Plan of Lectures

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

II. Effects of ν Mass: Neutrino Oscillations (Vacuum)

III. Matter Effects in Neutrino Oscillations

IV. The Emerging Picture and Some Lessons

Summary I+II+III

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  $\Rightarrow \nu_e \rightarrow \nu_\mu, \nu_\tau$ with $\Delta m^2 \sim 8 \times 10^{-5}$ eV^2 and $\tan^2\theta \sim 0.4$

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- Can we fit all toegether? What can we learn from all this?

Answer: Today

Plan of Lecture IV

Emerging Picture and Some Lessons

3ν Oscillations

Some Lessons:

- The Need of New Physics
- The Possibility of Leptogenesis

- We have learned:

  $*$ Atmospheric ν_μ disappear ($> 15\sigma$) most likely to ν_τ

  $*$ K2K: accelerator ν_μ disappear at $L \sim 250$ Km with E-distortion (~ 2.5–4σ)

  $*$ MINOS: accelerator ν_μ disappear at $L \sim 735$ Km with E-distortion ($\sim 5\sigma$)

  $*$ Solar ν_e convert to ν_μ or ν_τ ($> 7\sigma$)

  $*$ KamLAND: reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km with E-distortion ($\gtrsim 3\sigma$ CL)

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- We have important information (mostly constraints) from:

  ∗ The line shape of the Z: $N_{\rm weak} = 3$

  ∗ Limits from Short Distance Oscillation Searches at Reactor and Accelerators

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

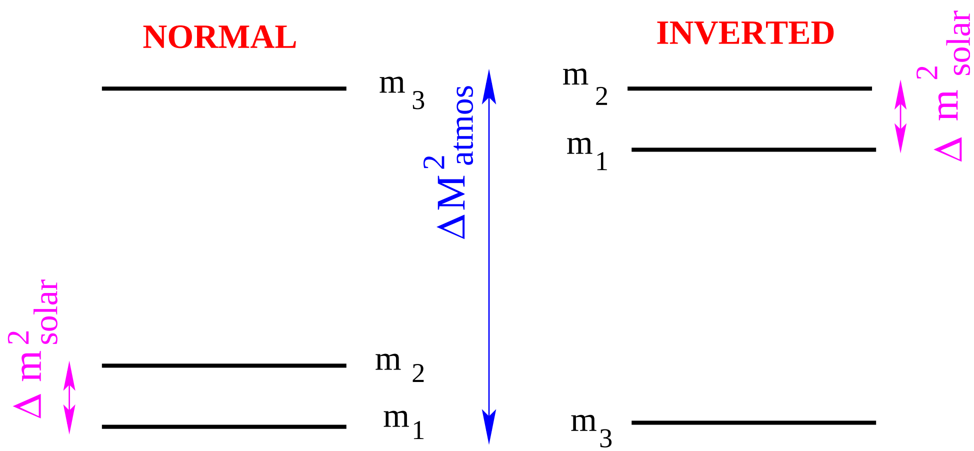
  ∗ From Astrophysics and Cosmology: BBN, CMBR, LSS ...

Solar+Atmospheric+Reactor+LBL 3ν 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



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_\odot \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

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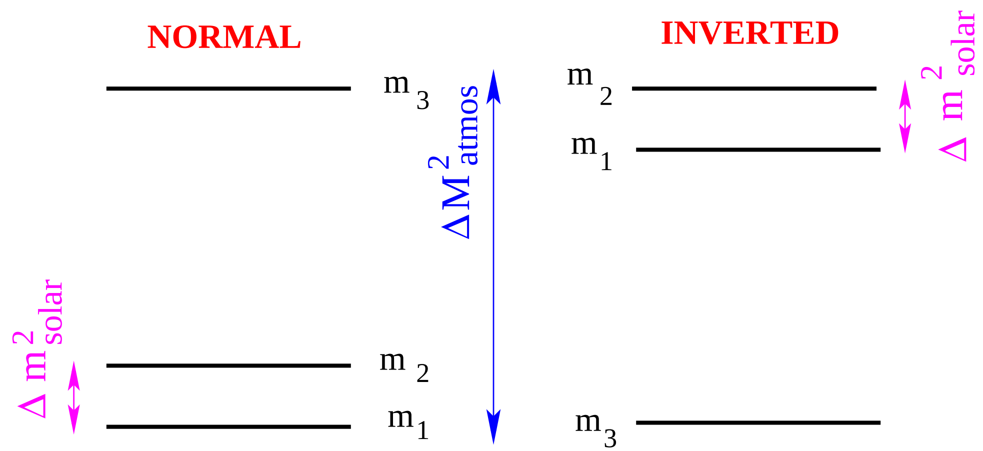

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Generic 3ν mixing effects:

– Effects due to θ_{13}

– Difference between Inverted and Normal

– Interference of two wavelength oscillations

– CP violation due to phase δ

3–ν Neutrino Oscillations

- In general one has to solve: $i\dfrac{d\vec{\nu}}{dt} = H\,\vec{\nu}$ $\quad H = U \cdot H_0^d \cdot U^\dagger + V$

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

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

$\ast$ For $\theta_{13} = 0$ solar and atmospheric oscillations decouple $\Rightarrow$ Normal$\equiv$ Inverted

- Solar and KamLAND $\rightarrow$ $\Delta m_{21}^2 = \Delta m_\odot^2 \quad \theta_{12} = \theta_\odot$
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– K2K+MINOS Probabilities Independent of θ_{12}, Δm^2_{21} 4

