Neutrino physics

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Two useful and updated references

- Carlo Giunti "Neutrino Unbound"

  http://www.nu.to.infn.it/

- Alessandro Strumia and Francesco Vissani review

  http://astrumia.home.cern.ch/astrumia/review.pdf

- 1998-: impressive acceleration of neutrino physics (after 70 yrs)
- Data interpretation (at last) pretty clean
- New physics!
- Cosmology (baryogenesis, CMB, LSS, BBN,...)
- Astrophysics (probe of SUN, SNe, HE sources,...)
- Particle physics (access $\Lambda \approx M_{GUT}$, unification, flavour, LFV)

Outline

I. Neutrino observables

- Neutrino parameters
- What do we know
- How do we know

II. Theoretical impact

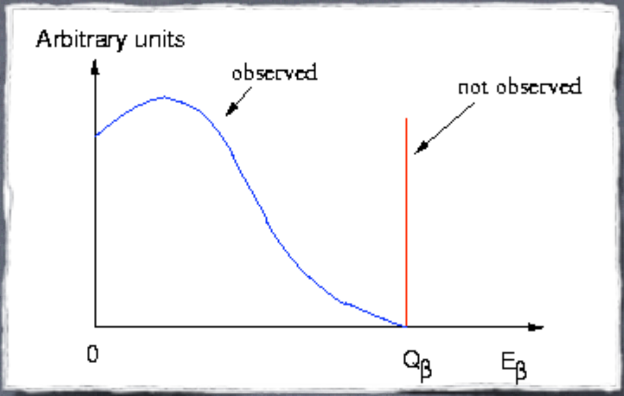
- Origin of neutrino masses
- Origin of the pattern of neutrino masses and mixing

The birth of neutrino physics (ν_e)

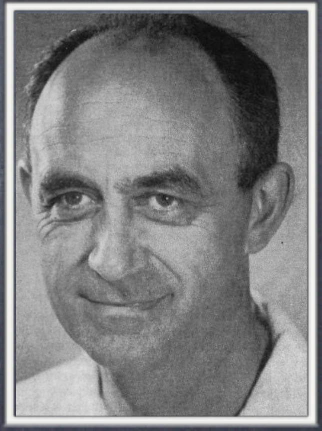
- Pauli 1930 postulated a new particle as a "desperate remedy" to save energy conservation

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}$$

$$\nu \equiv \nu_e$$



- Fermi 1934 "speculation too remote from reality": theory of neutrino (weak) interactions; ν = "neutrino"



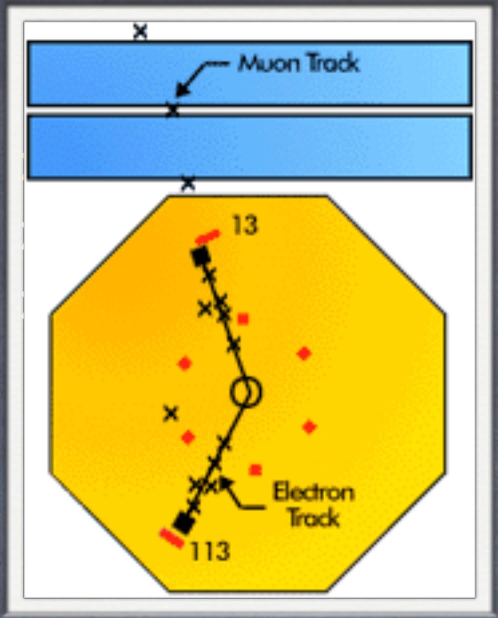
- Reines and Cowan 1956 detected (reactor) neutrinos through inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$

