Neutrino Oscillations and Beyond Standard Model Physics

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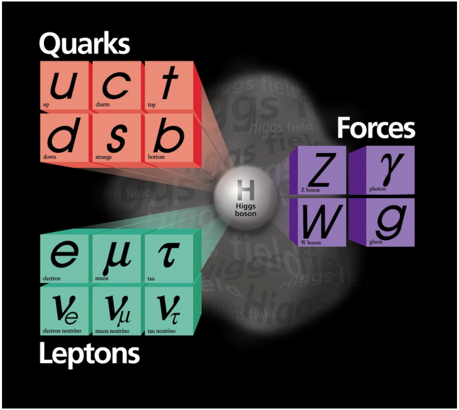
The Standard Model of particle physics



Neutrinos are special

- very light (neutrino mass $\lesssim 10^{-6}$ electron mass)
- the only (electrically) neutral fermions
  feel only the weak force and gravitation
- most abundant fermion in the Universe
  336 cosmic neutrinos/cm^3 (comparable to 411 CMB photons/cm^3)
- every second 10^{14} neutrinos from the Sun pass through your body
- neutrinos play a crucial role for
  - energy production in the Sun
  - nucleo sysnthesis: BBN, SN
  - generating the baryon asymmetry of the Universe (maybe)

- In the Standard Model neutrinos are massless.
- The observation of neutrino oscillations implies that neutrinos have non-zero mass.

$\Rightarrow$ Neutrino mass implies physics beyond the Standard Model.

Outline

Neutrino oscillations

Absolute neutrino mass

How to give mass to neutrinos

Final remarks

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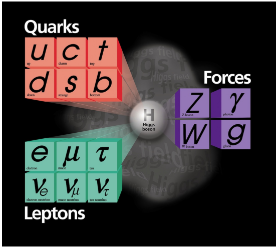
Flavour neutrinos



neutrinos are "partners" of the charged leptons
(doublet under the SU(2) gauge symmetry)

- A neutrino of flavour α is defined by the charged current interaction with the corresponding charged lepton, ex.:

$$\pi^+ \to \mu^+ \nu_\mu$$

the muon neutrino ν_μ comes together with the charged muon μ^+

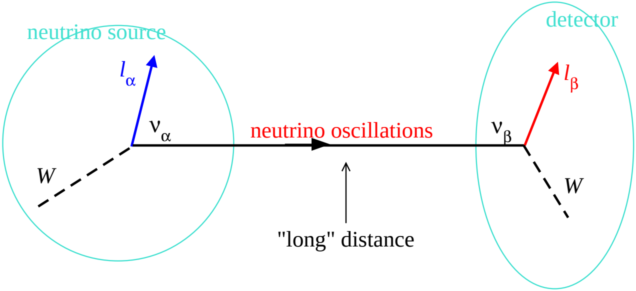
Lepton mixing

- Flavour neutrinos ν_α are superpositions of massive neutrinos ν_i:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i \qquad (\alpha = e, \mu, \tau)$$

- $U_{\alpha i}$: unitary lepton mixing matrix:
  Pontecorvo-Maki-Nakagawa-Sakata (PMNS)
- mismatch between mass and interaction basis
- in complete analogy to the CKM matrix in the quark sector

Neutrino oscillations



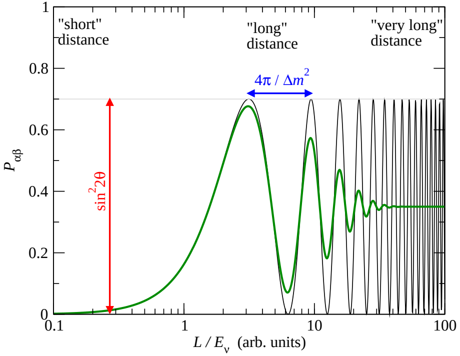
$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$ $\quad e^{-i(E_i t - p_i x)}$ $\quad |\nu_\beta\rangle = U^*_{\beta i}|\nu_i\rangle$

$$\begin{aligned} \mathcal{A}_{\nu_\alpha\to\nu_\beta} &= \langle\nu_\beta|\ \text{propagation}|\nu_\alpha\rangle = \sum_i U_{\beta i} U^*_{\alpha i} e^{-i(E_i t - p_i x)} \\ P_{\nu_\alpha\to\nu_\beta} &= \left|\mathcal{A}_{\nu_\alpha\to\nu_\beta}\right|^2 \end{aligned}$$

Neutrino oscillations: 2-flavour limit

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

$\Delta m^2 = m_2^2 - m_1^2$ $\quad \rightarrow$ oscillations are sensitive to mass differences



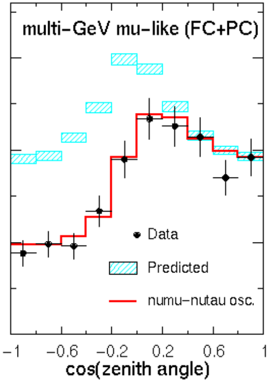
$$\frac{\Delta m^2 L}{4E_\nu} = 1.27 \frac{\Delta m^2[\mathrm{eV}^2] \, L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}$$

Neutrinos oscillate!

