Neutrino Parameters

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Mainly based on work done in collaboration with:
Outline:

- $3\nu$ mass-mixing parameters: notation, conventions, remarks
- Constraints on $(\Delta m^2, \sin^2\theta_{23}, \sin^2\theta_{13})$ from SK+K2K+CHOOZ
- Constraints on $(\Delta m^2, \sin^2\theta_{12}, \sin^2\theta_{13})$ from solar+KamLAND
- “Grand total” from neutrino oscillation searches
- Constraints coming from observables probing absolute masses
- Galactic SN and Next generation of Nucleon decay and Neutrino detectors
- Conclusions

Disclaimer: references in proceedings, not in this ppt
3ν mass-mixing parameters: notation, conventions, remarks
3ν mixing: notation, conventions, remarks

“PDG” choice: \[ \nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{i L} \quad (\alpha = e, \mu, \tau) \]

so that: \[ |\nu_{\alpha} > = \sum_{i=1}^{3} U_{\alpha i}^{*} |\nu_{i} > \quad (\alpha = e, \mu, \tau) \]

with: \[ U = O_{23} \Gamma_{\delta} O_{13} \Gamma_{\delta}^{+} O_{12} \]

where: \( O_{ij} = \text{real rotations by} \quad \theta_{ij} \in [0, \pi/2] \)

\( \Gamma_{\delta} = \text{diag}(1, 1, e^{i\delta}) \quad \text{with} \quad \delta \in [0, \pi/2] \)

- No need to adopt a different convention, although many authors do it (e.g. by choosing \( U \rightarrow U^{*}, \delta \rightarrow -\delta, \) or both). Better to stick to PDG.

- In the following, numerical examples worked out only for the two inequivalent CP conserving cases \( e^{i\delta} = \pm 1 \) \((\delta = 0 \text{ or } \delta = \pi)\).
**3ν masses: notation, conventions, remarks**

- **Most used ν\textsubscript{i} labelling** (including PDG & this talk)

  ![Diagram showing ν\textsubscript{3} > ν\textsubscript{2} > ν\textsubscript{1}]

  i.e.:

  \[
  \begin{align*}
  \Delta m_{21}^2 &= m_2^2 - m_1^2 > 0 \text{, always} \\
  \Delta m_{31}^2 &= m_3^2 - m_1^2 > 0 \text{, normal} \\
  \Delta m_{31}^2 &= m_3^2 - m_1^2 < 0 \text{, inverted}
  \end{align*}
  \]

- **Widely adopted notation:**

  \[
  (m_1^2, m_2^2, m_3^2) = m_1^2 + (0, \Delta m_{21}^2, \pm |\Delta m_{31}^2|)
  \]

  \[
  \begin{cases}
  + \text{ normal hierarchy} \\
  - \text{ inverted hierarchy}
  \end{cases}
  \]

  But (NH) \(\rightarrow\) (IH) mapping not exactly realized by just changing \(\Delta m_{31}^2 \rightarrow -\Delta m_{31}^2\), because

  - in normal hierarchy, \(|\Delta m_{31}^2| = \text{largest squared mass difference}
  - in inverted hierarchy, \(|\Delta m_{31}^2| = \text{next-to-largest squared mass difference}

  the above notation makes the comparison (NH) \(\rightarrow\) (IH) tricky.
For this reason, we prefer to adopt a more symmetrical convention,

\[(m_1^2, m_2^2, m_3^2) = \frac{m_1^2 + m_2^2}{2} + \left(\delta m^2, + \frac{\delta m^2}{2}, \pm \Delta m^2\right)\]

with \(\delta m^2 = \Delta m_{21}^2\) “solar splitting” as before

but \(\Delta m^2 = \frac{\Delta m_{31}^2 + \Delta m_{32}^2}{2}\) “atmospheric splitting” defined as the average of \(\Delta m_{31}^2\) and \(\Delta m_{32}^2\)

With this convention, swapping hierarchy is exactly equivalent to swap \(\pm \Delta m^2\):

\[(\text{NH} \leftrightarrow \text{IH}) \leftrightarrow (+\Delta m^2 \leftrightarrow -\Delta m^2)\]
3ν Majorana phases: notation, conventions, remarks

- If \( \nu = \overline{\nu} \), \( U \rightarrow U \cdot U_M \) where \( U_M \) contains two independent Majorana phases

