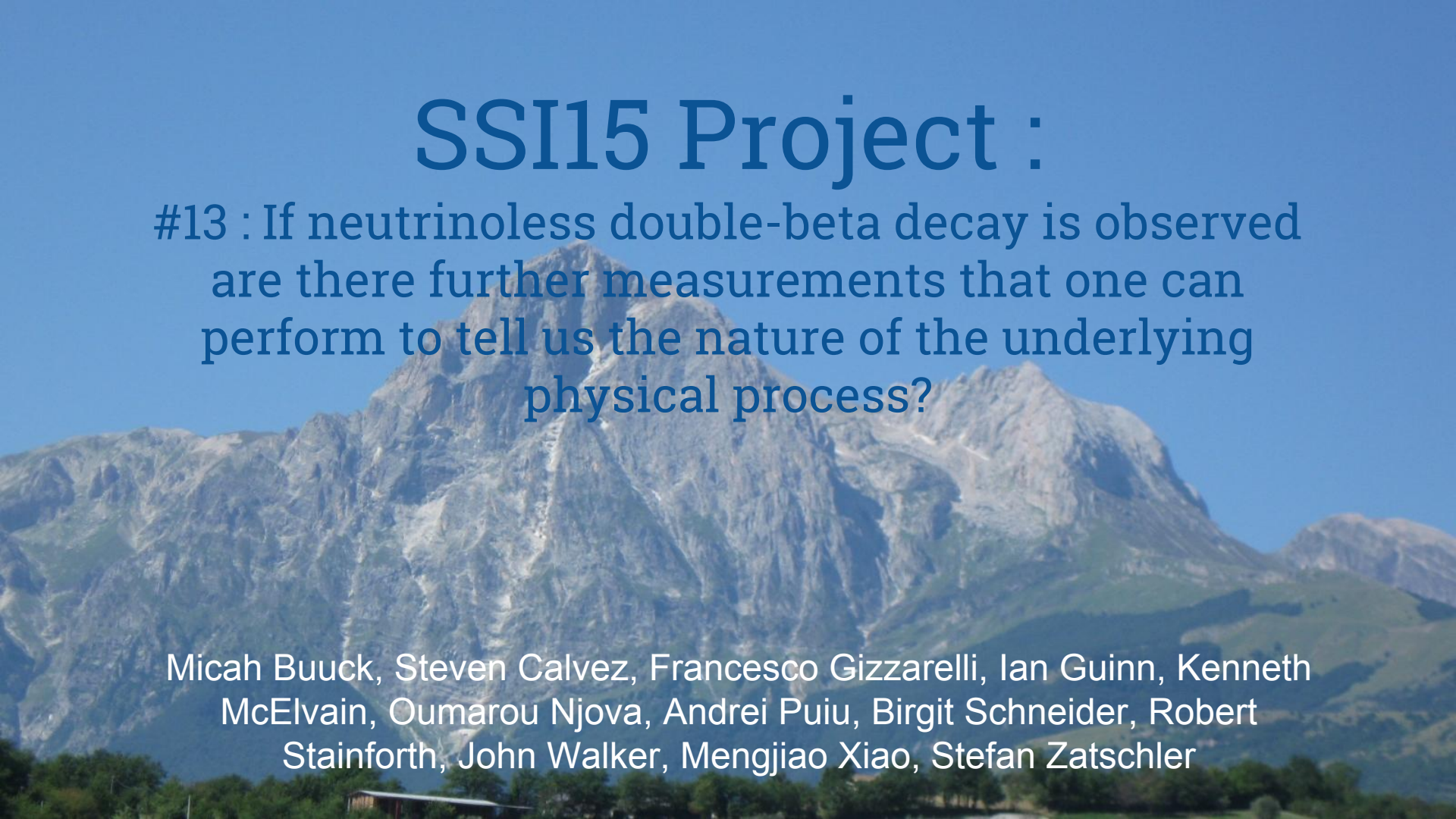
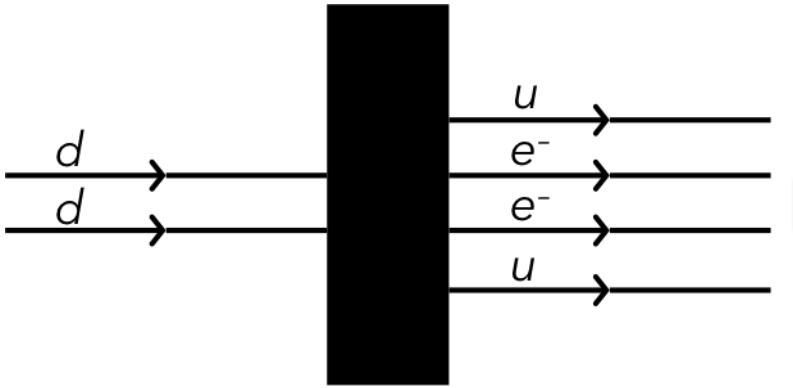


SSI15 Project :

#13 : If neutrinoless double-beta decay is observed are there further measurements that one can perform to tell us the nature of the underlying physical process?

