Plan of Lectures

I. Standard Neutrino Properties and Mass Terms (Beyond Standard)

II. Effects of $\nu$ Mass: Neutrino Oscillations (Vacuum)

III. Matter Effects in Neutrino Oscillations

IV. The Emerging Picture and Some Lessons
In the SM:

\[ m_0 = 0 \]

– neutrinos are left-handed (helicity 1):

\[ m_6 = 0 \]

– No distinction between Majorana or Dirac Neutrinos

Need to extend SM to add mass breaking total lepton number (L = L_e + L_\mu + L_\tau)

- Majorana:

\[ C \]

- Conserving total lepton number

- Dirac:

\[ \rho \]

- Always Lepton Mixing

Breaking of L_e L_\mu L_\tau

Neutrinomasses and mixing

Flavour oscillations

traveling through matter

Modification of oscillation pattern

Atmospheric, K2K and MINOS

(+ negative SBL searches)

Solar and KamLAND

Can we talk together? What can we learn from all this?

Answer: Today
• In the SM: \( \leftrightarrow m_\nu \equiv 0 \)
  
  – neutrinos are left-handed (\( \equiv \) helicity -1): \( m_\nu = 0 \Rightarrow \) chirality \( \equiv \) helicity
  
  – No distinction between Majorana or Dirac Neutrinos
Summary I+II+III

• In the SM: $\leftrightarrow m_\nu \equiv 0$
  
  – neutrinos are left-handed ($\equiv$ helicity -1): $m_\nu = 0 \Rightarrow$ chirality $\equiv$ helicity
  
  – No distinction between Majorana or Dirac Neutrinos

• $m_\nu \neq 0 \rightarrow$ Need to extend SM to add $m_\nu$
  
  – breaking total lepton number ($L = L_e + L_\mu + L_\tau$) $\rightarrow$ Majorana $\nu$: $\nu = \nu^C$
  
  – conserving total lepton number $\rightarrow$ Dirac $\nu$: $\nu \neq \nu^C$
  
  – Always Lepton Mixing $\equiv$ breaking of $L_e \times L_\mu \times L_\tau$
Summary I+II+III

• In the SM: $\leftrightarrow m_\nu \equiv 0$
  – neutrinos are left-handed ($\equiv$ helicity -1): $m_\nu = 0 \Rightarrow$ chirality $\equiv$ helicity
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• Neutrino masses and mixing $\Rightarrow$ Flavour oscillations

• $\nu$ traveling through matter $\Rightarrow$ Modification of oscillation pattern
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- neutrinos are left-handed (\( \equiv \) helicity -1): \( m_\nu = 0 \Rightarrow \) chirality \( \equiv \) helicity
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\( m_\nu \neq 0 \) \( \Rightarrow \) Need to extend SM to add \( m_\nu \)

- breaking total lepton number (\( L = L_e + L_\mu + L_\tau \)) \( \rightarrow \) Majorana \( \nu: \nu = \nu^C \)
- conserving total lepton number \( \rightarrow \) Dirac \( \nu: \nu \neq \nu^C \)
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- Neutrino masses and mixing \( \Rightarrow \) Flavour oscillations
- \( \nu \) traveling through matter \( \Rightarrow \) Modification of oscillation pattern

- Atmospheric, K2K and MINOS (+ negative SBL searches)
  \( \Rightarrow \nu_\mu \rightarrow \nu_\tau \) with \( \Delta m^2 \sim 2 \times 10^{-3} \) eV\(^2\) and \( \tan^2 \theta \sim 1 \)
- Solar and KamLAND
  \( \Rightarrow \nu_e \rightarrow \nu_\mu, \nu_\tau \) with \( \Delta m^2 \sim 8 \times 10^{-5} \) eV\(^2\) and \( \tan^2 \theta \sim 0.4 \)
Summary I+II+III

- In the SM: \( \leftarrow m_\nu \equiv 0 \)
  - neutrinos are left-handed (\( \equiv \) helicity -1): \( m_\nu = 0 \Rightarrow \text{chirality} \equiv \text{helicity} \)
  - No distinction between Majorana or Dirac Neutrinos
- \( m_\nu \neq 0 \) \( \rightarrow \) Need to extend SM to add \( m_\nu \)
  - breaking total lepton number (\( L = L_e + L_\mu + L_\tau \)) \( \rightarrow \) Majorana \( \nu: \nu = \nu^C \)
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  - Always Lepton Mixing \( \equiv \) breaking of \( L_e \times L_\mu \times L_\tau \)
- Neutrino masses and mixing \( \Rightarrow \) Flavour oscillations
- \( \nu \) traveling through matter \( \Rightarrow \) Modification of oscillation pattern
- Atmospheric, K2K and MINOS (+ negative SBL searches)
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  \( \Rightarrow \nu_e \rightarrow \nu_\mu, \nu_\tau \) with \( \Delta m^2 \sim 8 \times 10^{-5} \text{ eV}^2 \) and \( \tan^2 \theta \sim 0.4 \)
- Can we fit all together? What can we learn from all this?
  Answer: Today
Plan of Lecture IV

Emerging Picture and Some Lessons

$3\nu$ Oscillations

Some Lessons:

- The Need of New Physics
- The Possibility of Leptogenesis
We have learned:

* Atmospheric $\nu_\mu$ disappear ($> 15\sigma$) most likely to $\nu_\tau$
* K2K: accelerator $\nu_\mu$ disappear at $L \sim 250$ Km with $E$-distortion ($\sim 2.5–4\sigma$)
* MINOS: accelerator $\nu_\mu$ disappear at $L \sim 735$ Km with $E$-distortion ($\sim 5\sigma$)
* Solar $\nu_e$ convert to $\nu_\mu$ or $\nu_\tau$ ($> 7\sigma$)
* KamLAND: reactor $\bar{\nu}_e$ disappear at $L \sim 200$ Km with $E$-distortion ($\gtrsim 3\sigma$ CL)
* LSND found evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ but it is not confirmed
• We have learned:

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All this implies that neutrinos are massive
● We have learned:

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All this implies that neutrinos are massive

● We have important information (mostly constraints) from:

* The line shape of the Z: $N_{\text{weak}} = 3$

* Limits from Short Distance Oscillation Searches at Reactor and Accelerators

* Direct mass measurements: $^3H \rightarrow ^3He + e^- + \bar{\nu}_e$ and $\nu$-less $\beta \beta$ decay

