CP violation in Neutrino Sector and Proton Decay

3rd Korean Neutrino Observatory meeting
Kyungpook National University,
2 November, 2018

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Leptonic CP violation

- Fundamental missing link that needs to be addressed in LBL experiments is to measure δ_{CP} and to explore leptonic CP violation.

- It is likely that the CPV phase in ν oscillations is not directly responsible to generate the CPV leading to leptogenesis except for very special cases.

- But, there is no doubt that a demonstration of CPV in neutrino oscillations will provide a crucial guidepost for models of leptonic CPV and leptogenesis.

Origin of CP violation in Neutrino

Complex Phases in Neutrino Mixing Matrix

- 2−flavor neutrino framework : 1 mixing angle, no $\boldsymbol{\delta_{Dirac}}$, 1 $\boldsymbol{\delta_{Maj}}$ (if neutrinos are Majorana)
- 3−flavor neutrino framework $|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$

$$U \equiv U_{\mathrm{MNS}} \cdot \Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \mathrm{diag}(1, e^{i\beta}, e^{i\gamma})$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \mathrm{diag}(1, e^{i\beta}, e^{i\gamma})$$

Origin of CP violation in Neutrino

Complex Phases in Neutrino Mixing Matrix

As # of $\boldsymbol{\nu}$ increases, formalism rapidly gets complicated

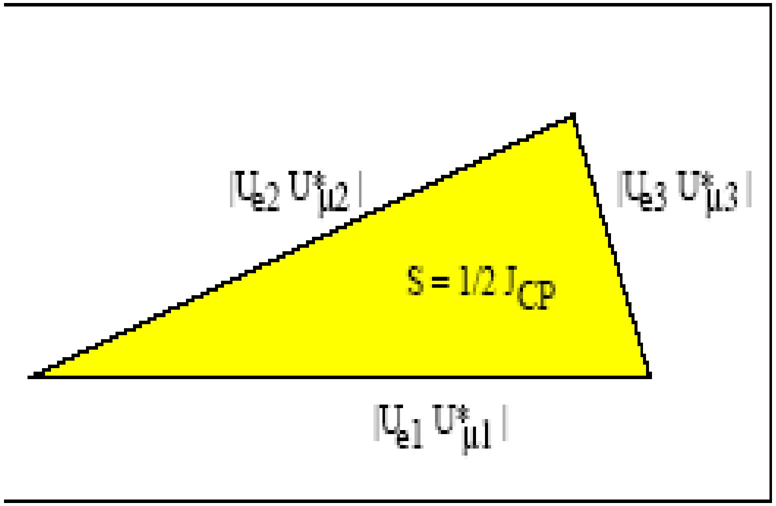
– For N neutrinos, # of mixing angles : $N(N-1)/2$

# of Dirac phase : $(N-1)(N-2)/2$

# of Majorana phase : $N-1$

(e.g. 4-ν : 6 angles, 3 Dirac phases, 3 Majorana phases)

Leptonic Unitary Triangle



- Method of LUT is complementary to the direct measurement of CPV
- For present maximally allowed |Ue3| & maximal CPV,

a precision better than 10% in measurements of the sides of the LUT will allow us to establish CPV at 3 sigma

(Farzan & Smirnov ‘02)

CP transformation

- Under CP transformation, neutrinos are replaced by their antineutrinos : $\boldsymbol{\nu_{a,b} \leftrightarrow \bar{\nu}_{a,b}}$

  it is equivalent to the complex conjugation of $\boldsymbol{U_{ai}}$:

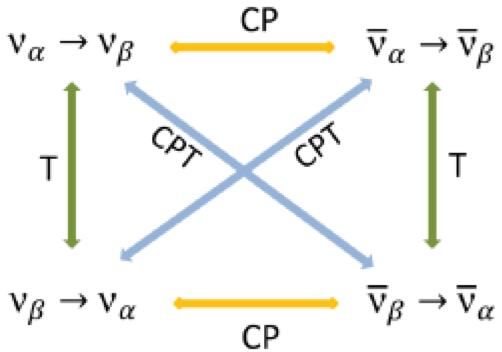
$$\boldsymbol{U_{ai} \rightarrow U_{ai}^{*} \ \ (\delta_{CP} \rightarrow -\delta_{CP})}$$

$$\boldsymbol{\Rightarrow P(\nu_a \rightarrow \nu_b) \rightarrow P(\bar{\nu}_a \rightarrow \bar{\nu}_b)}$$

- Time reversal transformation interchanges the initial and final evolution times, which is equivalent to the complex conjugation of $\boldsymbol{U_{ai}}$ in the neutrino oscillation probability
- Under the combined action of CP and T :

  CPT: $\boldsymbol{\nu_{a,b} \leftrightarrow \bar{\nu}_{a,b} \ \& \ t_i \leftrightarrow t_f \ (\nu_a \leftrightarrow \nu_b)}$

$$\boldsymbol{\Rightarrow P(\nu_a \rightarrow \nu_b) \rightarrow P(\bar{\nu}_b \rightarrow \bar{\nu}_a)}$$



Observables of CP violation

(1) Dirac CP violation

- A CP non−conserving value of $\boldsymbol{\delta_{Dirac}}$ can generate CP violating effects in neutrino oscillation.
- A measure of CP violation is provided by the asymmetry :

$$\boxed{A_{\mathrm{CP}}^{(l,l')} = P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'}) , \quad l \neq l' = e, \mu, \tau \,.}$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} \underbrace{- 4\sum_{i>j}^{n} \mathrm{Re}\left[U_{\alpha i}^{*} U_{\beta j}^{*} U_{\beta i} U_{\alpha j}\right] \sin^2 X_{ij}}_{\text{CP conserving}}$$

$$X_{ij} = \frac{\left(m_i^2 - m_j^2\right) L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{\mathrm{eV}^2} \frac{L/E}{m/\mathrm{MeV}}$$

$$\underbrace{- 2\sum_{i>j}^{n} \mathrm{Im}\left[U_{\alpha i}^{*} U_{\beta j}^{*} U_{\beta i} U_{\alpha j}\right] \sin 2X_{ij}}_{\text{CP violating}},$$

Observables of CP violation

(1) Dirac CP violation

- The magnitude of CPV effects in neutrino oscillations in the case of 3-flavor mixing is controlled by the rephrasing invariant J_{CP} : $A_{\mathrm{CP}}^{(e,\mu)} = A_{\mathrm{CP}}^{(\mu,\tau)} = -A_{\mathrm{CP}}^{(e,\tau)} = J_{\mathrm{CP}}\ F_{osc}^{vac}$

$$J_{\mathrm{CP}} = \mathrm{Im}\left\{U_{e2}U_{\mu 2}^{*}U_{e3}^{*}U_{\mu 3}\right\}$$

$$F_{osc}^{vac} = \sin(\frac{\Delta m_{21}^2}{2E}L) + \sin(\frac{\Delta m_{32}^2}{2E}L) + \sin(\frac{\Delta m_{13}^2}{2E}L)$$

(Barger, Whisnant, Phillips '84)

- In the standard parametrization:

$$J_{\mathrm{CP}} = \frac{1}{8}\cos\theta_{13}\sin 2\theta_{12}\ \sin 2\theta_{23}\ \sin 2\theta_{13}\ \sin\delta$$

- current neutrino data implies $|J_{CP}| < 0.039\sin\delta$

- Condition for CP violation
  - $\boldsymbol{\delta_{Dirac} \neq 0, \pi}$ & $\Delta m_{ij}^2 \neq 0$
  - no averaging regime
  - $L \neq 0$
- CP violation can not be observable in the disappearance channel ($\boldsymbol{P_{\alpha\alpha} = P_{\bar{\alpha}\bar{\alpha}}}$)

- To observe CPV effects in neutrino oscillations, both $\sin\left(\Delta m_{21}^2 \frac{L}{2E}\right)$ and $\sin\left(\Delta m_{31(32)}^2 \frac{L}{2E}\right)$ should be sufficiently large.

- For instance, $\sin\left(\Delta m_{31(32)}^2 \frac{L}{2E}\right) \sim 1$ can be achieved in experiments with accelerator $\boldsymbol{\nu_\mu}$ and $\boldsymbol{\bar{\nu}_\mu}$ beams with E to be order of GeV and L~1000 km.

- Thus, chance to observe CPV in neutrino oscillation requires experiments to have relatively long baselines.