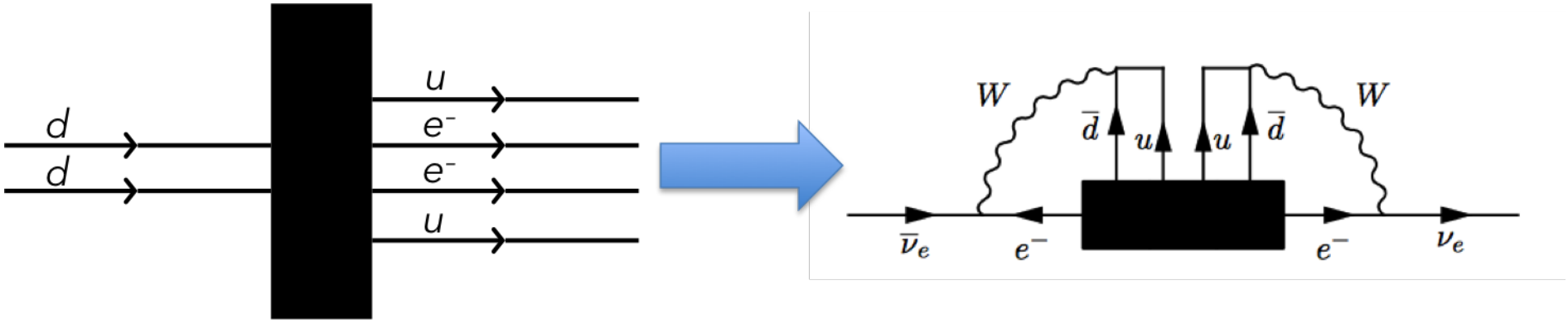
Micah Buuck, Steven Calvez, Francesco Gizzarelli, Ian Guinn, Kenneth McElvain, Oumarou Njova, Andrei Puiu, Birgit Schneider, Robert Stainforth, John Walker, Mengjiao Xiao, Stefan Zatschler

Does 0νββ decay imply Majorana neutrino masses?



Does 0νββ decay imply Majorana neutrino masses?

- Yes



Does 0νββ decay imply Majorana neutrino masses?

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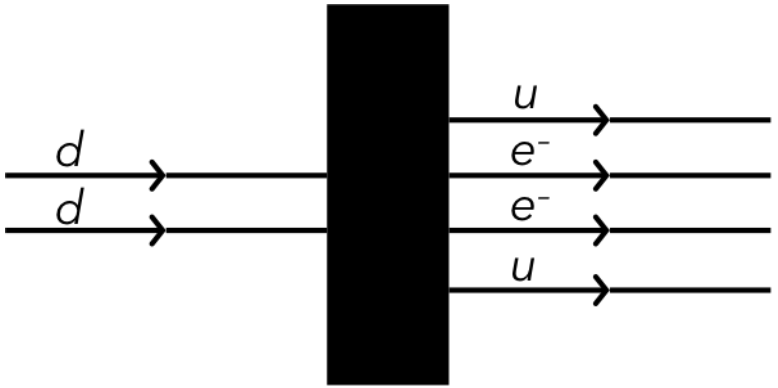
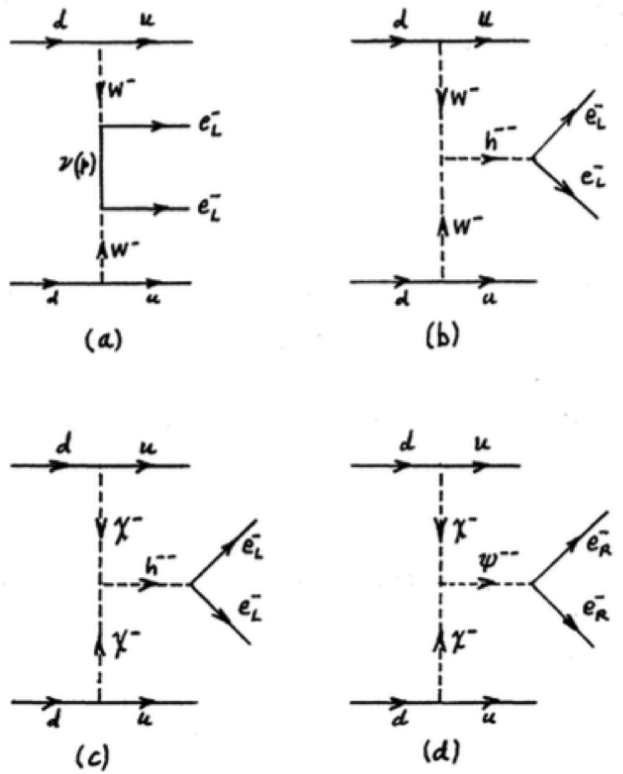
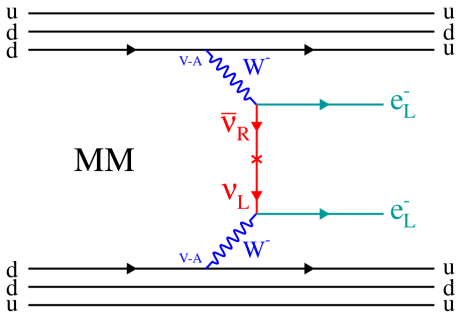