* From Astrophysics and Cosmology: BBN, CMBR, LSS ...
Solar+Atmospheric+Reactor+LBL $3\nu$ Oscillations

$U$: 3 angles, 1 CP-phase
+ (2 Majorana phases)

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{-i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Two mass schemes

$2\nu$ oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_\odot \ll \Delta M^2_{atm} \simeq \pm \Delta m^2_{32} \simeq \pm \Delta m^2_{31}$
**Solar+Atmospheric+Reactor+LBL 3\(\nu\) Oscillations**

\[ U : 3 \text{ angles, 1 CP-phase} \]
\[ + (2 \text{ Majorana phases}) \]
\[ \begin{pmatrix}
1 & 0 & 0 \\
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c_{13} & 0 & s_{13}e^{i\delta} \\
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\end{pmatrix} \begin{pmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \]

Two mass schemes:

- **NORMAL**
  - \(m_3\)
  - \(\Delta M_{\text{atm}}^2\)
  - \(\Delta m_{\text{solar}}^2\)

- **INVERTED**
  - \(m_2\)
  - \(m_1\)
  - \(\Delta M_{\text{atm}}^2\)
  - \(\Delta m_{\text{solar}}^2\)

\[ 2\nu \text{ oscillation analysis} \quad \Rightarrow \Delta m_{21}^2 = \Delta m_{\odot}^2 \ll \Delta M_{\text{atm}}^2 \approx \pm \Delta m_{32}^2 \approx \pm \Delta m_{31}^2 \]

**Generic 3\(\nu\) mixing effects:**
- Effects due to \(\theta_{13}\)
- Difference between Inverted and Normal
- Interference of two wavelength oscillations
- CP violation due to phase \(\delta\)
In general one has to solve:

\[ i \frac{d\bar{\nu}}{dt} = H \bar{\nu} \]

\[ H = U \cdot H_0^d \cdot U^\dagger + V \]

\[ H_0^d = \frac{1}{2E_\nu} \text{diag} \left(-\Delta m_{21}^2, 0, \Delta m_{32}^2\right) \]

\[ V = \text{diag} \left(\pm \sqrt{2}G_F N_e, 0, 0\right) \]
In general one has to solve:

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\[ V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right) \]

Hierarchical approximation:

\[ \Delta m_{21}^2 \ll \Delta m_{31}^2 \sim \Delta m_{32}^2 \]

* For \( \theta_{13} = 0 \) solar and atmospheric oscillations decouple \( \Rightarrow \) Normal\( \equiv \) Inverted

- Solar and KamLAND  \( \rightarrow \) \( \Delta m_{21}^2 = \Delta m_{\odot}^2 \)  \( \theta_{12} = \theta_{\odot} \)
- Atmospheric and LBL  \( \rightarrow \) \( \Delta m_{31}^2 = \Delta M_{atm}^2 \)  \( \theta_{23} = \theta_{atm} \)
In general one has to solve:

\[ i \frac{d \bar{\nu}}{dt} = H \bar{\nu} \]

\[ H = U \cdot H_0^d \cdot U^\dagger + V \]

\[ H_0^d = \frac{1}{2E_\nu} \text{diag} \left( -\Delta m_{21}^2, 0, \Delta m_{32}^2 \right) \]

\[ V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right) \]

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* For \( \theta_{13} \neq 0 \)
  
  – Solar and KamLAND: \( P_{ee}^{3\nu} = c_{13}^4 P_{ee}^{2\nu}(\Delta m_{12}^2, \theta_{12}) + s_{13}^4 \)
3–ν Neutrino Oscillations

- In general one has to solve:
  \[ i \frac{d\nu}{dt} = H \nu \]
  \[ H = U \cdot H_0^d \cdot U^\dagger + V \]
  \[ H_0^d = \frac{1}{2E_{\nu}} \text{diag} (-\Delta m_{21}^2, 0, \Delta m_{32}^2) \]
  \[ V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right) \]

- Hierarchical approximation:
  \[ \Delta m_{21}^2 \ll \Delta m_{31}^2 \sim \Delta m_{32}^2 \]

* For \( \theta_{13} = 0 \) solar and atmospheric oscillations decouple \( \Rightarrow \) Normal \( \equiv \) Inverted
  - Solar and KamLAND: \( \Delta m_{21}^2 = \Delta m_\odot^2 \) \( \theta_{12} = \theta_\odot \)
  - Atmospheric and LBL: \( \Delta m_{31}^2 = \Delta M_{atm}^2 \) \( \theta_{23} = \theta_{atm} \)

* For \( \theta_{13} \neq 0 \)
  - Solar and KamLAND: \( P_{ee}^{3\nu} = c_{13}^4 P_{ee}^{2\nu}(\Delta m_{12}^2, \theta_{12}) + s_{13}^4 \)
  - CHOOZ: \( P_{ee}^{CH} \approx 1 - 4c_{13}^2 s_{13}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \)
In general one has to solve:

\[ i \frac{d \bar{\nu}}{d t} = H \bar{\nu} \quad H = U \cdot H_0^d \cdot U^\dagger + V \]

\[ H_0^d = \frac{1}{2E_{\nu}} \text{diag} (-\Delta m_{21}^2, 0, \Delta m_{32}^2) \quad V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right) \]

Hierarchical approximation: \[ \Delta m_{21}^2 \ll \Delta m_{31}^2 \sim \Delta m_{32}^2 \]

* For \( \theta_{13} = 0 \) solar and atmospheric oscillations decouple \( \Rightarrow \) Normal \( \equiv \) Inverted
  - Solar and KamLAND \( \Rightarrow \) \( \Delta m_{21}^2 = \Delta m_{21}^2 \), \( \theta_{12} = \theta_{\odot} \)
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* For \( \theta_{13} \neq 0 \)
  - Solar and KamLAND: \( P_{3\nu}^{3\nu} = c_{13}^4 P_{ee}^{2\nu}(\Delta m_{12}^2, \theta_{12}) + s_{13}^4 \)
  - CHOOZ: \( P_{ee}^{CH} \approx 1 - 4 c_{13}^2 s_{13}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \)
  - K2K+MINOS Probabilities Independent of \( \theta_{12}, \Delta m_{21}^2 \)
In general one has to solve:

\[ i \frac{d\bar{\nu}}{dt} = H \bar{\nu} \]

\[ H = U \cdot H_0^d \cdot U^\dagger + V \]

\[ H_0^d = \frac{1}{2E_\nu} \text{diag} (-\Delta m_{21}^2, 0, \Delta m_{32}^2) \]

\[ V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right) \]
3–ν Atmospheric Neutrino Oscillation: Effect of $\theta_{13}$

