Neutrino physics (theory & phenomenology)

Gabriela Barenboim
U.Valencia and IFIC

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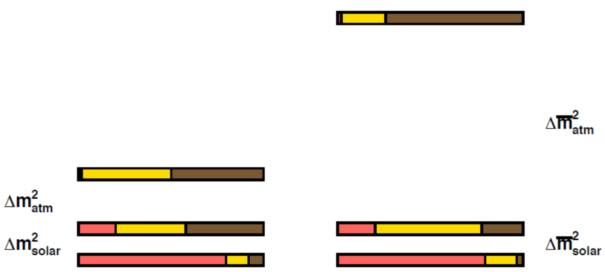
ν_{III}

HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

CPT violation



$$\frac{|\ m(K_0)\ - m(\overline{K_0}\ )\ |}{m_{K-av}} < 10^{-18}$$

$$m_{K-av} \approx \frac{1}{2}\ 10^9\ \text{eV}$$

$$(m(K_0) - m(\overline{K_0}\ )\ )(m(K_0) + m(\overline{K_0}\ )) < 2\ \ 10^{-18}\, m_{K-av}{}^2$$

$$|m^2(K_0)\ - m^2(\overline{K_0}\ )| \approx \frac{1}{2}\ \text{eV}^{\,2}$$

CPT tests

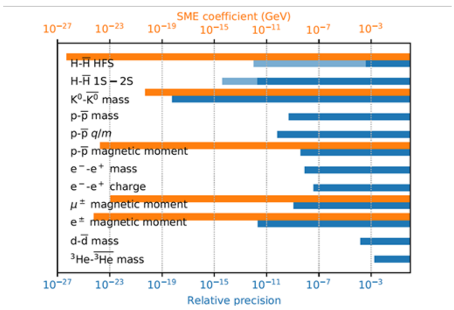
CPT invariance tested in several matter-antimatter systems:

neutral kaons

electron/positron

proton/antiproton

H/anti-H



E. Widmann, arXiv:2111.04056 [hep-ex]

Several experiments at the Antiproton Decelerator and ELENA(Extra Low Energy Antiproton) @CERN

Current bounds

- We can use data of various experiments to calculate the neutrino and antineutrino oscillation parameters:
  - Solar neutrino data: $\theta_{12}, \Delta m^2_{21}, \theta_{13}$
  - Neutrino mode in LBL: $\theta_{23}, \Delta m^2_{31}, \theta_{13}$
  - KamLAND data: $\overline{\theta}_{12}, \Delta \overline{m}^2_{21}, \overline{\theta}_{13}$
  - SBL reactors: $\overline{\theta}_{13}, \Delta \overline{m}^2_{31}$
  - Antineutrino mode in LBL: $\overline{\theta}_{23}, \Delta \overline{m}^2_{31}, \overline{\theta}_{13}$
- No bounds on CP-phases since all values are allowed

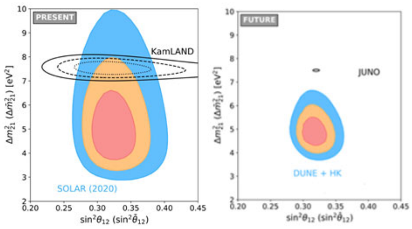
Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\|\Delta m^2_{31}\|$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

Current bounds

- We use the same data (except atmospheric neutrinos) as for the global fit to obtain

$$
\begin{aligned}
|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| &< 4.7 \times 10^{-5}\ \mathrm{eV}^2, \\
|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| &< 2.5 \times 10^{-4}\ \mathrm{eV}^2, \\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14, \\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.029, \\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.19.
\end{aligned}
$$



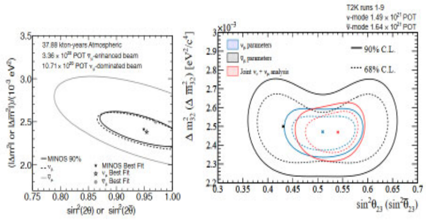
T2K results, a hint ?

- T2K studied neutrino and anti-neutrino oscillations separated

$$\sin^2\theta_{23} = 0.51, \quad \Delta m^2_{32} = 2.53 \times 10^{-3}\text{eV}^2$$

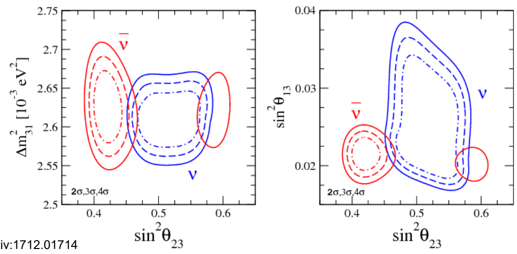
$$\sin^2\overline{\theta}_{23} = 0.42, \quad \Delta \overline{m}^2_{32} = 2.55 \times 10^{-3}\text{eV}^2$$

- Results are consistent with
- CPT-conservation



DUNE about T2K

If these values turn out to be the true values, DUNE would measure CPT-violation at more than 3σ confidence level