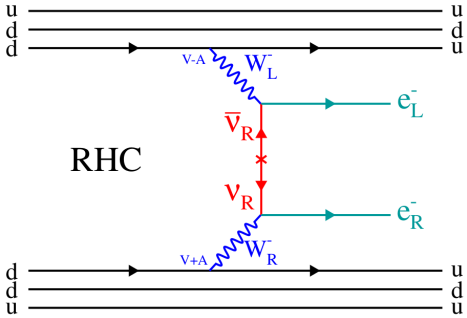


Some hypothesized mechanisms

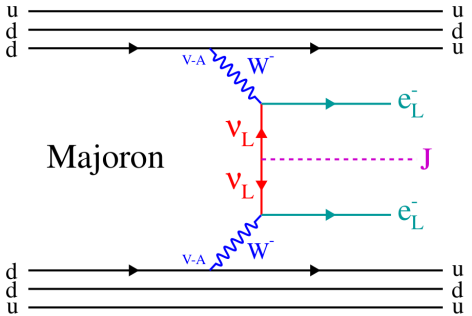
Mass Mechanism



Right-Handed Current

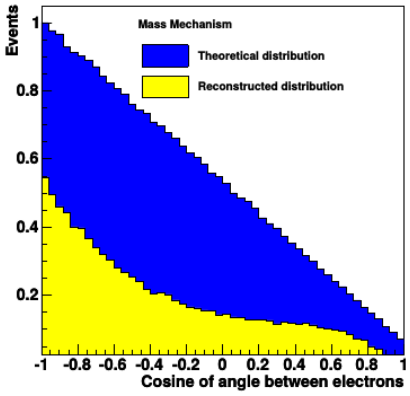


Majoron emission

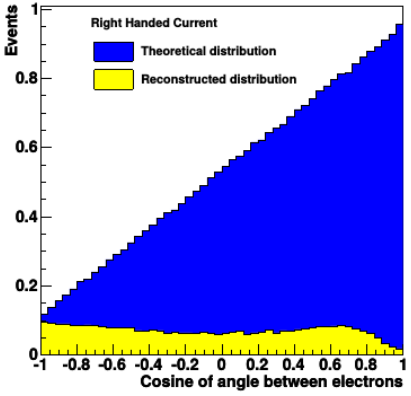


Topology measurements

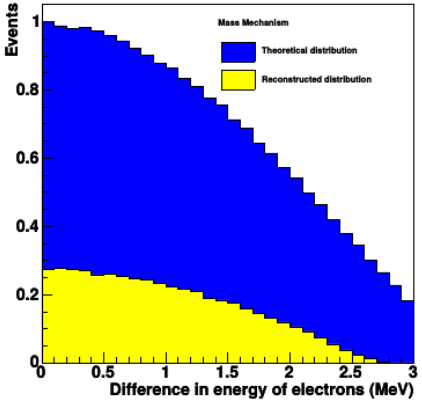
- Reconstructing the angle between the two electrons[1] and measuring their energy difference can discriminate between the Mass Mechanism (a) & (c) and the Right-Handed Current mechanism (b) & (d)
- In blue, the theoretical distributions, in yellow the reconstructed distributions for ^{82}Se in SuperNEMO[2] are shown



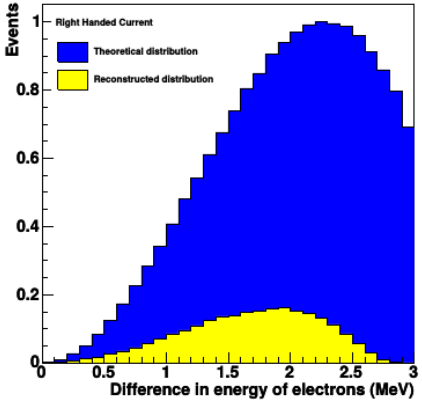
(a)



(b)



(c)



