Neutrino Part 1: 3-Flavor Mixing

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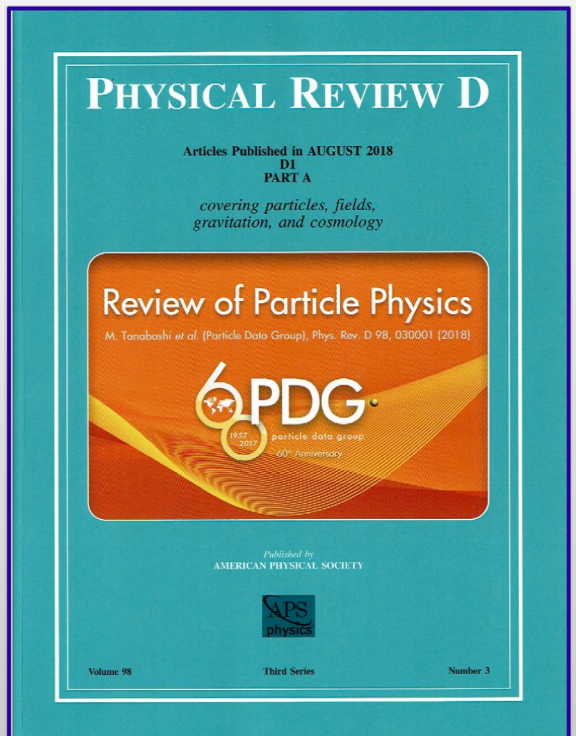


Outline:

- PDG Neutrino group members
- RPP2018 Highlights
- 3-Flavor Parametrizations
- Changes for future editions
- Global Fits Issues

PDG Neutrino Group

Neutrino Overseers:

- Cheng-Ju Lin (LBNL) → neutrino properties and 3-flavor mixing
- Sandro Bettini (INFN) → $0\nu/2\nu$ double-beta decays and BSM searches

Neutrino Ecoders:

- Kenzo Nakamura (KEK/ Kavli-IPMU)→ solar and atm
- Maury Goodman (ANL)→ accelerator
- Petr Vogel (Caltech) and Andre Piekpe (U. Alabama)→ reactor
- Keith Olive (U. Minnesota)→ cosmological

Review Authors:

Group of leading experts writing reviews covering a broad range of neutrino landscape: Gallagher, Goodman, Hayato, Lesgourgues, Lin, Nakamura, Petcov, Piepke, Olive, Verde, Vogel, Zeller.

RPP2018 Highlights

Precision era for neutrino mixing measurements

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2$$
$$\sin^2(\theta_{23}) = 0.421^{+0.033}_{-0.025} \quad (S = 1.3) \quad \text{(Inverted order, octant I)}$$
$$\sin^2(\theta_{23}) = 0.592^{+0.023}_{-0.030} \quad (S = 1.1) \quad \text{(Inverted order, octant II)}$$
$$\sin^2(\theta_{23}) = 0.417^{+0.025}_{-0.028} \quad (S = 1.2) \quad \text{(Normal order, octant I)}$$
$$\sin^2(\theta_{23}) = 0.597^{+0.024}_{-0.030} \quad (S = 1.2) \quad \text{(Normal order, octant II)}$$
$$\Delta m^2_{32} = (-2.56 \pm 0.04) \times 10^{-3}\ \text{eV}^2 \quad \text{(Inverted order)}$$
$$\Delta m^2_{32} = (2.51 \pm 0.05) \times 10^{-3}\ \text{eV}^2 \quad (S = 1.1) \quad \text{(Normal order)}$$
$$\sin^2(\theta_{13}) = (2.12 \pm 0.08) \times 10^{-2}$$

- **All except one mixing parameters are measured to a few percent level uncertainty**
- **Octant of θ_{23} and sign of Δm^2_{32} still not known**
- **CP violating phase is also not known at the moment**

New review on Neutrinos in Cosmology that discusses cosmological models (e.g. ΛCDM), neutrino density, number of active species, and sum of neutrino masses

