The Discovery Power of Future Neutrinoless Double Beta Decay Experiments

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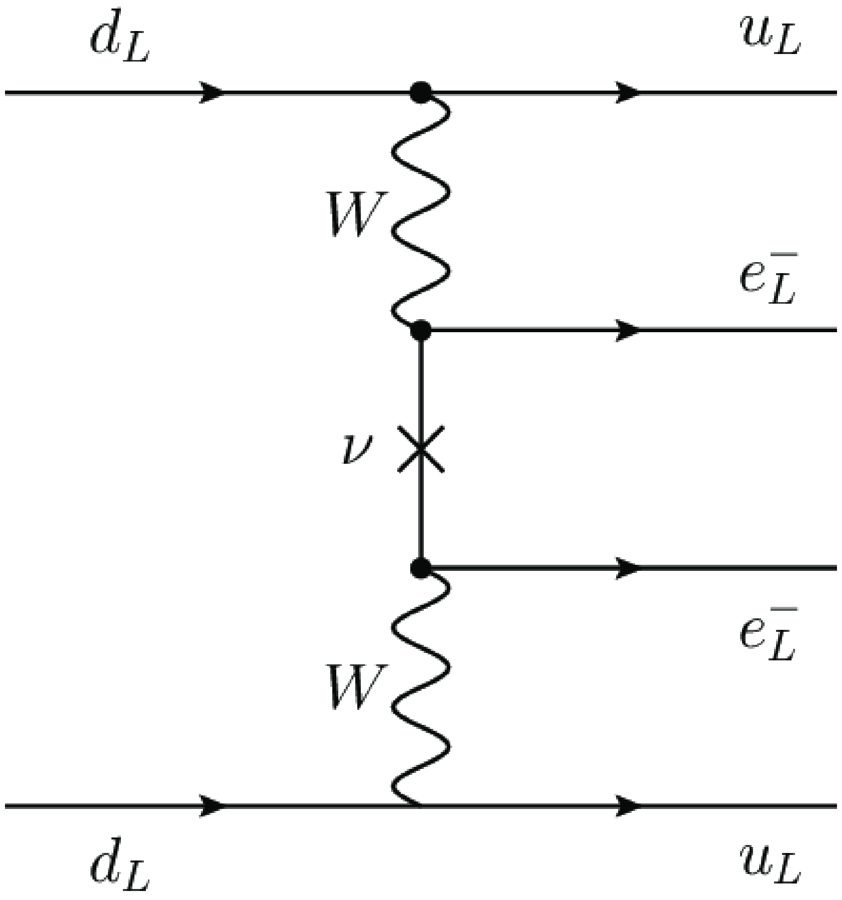
What is Neutrinoless Double Beta Decay?

- Neutrinoless Double Beta Decay ($0\nu\beta\beta$) is a nuclear beta Decay which emmits two left-handed electrons but no neutrinos.
- This could be possible due to the possible Majorana nature of neutrinos.
- Majorana mass term: $m\Psi_L^T C\Psi_L$

  Dirac mass term: $\mathrm{m_D}\overline{\Psi}_R\Psi_L$
- Majorana Particles are their own anti-particles.