- atmospheric neutrinos Super-Kamiokande

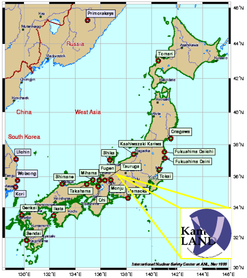
1998: strong zenith angle dependence of the observed flux of ν_μ

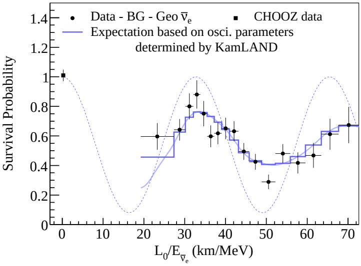
consistent with $\nu_\mu \to \nu_\tau$ oscillations



Neutrinos oscillate!

KamLAND reactor neutrino experiment ($\bar{\nu}_e \to \bar{\nu}_e$)





2004: evidence for spectral distortion

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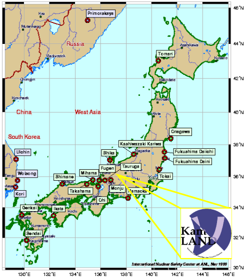

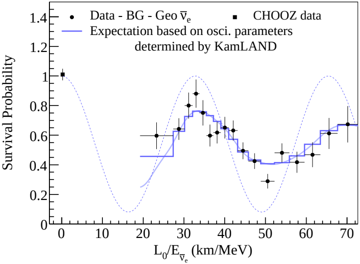

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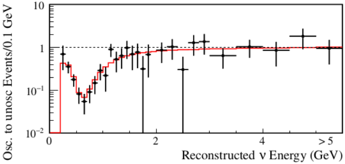
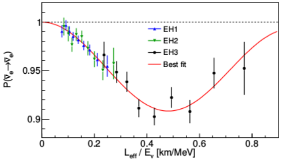


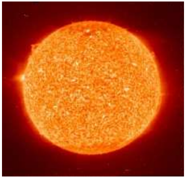
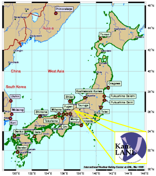
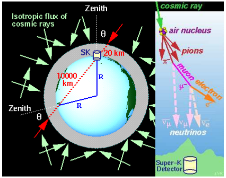
MINOS; T2K, 2015 $\nu_\mu \to \nu_\mu$



DayaBay, 2013 $\bar{\nu}_e \to \bar{\nu}_e$

Global data on neutrino oscillations

various neutrino sources, vastly different energy and distance scales:

sun	reactors	atmosphere	accelerators
			
Homestake,SAGE,GALLEX SuperK, SNO, Borexino	KamLAND, D-CHOOZ DayaBay, RENO	SuperKamiokande	K2K, MINOS, T2K OPERA

- global data fits nicely with the 3 neutrinos from the SM
  3-neutrino osc. params.: $\theta_{12}, \theta_{13}, \theta_{23}, \delta, \Delta m^2_{21}, \Delta m^2_{31}$
- a few "anomalies" at 2-3 σ: LSND, MiniBooNE, reactor anomaly, no LMA MSW up-turn of solar neutrino spectrum

