Neutrino Masses @ PDG

Ramon Miquel (ICREA / IFAE Barcelona)

- Brief history: 1996, 2002, 2006
- Current treatment. Data Nodes: “Neutrino Properties,” “Sum of Neutrino Masses,” “Limits from Neutrino-less Double-Beta Decay” + mixing, etc.
- Current treatment. Reviews: “Neutrino Mass and Flavor Change,” “Introduction to Neutrino Properties Listings,” “Neutrino-less Double Beta Decay”.
- Issues. Problems. Improvements?

Cast

Maury Goodman	Encoding of accelerator neutrino papers
Don Groom	Overseer emeritus
Boris Kayser	“Neutrino Mass, Mixing, and Flavor Change”
Dean Karlen	“Number of Light Neutrinos”
Ramon Miquel	Overseer
Hitoshi Murayama	Mega-plot with current oscillation parameters
Kenzo Nakamura	Encoding of extraterrestrial neutrino papers
	“Solar Neutrinos”
Keith Olive	Encoding of Astrophysical papers
Andreas Piepke	Encoding of Nuclear Physics papers
&	“Introduction to the Neutrino Properties Listings”
Petr Vogel	“Note on Neutrinoless Double-Beta Decay”

+ consultants, referees, verifiers…

ν_μ $J = \frac{1}{2}$

1996

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_μ MASS

Applies to ν_2, the primary mass eigenstate in ν_μ. Would also apply to any other ν_j which mixes strongly in ν_μ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the ν_e mass limit above.) Results based upon an obselete pion mass are no longer shown; they were in any cass less restrive than ASSAMAGAN 96.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.17	90	[1] ASSAMAGAN	96	SPEC	$m^2 = -0.016 \pm 0.023$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15		[2] DOLGOV	95	COSM	Nucleosynthesis
<0.48		[3] ENQVIST	93	COSM	Nucleosynthesis
<0.003		[4,5] MAYLE	93	ASTR	SN 1987A cooling
$<$ 0.025–0.030		[5,6] BURROWS	92	ASTR	SN 1987A cooling
<0.3		[7] FULLER	91	COSM	Nucleosynthesis
<0.42		[7] LAM	91	COSM	Nucleosynthesis
$<$ 0.028–0.15		[8] NATALE	91	ASTR	SN 1987A
<0.028		[5] GANDHI	90	ASTR	SN 1987A
<0.014		[5,9] GRIFOLS	90B	ASTR	SN 1987A
<0.06		[5,10] GAEMERS	89		SN 1987A
<0.50	90	[11] ANDERHUB	82	SPEC	$m^2 = -0.14 \pm 0.20$

ν_e

$J = \frac{1}{2}$

2002

The following results are obtained using neutrinos associated with e^+ or e^-. See Note on "Electron, muon, and tau neutrinos."

$\overline{\nu}$ MASS

Those limits given below for $\overline{\nu}$ mass that come from the kinematics of $^3\mathrm{H}\beta^-\overline{\nu}$ decay are the square roots of limits for $m^{2(\mathrm{eff})}_{\nu_e}$. These are obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3 OUR EVALUATION					
< 2.5	95	[1] LOBASHEV	99	SPEC	^{3}H β decay
< 2.8	95	[2] WEINHEIMER	99	SPEC	^{3}H β decay
<23		LOREDO	89	ASTR	SN 1987A
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.35	95	[3] BELESEV	95	SPEC	^{3}H β decay
<12.4	95	[4] CHING	95	SPEC	^{3}H β decay
<92	95	[5] HIDDEMANN	95	SPEC	^{3}H β decay
15^{+32}_{-15}		HIDDEMANN	95	SPEC	^{3}H β decay
<19.6	95	KERNAN	95	ASTR	SN 1987A
< 7.0	95	[6] STOEFFL	95	SPEC	^{3}H β decay

Issue

- The flavor eigenstates, such as ν_e, ν_μ, ν_τ, are not particles, in the sense that they do not have a mass, and do not propagate in free space. They are useful concepts.