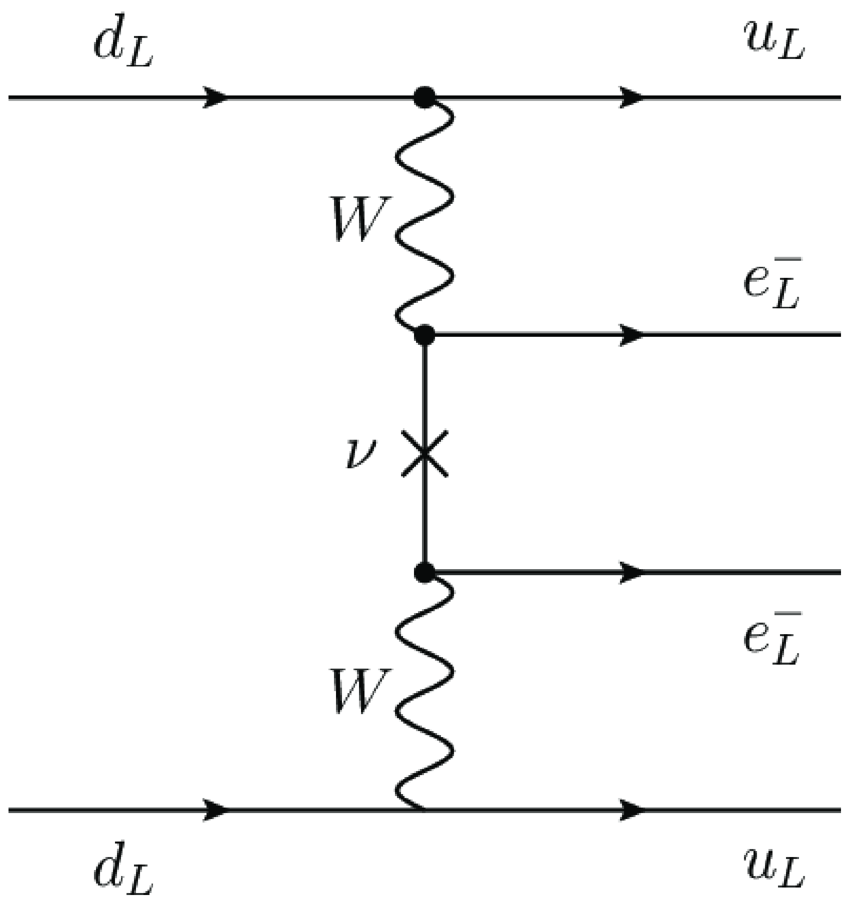
Why is Neutrinoless Double Beta Decay interesting?

- Signature of Majorana neutrinos or other BSM physics.

  ⇒ Special Origin of neutrino masses compared to other particles.

- $0\nu\beta\beta$ Decay violates Lepton Number Conservation.

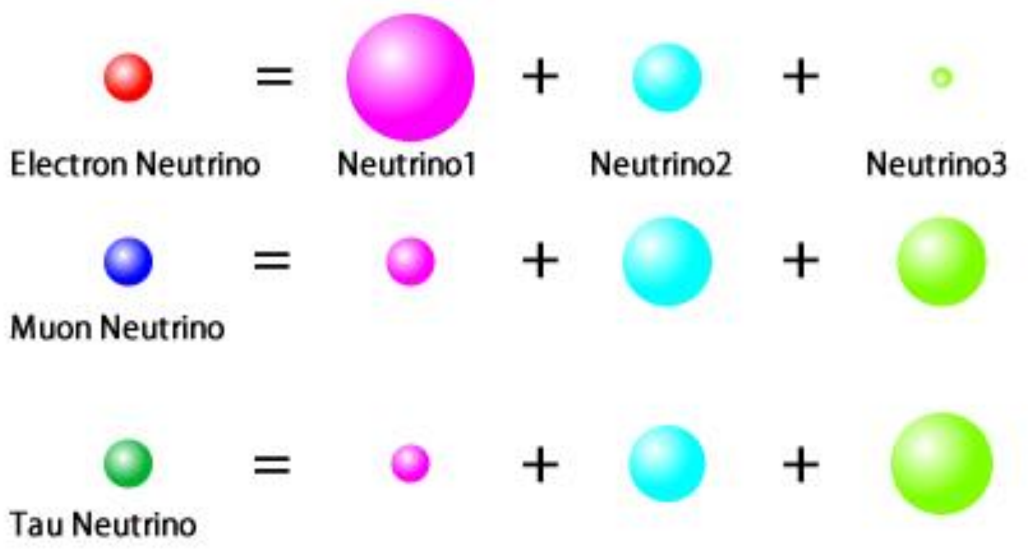
  ⇒ Possible explanation for matter-antimatter asymmetry.



