Neutrinos – The Known Unknowns

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Based on:

several decades of research on neutrino physics, including countless sleepless nights for theorists and many exhausting shifts for experimentalists

Final SGGDT Symposium, Ringberg Castle, 19-10-2015

Contents:

1. Neutrinos in the Standard Model

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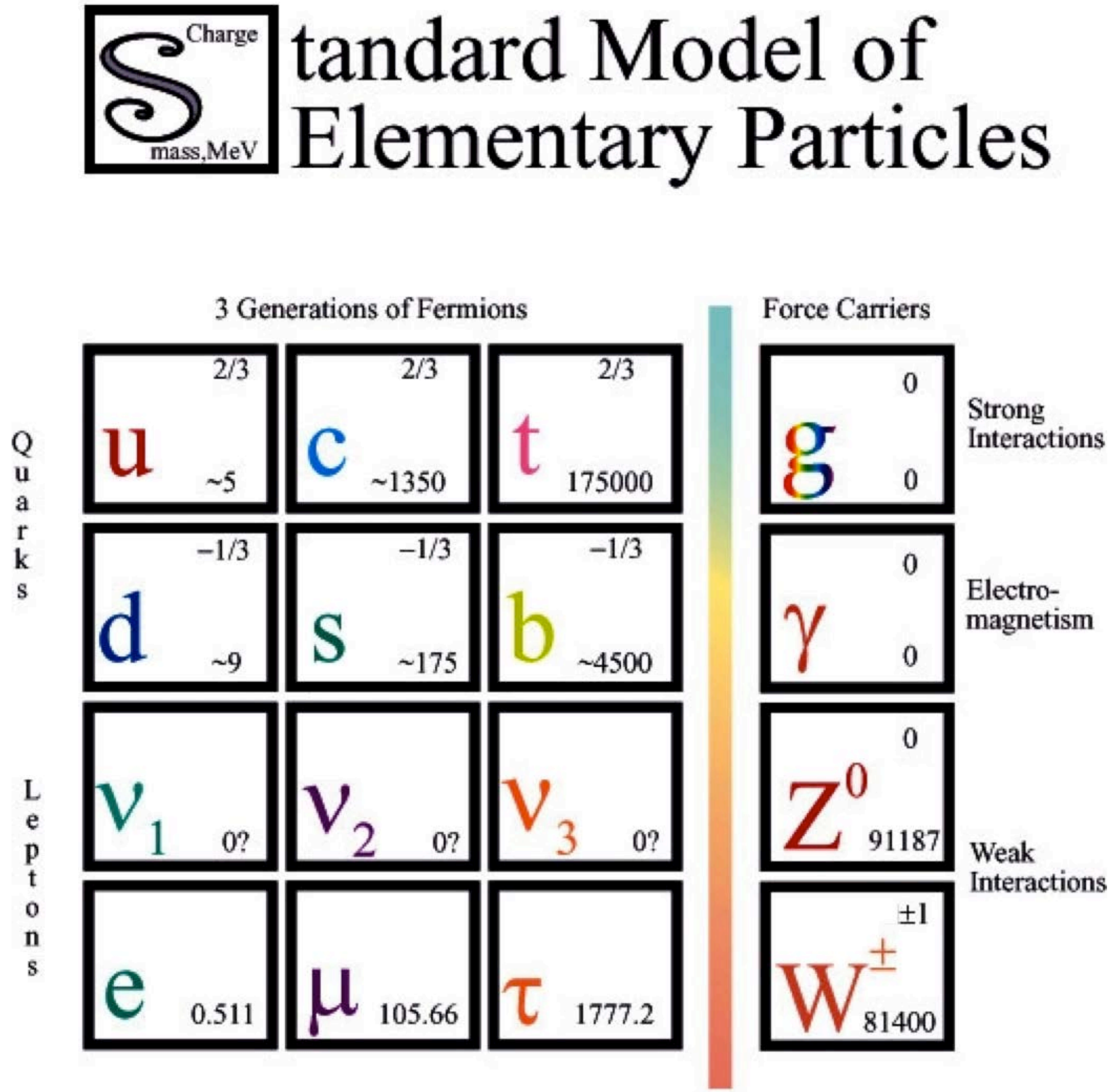
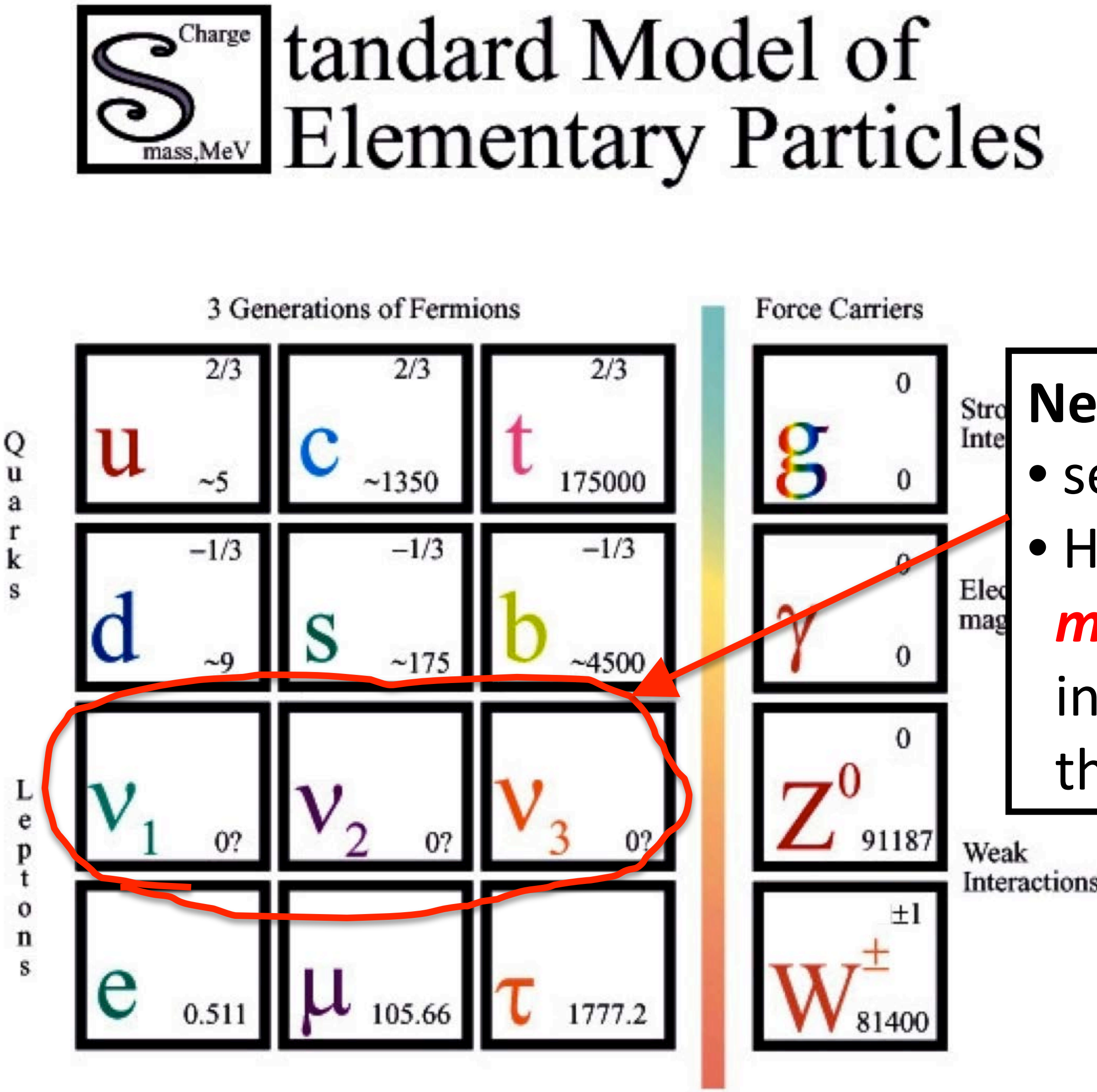