Global fit to 3-flavour oscillations

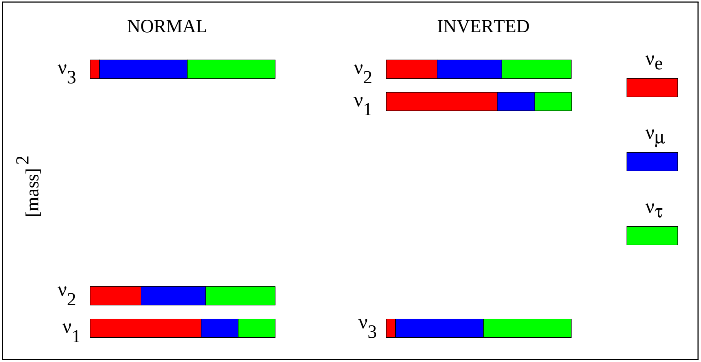
www.nu-fit.org

with C. Gonzalez-Garcia, M. Maltoni, 1409.5439

precision @ 3σ: $2\dfrac{x^{\rm up}-x^{\rm low}}{x^{\rm up}+x^{\rm low}}$

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range	
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$	14% (4.6°)
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$31.30 \to 35.90$	
$\sin^2\theta_{23}$	$0.451^{+0.051}_{-0.026}$	$0.382 \to 0.643$	$0.577^{+0.027}_{-0.035}$	$0.389 \to 0.644$	$0.385 \to 0.644$	32% (15°)
$\theta_{23}/^\circ$	$42.2^{+2.9}_{-1.5}$	$38.2 \to 53.3$	$49.4^{+1.6}_{-2.0}$	$38.6 \to 53.3$	$38.4 \to 53.3$	
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$	15% (1.2°)
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$	
$\delta_{\rm CP}/^\circ$	305^{+39}_{-51}	$0 \to 360$	251^{+66}_{-59}	$0 \to 360$	$0 \to 360$	∞
$\dfrac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$	14%
$\dfrac{\Delta m^2_{3i}}{10^{-3}\ {\rm eV}^2}$	$+2.458^{+0.046}_{-0.047}$	$+2.317 \to +2.607$	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix}+2.325 \to +2.599\\ -2.590 \to -2.307\end{bmatrix}$	11%

Neutrino mass states and mixing



The SM flavour puzzle

Lepton mixing:

$$\theta_{12} \approx 33^\circ \qquad \theta_{23} \approx 45^\circ \qquad \theta_{13} \approx 9^\circ$$

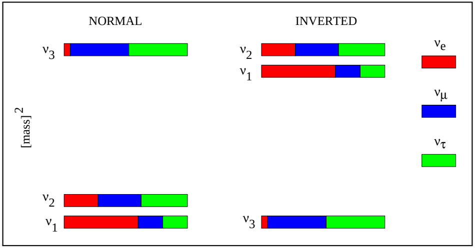
$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

Quark mixing:

$$\theta_{12} \approx 13^\circ \qquad \theta_{23} \approx 2^\circ \qquad \theta_{13} \approx 0.2^\circ$$

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & {\scriptstyle\epsilon} \\ \epsilon & 1 & {\scriptstyle\epsilon} \\ {\scriptstyle\epsilon} & {\scriptstyle\epsilon} & 1 \end{pmatrix}$$

Neutrino masses



- at least two neutrinos are massive
- typical mass scales:

$$\sqrt{\Delta m^2_{21}} \sim 0.0086\,\text{eV}\,, \qquad \sqrt{\Delta m^2_{31}} \sim 0.05\,\text{eV}$$

much smaller than other fermion masses ($m_e \approx 0.5 \times 10^6$ eV)

- 2 possibilities for the ordering of the mass states: normal vs inverted almost complete degeneracy in present data ($\Delta\chi^2 \approx 1$)

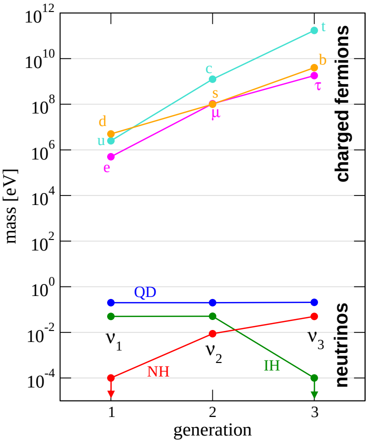
Normal versus "abnormal"

for inverted ordering leptons behave very different from quarks:

- the neutrino mass state mostly related to first generation would not be lightest
- there is strong degeneracy between at least two mass states:

$$deg \equiv \frac{m_2 - m_1}{\bar{m}} = 2\frac{\Delta m^2_{21}}{(m_1+m_2)^2}$$
$$\approx \frac{1}{2}\frac{\Delta m^2_{21}}{|\Delta m^2_{31}| + m_3^2} \leq \frac{1}{2}\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|}$$

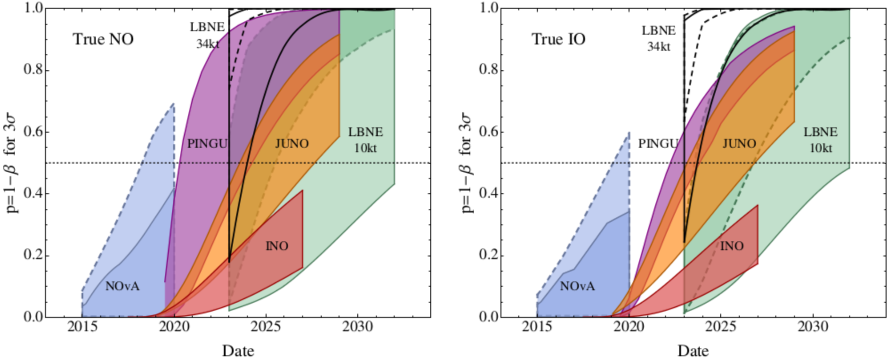
$$1.3\times 10^{-3}\left(\frac{\sum m_i}{0.5\,\mathrm{eV}}\right)^{-2} \leq deg \leq 1.8\times 10^{-2}$$