3–ν Atmospheric Neutrino Oscillation: Effect of θ_{13}

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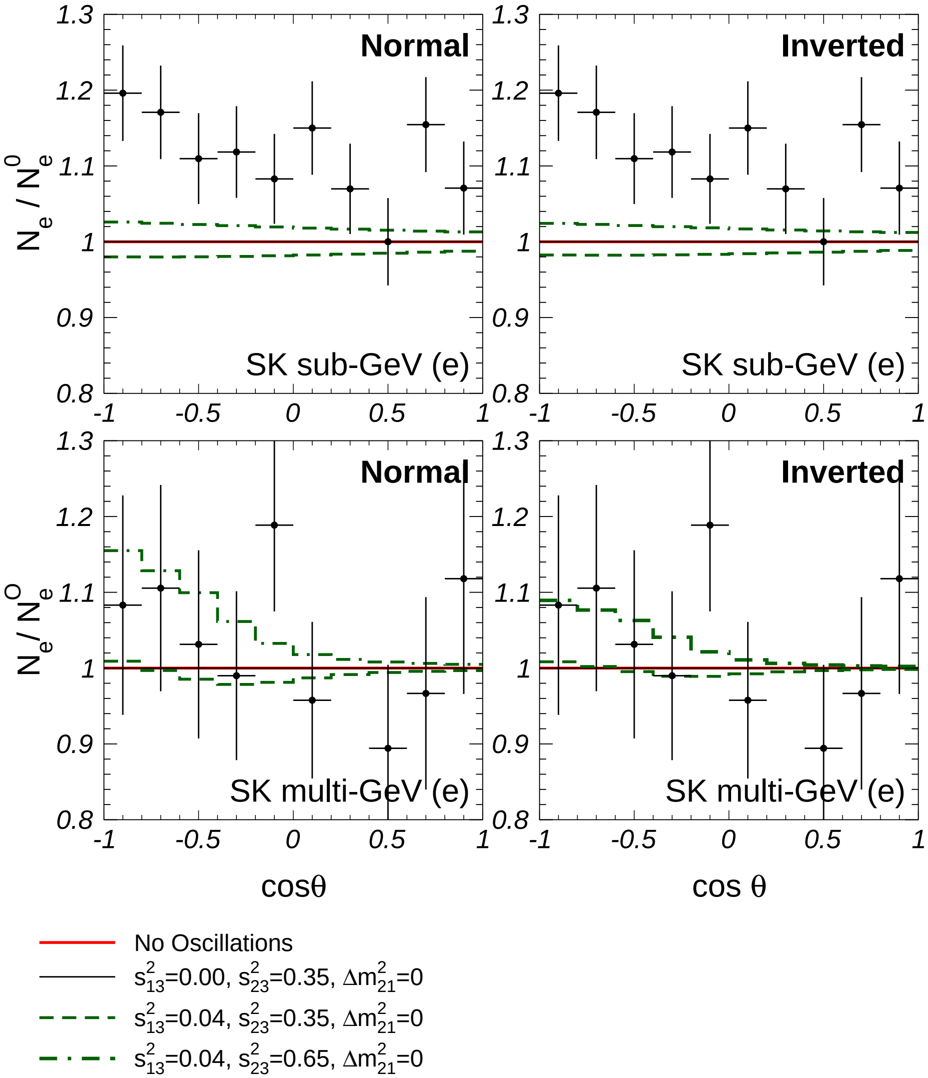
- Hierarchical approximation: $\Delta m^2_{21} \ll \Delta m^2_{31} \sim \Delta m^2_{32}$ $\Rightarrow$ neglect Δm^2_{21} in ATM

$$\begin{aligned}
P_{ee} &= 1 - 4 s^2_{13,m} c^2_{13,m}\, S_{31} \\
P_{\mu\mu} &= 1 - 4 s^2_{13,m} c^2_{13,m} s^4_{23}\, S_{31} - 4 s^2_{13,m} s^2_{23} c^2_{23}\, S_{21} - 4 c^2_{13,m} s^2_{23} c^2_{23}\, S_{32} \\
P_{e\mu} &= 4 s^2_{13,m} c^2_{13,m} s^2_{23}\, S_{31} \\
S_{ij} &= \sin^2\left(\frac{\Delta\mu^2_{ij}}{4E_\nu} L\right) \\
\Delta\mu^2_{21} &= \frac{\Delta m^2_{32}}{2}\left(\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} - 1\right) - E_\nu V_e \\
\Delta\mu^2_{32} &= \frac{\Delta m^2_{32}}{2}\left(\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} + 1\right) + E_\nu V_e \\
\Delta\mu^2_{31} &= \Delta m^2_{32}\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} \\
\sin 2\theta_{13,m} &= \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} \mp \frac{2E_\nu V_e}{\Delta m^2_{31}})^2 + \sin^2 2\theta_{13}}}
\end{aligned}$$

Pantaleone 94; Used by many ...

3–ν Atmospheric Neutrino Oscillation: Effect of θ_{13}

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



$$\frac{N_e}{N_{e0}} - 1 = \overline{P_{e\mu}\bar{r}}\left(s^2_{23} - \frac{1}{\bar{r}}\right)$$

