Neutrino properties: nature, mass & CP violation

I. Schienbein
LPSC

prepared together with P. Serpico (LAPTH) and A. Wingerter (LPSC)

Kick-off meeting, 12/10/2012, Annecy

Facts of life with neutrinos

Neutrino properties:
What we know in 2012

- very weakly interacting, electrically neutral, spin 1/2, tiny mass
- long lived (or stable), tiny or vanishing magnetic moment
- 3 light 'SM families' (ν_e, ν_μ, ν_τ)
- neutrinos oscillate $\Longleftrightarrow$ $m_\nu \neq 0$

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m <$ 2 eV (tritium decay)
Mean life/mass, $\tau/m >$ 300 s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m >$ 7×10^9 s/eV (solar)
Mean life/mass, $\tau/m >$ 15.4 s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.32 \times 10^{-10}\ \mu_B$, CL = 90% (solar)

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$
$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2
$\sin^2(2\theta_{23}) > 0.95$ [i]
$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2 [j]
$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

Neutrinos oscillate!

Neutrino oscillations

- 3 neutrino states → 3 masses m_1, m_2 , m_3

- States with definite masses (mass eigenstates) in general do not coincide with flavor states

- Quantum mechanics:
States with same quantum numbers can mix, as it happens for the quarks

- The mixing matrices V are 3x3 unitary matrices
  - CKM = Cabibbo-Kobayashi-Maskawa
  - PMNS = Pontecorvo;
    Maki-Nakagawa-Sakata

Flavor basis:

$$\{|\nu_e\rangle\ ,\ |\nu_\mu\rangle\ ,\ |\nu_\tau\rangle\}$$

Mass basis:

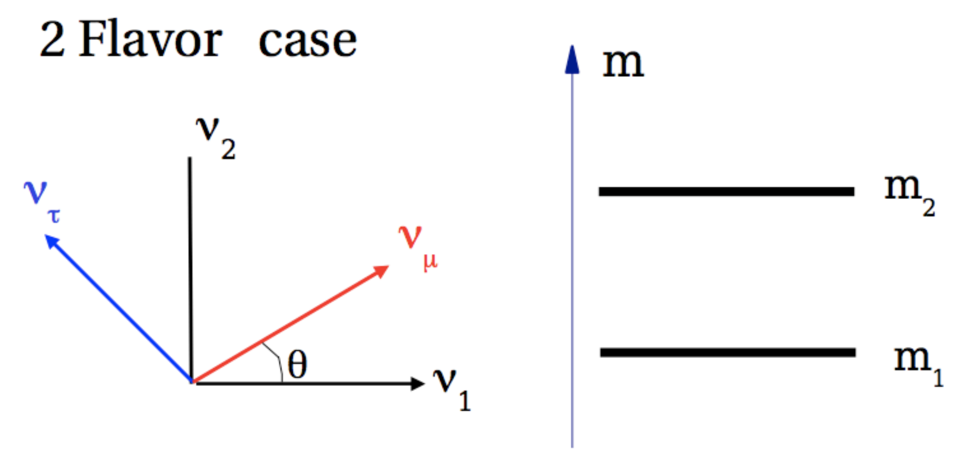
$$\{|\nu_1\rangle\ ,\ |\nu_2\rangle\ ,\ |\nu_3\rangle\}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V^{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V^{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillations

- Consider 2 flavor case:
  - for simplicity
  - dominant oscillations are well-described by 2-flavor mixing
- Flavor and mass eigenstates connected by a 2x2 rotation matrix



$$|\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\tau\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Neutrino propagation:

- ν_μ created at t=0 with 3-momentum **p**
- Neutrino state at time t
- Different mass components have different energy

$$|\nu(0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu(t)\rangle = e^{-iE_1t}\cos\theta\,|\nu_1\rangle + e^{-iE_2t}\sin\theta\,|\nu_2\rangle$$

$$E_i = \sqrt{p^2+m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq p + \frac{m_i^2}{2E}$$

Neutrino oscillations

Oscillation probability:

$$P(\nu_\mu \to \nu_\tau; t) = |\langle \nu_\tau | \nu(t) \rangle|^2$$
$$= |\{-\sin\theta\langle\nu_1| + \cos\theta\langle\nu_2|\}\{e^{-iE_1 t}\cos\theta|\nu_1\rangle + e^{-iE_2 t}\sin\theta|\nu_2\rangle\}|^2$$
$$= \cos^2\theta\sin^2\theta|e^{-iE_2 t} - e^{-iE_1 t}|^2$$
$$= 2\cos^2\theta\sin^2\theta\{1 - \cos[(E_2 - E_1)t]\}$$
$$= \sin^2 2\theta \sin^2\left[\frac{\Delta m^2}{4E} t\right]$$

$$\Delta m^2 = m_2^2 - m_1^2$$

As function of distance L=c*t=t:

$$P(\nu_\mu \to \nu_\tau; L) = \sin^2 2\theta \sin^2\left[\frac{\Delta m^2}{4E} L\right]$$
$$= \sin^2 2\theta \sin^2\left[1.27\Delta m^2(\text{eV}^2)\frac{L(\text{km})}{E(\text{GeV})}\right]$$

L/E determines sensitivity to Δm^2

Neutrino oscillations

3 flavor oscillations:

$$
\begin{aligned}
|\nu_e\rangle &= U^*_{e1}\,|\nu_1\rangle + U^*_{e2}\,|\nu_2\rangle + U^*_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U^*_{\mu 1}\,|\nu_1\rangle + U^*_{\mu 2}\,|\nu_2\rangle + U^*_{\mu 3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U^*_{\tau 1}\,|\nu_1\rangle + U^*_{\tau 2}\,|\nu_2\rangle + U^*_{\tau 3}\,|\nu_3\rangle
\end{aligned}
$$

atmospheric

solar

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

cross mixing

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

$$
P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\beta j} U^*_{\alpha j}\, e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2
$$

Results in the 3 flavor mixing scheme

flavor | atmospheric | cross-mixing | solar | mass

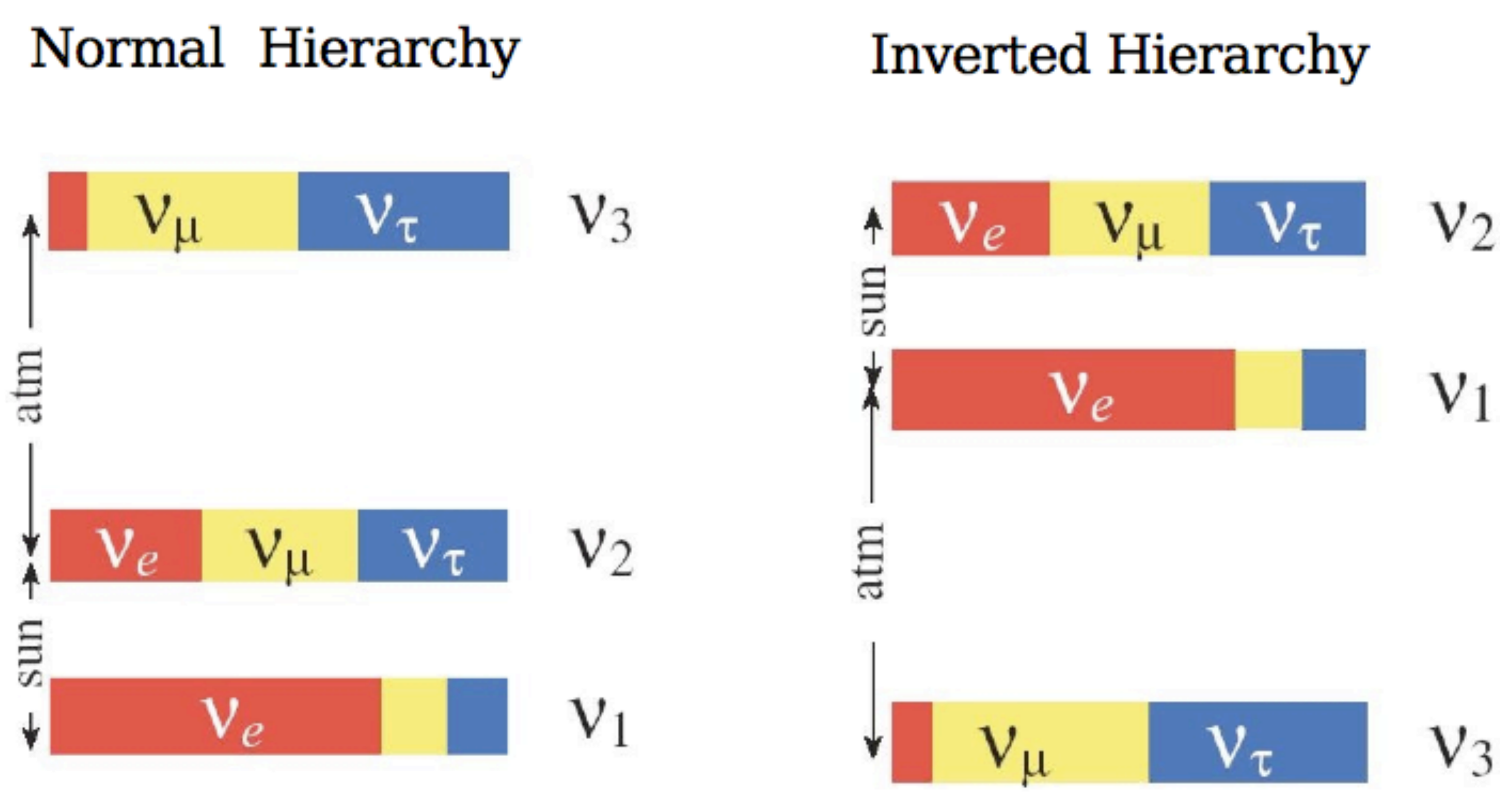
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

where cij=cosθij, sij=sinθij

	VALUE
Δm^2_{23}	2.35E-03 (eV^2)
Δm^2_{12}	7.58E-05 (eV^2)
$\sin^2\theta_{12}$	0.306
$\sin^2\theta_{23}$	0.42
$\sin^2\theta_{13}$	0.02 !
δ	?

arXiv:1106.6028 [hep-ph]

Neutrino state cross-composition



Discovery of a non-zero angle θ_{13}!

Leptonic CP violation: $\delta_{CP} \neq 0$?