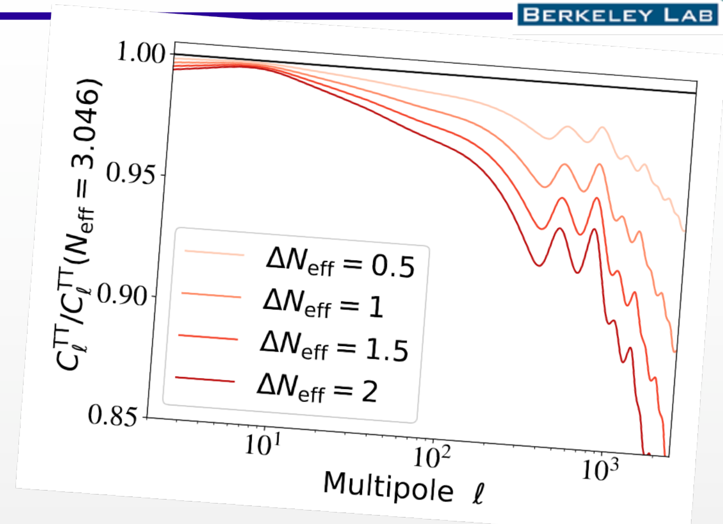
Neutrinos in Cosmology

25. Neutrinos in Cosmology

Written August 2017 by J. Lesgourgues (RWTH Aachen U.) and L. Verde (U. of Barcelona & ICREA).

25.1. Standard neutrino cosmology

Neutrino properties leave detectable imprints ... at can then be used to constr ... arkable interconnection and in ... cs and cosmology (for general ... already providing constraints c ... etitive with terrestrial experi ... s have shrinked by a factor of ... a may soon provide key infor ... ent of



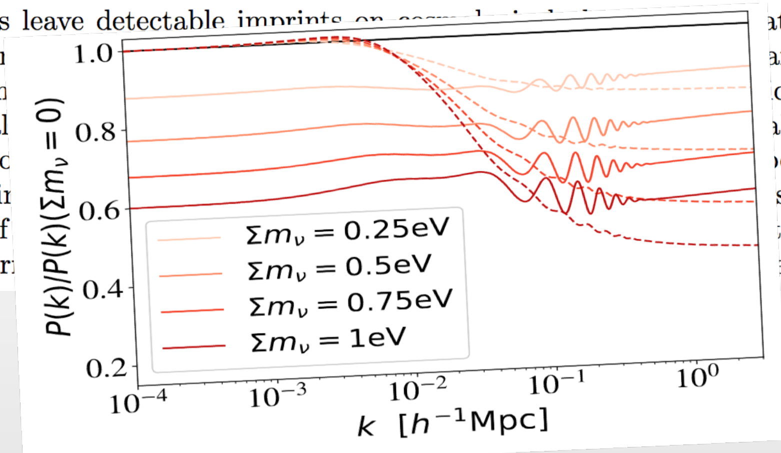


Table 25.1: Summary of $N_{\rm eff}$ constraints.

	Model	68%CL	Ref.
CMB alone			
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$	3.13 ± 0.32	[29]
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.08 ± 0.31	[35]
CMB + probes of background evolution			
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$	3.15 ± 0.23	[29]
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	$3.18^{+0.24}_{-0.27}$	[35]
CMB + probes of background evolution + LSS			
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$3.08^{+0.22}_{-0.24}$	[35]
" + BAO + JLA + HST	ΛCDM+$N_{\rm eff}$	3.41 ± 0.22	[31]
" + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.2 ± 0.5	[29]
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$N_{\rm eff}$+5-params.	$2.93^{+0.51}_{-0.48}$	[34]

25.2. Effects of neutrino properties on cosmological observables

As long as they are relativistic, *i.e.*, until some time deep inside the matter-domina regime for neutrinos with a mass $m_i \ll 3.15\,T_\nu^{\rm eq} \sim 1.5$ eV (see Big Bang Cosmolog Chap. 21 in this *Review*), neutrinos enhance the density of radiation: this effect is parameterised by $N_{\rm eff}$ and can be discussed separately from the effect of the mass that will be described later in this section. Increasing $N_{\rm eff}$ impacts the observab CMB anisotropies and matter fluctuations through background and perturba