Masses are in MeV

+ Higgs + antiparticles

1. Neutrinos in the Standard Model



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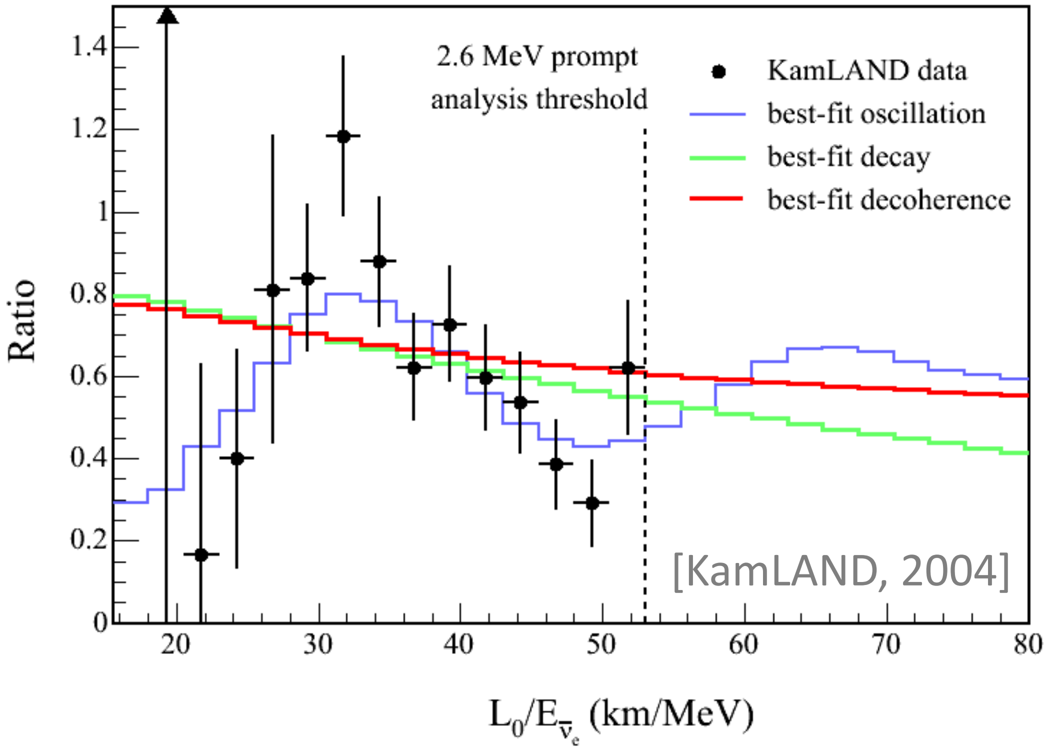
Neutrinos:
- seem to fit in well
- HOWEVER: they are ***massless in the SM*** while in reality we have seen that they are massive

+ Higgs + antiparticles

1. Neutrinos in the Standard Model



We know from neutrino oscillations that neutrinos MUST BE massive!!

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$ ➔ $m_2^2 - m_1^2 > 0$ & $|m_3^2 - m_1^2| \neq 0$

THUS:
at least two light ν's have non-zero mass!

1. Neutrinos in the Standard Model

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- no right-handed neutrinos ν_R in the SM: if they were present, we could write down a Dirac mass term (as for the other fermions)

$$\mathcal{L}_Y \supset -\overline{L}\tilde{H}y_\nu \nu_R + h.c. \to -\overline{L}\langle\tilde{H}\rangle y_\nu \nu_R + h.c. = -\overline{\nu_L} m_D \nu_R + h.c.$$

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typical Left-Right Yukawa coupling

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SM-Higgs

Higgs obtains a “VEV“ $v=<H>$

coupling × VEV is interpreted as MASS

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$$\mathcal{L}_{Y_T} = -\overline{L} i\sigma_2 T y_T L^c + h.c. \to -\overline{\nu_L} v_T y_T (\nu_L)^c + h.c.$$

$$\equiv -\frac{1}{2}\overline{\nu_L} m_L (\nu_L)^c + h.c.$$

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lepton-number violating (LNV) Yukawa coupling

coupling × VEV v_T again interpreted as MASS

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- only renormalisable couplings in the SM: otherwise, we could write down a direct (LNV!) mass term at mass dimension five

$$\mathcal{L}_5 = \frac{-y_{ij}}{\Lambda}(\overline{L_i^c}H)i\sigma_2(HL_j)$$

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coupling × v^2/Λ can be interpreted as MASS

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➔ ***beyond the SM, we quite generically violate (at least) one of these conditions***

THUS: having non-zero neutrino masses is generic, not exotic!!!