ν_μ

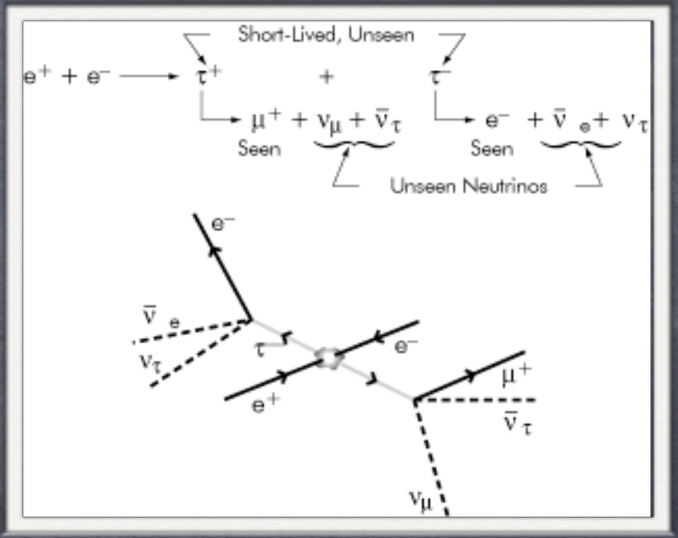
- "Missing momentum" in cosmic $\pi^\pm$ tracks: $\pi^+ \to \mu^+ \nu$

- ν from π decay detected by Lederman Schwartz Steinberger 1964: first (and prototypical) neutrino beam!
  - Protons on target → pions → neutrinos
  - Big detectors with strong shielding
- Neutrinos produced μ, not e: $\nu \equiv \nu_\mu$. Lepton (electron, muon) number conservation extended to neutrinos
- ($\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$)

ν_τ



- τ discovery at SPEAR, 1975: anomalous events $e^+e^- \rightarrow e\ \mu\ X$ (beginning of third family physics)