- In general one has to solve:
  \[ i \frac{d\nu}{dt} = H \nu \]
  \[ H = U \cdot H_0^d \cdot U^\dagger + V \]

\[ H_0^d = \frac{1}{2E_\nu} \text{diag} \left( -\Delta m_{21}^2, 0, \Delta m_{32}^2 \right) \]
\[ V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right) \]

- Hierarchical approximation:
  \[ \Delta m_{21}^2 \ll \Delta m_{31}^2 \sim \Delta m_{32}^2 \]
  \[ \Rightarrow \text{neglect } \Delta m_{21}^2 \text{ in ATM} \]

\[ P_{ee} = 1 - 4s_{13,m}^2c_{13,m} S_{31} \]
\[ P_{\mu\mu} = 1 - 4s_{13,m}^2c_{13,m}s_{23}^4 S_{31} - 4s_{13,m}^2s_{23}^2c_{23} S_{21} - 4c_{13,m} s_{23}^2c_{23} S_{32} \]
\[ P_{e\mu} = 4s_{13,m}^2c_{13,m}s_{23}^2 S_{31} \]

\[ S_{ij} = \sin^2 \left( \frac{\Delta \mu_{ij}^2}{4E_\nu} L \right) \]

\[ \Delta \mu_{21}^2 = \frac{\Delta m_{32}^2}{2} \left( \frac{\sin 2\theta_{13}}{\sin 2\theta_{13, m}} - 1 \right) - E_\nu V_e \]
\[ \Delta \mu_{32}^2 = \frac{\Delta m_{32}^2}{2} \left( \frac{\sin 2\theta_{13}}{\sin 2\theta_{13, m}} + 1 \right) + E_\nu V_e \]
\[ \Delta \mu_{31}^2 = \Delta m_{32}^2 \frac{\sin 2\theta_{13}}{\sin 2\theta_{13, m}} \]

\[ \sin 2\theta_{13, m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} + \frac{2E_\nu V_e}{\Delta m_{31}^2})^2 + \sin^2 2\theta_{13}}} \]
\[ \frac{N_e}{N_{e0}} - 1 = P_{e\mu} \tilde{r} \left( s_{23}^2 - \frac{1}{\tilde{r}} \right) \]

\[ \tilde{r} = \frac{N_{\mu0}}{N_{e0}} \]

\[ P_{e\mu} = 4 s_{13}^2 m^2_{13,m} \sin^2 \left( \frac{\Delta m^2_{31} L}{4 E_\nu} \frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} \right) \]

\[ \sin 2\theta_{13,m} = \sqrt{\left( \cos 2\theta_{13} \mp \frac{2 E_\nu V_{e\nu}}{\Delta m^2_{31}} \right)^2 + \sin^2 2\theta_{13}} \]
**3–ν Atmospheric Neutrino Oscillation: Effect of $\theta_{13}$**

Ahkmedov, Dighe, Lipari, Smirnov 99; Petcov, Maris 98; Palomares, Petcov, 03

\[
\frac{N_{e}}{N_{e0}} - 1 = P_{e\mu} \bar{r} \left( s_{23}^{2} - \frac{1}{\bar{r}} \right)
\]

\[
\bar{r} = \frac{N_{\mu0}}{N_{e0}}
\]

\[
P_{e\mu} = 4 s_{13}^{2} c_{13}^{2} m^{2}_{\nu} \sin^{2} \left( \frac{\Delta m^{2}_{31} L}{4E_{\nu}} \sin 2\theta_{13} \right)
\]

\[
\sin 2\theta_{13, m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} + \frac{2E_{\nu} V_{e}}{\Delta m^{2}_{31}})^{2} + \sin^{2} 2\theta_{13}}}
\]

- Multi-GeV: Enhancement due to Matter
  - Larger Effect in Normal
  - Possible Sensitivity to Mass Ordering
\[ \frac{N_e}{N_{e0}} - 1 = \overline{P}_{e\mu} \tilde{r} \left( s_{23}^2 - \frac{1}{\tilde{r}} \right) \]

\[ \tilde{r} = \frac{N_{\mu_0}}{N_{e0}} \]

\[ P_{e\mu} = 4 s_{13}^2 m c_{13,m}^2 \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \frac{\sin 2 \theta_{13}}{\sin 2 \theta_{13,m}} \right) \]

\[ \sin 2 \theta_{13,m} = \frac{\sin 2 \theta_{13}}{\sqrt{\left( \cos 2 \theta_{13} + \frac{2 E_\nu V_{e}}{\Delta m_{31}^2} \right)^2 + \sin^2 2 \theta_{13}}} \]

- Multi-GeV: Enhancement due to Matter
  - Larger Effect in Normal
  - Possible Sensitivity to Mass Ordering

- Sub-GeV: Vacuum Osc: Smaller Effect
  \[ r \simeq 2 \Rightarrow \theta_{23} < \frac{\pi}{4} \Rightarrow s_{23}^2 < \frac{1}{2} \Rightarrow N_e(\theta_{13}) < N_{e0} \]
  \[ \theta_{23} > \frac{\pi}{4} \Rightarrow s_{23}^2 > \frac{1}{2} \Rightarrow N_e(\theta_{13}) > N_{e0} \]
\( \Delta m_{21}^2 \) effects in ATM Data

Smirnov, Peres 99,01; Fogli, Lisi, Marrone 01; MC G-G, Maltoni 02; MCG-G, Maltoni, Smirnov hep-ph/0408170

- In general one has to solve:

\[
\frac{d\tilde{\nu}}{dt} = H \tilde{\nu}
\]

\[
H = U \cdot H_0^d \cdot U^\dagger + V
\]

\[
H_0^d = \frac{1}{2E_\nu} \text{diag} (-\Delta m_{21}^2, 0, \Delta m_{32}^2)
\]

\[
V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right)
\]
Smirnov, Peres 99,01; Fogli, Lisi, Marrone 01; MC G-G, Maltoni 02; MCG-G, Maltoni, Smirnov hep-ph/0408170

\[ \Delta m_{21}^2 \text{ effects in ATM Data} \]