Matter Effects

- Oscillation probability changes when neutrino passes through matter (MSW).
- In matter, VO parameters are connected to the new parameters in the following way

$$\left(\Delta m^2\right)^m = \sqrt{\left(\Delta m^2 \cos 2\theta - A\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2},$$

$$\sin 2\theta^m = \frac{\sin 2\theta \Delta m^2}{\left(\Delta m^2\right)^m}.$$

$$\boxed{A = \pm 2\sqrt{2} G_F N_e E,}$$

- For oscillations in matter, CP transformation implies not only complex conjugation of $\boldsymbol{U_{ai}}$, but also flipping the sign of A

- Unlike in vacuum, CP-odd effects in oscillations in matter exist even in 2-flavor case.

- In matter, the survival probabilities are not CP-invariant

$$P_{\alpha\alpha} \neq P_{\bar{\alpha}\bar{\alpha}}$$

- In 3-flavor scenario, besides the genuine CP asymmetry caused by the CP phase, we also have fake CP asymmetry induced by matter.

- We should disentangle fundamental CP violation from the matter induced one
  -by measuring E and/or L dependence of the oscillated signal

$\nu_\mu \rightarrow \nu_e$ in matter

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\;& 4c_{13}^2 \boxed{s_{13}^2} s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] && \rightarrow \theta_{13} \\
&+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} && \rightarrow \text{CP-even} \\
&- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underline{\sin\delta} \sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} && \rightarrow \text{CP-odd} \\
&+ 4s_{12}^2 c_{13}^2 (c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu} && \rightarrow \text{Solar} \\
&- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2), && \rightarrow \text{Matter}
\end{aligned}
$$

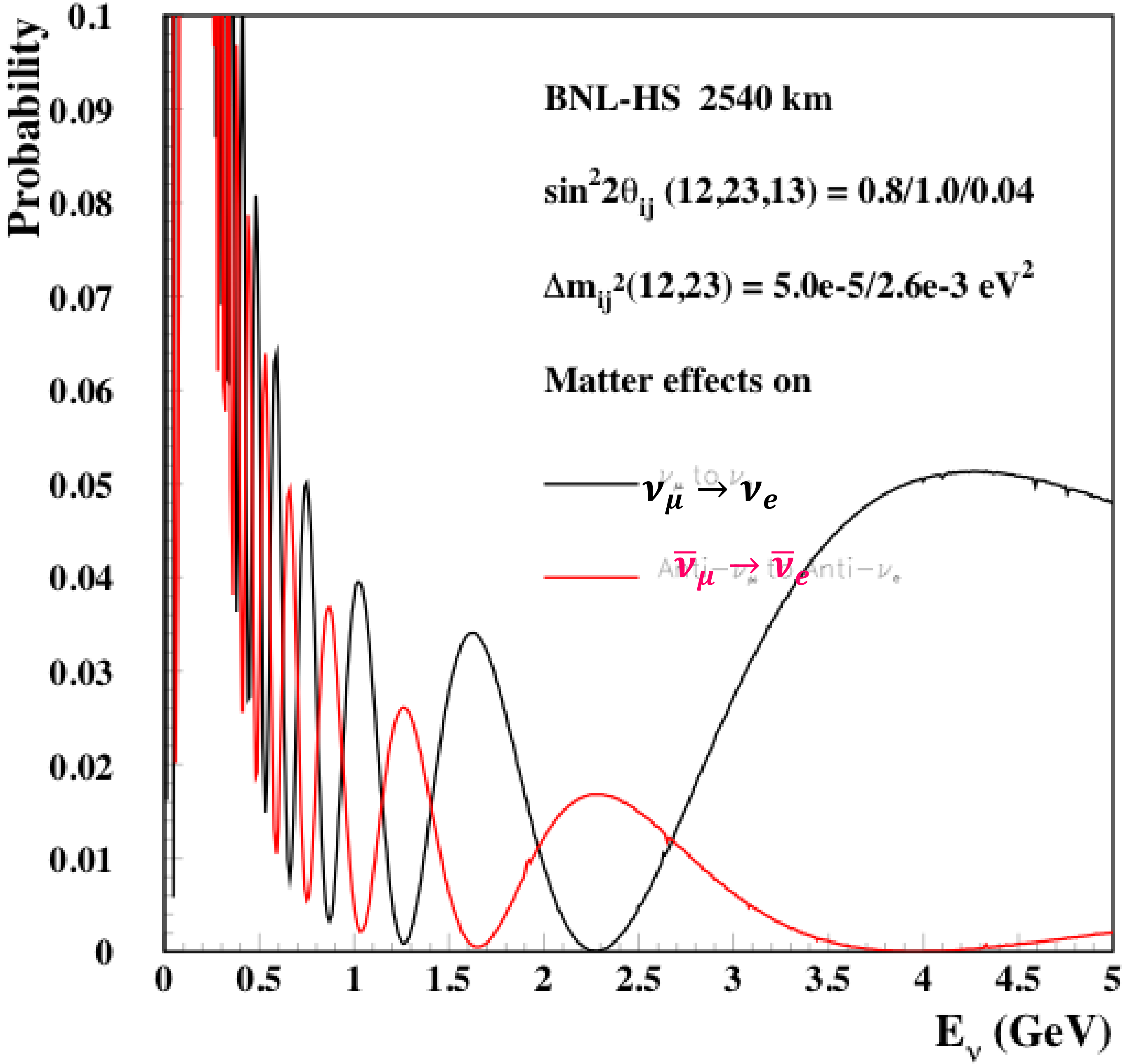
$s_{ij} = \sin\theta_{ij}$ $\quad c_{ij} = \cos\theta_{ij}$ $\quad a[eV^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times 10^{-5}\rho\left[{}^{g}/_{cm^3}\right]E_\nu[GeV]$

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ➡ $a \to -a \qquad \delta \to -\delta$

Fake CP violation

change sign for NH → IH

$P(\nu_\mu \to \nu_e)$ vs. $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for $\delta_{CP} = 45°$



W. Marciano

$P(\nu_\mu \rightarrow \nu_e)$ vs. $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ for $\delta_{CP} = 45°$