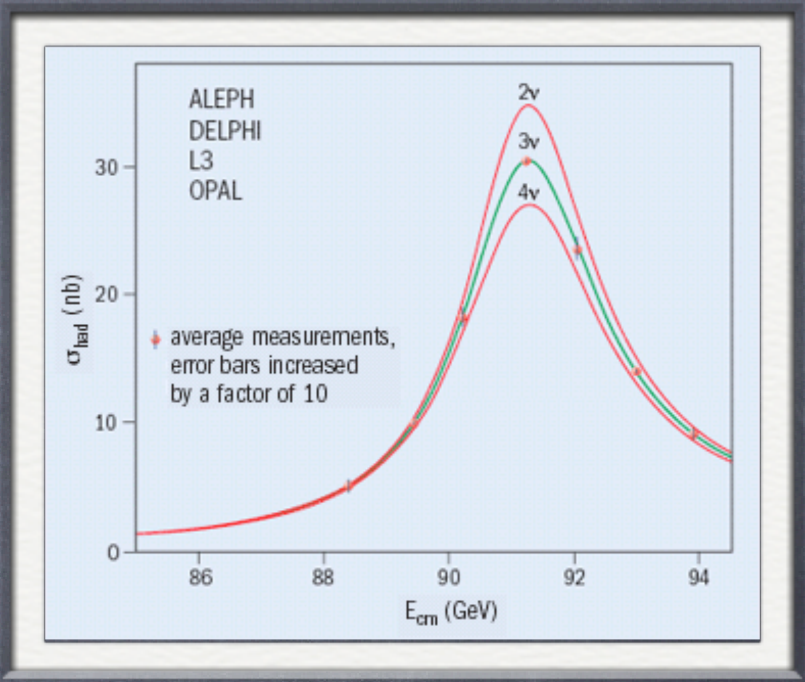


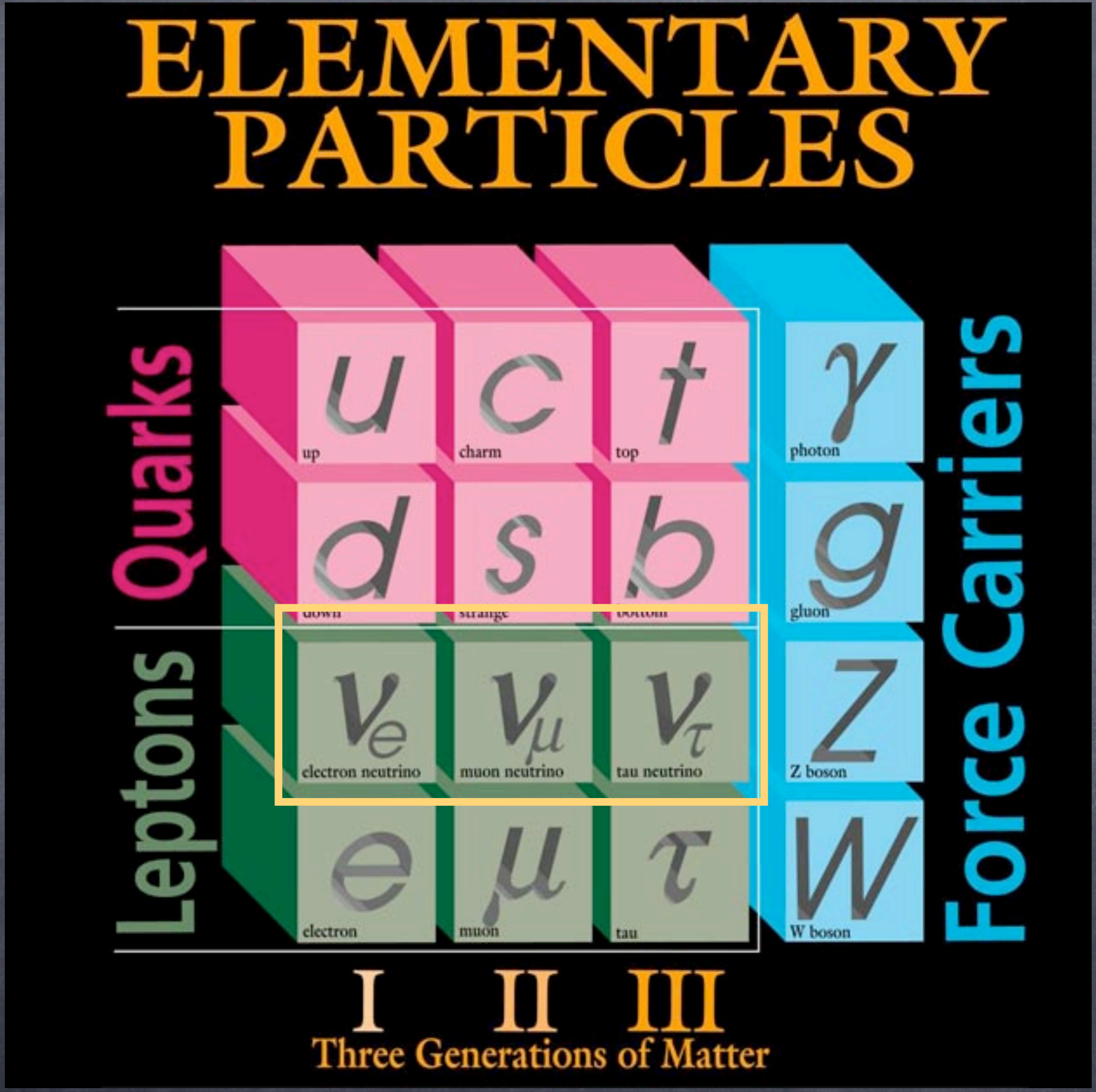
- L_e, L_μ violated? No: (τ decay too fast to be observed)
- ν_τ observed at FNAL in 2000 (beam dump; $D_s \rightarrow \tau\ \nu_\tau$; $\nu_\tau + N \rightarrow \tau + X$)

More ν's?