- PDG 2004 convention not unique:
  \[
  \begin{cases}
  U_M = \text{diag}(e^{\frac{i}{2} \alpha_1}, e^{\frac{i}{2} \alpha_2}, 1) & \rightarrow \text{Kayser} \\
  U_M = \text{diag}(1, e^{\frac{i}{2} \alpha_1}, e^{\frac{i}{2} (\alpha_2 + 2\delta)}) & \rightarrow \text{Vogel & Piepke}
  \end{cases}
  \]

- We adopt the Vogel & Piepke convention (with a slight change of notation)
  \[
  U_M = \text{diag}(1, e^{\frac{i}{2} \phi_2}, e^{\frac{i}{2} (\phi_3 + 2\delta)})
  \]
  so that the so-called “effective Majorana mass” in 0ν2β decay reads
  \[
  m_{\beta\beta} = \left| \sum U_{ei} m_i \right| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi} + s_{13}^2 m_3 e^{i\phi} \right|^2
  \]
  not explicitly dependent on \( \delta \)

- Convergence towards a unique convention on neutrino mixing angles, mass splittings and Majorana phases would be desirable.
Constraints on \((\Delta m^2, \sin^2\theta_{23}, \sin^2\theta_{13})\) from SK+K2K+CHOOZ
SK constraints on \((\Delta m^2, \sin^2 \theta_{23})\) at \(\sin^2 \theta_{13} = 0\)

- 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\) contours \((\Delta \chi^2 = 1, 4, 9)\) from SK atmospheric neutrinos (note linear scale).
- Some sensitivity to improved theoretical input:
  - about \(-0.5 \sigma\) shift of \(\Delta m^2\) from 1D to 3D atmospheric \(\nu\) fluxes
  - about \(-0.5 \sigma\) shift of \(\sin^2 \theta_{23}\) by including subleading effects due to LMA 
    \((\delta m^2 \approx 8 \times 10^{-5} \text{ eV}^2, \sin^2 \theta_{12} \approx 0.3)\)

LMA-induced shift is small …
SK and K2K constraints on $(\Delta m^2, \sin^2 \theta_{23})$ at $\sin^2 \theta_{13} = 0$

... but unaltered by K2K (~ poorly sensitive to $s_{23}^2$)

Main effects of adding K2K:

- upward shift of the best-fit of $\Delta m^2$
- significant reduction of the upper uncertainty on $\Delta m^2$

A joint, official SK + K2K combination would be desirable (note that interaction and detection systematics are similar and correlated in SK and K2K).
Constraints on ($\Delta m^2$, $\sin^2 \theta_{23}$) adding CHOOZ, with $\sin^2 \theta_{13}$ unconstrained

- Current results basically unchanged by leaving $s_{13}^2$ unconstrained (with CHOOZ data added) and by swapping hierarchy and/or CP-conserving cases.

- Reason: $s_{13}^2 \approx 0$ preferred by data, and for $s_{13}^2 \to 0$ predictions converge in the four panels.

- Situation may change if, e.g., a future reactor experiment finds $s_{13}^2 \neq 0$. In this case the current degeneracy among the four panels could be slightly lifted (not shown).
Constraints on ($\Delta m^2$, $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$) from SK + K2K + CHOOZ

- Global SK+K2K+CHOOZ analysis if we marginalize over the 4 cases:

$$\left( \text{sign}(\Delta m^2) = \pm 1 \right) \otimes (e^{i\delta} = \pm 1)$$

- Note: very weak correlations among the leading parameters

$$\Delta m^2, \sin^2 \theta_{23}, \sin^2 \theta_{13}$$
Constraints on $(\delta m^2, \sin^2 \theta_{12}, \sin^2 \theta_{13})$
from solar neutrinos + KamLAND
**“Historical” notes**

- **2001-2003**
  - Dramatic reduction of the \((\delta m^2, \theta_{12})\) parameter space (note change of scales)
  - Cl+Ga+SK (2001)
  - +KamLAND-I (2002)

- Direct proof of solar \(\nu_e \rightarrow \nu_{\mu,\tau}\) in SNO through comparison of CC, NC (and ES)
... in 2004 at $\theta_{13} = 0$

Adding KamLAND-II (with revised background):

unique Large Mixing Angle solution, (and another change of scale...)

Gianluigi Fogli  Next Generation of Nucleon Decay and Neutrino Detectors - Aussois (Savoie) 7-9 April 2005
What about MSW effects in the Sun?