ArXiv:1712.01714

- In experiments and in fits normally you assume CPT-conservation
- If CPT is not conserved this leads to impostor (fake) solutions in the fits
- To perform the standard fit you would calculate

$$\chi^2_{\rm total} = \chi^2(\nu) + \chi^2(\overline{\nu})$$

and then minimize this function

$$h(x,y) = f(x) + g(y)$$

$$\partial_x f(x) = 0 \qquad \partial_y g(y) = 0$$

$$x = y$$

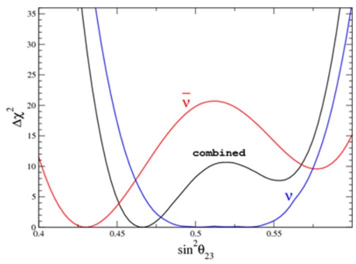
$$h(x) = f(x) + g(x)$$

$$\partial_x f(x) = \partial_x g(x) = 0$$

$$\partial_x f(x) = -\partial_x g(x)$$

Obtaining impostor solutions

- This was done for $\sin^2(\theta_{23}) = 0.5, \sin^2(\overline{\theta}_{23}) = 0.43$

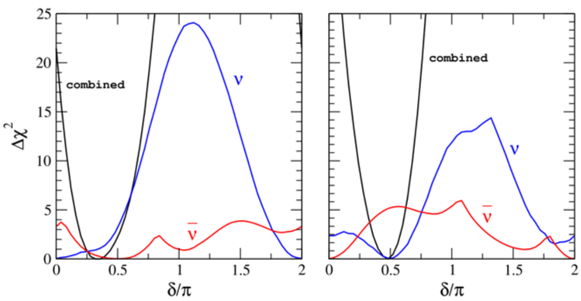


Combined best fit value is now $\sin^2(\theta_{23}^{\text{comb}}) = 0.467$

Real true values are disfavored at close to 3σ and more 5σ confidence levels

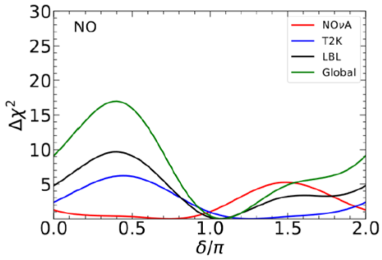
This can also happen

$\delta = \begin{cases} \pi/2 \\ 0 \end{cases}$ and $\bar{\delta} = \begin{cases} 0 \\ \pi/2 \end{cases}$



G.B., C. Ternes and M. Tortola, JHEP 07 (2020) 155

$\theta_{13} \neq \theta_{13}$ can account for different behavior in neutrino and antineutrino channels

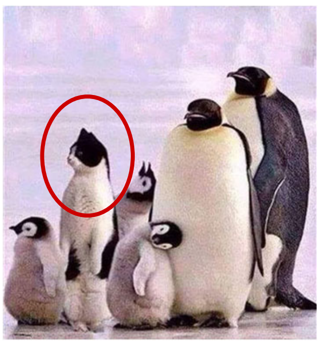


Tension between NOvA, T2K and SK atm. and $\delta_{bf} = 1.08\pi$

- Disfavours:
  - $\delta = \pi/2$ at 4.0σ
  - $\delta = 0$ at 3.0σ
  - $\delta = 3\pi/2$ with $\Delta\chi^2 = 4.9$

all values of δ and $\bar{\delta}$ remain allowed at ~ 1σ

The increasing precision in neutrino oscillation measurements requires a thorough analysis of the assumptions considered.



Distinguishing CPT violation from NSNI

The muon neutrino survival probability in matter can be written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_\nu \sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right).$$

in matter

$$\begin{aligned}\Delta m_\nu^2 \cos 2\theta_\nu &= \Delta m^2 \cos 2\theta + \epsilon_{\tau\tau} A\,, \\ \Delta m_\nu^2 \sin 2\theta_\nu &= \Delta m^2 \sin 2\theta + 2\epsilon_{\mu\tau} A\,.\end{aligned}$$

$$\begin{aligned}\Delta m_{\bar\nu}^2 \cos 2\theta_{\bar\nu} &= \Delta m^2 \cos 2\theta - \epsilon_{\tau\tau} A\,, \\ \Delta m_{\bar\nu}^2 \sin 2\theta_{\bar\nu} &= \Delta m^2 \sin 2\theta - 2\epsilon_{\mu\tau} A\,.\end{aligned}$$

$$4\Delta m^4 = \Delta m_\nu^4 + \Delta m_{\bar\nu}^4 + 2\Delta m_\nu^2 \Delta m_{\bar\nu}^2 \cos(2\theta_\nu - 2\theta_{\bar\nu})$$

$$\sin^2(2\theta) = \frac{(\Delta m_\nu^2 \sin(2\theta_\nu) + \Delta m_{\bar\nu}^2 \sin(2\theta_{\bar\nu}))^2}{\Delta m_\nu^4 + \Delta m_{\bar\nu}^4 + 2\Delta m_\nu^2 \Delta m_{\bar\nu}^2 \cos(2\theta_\nu - 2\theta_{\bar\nu})}$$

$$\begin{aligned}2\epsilon_{\tau\tau}^m A &= \Delta m_\nu^2 \cos(2\theta_\nu) - \Delta m_{\bar\nu}^2 \cos(2\theta_{\bar\nu}) \\ 4\epsilon_{\mu\tau}^m A &= \Delta m_\nu^2 \sin(2\theta_\nu) - \Delta m_{\bar\nu}^2 \sin(2\theta_{\bar\nu})\end{aligned}$$