- Z with at LEP I
- Depends on the number of (kinematically accessible) Z decay channels
- Measurement corresponds to Z-decay into the known charged particles with m < 45 GeV and 3 (2.98±0.01) neutrinos with
  - m < 45 GeV
  - standard weak interactions

  ("sterile neutrinos" not constrained)
- 3 families (with light neutrinos)





ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I II III
Three Generations of Matter

Neutrino oscillations and anomalies

- Pontecorvo 1957: ν-$\bar{\nu}$ oscillations
  (in analogy with $\bar{K}^0$-K^0 oscillations)

- Maki-Nakagawa-Sakata (MNS) 1962:
  ν_e-ν_μ mixing and $\mu \to e\,\gamma$
  (in a model of leptons bound into nuclei)

- Davis 1968: solar neutrino anomaly
  (exp technique suggested by Pontecorvo)
  solar neutrino flux ≈ 1/2 of Bahcall 1963 prediction

- "Modern" era 1998-: getting rid of flux uncertainties

Neutrino parameters

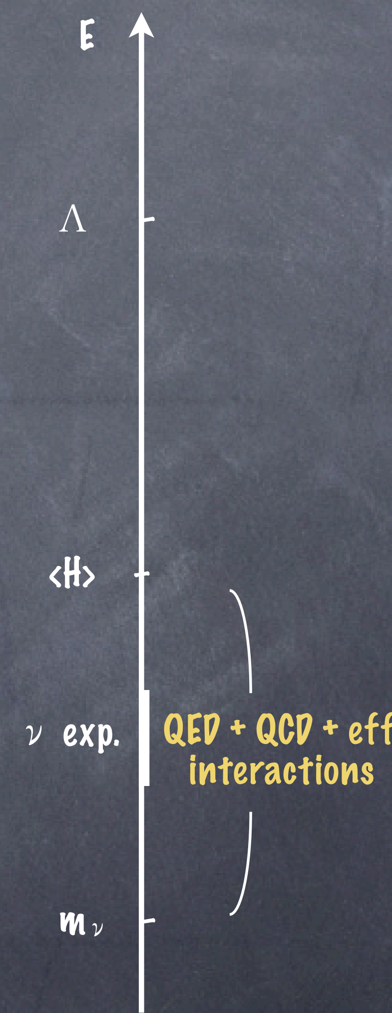
The framework

- $E \ll \langle H \rangle \approx 174$ GeV
- Relevant symmetries: QED ($U(1)_{em}$), QCD ($SU(3)_c$)
- Neutrino interactions described by 4 fermion Fermi Gamow-Teller Sudarshan-Marshak effective hamiltonian

$$\boxed{\mathcal{L}^{\text{eff}}_{E\ll M_Z} = \mathcal{L}^{\text{ren}}_{\text{QED+QCD}} + 4\,\frac{G_F}{\sqrt{2}}\, j^\mu_c\, j^\dagger_{c\mu} + \text{N.C.} + \ldots}$$

$$\boxed{j^\mu_c = \overline{\nu_{e_i}}\,\gamma^\mu P_L\, e_i + \overline{u_i}\,\gamma^\mu P_L\, d_i}$$

- Neutrinos are allowed to have masses m_1 m_2 m_3
- Mass eigenstates ν_1 ν_2 ν_3 diagonalize the mass matrix
  Flavour eigenstates ν_e ν_μ ν_τ paired to charged leptons in CC (also denoted ν_{ei}, i = 1,2,3)



$$\boxed{\nu_{ei} = U_{ij}\,\nu_j}$$

- U = PMNS (unitary) mixing matrix
- "Dirac" neutrinos: 4 = 3+1 physical parameters (as CKM)
  Standard parameterization:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- "Majorana" neutrinos: 6 = 3+3 physical parameters
  (2 extra CP-violating "Majorana" phases)

