Neutrino Oscillations and Beyond Standard Model Physics

KIT GK Elementarteilchenphysik

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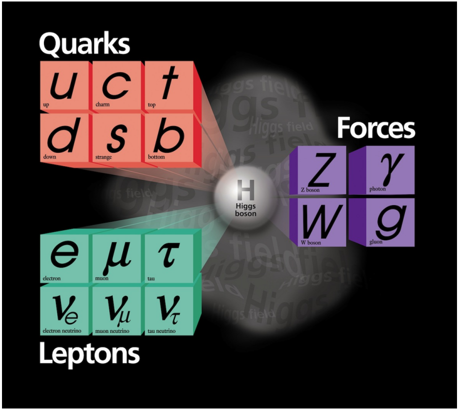
The Standard Model of particle physics



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

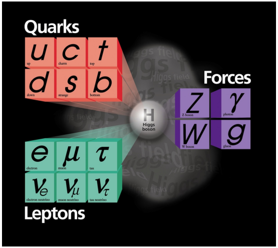
Status of neutrino mass and mixing
    The lepton mixing matrix and CP violation
    The neutrino mass spectrum

How to give mass to neutrinos

Final remarks

Outline

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^+

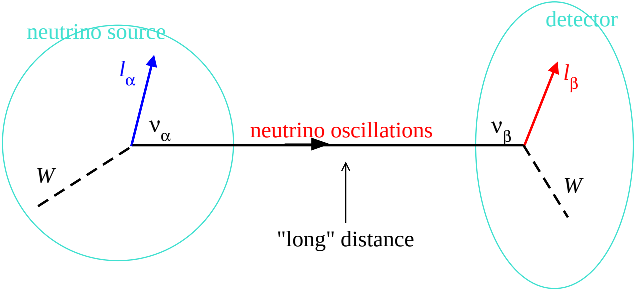
Lepton mixing

- 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



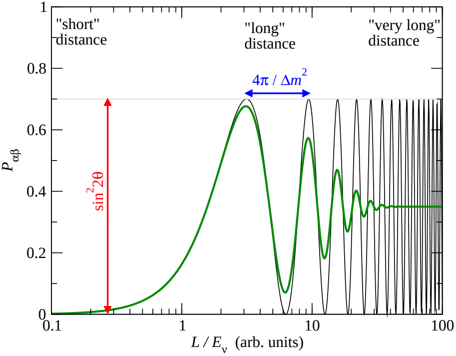
$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$ $\quad e^{-i(E_i t - p_i x)}$ $\quad |\nu_\beta\rangle = U^*_{\beta i}|\nu_i\rangle$

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

Neutrino oscillations: 2-flavour limit

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

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



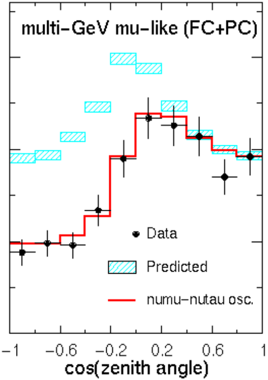
$$\frac{\Delta m^2 L}{4E_\nu} = 1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}$$

Neutrinos oscillate!

- atmospheric neutrinos Super-Kamiokande

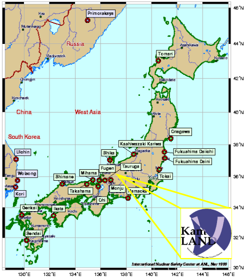
1998: strong zenith angle dependence of the observed flux of ν_μ

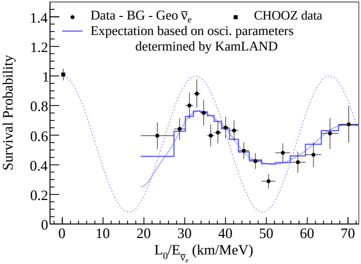
consistent with $\nu_\mu \to \nu_\tau$ oscillations



Neutrinos oscillate!