How to determine the mass ordering

- Find out whether the matter resonance in the 1-3 sector happens for neutrinos or antineutrinos
  - long-baseline accelerator experiments: NOvA, LBNF
  - atmospheric neutrino experiments: INO, PINGU, ORCA, HyperK
- Interference between oscillations with Δm^2_{21} and Δm^2_{31}
  - reactor experiments at 50 km: JUNO, RENO-50

Prospects for the mass ordering determination



probability to exclude the wrong ordering at 3σ

Blennow, Coloma, Huber, TS, 2013
Blennow, TS, 2013, 2012

CP violation

Leptonic CP violation will manifest itself in a difference of the vacuum oscillation probabilities for neutrinos and anti-neutrinos

Cabibbo, 1977; Bilenky, Hosek, Petcov, 1980, Barger, Whisnant, Phillips, 1980

Leptogenesis:

- provides mechanism to generate baryon asymmetry in the Universe
- requires CP violation at high temperatures
  (one of the Sacharov conditions)
- possible connection to CP violation in neutrino oscillations
  WARNING: model dependent!

The size of leptonic CP violation

$$P_{\nu_\alpha\to\nu_\beta} - P_{\bar\nu_\alpha\to\bar\nu_\beta} \propto J\,, \qquad J = |\mathrm{Im}(U_{\alpha1}U^*_{\alpha2}U^*_{\beta1}U_{\beta2})|$$

J: leptonic analogue to Jarlskog-invariant Jarlskog, 1985

using the standard parameterization:

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta \equiv J^{\max}\sin\delta$$

present data at 1 (3) σ NuFit 2.0

$$J^{\max} = 0.0329 \pm 0.0009\,(\pm 0.0027)$$

compare with Jarlskog invariant in the quark sector:

$$J_{\rm CKM} = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$$

- CPV for leptons might be a factor 1000 larger than for quarks
- OBS: for quarks we know J, for leptons only $J^{\max}$ (do not know δ!)

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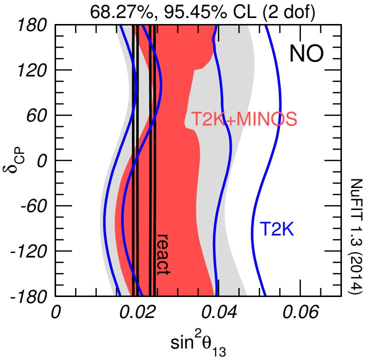
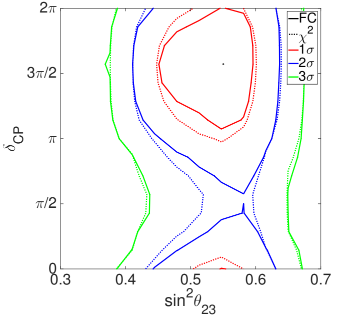
Complementarity between beam and reactor experiments





J. Elevant, TS, in prep

current data: slight preference for $\pi \lesssim \delta \lesssim 2\pi$ over $0 \lesssim \delta \lesssim \pi$
(very low significance!)

Search for CP violation in future experiments

measure difference in oscillations of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ is hard (cross sections, fluxes, matter effects,....)

long-baseline accelerator experiments

- T2K: J-PARC $\to$ SuperK / HyperK (285 km)
- NOvA: Fermilab $\to$ Soudan (800 km)
- LBNF: Fermilab $\to$ Homestake (1300 km)
- ESS-SB: Lund $\to$? (360/450 km)
- Neutrino Factory: ?

Outline

Neutrino oscillations

Absolute neutrino mass

How to give mass to neutrinos

Final remarks

Absolute neutrino mass

Three ways to measure absolute neutrino mass:

- Neutrinoless double beta-decay: $(A, Z) \to (A, Z+2) + 2e^-$
- Endpoint of beta spectrum: $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$
- Cosmology

Absolute neutrino mass

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  (with caveats: lepton number violation)
- Endpoint of beta spectrum: $^3\text{H} \to ^3\text{He} + e^- + \bar{\nu}_e$
  (experimentally challenging)
- Cosmology
  (with caveats: cosmological model)

Absolute neutrino mass

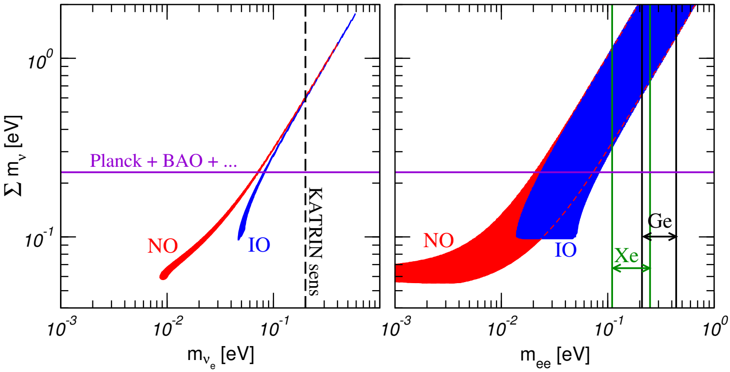
Three ways to measure absolute neutrino mass:
sensitive to different quantities