$$\bar{r} = \frac{N_{\mu 0}}{N_{e0}}$$

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

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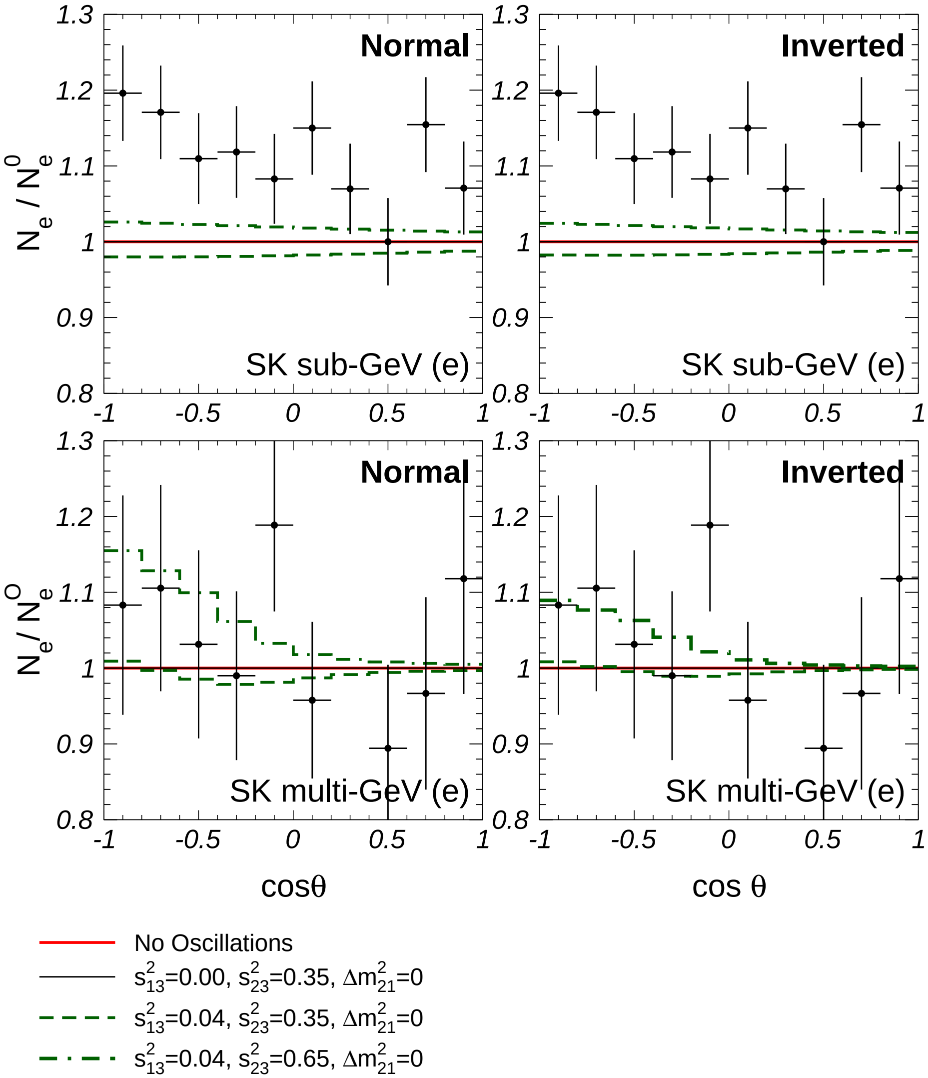

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Larger Effect in Normal

Possible Sensitivity to Mass Ordering

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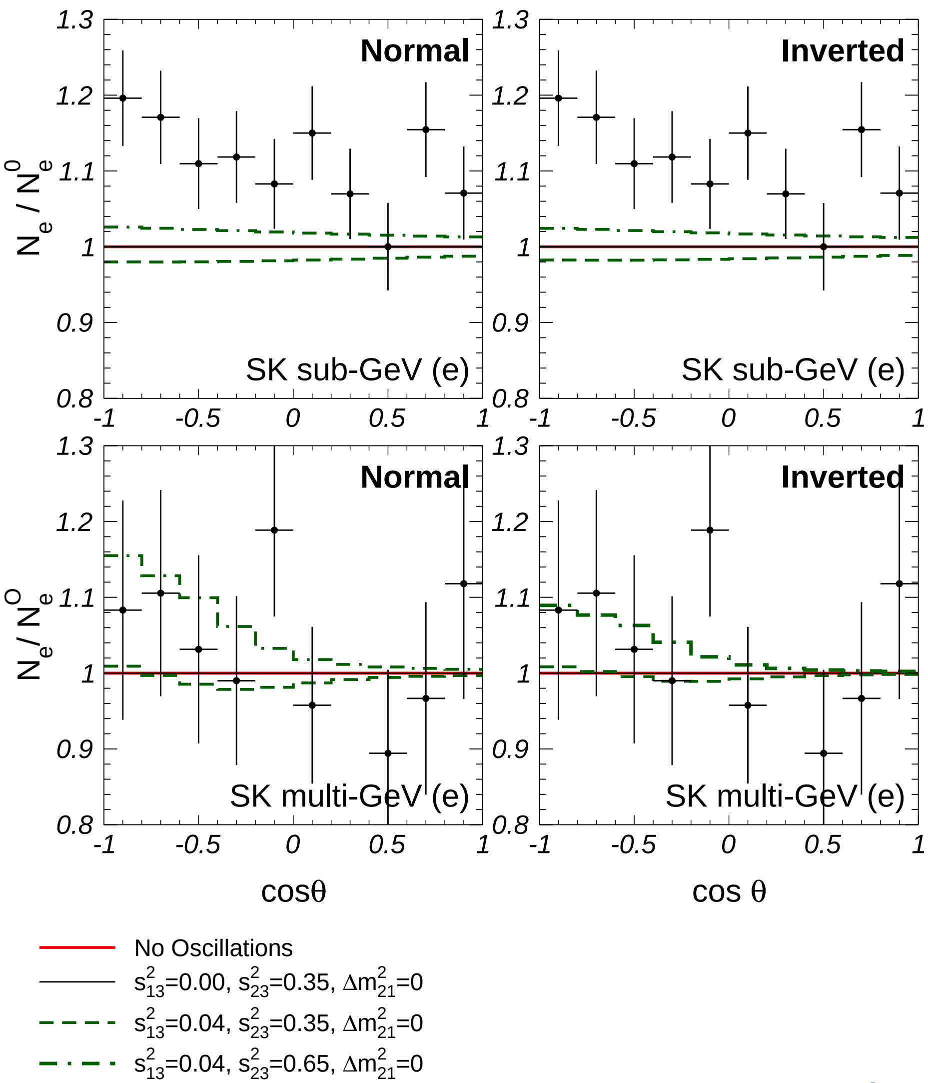