25.2.1. *Effect of $N_{\rm eff}$ on the CMB* :

The background effects depend on fixed when increasing $N_{\rm eff}$. If the densities of other species are kept fixed, a

25.4. Future prospects and outlook

The cosmic neutrino background has been detected indirectly at very high statistical significance. Direct detection experiments are now being planned, *e.g.*, at the Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY) [53]. The detection prospects crucially depend on the exact value of neutrino masses and on the

Mixing Parametrizations

Mixing parametrization used in PDG evolves over time:

- Started with 2-flavor mixing
- Transitioned to 3-flavor mixing in 2006
- Added CP-violating phase (δ_{CP}) in 2014
- In 2015 switched $\sin^2(2\theta)$ to $\sin^2(\theta)$

NOvA: PRD 98, 03201 (2018)

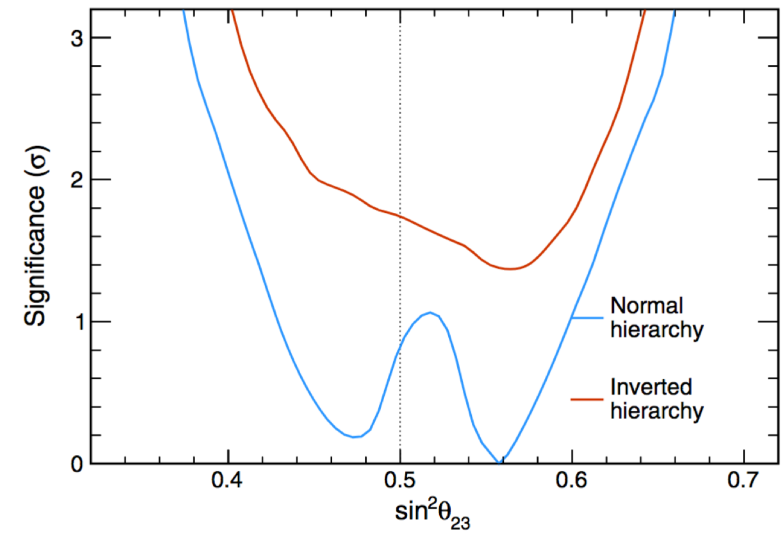


FIG. 14. Significance at which each value of $\sin^2\theta_{23}$ is disfavored in the normal (blue, lower) or inverted (red, upper) mass hierarchy. The vertical dotted line indicates the point of maximal mixing.

PDG 2018 Parametrization:

- Mixing angles $\sin^2(\theta_{12})$, $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$
- Mass differences Δm^2_{21}, Δm^2_{32}
- CP violating phase δ_{CP}

Four values of $\sin^2(\theta_{23})$ are quoted for different mass ordering and octant assumptions. NOvA data favors non-maximal θ_{23}

Consistent Oscillation Averages

From: Alessandra.Re@mi.infn.it
Subject: About the PDG 2017 update - neutrino oscillation parameters
Date: July 7, 2017 at 11:49:09 AM GMT+2

we (the Borexino collaboration) are writing some new articles and we would like to take your PDG review as reference as regards the neutrino oscillation parameters.

July 2017 is time of PDG-middle-term update so I checked on the webpage:
http://pdg.lbl.gov/2017/tables/rpp2017-sum-leptons.pdf
The "neutrino mixing" summary table at pg. 10.

I'm a bit confused now...

The values there reported are quite different from those "officially" included in Table 14.1, pg 8 of the 2016 review.
http://pdg.ihep.su/2017/reviews/rpp2016-rev-neutrino-mixing.pdf

As far as I understand, the 2016 values were taken from Capozzi, Lisi et al. (https://doi.org/10.1016/j.nuclphysb.2016.02.016):
where do the 2017 updated values come from? Is there any work I can read?

Thanks in advance!