- Neutrinoless double beta-decay: $(A, Z) \to (A, Z+2) + 2e^-$
  (with caveats: lepton number violation)
  $m_{ee} = |\sum_i U_{ei}^2 m_i|$

- Endpoint of beta spectrum: $^3\mathrm{H} \to ^3\mathrm{He} + e^- + \bar{\nu}_e$
  (experimentally challenging)
  $m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$

- Cosmology
  (with caveats: cosmological model)
  $\sum_i m_i$

Complementarity



$0\nu\beta\beta$: Ge: GERDA + HDM + IGEX, Xe: KamLAND-Zen + EXO

ranges due to NME compilation from Dev et al., 1305.0056

cosmology: Planck Dec. 2014

Outline

Masses in the Standard Model

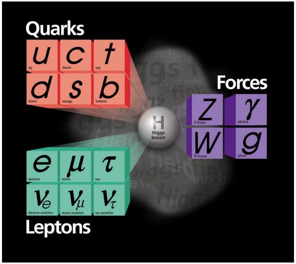
- The Standard Model has only one dimension full parameter: the vacuum expectation value of the Higgs:

$$\langle H \rangle \approx 174 \text{ GeV}$$

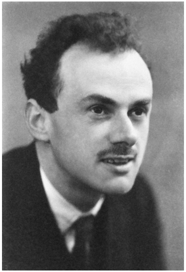
- All masses in the Standard Model are set by this single scale:

$$m_i = y_i \langle H \rangle$$

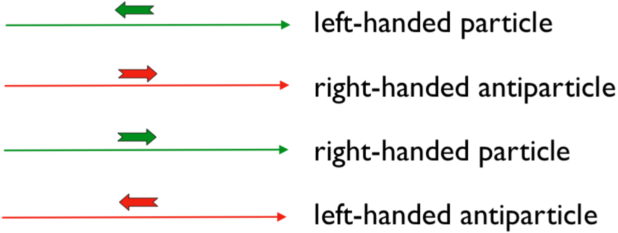
top quark: $y_t \approx 1$
electron: $y_e \approx 10^{-6}$



Masses in the Standard Model: Dirac fermions



Dirac: need 4 independent states to describe a massive fermion (spin-1/2 particle)



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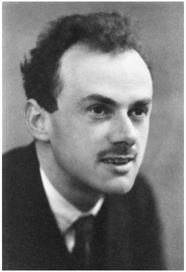
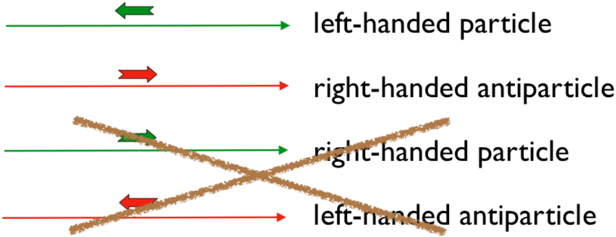


Dirac: need 4 independent states to describe a massive fermion (spin-1/2 particle)

BUT: in the SM there are no "right-handed neutrinos"

- complete gauge singlets
  (no interaction $\rightarrow$ "sterile neutrinos")
- no Dirac mass for neutrinos



Let's add right-handed neutrinos to the Standard Model

- Can now use the Higgs to give mass to neutrinos in the same way as for the other fermions:

Dirac mass: $m_D = y_\nu \langle H \rangle$

- BUT: need tiny coupling constant: $y_\nu \lesssim 10^{-11}$

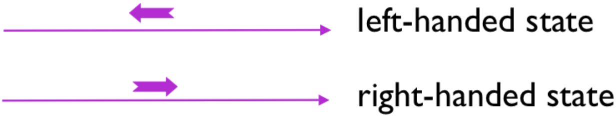
(top quark: $y_t \approx 1$, electron: $y_e \approx 10^{-6}$)

Majorana fermions

Majorana:

can make a massive fermion out of only two states

- concept of “particle” and “antiparticle” disappears
- a Majorana fermion “is its own antiparticle”
- cannot asign a conserved quantum number
  $\rightarrow$ a charged particle cannot be Majorana



The Standard Model + right-handed neutrinos

As soon as I introduce right-handed neutrinos (N_R) I can write down a Majorana mass term for them