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





2004: evidence for spectral distortion

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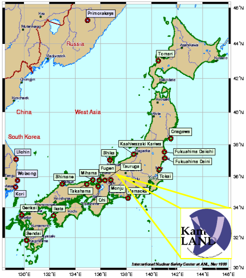

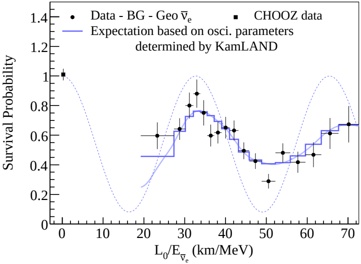

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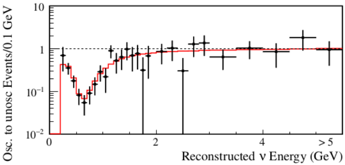
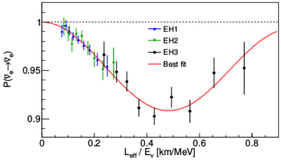


MINOS; T2K, 2015 $\nu_\mu \to \nu_\mu$

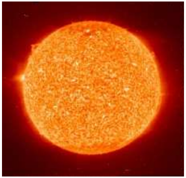


DayaBay, 2013 $\bar{\nu}_e \to \bar{\nu}_e$

Global data on neutrino oscillations

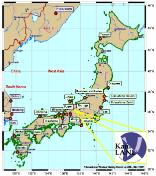
various neutrino sources, vastly different energy and distance scales:

sun



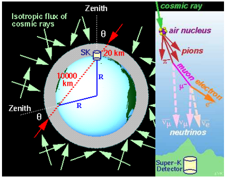
Homestake,SAGE,GALLEX
SuperK, SNO, Borexino

reactors



KamLAND, D-CHOOZ
DayaBay, RENO

atmosphere



SuperKamiokande

accelerators

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

Outline

Global fit to 3-flavour oscillations

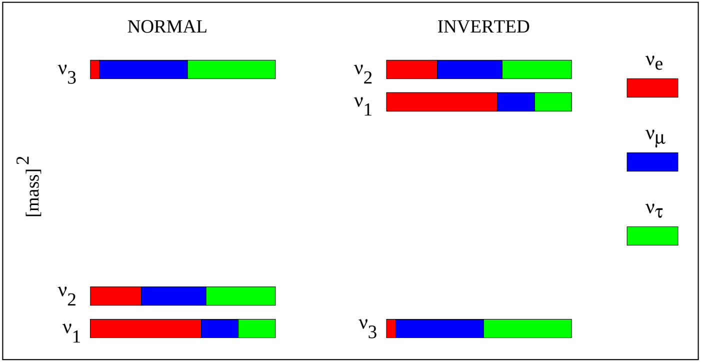
www.nu-fit.org

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 masses and mixing



The SM flavour puzzle

Lepton mixing:

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

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

Quark mixing:

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

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

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

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

J: leptonic analogue to Jarlskog-invariant Jarlskog, 1985

standard parameterization: $J = s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta \equiv J^{\max}\sin\delta$

present data NuFit 2.0: $J^{\max} = 0.0329 \pm 0.0009\,(1\sigma)$

compare with Jarlskog invariant in the quark sector:

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

- 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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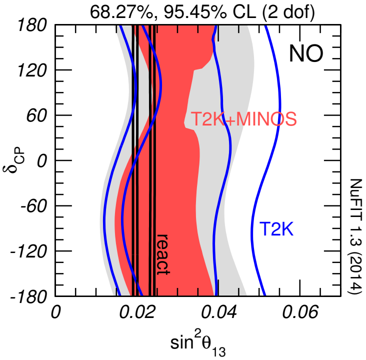
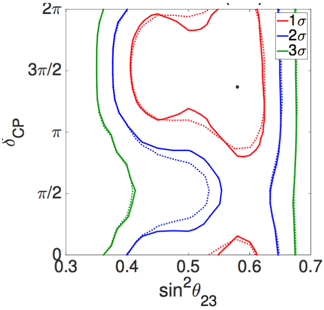
Complementarity between beam and reactor experiments



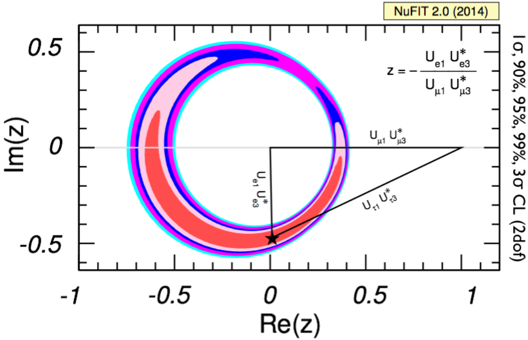


J. Elevant, TS, 1506.07685

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

Leptonic unitarity triangle

Unitarity triangle based on the 1st and 3rd column of U_{PMNS}



- unitarity is assumed (no test of unitarity!)
- still far from knowledge we have on UT in quark sector
- main science goal of future accelerator neutrino program
  T2K, NOvA, DUNE,... (challenging!)