Basic Neutrino Physics

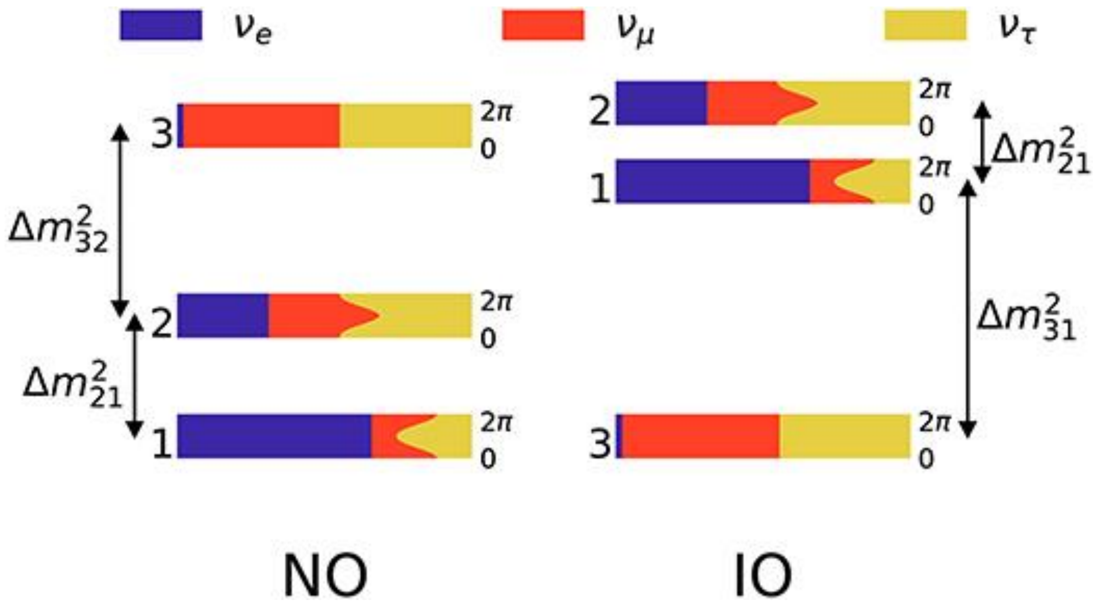
- A Neutrino of a given flavor is a superposition of mass eigenstates
- The connection between flavor and mass basis is given by the PMNS matrix U
- The superposition of a flavor eigenstate is given by

$$\nu_\alpha = \sum_i U^*_{\alpha i} \nu_i$$



Basic Neutrino Physics

- The masses of the different mass eigenstates can be sorted in two ways.
- The mass splitting is deterimend by Neutrino Oscillation Experiments
- The Inverted Ordering (IO) and the Normal Ordering (NO)



Great Experimental Effort has been done

- $0\nu\beta\beta$ Decay Experiments search for this signature in nuclear decays.

- A key parameter of $0\nu\beta\beta$ Decay is the effective Majorana mass:

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e_1^{i\alpha_1} + s_{13}^2 m_3 e^{i\alpha_2}|$$

with c_{ij} and s_{ij} being the cosines and sines of the PMNS parameters, m_i the mass of neutrinos mass eigenstates and α_i the Majorana phases.

The PMNS parameters are comparable well measured by oscillation experiments.

Great Experimental Effort has been done

- $0\nu\beta\beta$ Decay Experiments measure the half-life $T_{\frac{1}{2}}^2$ of neutrons decaying via $0\nu\beta\beta$

$$\frac{1}{T_{\frac{1}{2}}} = G_{0\nu}|M_{0\nu}|^2 \left(\frac{|m_{\beta\beta}|}{m_e}\right)^2$$

With $G_{0\nu}$ the phase space factor, $M_{0\nu}$ the nuclear matrix element and m_e the electron mass.

- The current bounds on $T_{\frac{1}{2}}$ are: CUORE $> 3.2 \times 10^{25}\ yrs$ C.I.

EXO-200 $> 3.5 \times 10^{25} yrs$ C.L.

GERDA $> 1.8 \times 10^{26}$yrs C.L.

KamLAND-Zen $> 2.3 \times 10^{26}\ yrs$ C.L.