Dirac mass:	$m_D = y_\nu \langle H \rangle$	
Majorana mass:	M_R	(explicit mass term for N_R)

M_R :

- new mass scale in the theory
- NOT related to the Higgs vacuum expectation value
- it is the scale of lepton number violation
- allowed by the gauge symmetry of the Standard Model but breaks lepton number

Remark on pure Dirac neutrinos

- Dirac neutrinos correspond to the specific choice of $M_R = 0$ for the Majorana mass
- This choice is technically natural (protected by Lepton number)
  - the symmetry of the Lagrangian is increased by setting $M_R = 0$
  - M_R will remain zero to all loop order (if there is no other source of lepton number violation)
- Also the tiny coupling constants $y_\nu \sim 10^{-11}$ are protected and technically natural (chiral symmetry)
- The values $M_R = 0$ and $y_\nu \sim 10^{-11}$ are considered "special" and/or "unaesthetic" by many theorists...

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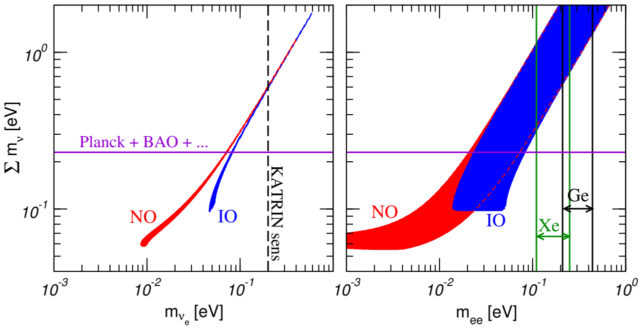
Testing the Majorana nature

Neutrinoless double-beta decay: $(A, Z) \to (A, Z+2) + 2e^-$

- observation of this process would prove that lepton number is violated
- in this case $M_R = 0$ will no longer be "natural"
  Schechter, Valle, 1982; Takasugi, 1984



Let's allow for lepton number violation

What is the value of M_R?

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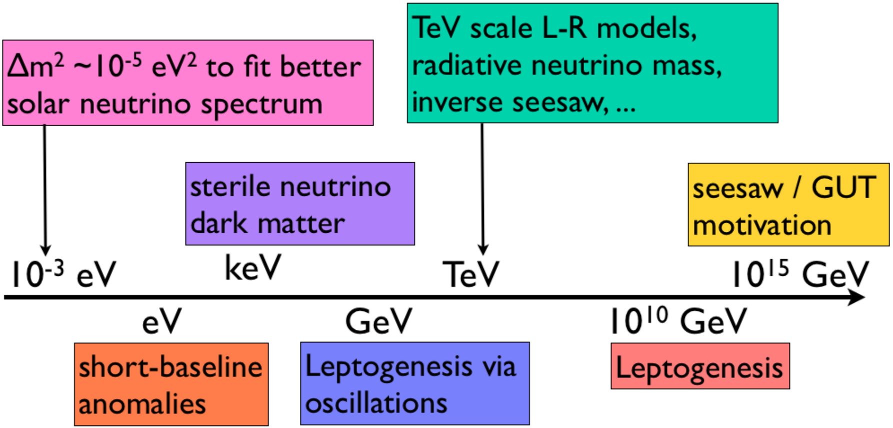

The Seesaw mechanism

let's assume $m_D \ll M_R$, then the mass matrix $\begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix}$ can be approximately block-diagonalized to

$$\begin{pmatrix} m_\nu & 0 \\ 0 & M_R \end{pmatrix} \quad \text{with} \quad m_\nu = -\frac{m_D^2}{M_R}$$

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Seesaw:

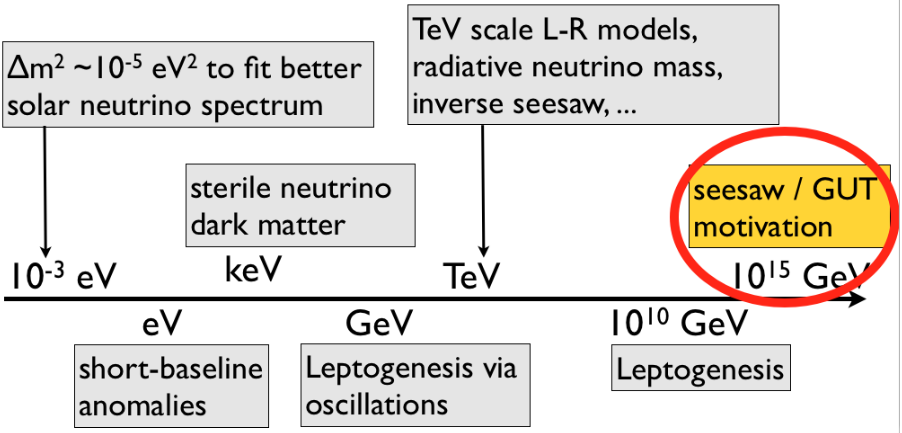
the Standard Model neutrinos are light because N_R are heavy