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- Sub-GeV: Vacuum Osc: Smaller Effect

$$r \simeq 2 \Rightarrow \begin{array}{l} \theta_{23} < \frac{\pi}{4} \Rightarrow s^2_{23} < \frac{1}{2} \Rightarrow N_e(\theta_{13}) < N_{e0} \\ \theta_{23} > \frac{\pi}{4} \Rightarrow s^2_{23} > \frac{1}{2} \Rightarrow N_e(\theta_{13}) > N_{e0} \end{array}$$

Δm^2_{21} 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: $i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}$ $\quad H = U \cdot H_0^d \cdot U^\dagger + V$

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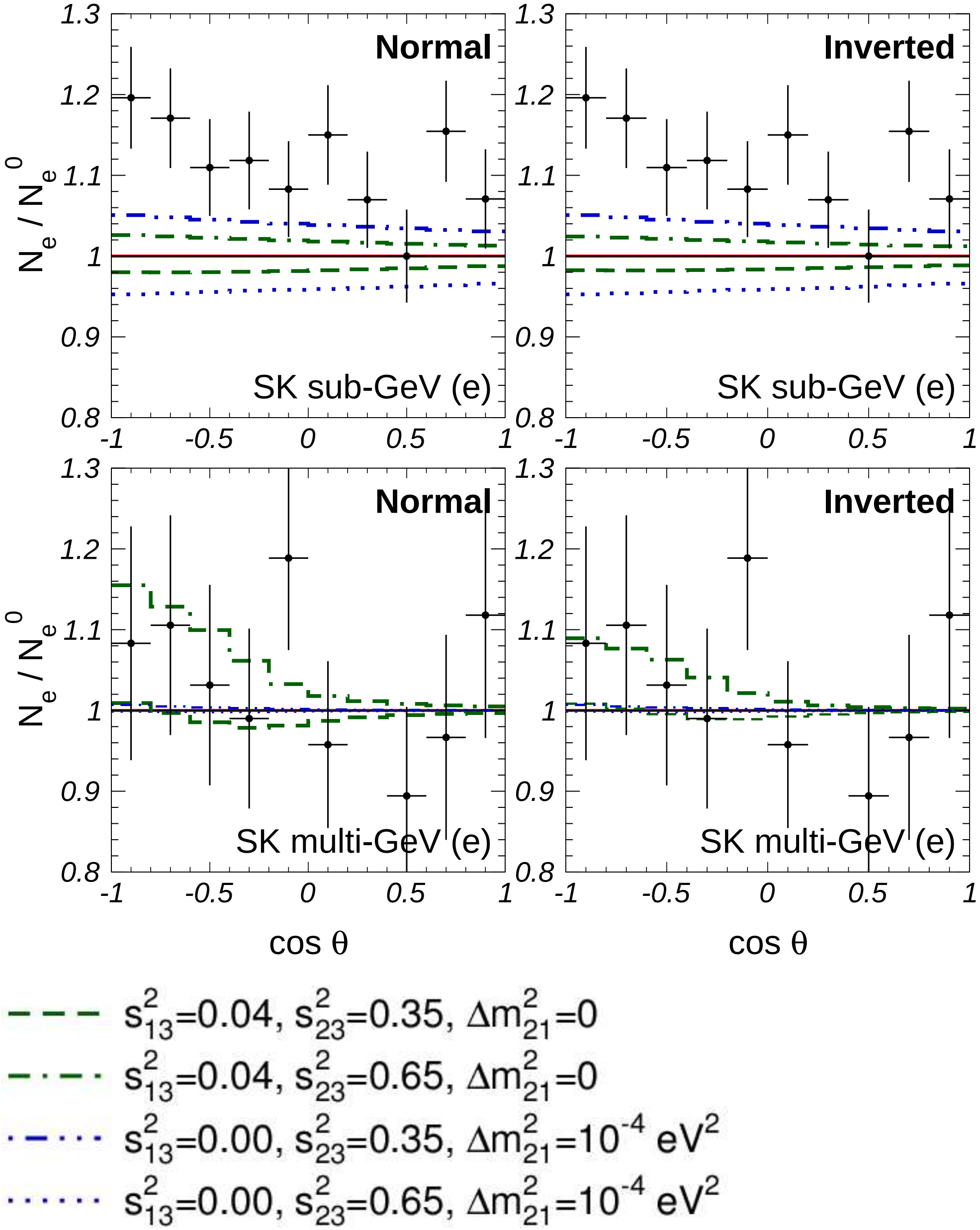
- Neglecting θ_{13}:

$$\begin{aligned}
P_{ee} &= 1 - P_{e2} \\
P_{e\mu} &= c^2_{23} P_{e2} \\
P_{\mu\mu} &= 1 - c^4_{23} P_{e2} - 2 s^2_{23} c^2_{23}\left[1 - \sqrt{1 - P_{e2}}\cos\phi\right] \\
P_{e2} &= \sin^2 2\theta_{12,m} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\frac{\sin 2\theta_{12}}{\sin 2\theta_{12,m}}\right) \\
\sin 2\theta_{12,m} &= \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \frac{2E_\nu V_e}{\Delta m^2_{21}})^2 + \sin^2 2\theta_{12}}} \\
\phi &\approx (\Delta m^2_{31} + s^2_{12}\,\Delta m^2_{21})\frac{L}{2E_\nu}
\end{aligned}$$

