Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Number of Neutrino Types

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 March 2008 by D. Karlen (University of Victoria and TRIUMF).

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, $(\Gamma_\nu/\Gamma_\ell)_{\rm SM} = 1.991 \pm 0.001$, 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 $e^+e^- \to \nu\overline{\nu}\gamma$. 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 with the lower energy data, the result is $N_\nu = 2.92 \pm 0.05$.

Experiments at $p\overline{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \to \ell^\pm\nu$ to $Z \to \ell^+\ell^-$ events [5]. 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.

References

1. ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and LEP Electroweak Working Group, and SLD Electroweak Group, and SLD Heavy Flavour Group, Phys. Reports **427**, 257 (2006).

2. VENUS: K. Abe *et al.*, Phys. Lett. **B232**, 431 (1989);
   ASP: C. Hearty *et al.*, Phys. Rev. **D39**, 3207 (1989);
   CELLO: H.J. Behrend *et al.*, Phys. Lett. **B215**, 186 (1988);
   MAC: W.T. Ford *et al.*, Phys. Rev. **D33**, 3472 (1986);
   MARK J: H. Wu, Ph.D. Thesis, Univ. Hamburg (1986).
3. L3: M. Acciarri *et al.*, Phys. Lett. **B431**, 199 (1998);
   DELPHI: P. Abreu *et al.*, Z. Phys. **C74**, 577 (1997);
   OPAL: R. Akers *et al.*, Z. Phys. **C65**, 47 (1995);
   ALEPH: D. Buskulic *et al.*, Phys. Lett. **B313**, 520 (1993).
4. DELPHI: J. Abdallah *et al.*, Eur. Phys. J. **C38**, 395 (2005);
   L3: P. Achard *et al.*, Phys. Lett. **B587**, 16 (2004);
   ALEPH: A. Heister *et al.*, Eur. Phys. J. **C28**, 1 (2003);
   OPAL: G. Abbiendi *et al.*, Eur. Phys. J. **C18**, 253 (2000).
5. UA1: C. Albajar *et al.*, Phys. Lett. **B198**, 271 (1987);
   UA2: R. Ansari *et al.*, Phys. Lett. **B186**, 440 (1987).

Number from e^+e^- Colliders

Number of Light ν Types

VALUE	*DOCUMENT ID*		*TECN*
2.9963±0.0074	[1] JANOT	20	

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

VALUE	*DOCUMENT ID*		*TECN*
2.9918±0.0081	[2] VOUTSINAS	20	
2.9840±0.0082	[3] LEP-SLC	06	RVUE
3.00 ±0.05	[4] LEP	92	RVUE

[1] JANOT 20 applies a correction to LEP-SLC 06 using an updated Bhabha cross section calculation. This result also includes a correction to account for correlated luminosity bias as presented in VOUTSINAS 20.

[2] VOUTSINAS 20 applies a correction to LEP-SLC 06 to account for correlated luminosity bias.

[3] Combined fit from ALEPH, DELPHI, L3 and OPAL Experiments.

[4] 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 $e^+e^- \to \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–209 GeV.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
2.92±0.05 OUR AVERAGE	Error includes scale factor of 1.2.			
2.84±0.10±0.14	ABDALLAH	05B	DLPH	$\sqrt{s}$ = 180–209 GeV
2.98±0.05±0.04	ACHARD	04E	L3	1990-2000 LEP runs
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
2.89±0.32±0.19	ABREU	97J	DLPH	1993–1994 LEP runs
3.23±0.16±0.10	AKERS	95C	OPAL	1990–1992 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. • • •

$2.84 \pm 0.15 \pm 0.14$	ABREU	00Z	DLPH	1997–1998 LEP runs
3.01 ± 0.08	ACCIARRI	99R	L3	1991–1998 LEP runs
$3.1 \pm 0.6 \pm 0.1$	ADAM	96C	DLPH	$\sqrt{s} = 130$, 136 GeV

Limits from Astrophysics and Cosmology

Effective Number of Light ν Types

"Light" means here with a mass < about 1 MeV. The quoted values correspond to N_{eff}, where $N_{\text{eff}} = 3.045$ in the Standard Model with $N_\nu = 3$. See also reviews on "Big-Bang Nucleosynthesis" and "Neutrinos in Cosmology."

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.3–3.2	95	[1] VERDE	17	COSM	
2.88 ± 0.20	95	[2] ROSSI	15	COSM	
3.3 ± 0.5	95	[3] ADE	14	COSM	Planck
$3.78^{+0.31}_{-0.30}$		[4] COSTANZI	14	COSM	
3.29 ± 0.31		[5] HOU	14	COSM	
< 3.80	95	[6] LEISTEDT	14	COSM	
< 4.10	95	[7] MORESCO	12	COSM	
< 5.79	95	[8] XIA	12	COSM	
< 4.08	95	MANGANO	11	COSM	BBN
0.9–8.2		[9] ICHIKAWA	07	COSM	
3–7	95	[10] CIRELLI	06	COSM	
2.7–4.6	95	[11] HANNESTAD	06	COSM	
3.6–7.4	95	[10] SELJAK	06	COSM	
< 4.4		[12] CYBURT	05	COSM	
< 3.3		[13] BARGER	03C	COSM	
1.4–6.8		[14] CROTTY	03	COSM	
1.9–6.6		[14] PIERPAOLI	03	COSM	
2–4		LISI	99	COSM	BBN
< 4.3		OLIVE	99	COSM	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	COSM	High D/H quasar abs.
< 3.9		FIELDS	96	COSM	BBN; high ^{4}He and ^{7}Li
< 4.5		KERNAN	96	COSM	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		[15] SHVARTSMAN	69		Cosmology
		HOYLE	64		Cosmology

[1] Uses Planck Data combined with an independent standard measure of distance to the sound horizon to set a limit on the total number of neutrinos. Only CMB and early-time information are used.