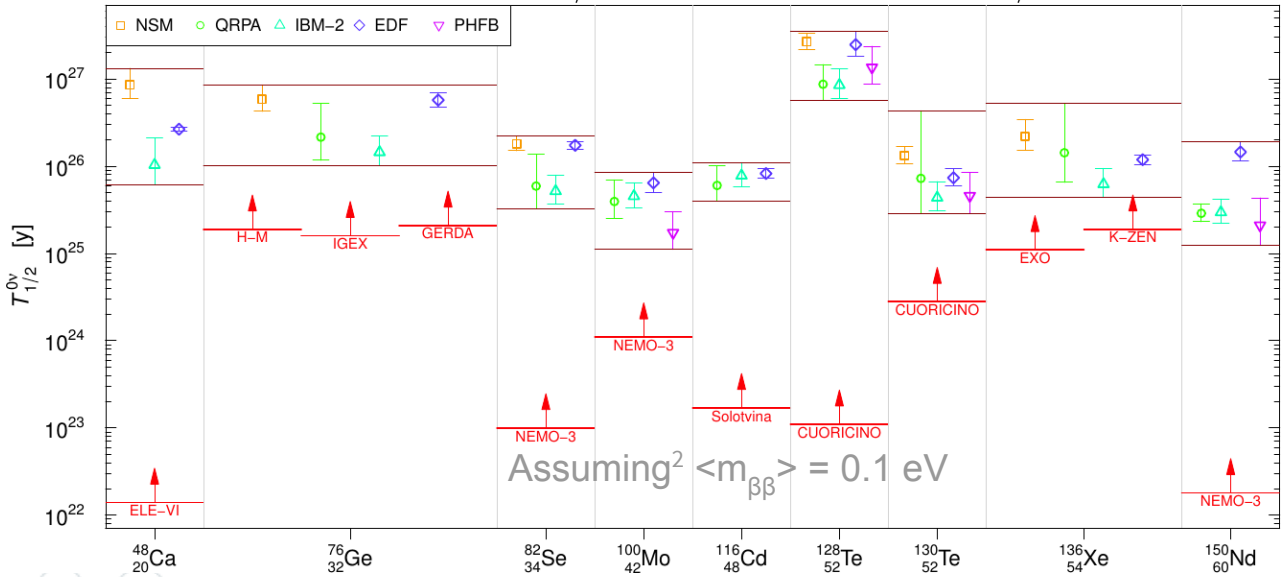
(d)

[1] *Electron angular correlation as a probe of new physics. A. Ali, A.V. Borisov, D.V. Zhuridov arXiv:hep-ph/0606072*
[2] *Probing new physics models of neutrinoless double beta decay with SuperNEMO. R. Arnold et al. arXiv:1005.1241*

Isotope comparison

- Measuring the neutrinoless double-beta decay half-life for several isotopes can also help to identify the underlying mechanism

For instance[1]: $\text{Mass Mechanism}: \frac{T^{82}_{1/2}Se}{T^{150}_{1/2}Nd} = 2.45$ or $\text{RHC}_\lambda: \frac{T^{82}_{1/2}Se}{T^{150}_{1/2}Nd} = 3.64$

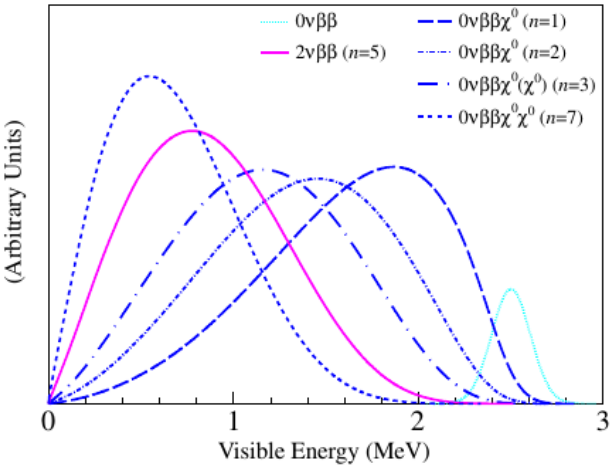


[1] *Probing new physics models of neutrinoless double beta decay with SuperNEMO.* R. Arnold et al. arXiv:1005.1241
[2] *A probe of physics beyond the standard model*. Bilenky and Giunti. arXiv:1411.4791v2

Spectral shape

- An accurate measurement of the spectral shape could provide informations on the 0νββ Majoron emission mode:

Theoretical energy spectra for different spectral indices[1]



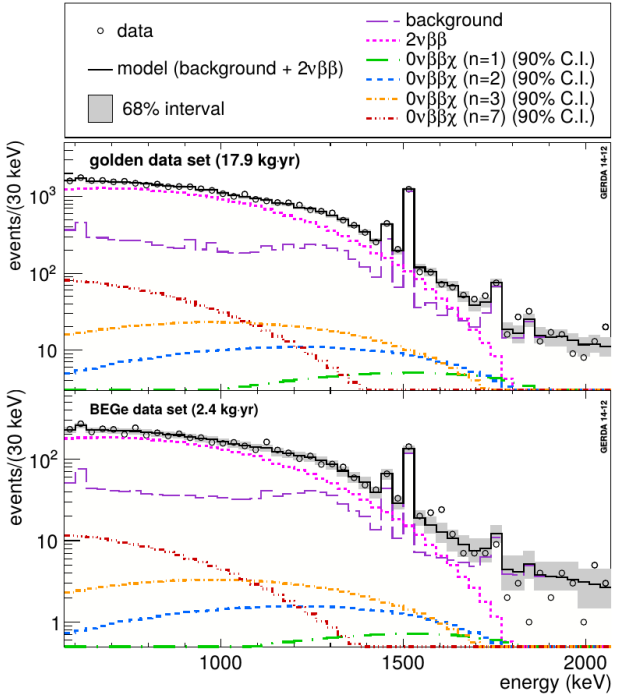
Phase space: $dN/dK \sim (Q_{\beta\beta} - K)^n$