- ν_1, ν_2, ν_3 are the particles in the usual sense of the word. Some similarity to neutral K system.

[Presented in 11/04 PDG Adv. Comm. Meet.] Summary of Workshop on 11/12/04 (III)

- Sections on ν_e, ν_μ, ν_τ:
  - Eliminate "particles" called ν_e, ν_μ, ν_τ.
  - Rename nodes with masses, etc. to reflect what is really being measured. Example: $m_{\nu_e}^{2(eff)} \equiv \sum_j |U_{ej}|^2 m_{\nu_j}^2$.
  - Same thing for lifetime to mass ratio, magnetic moment, electric dipole moment, etc.
  - In some cases (astrophysics), limits apply to all flavors: only one node needed.
  - Remove many obsolete results, mostly in mass ranges that are now irrelevant.
  - Add node for ν_2 lifetime to mass ratio (from limits to Majoron-emission decays of solar neutrinos).

Advice

PDG Advisory Committee Meeting, November 14-15, 2004

6. Neutrinos (Listings)

Any change of notation in the neutrino sector should be approached with great care, and it should not be implemented before a general consensus has been reached within the PDG and with the outside community concerned.

Consistent with this advice, and led by K. Olive, the old notation was eliminated without new notation being introduced. The effective mass, lifetime, etc. limits are limits to linear combinations of properties of the mass eigenstates. So, we decided on the scheme which is in RPP2006 - it's a clear improvement over 2004. The main mission, to do away with ν_e, ν_μ and ν_τ, was accomplished.

Neutrino Properties

2006

A REVIEW GOES HERE – Check our WWW List of Reviews

$\overline{\nu}$ MASS (electron based)

Those limits given below are for the square root of $m^{2(\mathrm{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of ^{3}H$\beta^-\overline{\nu}$ decay are the square roots of the limits for $m^{2(\mathrm{eff})}_{\nu_e}$. Obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 2	**OUR EVALUATION**				
< 2.3	95	[1] KRAUS	05	SPEC	^{3}H β decay
< 2.5	95	[2] LOBASHEV	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<21.7	90	[3] ARNABOLDI	03A	BOLO	^{187}Re β-decay
< 5.7	95	[4] LOREDO	02	ASTR	SN1987A
< 2.8	95	[5] WEINHEIMER	99	SPEC	^{3}H β decay
< 4.35	95	[6] BELESEV	95	SPEC	^{3}H β decay
<12.4	95	[7] CHING	95	SPEC	^{3}Hβ decay
<92	95	[8] HIDDEMANN	95	SPEC	^{3}H β decay

The 2006 "Revolution"

- The revisions in the neutrino properties sections eliminating misleading names like "ν_e mass" and removing duplicate structures have been considered successful, although some degree of fine-tuning may be useful.

- The revisions in the neutrino mixing sections added nodes on θ's and Δm^2, and eliminated (many more) nodes on probabilities of oscillations.
  - This has been regarded as useful and successful

[Presented in 11/04 PDG Adv. Comm. Meet.] Summary of Workshop on 11/12/04 (I)

- Mixing
  - Introduce new “nodes” with measurements of θ_{12}, θ_{23}, θ_{13}, Δm^2_{12}, Δm^2_{23} in the 3-neutrino scenario, including mini-review explaining how it is done, assumptions, etc.
  - Remove Don’s two-flavor mini-review which focuses on understanding limits.
  - Keep solar fluxes, atmospheric flux ratios, reactor flux ratios. Add accelerator flux ratios.
  - Remove obsolete oscillation limits in Δm^2 regions we now know are irrelevant.
  - Keep LSND-related limits from $\nu_\mu \leftrightarrow \nu_e$ oscillation searches.