- In general one has to solve:

\[
\begin{align*}
\frac{d\tilde{\nu}}{dt} &= H \tilde{\nu} \\
H &= U \cdot H_0^d \cdot U^\dagger + V
\end{align*}
\]

\[
H_0^d = \frac{1}{2E_{\nu}} \text{diag} \left( -\Delta m_{21}^2, 0, \Delta m_{32}^2 \right) \quad V = \text{diag} \left( \pm \sqrt{2} G_F N_e, 0, 0 \right)
\]

- Neglecting \( \theta_{13} \):

\[
\begin{align*}
P_{ee} &= 1 - P_{e2} \\
P_{e\mu} &= c_{23}^2 P_{e2} \\
P_{\mu\mu} &= 1 - c_{23}^4 P_{e2} - 2s_{23}^2 c_{23}^2 \left[ 1 - \sqrt{1 - P_{e2} \cos \phi} \right] \\
P_{e2} &= \sin^2 2\theta_{12,m} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_{\nu}} \frac{\sin 2\theta_{12}}{\sin 2\theta_{12,m}} \right) \\
\sin 2\theta_{12,m} &= \sqrt{\left( \cos 2\theta_{12} + \frac{2E_{\nu} V_e}{\Delta m_{21}^2} \right)^2 + \sin^2 2\theta_{12}} \\
\phi &\approx \left( \Delta m_{31}^2 + s_{12}^2 \Delta m_{21}^2 \right) \frac{L}{2E_{\nu}}
\end{align*}
\]
\[ \Delta m_{21}^2 \text{ effects in ATM Data} \]

\[ \frac{N_e}{N_{e0}} - 1 = P_{e2} \sqrt{c_{23}^2 - \frac{1}{r^2}} \]

\[ P_{e2} = \sin^2 2\theta_{12,m} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_{\nu}} \frac{\sin 2\theta_{12}}{\sin 2\theta_{12,m}} \right) \]

\[ \sin 2\theta_{12,m} = \frac{\sin^2 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} + \frac{2E_{\nu}}{\Delta m_{21}^2})^2 + \sin^2 2\theta_{12}}} \]

- \( s_{13}^2 = 0.04, s_{23}^2 = 0.35, \Delta m_{21}^2 = 0 \)
- \( s_{13}^2 = 0.04, s_{23}^2 = 0.65, \Delta m_{21}^2 = 0 \)
- \( s_{13}^2 = 0.00, s_{23}^2 = 0.35, \Delta m_{21}^2 = 10^{-4} \text{ eV}^2 \)
- \( s_{13}^2 = 0.00, s_{23}^2 = 0.65, \Delta m_{21}^2 = 10^{-4} \text{ eV}^2 \)
**$\Delta m_{21}^2$ effects in ATM Data**

\[
\frac{N_e}{N_{e0}} - 1 = P_{e2} \bar{r} (c_{23}^2 - \frac{1}{r})
\]

\[
P_{e2} = \sin^2 2\theta_{12,m} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \sin 2\theta_{12,m} \right)
\]

\[
\sin 2\theta_{12,m} = \frac{\sin^2 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} + \frac{2E_\nu}{\Delta m_{21}^2})^2 + \sin^2 2\theta_{12}}}
\]

For Sub-GeV:

\[
P_{e2} = \frac{(\Delta m_{21}^2)^2}{(2E_{\nu})^2} \sin^2 2\theta_{12} \sin^2 \frac{V_e L}{2}
\]

\[
\theta_{23} < \frac{\pi}{4} \Rightarrow c_{23}^2 > \frac{1}{2} \Rightarrow N_e(\theta_{13}) > N_{e0}
\]

\[
\theta_{23} > \frac{\pi}{4} \Rightarrow c_{23}^2 < \frac{1}{2} \Rightarrow N_e(\theta_{13}) < N_{e0}
\]

⇒ Sensitiv to Deviations from Maximal $\theta_{23}$

⇒ Sensitivity to Octant of $\theta_{23}$

(even for vanishing $\theta_{13}$)

⇒ Effect proportional to $(\Delta m_{21}^2)^2$
Beyond Hierarchical: Effect $\theta_{13} \times \Delta m_{21}^2$ in ATM

For sub-GeV energies

$$\frac{N_e}{N_0^e} - 1 \simeq \overline{P_{e2}} \overline{r}(c_{23}^2 - \frac{1}{r}) + 2s_{13}^2 \overline{r}(s_{23}^2 - \frac{1}{r}) - \overline{r}s_{13}c_{13}^2 \sin 2\theta_{23} \left( \cos \delta \cos \overline{R}_2 - \sin \delta \sin \overline{R}_2 \right)$$

$$P_{e2} = \sin^2 2\theta_{12,m} \sin^2 \frac{\phi_m}{2}$$

$$R_2 = -\sin 2\theta_{12,m} \cos 2\theta_{12,m} \sin^2 \frac{\phi_m}{2}$$

$$\overline{\cos \theta} \simeq \theta_{13} \left( 1 + \frac{2E\nu V_{ee}}{\Delta m_{31}^2} \right)$$

$$I_2 = -\frac{1}{2} \sin 2\theta_{12,m} \sin \phi_m$$

$$\phi \approx (\Delta m_{31}^2 + s_{12}^2 \Delta m_{21}^2) \frac{L}{2E\nu}$$

![Graph showing normal and inverted neutrino oscillations with various CP phases]
Global Analysis: Three Neutrino Oscillations

M.C. G-G, M. Maltoni, ArXiV/0704.1800
Global Analysis: Three Neutrino Oscillations

The derived ranges:

\[
\Delta m_{21}^2 = 7.7^{+0.22}_{-0.21} (^{+0.67}_{-0.61}) \times 10^{-5} \text{ eV}^2 \quad \left| \Delta m_{31}^2 \right| = 2.37 \pm 0.17 (0.46) \times 10^{-3} \text{ eV}^2
\]

\[
|U_{LEP}|_{3\sigma} = \begin{pmatrix}
0.79 \rightarrow 0.86 & 0.50 \rightarrow 0.61 & 0.00 \rightarrow 0.20 \\
0.25 \rightarrow 0.53 & 0.47 \rightarrow 0.73 & 0.56 \rightarrow 0.79 \\
0.21 \rightarrow 0.51 & 0.42 \rightarrow 0.69 & 0.61 \rightarrow 0.83
\end{pmatrix}
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\end{pmatrix} \]

with structure

\[ |U_{\text{LEP}}| \simeq \begin{pmatrix}
\frac{1}{\sqrt{2}} (1 + \mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}} (1 - \mathcal{O}(\lambda)) & \epsilon \\
-\frac{1}{2} (1 - \mathcal{O}(\lambda) + \epsilon) & \frac{1}{2} (1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \\
\frac{1}{2} (1 - \mathcal{O}(\lambda) - \epsilon) & -\frac{1}{2} (1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \\
\end{pmatrix} \quad \lambda \sim 0.2 \quad \epsilon \lesssim 0.2 \]
Global Analysis: Three Neutrino Oscillations