What is the Seesaw scale?

$$m_\nu = -\frac{m_D^2}{M_R}\,, \qquad m_D = y_\nu \langle H \rangle$$

- assume $m_D \sim m_t$ (or $y_\nu \sim 1$)
- neutrino masses of $m_\nu \lesssim 1$ eV then imply $M_R \sim 10^{14}$ GeV
- very high scale - close to scale for grand unification $\Lambda_{\rm GUT} \sim 10^{16}$ GeV
  GUT origin of neutrino mass?
- Ex.: SO(10) grand unified theory Mohapatra, Senjanovic,...
  16-dim representation contains all SM fermions + N_R

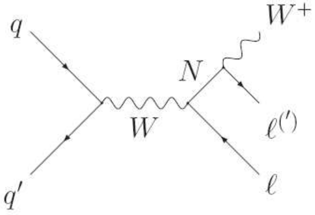
Sterile neutrinos: at the GUT scale?



What is the Seesaw scale?

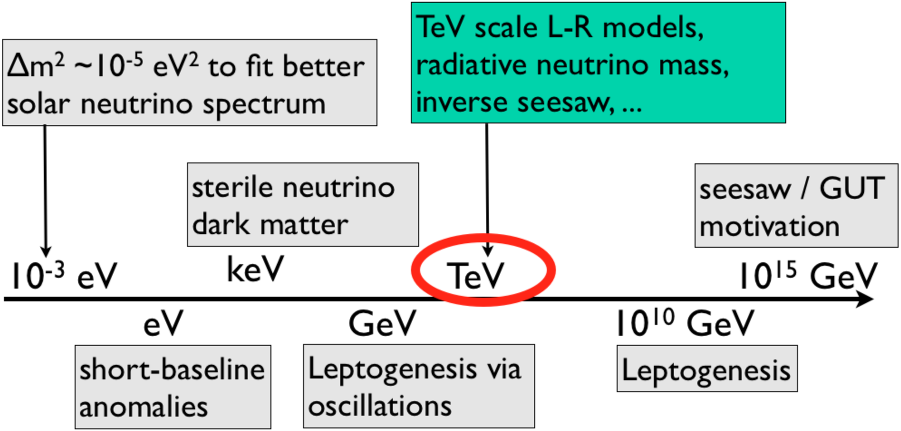
$$m_\nu = -\frac{m_D^2}{M_R}\,, \qquad m_D = y_\nu \langle H \rangle$$

- assume $m_D \sim m_e$ (or $y_\nu \sim 10^{-6}$)
- neutrino masses of $m_\nu \lesssim 1$ eV then imply $M_R \sim 1$ TeV
- potentially testable at LHC

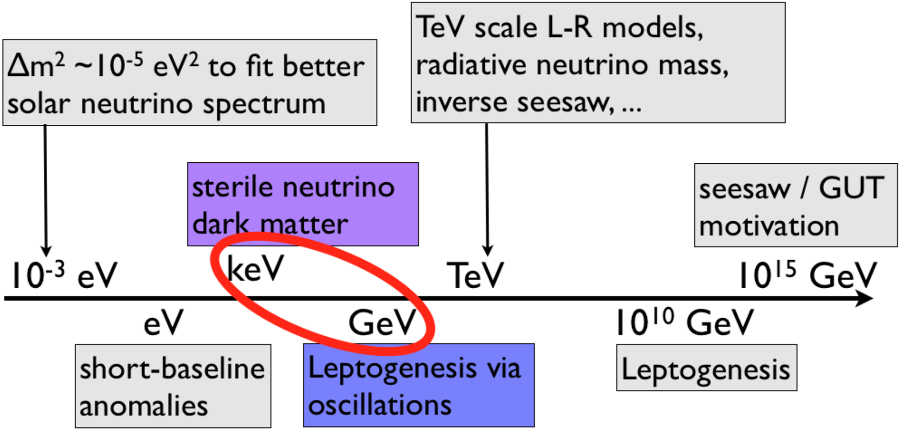


(however: couplings are too small...)

Sterile neutrinos: at the scale TeV?

