Neutrino Theory

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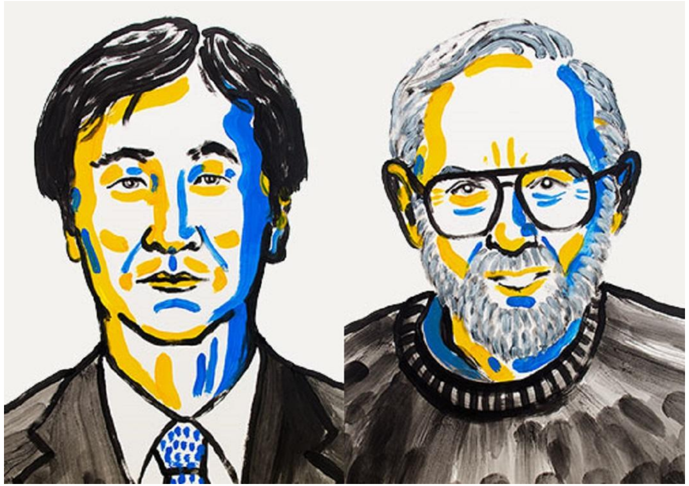
On the trail of neutrino mass

- In 2015, the Nobel Committee awarded the prize in Physics to A. MacDonald and T. Kajita

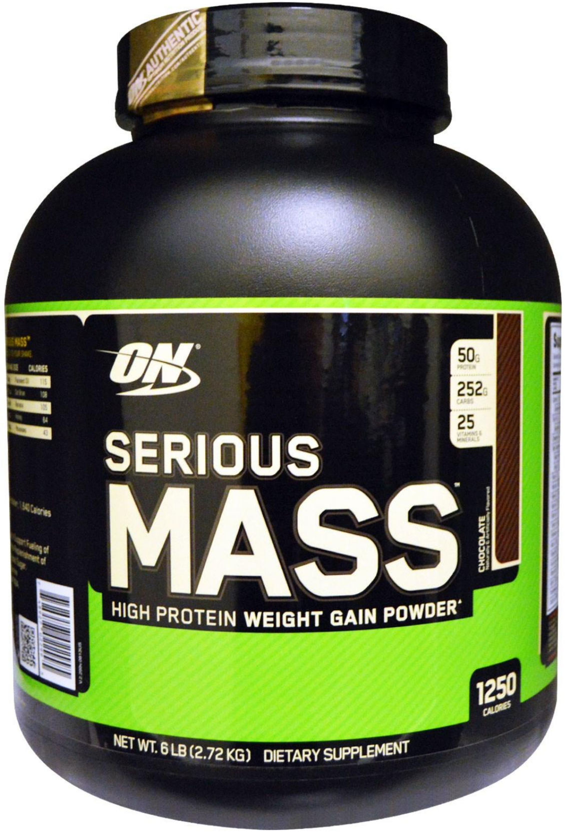
  "for the discovery of neutrino oscillations, which shows that neutrinos have mass"



- And yet, neutrino masses have no explanation in the Standard Model.
- A major theoretical effort is spent on understanding how neutrinos get mass, the implications of these models and their phenomenology at low-energies. This will be the focus of today's talk.
- Much more beyond this that I won't mention today
  - nu-nuclear cross-sections
  - cosmological/astrophysical neutrinos
  - reactor/Gallium/SBL anomalies
  - collider signatures
  - cLFV searches
  - ...