Δm^2_{21} effects in ATM Data



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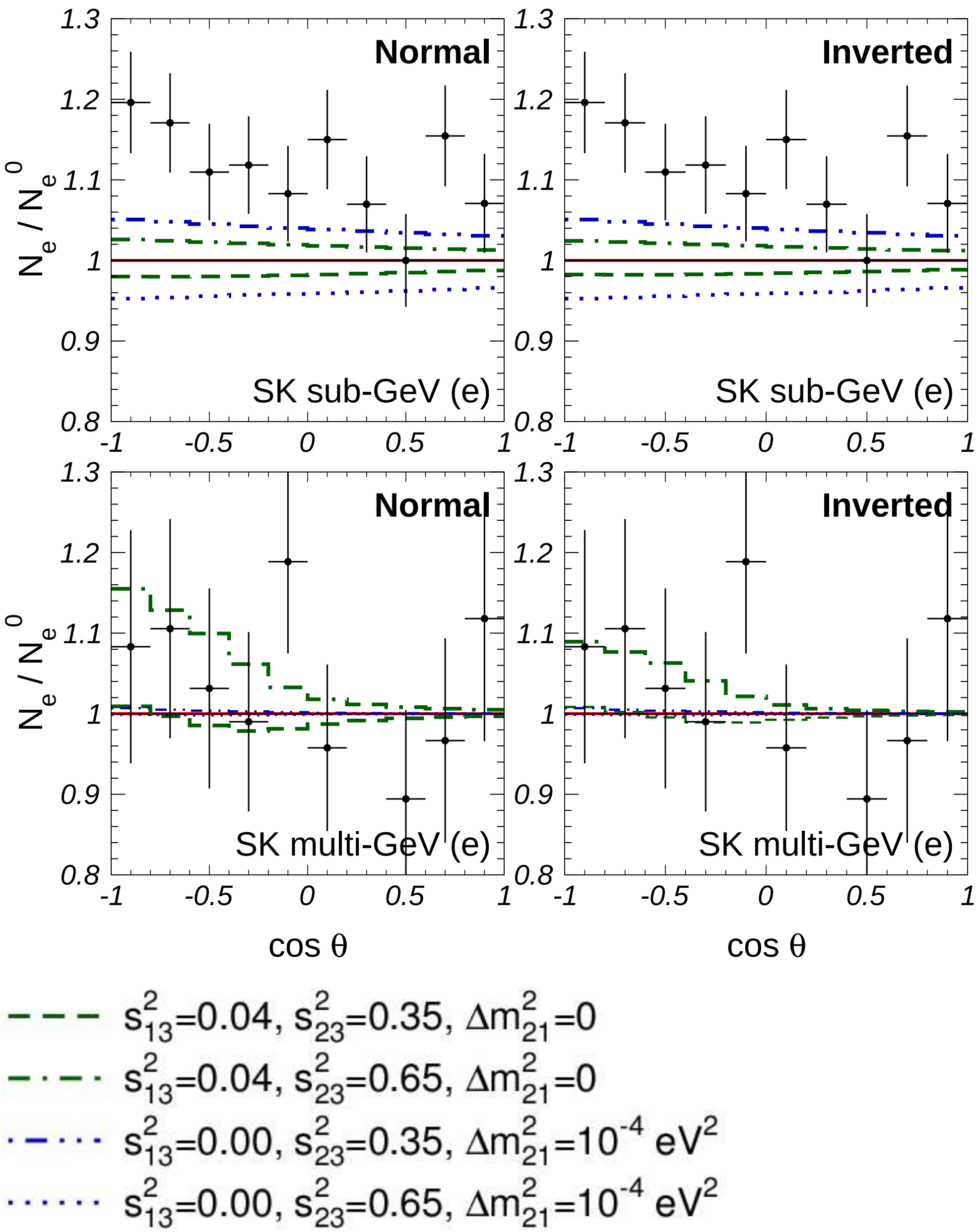

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For Sub-GeV:

$$P_{e2} = \frac{(\Delta m^2_{21})^2}{(2EV_e)^2}\sin^2 2\theta_{12} \sin^2\frac{V_e L}{2}$$

$$\theta_{23} < \frac{\pi}{4} \Rightarrow c^2_{23} > \frac{1}{2} \Rightarrow N_e(\theta_{13}) > N_{e0}$$

$$\theta_{23} > \frac{\pi}{4} \Rightarrow c^2_{23} < \frac{1}{2} \Rightarrow N_e(\theta_{13}) < N_{e0}$$

$\Rightarrow$ Sensitiv to Deviations from Maximal θ_{23}

$\Rightarrow$ Sensitivity to Octant of θ_{23}

(even for vanishing θ_{13})