- Results “relevant” to LSND were kept
- Since we didn’t know what LSND measured, if it was right, this was not 100% straightforward
- This was done in conjunction with MiniBooNE spokespersons

(C) Other neutrino mixing results

The LSND collaboration reported in AGUILAR 01 a signal which is consistent with $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations. In a three neutrino framework, this would be a measurement of θ_{12} and Δm^2_{21}. This does not appear to be consistent with the interpretation of other neutrino data, particularly solar neutrino experiments. If the LSND anomaly is correct, a more complicated framework is required, perhaps involving one or more sterile neutrinos, or even CPT violation. The following listings include results which might be relevant towards understanding or ruling out the LSND observations. They include searches for $\nu_\mu \rightarrow \nu_e$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$, sterile neutrino oscillations, and CPT violation.

Current Treatment. Data Nodes

- anti- ν mass (electron based), anti- ν mass squared (electron based), ν mass (electron based)

$$m_{\nu_e}^{2(\text{eff})} \equiv \sum_i |U_{ei}|^2 \; m_{\nu_i}^2,$$

- ν mass (muon based), ν mass (tau based)
- Sum of neutrino masses, m_{tot}, with a short introduction.
- ⟨m ν⟩ , The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double-β Decay

$$\langle m_\nu \rangle = |\Sigma \; U_{1j}^2 m_{\nu_j}|$$

SUM OF THE NEUTRINO MASSES, m_{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_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 1.1		[54] ICHIKI	09	COSM	
$<$ 1.3		[55] KOMATSU	09	COSM	WMAP
$<$ 1.2		[56] TERENO	09	COSM	
$<$ 0.33		[57] VIKHLININ	09	COSM	
$<$ 0.28		[58] BERNARDIS	08	COSM	
$<$ 0.17–2.3		[59] FOGLI	07	COSM	
$<$ 0.42	95	[60] KRISTIANSEN	07	COSM	
$<$ 0.63–2.2		[61] ZUNCKEL	07	COSM	
$<$ 0.24	95	[62] CIRELLI	06	COSM	
$<$ 0.62	95	[63] HANNESTAD	06	COSM	

Most of these papers were missed by our literature searchers : JCAP, MNRAS...

Found by Keith Olive

[54] Constrains the total mass of neutrinos from weak lensing measurements when combined with CMB. Limit improves to 0.54 eV when supernovae and baryon acoustic oscillation observations are included. Assumes ΛCDM model.

[55] Constrains the total mass of neutrinos from five-year WMAP data. Limit improves to 0.67 eV when supernovae and baryon acoustic oscillation observations are included. Limits quoted assume the ΛCDM model. Supersedes SPERGEL 07.

Different assumptions on cosmological priors and different data sets lead to different limits

$\langle m_\nu \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double-β Decay

$\langle m_\nu \rangle = |\Sigma\, U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to n and where n = number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{ej}, not $|U_{ej}|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

VALUE (eV)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 0.19–0.68	90	^{130}Te	0ν	TeO_2 bolometer	[77] ARNABOLDI	08
$<$ 3.5–22	90	^{48}Ca	0ν	CaF_2 scint.	[78] UMEHARA	08
$<$ 9.3–60	90	^{100}Mo	$0^+ \rightarrow 0^+_1$	NEMO-3	[79] ARNOLD	07
$<$ 6500	90	^{100}Mo	$0^+ \rightarrow 2^+$	NEMO-3	[80] ARNOLD	07
0.32±0.03	68	^{76}Ge	0ν	Enriched HPGe	[81] KLAPDOR-K...	06A
$<$ 0.2–1.1	90	^{130}Te		Cryog. det.	[82] ARNABOLDI	05
$<$ 0.7–2.8	90	^{100}Mo	0ν	NEMO-3	[83] ARNOLD	05A
$<$ 1.7–4.9	90	^{82}Se	0ν	NEMO-3	[84] ARNOLD	05A
$<$ 0.37–1.9	90	^{130}Te		Cryog. det.	[85] ARNABOLDI	04
$<$ 0.8–1.2	90	^{100}Mo	0ν	NEMO-3	[86] ARNOLD	04
$<$ 1.5–3.1	90	^{82}Se	0ν	NEMO-3	[86] ARNOLD	04
0.1–0.9	99.7	^{76}Ge		Enriched HP Ge	[87] KLAPDOR-K...	04A

Spread due to spread in nuclear matrix element calculations

Reviews

- Neutrino mass and mixing review by Boris Kayser.
- Introduction to neutrino properties review by Petr Vogel and Andreas Piepke.
- Neutrinoless double-beta decay review by Vogel and Piepke.
- Solar neutrino review by Kenzo Nakamura.