- $\theta_{13} \neq 0$: necessary condition for leptonic CP violation
  - $\theta_{13} = 0$: effective 2 flavor mixing
  - CP violation only with unitary 3x3 matrices (or larger)
- Dirac-neutrinos: 1 CP violating phase
- Majorana-neutrinos: 2 additional CP violating phases
- CP violation in quark sector not sufficient to explain the baryon asymmetry of the universe (BAU)
- Leptonic CPV would give an additional contribution

Measurement of δ_{CP} exciting challenge

Neutrinos and the Standard Model

Neutrinos and the Standard Model

- Neutrino oscillations:
  - at least two massive neutrino states
  - why should neutrinos be massless anyway? (no symmetry)
- In the original SM, neutrinos are massless
  $\Longrightarrow$ oscillation results = physics beyond the SM
- However, massive neutrinos possible by a **minimal** extension of the SM:
  - right-handed neutrino
  - gauge singlet ("sterile neutrino")
  - can be a Dirac fermion like the electron
    - ★ mass term via Yukawa interaction with Higgs boson (Higgs mechanism)
    - ★ neutrino masses of order meV: tiny(!) Yukawa couplings

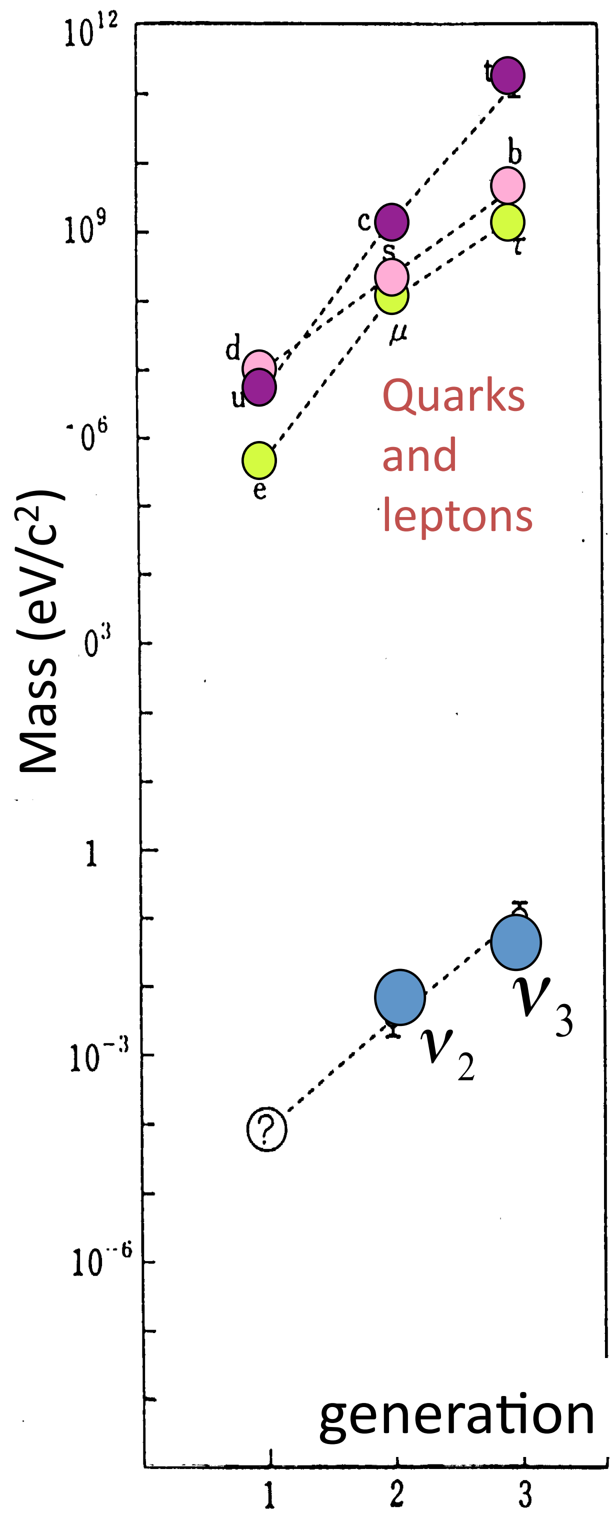
Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\frac{1}{2}$	**3**	**2**	$\frac{1}{3}$
u_R^c	$\frac{1}{2}$	$\overline{\mathbf{3}}$	**1**	$-\frac{4}{3}$
d_R^c	$\frac{1}{2}$	$\overline{\mathbf{3}}$	**1**	$\frac{2}{3}$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\frac{1}{2}$	**1**	**2**	-1
ν_R^c	$\frac{1}{2}$	**1**	**1**	0
e_R^c	$\frac{1}{2}$	**1**	**1**	2
$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	0	**1**	**2**	1
G_μ^α	1	**8**	**1**	0
W_μ^a	1	**1**	**3**	0
B_μ	1	**1**	**1**	0

Neutrinos and the Standard Model

- Neutrino oscillations:
  - at least two massive neutrino states
  - why should neutrinos be massless anyway? (no symmetry)
- In the original SM, neutrinos are massless
  $\Longrightarrow$ oscillation results = physics beyond the SM
- Conversely, neutrino only fermion in the SM without electric charge:
  - can be its own anti-particle (like γ, Z^0,π^0,η)
  - it's called Majorana-Neutrino (ν^M) if it is its own anti-particle: $\nu^M=(\nu^M)^c$
  - **non-minimal** extension of the SM:
    - ★ mass term in $\mathscr{L}$ can be a gauge singlet
      $\Longrightarrow$ heavy mass term possible
      [not related to the Higgs mechanism]
    - ★ seesaw mechanism can explain tiny masses

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\frac{1}{2}$	**3**	**2**	$\frac{1}{3}$
u_R^c	$\frac{1}{2}$	$\overline{\mathbf{3}}$	**1**	$-\frac{4}{3}$
d_R^c	$\frac{1}{2}$	$\overline{\mathbf{3}}$	**1**	$\frac{2}{3}$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\frac{1}{2}$	**1**	**2**	-1
ν_R^c	$\frac{1}{2}$	**1**	**1**	0
e_R^c	$\frac{1}{2}$	**1**	**1**	2
$H = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$	0	**1**	**2**	1
G_μ^α	1	**8**	**1**	0
W_μ^a	1	**1**	**3**	0
B_μ	1	**1**	**1**	0

Neutrinos and the Standard Model



Why the neutrino mass is so small ?

$$\left(\frac{m(\nu_3)}{m(top\ quark)}\right) \approx \left(\frac{1}{3\times 10^{12}}\right)$$

See-saw mechanism

Minkowsky, Yanagida, Gell-mann, Ramond, Slansky

$$m_\nu \approx \frac{m_q^{\ 2}}{m_N}$$

If we input $m_{\nu 3}$ and m_q (m_{top} is used), we get $m_N = 10^{15}$ GeV

This suggests that physics of neutrino mass could be related to physics of Grand Unification!

The SM with massive neutrinos

(i) Too many free parameters

Gauge sector: 3 couplings g', g, g_3	3
Quark sector: 6 masses, 3 mixing angles, 1 CP phase	10
Lepton sector: 6 masses, 3 mixing angles and 1-3 phases	10
Higgs sector: Quartic coupling λ and vev v	2
θ parameter of QCD	1
	26

(ii) Structure of gauge symmetry

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \overset{?}{\subset} \mathrm{SU}(5) \overset{?}{\subset} \mathrm{SO}(10) \overset{?}{\subset} \mathrm{E}_6 \overset{?}{\subset} \mathrm{E}_8$$

Why 3 different coupling constants g', g, g_3?

(iii) Structure of family multiplets

$$\underset{Q}{(\mathbf{3},\mathbf{2})_{1/3}} + \underset{\bar{u}}{(\bar{\mathbf{3}},\mathbf{1})_{-4/3}} + \underset{\bar{e}}{(\mathbf{1},\mathbf{1})_{-2}} + \underset{\bar{d}}{(\bar{\mathbf{3}},\mathbf{1})_{2/3}} + \underset{L}{(\mathbf{1},\mathbf{2})_{-1}} + \underset{\bar{\nu}}{(\mathbf{1},\mathbf{1})_{0}} \overset{?}{=} \mathbf{16}$$

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\frac{1}{2}$	**3**	**2**	$\frac{1}{3}$
u_R^c	$\frac{1}{2}$	$\bar{\mathbf{3}}$	**1**	$-\frac{4}{3}$
d_R^c	$\frac{1}{2}$	$\bar{\mathbf{3}}$	**1**	$\frac{2}{3}$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\frac{1}{2}$	**1**	**2**	-1
ν_R^c	$\frac{1}{2}$	**1**	**1**	0
e_R^c	$\frac{1}{2}$	**1**	**1**	2
$H = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$	0	**1**	**2**	1
G_μ^α	1	**8**	**1**	0
W_μ^a	1	**1**	**3**	0
B_μ	1	**1**	**1**	0

Fits nicely into the 16-plet of SO(10)

Majorana or Dirac?
That is here the question

Nature of neutrinos: Majorana or Dirac?

- Lepton number:
  - L=1 for neutrinos
  - L = -1 for anti-neutrinos
  - L **not conserved** for Majorana-Neutrinos

$$\nu_e + n \to e^- + p$$
$$L = 1 + 0 = 1 + 0$$

Lepton number conserved; Reaction has been observed

$$\nu_e = \bar{\nu}_e$$

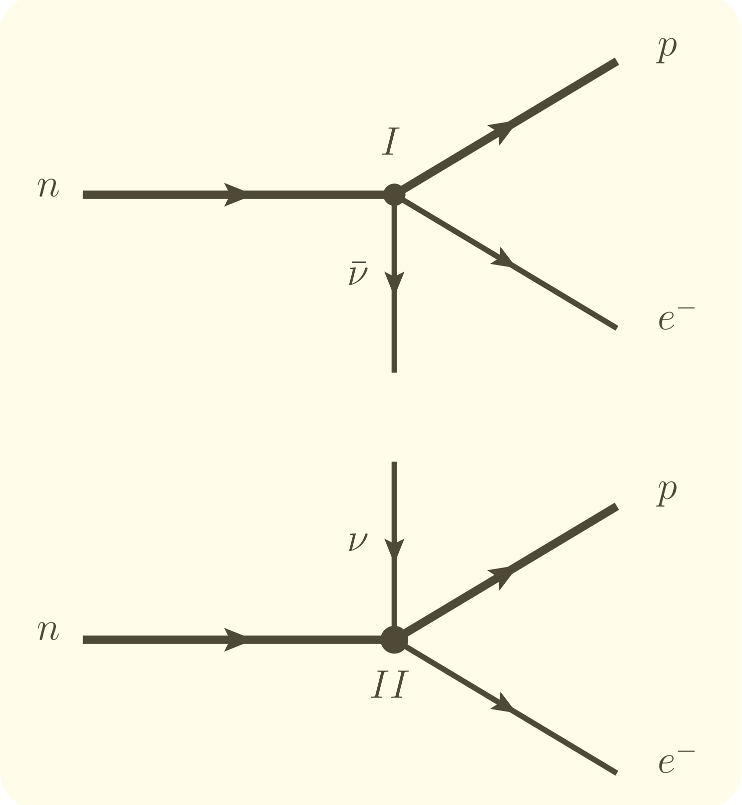
$$\bar{\nu}_e + n \to e^- + p$$
$$L = -1 + 0 \neq 1 + 0$$