G.B., C. Ternes and M. Tortola, Eur.Phys.J.C 79 (2019) 5, 390

Violations of Lorentz invariance

Lorentz violation

$$(h_{\rm eff})_{ab} = \frac{m_{ab}^2}{2E} + \frac{1}{E}\left[(a_L)^\alpha p_\alpha - (c_L)^{\alpha\beta} p_\alpha p_\beta\right]_{ab}$$

standard Lorentz covariant term

violates both CPT and Lorentz invariance

Violations of Lorentz invariance

Lorentz violation

$$(h_{\text{eff}})_{ab} = \frac{m^2_{ab}}{2E} + \frac{1}{E}\left[(a_L)^{\alpha} p_{\alpha} - (c_L)^{\alpha\beta} p_{\alpha} p_{\beta}\right]_{ab}$$

standard Lorentz covariant term

violates both CPT and Lorentz invariance

As usual, the oscillation probability is governed by the difference of the eigenvalues of the effective hamiltonian.

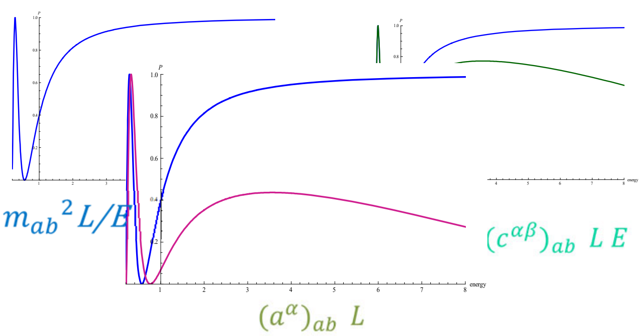
$$\sin^2(\Delta_{ab}\ \ L/2)$$

$m_{ab}{}^2 L/E$

$(a^{\alpha})_{ab}\ \ L$

$(c^{\alpha\beta})_{ab}\ \ L\,E$

$$P(\nu_{\mu} \to \nu_{\mu}) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$



Neutrinos,
In and Beyond the Standard Model:

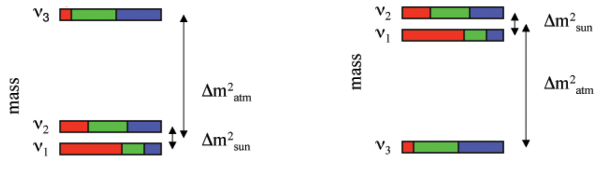
NEUTRINO MASS:

$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2 \qquad L/E = 500\ km/GeV$$

$$\delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2 \qquad L/E = 15\ km/MeV$$

$$\Downarrow$$

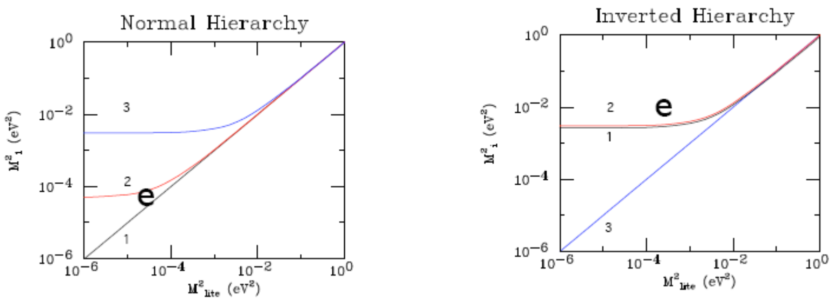
$$m_\nu^{Heavy} > \sqrt{\delta m^2_{atm}} = 50 meV$$



Normal mass hierarchy

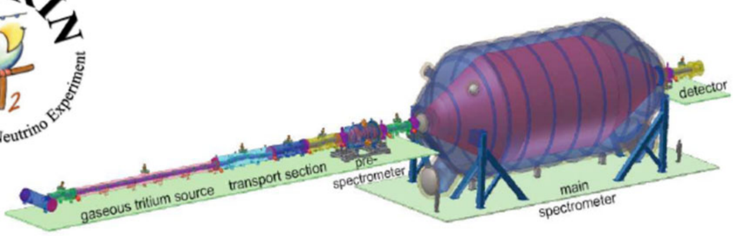
Inverted mass hierarchy

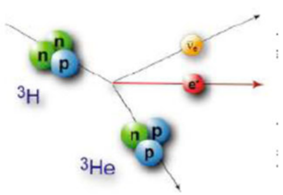
Masses:



States 1 and 2 are ν_e rich.