INTRODUCTION TO THE NEUTRINO PROPERTIES LISTINGS

Revised August 2007 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

A limit on $\langle m_\beta^2 \rangle$ implies an *upper* limit on the *minimum* value m^2_{min} of $m^2_{\nu_i}$, independent of the mixing parameters U_{ei}: $m^2_{min} \leq \langle m_\beta^2 \rangle$. However, if and when the value of $\langle m_\beta^2 \rangle$ is determined and the study of neutrino oscillations provides us with the values of *all* neutrino mass-squared differences Δm^2_{ij} and the mixing parameters $|U_{ei}|^2$, then the individual neutrino mass squares $m^2_{\nu_j} = \langle m_\beta^2 \rangle - \sum_i |U_{ei}|^2 \Delta m^2_{ij}$ can be determined.

All confirmed neutrino oscillation experiments using solar, reactor, atmospheric and accelerator neutrinos can be described using three active neutrino flavors, *i.e.*, two mass splittings and three mixing angles. Combined three neutrino analyses determine the squared mass differences and two of the mixing angles to within reasonable accuracy. For given $|\Delta m^2_{ij}|$, a limit on $\langle m_\beta^2 \rangle$ from beta decay defines an *upper* limit on the *maximum* value m_{max} of m_{ν_i}: $m^2_{max} \leq \langle m_\beta^2 \rangle + \sum_{i<j} |\Delta m^2_{ij}|$. The analysis of the low energy beta decay of tritium, combined with the oscillation results, thus limits *all* active neutrino masses.