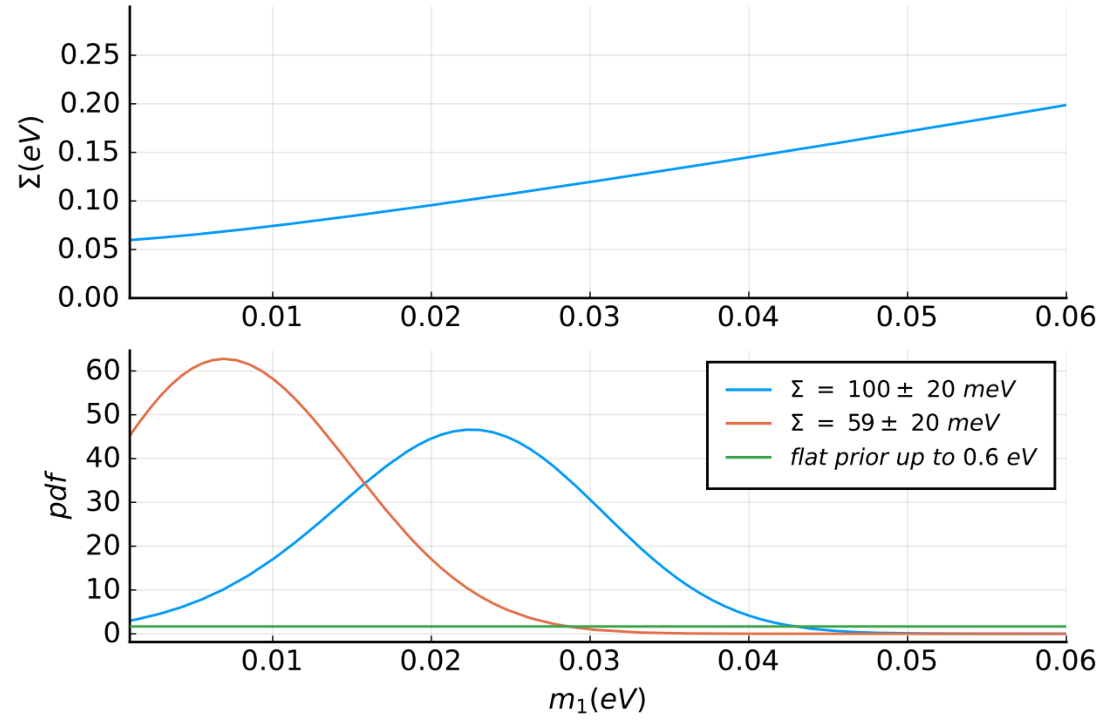
What can we learn from the current data for $0\nu\beta\beta$ parameters?

- The likelihoods of $0\nu\beta\beta$ Decay Experiments $L_{0\nu\beta\beta}$ give us an upper bound on $m_{\beta\beta}$.
- Neutrino Oscillation experiments give us a likelihood L_{osc} on PMNS parameters which also effect $m_{\beta\beta}$.
- Cosmological experiments (Planck mission, Euclid, Desi) give us a likelihood L_{cosmo} on the neutrino mass sum $\Sigma = \sum_i m_i$.
- In our work we combine this likelihoods $L_{total} = L_{0\nu\beta\beta} \times L_{osc} \times L_{cosmo}$ and perform a Bayesian analysis to create a posterior for all relevant parameters.

How is Cosmology entangled with the field?

- The currents strongest bound by Planck (model dependent) is $\Sigma < 0.12\mathrm{eV}$.
- A measurement of Σ together with the oscillation parameters translates into a measurement on the lightest mass eigenstate.
- Current operating (Desi) and planned (Euclid) experiments aim to measure Σ.

Upper or lower bounds will influence the field of $0\nu\beta\beta$ Decay searches.



The Future of $0\nu\beta\beta$ Decay Experiments

- The leading funded Next-Gen experiments are: LEGEND-1000, nEXO, CUPID.
- These experiments use different isotopes and report different expectations in signal counts and background estimation.
- These experiments are built to investigate the whole parameter space of inverted mass ordering.
- But is there a chance to detect $0\nu\beta\beta$ Decay in case of normal mass ordering?

How to estimate the Discovery Probability of Future Experiments?

- We want to investigate a scenario where we combine all three experiments and calculate their combined Discovery Probability (P_D)

- We define two exhaustive hypothesis namely, H_1 with Majorana neutrinos and H_0 with just background.

- As a background statistic we assume Poisson statistics for all experiments:

$$P(D|H_0) = \prod_i e^{-\lambda_i} \frac{\lambda_i^{n_i}}{n_i!}$$

with D is the Data and λ_i being the background expectation of the experiments.

How to estimate the Discovery Probability of Future Experiments?