KATRIN
Karlsruhe Tritium Neutrino Experiment

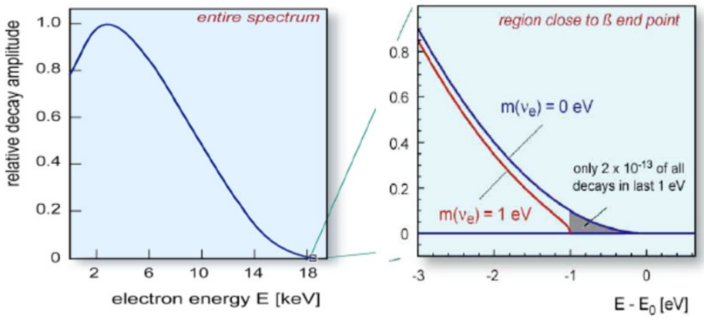




Requirements:
- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)



Decay Rate:

$$|\langle ^3He + e^- + \bar{\nu}|T|^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

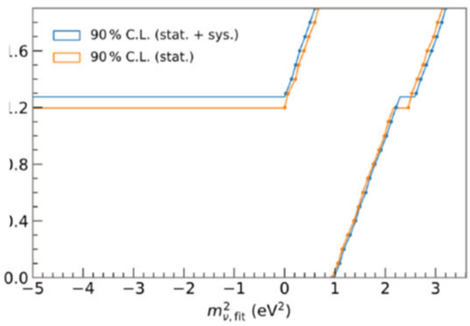
if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

$$|\langle ^3He + e^- + \bar{\nu}|T|^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

- **KATRIN upper limit on neutrino mass:**

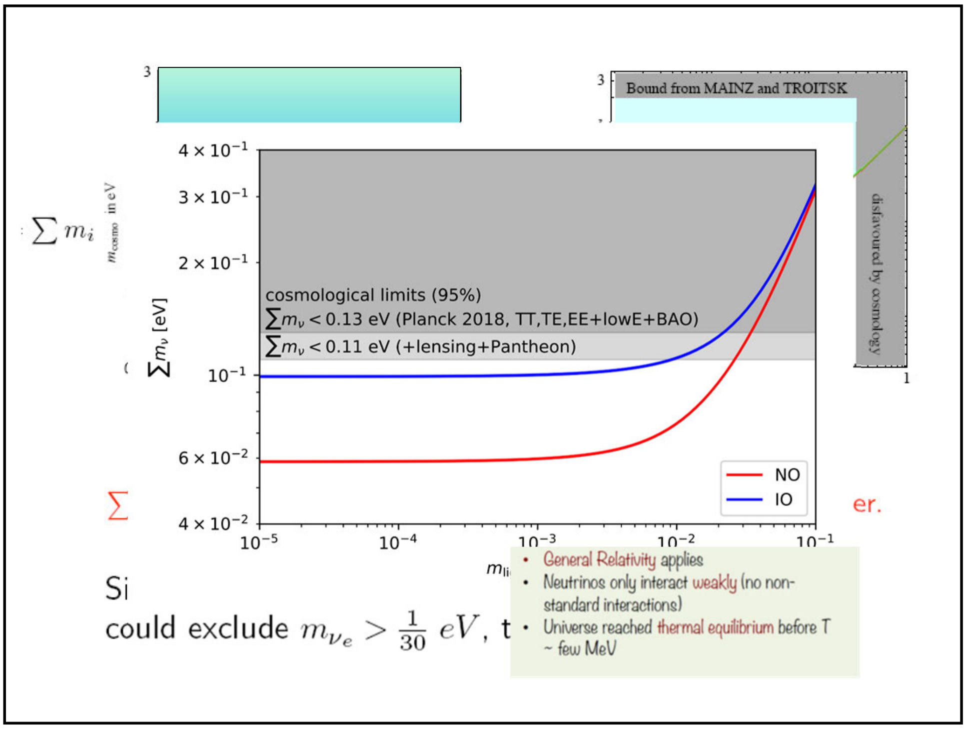
LT m(ν) < 1.1 eV (90% CL)

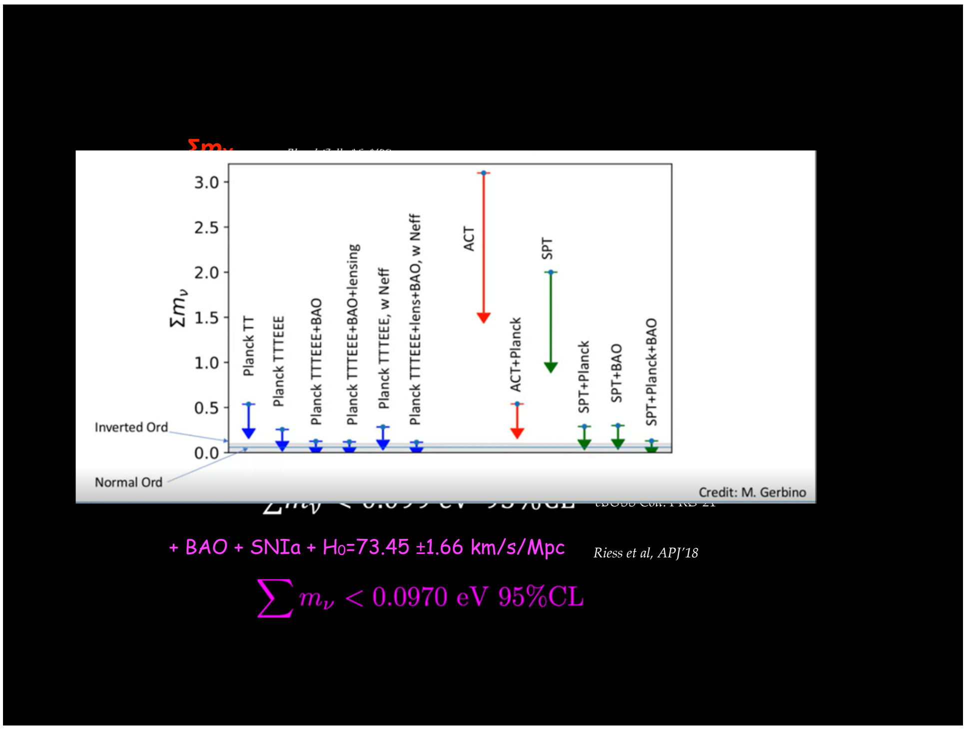
FC m(ν) < 0.8 eV (90% CL)
< 0.9 eV (95% CL)