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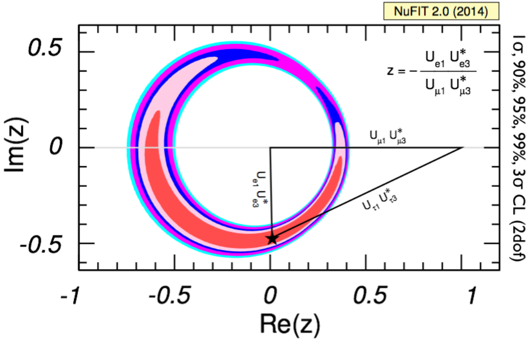

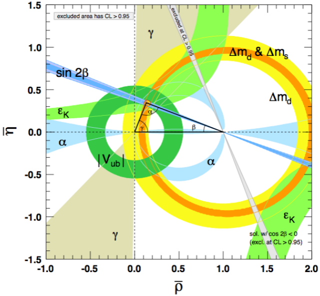

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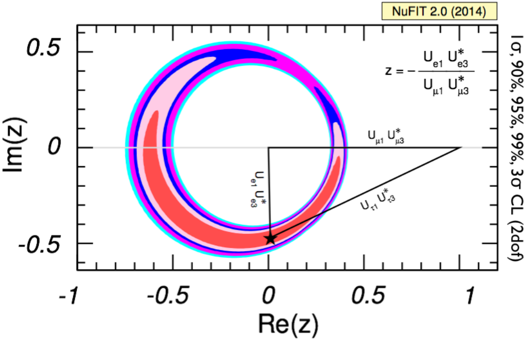

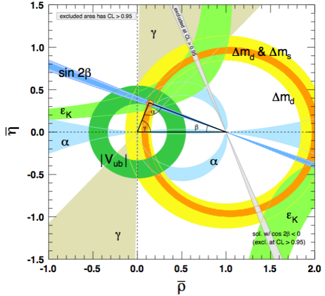

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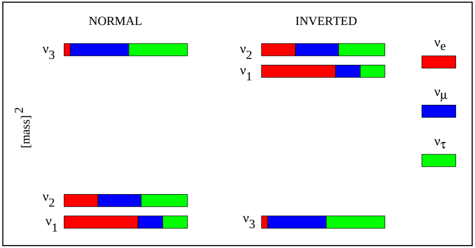
Neutrino masses

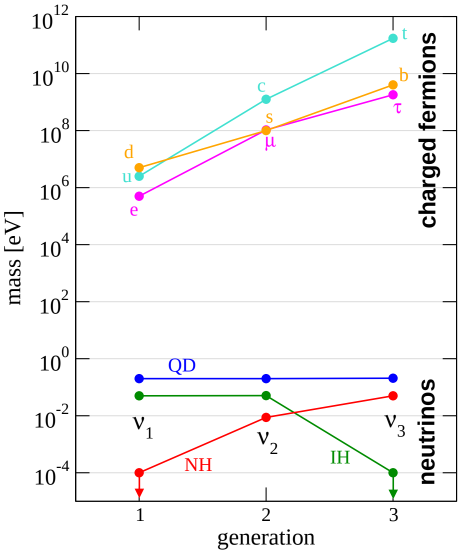


- at least two neutrinos are massive
- typical mass scales:

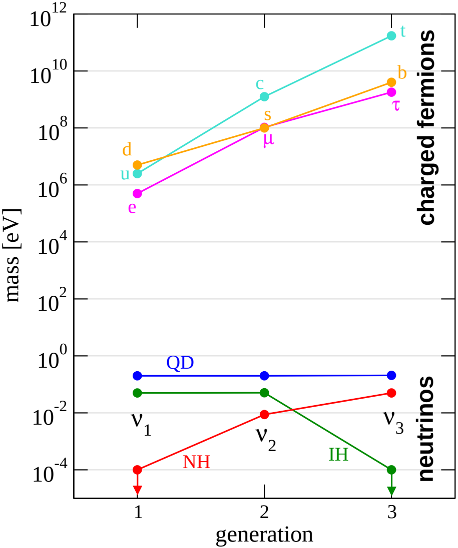
$$\sqrt{\Delta m^2_{21}} \sim 0.0086\,\text{eV}\,, \qquad \sqrt{\Delta m^2_{31}} \sim 0.05\,\text{eV}$$