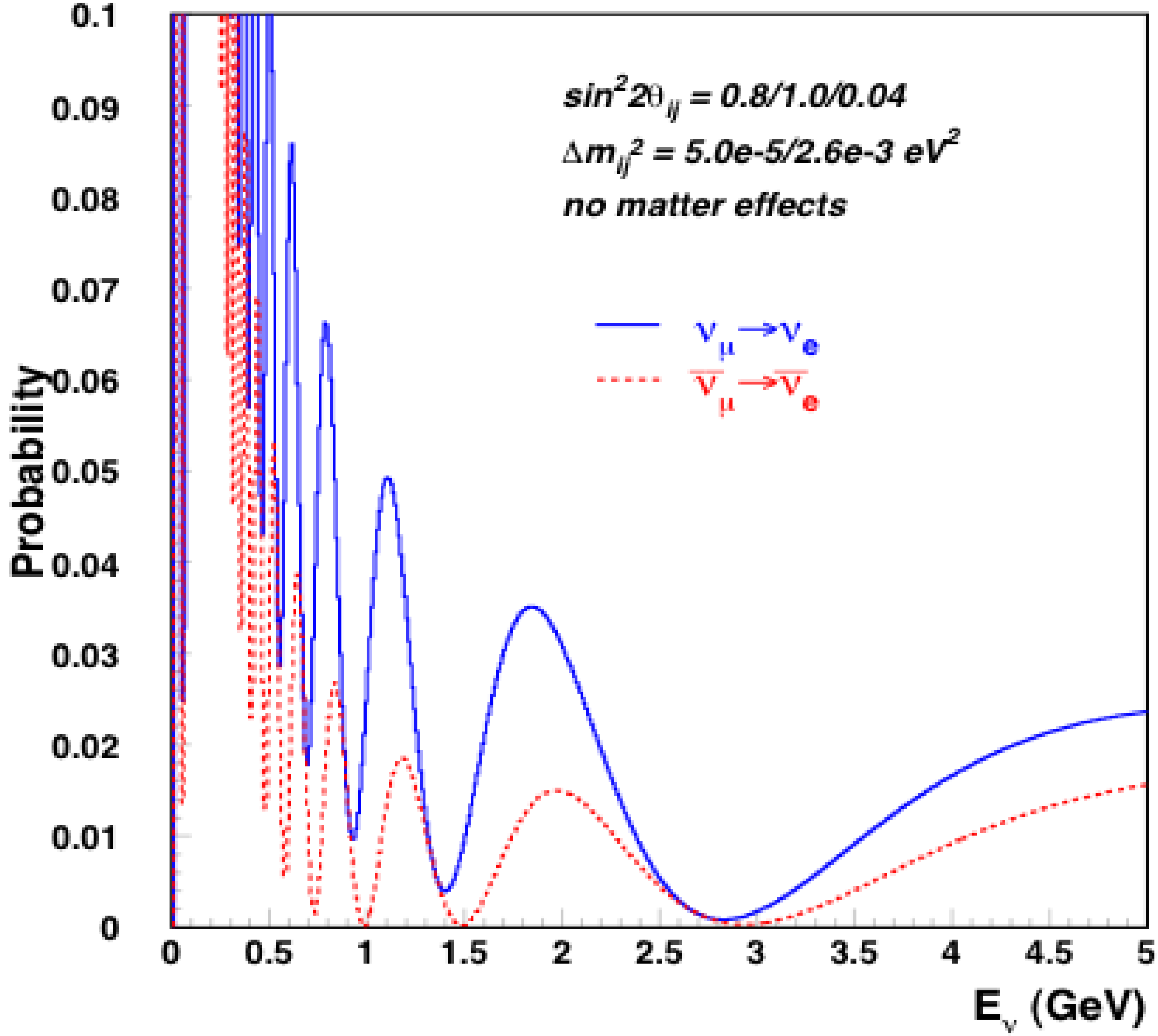


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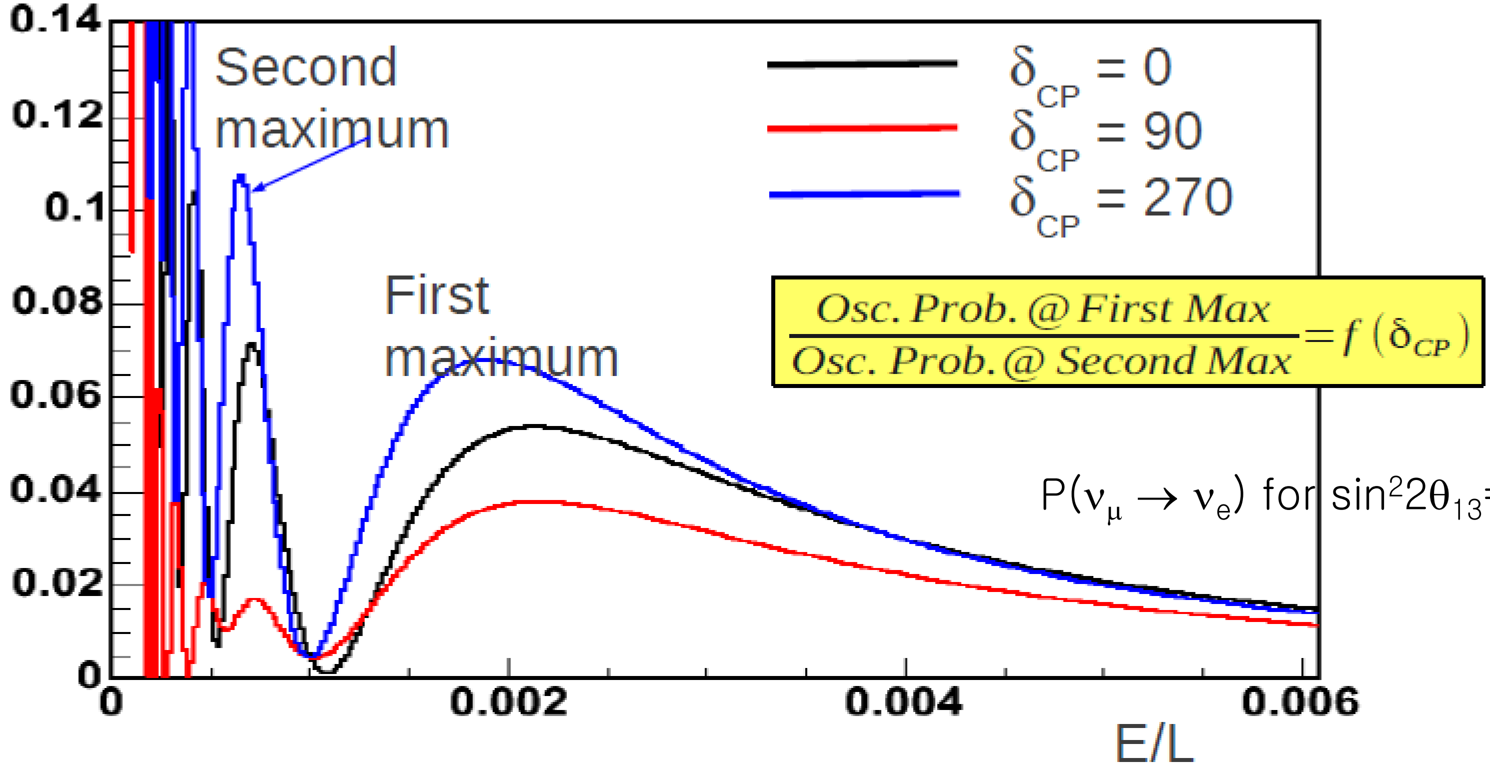
Figure 23: Probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at 2540 km in vacuum, assuming a $\delta_{CP} = 45°$ CP violation phase. It can be seen that the CP asymmetry between ν_μ and

$\nu_\mu \rightarrow \nu_e$ oscillation probability



(S. Parke , Olssen et al.)

$$\Delta CP(\delta) \equiv P(\nu_\mu \rightarrow \nu_e : \delta) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e : \delta)$$

ν and anti−ν narrow beams tuned to 1st oscillation maximum

$$\Delta\delta \equiv P(\nu_\mu \rightarrow \nu_e : \delta=\pi/2) - P(\nu_\mu \rightarrow \nu_e : \delta=0)$$

wide ν (anti−ν) beam to cover 1st and 2nd oscillation maxima

Hint of CP violation in ν osciilation

- From combined analysis of neutrino and antineutrino oscillations at T2K ('17)

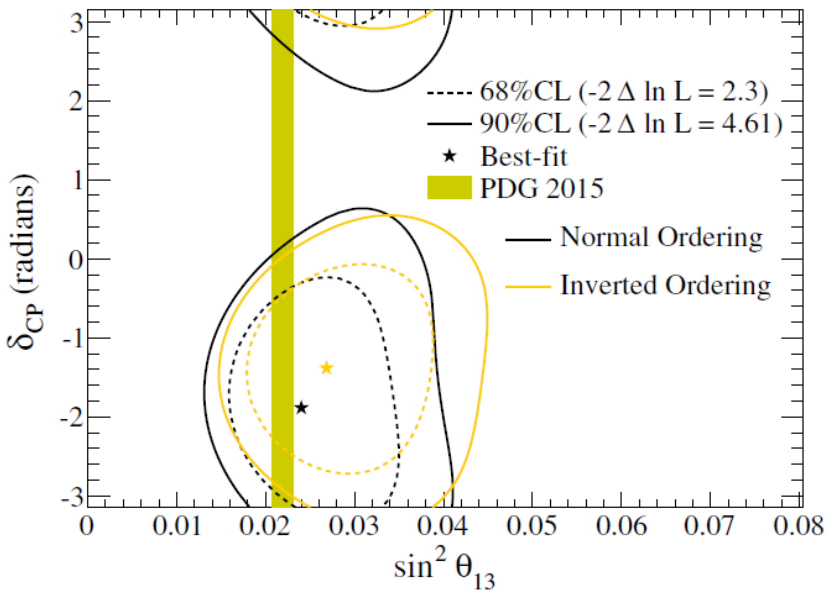
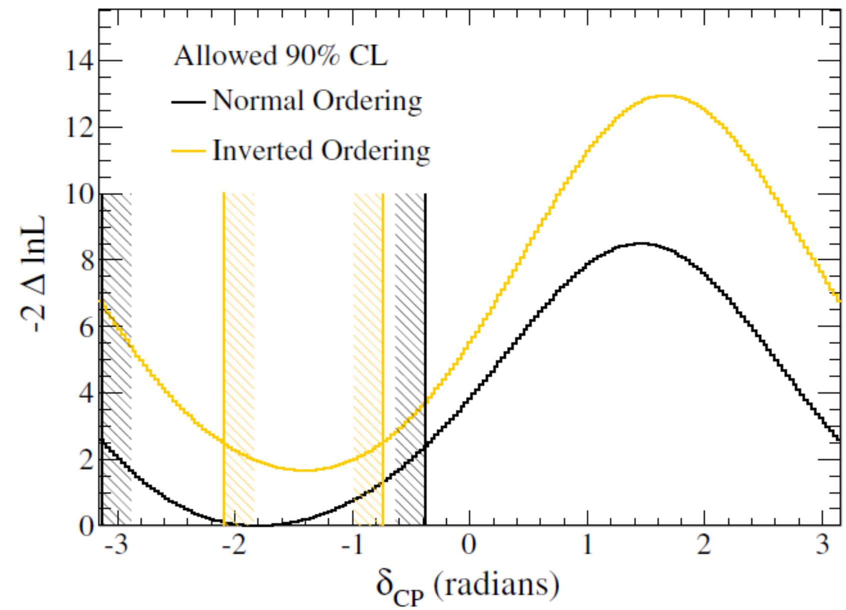


FIG. 6. The 68% (90%) constant $-2\Delta \ln L$ confidence regions in the $\delta_{CP} - \sin^2\theta_{13}$ plane are shown by the dashed (continuous) lines, computed independently for the normal (black) and inverted (yellow) mass ordering. The best-fit point is shown by a star for each mass-ordering hypothesis. The 68% confidence region from reactor experiments on $\sin^2\theta_{13}$ is shown by the yellow vertical band.