Approach:
- Change MSW potential “by hand”
  \[ V \rightarrow a_{\text{MSW}} V \]
- Reanalysis of all data in terms of \((\delta m^2, \theta_{12}, a_{\text{MSW}})\)
- Project \((\delta m^2, \theta_{12})\) away and check if \(a_{\text{MSW}} \sim 1\)

Results:
- with 2004 data,
  - \(a_{\text{MSW}} \sim 1\) within a factor \~ 2
  - \(a_{\text{MSW}} \sim 0\) excluded

But: expected subleading effect in the Earth (day-night difference) still below experimental uncertainties.

(... a way of “measuring” \(G_F\) through solar neutrino oscillations ...)

Gianluigi Fogli
Next Generation of Nucleon Decay and Neutrino Detectors - Aussois (Savoie) 7-9 April 2005
2005 (last month)

- Previous results basically confirmed
- Slightly higher ratio $\frac{\text{CC/NC}}{\text{NC}} \sim P(\nu_e \rightarrow \nu_e)$
- Slight shift ($<1\sigma$ upwards) of the allowed range for $\theta_{12}$

New data + detailed analysis from SNO
3ν analysis of 2004 solar + KamLAND data (θ_{13} free)

- Solar and KamLAND data also prefer
  \[ \theta_{13} \sim 0 \]
  consistency with SK + CHOOZ (non trivial)

- Present bounds on (δm^2, θ_{12}) not significantly altered for unconstrained θ_{13}

[SNO 2005 data not included]
“Grand Total” from global analysis of oscillation data
Marginalized $\Delta \chi^2$ curves for each parameter (2004)

Consistency of all data in preferring

$$\sin^2 \theta_{13} \sim 0$$

(best fit ≠ 0, but not statistically significant)
Numerical ± 2σ ranges (95% CL for 1 dof), 2004 data

\[ \delta m^2 = 8.0^{+0.8}_{-0.7} \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m^2 = 2.4^{+0.5}_{-0.6} \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 \theta_{12} = 0.29^{+0.05}_{-0.04} \ ]
\[ \sin^2 \theta_{23} = 0.45^{+0.18}_{-0.11} \]
\[ \sin^2 \theta_{13} \leq 0.035 \]
\[ \text{sign}(± \Delta m^2): \text{unknown} \]
\[ \text{CP phase } \delta: \text{unknown} \]

SNO’05: 0.29 → 0.31
Probing absolute $\nu$ masses through non-oscillation searches
Three main tools, identified with three observables sensitive to absolute $\nu$ masses

1) $\beta$ decay: $m_i \neq 0$ can affect the spectrum endpoints. Sensitivity to the so-called "effective electron mass": (most direct method)

\[
m_\beta = \left[ c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \right]^{1/2}
\]

2) $0\nu2\beta$ decay: can occur if $m_i \neq 0$ and $\nu = \nu^\ast$. Sensitivity to the so-called "effective Majorana mass" (and phases):

\[
m_{\beta\beta} = \left[ c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi} + s_{13}^2 m_3 e^{i\phi} \right]^{1/2}
\]

3) Cosmology: $m_i \neq 0$ can affect large scale structure in (standard) cosmology, constrained by CMB and other cosmological observations. They probe:

\[
\Sigma = m_1 + m_2 + m_3
\]

In the following we present a global phenomenological analysis of the constraints applicable in the parameter space

\[
(m_\beta, m_{\beta\beta}, \Sigma)
\]

for both normal and inverted hierarchies.
Constraints from oscillation data only

Even without non-oscillation data the \((m_\beta, m_{\beta\beta}, \Sigma)\) parameter space is constrained by the oscillation results.

Note:

- Significant correlations
- Partial overlap between the two hierarchies
- Large \(m_{\beta\beta}\) spread due to the unknown Majorana phases
Input from Tritium $\beta$-decay experiments

$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$

Updated determinations:

- **Mainz** $\Rightarrow m^2_\beta = -1.2 \pm 3.0$ eV$^2$
- **Troitsk** $\Rightarrow m^2_\beta = -2.3 \pm 3.2$ eV$^2$

By restricting the domain to the physical region,

- $m_\beta < 2.2$ eV 95% C.L.
- $m_\beta < 2.1$ eV 95% C.L.

By combining the two determinations

$m_\beta < 1.8$ eV at 95% C.L. (Mainz + Troitsk)

- Limit less conservative than in other approaches
- In any case, present limits too weak to contribute significantly to restrict the parameter space

$(m_\beta, m_{\beta\beta}, \Sigma)$
Input from Germanium 0ν2β-decay experiments

Several experiments, using different isotopes, with negative results.