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very different from quark’s

$$|U_{CKM}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix} \begin{pmatrix} \lambda \sim 0.2 \end{pmatrix}$$
Open Questions

(1) Is $\theta_{13} \neq 0$? How small?
(2) Is $\theta_{23} = \frac{\pi}{4}$? If not, is it $>$ or $<$?
(3) Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?
(4) What is the ordering of the neutrino states?
(5) Are neutrino masses:
   - hierarchical: $m_i - m_j \sim m_i + m_j$?
   - degenerated: $m_i - m_j \ll m_i + m_j$?
(6) Dirac or Majorana?

To answer (1)–(4): Proposed new generation $\nu$ osc experiments:

– Medium Baseline Reactor Experiment: Double-Chooz, Daya Bay
– Conventional (=from $\pi$ decay) Superbeams: T2K, Nova (?)
– $\nu$-factory: clean $\nu$ beam from $\mu$ decay
– $\nu_e$ or $\bar{\nu}_e$ beam from nuclear $\beta$ decay ($\beta$ beam)
Some Lessons: New Physics
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A fermion mass can be seen as at a Left-Right transition

$$m_f \bar{f}_L f_R$$  (this is not $SU(2)_L$ gauge invariant)
Some Lessons: New Physics

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If the SM is *the fundamental theory*:

– All terms in lagrangian (including masses) must be \( \left\{ \begin{array}{l}
gauge\ \text{invariant} \\
\text{renormalizable (dim} \leq 4\text{)}
\end{array} \right. \)
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- A gauge invariant fermion mass is generated by interaction with the Higgs field \( \lambda_f \bar{f}_L \phi f_R \rightarrow m_f = \lambda_f v \)
  \( (v \equiv \text{Higgs vacuum expectation value } \sim 250 \text{ GeV}) \)
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\[ \Rightarrow \text{No renormalizable gauge-invariant operator for tree level } \nu \text{ mass} \]
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- SM gauge invariance also implies the accidental symmetry

\[ G^\text{global}_{\text{SM}} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \Rightarrow m_\nu = 0 \text{ to all orders} \]
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Thus the most striking implication of \( \nu \) masses:

There is New Physics Beyond the SM
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Thus the most striking implication of $\nu$ masses:

**There is New Physics Beyond the SM**

And it is also the only solid evidence!  
To go further one has to be cautious…
Lessons: The Scale of New Physics
If SM is an effective low energy theory, for $E \ll \Lambda_{NP}$

- The same particle content as the SM and same pattern of symmetry breaking
- But there can be non-renormalizable operators

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_n \frac{1}{\Lambda_{NP}^{n-4}} \mathcal{O}_n \]
Lessons: The Scale of New Physics

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First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_n \frac{1}{\Lambda_{NP}^{n-4}} \mathcal{O}_n$$

$$\mathcal{L}_5 = \frac{Z_{ij}^\nu}{\Lambda_{NP}} \left( \tilde{\phi}^\dagger L_{Lj} \right) \left( \overline{L_{Li}} \tilde{\phi}^* \right)$$
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which after symmetry breaking

induces a \( \nu \) Majorana mass

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(M_{\nu})_{ij} = \frac{Z^{\nu}_{ij}}{2} \frac{v^2}{\Lambda_{NP}}
\]
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which after symmetry breaking
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\[ \mathcal{L}_5 = \frac{Z_{ij}}{\Lambda_{NP}} \left( \tilde{\phi}^\dagger L L_{ij} \right) \left( \tilde{L}^c_{Li} \tilde{\phi}^* \right) \]

\[ (M_\nu)_{ij} = \frac{Z_{ij}^\nu}{2} \frac{v^2}{\Lambda_{NP}} \]

$\mathcal{L}_5$ breaks total lepton and lepton flavour numbers
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which after symmetry breaking

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Implications:

- It is natural that $\nu$ mass is the first evidence of NP
- Naturally $m_\nu \ll$ other fermions masses $\sim \chi^f \nu$
- $m_\nu > \sqrt{\Delta m_{atm}^2} \sim 0.05$ eV $\Rightarrow \Lambda_{NP} < 10^{15}$ GeV
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But this is scale was already known to particle physicists...
$m_\nu > \sqrt{\Delta m^2_{atm}} \sim 0.05\text{eV} \Rightarrow 10^{10} < \Lambda_{NP} < 10^{15}\text{GeV}$

Also the generated neutrino mass term is Majorana:

$\Rightarrow$ It violates total lepton number

$$\mathcal{L}_5 = \frac{Z_{ij}^\nu}{\Lambda_{NP}} \left( \bar{\tilde{\phi}}^\dagger L_{L\ j} \right) \left( \overline{L_{L\ i}} \tilde{\phi}^* \right)$$

New Physics Scale close to Grand Unification scale
The See-Saw

Simplest NP: add right-handed $R$ ($= SM$ singlet) neutrinos well above the electroweak (EW) scale $L$

$$\begin{align*}
    L_{NP} &= 1 - \frac{1}{2} M^{R}_{ij} R_{ij} c_{i} + \frac{1}{2} M^{R}_{ij} \approx y L_{Lj} + h : c \end{align*}$$

$R$ is an EW singlet ($M^{R}_{ij} \gg$ EW scale)

Below EW symmetry breaking scale ($E$ $M^{R}_{ij}$ $L_{NP}$ $L$ $L_{ij} = (T_{ij})$ $M^{R}_{ij} \sim y L_{Lj}$ $L_{cLi} \sim$ $m_{TD}$ $1 - M^{R}_{ij} m_{D}$

This is the see-saw

Lessons:

- $L_{NP}$ contains 18 parameters which we want to know
- $L_{5}$ contains 9 parameters which we can measure

Same $O_{5}$ can give very different $L_{NP}$

It is difficult to "imply" bottom-up (model independently)
The See-Saw

Simplest NP: add right-handed $\nu_R$ (=SM singlet) neutrinos
The See-Saw

Simplest NP: add right-handed $\nu_R$ (=SM singlet) neutrinos

Well above the electroweak (EW) scale

$$-\mathcal{L}_{\text{NP}} = \frac{1}{2} M_{Rij} \bar{\nu}_{Ri} \nu^c_{Rj} + \chi_{ij} \bar{\nu}_{Ri} \bar{\phi}^\dagger L_L j + \text{h.c.}$$
The See-Saw