Bulking up

Surveying the options for neutrino mass generation



Low-scale neutrino mass

Below the EW scale, all mass mechanisms appear in one of two forms

$$\mathcal{L} \supset m_{ij} \overline{\nu_L^i} \nu_R^j$$

$$\mathcal{L} \supset m_{ij} \overline{\nu_L^i} (\nu_L^j)^c$$

Observables:

- PMNS matrix (3 angles, 1+2 phases)
- Two mass-squared splittings
- One absolute mass scale parameter (e.g. the lightest mass)
- L=2 lepton number violating effects proportional to neutrino mass

Almost identical descriptions in terms of 7 (+2) low-scale mixing parameters:

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{matrix} \Delta m^2_{21} \\ \Delta m^2_{31} \end{matrix} \quad m_0$$

Mechanisms for neutrino mass

- Neutrinos in the SM are massless for two key reasons:
  - Assumed field content (no RH neutrinos, no exotic Higgses)
  - Renormalizability (no higher dimension operators, e.g Weinberg operator)

- To introduce masses we must either introduce new particles, or abandon renormalizability and work in an effective field theory (which in most cases is tantamount to adding new particles).

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A first attempt: Dirac mass. RH partners introduced, allows for Yukawa interaction.

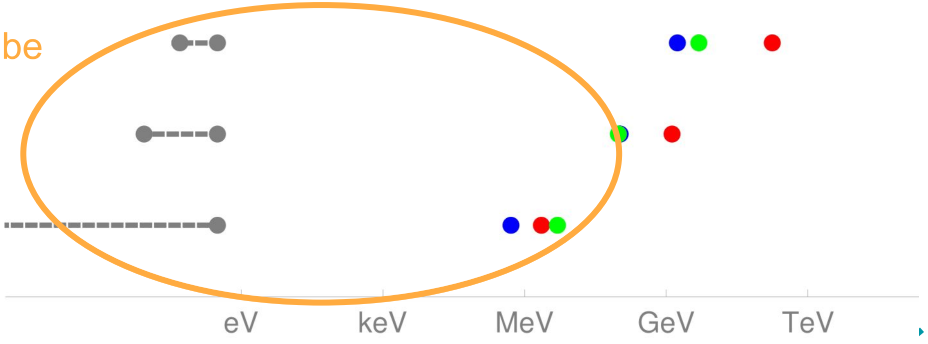
$$y_{ij}\overline{L^i}H\nu_R^j$$

Perfectly consistent, but to agree with data, we require two pieces of fine tuning:

Must be tuned away.

$$M_{ij}\overline{\nu_R^i}\left(\nu_R^j\right)^c$$

Hierarchy must be put in by hand.



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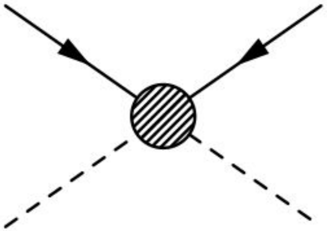
A second attempt: New particles at high scales. Low-scale effects described by an Effective Field Theory.

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Naturally small due to scale suppression.

At dim = 5:

$$\mathcal{L}_5 = c_5 \overline{L} H H L^c + \text{h.c.}$$
$$= \frac{c_5 v^2}{2} \overline{\nu_L} (\nu_L)^c$$



(Weinberg 1979)

Many more possibilities

A very incomplete list:

- *Natural Dirac models* e.g. neutrinophilic 2HDM, pseudo-Dirac, left-right symmetry, radiative models, extra dimensions, …
- *Seesaw mechanisms* e.g. Type I, Type II and Type III.
- *Non-minimal seesaws* e.g. inverse-, double-, linear-seesaws (multiple mediator, tree-level)
- *Radiative completions of Weinberg* e.g. Zee-Babu, Ma's scotogenic model, ...
- *Mass from higher d>5 operators* e.g. tree-level options up to d=11, radiative versions studied up to d=7.
- *Also:* Flavour symmetric models, GUT models, gravitational effects …

As you can see: the generation of mass is (relatively) easy!