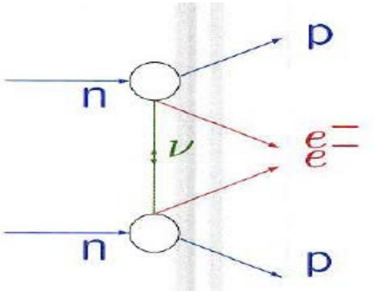
CP conservation(δ_{CP}=0, π) is excluded at 90% CL

Observables of CP violation

(2) Majorana CP violation

- The flavor oscillation probabilities $P(\nu_\alpha \leftrightarrow \nu_\beta)$ are insensitive to the Majorana phases.
- If ν_j are Majorana particles with definite mass, their exchange can trigger process in which the total lepton number changes by 2 units : $K^+ \to \pi^- + \mu^+ + \mu^+$, $e^- + (A, Z) \to e^+ + (A, Z-2)$, etc.
- But the rates of those processes are extremely small.

Observables of CP violatior



(2) Majorana CP violation

- The searches for neutrinoless double beta ($\beta\beta0\nu$) decay, (A, Z) $\rightarrow$(A, Z+2) +e^-+e^- are unique in reaching sensitivity to observe this process triggered by the exchange of light ν_j .
- The corresponding ($\beta\beta0\nu$) decay amplitude has the form :

$$A(\beta\beta0\nu) = \boldsymbol{G_F^2} | < \boldsymbol{m} > | \boldsymbol{M(A,Z)}$$

$$\boxed{|\langle m \rangle| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i(\alpha_{31} - 2\delta)} \right|}$$

$$|\langle m \rangle| \cong |\sqrt{\Delta m_{21}^2}\, s_{12}^2 + \sqrt{\Delta m_{31}^2}\, s_{13}^2 e^{i(\alpha_{32} - 2\delta)}|, \ \alpha_{32} = \alpha_{31} - \alpha_{21}, \quad \text{NH},$$

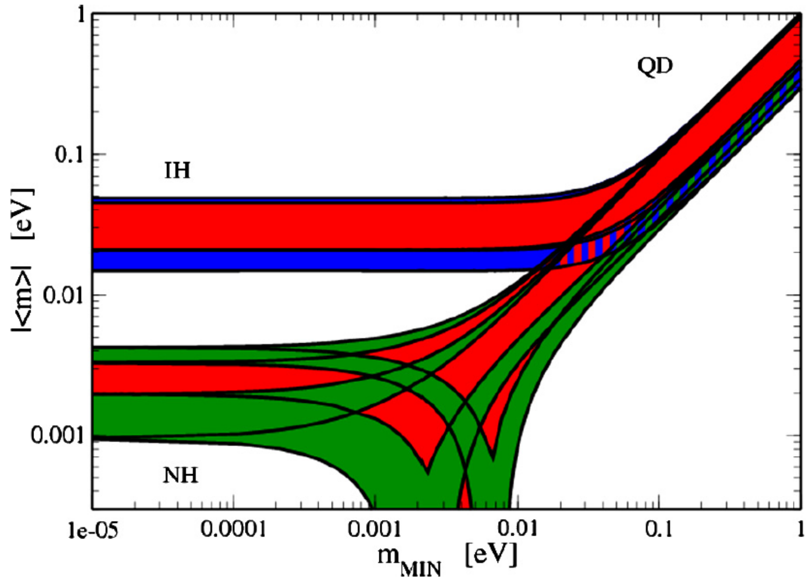
$$|\langle m \rangle| \cong \sqrt{|\Delta m_{32}^2|} \left| c_{12}^2 + s_{12}^2\, e^{i\alpha_{21}} \right|, \quad \text{IH},$$

$$|\langle m \rangle| \cong m_0 \left| c_{12}^2 + s_{12}^2\, e^{i\alpha_{21}} \right|, \quad \text{QD}.$$

- Using the 3σranges of the allowed values of the neutrino oscillation parameters

0.58×10^{-3} eV $\lesssim |\langle m \rangle| \lesssim 4.22 \times 10^{-3}$ eV in the case of NH spectrum;
1.3×10^{-2} eV $\lesssim |\langle m \rangle| \lesssim 5.0 \times 10^{-2}$ eV in the case of IH spectrum;
2.8×10^{-2} eV $\lesssim |\langle m \rangle| \lesssim m_0$ eV, $m_0 \gtrsim 0.10$ eV, in the case of QD spectrum.

- The difference in the ranges of $| < \boldsymbol{m} > |$ in the cases of NH, IH and QD opens up the possibility to get information about the type of neutrino mass spectrum.



Remarks on ββ0ν

- A large number of experiments of a new generation aim at sensitivity to $|\langle m \rangle| \sim (0.01–0.05)$eV : CUORE($^{130}Te$), GERDA($^{76}Ge$), SuperNEMO, EXO($^{136}Xe$), MAJORANA($^{76}Ge$), AMoRE($^{100}Mo$), MOON($^{100}Mo$), COBRA ($^{116}Cd$), CANDLES ($^{48}Ca$), KamLAND-Zen ($^{136}Xe$), SNO+($^{130}Te$)....

- GERDA, EXO and KamLAND-Zen have provided already the best lower limits on the (ββ0ν) decay half-lives of ^{76}Ge and ^{136}Xe.

- The experiments listed above are aiming to probe the QD and IH ranges. If the future $(\beta\beta)_{0\nu}$-decay experiments show that $|m|<0.01$eV, both the IH and the QD spectrum will be ruled out for massive Majorana neutrinos.

- If the (ββ0ν) decay will be observed in these experiments, the measurement of the (ββ0ν) decay half-life might allow to obtain constraints on the Majorana phase α

Remarks on $\beta\beta 0\nu$

- Proving that the CP symmetry is violated in the lepton sector due to Majorana CPV phases is remarkably challenging: it requires quite accurate measurements of $|\langle m\rangle|$and holds only for a limited range of values of the relevant parameters.

- Obtaining quantitative information on the neutrino mixing parameters from a measurement of $(\beta\beta)0\nu$-decay half-life would be impossible without sufficiently precise knowledge of the corresponding NME of the process.

Prediction of CP violation

μ-τ reflection symmetry Harrison, Scott, 02, 04; Grimus, Lavoura, 04

$$M_\nu = \begin{pmatrix} A & B & B^* \\ B & C & D \\ B^* & D & C^* \end{pmatrix} \quad \textbf{Invariant under:} \quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \to \begin{pmatrix} \nu_e^c \\ \nu_\tau^c \\ \nu_\mu^c \end{pmatrix}$$

Predictions: $\theta_{23} = 45°$, $\delta = 90°$ or $270°$, but θ_{12} and θ_{13} are left arbitrary

If combined with a flavor symmetry, both θ_{12} and θ_{13} can be constrained

Generalized CP

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \to X \begin{pmatrix} \nu_e^c \\ \nu_\mu^c \\ \nu_\tau^c \end{pmatrix}$$

***X* depends on a chosen flavor symmetry**

Holthhausen et al., 13

Both *δ*=0 or 180° and 90° or 270° are predicted by popular symmetry groups, e.g., A_4 and S_4.

$$\begin{tikzcd}
\Phi \arrow[r, "g'"] \arrow[d, "CP"'] & \rho(g')\Phi = X\rho(g)^* X^{-1}\Phi \\
X\Phi^* \arrow[r, "g"'] & X\rho(g)^*\Phi^* \arrow[u, "CP^{-1}"']
\end{tikzcd}$$

Non-typical values are also possible for some other groups, e.g., Δ(48). Ding, Y.L. Zhou, 14

- Alternatively, we can predict possible size of LCPV

  -- From the point of view of calculability, it is conceivable that a LCP phase may be estimated in terms of some observables.