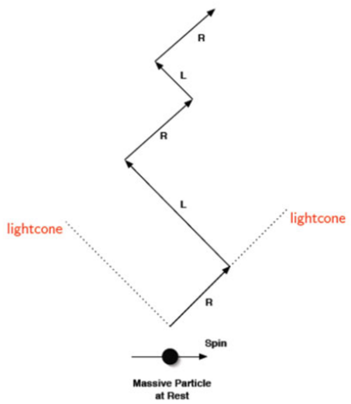
- **1000 days of measurements** at
nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2})
3 tritium campaigns (65 days each)
per calendar year

sensitivity m(ν_e) = 0.2 eV (90% CL)
0.35 eV (5σ)


Bound from MAINZ and TROITSK
disfavoured by cosmology
cosmological limits (95%)
$\sum m_\nu < 0.13$ eV (Planck 2018, TT,TE,EE+lowE+BAO)
$\sum m_\nu < 0.11$ eV (+lensing+Pantheon)
$\sum m_\nu$ [eV]
$\sum m_i$
NO
IO
er.
Si
could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, t
General Relativity applies
Neutrinos only interact weakly (no non-standard interactions)
Universe reached thermal equilibrium before T ~ few MeV


Σm_ν
Planck TT
Planck TTTEEE
Planck TTTEEE+BAO
Planck TTTEEE+BAO+lensing
Planck TTTEEE, w Neff
Planck TTTEEE+lens+BAO, w Neff
ACT
ACT+Planck
SPT
SPT+Planck
SPT+BAO
SPT+Planck+BAO
Inverted Ord
Normal Ord
Credit: M. Gerbino
+ BAO + SNIa + H0=73.45 ±1.66 km/s/Mpc
Riess et al, APJ'18
$\sum m_\nu < 0.0970$ eV 95%CL

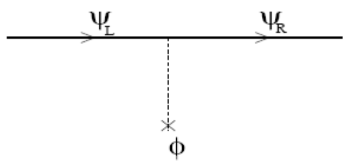
What is Fermion Mass ???



A mass can be thought of as a $L \leftrightarrow R$ transition:

$$m\,\overline{\psi_L}\psi_R + h.c.$$

In the SM fermion masses originate in the interaction with the Higgs field:



$$\lambda_f\,\overline{\psi_L}\,\Phi\,\psi_R + h.c. \rightarrow m_f = \lambda_f\,v$$

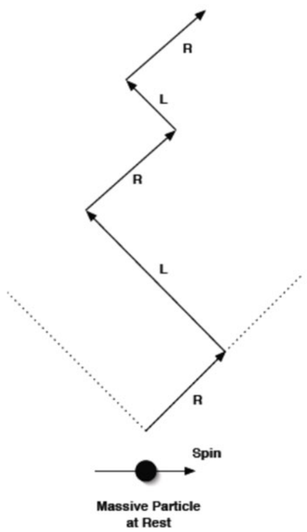
Fermion Masses:

	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)

CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.



Mass couples L to R:

$$P^2 = M^2, \quad P \cdot S = 0 \quad and \quad S^2 = -1$$

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless left massless

A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu	CPT:	Anti-Nu	
Left Chiral	$\boldsymbol{\nu_L}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_R}$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	$\boldsymbol{\nu_R}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_L}$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

ν_L to $\bar{\nu}_R$ $\qquad$ ν_L to ν_R

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$\bar{\nu}_R$ to $\bar{\nu}_L$ $\qquad$ ν_R to $\bar{\nu}_L$

Two Majorana neutrinos
with masses m_D^2/M and M

Seesaw:
Yanagida, Gell-man-Ramond-Slansky

- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

Also applies to sterile neutrinos.

Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

The consequences of this alternative are profound:

- Physics beyond the SM at a scale M!
- Majorana fermions carry no conserved charge: L is violated !

$$\nu_L \to e^{i\alpha}\nu_L$$

does not leave the Majorana mass term invariant.
→ Most welcome for baryogenesis: a mechanism to understand the matter-antimatter asymmetry in the Universe emerges naturally
→ Most welcome by string theory: it is difficult to get global $U(1)$ charges conserved

Leptogenesis

Baryon Asymmetry is created by a Lepton Asymmetry produced by the decays of super heavy Majorana Neutrinos.

$$\frac{\Gamma(N \to l^+\phi^-) - \Gamma(N \to l^-\phi^+)}{\Gamma(N \to l^+\phi^-) + \Gamma(N \to l^-\phi^+)}$$