Recently, members of the Heidelberg-Moscow experiment have claimed the detection of a 0ν2β signal from the $^{76}$Ge isotope.

From the available estimates of the nuclear matrix elements with their uncertainties one can derive an estimate of the “effective Majorana mass”. However, since the claim from Heidelberg-Moscow has been subject to criticism, in the following, we assume two possible 0ν2β inputs for the global analysis (1σ error):

$$
\begin{align*}
\log_{10}(m_{\beta\beta}/\text{eV}) &= -0.23 \pm 0.18 \quad \text{0ν2β claim assumed} \\
\log_{10}(m_{\beta\beta}/\text{eV}) &= -0.23 + 0.18 \quad \text{0ν2β claim rejected} \quad \text{(only upper limit)}
\end{align*}
$$

Finally, concerning the two unknown Majorana phases,

$$\phi_2, \phi_3$$

are assumed independent and uniformly distributed in the range $[0, \pi]$. 

\[ \text{(Diagram)} \]
Constraint on $\Sigma$ from cosmological data

Likelihood distribution for $\Sigma$ from joint analysis of several data sets. No evidence for a $\nu$ mass and upper bounds depending on several inputs and priors. In particular

- CMB + LSS (+ SN-Ia + HST)
  - with LSS from SDSS
  - $\Sigma < 1.4 \text{ eV} \ (2\sigma)$

- the same + Lyman-$\alpha$ from SDSS
  - (with LSS from SDSS)
  - $\Sigma < 0.47 \text{ eV} \ (2\sigma)$
  - even though the effect of systematics needs here to be explored further.
Adding upper bounds from laboratory and cosmology

Added to the $\nu$ oscillation data the bounds (2$\sigma$ level) on:

- $m_\beta$ (Mainz + Troitsk)
- $\Sigma$ (CMB + 2dF)
- $m_{\beta\beta}$ (upper limit only)

The cosmological upper limit on $\Sigma$ formally dominates over the lab upper limits on $m_\beta$ and $m_{\beta\beta}$.

This bound, via the correlations induced by oscillation data, provides upper limits also on $m_\beta$ and $m_{\beta\beta}$, stronger than the present lab limits by a factor $\sim 4$.  

2$\sigma$ bounds from:
- $\nu$ oscillation data
- $\Sigma$ (CMB + 2dF)
- $m_\beta$ (Mainz + Troitsk)
- $m_{\beta\beta}$ (upper limit only)
Adding lower bounds on $m_{\beta\beta}$ from the claimed $0\nu2\beta$ signal

Added a lower bound on $m_{\beta\beta}$ at the $2\sigma$ level.

$2\sigma$ bounds from:
- $\nu$ oscillation data
- $\Sigma$ (CMB + 2dF)
- $m_{\beta}$ (Mainz + Troitsk)
- $m_{\beta\beta}$ (Klapdor et al. claim)

Combination of all data possible, with overlap of the two hierarchies (degenerate spectrum with “large” masses).

However, the global allowed region extends somewhat outside the $2\sigma$ limits from cosmology and $0\nu2\beta$ data separately: a clear indication of some tension between the two sets of data.
Adding Lyman-a forest to cosmological data

This modifies the upper limit on $\Sigma$, improved by a factor $\sim 3$.

A. $0\nu2\beta$ claim rejected

The upper limit on $\Sigma$, through the correlation effects, transforms into upper limits on $m_\beta$ and $m_{\beta\beta}$, an order of magnitude stronger than the present upper limits.

- Bounds strong enough to approach the regime of partially degenerate spectrum.
- Bounds set very stringent limits for future lab experiments ($\sim$ factor 10 of improvement).

2$\sigma$ bounds from:
- $\nu$ oscillation data
- $\Sigma$ (CMB + 2dF + Ly-$\alpha$)
- $m_\beta$ (Mainz + Troitsk)
- $m_{\beta\beta}$ (upper limit only)
B. $0\nu2\beta$ claim accepted

The strong upper bound on $\Sigma$ increases the tension between cosmological data and $0\nu2\beta$ claim.