  -- What observables can be responsible for prediction of LCP phase, masses, mixing angles, or all of them ?

- We come up with a simple scheme to calculate the possible size of LCP phase in terms of two or three ν mixing angles only, in the standard parameterization of neutrino mixing matrix.

Prediction of LCPV

- Modifying Tri-Bimaximal mixing matrix

$$V=\begin{cases} U^{TBM}\cdot U_{ij}(\theta,\xi) \\ U_{ij}{}^{+}(\theta,\xi)\cdot U^{TBM} \end{cases}$$

$$U^{TBM}=\begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

(Harrison, Perkins, Scott, 02)

- θ possibly gives rise to non-zero θ_{13} & possible deviation from maximal for θ_{23}.

We call those forms modified TBM parameterization .

(Kang & CSKim ‘14)

Prediction of LCPV

- Any forms of neutrino mixing matrix should be equivalent to the PMNS matrix presented in the standard PDG form :
- $U^{ST} = U_{23}(\theta_{23})U_{13}(\theta_{13},\delta_D)U_{12}(\theta_{12})P_\phi$

$$= \begin{pmatrix} c_{12}c_{13} & -s_{12}c_{13} & s_{13}e^{i\delta_D} \\ * & * & -s_{23}c_{13} \\ * & * & c_{23}c_{13} \end{pmatrix} \cdot \begin{pmatrix} e^{i\phi_1} & & \\ & e^{i\phi_2} & \\ & & e^{i\phi_3} \end{pmatrix}$$

$$= P_\alpha \cdot V \cdot P_\beta$$

$$\Rightarrow \quad \boxed{V_{ij}e^{i(\alpha_i+\beta_j)} = (U^{ST})_{ij}}$$

Estimations of LCPV

- For $$V = \begin{cases} U^{TBM} \cdot U_{23}(\theta, \xi) & (case\ A) \\ U^{TBM} \cdot U_{13}(\theta, \xi) & (case\ B) \end{cases}$$

- Using $|V_{13}| = |U_{13}{}^{ST}|$ and $\left|{}^{V_{11}}/_{V_{12}}\right| = \left|{}^{U_{11}{}^{ST}}/_{U_{12}{}^{ST}}\right|$, we get

$$s_{12}{}^2 = \begin{cases} 1 - \frac{2}{3(1-s_{13}{}^2)} & (case\ A) \\ \frac{1}{3(1-s_{13}{}^2)} & (case\ B) \end{cases}$$

- From the explicit form of V for case A, we see that

$$\frac{V_{23}-V_{33}}{V_{22}-V_{32}} = \frac{V_{13}}{V_{12}} \quad \text{and} \quad V_{21} = -V_{31}$$

Estimations of LCPV

- Using $V_{ij}e^{i(\alpha_i+\beta_j)} = (U^{ST})_{ij}$, we can get

$$\frac{U_{13}{}^{ST}}{U_{12}{}^{ST}} = \frac{U_{23}{}^{ST}U_{31}{}^{ST} + U_{33}{}^{ST}U_{21}{}^{ST}}{U_{22}{}^{ST}U_{31}{}^{ST} + U_{32}{}^{ST}U_{21}{}^{ST}}$$

- Presenting $U_{ij}{}^{ST}$ in terms of θ_{ij} and δ_D,

$$\cos\delta_D = \frac{1}{\tan 2\theta_{23}} \cdot \frac{1-5s_{13}{}^2}{s_{13}\sqrt{2-6s_{13}{}^2}}$$

- Leptonic Jarlskog invariant :

$$J_{CP}{}^2 = (\mathrm{Im}[U_{11}{}^{ST}U_{12}{}^{ST*}U_{21}{}^{ST}U_{11}{}^{ST*}])^2$$
$$= \frac{1}{12^2}(8s_{13}{}^2(1-3s_{13}{}^2) - \cos 2\theta_{23}\, s_{13}{}^2)$$

Estimations of LCPV

- Taking the same procedure described for case A,

Cases		$\cos\delta_D$	$\mathrm{J}_{\mathrm{CP}}^2$
B	$\frac{V_{21}-V_{31}}{V_{23}-V_{33}}=\frac{V_{11}}{V_{13}}$	$-\eta_{23}\frac{1-2s_{13}^2}{s_{13}\sqrt{2-3s_{13}^2}}$	$\frac{1}{6^2}[s_{13}^2(2-3s_{13}^2)-\kappa_{23}]$
C	$\frac{V_{12}-V_{11}}{V_{21}-V_{22}}=\frac{V_{13}}{V_{23}}$	$\eta_{12}\frac{1-3s_{13}^2}{s_{13}\sqrt{1-2s_{13}^2}}$	$\frac{1}{8^2}[4s_{13}^2(1-2s_{13}^2)-\kappa_{12}]$
D	$\frac{V_{11}-V_{12}}{V_{32}-V_{31}}=\frac{V_{13}}{V_{33}}$	$-\eta_{12}\frac{1-3s_{13}^2}{s_{13}\sqrt{1-2s_{13}^2}}$	$\frac{1}{8^2}[4s_{13}^2(1-2s_{13}^2)-\kappa_{12}]$

$$\eta_{ij}=\frac{1}{2\tan 2\theta_{ij}}\ \text{and}\ \kappa_{ij}=\cos^2 2\theta_{ij}\cdot c_{13}^4$$