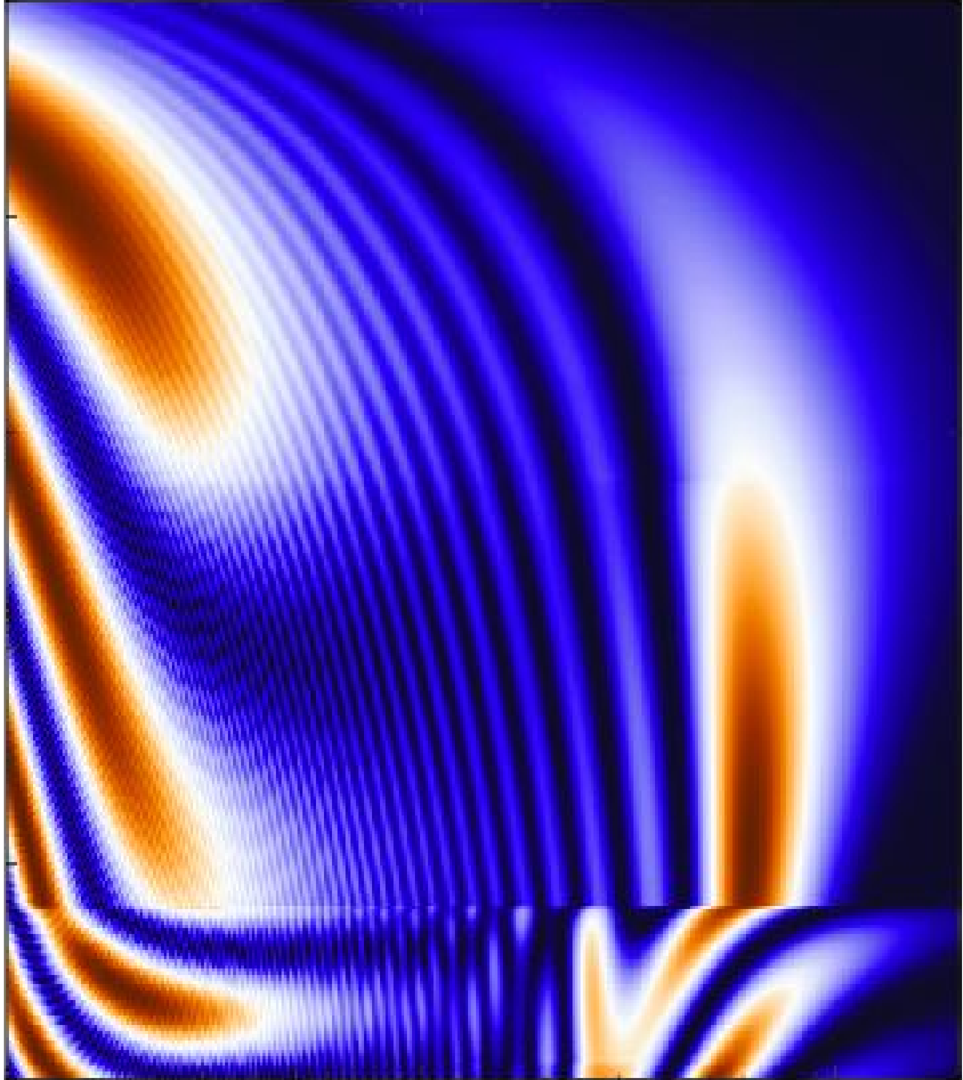
The challenge is to identify the genuine BSM mechanism underlying neutrino mass generation.

Potential to fundamentally change our view of:

CP violation
Lepton Number Violation
Flavour in the (B)SM
The scale and nature of new physics
And more...

Low-scale mass phenomenology

Exploring neutrino mass terms at low energies



Oscillogram *JUNO Coll.* 1507.05613

Our current knowledge of neutrino mass terms comes from oscillation measurements.

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$7.99 \to 8.91$
$\delta_{\mathrm{CP}}/^\circ$	261^{+51}_{-59}	$0 \to 360$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

NuFit coll. 1611.01514

Our current knowledge of neutrino mass terms comes from oscillation measurements.