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 ($\Delta\chi^2 \approx 1$)



- Why are neutrino masses so small?
- If the neutrino mass spectrum is inverted or quasi-degenerate it is very different from all other fermions in the SM



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Determination of the neutrino mass ordering

- Looking for the matter effect in transitions involving Δm^2_{31}
    - long-baseline accelerator experiments NOvA, DUNE
    - atmospheric neutrino experiments PINGU, ORCA, INO
- Interference effect of oscillations with Δm^2_{31} and Δm^2_{21}
    - reactor experiment at 60 km JUNO

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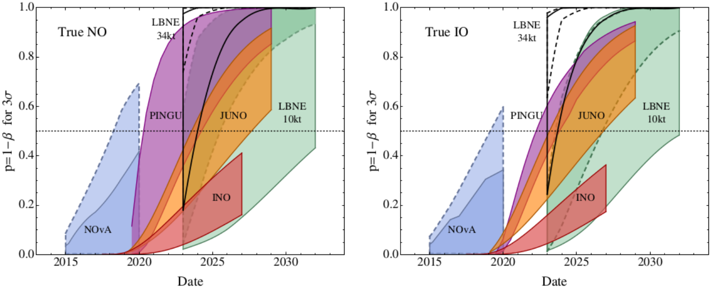

determination of the mass ordering at $2-3\sigma$ is likely within 5–10 years

Blennow, Coloma, Huber, TSM, 1311.1822; Blennow, TSM, 1306.3988

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

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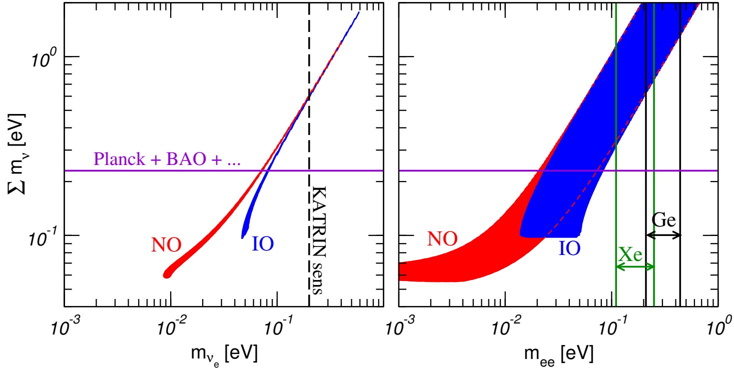
  (with caveats: cosmological model)

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

Neutrino oscillations

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How to give mass to neutrinos

Final remarks

Masses in the Standard Model

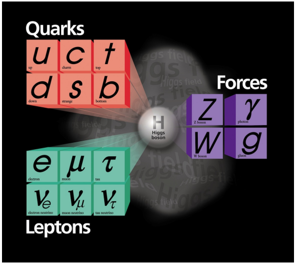
- The Standard Model has only one dimension full parameter: the vacuum expectation value of the Higgs:

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

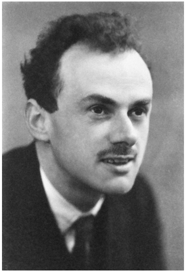
- All masses in the Standard Model are set by this single scale:

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

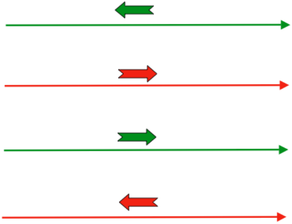
top quark: $y_t \approx 1$
electron: $y_e \approx 10^{-6}$