2. What is Neutrino Mixing?

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For neutrinos, it holds that:

mass basis ≠ flavour basis

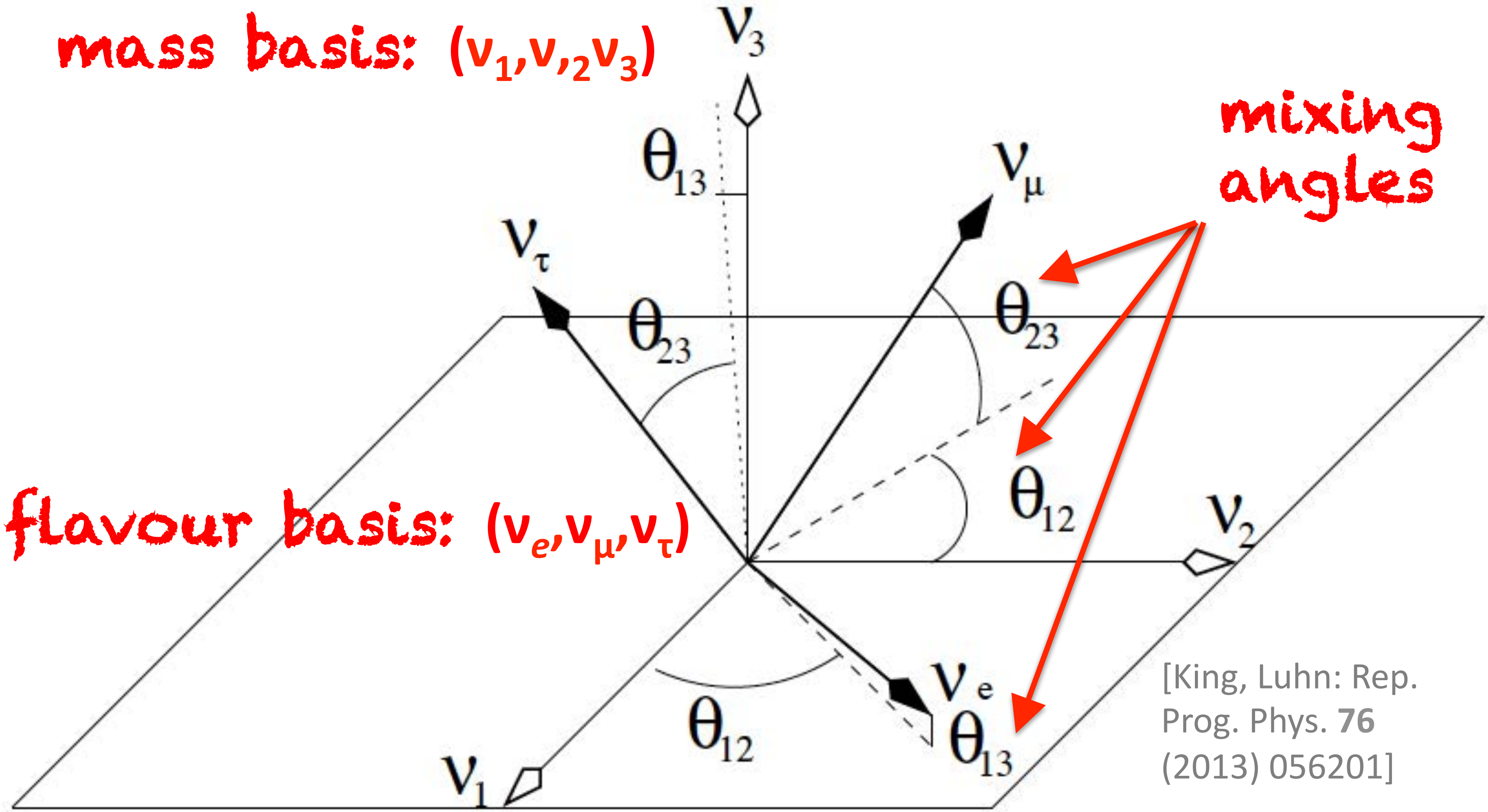
BUT:

What does that mean?!? In fact, it's simple...

- while an electron e has a well-defined electron mass m_e...
- ... an electron neutrino ν_e does NOT have an "electron neutrino mass" m_{ν_e}, but instead it is a quantum-mechanical superposition of several mass eigenstates with masses $m_{1,2,3}$

2. What is Neutrino Mixing?

Mathematically, this can beinterpreted as a rotation in an abstract "flavour space":



[King, Luhn: Rep. Prog. Phys. **76** (2013) 056201]

2. What is Neutrino Mixing?

The "oscillation parameters" (= mixing angles θ_{12}, θ_{13}, θ_{23} and mass-square differences $m_2^2-m_1^2$ and $|m_3^2-m_1^2|$) can be measured:

NuFIT 2.0 (2014)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix}+2.325 \to +2.599\\ -2.590 \to -2.307\end{bmatrix}$

[Bergström, Gonzalez-Garcia, Maltoni, Schwetz: www.nu-fit.org]

3. Neutrino Masses & LNV

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Why are neutrino masses so intimately connected to lepton number violation?!?

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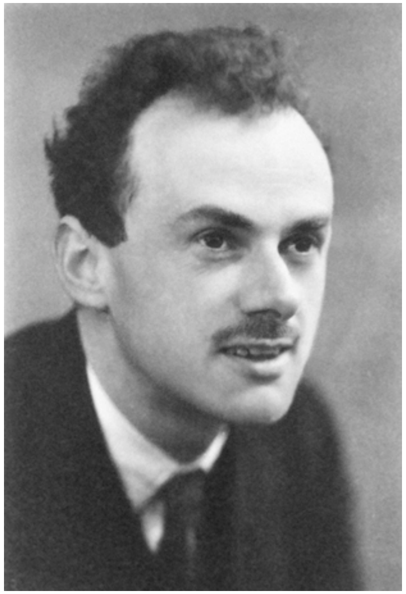
...this question is intimately connected to neutrinos being Dirac or Majorana particles:

DIRAC

$\nu \neq \bar{\nu}$



VS.

MAJORANA

$\nu = \bar{\nu}$

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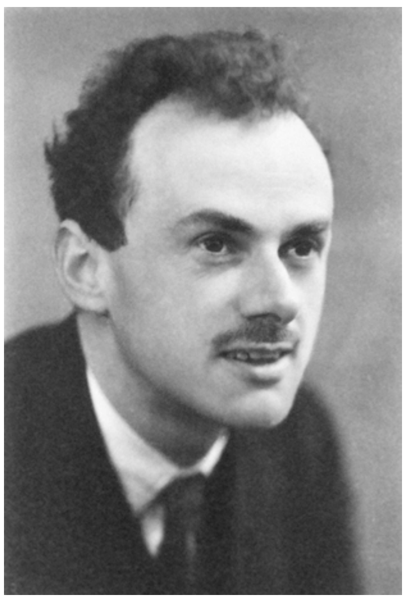

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Dirac mass term → 1 : 0

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Very common prejudice:

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Correct is:

THE STANDARD MODEL ONLY CONSERVES LEPTON NUMBER PERTURBATIVELY.

