE	82	COSM	Dirac ν
$<$200–2000	[15] OLIVE	82	COSM	Majorana ν

[15] Depending on interaction strength G_R where $G_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>$ 10	[16] OLIVE	82	COSM	$G_R/G_F < 0.1$
$>$100	[16] OLIVE	82	COSM	$G_R/G_F < 0.01$

[16] These results apply to heavy Majorana neutrinos and are summarized by the equation: $m_\nu > 1.2$ GeV (G_F/G_R). The bound saturates, and if G_R is too small no mass range is allowed.

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HEISTER	03C	EPJ C28 1	A. Heister *et al.*	(ALEPH Collab.)
PIERPAOLI	03	MNRAS 342 L63	E. Pierpaoli	
SPERGEL	03	APJS 148 175	D.N. Spergel *et al.*	
ELGAROY	02	PRL 89 061301	O. Elgaroy *et al.*	
LEWIS	02	PR D66 103511	A. Lewis, S. Bridle	
WANG	02	PR D65 123001	X. Wang, M. Tegmark, M. Zaldarriaga	
CYBURT	01	ASP 17 87	R.H. Cyburt, B.D. Fields, K.A. Olive	
KNELLER	01	PR D64 123506	J.P. Kneller *et al.*	
ABBIENDI,G	00D	EPJ C18 253	G. Abbiendi *et al.*	(OPAL Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
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ACCIARRI	99R	PL B470 268	M. Acciarri *et al.*	(L3 Collab.)
CROFT	99	PRL 83 1092	R.A.C. Croft, W. Hu, R. Dave	
LISI	99	PR D59 123520	E. Lisi, S. Sarkar, F.L. Villante	
OLIVE	99	ASP 11 403	K.A. Olive, D. Thomas	
ABREU	97J	ZPHY C74 577	P. Abreu *et al.*	(DELPHI Collab.)
COPI	97	PR D55 3389	C.J. Copi, D.N. Schramm, M.S. Turner	(CHIC)
HATA	97B	PR D55 540	N. Hata *et al.*	(OSU, PENN)
OLIVE	97	ASP 7 27	K.A. Olive, D. Thomas	(MINN, FLOR)
ADAM	96C	PL B380 471	W. Adam *et al.*	(DELPHI Collab.)
CARDALL	96B	APJ 472 435	C.Y. Cardall, G.M. Fuller	(UCSD)
FIELDS	96	New Ast 1 77	B.D. Fields *et al.*	(NDAM, CERN, MINN+)
KERNAN	96	PR D54 3681	P.S. Kernan, S. Sarkar	(CASE, OXFTP)
OLIVE	95	PL B354 357	K.A. Olive, G. Steigman	(MINN, OSU)
BUSKULIC	93L	PL B313 520	D. Buskulic *et al.*	(ALEPH Collab.)
LEP	92	PL B276 247	LEP Collabs.	(LEP, ALEPH, DELPHI, L3, OPAL)
WALKER	91	APJ 376 51	T.P. Walker *et al.*	(HSCA, OSU, CHIC+)
DENEGRI	90	RMP 62 1	D. Denegri, B. Sadoulet, M. Spiro	(CERN, UCB+)
OLIVE	90	PL B236 454	K.A. Olive *et al.*	(MINN, CHIC, OSU+)
COWSIK	85	PL 151B 62	R. Cowsik	(TATA)
FREESE	84	NP B233 167	K. Freese, D.N. Schramm	(CHIC, FNAL)
SCHRAMM	84	PL 141B 337	D.N. Schramm, G. Steigman	(FNAL, BART)
YANG	84	APJ 281 493	J. Yang *et al.*	(CHIC, BART)
OLIVE	82	PR D25 213	K.A. Olive, M.S. Turner	(CHIC, UCSB)
BERNSTEIN	81	PL 101B 39	J. Bernstein, G. Feinberg	(STEV, COLU)
OLIVE	81	APJ 246 557	K.A. Olive *et al.*	(CHIC, BART)
OLIVE	81C	NP B180 497	K.A. Olive, D.N. Schramm, G. Steigman	(EFI+)
STEIGMAN	79	PRL 43 239	G. Steigman, K.A. Olive, D.N. Schramm	(BART+)
YANG	79	APJ 227 697	J. Yang *et al.*	(CHIC, YALE, VIRG)
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