Lepton number not conserved; Reaction has **not** been observed

- The second reaction should be possible if $\nu_e = \bar{\nu}_e$
  - Not observed! Naive conclusion: electron-neutrino is not Majorana!
  - Conclusion valid only for $m_\nu \neq 0$! Otherwise:
    - neutrino (h=-1)
    - anti-neutrino (h=+1)
    - and vertex with h=+1 might be forbidden

Neutrinoless double-beta decay

Vertex I	:	n	→	$p + e^- + \bar{\nu}_e$
Vertex II	:	ν_e + n	→	$p + e^-$
Together	:	2 n	→	$2p + 2e^-$
L	=	0	≠	0 + 2



- Necessary condition: neutrinos are Majorana fermions $\nu_e = \bar{\nu}_e$
- **If observed $\Rightarrow$ neutrinos are Majorana fermions**
- Even for Majorana neutrinos: forbidden if neutrinos massless and interaction vertices with fixed helicity
  - the smaller masses, the smaller 0νββ
  - m=0: distinction between Majorana and Dirac neutrinos not possible

Enigmatic neutrino masses

Neutrino masses

- **Why knowledge of neutrino masses interesting?**
  - Fundamental parameters of the SM
  - Neutrinos with O(meV) masses make the fermion mass spectrum of the SM even more bizarre! (14 orders of magnitude!)
  - Need masses to compute contribution of the neutrinos to the matter density of the universe
    - ★ Matter density important for the evolution of the universe
    - ★ Contribute a part to the non-baryonic dark matter (hot DM)
- **How to determine neutrino masses?**
  - direct determination via kinematics of weak decays (tritium β decay)
  - neutrino oscillations
  - neutrinoless double-beta-decay

Neutrino masses

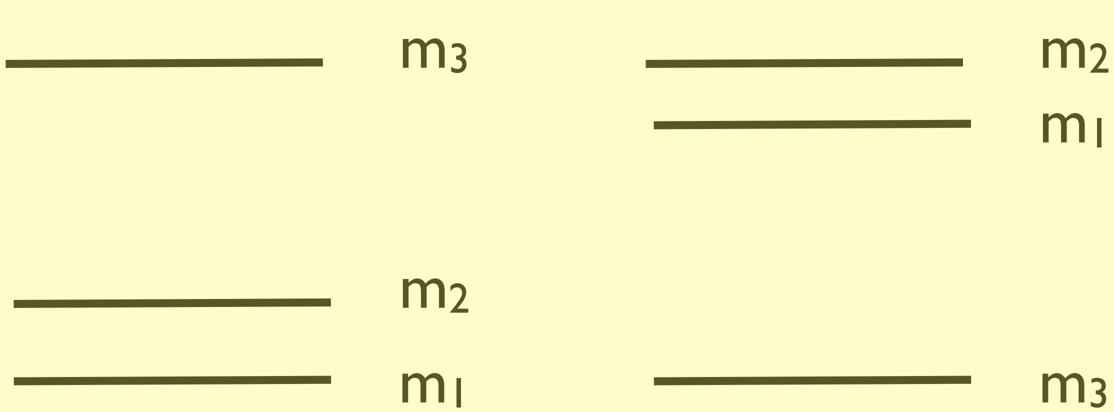
Oscillations:

$$\Delta m^2_{32} = m^2_3 - m^2_2 = 2.3 \times 10^{-3}\ \text{eV}^2$$

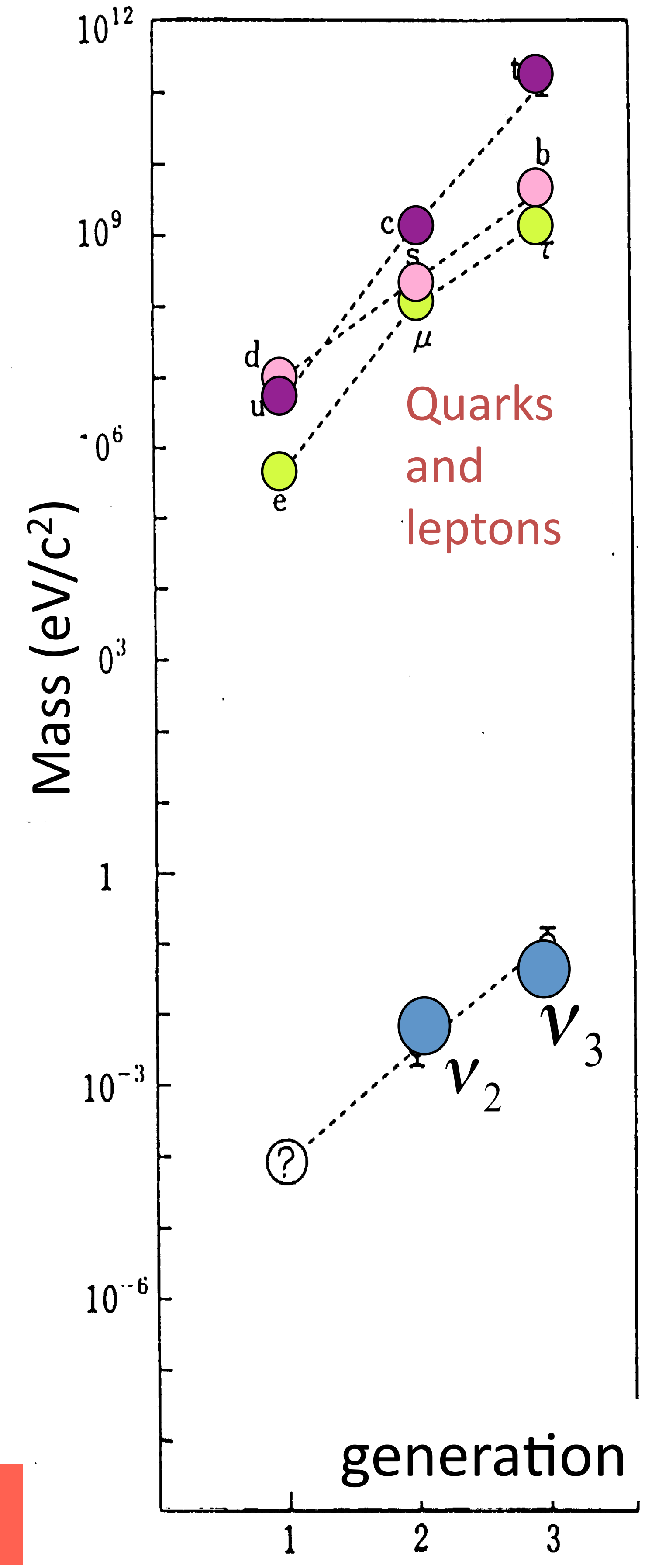
$$\Delta m^2_{21} = m^2_2 - m^2_1 = 7.5 \times 10^{-5}\ \text{eV}^2$$

Oscillations in matter: $m_2 > m_1$

Sign of Δm^2_{32} unknown:
normal or inverted hierarchy



Mass m of heaviest neutrino:
$\Delta m^2_{32} \simeq m^2$, $m \simeq 50$ meV



ENIGMASS: Fermion masses over 14 orders of magnitude

Flavor symmetries:
Fun for theorists?

Neutrino mixing

- Neutrinos have mass and the different flavors can mix

  Super-Kamiokande Collaboration, Y. Fukuda *et al.*, "Evidence for oscillation of atmospheric neutrinos," *Phys. Rev. Lett.* **81** (1998) 1562–1567, hep-ex/9807003

  SNO Collaboration, Q. R. Ahmad *et al.*, "Direct evidence for neutrino flavor transformation from neutral-current interactions in the Sudbury Neutrino Observatory," *Phys. Rev. Lett.* **89** (2002) 011301, nucl-ex/0204008

- Charged lepton and neutrino mass matrices cannot be simultaneously diagonalized

$$\hat{M}_{\ell^+} = D_L M_{\ell^+} D_R^\dagger, \quad \hat{M}_\nu = U_L M_\nu U_R^\dagger$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix

  B. Pontecorvo, "Mesonium and antimesonium," *Sov. Phys. JETP* **6** (1957) 429

  Z. Maki, M. Nakagawa, and S. Sakata, "Remarks on the unified model of elementary particles," *Prog. Theor. Phys.* **28** (1962) 870–880

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{D_L U_L^\dagger}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mixing

mismatch between flavour and mass basis expressed via mixing matrix U

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{lk} \equiv \sin\theta_{lk}$, $c_{lk} \equiv \cos\theta_{lk}$

$$\overset{\Delta m^2_{32}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \overset{\Delta m^2_{31}}{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}} \overset{\Delta m^2_{21}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

2-3 sector: atmospheric anomaly → consistent with maximal mixing (SK, LBL dis.)

3-flavour effects (& CP) suppressed by the smallness of θ_{13} and $\Delta m_{21}^2 << \Delta m_{31}^2$ Reactor (dis)+LBL (app.)

1-2 sector: “solar ν problem” → LMA & MSW in the Sun Radiochemical, SNO, Borexino, SK, KamLAND

dominant oscillations are well described by effective two-flavour mixing

Tribimaximal mixing

- ➢ Until recently, our best guess was tribimaximal mixing (TBM)

P. F. Harrison, D. H. Perkins, and W. G. Scott, "Tri-bimaximal mixing and the neutrino oscillation data," *Phys. Lett.* **B530** (2002) 167, hep-ph/0202074

$$U_{\rm PMNS} \stackrel{?}{=} U_{\rm HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$\hookrightarrow \quad \theta_{12} = 35.26^\circ, \quad \theta_{23} = 45^\circ, \quad \theta_{13} = 0^\circ$$

- ➢ Agreement still quite good for θ_{12}, θ_{23}, but $\theta_{13} = 0^\circ$ excluded @5σ

Forero et al, 1205.4018, **DAYA-BAY** Collaboration, 1203.1669, **RENO** Collaboration, 1204.0626