$Q_{\beta\beta}$ … Q-value of decay

K … sum energy of both electrons

n … spectral index

GERDA Phase I results[2]



[1]KamLAND-Zen Collab., arXiv:1205.6372v2

[2]GERDA Collab., arXiv:1501.02345v1

Heavy Majorana neutrino production at the LHC

What is the see-saw mechanism?

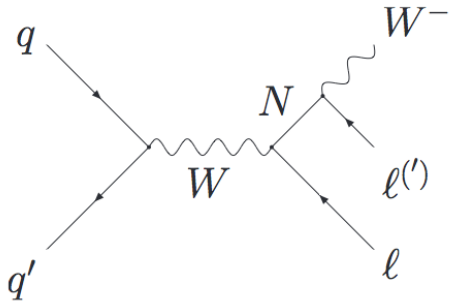
- Explains lightness of neutrino mass by introducing extra fermions.
- Obtain LH majorana mass term when electroweak symmetry is broken.
- Heaviness RH neutrino related to lightness of LH neutrino.
- If extra fermions are singlets: Type I see-saw mechanism.

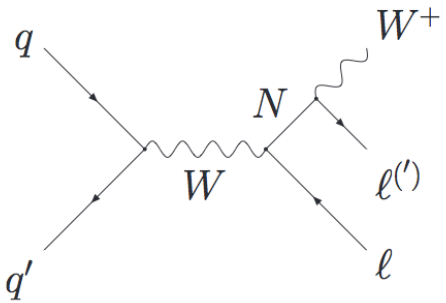
$$m_\nu \sim Y^2 v^2 / 2m_N$$

If neutrinoless double beta decay discovered by current generation of experiments, light majorana mass must be relatively heavy.

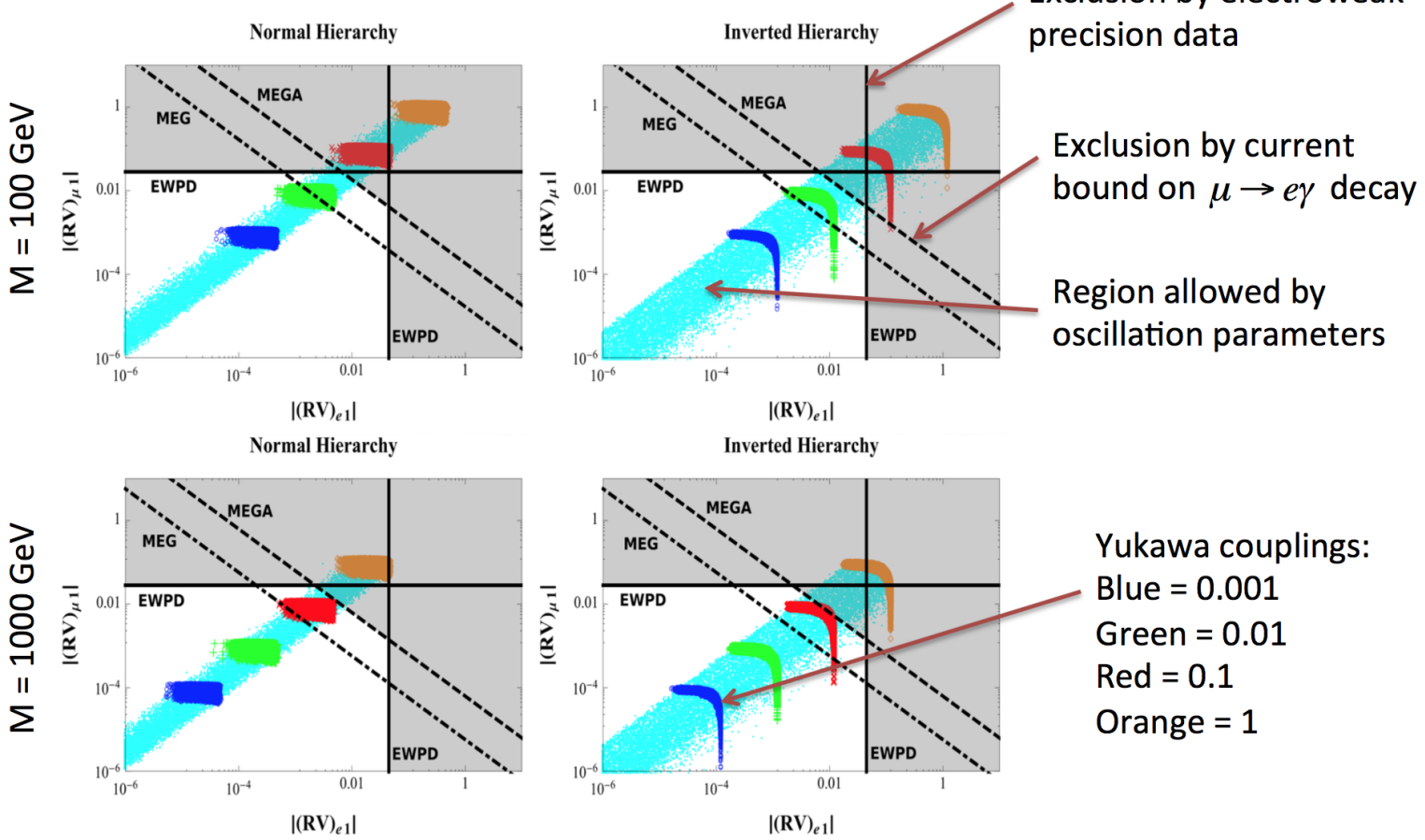
RH neutrinos could have masses O(100-1000) GeV if Yukawa couplings are sizeable.