$\Rightarrow$ Effect proportional to $(\Delta m^2_{21})^2$

Beyond Hierarchical: Effect $\theta_{13} \times \Delta m^2_{21}$ in ATM

Smirnov, Peres 01,03, MC G-G, Maltoni 02

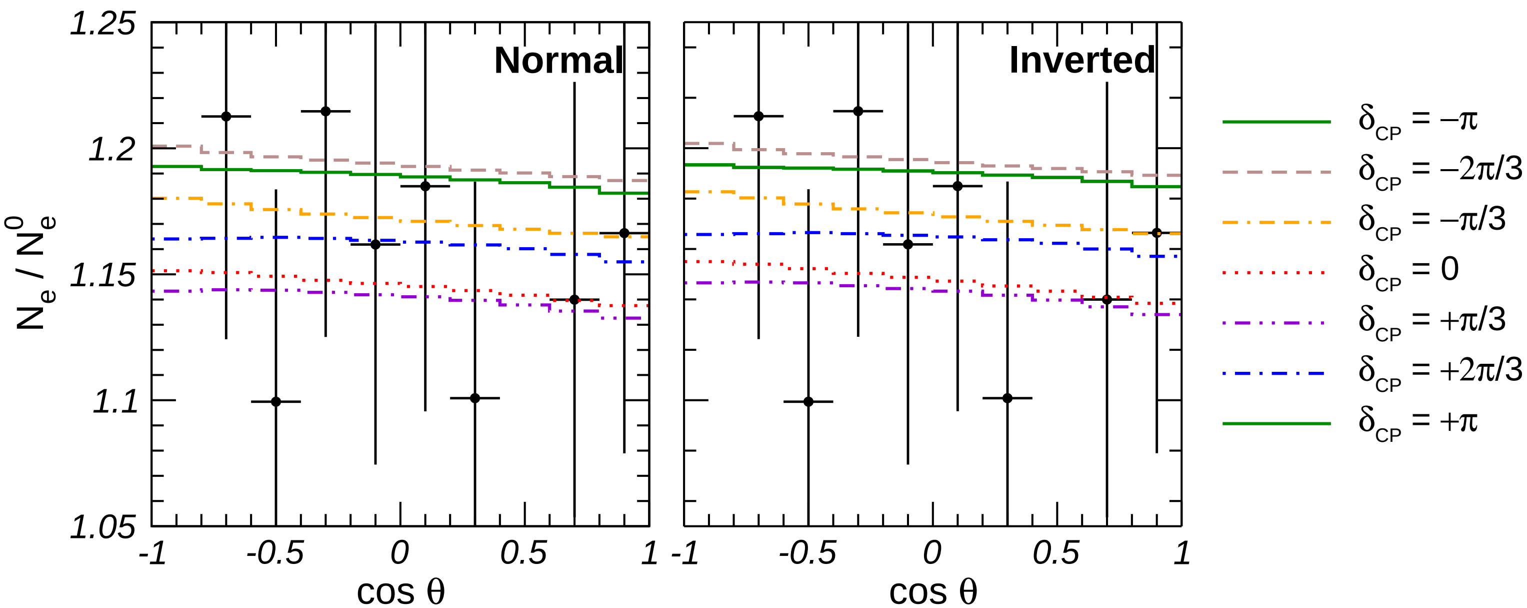
For sub-GeV energies

$$\frac{N_e}{N_e^0} - 1 \simeq \overline{P_{e2}}\,\overline{r}(c^2_{23} - \frac{1}{\overline{r}}) + 2\tilde{s}^2_{13}\overline{r}(s^2_{23} - \frac{1}{\overline{r}}) - \overline{r}\tilde{s}_{13}\tilde{c}^2_{13}\sin 2\theta_{23}(\cos\delta_{CP}\,\overline{R_2} - \sin\delta_{CP}\overline{I_2})$$

$$P_{e2} = \sin^2 2\theta_{12,m}\,\sin^2\frac{\phi_m}{2} \qquad \sin 2\theta_{12,m} = \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \frac{2E_\nu V_e}{\Delta m^2_{21}})^2 + \sin^2 2\theta_{12}}}$$

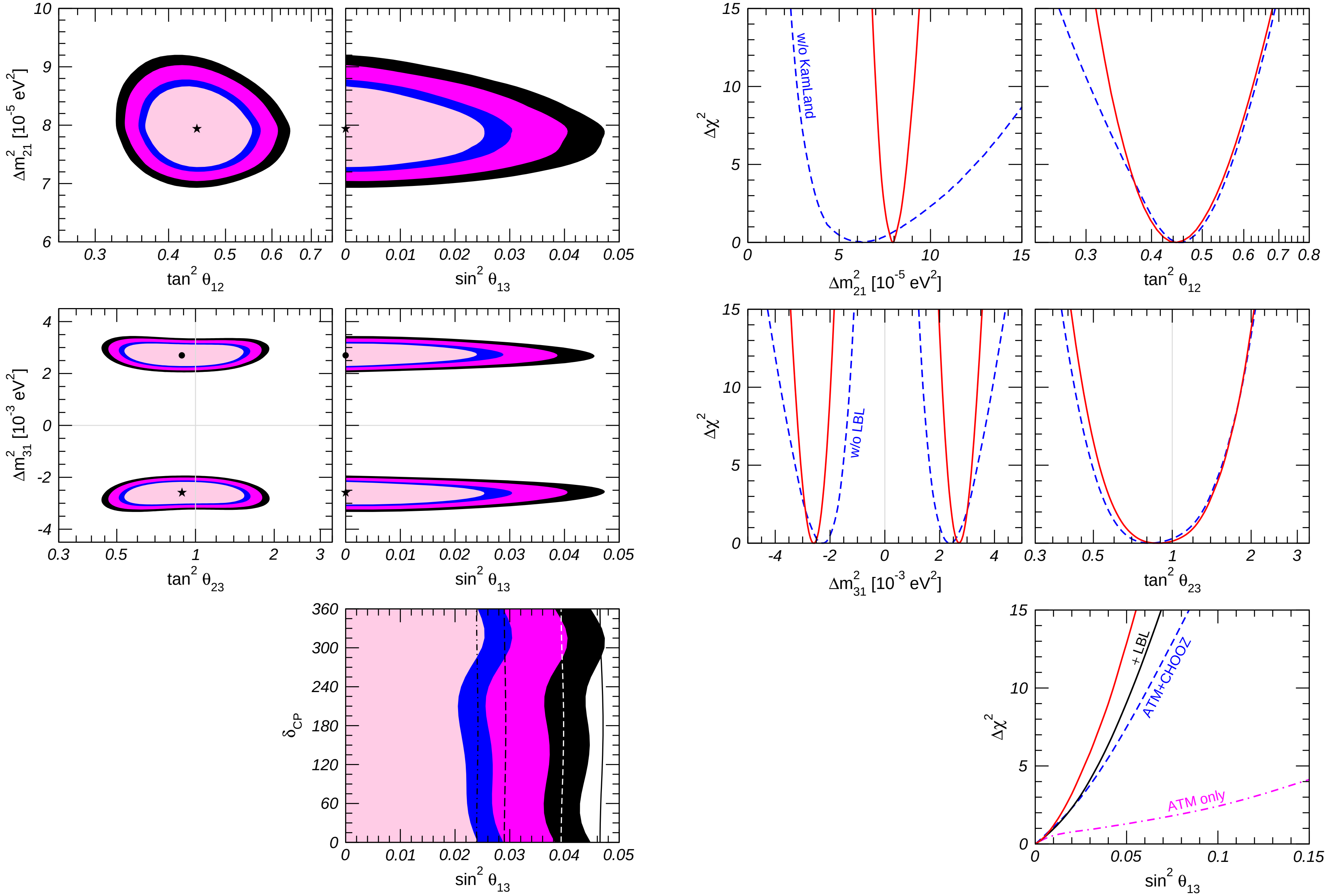
$$R_2 = -\sin 2\theta_{12,m}\cos 2\theta_{12,m}\,\sin^2\frac{\phi_m}{2} \qquad I_2 = -\frac{1}{2}\sin 2\theta_{12,m}\,\sin\phi_m$$

$$\tilde{\theta}_{13} \approx \theta_{13}\left(1 + \frac{2E_\nu V_e}{\Delta m^2_{31}}\right) \qquad \phi \approx (\Delta m^2_{31} + s^2_{12}\,\Delta m^2_{21})\frac{L}{2E_\nu}$$