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

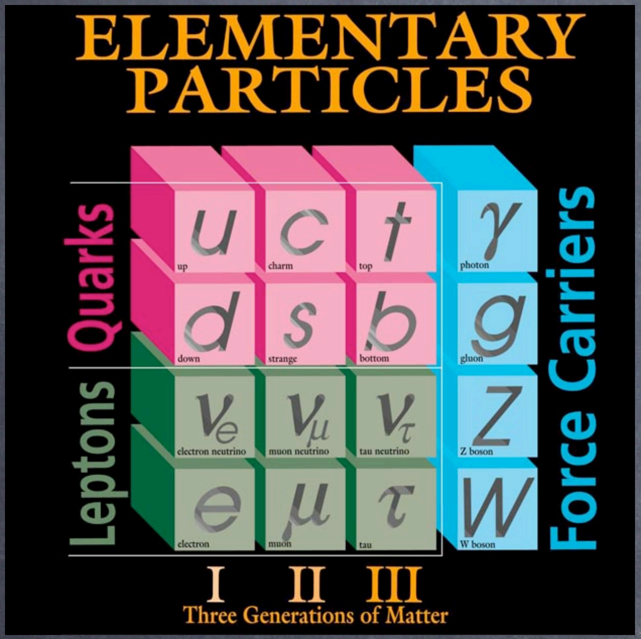
Dirac and Majorana neutrinos

- Dirac neutrinos:
  - $\nu \neq \overline{\nu}$
  - lepton number conserved
  - $\nu = \nu_L + \nu_R$
- Majorana neutrinos:
  - $\nu = \overline{\nu}$
  - lepton number violated
  - $\nu = \nu_L$
- The distinction is irrelevant
  - in oscillation experiments ($E \gg m_\nu$)
  - most experiments except when lepton number violation plays a role ($0\nu2\beta$)

(Interlude: the neutrino mass term)

Left- and Right-handed

The Dirac spinor e is not elementary: $e = e_L + e_R$



$$\boxed{u_{iL} \quad d_{iL} \quad \nu_{iL} \quad e_{iL} \qquad L}$$

$$u_{iR} \quad d_{iR} \quad e_{iR} \qquad R$$

$$\overline{u_{iL}} \quad \overline{d_{iL}} \quad \overline{\nu_{iL}} \quad \overline{e_{iL}} \qquad R$$

$$\boxed{\overline{u_{iR}} \quad \overline{d_{iR}} \quad \overline{e_{iR}} \qquad L}$$

Most general gauge transformation can mix all L

Most general mass term combines LL (in gauge invariant way)

(will not specify the Lorentz contraction)

Fermion mass terms

ψ_i "L" fermions

Most general mass term: $\frac{m_{ij}}{2}\psi_i\psi_j$

m_{ij} symmetric

ψ

$\frac{m}{2}\psi\psi$

"Majorana"
breaks any charge of ψ

example: $\psi = \nu_L$
$m \neq 0$ allowed by QED+QCD
breaks lepton number

Fermion mass terms

ψ_i “L” fermions

Most general mass term: $\frac{m_{ij}}{2}\psi_i\psi_j$

m_{ij} symmetric

(e.g. Dirac neutrino mass term: $m\,\overline{\nu_R}\nu_L$

$\psi^c = \overline{\nu_R} \quad \psi = \nu_L$

needs ν_R

does not break lepton number)

ψ, ψ^c

$$\underbrace{\frac{m_1}{2}\psi\psi + \frac{m_2}{2}\psi^c\psi^c}_{\text{“Majorana”}} + \underbrace{m\psi^c\psi}_{\text{“Dirac”}}$$

“Majorana”

“Dirac”
$Q(\psi) + Q(\psi^c) = 0$
(all charged SM fermions)

(e.g. electron mass term: $m\,\overline{e_R}e_L$

$\psi^c = \overline{e_R} \quad \psi = e_L$)

Most general mass terms (no ν_R)

- L fields:

	u_L	d_L	ν_L	e_L	$\overline{u_R}$	$\overline{d_R}$	$\overline{e_R}$
Q	⅔	–⅓	0	–1	–⅔	⅓	1
$SU(3)_c$	3	3	1	1	$\bar{3}$	$\bar{3}$	1