Masses in the Standard Model: Dirac fermions



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



left-handed particle

right-handed antiparticle

right-handed particle

left-handed antiparticle

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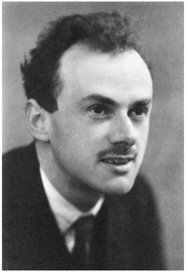
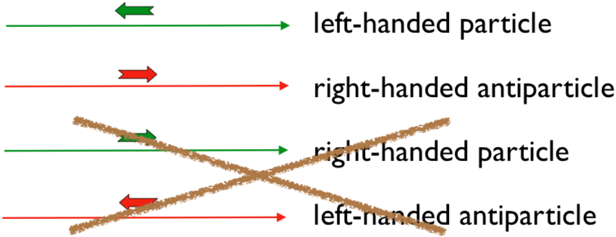


Dirac: need 4 independent states to describe a massive fermion (spin-1/2 particle)

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

- complete gauge singlets
  (no interaction → “sterile neutrinos”)
- no Dirac mass for neutrinos



left-handed particle

right-handed antiparticle

~~right-handed particle~~

~~left-handed antiparticle~~

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: $y_\nu \lesssim 10^{-11}$

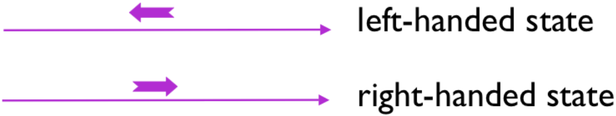
  (top quark: $y_t \approx 1$, electron: $y_e \approx 10^{-6}$)

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
  → 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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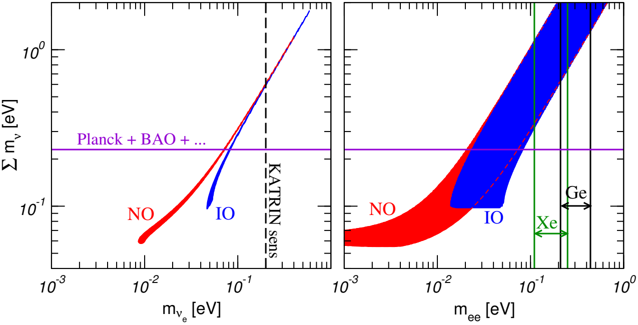
Testing the Majorana nature

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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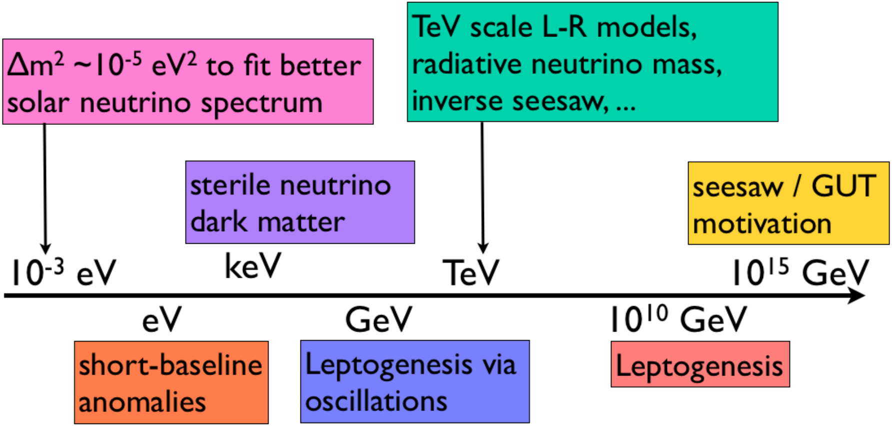

The Seesaw mechanism

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:

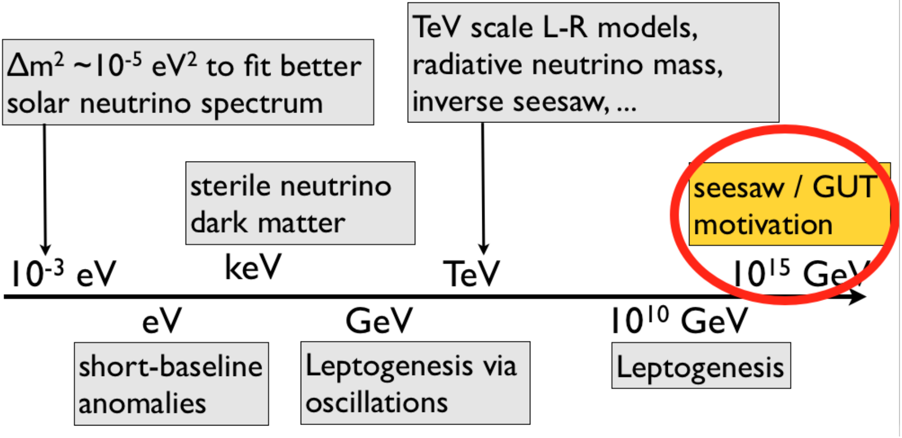
the Standard Model neutrinos are light because N_R are heavy

What is the Seesaw scale?