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THE STANDARD MODEL ONLY CONSERVES LEPTON NUMBER PERTURBATIVELY.

→ beyond Feynman diagram level, there exist processes ("sphalerons") that conserve (B-L) but violate (B+L)

→ lepton number is NOT sacrosanct

3. Neutrino Masses & LNV

Thus, new physics beyond the SM generically violates lepton number:

- e.g. triplet Yukawa coupling:

$$\mathcal{L}_{Y_T} = -\overline{L} i\sigma_2 T y_T L^c + h.c.$$

Each has lepton number +1

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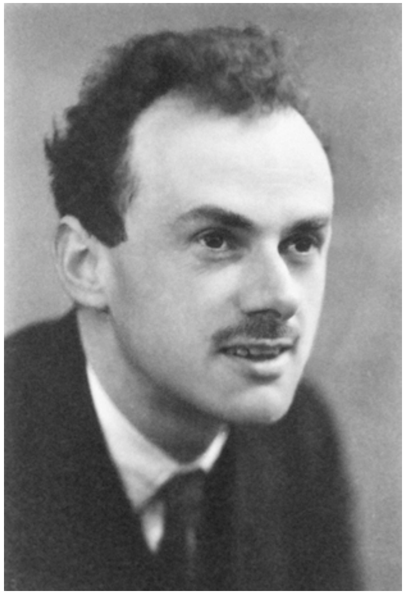

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1 : 1

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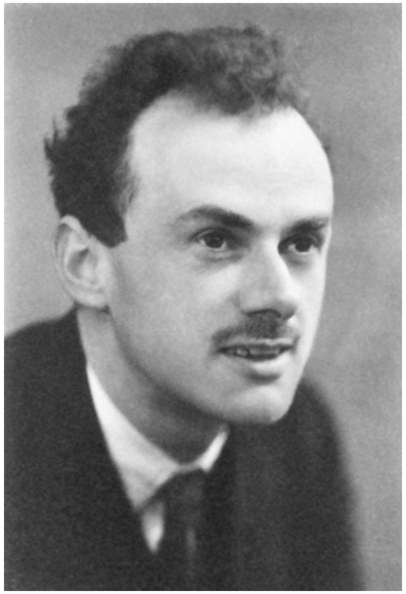

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1 : 2

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- right-handed neutrinos can form a so-called Majorana mass term:

$$\mathcal{L}_M = -\frac{1}{2}\overline{(\nu_R)^c} M_R \nu_R + h.c.$$

Each has lepton number -1

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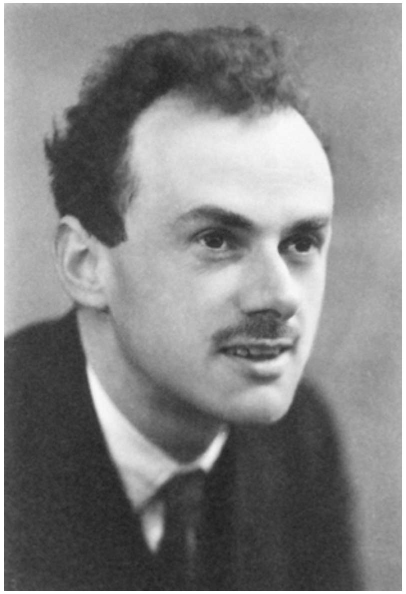


VS.

MAJORANA

$\nu = \bar{\nu}$

1 : 3

3. Neutrino Masses & LNV

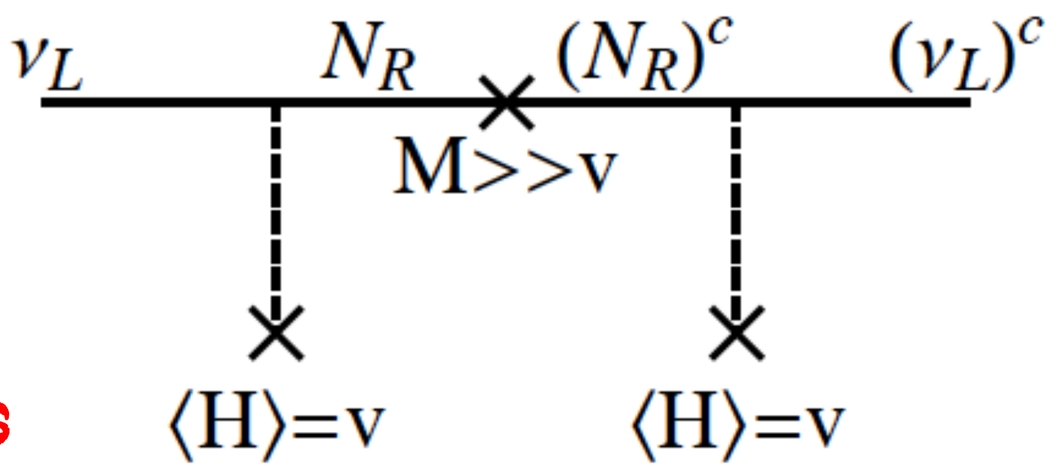
The latter possibility is often used to "explain" why neutrino masses are so small:

LH and RH neutrinos

$$\mathcal{L}_\nu = -\frac{1}{2}(\overline{\nu_L}, \overline{(N_R)^c}) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix} + h.c.$$

$$m_\nu = -m_D M_R^{-1} m_D^T$$

Effectively, large RH neutrino masses "suppress" light LH neutrino masses



"SEESAW MECHANISM"