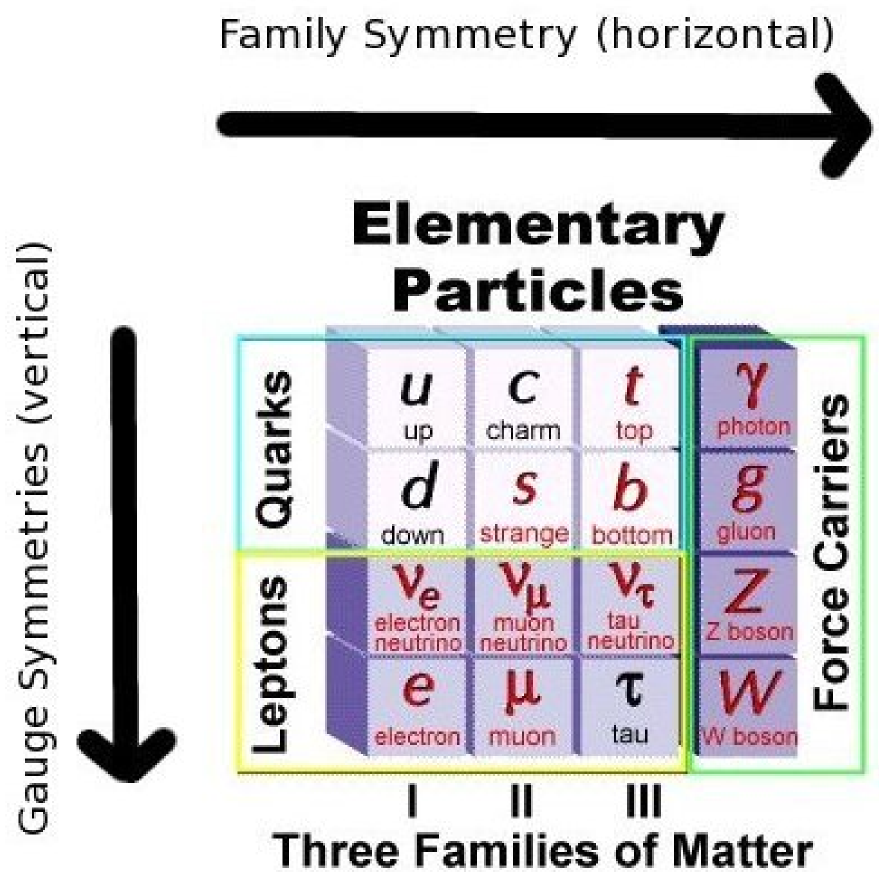
Parameter	Tribimaximal	Global fit 1σ	Daya Bay	Reno	
θ_{12}	35.26°	$33.40^\circ - 35.37^\circ$	-	-	✓
θ_{23}	45.00°	$41.55^\circ - 49.02^\circ$	-	-	✓
θ_{13}	0.00°	$8.53^\circ - 9.80^\circ$	8.8°	9.8°	✗

Fun for theorists

- Regular pattern of PMNS-matrix:

$$U_{\rm PMNS} \stackrel{?}{=} U_{\rm HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix} \sim \begin{pmatrix} 2 & 1 & 0 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

- Suggestive of a discrete family symmetry.
  Introduce relation between families of quarks and leptons:



Questions

- Why is mixing in the quark sector so different from mixing in the lepton sector?

Minimal mixing in the quark sector:

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.22 & 0.00 \\ 0.22 & 0.97 & 0.04 \\ 0.00 & 0.04 & 0.99 \end{pmatrix}$$

Maximal/Large mixing in lepton sector:

$$U_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \simeq \begin{pmatrix} 0.8 & 0.5 & 0.0 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

$\theta_{13} = 9.3°$:

$$U_{\rm PMNS} = \begin{pmatrix} 0.8 & 0.55 & 0.16z^* \\ -0.4-0.1z & 0.6-0.06z & 0.7 \\ 0.4-0.1z & -0.6-0.06z & 0.7 \end{pmatrix}, \; z = e^{i\delta}$$

- Which discrete group to take? [S_3,A_4, S_4, T_7,$\Delta(96)$,...]
  - Many discrete groups can give tribimaximal mixing (ruled out now)
    K. M. Parattu, A. Wingerter, "Tribimaximal Mixing From Small Groups", PRD84(2011)013011
  - Look for groups that give $\theta_{13} \neq 0$? (Still many possibilities!)
    C. Luhn, K. M. Parattu, A. Wingerter, "A Minimal Model of Neutrino Flavor", 1210.1197
  - Keep tribimaximal mixing at leading order and include higher dimensional ops.?
- Need guiding principle; More fundamental theory which "predicts" flavor symmetry

Who does not believe in sterile neutrinos?

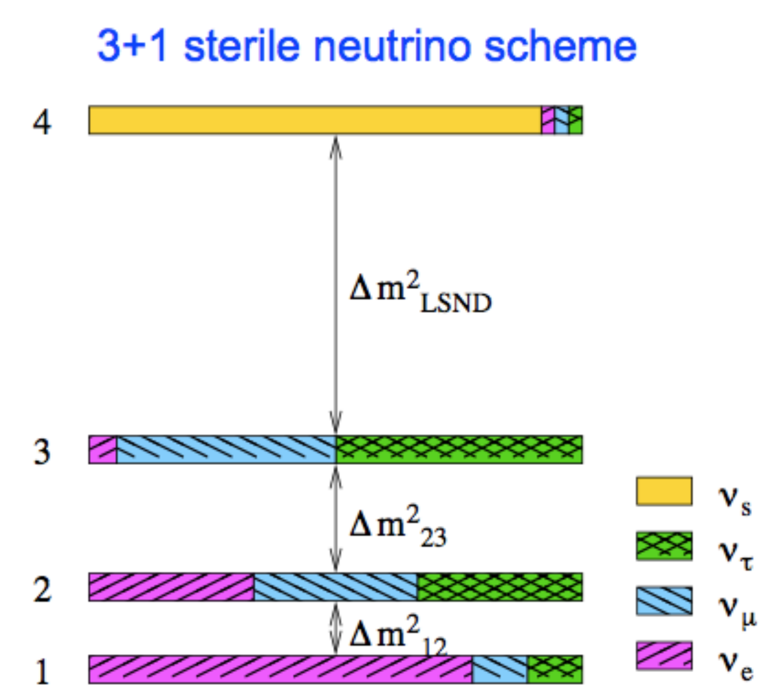
Sterile neutrinos

- Sterile neutrinos:
  - SM gauge group singlets (do not interact via weak force)
  - Mixed with active neutrinos

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

- Simplest models to give mass to neutrinos include such fields

- Mass scale of (some) these states?
  - Order eV: modifies neutrino oscillations (more freedom to explain certain puzzles)
  - Order 10^{15} GeV: seesaw, GUTs (theoretically more appealing?)



Sum puzzles

LSND

anti-ν_μ → anti-ν_e 87.9 ± 22.4 ± 6.0 excess events, 3.8 σ away from zero
(< 2.3 σ according to background analysis in 1112.0907 ?!)

KARMEN

anti-ν_μ → anti-ν_e tight constraints on LSND (slightly smaller L/E)

MiniBoone (ν)

ν_μ → ν_e $E > 475$ MeV (a priori search region): no excess,
$E < 475$ MeV: ~3 σ excess (after unblinding, background understood?)

MiniBoone (anti-ν)

anti-ν_μ → anti-ν_e inconclusive, consistent with both **ν**-run results and LSND

Reactor Anomaly

anti-ν_e flux predictions from reactors require to convert measured *e*-spectra from ^{235}U, ^{239}Pu, ^{241}Pu into ν-spectra: recent calculation yield 3% higher fluxes (*Mueller et al., 1101.2663, P. Huber, 1106.0687*) Hints of "short baseline disappearance"?

Gallium Anomaly

deficit of ν_e measured in the GALLEX and SAGE solar ν-detectors (~3 σ? See e.g. *Giunti & Laveder, 1106.3244*)

LSND

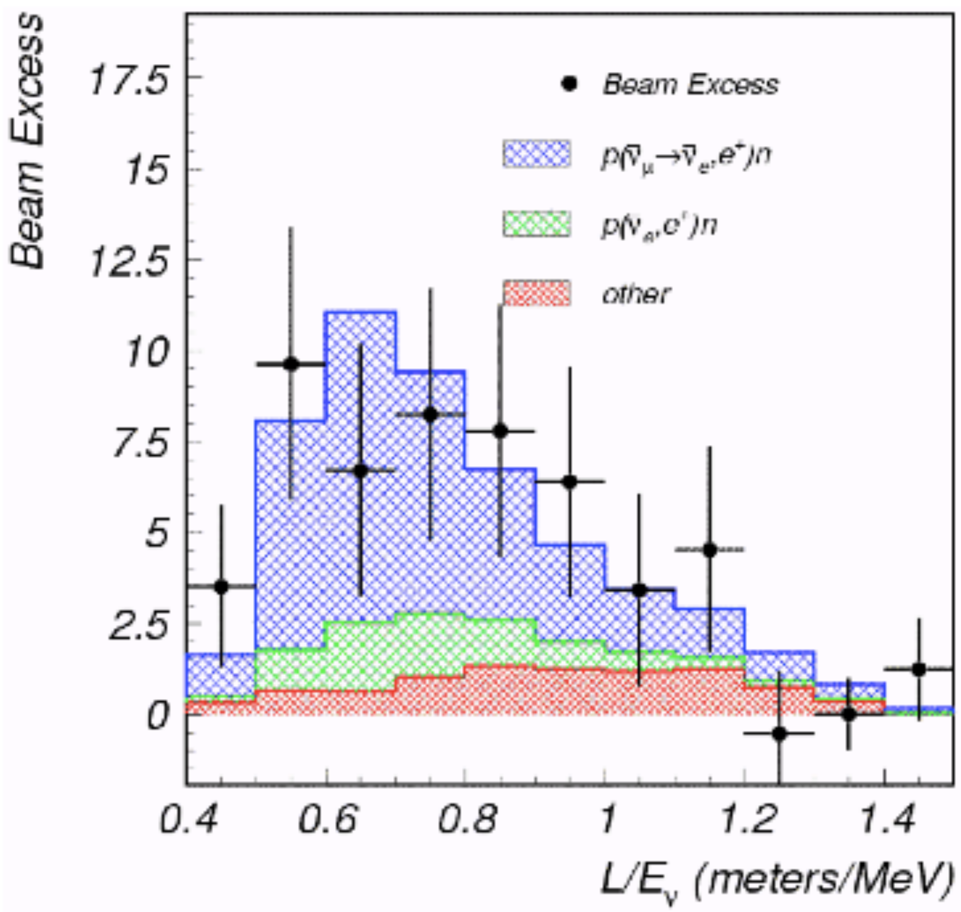
The LSND experiment observed a small excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam.