- Could be detected at the LHC. [1]





[1] F. del Aguila, J. A. Aguilar-Saavedra, R. Pittau, JHEP 0710 (2007) 047. [hep-ph/0703261].



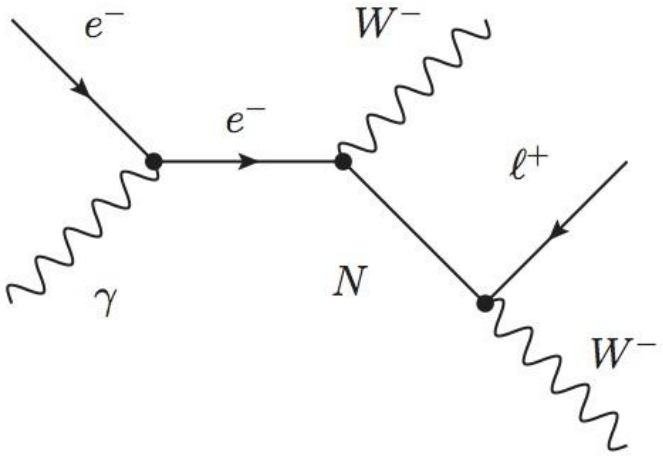
Higher RH majorana mass allows stronger Yukawa couplings

[1] A. Ibarra, E. Molinaro and S.T. Petcov, Phys. Rev. D84 (2011) 013005, arXiv:1103.6217.

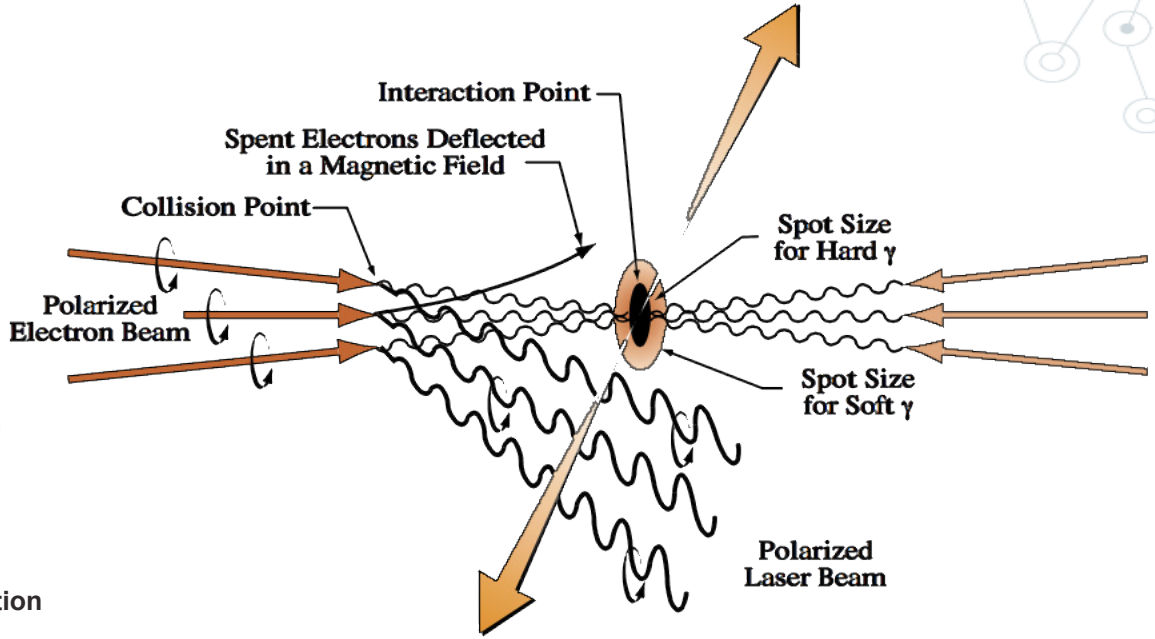
Heavy Neutrino Production at e-gamma Colliders

Two distinct advantages over hadron-hadron colliders: [1]

- Electroweak process ⇒ fewer hadron processes ⇒ fewer backgrounds.
- Initial lepton state L=+1 ⇒ better discrimination for lepton number violated final state.