Best regards,
Alessandra

Neutrino Review

Table 1
Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass–mixing parameters. See also Fig. 1 for a graphical representation of the results. We recall that Δm^2 is defined as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The last row reports the (statistically insignificant) overall χ^2 difference between IH and NH.

Parameter	Hierarchy	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	NH or IH	7.37	7.21–7.54	7.07–7.73	6.93–7.97
$\sin^2\theta_{12}/10^{-1}$	NH or IH	2.97	2.81–3.14	2.65–3.34	2.50–3.54
$\Delta m^2/10^{-3}$ eV^2	NH	2.50	2.46–2.54	2.41–2.58	2.37–2.63
$\Delta m^2/10^{-3}$ eV^2	IH	2.46	2.42–2.51	2.38–2.55	2.33–2.60
$\sin^2\theta_{13}/10^{-2}$	NH	2.14	2.05–2.25	1.95–2.36	1.85–2.46
$\sin^2\theta_{13}/10^{-2}$	IH	2.18	[illegible]	1.96–2.38	1.86–2.48
$\sin^2\theta_{23}/10^{-1}$	NH	4.37	4.17–4.70	3.97–5.63	3.79–6.16
$\sin^2\theta_{23}/10^{-1}$	IH	5.69	4.28–4.91 ⊕ 5.18–5.97	4.04–6.18	3.83–6.37
δ/π	NH	1.35	[illegible]	0.92–1.99	0–2
δ/π	IH	1.32	1.07–1.67	0.83–1.99	0–2
$\Delta\chi^2_{\text{I-N}}$	IH–NH	+0.98			

Neutrino Mixing

PDG Listing

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$$\sin^2(\theta_{23}) = 0.51 \pm 0.04 \quad \text{(normal mass hierarchy)}$$
$$\sin^2(\theta_{23}) = 0.50 \pm 0.04 \quad \text{(inverted mass hierarchy)}$$
$$\Delta m^2_{32} = (2.45 \pm 0.05) \times 10^{-3}\ \text{eV}^2\ [i] \quad \text{(normal mass hierarchy)}$$
$$\Delta m^2_{32} = (2.52 \pm 0.05) \times 10^{-3}\ \text{eV}^2\ [i] \quad \text{(inverted mass hierarchy)}$$
$$\sin^2(\theta_{13}) = (2.10 \pm 0.11) \times 10^{-2}$$

Next edition needs to be more explicit on what are the official PDG numbers

Global Fits?

As neutrino experiments become more and more precise, sub-leading effects (correlations among mixing parameters) are becoming important

Global fits information are used if the experiment quote the value in their paper. Otherwise, a straight-averaging is used

Ideal solution is for ALL neutrino experiments to work together and combine their results in a global fit. Takes time and not likely to happen soon

Ongoing discussion to adopt global fits results from phenomenologists as official PDG values. Some pros and cons for this approach. Not a long term solution

Mini-Workshop(?) with neutrino experts to find a consensus moving forward

Changes Under Discussion

- Start including mass ordering data in the Listings
- Evaluate Δm^2 parametrization. Current generation of experiments are measuring Δm^2_{ee} and $\Delta m^2_{\mu\mu}$, which is a mixture of Δm^2_{32} and Δm^2_{21}
- Switch averages to global fits. May need inputs from a broader community in the decision process
- Remove obsolete BSM results and move relevant measurements and new results into a separate section devoted to searches beyond the 3-flavor mixing paradigm (See Bettini's talk)

Concluding Remarks

With a plethora of active and new experiments, neutrino data will continue to be one of the key components of PDG

Results expected from:

- Current experiments: T2K, Super-K, MINERvA, NOvA, Daya Bay, Double Chooz, RENO, IceCube, OPERA, MicroBooNE, Borexino, etc.
- Data expected in near term: SBND, ICARUS, short-baseline reactor experiments, JUNO, INO, etc.
- Longer term: DUNE and Hyper-K

Cosmology will continue to play important role

We (PDG) are actively engaged to ensure the needs of the community are addressed