$\Gamma(N \to l^{\pm}\phi^{\mp})$ depends on the Majorana Phases in the MNS mixing matrix.

$$B_{now} = \frac{1}{2}(B-L) + \frac{1}{2}(B+L) = \frac{1}{2}(B-L)_{ini} = -\frac{1}{2}L_{ini}$$

0

Final asymmetry:

$$Y_B = 10^{-2} \overbrace{\epsilon_1}^{\mathrm{CP-asym}} \overbrace{\kappa}^{\mathrm{eff.\ factor}}$$

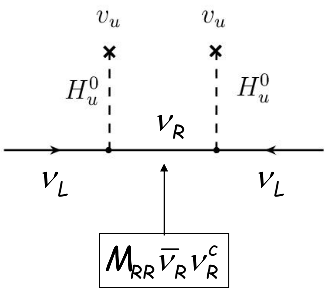
$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

κ efficiency factor which depends on the non-equilibrium dynamics.

A relation between the baryon number of the Universe and the neutrino flavour parameters!

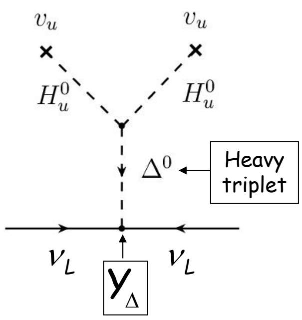
Types of see-saw mechanism

Type I see-saw mechanism



$$m_{LL}^{I} \approx -m_{LR} M_{RR}^{-1} m_{LR}^{T}$$

Type II see-saw mechanism

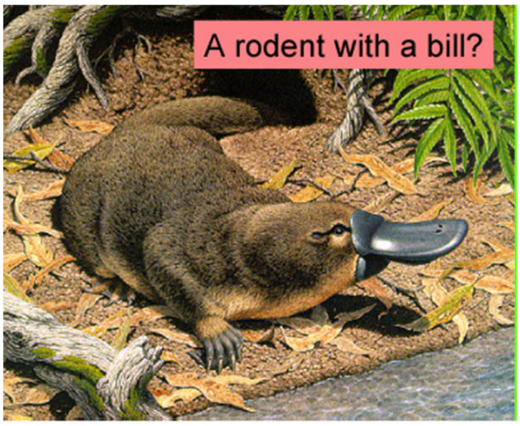


$$m_{LL}^{II}\,\bar{\nu}_L\nu_L^c \approx Y_\Delta \frac{v_u^2}{M_\Delta}$$

Naturalness may be over rated …

Does this look natural ??

næbdyr

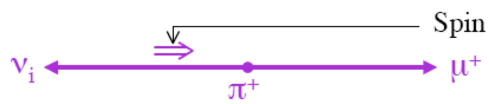


How Can We Demonstrate That $\bar{\nu}_i = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \to \ell^-$; $\bar{\nu} \to \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

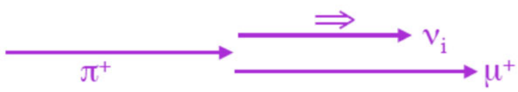
Produce a ν_i via—



Pion Rest Frame

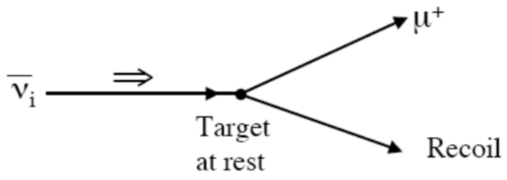
Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$



Lab. Frame

The SM weak interaction causes—



$\nu_i = \overline{\nu}_i$ means that $\nu_i(h) = \overline{\nu}_i(h)$.

helicity

If $\nu_i \xrightarrow{\Rightarrow} \; = \; \overline{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

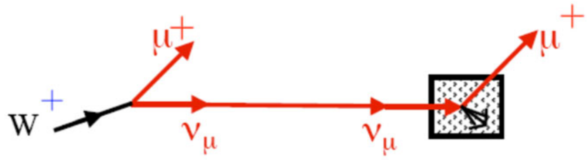
$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi \text{ (Lab)} > 10^4 \text{ TeV} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

Fraction of all π–decay that get helicity flipped

$$\approx \left(\frac{m_\nu}{E_\nu(\pi \text{ Rest Frame})} \right)^2 \sim 10^{-16} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

For Majorana Neutrinos

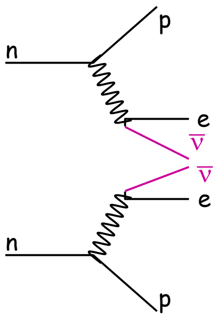


Not Observed

Allowed

BUT Suppressed by $\frac{m_\nu^2}{E^2} \sim 10^{-20}$!!!

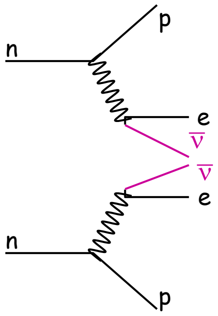
➢ How we can find out ?

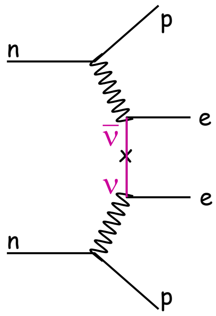


SM double weak process

4 body decay: continuos spectrum for the e energy sum

➢ How we can find out ?