Numerical Results

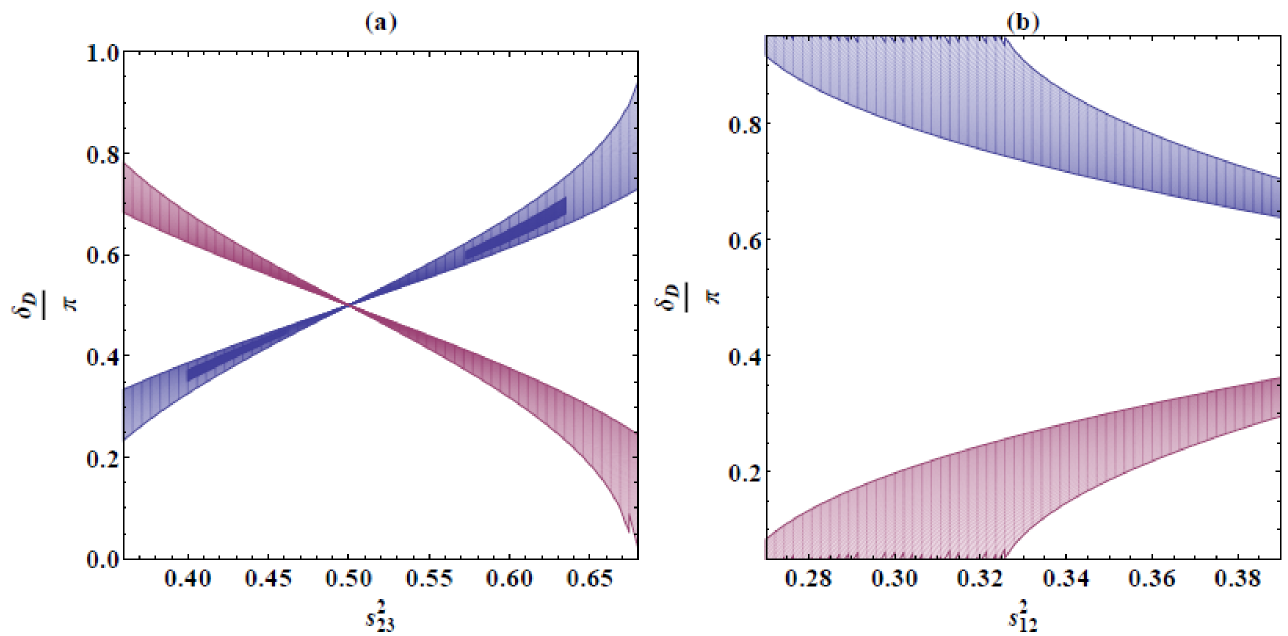


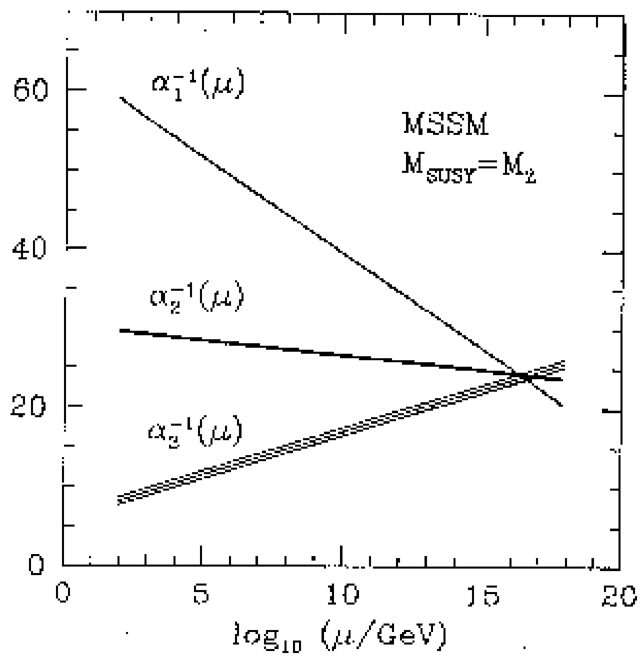
FIG. 1. Predictions of δ_D/π in terms of s_{23}^2 (l(a): Cases A and B) and s_{12}^2 ((b): Cases C and D) based on the experimental data given at 3σ C.L. and 1σ C.L. (only for Case–A). Regions in blue (red) correspond to Cases A and C (B and D).

Proton Decay

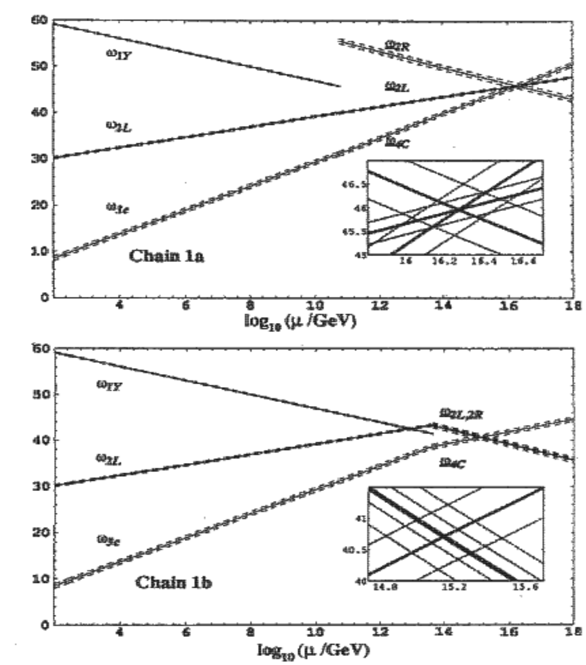
- The stability of the proton represents one of the greatest theoretical and experimental challenges in particle physics today.
- Most grand unified theories predict decay of the proton.
- Experimentally, however, the proton seems determined to outlive us all.

Hypothesis of Grand unification

- Grand unification is an interesting hypothesis which says that all forces and all matter become one at high E no matter how different they look at low E.
- Supporting the hypothesis of grand unification would be coupling unification at high energies:



Weak scale susy



Non SUSY SO(10) with seesaw

Almost all GUTs allow proton decay

- B and L numbers are conserved to very good precision in low-energy experiments. (accidental sym. in SM)
- These symmetries will likely be broken in beyond-SM theories, taken into account by new high-dimensional operators.
- In a typical GUT, quarks and leptons are placed in the same representation of some unification group.
  - SU(5) example; $F = (d_1, d_2, d_3, \nu, e)$
- Hence B and L numbers are no longer separately conse rved and proton is not absolutely stable!
- Decay product:
  - light leptons (μ, e, ν) + light mesons (π, K)
  - Example: $P \rightarrow \pi^0 + e^+$

- Coupling unification, $m_b = m_\tau$ often cited as evidence for GUTs are not really so.

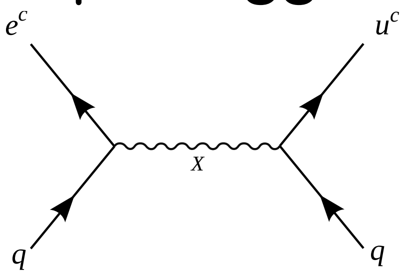
- But, true test of GUTs is proton decay;

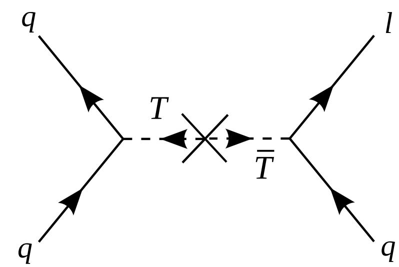
  In particular no proton decay to the level of $\mathbf{10^{36-37}}$ years will be evidence against GUTs.

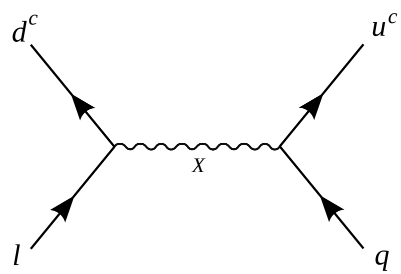
- Study of nucleon decay provides one of the few approaches to the problem of confronting grand unified theories with experimental data, and any progress toward this goal has unique value for the future development of physics.

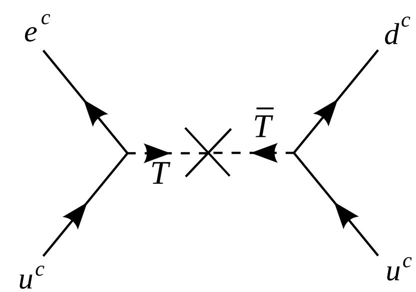
Non-SUSY-GUT

- In non-SUSY GUT, proton decay is mediated by X, Y gauge & triple Higgs:









- Dim-6 proton decay operators :

$$\frac{qql}{\Lambda^2}, \ \frac{d^c u^c u^c e^c}{\Lambda^2}, \ \frac{\overline{e^c u^c} qq}{\Lambda^2}, \ \frac{\overline{d^c u^c} ql}{\Lambda^2}$$

they violate B and L but not B-L

Non-SUSY-GUT

- Dominant decay mode $\boldsymbol{p \to e^+\pi^0}$
- The lifetime is simply,

$$\tau(\boldsymbol{p \to e^+\pi^0}) \sim M_G^4/(\alpha_G^2 m_p^5)$$

$$\tau/B(\boldsymbol{p \to e^+\pi^0}) \sim 10^{29\pm2} yr$$

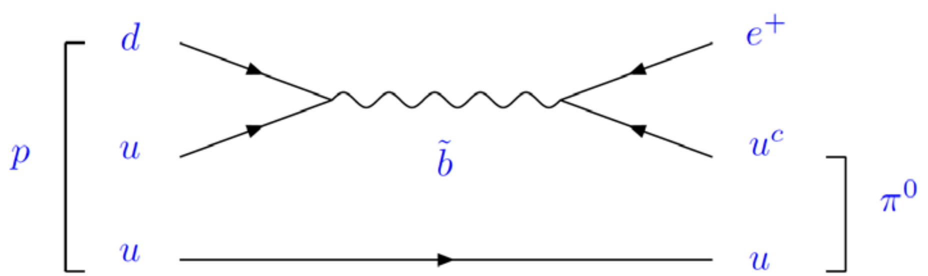
- Given a unified coupling and GUT scale, one can predict the lifetime, which can be tested immediately in experiments.
  - $(\tau/B(\boldsymbol{p \to e^+\pi^0}) > 1.6 \times 10^{34}$ yr, 90% CL) from SuperK
  - at least Non-SUSY SU(5) & min. SO(10) ruled out!
- Introducing SUSY increases GUT scale by x10, proton lifetime is increased by x10^4, suppressing dim-6 op.