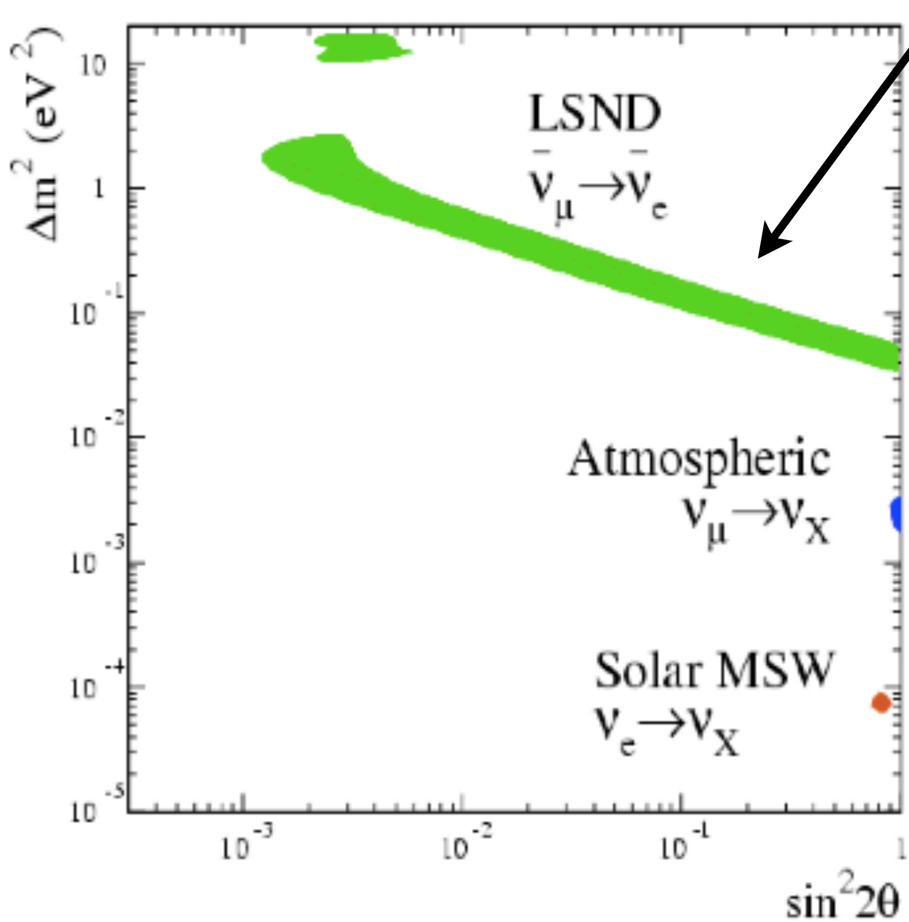
Data excess: 87.9 ± 22.4 ± 6.0 (3.8 σ)

Best fit: $\Delta m^2 \sim 1$ eV^2, $\sin^2 2\theta \sim 0.003$

requires a 3rd Δm^2

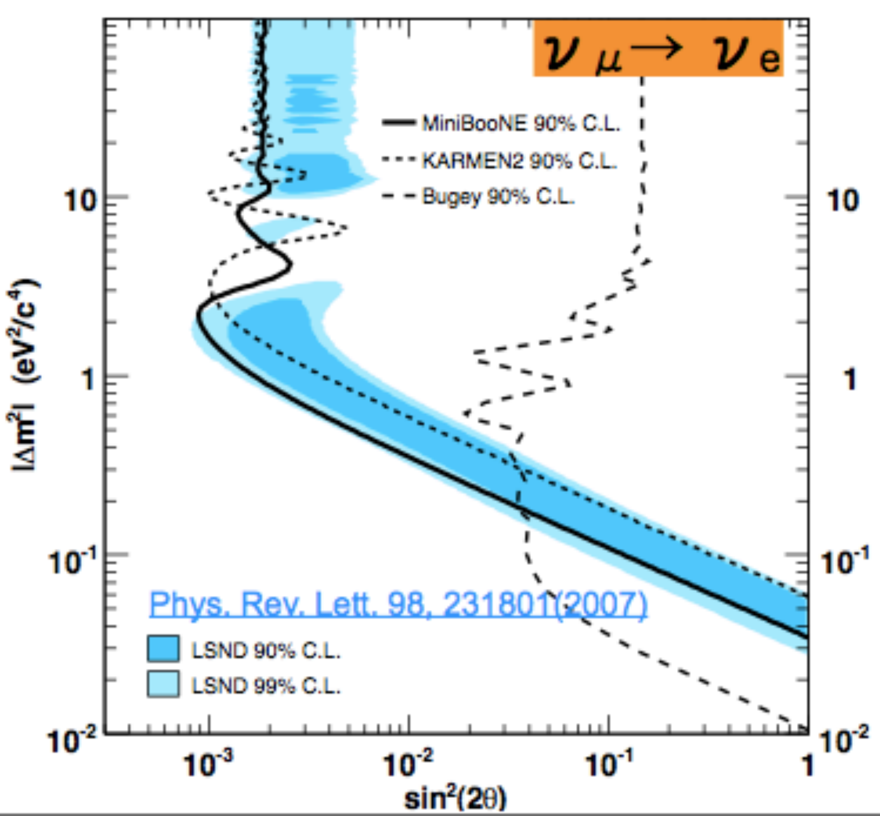
Phys.Rev.D 64, 112007 (2001)

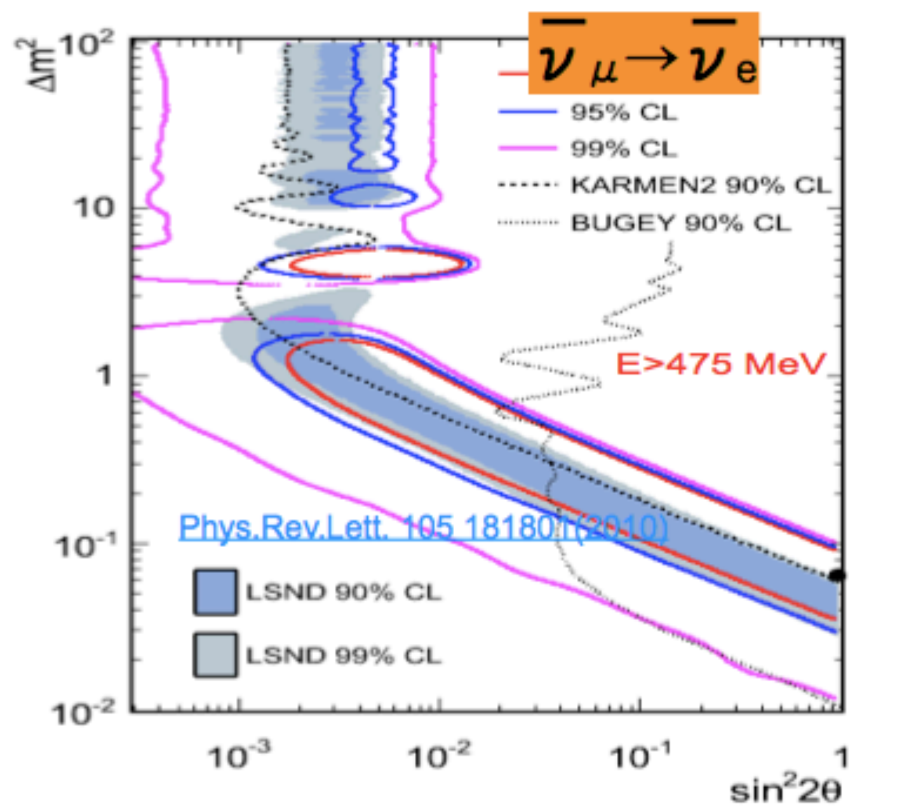




MiniBooNE ν_e results

- MiniBooNE recently tested the LSND signal.
- Ruled out most of LSND region in $\nu_\mu \rightarrow \nu_e$ search.
- However, observed (small) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess.
  - Consistent with LSND???





Affaire à suivre….

Sterile neutrinos and cosmology

Early universe would produce sterile neutrinos

- For parameters suggested by laboratory anomalies:
  - active neutrinos oscillate into sterile neutrinos **before** decoupling
  - there is time to replenish the active neutrinos via ordinary weak interactions with electrons
  - hence the additional species can be brought into equilibrium
  - Signatures: $N_{eff} \sim 4$ (5) in 3+1 (3+2) models

- Big Bang Nucleosynthesis (BBN)
  - excludes $N_{eff} = 5$, barely consistent with $N_{eff} = 4$
  - small preference for $N_{eff} \geq 3$ (1 σ)
    G. Mangano, P. Serpico, PLB701(2011)296

- CMB data have a small preference for $N_{eff} \geq 3$

Early universe would produce sterile neutrinos

- Are sterile ν's fitting the lab. anomalies the cause of $N_{eff}>3$? Most likely not!
  - In 3+1 models (fully thermalized) $m_4<0.48$ eV (95% CL) (vs. about 1 eV expected from Lab)
  - In 3+2 models (fully thermalized) $m_4 + m_5<0.9$ eV (95% CL)
    (vs. about 1.5 eV expected from Lab)
- What if Lab confirms eV-scale sterile neutrinos?
  - One would need to go to much more contrived cosmologies!

Concluding wishlist

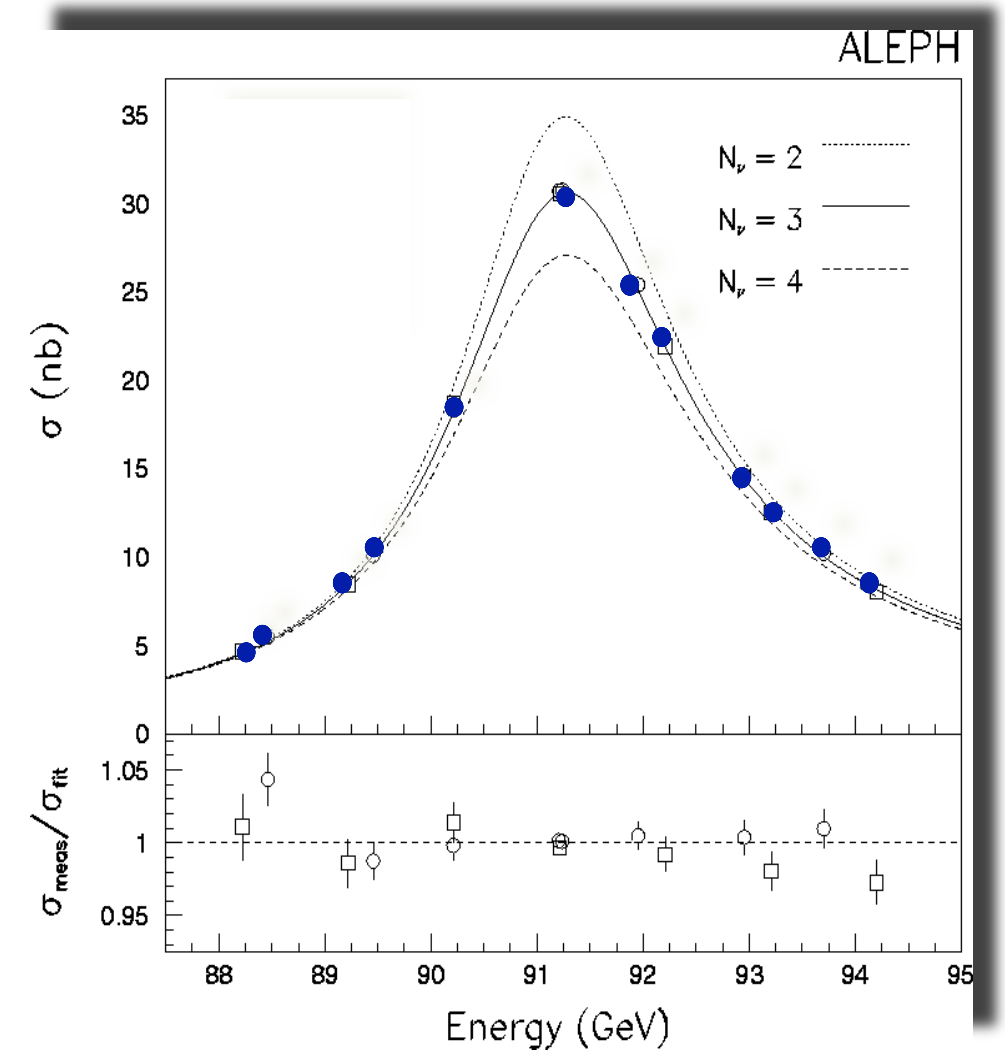
Neutrino properties: What we want to know

- **nature of neutrinos**:
  - Majorana or Dirac fermions?
  - are there sterile neutrinos?
- **neutrino masses**:
  - what are the absolute neutrino masses?
  - normal ($m_2 \ll m_3$) or inverted ($m_2 \gg m_3$) mass hierarchy?
    [we know $m_2 > m_1$ from MSW effect]
- **mixing matrix** (PMNS-matrix):
  - more precise measurement of mixing angles
  - is the PMNS matrix unitary?
  - is there leptonic CP violation?