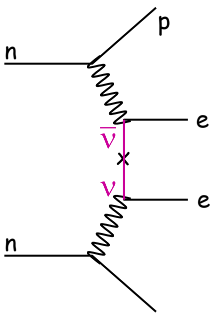
SM double weak process

4 body decay: continuos spectrum for the e energy sum

Only allowed for Majorana ν

2 body decay: e energy sum is a delta

$\bar{\nu}_i$ is emitted (RH + $O(m_i/E)$ LH)



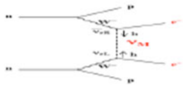
Amp[ν_i contribution] ~ m_i

$$\text{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right|$$

effective mass

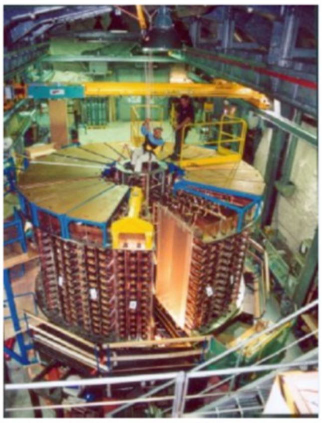
Neutrinoless double beta decay

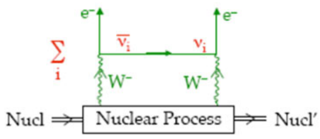
- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

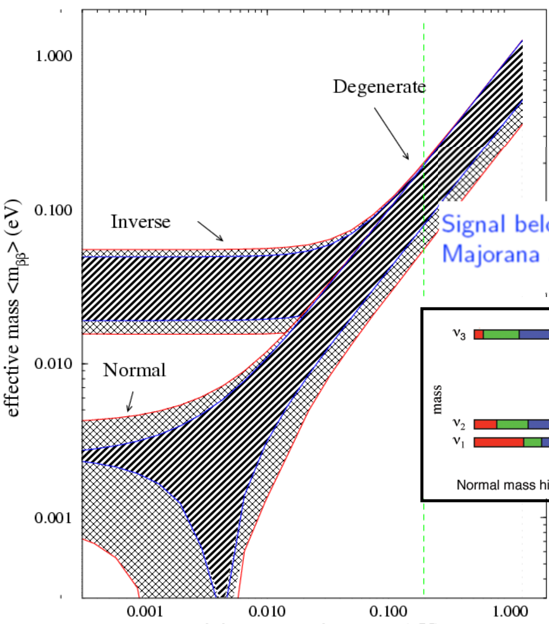
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$





Effective neutrino mass in 0ν ββ decay

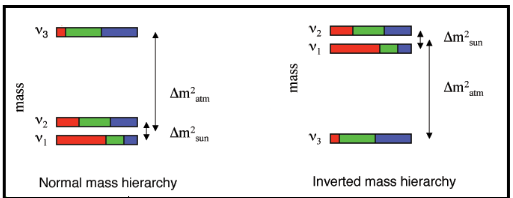
LMA solution, crosshatched region with errors



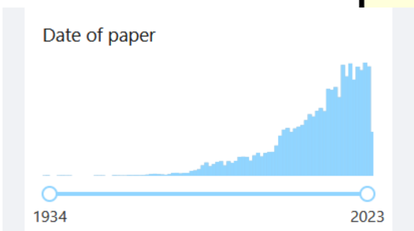
$m_{\beta\beta} = | \sum m_i U_{ei}^2 |$

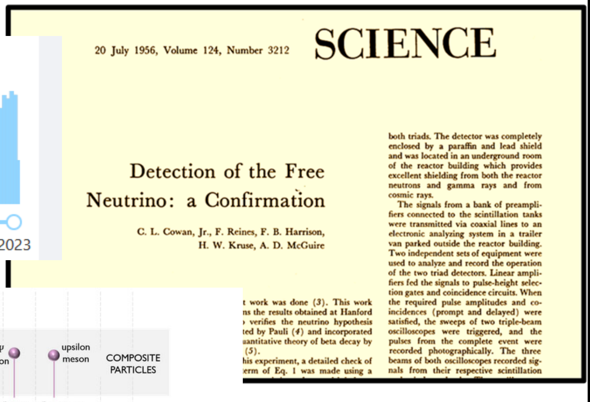
dividing point $m_{\beta\beta} \approx 10meV$

Signal below ~ 10 meV would imply Majorana and Normal Hierarchy!



NEUTRINOS AGE WELL





20 July 1956, Volume 124, Number 3212 **SCIENCE**

Detection of the Free Neutrino: a Confirmation

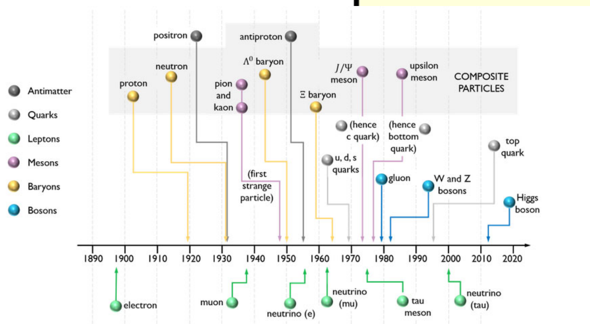
C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

t work was done (3). This work ns the results obtained at Hanford verifies the neutrino hypothesis ted by Pauli (4) and incorporated uantitative theory of beta decay by (5).