Example tree-level diagram for heavy neutrino production



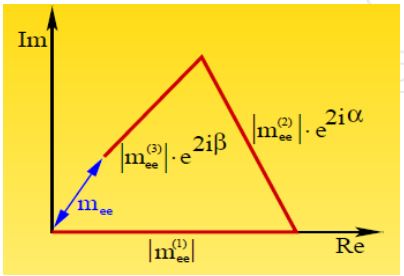
Principle of electron-gamma production for an e-gamma collider

[1] J.Peressutti et al., Phys Rev D, 90, 013003 (2014)
[2] K. Kim et.al, SLAC: Beamline Issue 26. (1996)

Measuring the Majorana CP Phases

Measuring $m_{\beta\beta}$ will place a constraint on the two CP phases, assuming you know the majorana masses and Dirac phase. A second measurement is needed…

$$|m_{\beta\beta}| = \left||U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\alpha} m_2 + |U_{e3}|^2 e^{2i\beta} m_3\right|$$

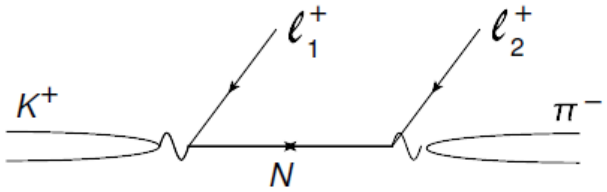


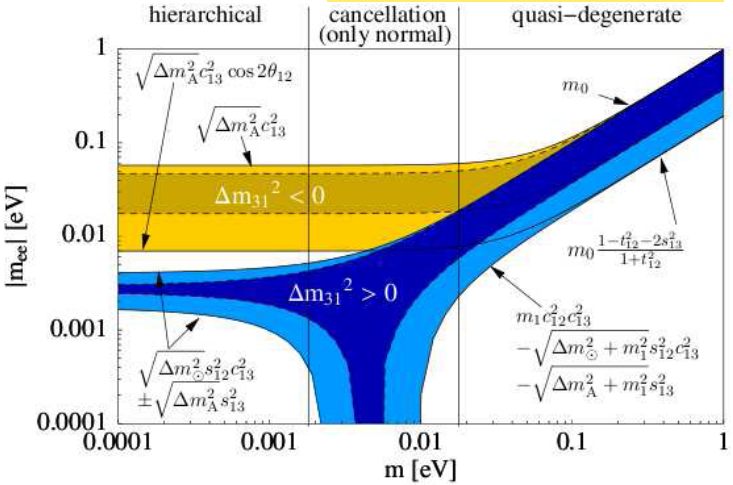
One possibility is to measure the effective mass for a different decay

$$|m_{\alpha\beta}| = |\sum_i U_{\alpha i} U_{\beta i} m_i|$$

One possibility is to measure $m_{\mu e}$ with: $K^+ \to \pi^- e^+ \mu^+$

However, this has a branching ratio <10^{-30}



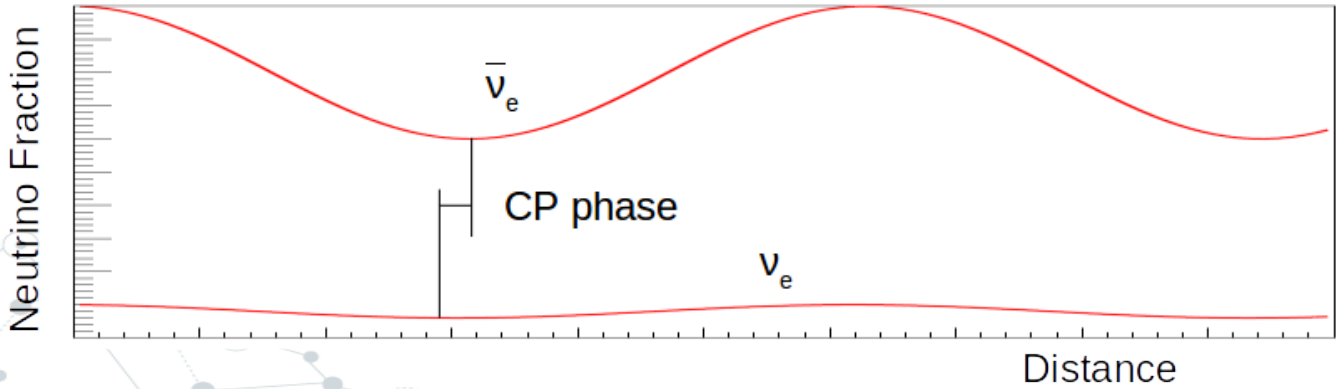


Measuring the Majorana CP Phases

Can directly measure CP Phases in neutrino-antineutrino oscillation by comparing anti-neutrino disappearance to neutrino appearance:

$$P(\bar{\nu}_\alpha \to \nu_\beta) = \frac{1}{E^2}\left|\sum_{i,j} U_{\alpha i}U_{\beta i}U^*_{\alpha j}U^*_{\beta j}m_i m_j e^{i\frac{\Delta m^2_{ij}L}{2E}}\right|$$