[2] ROSSI 15 sets limits on the number of neutrino types using BOSS Lyman alpha forest data combined with Planck CMB data and baryon acoustic oscillations.

[3] Fit to the number of neutrino degrees of freedom from Planck CMB data along with WMAP polarization, high L, and BAO data.

[4] Fit to the number of neutrinos degrees of freedom from Planck CMB data along with BAO, shear and cluster data.

[5] Fit based on the SPT-SZ survey combined with CMB, BAO, and H_0 data.

[6] Constrains the number of neutrino degrees of freedom (marginalizing over the total mass) from CMB, CMB lensing, BAO, and galaxy clustering data.

[7] Limit on the number of light neutrino types from observational Hubble parameter data with seven-year WMAP data, SPT, and the most recent estimate of H_0. Best fit is 3.45 ± 0.65.

[8] Limit on the number of light neutrino types from the CFHTLS combined with seven-year WMAP data and a prior on the Hubble parameter. Best fit is $4.17^{+1.62}_{-1.26}$. Limit is relaxed to $3.98^{+2.02}_{-1.20}$ when small scales affected by non-linearities are removed.

[9] Constrains the number of neutrino types from recent CMB and large scale structure data. No priors on other cosmological parameters are used.

[10] Constrains the number of neutrino types from recent CMB, large scale structure, Lyman-alpha forest, and SN1a data. The slight preference for $N_\nu > 3$ comes mostly from the Lyman-alpha forest data.

[11] Constrains the number of neutrino types from recent CMB and large scale structure data. See also HAMANN 07.

[12] Limit on the number of neutrino types based on ^{4}He and D/H abundance assuming a baryon density fixed to the WMAP data. Limit relaxes to 4.6 if D/H is not used or to 5.8 if only D/H and the CMB are used. See also CYBURT 01 and CYBURT 03.

[13] 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.

[14] 95% confidence level range on the number of neutrino flavors from WMAP data combined with other CMB measurements, the 2dfGRS data, and HST data.

[15] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

VALUE	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<20	[1] OLIVE	81C	COSM
<20	[1] STEIGMAN	79	COSM

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

REFERENCES FOR Limits on Number of Neutrino Types

JANOT	20	PL B803 135319	P. Janot, S. Jadach	(CERN, CRAC)
VOUTSINAS	20	PL B800 135068	G. Voutsinas *et al.*	(CERN, BOHR)
VERDE	17	JCAP 1704 023	L. Verde *et al.*	
ROSSI	15	PR D92 063505	G. Rossi *et al.*	
ADE	14	AA 571 A16	P.A.R. Ade *et al.*	(Planck Collab.)
COSTANZI	14	JCAP 1410 081	M. Costanzi *et al.*	(TRST, TRSTI)
HOU	14	APJ 782 74	Z. Hou *et al.*	
LEISTEDT	14	PRL 113 041301	B. Leistedt, H.V. Peiris, L. Verde	
MORESCO	12	JCAP 1207 053	M. Moresco *et al.*	
XIA	12	JCAP 1206 010	J.-Q. Xia *et al.*	
MANGANO	11	PL B701 296	G. Mangano, P. Serpico	
HAMANN	07	JCAP 0708 021	J. Hamann *et al.*	
ICHIKAWA	07	JCAP 0705 007	K. Ichikawa, M. Kawasaki, F. Takahashi	
CIRELLI	06	JCAP 0612 013	M. Cirelli *et al.*	
HANNESTAD	06	JCAP 0611 016	S. Hannestad, G. Raffelt	
LEP-SLC	06	PRPL 427 257	ALEPH, DELPHI, L3, OPAL, SLD and working groups	

SELJAK	06	JCAP 0610 014	U. Seljak, A. Slosar, P. McDonald	
ABDALLAH	05B	EPJ C38 395	J. Abdallah *et al.*	(DELPHI Collab.)
CYBURT	05	ASP 23 313	R.H. Cyburt *et al.*	
ACHARD	04E	PL B587 16	P. Achard *et al.*	(L3 Collab.)
BARGER	03C	PL B566 8	V. Barger *et al.*	
CROTTY	03	PR D67 123005	P. Crotty, J. Lesgourgues, S. Pastor	
CYBURT	03	PL B567 227	R.H. Cyburt, B.D. Fields, K.A. Olive	
HEISTER	03C	EPJ C28 1	A. Heister *et al.*	(ALEPH Collab.)
PIERPAOLI	03	MNRAS 342 L63	E. Pierpaoli	
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.)
ACCIARRI	99R	PL B470 268	M. Acciarri *et al.*	(L3 Collab.)
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)
AKERS	95C	ZPHY C65 47	R. Akers *et al.*	(OPAL Collab.)
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+)
OLIVE	90	PL B236 454	K.A. Olive *et al.*	(MINN, CHIC, OSU+)
YANG	84	APJ 281 493	J. Yang *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, UVA)
STEIGMAN	77	PL 66B 202	G. Steigman, D.N. Schramm, J.E. Gunn	(YALE, CHIC+)
PEEBLES	71	Physical Cosmology	P.Z. Peebles	(PRIN)
Princeton Univ. Press (1971)				
SHVARTSMAN	69	JETPL 9 184 Translated from ZETFP 9 315.	V.F. Shvartsman	(MOSU)
HOYLE	64	NAT 203 1108	F. Hoyle, R.J. Tayler	(CAMB)