SUSY-GUT

- Unlike SM, there are more dangerous terms which violate B and L.

$$W = \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$

– Dim. 4 proton decay operators

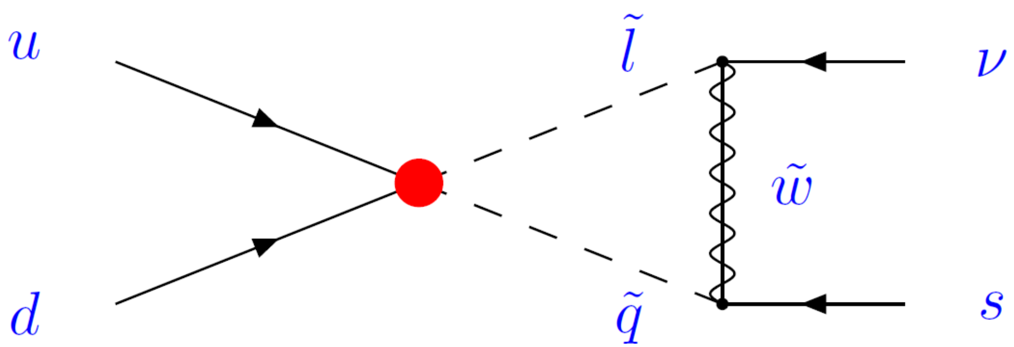


$$\propto \frac{1}{m_{\tilde{b}}^2}$$

- They either violate B or L, but not both, generating huge B and L number violations.
- To avoid fast proton decay, we impose R-parity .

SUSY-GUT

- **Effective Dimension-5 operator :**
  - There is a contribution to 4-fermion operators from a SUSY particle loop , called dim. "5 operators"



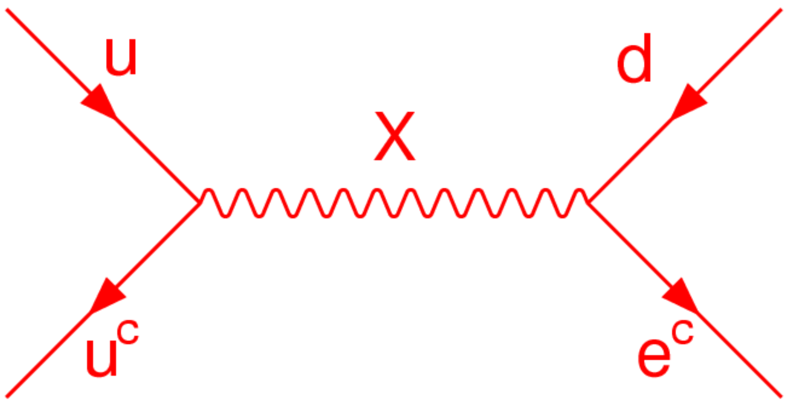
  - Such diagram gives rise to Dim.5 proton decay operators

$$QQQL, \quad u^c u^c d^c e^c$$

    - they are enhanced by $\frac{M_{hc}}{M_{SUSY}}$ compared to non-SUSY

SUSY-GUT

- Gauge Boson exchange:



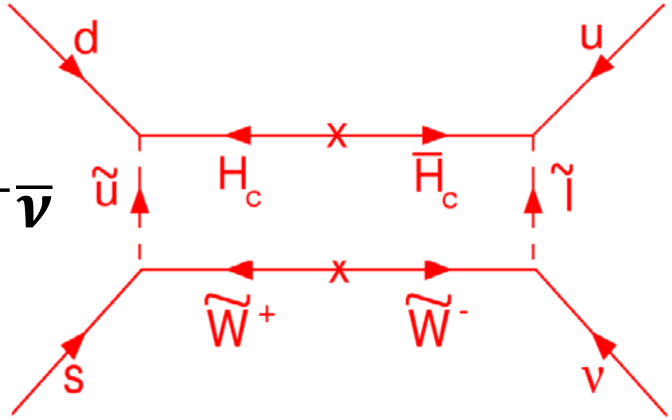
$$P \rightarrow e^{+}\pi^{0} \qquad \tau(P \rightarrow e^{+}\pi^{0}) \cong \frac{M_X^4}{g^4\, m_p^5} \sim 10^{36\pm1} yrs$$

SUSY SU(5)

- Unification of the gauge coupling constants depends on the color−triplet threshold.
- At two−loop level, this gives a constraint for the success of unification: 3.5×10^{14} GeV $< M_C < 3.6 \times 10^{15}$ GeV

$$O_{p-decay} \cong \frac{1}{M_U} QQ\tilde{Q}\tilde{L}$$

$$p \to K^+ \overline{\nu}$$



$$\tau^{-1} \sim [Y^2/(M_c\, M_{SUSY})]^2$$

- p $\to K^+\nu$ limit constraints the mass scale to be

$$M_C > 2 \times 10^{17} \text{ GeV}$$

- The conflict rules out the simple SUSY SU(5)

SO(10) models

- There are many SO(10) models which claim to fit all fermion masses, mixings including ν mixing matrix.

- Generally they predict fast proton decay rates, but

- In SO(10) where B−L is broken by 16_H , SU(5) type problem avoided due to cancellation between diagrams.

$$\tau(p \to \bar{\nu} K^+) \lesssim 10^{34} \text{ yr}$$
$$Br(p \to \mu^+ K^0) \sim 10\%$$

(Babu, Pati and Wilczek)

- Recent theoretical works suggest that if SUSY SO(10) provides the framework for GUT, the proton lifetime (into the favored νK^+ decay mode) must lie within about one order of magnitude of present limits.

Experiments

- The search for nucleon decay requires massive detectors.
- A search with a sensitivity of 10^{35} years, for example, requires a detector with approximately 10^{35} nucleons.
- Since there are 6×10^{29} nucleons per ton of material, this implies detectors of a few 100 kiloton scale.
- The "classical" proton decay mode, $p \to e+ \pi^0$, can be efficiently detected with low background.
- At present, the best limit on this mode ($\tau/B > 1.6 \times 10^{34}$ yr, 90% CL) comes from a 0.306 Mt–yr exposure of SK.
- SUSY theories favor $p \to \nu K^+$, which is experimentally more difficult due to the unobservable neutrino.
- The present combined limit is $\tau/B > 5.9 \times 10^{33}$yr (90% CL) from a 0.260 Mt–yr exposure.

Experiments

Detector	type	Exposure (kt−year)
Frejus	Fe	2.0
HPW	H_2O	<1.0
IMB	H_2O	11.2
Kamiokande	H_2O	3.8
KGF	Fe	<1.0
NUSEX	Fe	<1.0
Soudan 1	Fe	<1.0
Soudan 2	Fe	5.9
Super−Kamiokande	H_2O	79.3

4×10^{32}

Future experimental opportunities

- Japan: Hyper–K
- US: DUSEL (UNO or LAr)
- Europe: 100 kt LAr TPC, 1Mt WC detector at Frejus.