- Gauge invariant LL terms:

$$\boxed{m_u \overline{u_R} u_L + m_d \overline{d_R} d_L + m_e \overline{e_R} e_L + \frac{m_\nu}{2} \nu_L \nu_L}$$

With ν_R

- ν_R: charge and color singlet (as ν_L) but does not enter weak interactions

$$\frac{m_L}{2}\nu_L\nu_L \to \frac{m_L}{2}\nu_L\nu_L + \frac{m_R}{2}\overline{\nu_R\nu_R} + m_N\overline{\nu_R}\nu_L$$

- Dirac limit (lepton number conserved): $m_L = 0$, $m_R = 0$

$$\frac{m_L}{2}\nu_L\nu_L \to m_N\overline{\nu_R}\nu_L$$

- For definitess (and theoretical prejudice, see later) we will focus on Majorana type mass terms

Masses and mixings: quarks

- Mass eigenstates

$$\boxed{m^D = U^\dagger_{d_R} m^D_{\rm diag} U_{d_L} \quad m^U = U^\dagger_{u_R} m^U_{\rm diag} U_{u_L}}$$

$$\begin{cases} d'_{iR} = U^{d_R}_{ij} d_{jR} \\ d'_{iL} = U^{d_L}_{ij} d_{jL} \end{cases}, \begin{cases} u'_{iR} = U^{u_R}_{ij} u_{jR} \\ u'_{iL} = U^{u_L}_{ij} u_{jL} \end{cases}$$

$$\boxed{m^D_{ij} \overline{d_{iR}} d_{jL} + m^U_{ij} \overline{u_{iR}} u_{jL} = m_{d_i} \overline{d'_{iR}} d'_{iL} + m_{u_i} \overline{u'_{iR}} u'_{iL}}$$

- In terms of mass eigenstates:

$$\boxed{j^\mu_{\rm c,had} = \overline{u}_{iL} \gamma^\mu d_{iL} = V_{ij} \overline{u'_{iL}} \gamma^\mu d'_{jL}}$$

$$j^\mu_{\rm n,had} = (j^\mu_{\rm n,had})'$$

$$j^\mu_{\rm em,had} = (j^\mu_{\rm em,had})'$$

$\boxed{V = U_{u_L} U^\dagger_{d_L}}$ Cabibbo Kobayashi Maskawa (CKM) matrix

Physical parameters in V

$$m_{d_i}\overline{d_{iR}}d_{iL} + m_{u_i}\overline{u_{iR}}u_{iL} \qquad j^\mu_{\rm c,had} = V_{ij}\overline{u}_{iL}\gamma^\mu d_{jL}$$

$$V = \underbrace{\begin{pmatrix} e^{i\tau_1} & & \\ & e^{i\tau_2} & \\ & & e^{i\tau_3} \end{pmatrix}}_{\text{unphysical}} \begin{pmatrix} \text{standard par.} \end{pmatrix} \underbrace{\begin{pmatrix} 1 & & \\ & e^{i\sigma} & \\ & & e^{i\rho} \end{pmatrix}}_{\text{unphysical}}$$

9 = 3 + 3 + 1 + 2

Masses and mixings: leptons

- Mass eigenstates

$$\boxed{m^\nu = U_{\nu_L}^T m_{\rm diag}^D U_{\nu_L} \quad m^E = U_{e_R}^\dagger m_{\rm diag}^E U_{e_L}}$$

$$\nu'_{iL} = U_{ij}^{\nu_L} \nu_{jL}, \begin{cases} e'_{iR} = U_{ij}^{e_R} e_{jR} \\ e'_{iL} = U_{ij}^{e_L} e_{jL} \end{cases}$$

$$\boxed{\frac{m_{ij}^\nu}{2} \nu_{iL} \nu_{jL} + m_{ij}^E \overline{e_{iR}} e_{jL} = \frac{m_{\nu_i}}{2} \nu'_{iL} \nu'_{iL} + m_{e_i} \overline{e'_{iR}} e'_{iL}}$$