We have learnt a lot but there are still key questions to answer:

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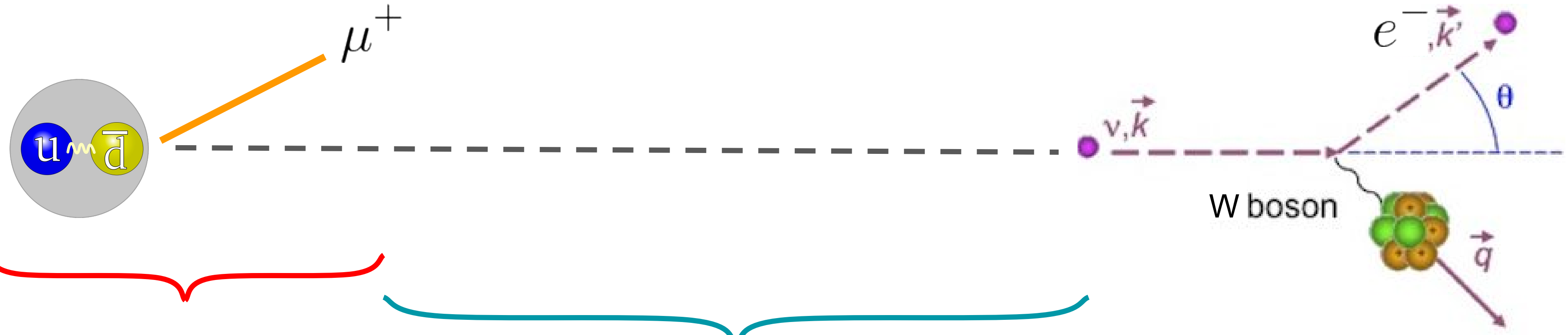
What is the value of theta23? Does it sit in the upper or lower octant? Is it maximal?

What is the value of the CP phase? Does CPV exist in the leptonic sector?

Do neutrinos have normal or inverted ordering?

NuFit coll. 1611.01514

Neutrino oscillation



Neutrinos are produced in a coherent superposition of mass eigenstates.

$$\nu_\alpha = U_{\alpha i} \nu_i$$

Coherence conditions must be satisfied by production mechanism (they almost always are).

Propagation generates mass dependent phase factors.

$$|\nu_\alpha(L)\rangle = \sum_i U_{\alpha i} e^{-i \frac{m_i^2 L}{2E}} |\nu_i(0)\rangle$$

Phase can depend on medium.

Detection projects us back onto the flavour basis.

Flavour transitions can occur.

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U_{\alpha i} U^*_{\beta i} e^{-i \frac{m_i^2 L}{2E}} \right|^2$$

We can compute probabilities in perturbation theory:

$$\epsilon = \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \approx 0.02$$

First oscillation maximum depends on matter effects.

$$P(\nu_\mu \to \nu_e; E, L) = \frac{4}{(1-r_A)^2} \sin^2\theta_{23} \sin^2\theta_{13} \sin^2\left(\frac{(1-r_A)\Delta L}{2}\right)$$
$$+ 8J_r \frac{\epsilon}{r_A(1-r_A)} \cos\left(\delta + \frac{\Delta L}{2}\right) \sin\left(\frac{r_A \Delta L}{2}\right) \sin\left(\frac{(1-r_A)\Delta L}{2}\right)$$
$$+ \mathcal{O}\left(\epsilon^2\right)$$

First appearance of Δm^2_{21}

Fundamental CP violation appears at next-to-leading order.

Asano and Minakata 1103.4387

Alongside leptonic CPV, the mass ordering and the octant of theta23, precision oscillation physics will be able to test the oscillation paradigm itself:

Does the data agree with our simplest extensions of the SM?

- Sterile neutrinos
- Non-unitarity
- Non-standard interactions
- ...

Does the data contain any signs of new symmetries or principles at play?

- Maximal angles
- Sum rule correlations
- Approximate CP conservation
- ...

Neutrino oscillation is a unique tool for probing novel features of the new SM.

It may be the gateway towards additional new physics.