3. Neutrino Masses & LNV

Experimental consequences: LNV processes

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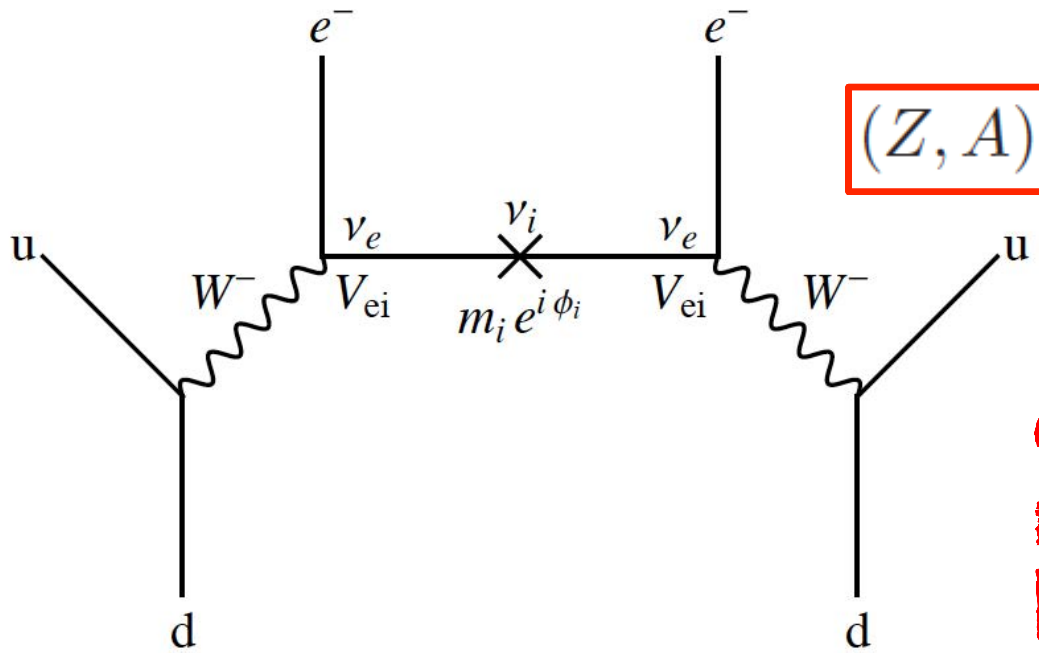
- neutrinoless double beta decay (0νββ)



$$(Z, A) \rightarrow (Z+2, A) + e^- + e^-$$

Clearly violates lepton number by two units

➔ **THE REASON WE ARE HERE THIS WEEK!!!**

3. Neutrino Masses & LNV

Experimental consequences: LNV processes

- neutrinoless double beta decay **($0\nu\beta\beta$)**

- μ^-–e^+ conversion in muonic atoms
  ... also violates lepton number by two units
  ... great experimental advances expected

- (di-)muonium conversion
  ... leptonic bound states (e.g. e^+–μ^-)
  ... quite generically hard to measure

- lepton number violating processes at future lepton colliders (e.g. $e^+e^+ \rightarrow l^- l'^- + 4W^+$)
  ... may be an interesting route to go

3. Neutrino Masses & LNV

What do we learn if we observe $0\nu\beta\beta$?!?

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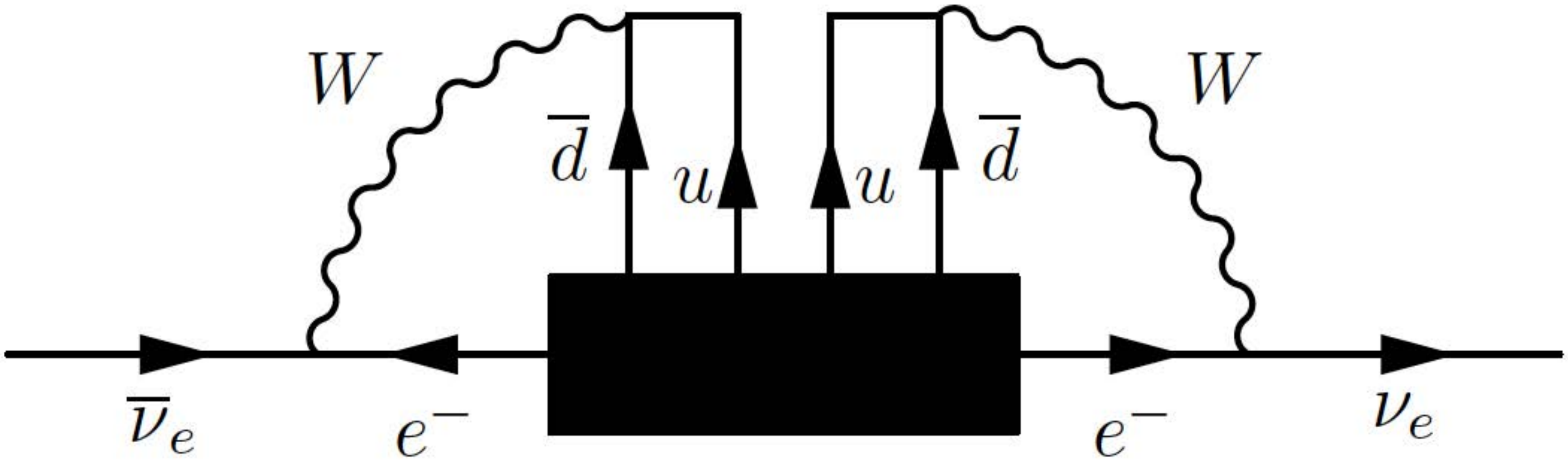
What do we learn if we observe 0νββ?!?

[Schechter, Valle: Phys. Rev. **D25** (1982) 2951]