- In terms of mass eigenstates:

$$\boxed{j^\mu_{\rm c,lep} = \overline{\nu}_{iL} \gamma^\mu e_{iL} = U_{ij}^\dagger \overline{\nu'_{iL}} \gamma^\mu e'_{jL}}$$

$$j^\mu_{\rm n,lep} = (j^\mu_{\rm n,lep})'$$

$$j^\mu_{\rm em,lep} = (j^\mu_{\rm em,lep})'$$

$\boxed{U = U_{e_L} U_{\nu_L}^\dagger}$ Pontecorvo - Maki Nakagawa Sakata (P-MNS) matrix

Physical parameters in U

$$\frac{m_{\nu_i}}{2}\nu_{iL}\nu_{iL} + m_{e_i}\overline{e_{iR}}e_{iL} \qquad j^{\mu\dagger}_{\mathrm{c,lep}} = U_{ij}\bar{e}_{iL}\gamma^\mu\nu_{jL}$$

$$U = \underbrace{\begin{pmatrix} e^{i\gamma_1} & & \\ & e^{i\gamma_2} & \\ & & e^{i\gamma_3} \end{pmatrix}}_{\text{unphysical}} \Big(\text{standard par.}\Big) \underbrace{\begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}}_{\substack{\text{physical} \\ \text{(Majorana)}}}$$

$$9 = 3 + 3 + 1 + 2$$

(End of interlude)

Physical mass and mixing parameters in the lepton sector

$$\frac{m_{\nu_i}}{2}\nu_{iL}\nu_{iL} + m_{e_i}\overline{e_{iR}}e_{iL} \qquad j^{\mu}_{\mathrm{c,lep}} = U^{\dagger}_{ij}\overline{\nu}_{iL}\gamma^{\mu}e_{jL}$$

$$\boxed{m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3},\ \theta_{23},\ \theta_{12},\ \theta_{13},\ \delta,\ \alpha,\ \beta}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

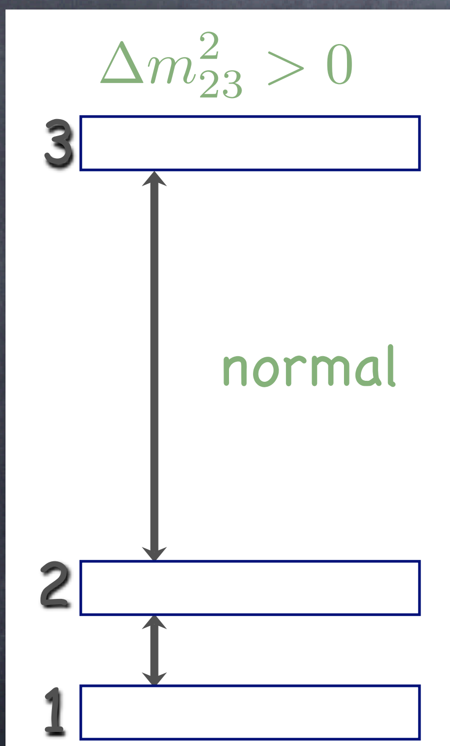
$$0 \le \theta_{23}, \theta_{12}, \theta_{13} \le \frac{\pi}{2}, \quad 0 \le \delta < 2\pi, \quad 0 \le \alpha, \beta < 2\pi$$

Standard labeling of eigenstates

$0 < \Delta m^2_{12} < |\Delta m^2_{23}|$ uniquely defines the labeling

$\Delta m^2_{12} > 0$ by definition; Δm^2_{23} can have both signs

$$\begin{pmatrix} \Delta m^2_{\mathrm{SUN}} \equiv \Delta m^2_{12} \\ \Delta m^2_{\mathrm{ATM}} \equiv \Delta m^2_{23} \end{pmatrix}$$



e.g.:

$m_1 < m_2 \ll m_3$

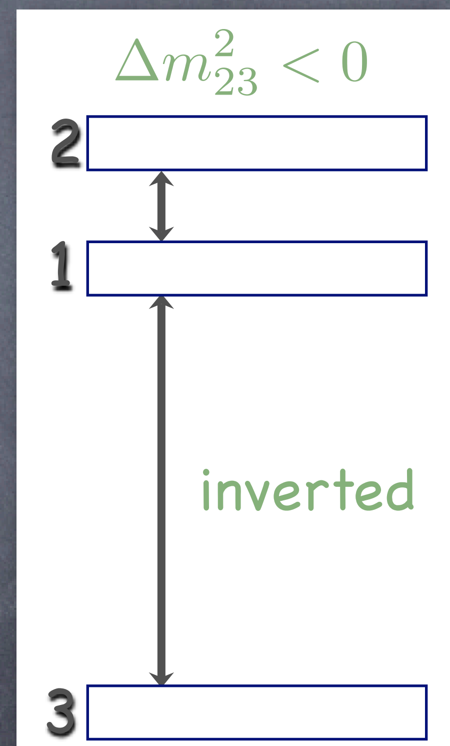
(hierarchical)

$m_1 \approx m_2 \approx m_3$

(degenerate)

$m_1 \approx m_2 < m_3$

(neither)



e.g.:

$m_1 \approx m_2 > m_3$

(inverse hierarchical)

$m_1 \approx m_2 \approx m_3$

(degenerate)

$$\boxed{\Delta m^2_{ij} \equiv m^2_j - m^2_i}$$

Neutrino parameters: what do we know?

Accessible
to oscillations

Charged
sector

$m_{e,\mu,\tau}$

Δm^2_{12}

$|\Delta m^2_{23}|$

$\text{sign}(\Delta m^2_{23})$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

Not accessible
to oscillations

m_{lightest}

α

β

$(\Delta m^2_{ij} \equiv m^2_{\nu_j} - m^2_{\nu_i})$

Accessible
to oscillations

Not accessible
to oscillations

Charged
sector

$$\Delta m^2_{12}$$

$$|\Delta m^2_{23}|$$

$$m_{\mathrm{lightest}}$$

$$m_{e,\mu,\tau}$$

$$\alpha$$

$$\mathrm{sign}(\Delta m^2_{23})$$

$$\beta$$

Well known

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

Known

Bounds

$$\Delta m^2_{\mathrm{ATM}} \sim 2.4 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45^\circ$$ (ATM, K2K, Minos)

$$\Delta m^2_{\mathrm{SUN}} \sim 0.76 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 35^\circ$$ (SUN, KamLAND)

$$\theta_{13} < 7^\circ \quad (2\sigma)$$ (CHOOZ, Palo Verde + ATM)

$$|m_{ee}| = |U^2_{ei} m_{\nu_i}| < \mathcal{O}(1) \times 0.4\,\mathrm{eV}$$ (Heidelberg-Moscow)

$$(m^\dagger m)_{ee} = |U_{ei}|^2 m^2_{\nu_i} < (2.2\,\mathrm{eV})^2$$ (Mainz, Troitsk)

$$\sum_i m_{\nu_i} < \mathcal{O}(1)\ \mathrm{eV}\ \ (\mathrm{priors})$$ (Cosmology)

Guidelines for theory:

$$\boxed{m_{\nu_i} \ll 174\,\mathrm{GeV}}$$

$$\theta_{23} \sim 45^\circ (= 45^\circ ?)$$

$$\theta_{12} \sim 30^\circ\text{–}35^\circ \neq 45^\circ\ \ (> 5\sigma)$$

$$\theta_{13} < 10^\circ$$

$$|\Delta m^2_{12} / \Delta m^2_{23}| \approx 0.035 \ll 1$$