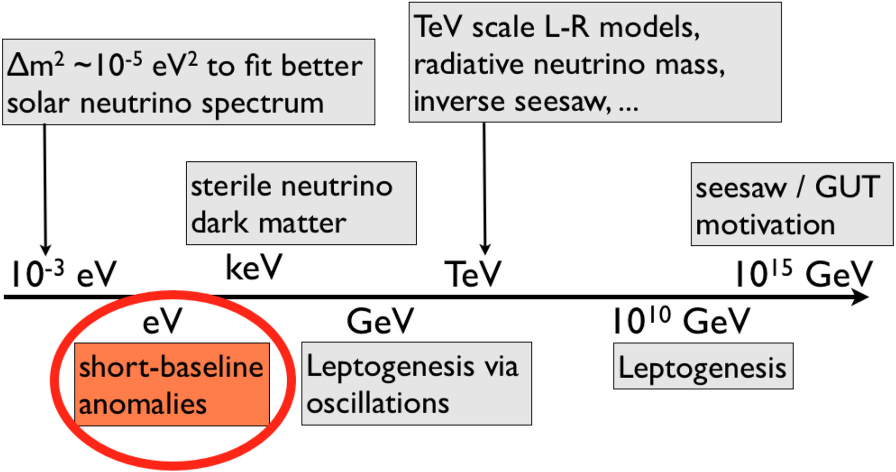


νMSM Shaposhnikov,...



very economic model with minimal amount of "new physics"

Sterile neutrinos at the eV scale?



exper. hints, however, inconsistent with each other and with cosmology

Kopp, Machado, Maltoni, TS, 2013

Neutrino mass DOES NOT imply right-handed neutrinos!

It is easy to arrange for lepton number violation without introducing right-handed neutrinos

Ex., extending the scalar sector of the Standard Model

- SU(2) triplet Higgs ("type-II Seesaw")
- neutrino mass generation via loop diagrams Zee; Zee, Babu;...
  - typical involve new physics at TeV scale
  - can also be linked to a DM candidate e.g., Ma, 2006;...

The Weinberg operator

Assume there is new physics at a high scale Λ. It will manifest itself by non-renormalizable operators suppressed by powers of Λ.

Weinberg 1979: there is a unique dim-5 operator consistent with the gauge symmetry of the SM, and this operator will lead to a Majorana mass term for neutrinos after EWSB:

$$y^2 \frac{L^T \tilde{H}^* \tilde{H}^\dagger L}{\Lambda} \qquad \longrightarrow \qquad m_\nu \sim y^2 \frac{\langle H \rangle^2}{\Lambda}$$

Λ : scale of lepton number breaking

- generically effects of "Λ" are either suppressed by the high scale or by tiny couplings y
- hope for other "new physics" effects beyond neutrino mass

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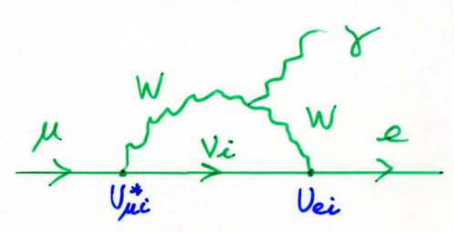
Lepton flavour violation

- Neutrino oscillations imply violation of lepton flavour, e.g.: $\nu_\mu \to \nu_e$
- Can we see also LFV in charged leptons?

$$\mu^\pm \to e^\pm \gamma$$
$$\tau^\pm \to \mu^\pm \gamma$$
$$\mu^+ \to e^+ e^+ e^-$$
$$\mu^- + N \to e^- + N$$

Can we see also LFV in charged leptons?

Yes, BUT: $\mu^\pm \to e^\pm\gamma$ in the SM + ν mass:



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W}\right|^2 \lesssim 10^{-54}$$

- unobservably small (present limits: $\sim 10^{-13}$)
- observation of $\mu \to e\gamma$ implies new physics beyond neutrino mass

$\mu \to e\gamma$ and new physics

generically one expects

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-10} \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{\theta_{e\mu}}{10^{-2}}\right)^2$$

we are sensitive to new physics in the range 1 to 1000 TeV

Examples:

- TeV scale SUSY
- TeV scale neutrino masses (triplet, Zee-Babu,...)

Comments on charged LFV

- LFV does NOT probe neutrino Majorana mass
  (conserves lepton number)
  LFV: dim-6 operators, Majorana mass: dim-5 operator

  $\rightarrow$ need a lepton number violating process to test mass directly

- cLFV is sensitive to new physics at the 1–1000 TeV scale, which will be (indirectly) related to the mechanism for neutrino mass

- let's hope for a signal!
  this will provide extremely valuable information on BSM
  ratios of various LFV channels can give crucial insight on the model

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Outline

Final remarks

- We had exciting discoveries in the last years in neutrino physics, implying that the Standard model has to be extended in some way.
- identifying the mechanism for neutrino mass is one of the most important open questions in particle physics ... may be a difficult task (the answer could be elusive forever)
- Let's hope for new signals:
    - collider experiments at the TeV scale (LHC)
    - searches for charged lepton flavour violation
    - lepton number violation and absolute neutrino mass
    - astroparticle physics
- neutrinos may provide crucial complementary information on physics beyond the Standard Model and a possible theory of flavour.