Schechter-Valle theorem: *ANY* 0νββ-operator leads to a Majorana neutrino mass



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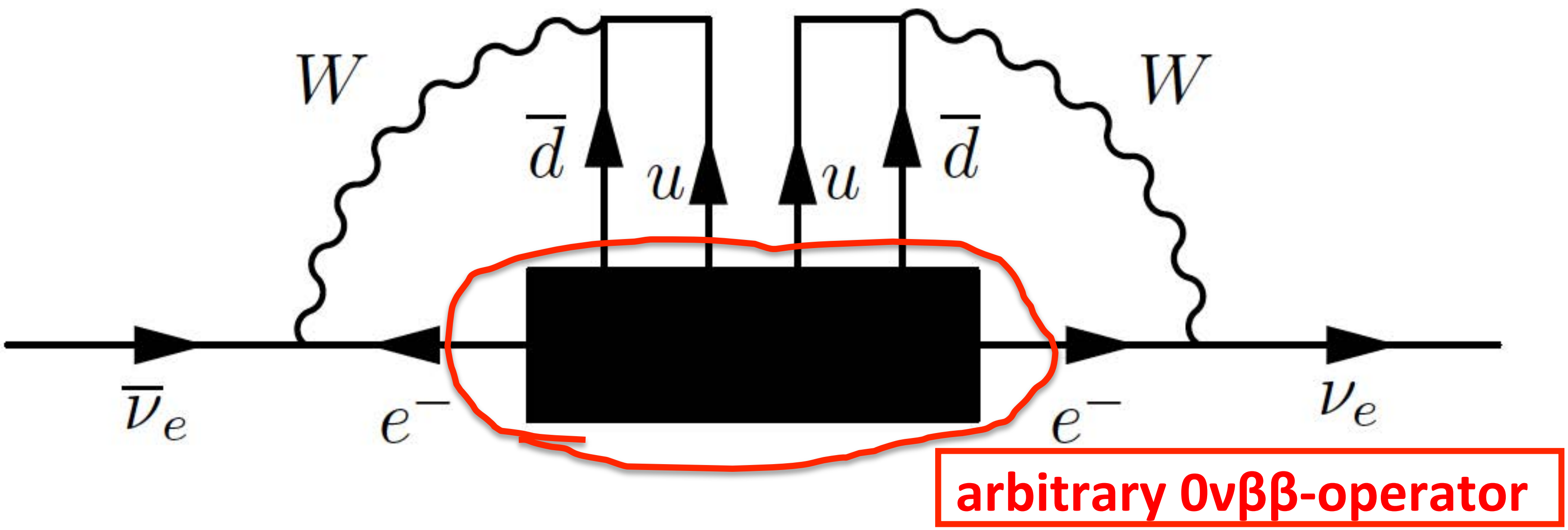

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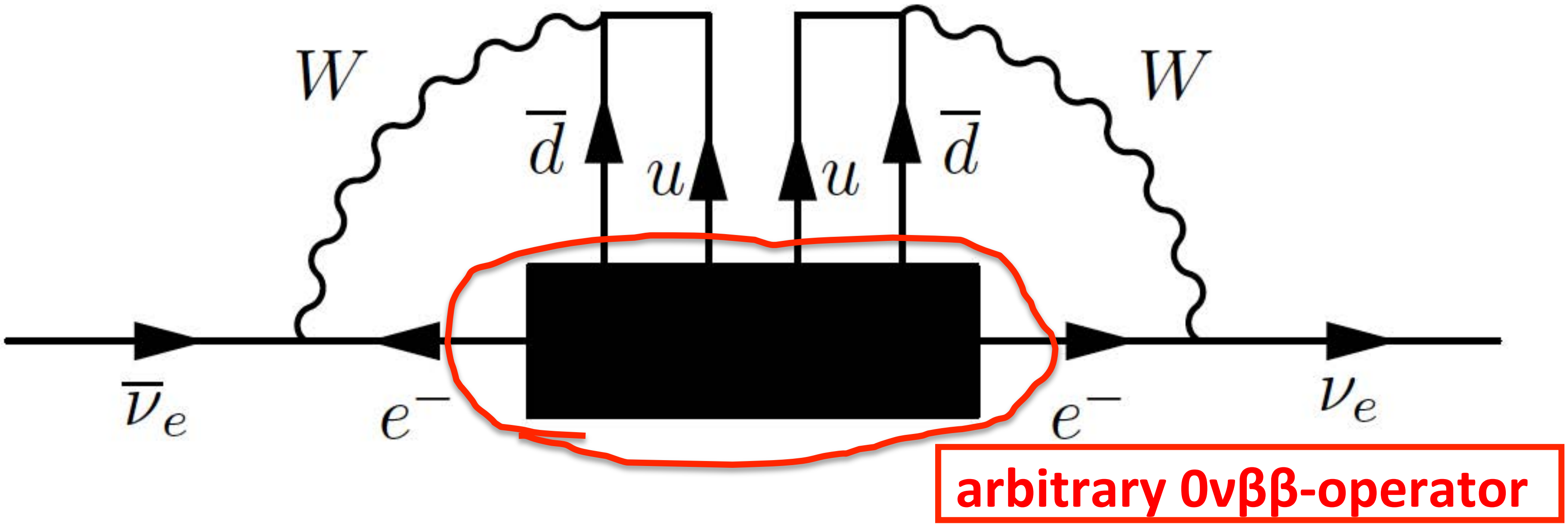

TRUE... unless the operator is $\overline{u}P_L d\, \overline{u}P_L d\, \overline{e}P_L e^c$
... then the mass contribution is zero!!!

[Dürr, Lindner, **AM**: JHEP **1106** (2011) 091]

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Drawing a Feynman diagram is just not enough to derive very strong conclusions!

arbitrary 0νββ-operator

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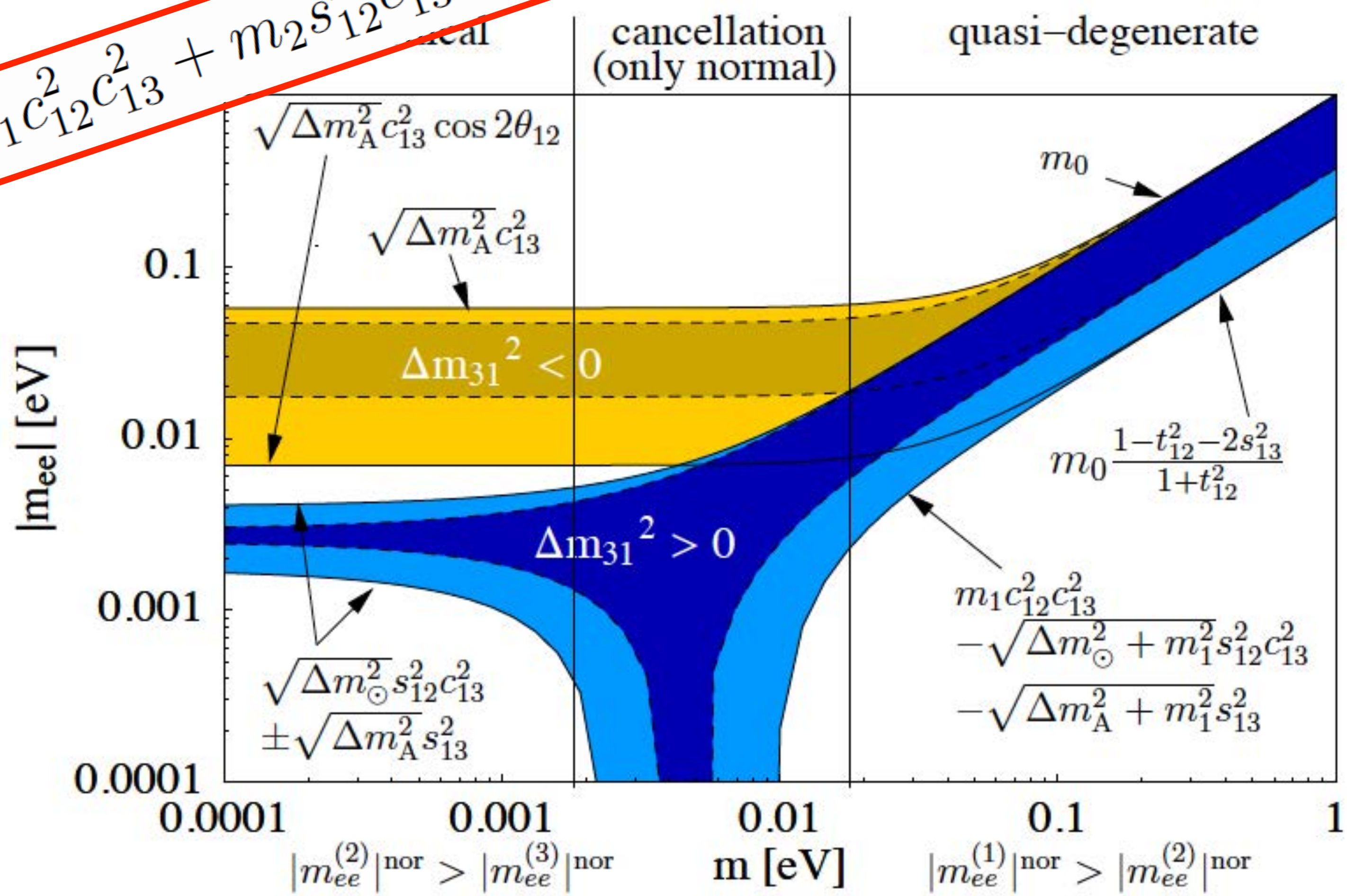
IF 0νββ is mediated by light neutri… exchange, **THEN** the ampl… …nstrains the effective neutri… $|m_{ee}|$:

$$|m_{ee}|_{PDG} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-2\delta)}|$$



[Lindner, **AM**, Rodejohann: Phys. Rev. **D73** (2006) 053005]

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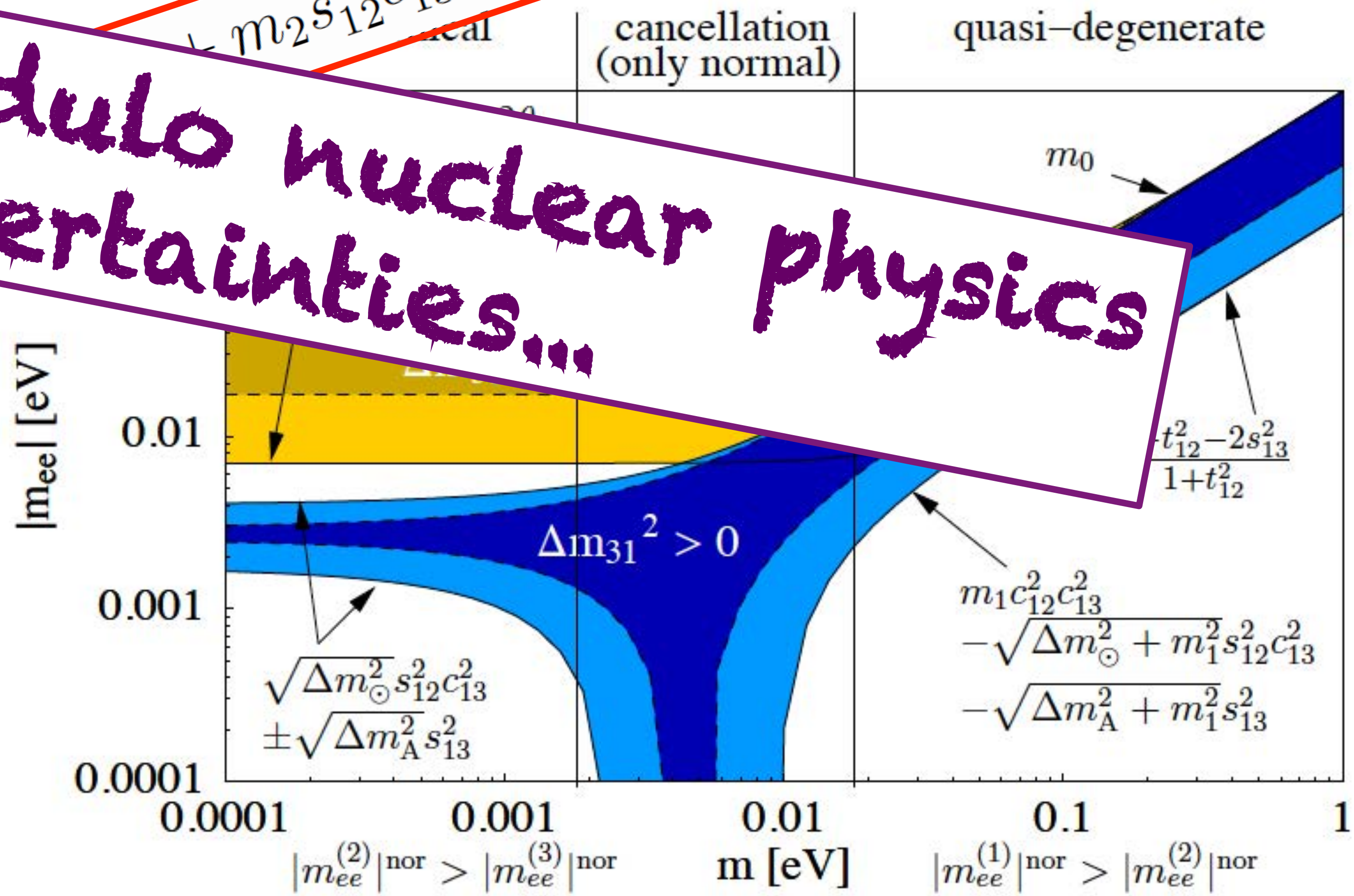
IF 0νββ is mediated by light neutri[...]o exchange, **THEN** the ampl[...] [...]nstrains the effective neutri[...] $|m_{ee}|$:

$$|m_{ee}| [\ldots] + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-2\delta)}|$$

Modulo nuclear physics uncertainties...