NEUTRINOLESS DOUBLE-β DECAY

Revised November 2007 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

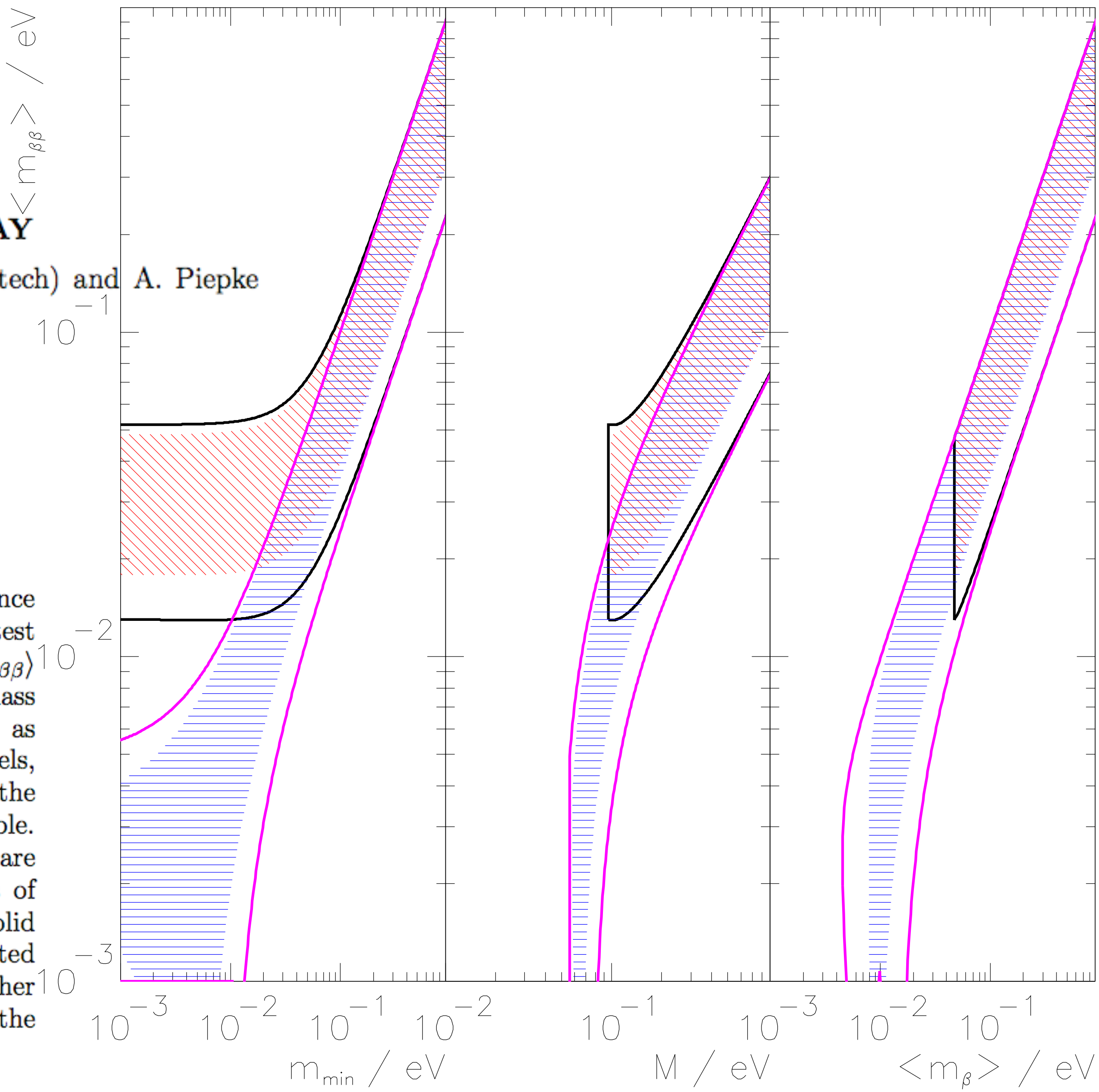

Figure 1: The left panel shows the dependence of $\langle m_{\beta\beta} \rangle$ on the absolute mass of the lightest neutrino m_{min}. The middle panel shows $\langle m_{\beta\beta} \rangle$ as a function of the summed neutrino mass M, while the right panel depicts $\langle m_{\beta\beta} \rangle$ as a function of the mass $\langle m_\beta \rangle$. In all panels, the width of the hatched areas is due to the unknown Majorana phases and thus irreducible. The allowed areas given by the solid lines are obtained by taking into account the errors of the oscillation parameters. The two sets of solid lines correspond to the normal and inverted hierarchies. These sets merge into each other for $\langle m_{\beta\beta} \rangle \geq 0.1$ eV, which corresponds to the degenerate mass pattern.

Issues: Listings

- Is the structure of the current “Neutrino Properties” adequate? Can it be improved?
- In light of the MiniBooNE results, the “Other Neutrino Mixing Results” section should probably be hidden in 2010.
- We should be on the watch for what new nodes (if any) may be needed for new paradigms ($>3\nu$, etc.)

Issues: Reviews

- The listings state and assume $\Delta m^2_{atm} \approx \Delta m^2_{31} \approx \Delta m^2_{32}$
- This is appropriate for now.
- However, there is a great deal of interesting physics at the next level, and the reviews allude to this in ways that are not totally consistent.
- They need to be carefully re-edited with this in mind

Issues: Encoding

- Growing number of “cosmo” papers dealing with neutrino mass and number of neutrinos published in journals we do not follow: JCAP, MNRAS...

Conclusions

- Neutrino physics has entered a mature phase.
- PDG has adapted well to the changes in our understanding of neutrino physics.
- Several reviews help the reader follow this rather complicated subject.
- Treatment of ν_e, ν_μ, ν_τ vs. ν_1, ν_2, ν_3 may be improved. Suggestions welcome.
- Minor changes in the listings will be applied for 2010.
- Future changes may depend on the outcome of new experiments: Double Chooz, T2K, Katrin, Daya Bay, Nova, etc.

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 $n_\gamma = 412 \text{ cm}^{-3}$, we have

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

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

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

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

Issues: Change Neutrino Names?

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3