Simplest NP: add right-handed $\nu_R$ (=SM singlet) neutrinos

Well above the electroweak (EW) scale

$$-\mathcal{L}_{NP} = \frac{1}{2} M_{Rij} \bar{\nu}_R^i \nu_R^j + \lambda_{ij} \bar{\nu}_R^i \tilde{\phi}^\dagger L_L^j + \text{h.c.}$$

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Below EW symmetry breaking scale ($E \ll M_R$):

a) $m_D = \lambda^\nu v \sim$ mass of other fermions is generated

b) $\nu_R$ are so heavy that can be “integrated out”
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b) $\nu_R$ are so heavy that can be “integrated out”

$$\downarrow \quad E \ll M_R$$

$$\mathcal{L}_{\text{NP}} \Rightarrow \mathcal{L}_5 = \frac{(\lambda^T \lambda)_ij}{M_R} \left( \tilde{\phi}^\dagger L_L j \right) \left( \bar{L}^c_{Li} \tilde{\phi}^* \right) \Rightarrow m_\nu = m_D^T \frac{1}{M_R} m_D$$
Simplest NP: add right-handed $\nu_R$ (=SM singlet) neutrinos

Well above the electroweak (EW) scale

$$-\mathcal{L}_{NP} = \frac{1}{2} M_{Ri j} \bar{\nu}_{Ri} \nu_{Rj}^c + \lambda_{ij}^\nu \nu_{Ri} \phi^\dagger L_{Lj} + \text{h.c.}$$

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$$\Downarrow \quad E \ll M_R$$

$$\mathcal{L}_{NP} \Rightarrow \mathcal{L}_5 = \frac{(\lambda^T \lambda)_ij}{M_R} \left( \phi^\dagger L_{Lj} \right) \left( \overline{L^c_{Li}} \phi^* \right) \Rightarrow m_\nu = m_D \frac{1}{M_R} m_D$$

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- $\mathcal{L}_5$ contains 9 parameters which we can measure

$\Rightarrow$ Same $O_5$ can give very different $\mathcal{L}_{NP}$

$\Rightarrow$ It is difficult to “imply” bottom-up (model independently)
Leptogenesis

Baryogenesis and the SM from Nucleosynthesis and CMBR data.

\[ Y_B = n_B/n_s = 10^{10} \]

Leptogenesis can be dynamically generated if three Sakharov conditions are verified:

- Baryon number is violated
- C and CP are violated
- Departure from thermal equilibrium

The SM verifies these conditions:

- Conserves \( B_L \) but violates \( B_L + L \)
- CP violation due to CKM
- Departure from thermal equilibrium at the Electroweak Phase Transition

But the SM fails on two points:

- With the bound of SM Higgs mass, the EWPT is not first-order PT
- CKM CP violation is too suppressed
Leptogenesis

Baryogenesis and the SM

- From Nucleosythesys and CMBR data \( Y_B = \frac{n_b - n_{\bar{b}}}{s} = \frac{n_b}{s} \approx 10^{-10} \)
Baryogenesis and the SM

- From Nucleosytesys and CMBR data, $Y_B = \frac{n_b - n_{\bar{b}}}{s} = \frac{n_b}{s} \sim 10^{-10}$

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Leptogenesis

Baryogenesis and the SM

- From Nucleosythesys and CMBR data ⇒
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  – C and CP are violated
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  → Departure from thermal equilibrium at \( \text{Electroweak Phase Transition} \)
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$Y_{B,SM} \ll 10^{-10}$
From the analysis of oscillation data, $m_3^2 - m_0^2 < 0.5\text{ eV}$. If $m$ is generated via the seesaw mechanism, \[ L = \frac{1}{2} M \bar{R} \nu \bar{R} \nu, \] leptogenesis can be discussed in detail. Lepton number is violated if $M_R \lesssim 10^{15} \text{ GeV}$. Decay of $R$ can be out of equilibrium (if $R$ is the Universe expansion rate). Leptogenesis generation of lepton asymmetry $Y_L$ at the electroweak transition: $Y_L$ is transformed in $Y_B$.
• From the analysis of oscillation data ⇒ \( m_{\nu_3} \gtrsim 0.05 \text{ eV} \)
Leptogenesis

- From the analysis of oscillation data \( \Rightarrow \quad m_{\nu_3} \gtrsim 0.05 \, \text{eV} \)
- If \( m_\nu \) is generated via the See-saw mechanism

\[
-\mathcal{L}_{\text{NP}} = \frac{1}{2} M_{Ri j} \bar{\nu}_{Ri} \nu_{Rj}^c + \lambda_{i j}^\nu \bar{\nu}_{Ri} \phi^\dagger L_{Lj} \Rightarrow m_\nu \sim \frac{\lambda^2 \langle \phi \rangle^2}{M_R}
\]
Leptogenesis

- From the analysis of oscillation data ⇒ \( m_{\nu_3} \gtrsim 0.05 \) eV

- If \( m_\nu \) is generated via the See-saw mechanism
  
  \[-L_{NP} = \frac{1}{2} m R_{ij} \bar{\nu}_R \nu_R^c + \lambda_{ij} \bar{\nu}_R \phi^+ L L_j \Rightarrow m_\nu \sim \frac{\lambda^2 \langle \phi \rangle^2}{M_R} \]

\[ (M_{\nu_3}/\lambda^2_3 \lesssim 10^{15} \text{ GeV}) \]
Leptogenesis

- From the analysis of oscillation data $\Rightarrow m_{\nu_3} \gtrsim 0.05$ eV

- If $m_\nu$ is generated via the See-saw mechanism

\[ -\mathcal{L}_{NP} = \frac{1}{2} M_{R_{ij}} \bar{\nu}_{R_i} \nu_{R_j} + \lambda_{ij}^{\nu} \bar{\nu}_{R_i} \tilde{\phi}^\dagger L_{L_j} \Rightarrow m_\nu \sim \frac{\lambda^2 \langle \phi \rangle^2}{M_R} \]

$\Rightarrow$ Lepton Number is Violated ($M_R$)