Global Analysis: Three Neutrino Oscillations

M.C. G-G, M.Maltoni, ArXiV/0704.1800



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The derived ranges:

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

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

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very different from quark's

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Open Questions

We still ignore:

(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 ν osc experiments:

– Medium Baseline Reactor Experiment: *Double-Chooz, Daya Bay*

– Conventional (=from π decay) Superbeams: *T2K, Nova (?)*

– ν-factory: clean ν beam from μ decay

– ν_e or $\bar{\nu}_e$ beam from nuclear β decay (β beam)

Some Lessons: New Physics

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And it is also the only solid evidence! To go further one has to be cautious…

Lessons: The Scale of New Physics

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But this is scale was already known to particle physicists...

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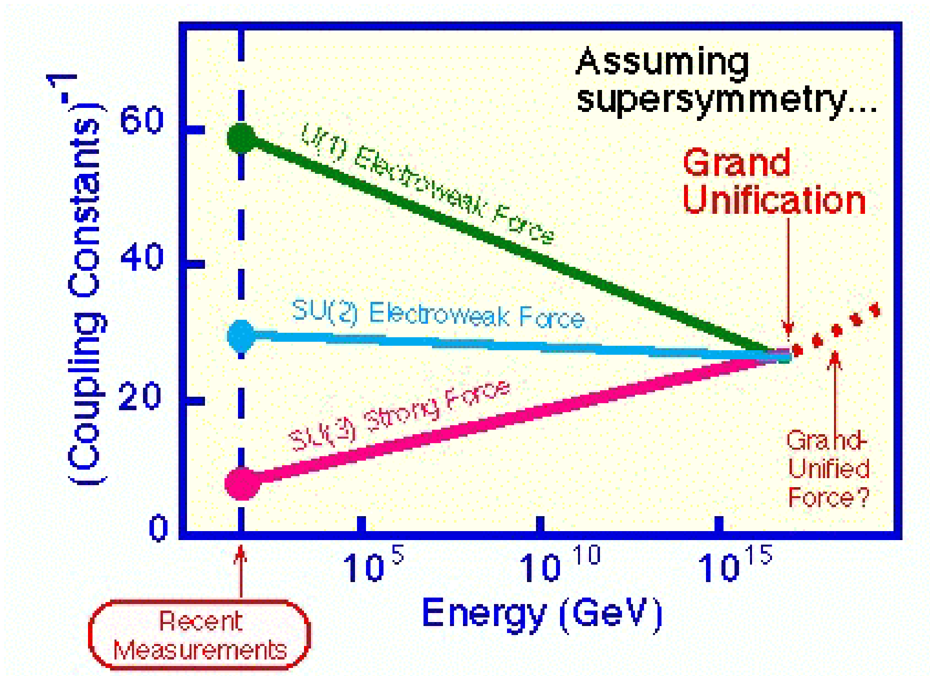
$m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05{\rm eV} \Rightarrow 10^{10} < \Lambda_{\rm NP} < 10^{15}{\rm GeV}$

New Physics Scale close to Grand Unification scale



Also the generated neutrino mass term is Majorana :

$\Rightarrow$ It violates total lepton number

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Lessons:

– $\mathcal{L}_{\rm NP}$ contains 18 parameters which we want to know

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

$\Rightarrow$ Same $\mathcal{O}_5$ can give very different $\mathcal{L}_{\rm NP}$

$\Rightarrow$ It is *difficult* to "imply" bottom-up (model independently)

Leptogenesis

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⇒ Lepton Number is Violated (M_R)

⇒ New Sources of CP violation λ

⇒ Decay of ν_R can be out of equilibrium

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

⇓

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 the See-saw mechanism

$$-\mathcal{L}_{\rm NP} = \frac{1}{2} M_{Rij} \overline{\nu_{Ri}} \nu_{R}{}^{c}_{j} + \lambda^{\nu}_{ij} \overline{\nu_{Ri}} \tilde{\phi}^{\dagger} L_{Lj}$$

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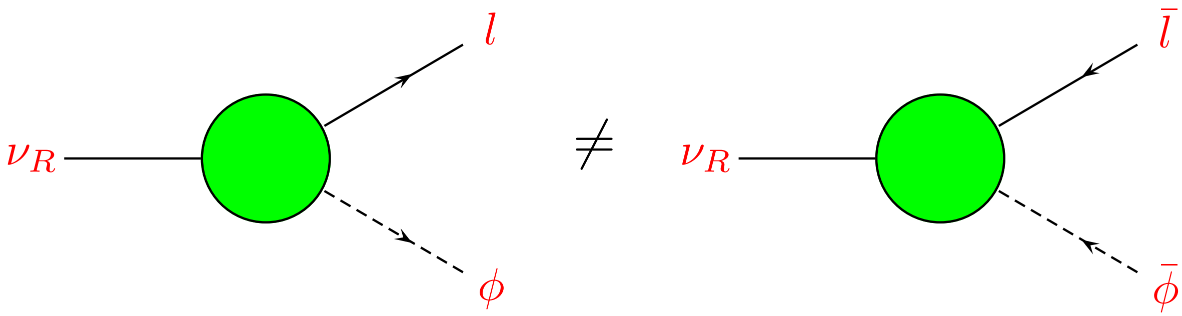