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

- 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 $\Lambda_{\mathrm{GUT}} \sim 10^{16}$ 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?



$\Delta m^2 \sim 10^{-5}$ eV^2 to fit better solar neutrino spectrum

sterile neutrino dark matter

TeV scale L-R models, radiative neutrino mass, inverse seesaw, ...

seesaw / GUT motivation

10^{-3} eV

keV

TeV

10^{15} GeV

eV

GeV

10^{10} GeV

short-baseline anomalies

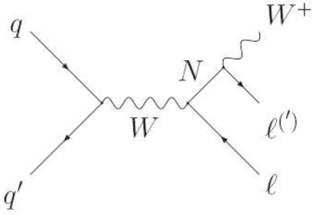
Leptogenesis via oscillations

Leptogenesis

What is the Seesaw scale?

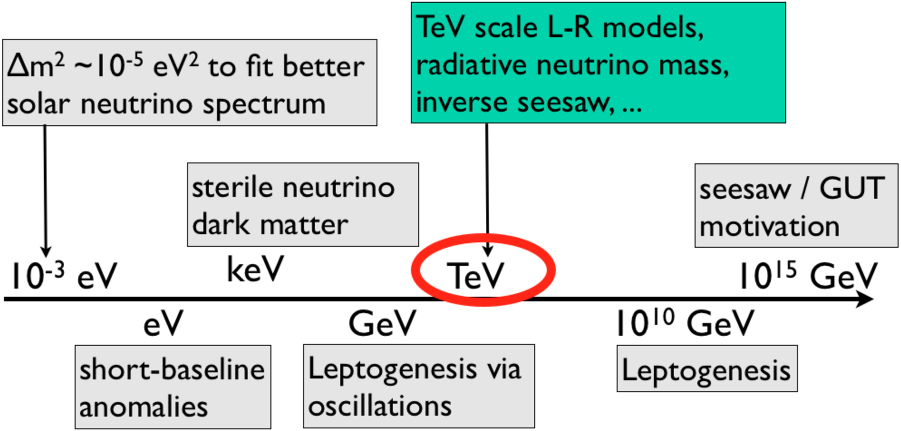
$$m_\nu = -\frac{m_D^2}{M_R}\,, \qquad m_D = y_\nu \langle H \rangle$$

- 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?



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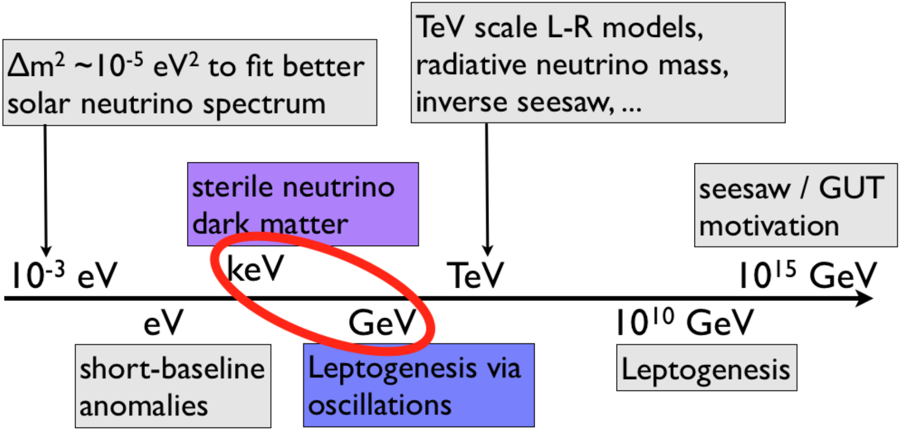
Leptogenesis

νMSM Shaposhnikov,...