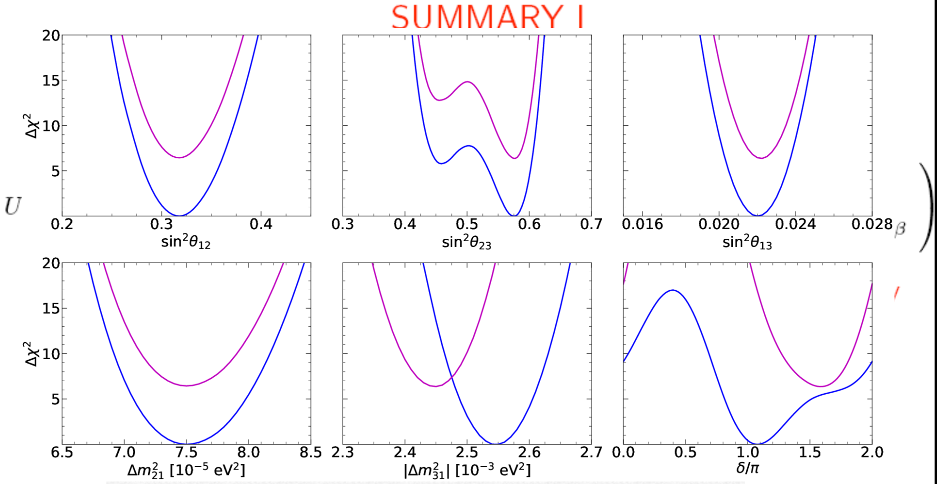
his experiment, a detailed check of erm of Eq. 1 was made using a

both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

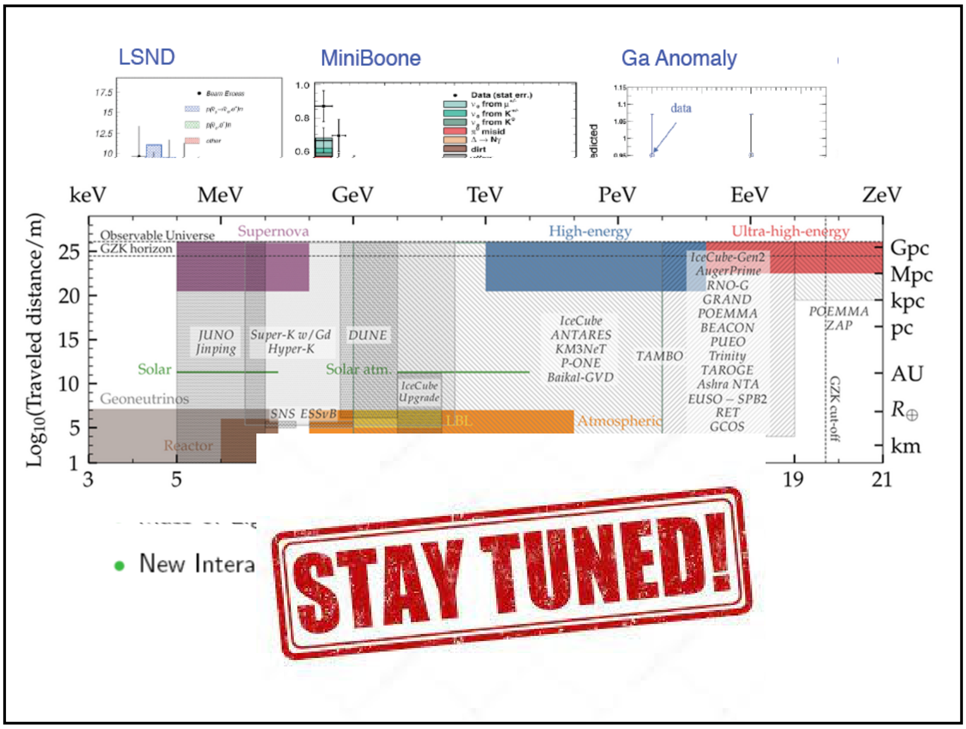
The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation



SUMMARY I



$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ_{CP}/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ_{CP}/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96


LSND
MiniBoone
Ga Anomaly
keV
MeV
GeV
TeV
PeV
EeV
ZeV
Log10(Traveled distance/m)
Observable Universe
GZK horizon
Supernova
High-energy
Ultra-high-energy
Gpc
Mpc
kpc
pc
AU
km
JUNO Jinping
Super-K w/Gd Hyper-K
DUNE
Solar
Solar atm.
IceCube Upgrade
Geoneutrinos
SNS ESSνB
Reactor
LBL
Atmospheric
IceCube ANTARES KM3NeT P-ONE Baikal-GVD
TAMBO
IceCube-Gen2 AugerPrime RNO-G GRAND POEMMA BEACON PUEO Trinity TAROGE Ashra NTA EUSO – SPB2 RET GCOS
POEMMA ZAP
GZK cut-off
New Intera
STAY TUNED!