Merci!

How Many Light Neutrinos Exist ?

Answer : 3



$$Z^0 \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$

$$\Gamma_{\nu\bar{\nu}} = 166.9 \text{ MeV}$$

$$\Gamma_{\text{invisible}} = N_\nu \, \Gamma_{\nu\bar{\nu}}$$

$$\Gamma_{\text{invisible}} = \Gamma_{\text{tot}} - \Gamma_{\text{vis}} = 498 \pm 4.2 \text{ MeV}$$

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} = 2.994 \pm 0.012$$

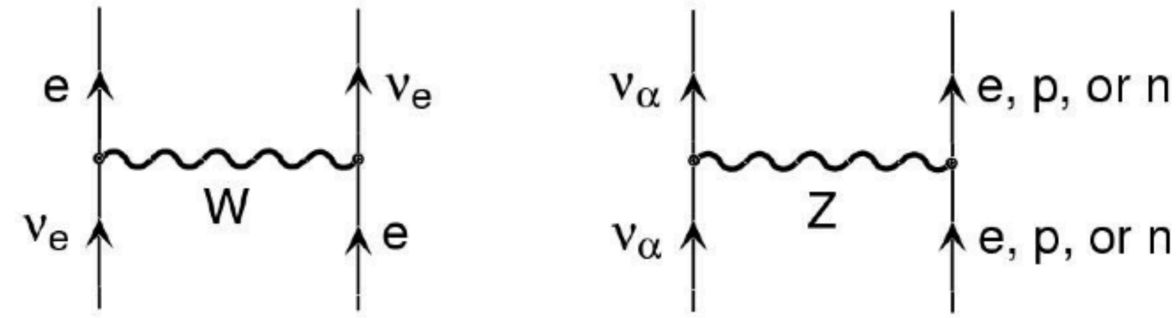
Neutrino oscillations in matter (MSW effect)

Mikheyev-Smirnov-Wolfenstein (MSW) effect:

Matter along the path of a neutrino:
equivalent to the presence of an effective potential

- different potentials for different flavors
- the effective potential affects the flavor propagation in matter
- matter effective potentials have opposite signs for neutrinos and anti-neutrinos

Effective Potential in Ordinary Matter



$$V_{\nu_\mu e} = V_{\nu_\tau e} = V^Z_{\nu_e e} = -\frac{\sqrt{2}}{2} G_F N_e$$

$$V_{\nu_\mu p} = V_{\nu_\tau p} = V_{\nu_e p} = +\frac{\sqrt{2}}{2} G_F N_p$$

$$V_{\nu_\mu n} = V_{\nu_\tau n} = V_{\nu_e n} = -\frac{\sqrt{2}}{2} G_F N_n$$

$$V_{\nu_e e} = V^Z_{\nu_e e} + V^W_{\nu_e e} = -\frac{\sqrt{2}}{2} G_F N_e + \sqrt{2} G_F N_e$$

Neutrino interactions

$$\frac{d\sigma}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + (g_V^{\nu e} \mp g_A^{\nu e})^2(1-y)^2\right]$$

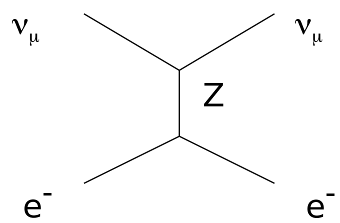
$$\sigma = \frac{G_F^2 m_e E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + \frac{1}{3}(g_V^{\nu e} \mp g_A^{\nu e})^2\right]$$

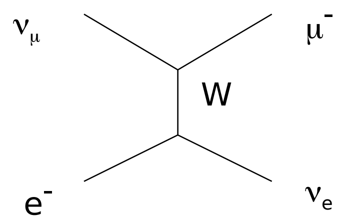
$$(g_V^{\nu e} \pm g_A^{\nu e})^2 = \rho^2(1 - 4s_w^2 + 4s_w^4)\,,\ (g_V^{\nu e} \mp g_A^{\nu e})^2 = \rho^2(4s_w^4)$$

$$\sigma(\nu_\mu e) = \frac{G_F^2 m_e E_\nu}{2\pi}\rho^2\left[1 - 4s_w^2 + \frac{16}{3}s_w^4\right]$$

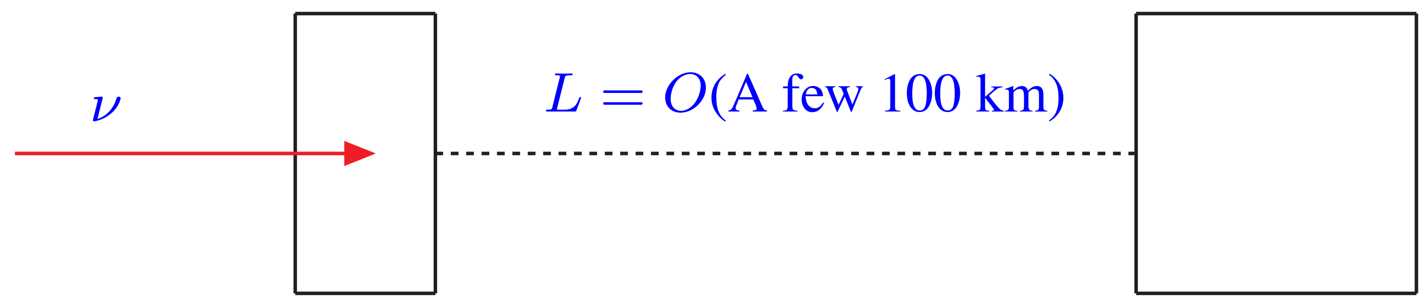
$$\sigma(\bar{\nu}_\mu e) = \frac{G_F^2 m_e E_\nu}{2\pi}\rho^2\left[\frac{1}{3} - \frac{4}{3}s_w^2 + \frac{16}{3}s_w^4\right]$$

- NC ES $\quad \nu_\mu + e^- \rightarrow \nu_\mu + e^-$, $\quad \bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
- CC QE (IMD) $\quad \nu_\mu + e^- \rightarrow \mu^- + \nu_e$
- NC DIS $\quad \nu_\mu + q \rightarrow \nu_\mu + X$, $\quad \bar{\nu}_\mu + q \rightarrow \bar{\nu}_\mu + X$
- CC DIS $\quad \nu_\mu + q \rightarrow \mu^- + X$, $\quad \bar{\nu}_\mu + q \rightarrow \mu^+ + X$





Long Baseline experiments



Near detector:

- neutrino flux
- neutrino beam energy spectrum
- cross sections before oscillation

Far detector:

- observation of charged and neutral current reactions

LBL	Beam	Place	L [km]	<E_ν> [GeV]	Target	Year	Goals
K2K	12 GeV proton	KEK → SK	250	1.4	H_2O	1999-2004	ν_μ
T2K	50 GeV proton	JParc → SK	295	~0.6	H_2O	2010-	ν_μ, ν_e ; θ_{13}, δ Δm_{23}^2, θ_{23} νA x-secs.
MINOS	NuMI	FNAL → Soudan	735	3, 7, 15	Fe	2005-2014	NC/CC ratio ν_μ , ν_e; θ_{13}; ν_S
OPERA	CNGS	CERN → GS	732	17	Pb	2008-2012	ν_τ
NOvA	NuMI	FNAL → Ash River	810	~2	liquid scint.	2013-	ν_μ, ν_e ; θ_{13}, δ mass hierarchy νA x-secs.

Neutrino cross sections

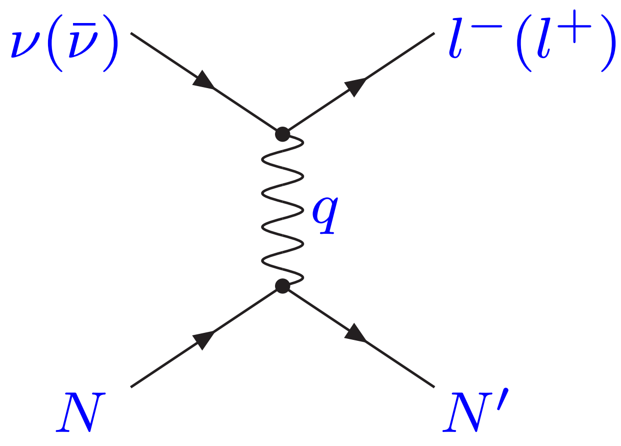
Flux $\otimes$ Cross section $\otimes$ Nuclear effects

current precision: ca. 30%

need to improve this for precision measurements
of the MNS mixing matrix!