- $0\nu2\beta$ claim
- cosmological and oscillation data

The absence of overlap is a clear symptom of problems either in some data or in the theoretical interpretation, and prevents any global combination of data. However …

It is premature to conclude that the $0\nu2\beta$ claim is “ruled out” by cosmological data indeed

- cosmological data are rather indirect
- systematics of Lyman-$\alpha$ data are still to be scrutinized carefully

and more generally

- $0\nu2\beta$ decay might receive contribution from new physics effect beyond light Majorana $\nu$
- some assumptions about standard three $\nu$ mixing and cosmological scenarios may be wrong
Galactic SN and Next generation of Nucleon decay and Neutrino detectors
NNN detectors and galactic SN

Two of the currently unknown parameters, sign($\Delta m^2$) and $\theta_{13}$, might be accessed in a large scale (e.g. 0.4 Mton) Cherenkov detector through their effect on supernova $\nu$ oscillations.

- Radial profiles of the $\nu$ potential $V(x)$ at different times $t$ for simplified SN shock-waves:
  - upper panel: forward shock only
  - lower panel: forward plus reverse shock

- Main feature is a sharp discontinuity at the shock front (which can induce a strongly non-adiabatic transition) leaving behind an extended rarefaction zone.

- In both panels, the band shown are spanned by the $\nu$ wavenumber $k_H = \Delta m^2/2E$ for $E \in [2,60]$ MeV. The band marks the region where matter effects are potentially important ($V \sim k_H$).

- From the radial profiles one can derive the so-called crossing probability $P_H$

$$P_H = P_H[\Delta m^2/E, \sin^2\theta_{13}, V(x,t)]$$
Neutrino crossing probability

On the basis of the shock wave profiles, the $\nu$ crossing probability $P_H(t)$ can be estimated for representative values of $\sin^2\theta_{13}$ and fixed $E_\nu$.

- In the figure we report $P_H(t)$ for
  - relatively large $\nu$ energy ($E_\nu = 50$ MeV);
  - $\sin^2\theta_{13} = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$;
  - both shock wave profiles.

- $P_H(t)$ changes rapidly at the times indicated by dotted vertical lines:
  - For forward shock waves, when the static profiles is first perturbed by the forward shock front and then by the rarefaction zone.
  - For forward+reverse shock waves, both forward and reverse shock fronts perturb the static profiles.
Signatures of shock wave effects

An analysis of the absolute time spectra shows that the signatures of shock wave effects can be enhanced by comparing time spectra at different energies.

- In particular, in the case of inverted hierarchy, with a proper choice of $E_c$ and $E_H$ we have
  \[
  \frac{N(E_c, t)}{N(E_H, t)} \sim [1 - \cos^2 \theta_{12} P_H(E_H, t)]^{-1}
  \]

- We can track the crossing probability (if the $\nu$ mass hierarchy is inverted), so obtaining a real-time movie of the shock wave effects, for both
  - forward shock waves …
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  - forward shock waves …
  - forward+reverse shock waves
Conclusions

Recent years have been exciting …

- neutrino mass and mixing are now an established fact
- $3\nu$ oscillation scenario basically OK (convergence on notation desirable)
- two couples of parameters measured: $(\delta m^2, \theta_{12})$ and $(\Delta m^2, \theta_{23})$
- non-trivial consistency of all data towards small $\theta_{13}$
- evidence of matter effects in solar neutrino flavor transitions
- upper bounds on $\nu$ masses in sub(eV) range from $\beta$-decay, $0\nu2\beta$-decay and cosmology

... but our knowledge is still poor:

- kinematical unknowns: $\theta_{13}$, CP violation, mass hierarchy, absolute mass
- dynamical unknowns: new neutrino properties and/or interactions (LSND?)
- theoretical unknowns: making sense of parameters, finding underlying symmetries and scales
This workshop certainly help us to better understand how NNN detectors can:

- shed light on these great puzzles through high-statistics measurements of:
  - astrophysical neutrinos (solar, atmospheric, supernova)
  - man-made neutrinos (reactors, accelerators)
- as well as to provide a link between lower and higher energies through:
  - nucleon decay
Input from cosmological data

Joint analysis of several data sets. In particular, the following data set have been considered:

- CMB (Cosmic Microwave Background) data from
  - Temperature and cross polarization from WMAP (with LAMBDA code)
  - BOOMERanG-98
  - DASI (Degree Angular Scale Interferometer)
  - MAXIMA-1
  - CBI (Cosmic Background Imager)
  - VSAE (Very Small Array Extended)

- LSS (Large Scale Structure) with power spectrum of galaxies from
  - either 2dF (2 degrees Fields) Galaxy Redshift Survey
  - or SDSS (Sloan Digital Sky Survey)

- Ly$\alpha$ (Lyman alpha) Forest in the SDSS

- SN-Ia luminosity measurements (GOLD data set)

- Hubble constant from the HST (Hubble Space Telescope) measurements