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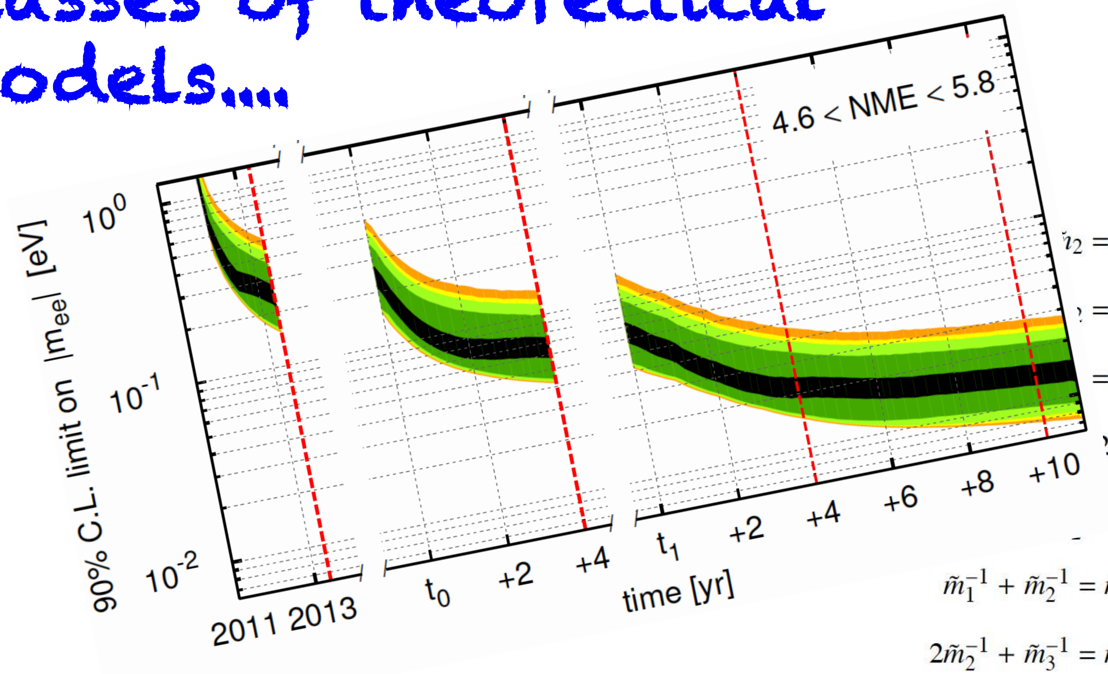
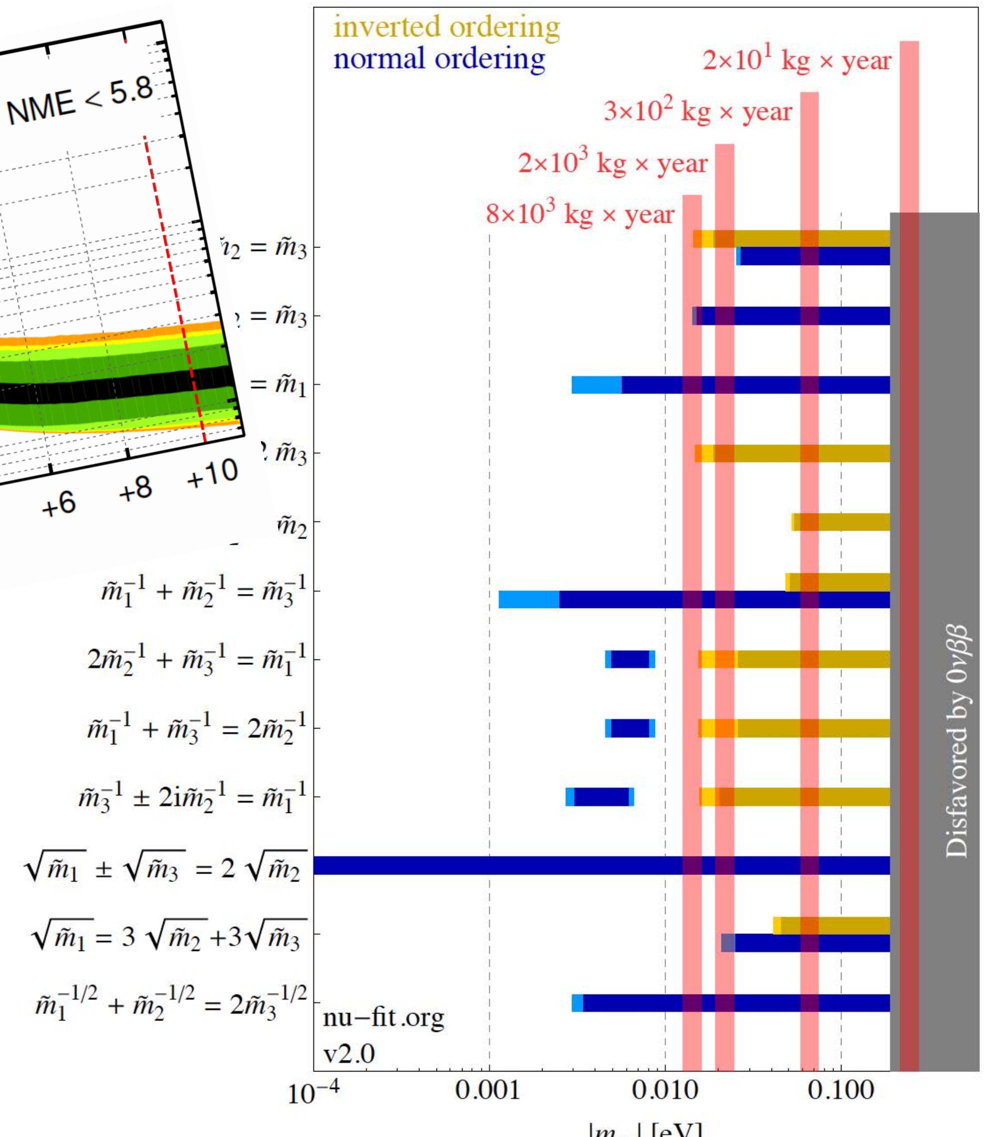
3. Neutrino Masses & LNV

In the long run, we may nevertheless probe classes of theorectical models....





... in particular if theorists and experimentalists collaborate!!!

[Agostini, **AM**, Zuber: 1506.06133]

5. Conclusions

- **Neutrinos...** probably hold mysteries because they just seem not to be like SM-fermions

- **Neutrino mixing...** is experimentally established and suggests to go even further

- **Neutrinoless double beta decay...** would revolutionise the field if seen

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... so please do your best!!! ;-)


THANK YOU!!!