- Next Generation $\rightarrow 10^{35}$yr $\rightarrow$ >300Kton H_20

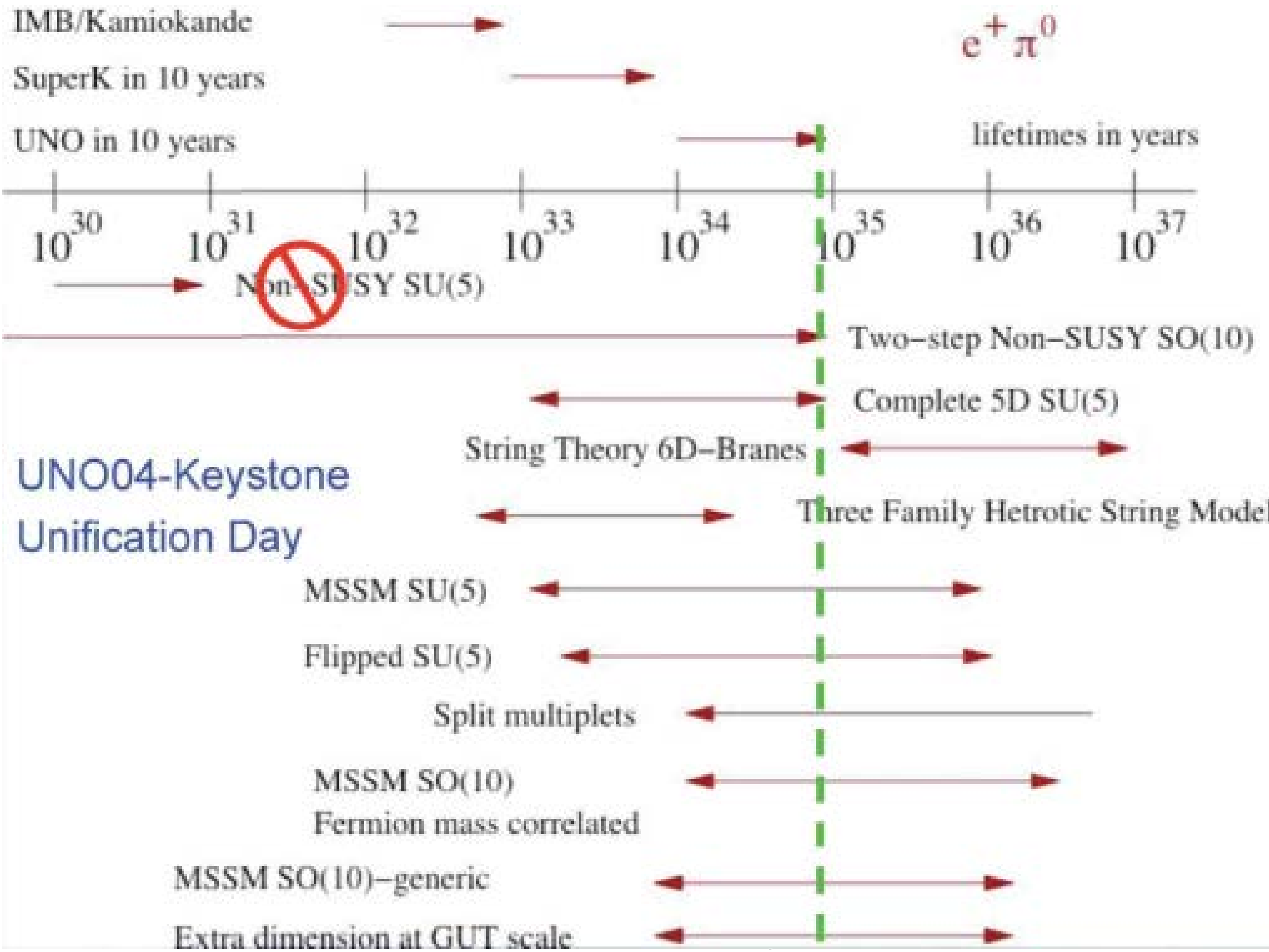
  ➔ approaching to test SUSY GUTS $\tau(p \rightarrow e^+\pi^0)$

  $\approx 10^{35}(m_X/10^{16}\text{GeV})^4$yr

  e.g. UNO Proposal 500Kton H_2O (22xSuperK)

  Homestake 300Kton H_2O (Phase I)

Exp. vs. theory



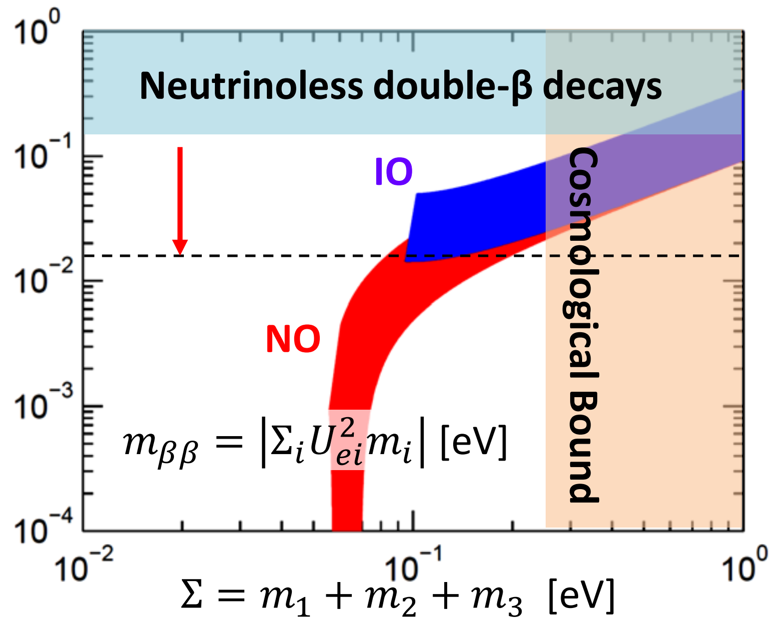
- Opportunist:

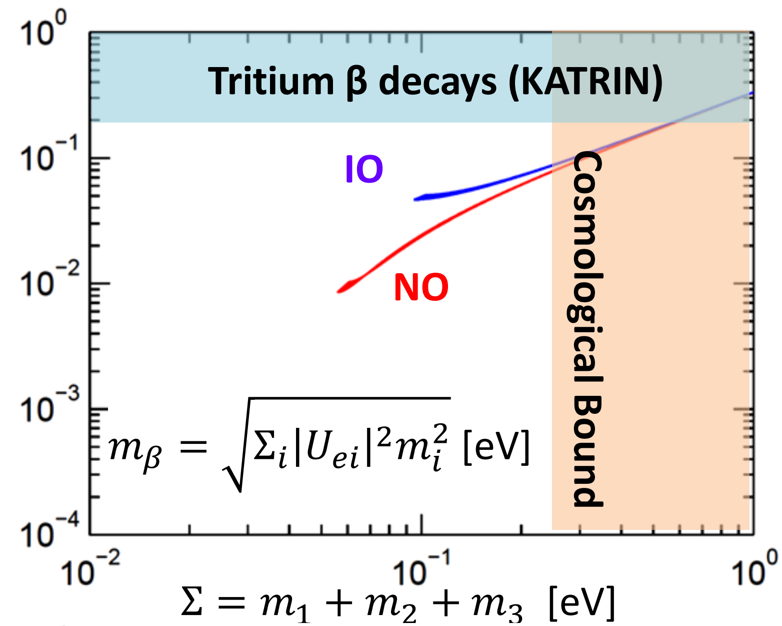
  Neutrino mass and proton decay probe physcs at extremely high-energy scale, otherwise unreachable using the conventional particle accelerator.
- Pragmatist:

  Whatever the new physics might be, one can always probe the low-energy B/L number violating limit, which might or might not be signals for GUT.

- Recent theoretical work suggests that if super-symmetric SO(10) provides the framework for grand-unification, the proton lifetime (into the favored νK^+ decay mode) must lie within about one order of magnitude of present limits. Similarly, SO(10) theories suggest $\tau/\beta(e\pi^0) \approx 10^{35}$ years—about a factor of ten beyond the present limit.

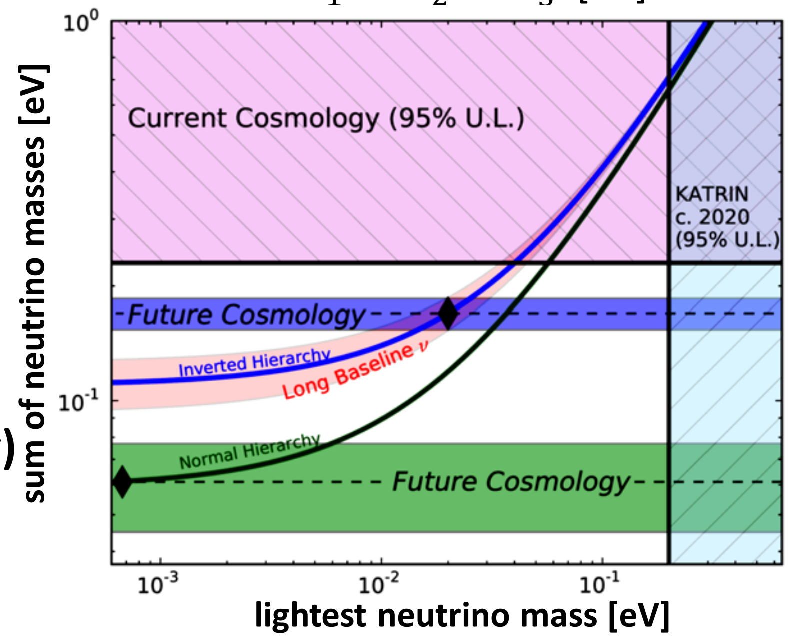
Fundamental Properties of Neutrinos: *absolute masses*





Constraints on absolute neutrino masses

- **Tritium β decays (95% C.L.)**
  $m_\beta < 2.3$ eV (Mainz)
  2.1 eV (Troitzk)
- **Neutrinoless double-β decays (90% C.L.)**
  $m_{\beta\beta} < (0.15 \sim 0.52)$ eV (KamLAND-Zen)
  $(0.22 \sim 0.64)$ eV (GERDA)
- **Cosmological observations (95% probability)**
  $\Sigma < 0.23$ eV (Planck)



Abazajian et al., 15; See van Eijndhoven's talk