- The set of parameters in our analysis is $\theta = (m_1, \Delta m_{12}, \Delta m_{13}, s_{12}, s_{13}, \alpha_1, \alpha_2, NME)$

- The probability of a set of signal counts $\{n\}$ given a set of parameters is:

$$P(\{n\}|\theta) = \prod_i e^{-(\lambda_i+\nu_i)} \frac{(\lambda_i+\nu_i)^n}{n_i!}$$

With ν_i the signal expectations for each experiment, respectively.

- Then we can calculate the probability of the data given H_1

$$P(D|H_1) = \int_0^\infty P(\{n\}|\nu(\theta))P(\theta|H_1)d\theta = E\big(P(\{n\}|\nu(\theta))\big)_{P(\theta)}$$

How to estimate the Discovery Probability of Future Experiments?

- With the Definition of $P(D|H_1)$ and $P(D|H_0)$ one can now define the Bayes factor $\mathcal{O}$

$$\mathcal{O} = \frac{P(D|H_1)}{P(D|H_0)} \times \frac{P(H_1)}{P(H_0)}$$

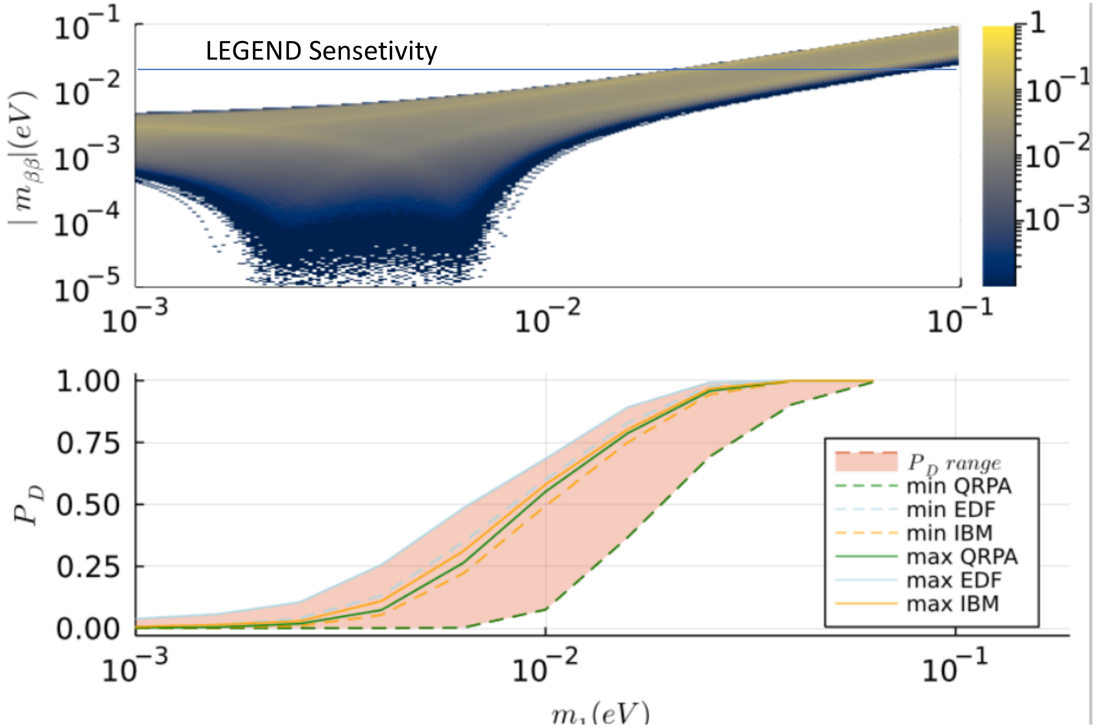
With $P(H_{1/0})$ are the prior odds we assign to the hypothesis and we take them equal.