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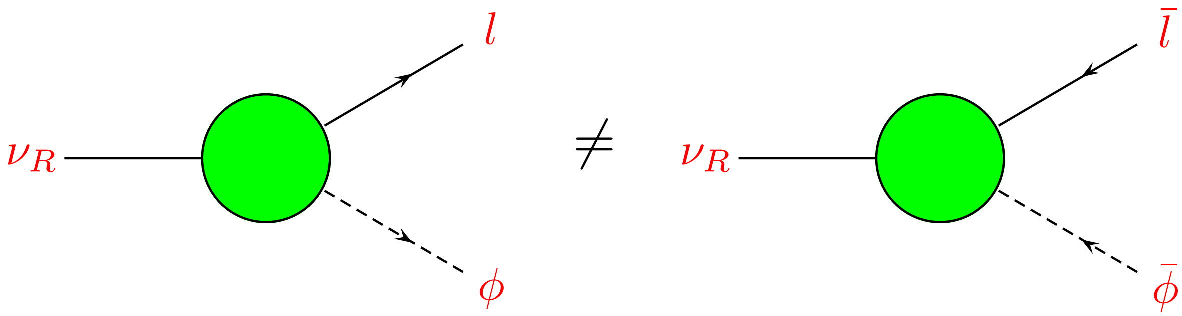

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$$\epsilon_L = \frac{\Gamma(\nu_R \to \phi\, l_L) - \Gamma(\nu_R \to \overline{\phi}\, \overline{l_L})}{\Gamma(\nu_R \to \phi\, l_L) + \Gamma(\nu_R \to \overline{\phi}\, \overline{l_L})} = -\frac{1}{8\pi} \sum_k \frac{Im[(\lambda\lambda^{\dagger})^2_{k1}]}{(\lambda\lambda^{\dagger})_{11}}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

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

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

$n_{\nu_R} \equiv$ density of ν_R $\quad$ ($d < 1 \equiv$ dilution factor)

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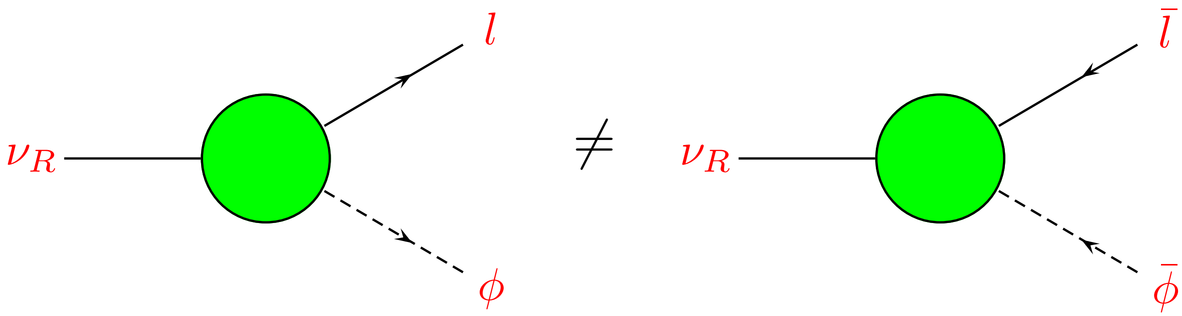

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Out of Equilibrium condition $\Gamma_{\nu_R} \ll H\big|_{T=M_{\nu_R}} \Rightarrow \tilde{m}_1 \equiv \frac{(\lambda\lambda^\dagger)^2_{11} \langle\phi\rangle^2}{M_{\nu_{R1}}} \lesssim 5 \times 10^{-3} eV$

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

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M_R is a 3×3 symmetric matrix

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$\Rightarrow$ M^ν has 6 physical phases

$\Rightarrow$ It is easy to generate $\epsilon_L \sim 10^{-6}$

$\Rightarrow$ $m^\nu_{\rm light} = m_D^T M_N^{-1} m_D$ has 3 physical phases

Oscillation experiments can only see one of these three phases

$\Rightarrow$ No direct correspondence between CPV in leptogenesis and CPV in oscillations

- The final Y_B depends on:
  - ϵ_L the CP asymmetry
  - $M_{\nu_{R1}}$ the mass of the lightest ν_R
  - $\tilde{m}_1 \equiv \frac{(\lambda\lambda^\dagger)^2_{11}\langle\phi\rangle^2}{M_{\nu_{R1}}}$ the *effective* neutrino mass
  - $m^2_{\nu_1} + m^2_{\nu_2} + m^2_{\nu_3}$ 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

Summary

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- Neutrino oscillation searches have shown us
  - $\Delta m^2_{31} \sim 2 \times 10^{-3}$ eV^2 and $\Delta m^2_{21} \sim 8 \times 10^{-5}$ eV^2 $\Rightarrow$ ν's are massive
  - $|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix}$ $\lambda \sim 0.2$, $\epsilon \lesssim 0.2$ $\Rightarrow$ Different from U_{CKM}

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

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  (a) *breaking* total lepton number $\longrightarrow$ Majorana ν : $\nu = \nu^C$

  (b) *conserving* total lepton number $\longrightarrow$ Dirac ν : $\nu \neq \nu^C$
- Majorana $\nu' s$ are more *Natural*: appear *generically* if SM is a LE effective theory
  - $\Lambda_{NP} \lesssim 10^{15}$ 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 θ_{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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Proposed new generation ν osc experiments:

– LBL with Conventional Superbeams and/or β beams and/or ν-factory:

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Also no-oscillation experiments:

– ν-less $\beta\beta$ decay, ^3H beta decay

– Interesting input from cosmological data

Rich and *Challenging* Experimental Program