Neutrino nucleon interactions

- Quasi-elastic scattering (QE)

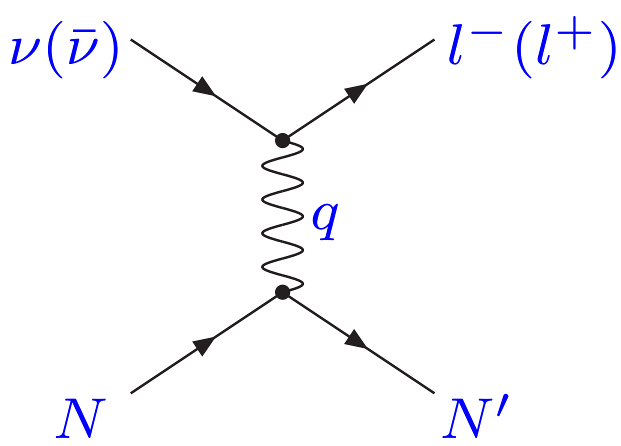


CC: $\nu(\bar{\nu}) + N \to l^-(l^+) + N'$

NC: $\nu(\bar{\nu}) + N \to \nu(\bar{\nu}) + N'$

Neutrino nucleon interactions

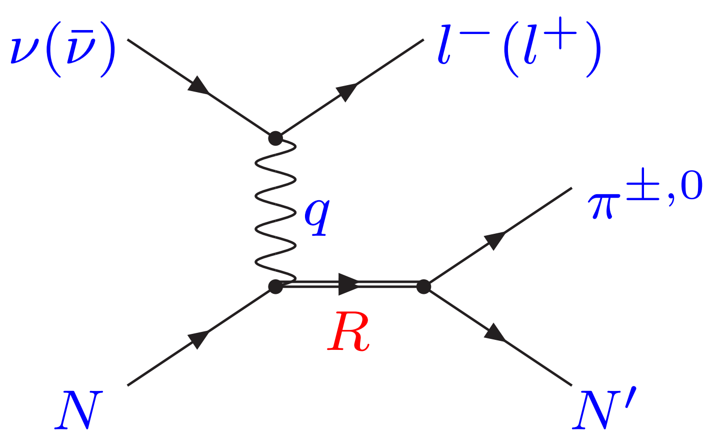
- Quasi-elastic scattering (QE)



CC: $\nu(\bar{\nu}) + N \to l^-(l^+) + N'$

NC: $\nu(\bar{\nu}) + N \to \nu(\bar{\nu}) + N'$

- Resonance production (RES)

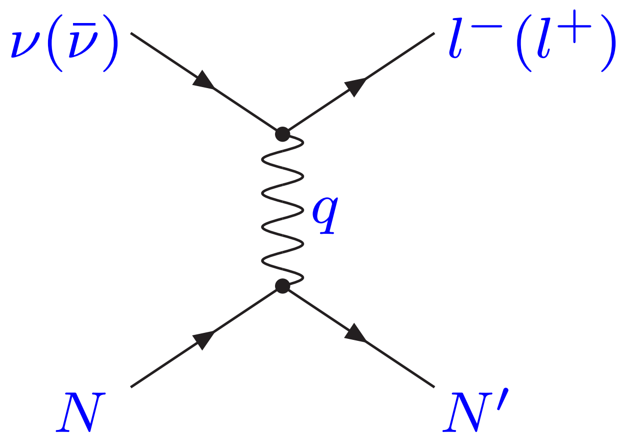


Charged Current (CC):
$\nu(\bar{\nu}) + N \to l^-(l^+) + N + \pi^{\pm,0}$

Neutral Current (NC):
$\nu(\bar{\nu}) + N \to \nu(\bar{\nu}) + N + \pi^{\pm,0}$

Neutrino nucleon interactions

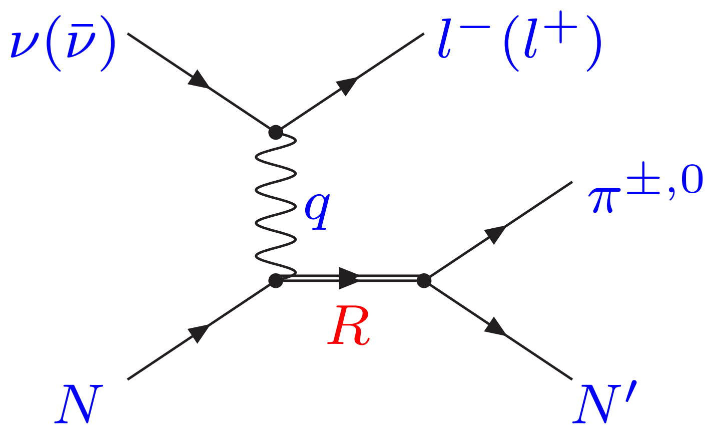
- Quasi-elastic scattering (QE)



CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N'$

NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N'$

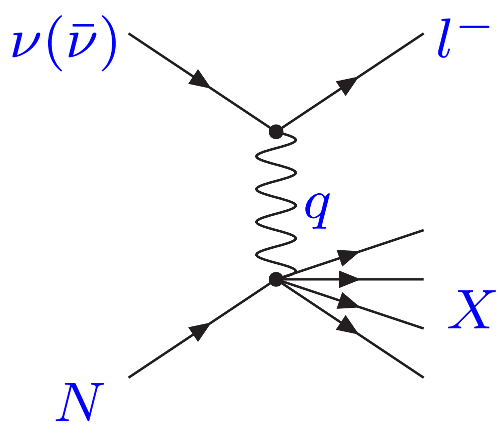
- Resonance production (RES)



Charged Current (CC):
$\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N + \pi^{\pm,0}$

Neutral Current (NC):
$\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N + \pi^{\pm,0}$

- Deep inelastic scattering (DIS)

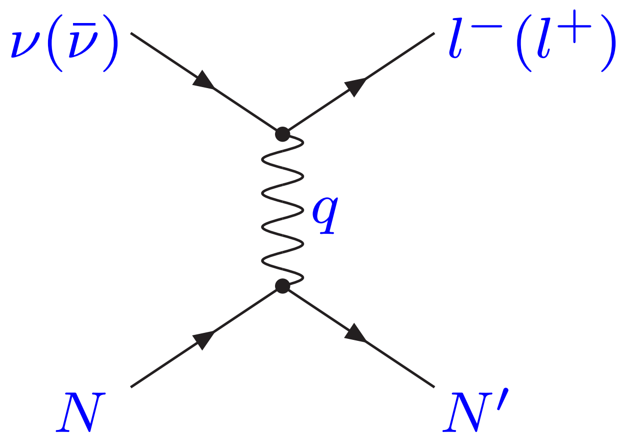


CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + X$

NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + X$

Neutrino nucleon interactions

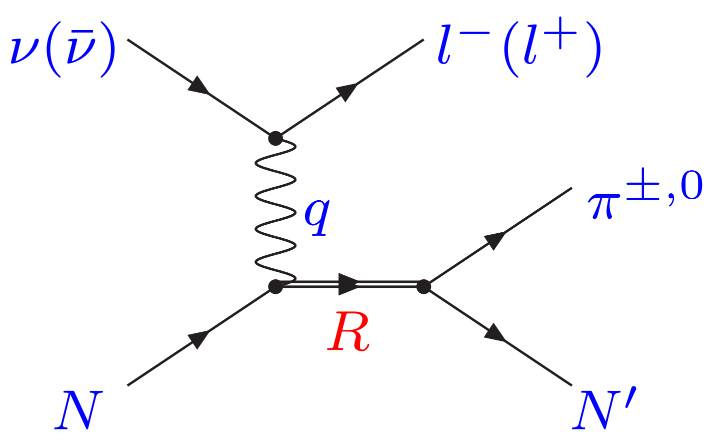
- Quasi-elastic scattering (QE)



CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N'$

NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N'$

- Resonance production (RES)

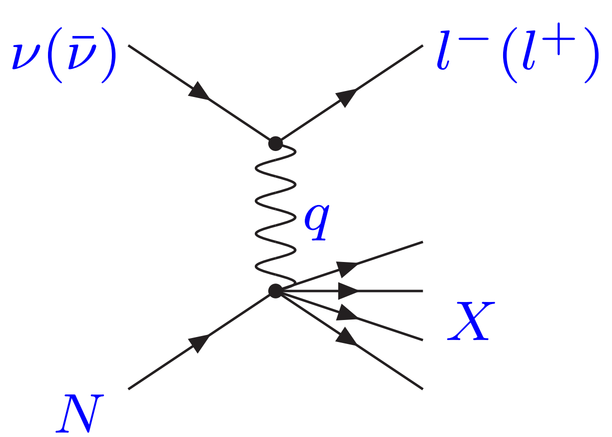


Charged Current (CC):
$\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N + \pi^{\pm,0}$

Neutral Current (NC):
$\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N + \pi^{\pm,0}$

Need these cross sections on free nucleons and nuclear targets

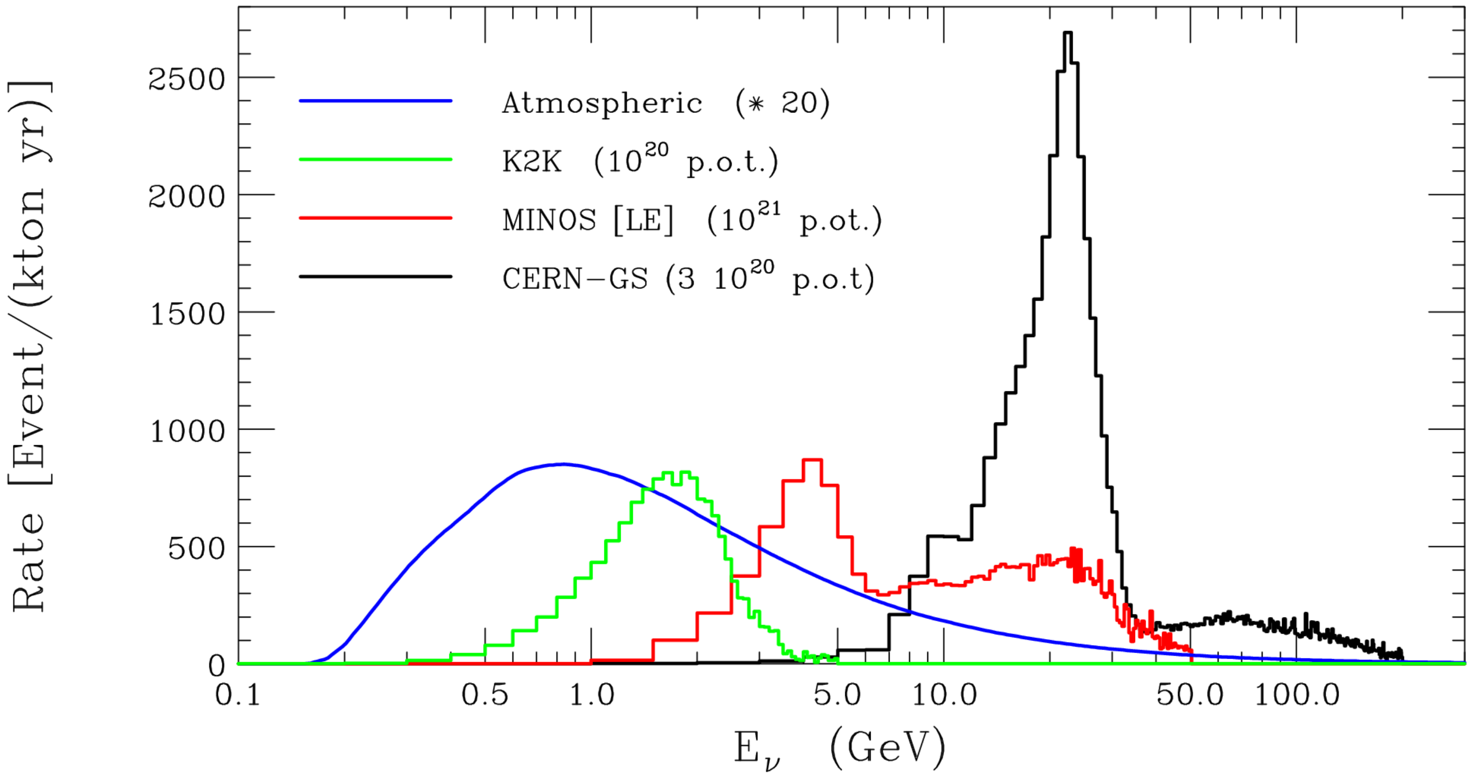
- Deep inelastic scattering (DIS)