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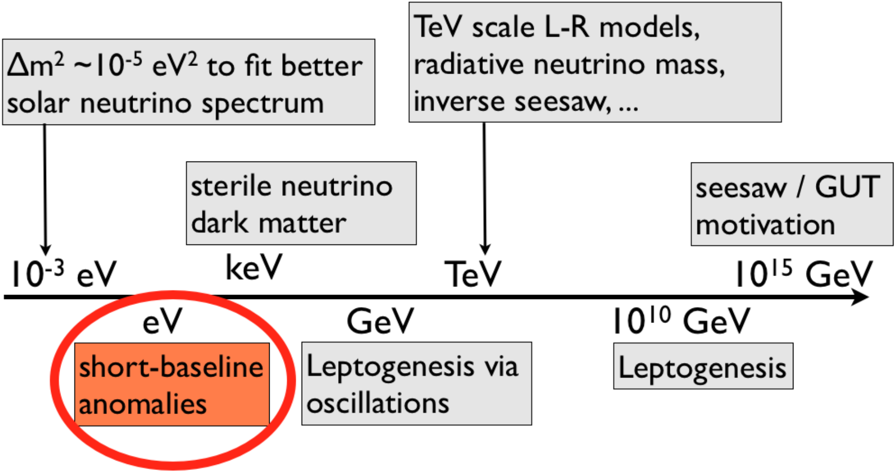
Leptogenesis via oscillations

Leptogenesis

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, Schwetz, 1303.3011

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;...

Higgs-triplet / Type-II Seesaw

Let's add a triplet Δ under $\mathrm{SU}(2)_L$ to the SM:

$$\mathcal{L}_\Delta = f_{ab}\, L_a^T\, C^{-1}\, i\tau_2 \Delta\, L_b + \mathrm{h.c.}\,,$$

$$\Delta = \begin{pmatrix} H^+/\sqrt{2} & H^{++} \\ H^0 & -H^+/\sqrt{2} \end{pmatrix}$$

The VEV of the neutral component $\langle H^0 \rangle \equiv v_T/\sqrt{2}$ induces a Majorana mass term for the neutrinos:

$$\frac{1}{2}\nu_{La}^T C^{-1} m^\nu_{ab}\, \nu_{Lb} + \mathrm{h.c.} \qquad \text{with} \qquad m^\nu_{ab} = \sqrt{2}\, v_T\, f_{ab} \lesssim 10^{-10}\,\mathrm{GeV}$$

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need either low v_T or small f_{ab} or some combination thereof

small v_T from Higgs potential → Seesaw type-II (very heavy Triplet)

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TeV scale triplet: test at LHC

$$pp \to Z^*(\gamma^*) \to H^{++} H^{--} \to \ell^+\ell^+\,\ell^-\ell^-$$

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

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- hope for other "new physics" effects beyond neutrino mass

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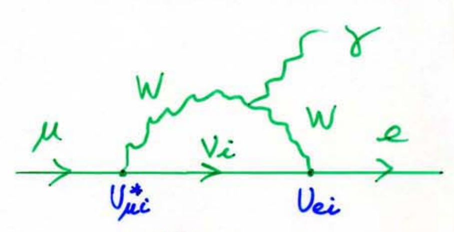
Lepton flavour violation

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

$$\begin{aligned}
&\mu^\pm \to e^\pm \gamma \\
&\tau^\pm \to \mu^\pm \gamma \\
&\mu^+ \to e^+ e^+ e^- \\
&\mu^- + N \to e^- + N
\end{aligned}$$

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,...)

LFV does NOT probe neutrino Majorana mass, but (lepton number conserving) new physics presumably related to neutrino mass
LFV: dim-6 operators, Majorana mass: dim-5 operator

→ need a lepton number violating process to test mass directly

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Outline

Neutrino oscillations

Status of neutrino mass and mixing
    The lepton mixing matrix and CP violation
    The neutrino mass spectrum

How to give mass to neutrinos

Final remarks

In the SM neutrinos are massless because…

1. there are no right-handed neutrinos to form a Dirac mass term
2. because of the field content (scalar sector) and gauge symmetry lepton number[1] is an accidental global symmetry of the SM and therefore no Majorana mass term can be induced.
3. restriction to renormalizable terms in the Lagrangian

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[1] B-L at the quantum level

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3. restriction to renormalizable terms in the Lagrangian

Neutrino oscillations imply that at least one of those have to be violated

$\Rightarrow$ physics beyond the SM!

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[1] B-L at the quantum level

- 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.