$\Rightarrow$ New Sources of CP violation $\lambda$

$\Rightarrow$ Decay of $\nu_R$ can be out of equilibrium

(if $\Gamma_{\nu_R} \ll$ Universe expansion rate) $\Rightarrow \Gamma_{\nu_R} \ll H\big|_{T=M_{\nu_R}}$
From the analysis of oscillation data $\Rightarrow m_{\nu_3} \gtrsim 0.05 \text{ eV}$

If $m_{\nu}$ is generated via the See-saw mechanism

$$-\mathcal{L}_{NP} = \frac{1}{2} M_{R_{ij}} \bar{\nu}_{R_i} \nu_{R_j} + \lambda_{ij} \bar{\nu}_{R_i} \phi^\dagger L_{L_j} \Rightarrow m_{\nu} \sim \frac{\lambda^2 \langle \phi \rangle^2}{M_R}$$

$\Rightarrow$ Lepton Number is Violated ($M_R$)

$\Rightarrow$ New Sources of CP violation $\lambda$

$\Rightarrow$ Decay of $\nu_R$ can be out of equilibrium

(if $\Gamma_{\nu_R} \ll \text{Universe expansion rate}) \Rightarrow \Gamma_{\nu_R} \ll H \big|_{T=M_{\nu_R}}$

Leptogenesis $\equiv$ generation of lepton asymmetry $Y_L$
Leptogenesis

- From the analysis of oscillation data ⇒ \( m_{\nu_3} \gtrsim 0.05 \text{ eV} \)

- If \( m_\nu \) is generated via the See-saw mechanism

\[
-\mathcal{L}_{\text{NP}} = \frac{1}{2} M_{Rij} \bar{\nu}_{Ri} \nu_{Rj}^c + \lambda_{ij} \bar{\nu}_{Ri} \phi^\dagger L_{Lj} \Rightarrow m_\nu \sim \frac{\lambda^2 \langle \phi \rangle^2}{M_R}
\]

⇒ Lepton Number is Violated \((M_R)\)

⇒ New Sources of CP violation \(\lambda\)

⇒ Decay of \(\nu_R\) can be out of equilibrium

(if \(\Gamma_{\nu_R} \ll \text{Universe expansion rate}\)) ⇒ \(\Gamma_{\nu_R} \ll H\big|_{T=M_{\nu_R}}\)

⇒ \text{Leptogenesis} ≡ generation of lepton asymmetry \(Y_L\)

- At the electroweak transition sphaleron processes:

⇒ \(Y_L\) is transformed in \(Y_B \simeq -\frac{Y_L}{2}\)
In the See-saw mechanism, the Lagrangian is given by:

\[ -\mathcal{L}_{NP} = \frac{1}{2} M_{R_{ij}} \bar{\nu}_{R_i} \nu_{R_j}^c + \lambda_{ij} \bar{\nu}_{R_i} \hat{\phi}^\dagger L_j \]
Physics of Massive Neutrinos

- In the See-saw mechanism

\[-\mathcal{L}_{NP} = \frac{1}{2} M_{Rij} \overline{\nu_{Ri}} \nu_{Rj}^c + \lambda_{ij}^\nu \overline{\nu_{Ri}} \phi^\dagger L_{Lj} \]

- In the Early Universe decay of heavy $\nu_R$:

\[\Gamma(\nu_R \rightarrow \phi l_L) = \frac{1}{8\pi} \sum_i (\lambda \lambda^\dagger)_{ii}^2 M_{\nu_{Ri}} \]
In the the **See-saw** mechanism

\[ -\mathcal{L}_{\text{NP}} = \frac{1}{2} M_{Ri} \bar{\nu}_i \nu_{Rj} + \frac{\lambda_{ij}}{v_R} \bar{\nu}_i \phi^+ L_{Lj} \]

- In the Early Universe decay of heavy $\nu_R$

\[ \Gamma(\nu_R \rightarrow \phi l_L) = \frac{1}{8\pi} \sum_i (\lambda \lambda^\dagger)_{ii}^2 M_{\nu_{Ri}} \]

- CP can be violated at 1-loop

(This requires 3 light generations and at least 2$\nu_R$)
In the See-saw mechanism

\[-\mathcal{L}_{NP} = \frac{1}{2} M_{Ri} \bar{\nu}_{Ri} \nu_{Rj}^c + \lambda_{ij}^{\nu} \bar{\nu}_{Ri} \phi^\dagger L_{Lj}\]

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  \[\Gamma(\nu_R \rightarrow \phi l_L) = \frac{1}{8\pi} \sum_i (\lambda \lambda^\dagger)_{ii}^2 M_{\nu_{Ri}}\]

- CP can be violated at 1-loop

\[\epsilon_L = \frac{\Gamma(\nu_R \rightarrow \phi l_L) - \Gamma(\nu_R \rightarrow \bar{\phi} \bar{l}_L)}{\Gamma(\nu_R \rightarrow \phi l_L) + \Gamma(\nu_R \rightarrow \bar{\phi} \bar{l}_L)} = -\frac{1}{8\pi} \sum_k \frac{\text{Im}[(\lambda \lambda^\dagger)^2_{k1}]}{(\lambda \lambda^\dagger)_{11}} \times f \left( \frac{M_{\nu_{Rk}}}{M_{\nu_{R1}}} \right)\]

\[|\epsilon_L| \lesssim 0.1 \frac{M_{\nu_{R1}}}{\langle \phi \rangle^2} (m_{\nu_3} - m_{\nu_1})\]

\[n_{\nu_R} \equiv \text{density of } \nu_R \quad (d < 1 \equiv \text{dilution factor})\]
In the See-saw mechanism

\[ -\mathcal{L}_{\text{NP}} = \frac{1}{2} M_{Rij} \bar{\nu}_{Ri} \nu_{Rj}^c + \lambda_{ij} \bar{\nu}_{Ri} \phi^\dagger L_{Lj} \]

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\[ \Rightarrow |\epsilon_L| \lesssim 0.1 \frac{M_{\nu_R1}}{\langle \phi \rangle^2} (m_{\nu_3} - m_{\nu_1}) \]

\[ Y_L = \frac{n_{\nu_R}}{s} \epsilon_L d \sim 10^{-3} d \epsilon_L \]

\[ n_{\nu_R} \equiv \text{density of } \nu_R \quad (d < 1 \equiv \text{dilution factor}) \]