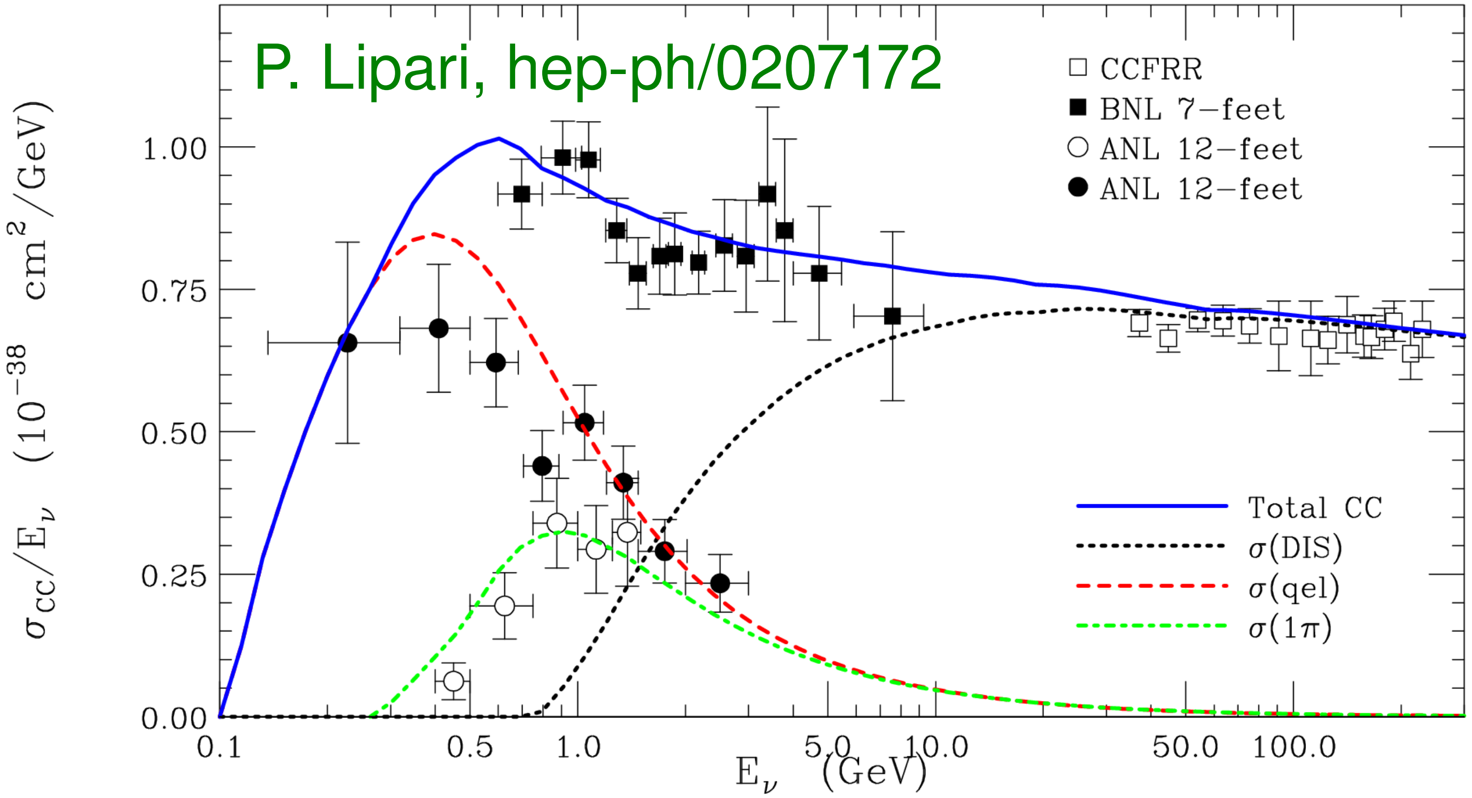
CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + X$

NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + X$

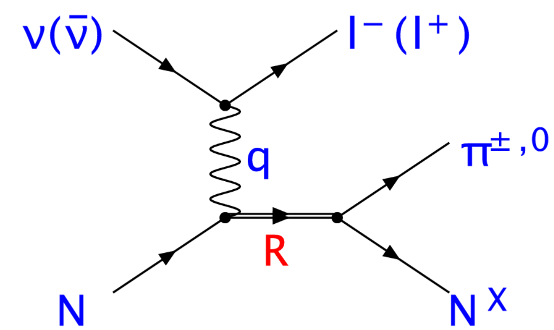
Neutrino cross sections at atmospheric ν energies



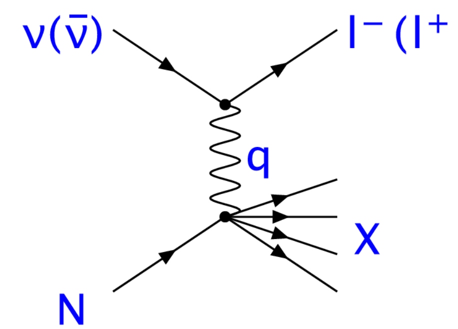
Paschos,JYY,PRD65(2002)033002



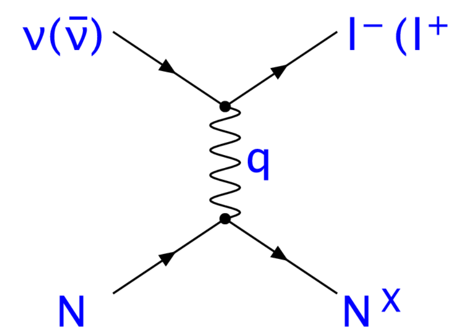
- Resonance production (RES)



- Deep inelastic scattering (DIS)



- Quasi-elastic scattering (QE)

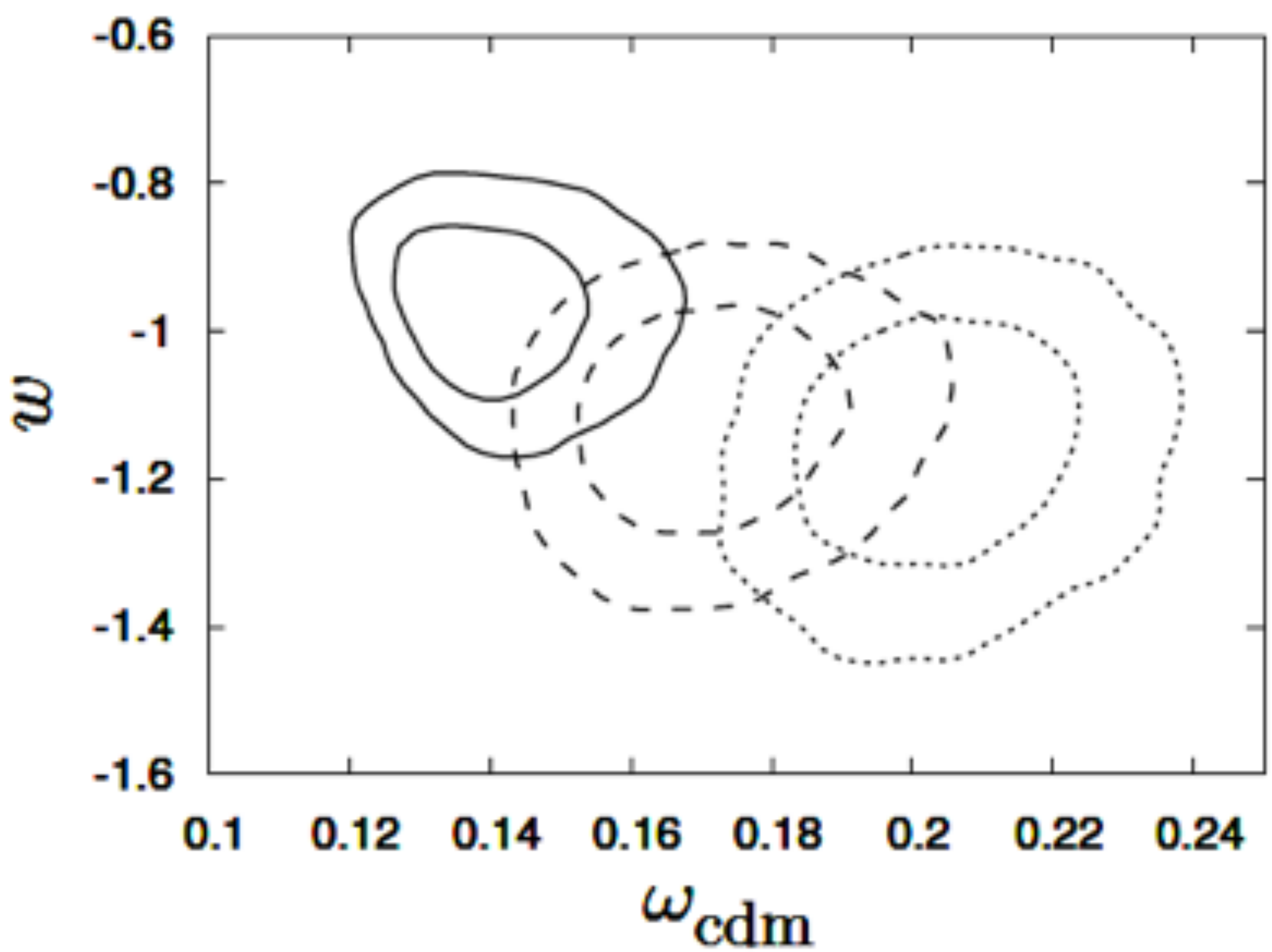


What if Lab confirms eV-scale steriles?

One would need to go to contrived (hence exciting?!) cosmologies

- ✓ Introduce chemical potentials of O(0.1) to get around BBN (how to generate them?)
- ✓ modify dark energy sector (eg. wCDM) plus add additional non-massive radiation
- ✓ Explain why cluster determination of DM does not seem to fit (any idea?)

see e.g. Hamann et al., 1108.4136



Fortunately, progress is forthcoming...