- We define a discovery when $\mathcal{O} \geq 10$ which means that H_1 is ten times more likely than H_0
- The Discovery Probability P_D we calculate then via sampling first a set of parameters from the posterior $\{\theta\}$ and then sample for these sets of counts $\{n\}$ for each experiment.

$$P_D = \mathrm{E}\left[\mathrm{E}\left[\mathrm{I}\left(\frac{E\left[P\left(\{n\}|\theta\right)\right]_{P(\theta)}}{P\left(\{n\}|H_0\right)}\right)\right]_{P\left(\{n\}|\theta\right)}\right]_{P(\theta)}$$

Results of our Analysis

- We perform a scan over m_1 for different NME models.
- We find that the P_D starts rising for values of m_1 > 1meV.
- Another result is that the P_D rises even stronger as soon we crossed the values for m_1 were the majorana phases can lead to cancellation.



Results of our Analysis

- First we investigate two different scenarios:

  -with Cosmology

  -without Cosmology

- Then we investigate two hypothetical scenarios:

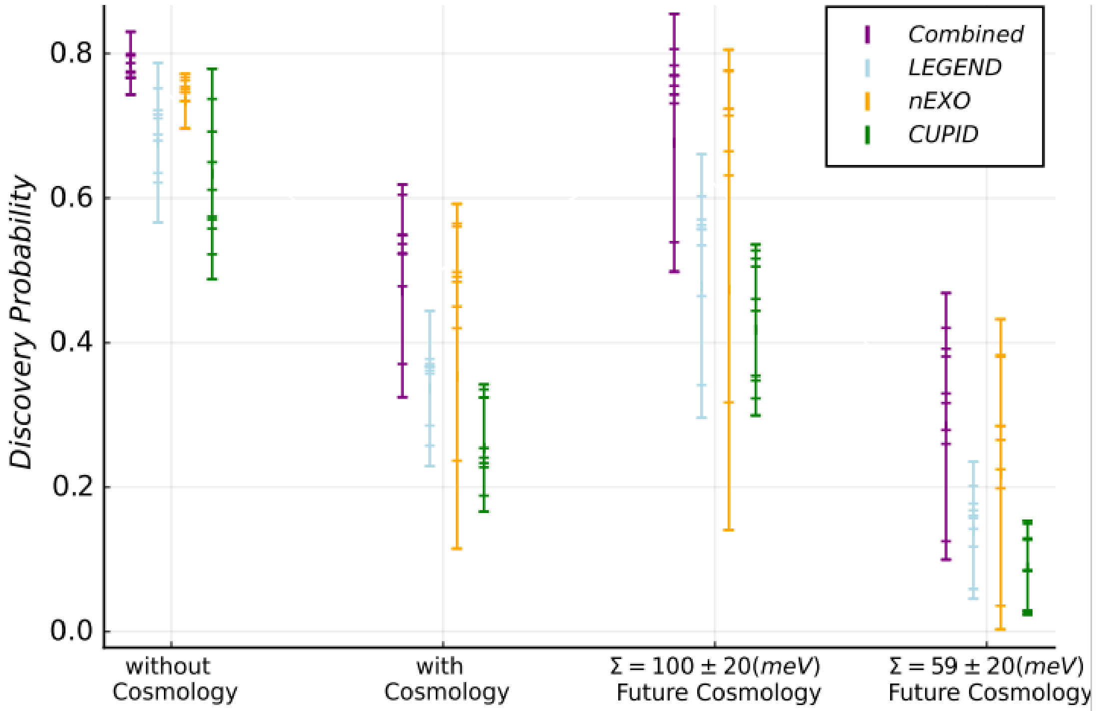
  - Future Cosmology with $\Sigma = 100\text{meV}$

  - Future Cosmology with $\Sigma = 59\text{meV}$

- In the most optimistic scenarios we can reach a P_D between 80-90%!

- Even for most pessimistic scenarios the P_D can reach still up to 50%.

- All calculations are heavily influenced by the chosen NME model!



Conclusion

- Cosmology and $0\nu\beta\beta$ Decay search is a heavily entangled field and future cosmologcial experiments can tell us a lot of possible discoveries of Next-Gen $0\nu\beta\beta$ Decay experiments.

- In case $m_1 \rightarrow 0$ the P_D goes also to 0.

- The different available NME Models can influence the P_D of the experiments.

- Several Experiments with different isotopes can partially compensate the uncertainty caused by the different theoretical values for the NME´s.

- In the most optimistic scenarios the P_D can range between 80-90%!

Overall: $0\nu\beta\beta$ Decay search is at a turning point with a lot of new results in the near future!