Out of Equilibrium condition $\Gamma_{\nu_R} \ll H \Big|_{T=M_{\nu_R}} \Rightarrow \tilde{m}_1 \equiv \frac{(\lambda \lambda^\dagger)_{11}^2 \langle \phi \rangle^2}{M_{\nu_R1}} \lesssim 5 \times 10^{-3} \text{ eV}$
In the **See-saw** mechanism

\[
\mathcal{L}_{\text{NP}} = \frac{1}{2} M_{Rij} \overline{\nu_Ri} \nu_R^c_j + \lambda_{ij}^{\nu} \overline{\nu_Ri} \tilde{\phi}^\dagger L_{Lj}
\]

\[
M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}
\]

\[m_D = \lambda \langle \phi \rangle \] is a $3 \times 3$ matrix

$M_R$ is a $3 \times 3$ symmetric matrix

⇒ $M^\nu$ has 6 physical phases
• In the See-saw mechanism

\[ -\mathcal{L}_{NP} = \frac{1}{2} M_{Rij} \bar{\nu}_{Ri} \nu_{Rj}^c + \lambda_{ij}^\nu \bar{\nu}_{Ri} \tilde{\phi}^\dagger L_{Lj} \]

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\[ m_D = \lambda \langle \phi \rangle \text{ is a } 3 \times 3 \text{ matrix} \]

\[ M_R \text{ is a } 3 \times 3 \text{ symmetric matrix} \]

⇒ \( M^\nu \) has 6 physical phases

⇒ It is easy to generate \( \epsilon_L \sim 10^{-6} \)

⇒ \( m^\nu_{light} = m_T^D M_N^{-1} m_D \) has 3 physical phases

        Oscillation experiments can only see one of these three phases

⇒ No direct correspondence between CPV in leptogenesis and CPV in oscillations
The final $Y_B$ depends on:

- $\epsilon_L$ the CP asymmetry
- $M_{\nu_R1}$ the mass of the lightest $\nu_R$
- $\tilde{m}_1 \equiv \frac{(\lambda \lambda^\dagger)_{11}^2 \langle \phi \rangle^2}{M_{\nu_R1}}$ the effective neutrino mass
- $m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2$ the sum of the light neutrinos mass squared

To generate the required $Y_B$:

- $M_{\nu_R1} \gtrsim 4 \times 10^8$ GeV
- $m_{\nu_3} \lesssim 0.12$ eV
- Large CP phases
  
  The CP violating phase relevant for leptogenesis may not be the same as the one relevant for oscillations
Neutrino oscillation searches have shown us 

\[ m^2_{23} = 1 \times 10^{-3} \text{eV}^2 \text{ and } m^2_{21} = 8 \times 10^{-5} \text{eV}^2 \]

's are massive.

Different from the CKM:

\[ m^2_{66} = 0 \]

\[ m^2_{66} = C \]

Majorana: \[ m^2_{66} = 0 \]

Dirac: \[ m^2_{66} = C \]

\[ m^2_{66} = C \|

Majorana are more natural.

They appear generically if the SM is an effective theory – NP.

Results fit well with GUT expectations – Leptogenesis may explain the baryon asymmetry.
Summary

- Neutrino oscillation searches have shown us

\[ \Delta m^2_{31} \sim 2 \times 10^{-3} \text{ eV}^2 \text{ and } \Delta m^2_{21} \sim 8 \times 10^{-5} \text{ eV}^2 \Rightarrow \nu\text{'s are massive} \]

\[ -|U_{\text{LEP}}| \simeq \begin{pmatrix}
\frac{1}{\sqrt{2}} (1 + \mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}} (1 - \mathcal{O}(\lambda)) & \epsilon \\
-\frac{1}{2} (1 - \mathcal{O}(\lambda) + \epsilon) & \frac{1}{2} (1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \\
\frac{1}{2} (1 - \mathcal{O}(\lambda) - \epsilon) & -\frac{1}{2} (1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}}
\end{pmatrix} \Rightarrow \lambda \sim 0.2 \]

\[ \epsilon \lesssim 0.2 \Rightarrow \text{Different from } U_{\text{CKM}} \]
Summary

Neutrino oscillation searches have shown us

\[ - \Delta m_{31}^2 \sim 2 \times 10^{-3} \text{ eV}^2 \text{ and } \Delta m_{21}^2 \sim 8 \times 10^{-5} \text{ eV}^2 \Rightarrow \nu \text{'s are massive} \]

\[ |U_{\text{LEP}}| \approx \begin{pmatrix} \frac{1}{\sqrt{2}} (1 + \mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}} (1 - \mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2} (1 - \mathcal{O}(\lambda) + \epsilon) & \frac{1}{2} (1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2} (1 - \mathcal{O}(\lambda) - \epsilon) & -\frac{1}{2} (1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \lambda \sim 0.2 \]

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\[ m_\nu \neq 0 \Rightarrow \text{Need to extend SM} \text{ It can be done:} \]

(a) breaking total lepton number \( \rightarrow \text{Majorana } \nu : \nu = \nu^C \)

(b) conserving total lepton number \( \rightarrow \text{Dirac } \nu : \nu \neq \nu^C \)
Neutrino oscillation searches have shown us

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\[ m_\nu \neq 0 \Rightarrow \text{Need to extend SM} \quad \text{It can be done:} \]

(a) breaking total lepton number \( \rightarrow \) Majorana \( \nu : \nu = \nu^C \)

(b) conserving total lepton number \( \rightarrow \) Dirac \( \nu : \nu \neq \nu^C \)

Majorana \( \nu \)'s are more Natural: appear generically if SM is a LE effective theory

\[ \Lambda_{NP} \lesssim 10^{15} \text{ GeV} \]

Results Fit well with GUT expectations

Leptogenesis may explain the baryon asymmetry
Conclusions

Still open questions

Is $\theta_{13} \neq 0$?
Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?
Is $\theta_{23}$ large or maximal?

Normal or Inverted mass ordering?

Are neutrino masses:

- hierarchical: $m_i - m_j \sim m_i + m_j$?
- degenerated: $m_i - m_j \ll m_i + m_j$?

Dirac or Majorana? what about the Majorana Phases?

...
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- To answer:

  \[ \ldots \]

Proosed new generation $\nu$ osc experiments:

- LBL with Conventional Superbeams and/or $\beta$ beams and/or $\nu$-factory:
- Medium Baseline Reactor Experiment
Conclusions

- Still open questions

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Also no-oscillation experiments:

- $\nu$-less $\beta\beta$ decay, $^3$H beta decay
- Interesting input from cosmological data

Rich and Challenging Experimental Program