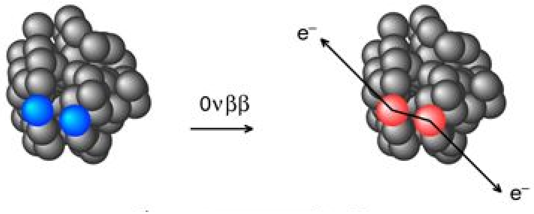
We must investigate it as comprehensively and with as much precision as possible.

Neutrino mass beyond oscillation

Oscillation is currently our only means of exploring neutrino mass. It is highly desirable to observe the effect of mass in other processes.

The next major hurdle for neutrino mass exploration will be to identify positive evidence for its role beyond oscillation.

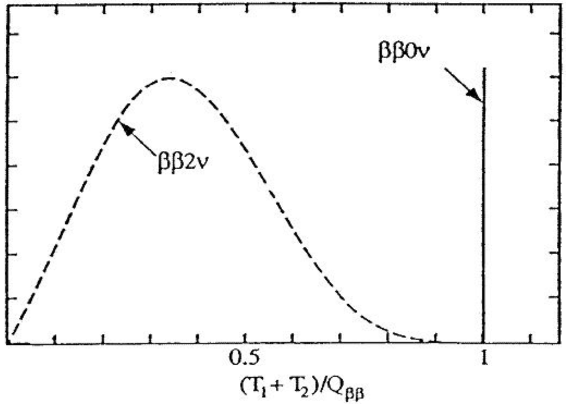
For example: $0\nu\beta\beta$



Nuclear decay: $2n \rightarrow 2p + 2e^{-}$

Observation would be proof of lepton number violation.

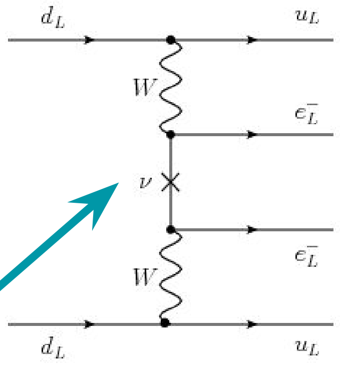
Very clean signature:



Light majorana exchange

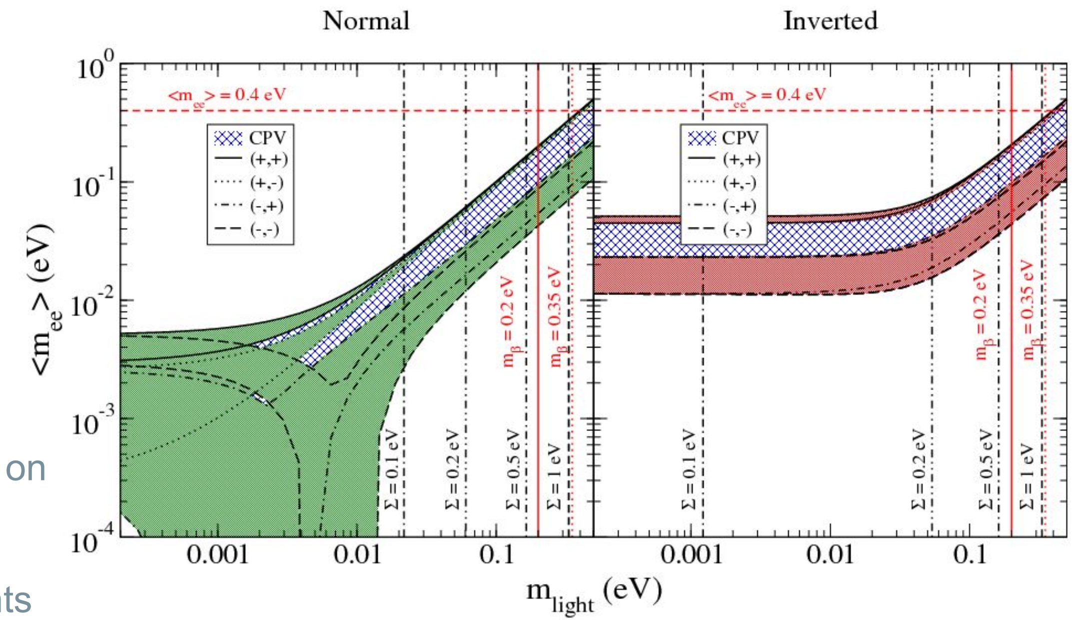
Simplest mechanism, naturally linked to neutrino mass.

Rate governed by mixing angles and masses, including Majorana phases and absolute mass scale.



Possible due to LNV propagator of majorana fermion.

$$|m_{\beta\beta}| = \left|\sum_{i=1}^{3} m_i U_{ei}^2\right| = \left|m_1 \cos^2\theta_{12}\cos^2\theta_{13} + m_2 \sin^2\theta_{12}\cos^2\theta_{13}e^{i\beta_1} + m_3 \sin^2\theta_{13}e^{i\beta_2}\right|$$



For inverted ordering there is a lower bound on the rate.

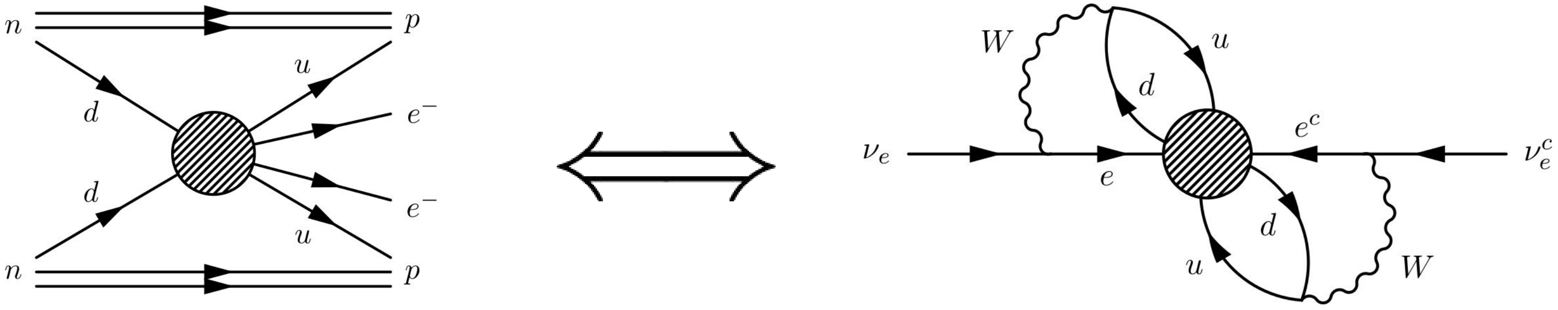
This allows for complementary measurements between NDBD and oscillation physics!

Rodejohann 1206.2560

$0\nu\beta\beta$ decay: exotic mechanisms

- Searching for neutrinoless beta-decay (NDBD) is not narrowly focused on light majorana masses.
  - Many mechanisms exist for L=2 contributions to the decay rate.

However, all mechanisms are all linked *in some way* to neutrino mass generation. (Schechter & Valle 1982)



Any mechanism for NDBD contributes to neutrino majorana masses (and vice versa).

However, these processes can occur at unexpected scales. An anomalously large NDBD rate would be highly informative on the nature of the new physics responsible for neutrino mass.

Discrepancies between oscillation and NDBD could tell us unique information about neutrino mass.

In summary

- Neutrinos are massive, but explaining this theoretically requires new (undiscovered) particles.

- Precision neutrino experiments are constraining the sector as never before. We can expect unprecedented knowledge of low-scale parameters. (Look out for discrepancies in results and between experiments!)

- Study of neutrino masses offers many potential major discoveries:
    - Leptonic CP violation
    - Lepton number violation
    - Unusual flavour structures
    - New particles

- A diverse experimental programme, and close collaboration between theory and experiment is essential to fully explore the mechanism which completes the neutrino sector.

Thank you

And thanks to...