Neutrino-antineutrino oscillation has same frequencies as normal oscillation, but is suppressed by $(m_\nu/E)^2$ and is phase shifted according to the CP-phases



Improving Nuclear Matrix Elements

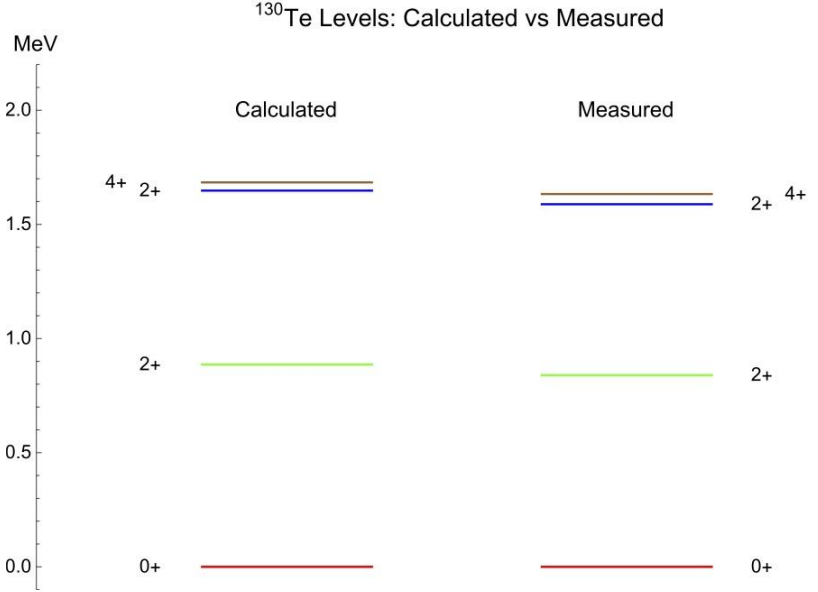
$$\Gamma^{0\nu} = \underbrace{G^{0\nu}(\Delta M, Z)}_{\text{particle physics, well understood}} \quad \underbrace{\left|M^{0\nu}\right|^2}_{\text{nuclear matrix element, poorly understood}} \quad m_e^{-2} \quad \underbrace{\left|m_{\beta\beta}\right|^2}_{\text{Effective mass, contains Majorana phase}}$$

- Nuclear matrix element uncertainties are larger than the signals we will want to see. Examples:
  - Extracting the Majorana phase from once the mass hierarchy is resolved. $m_{\beta\beta} = \sum_m \lambda_m U_{em}^2 M_m$
  - Using the angle between outgoing electrons as a signal of alternate mechanisms, ...
- Problems
  - g_A (quenching) in the nucleus - get nuclear currents right.
  - Nucleon correlation - phase and relative momentum and spins of likely pairs of nucleons in decay and possible protons pairs.

Shell Model

Shell model single particle states for ^{130}Te are harmonic oscillator states above ^{100}Sn core: $1g_{7/2}$, $2d_{5/2}$,$2d_{3/2}$, $3s_{1/2}$,$1h_{11/2}$ for 32 single particle states.

Nuclear basis states are products of antisymmetrized product states of protons and neutrons with about 0.5M states.



GCN5082 interaction, no truncation, with BIGSTICK code

+ Shell model calculations give a microscopic description of states which includes all correlations

$$P_{\beta\beta} = \frac{1}{4}\left|\sum_{\alpha\beta\gamma\delta}\left\langle {}^{130}Xe_{g.s.}, e_1 e_2 \left| a_\alpha^\dagger a_\beta^\dagger b_\gamma b_\delta \right| {}^{130}Te_{g.s.}\right\rangle \left\langle \alpha\beta \left| A \right| \gamma\delta \right\rangle\right|^2$$

A is the usual diagram with nuclear currents. Inputs are spins and momenta.

Needed Experiments

- Problem: Model space is truncated to make calculation feasible.
  - Core is frozen and higher single particle states excluded.
  - Recent Change: Older calculations restricted the number of excited particles. Not needed any more.
  - Operators like the nuclear current need renormalization to account for excluded states.
- Need neutrino experiments on light elements where we can check our understanding of the effect of truncation on the the nuclear current.
- Need experiments to probe correlation effects for isotopes used in neutrinoless double beta decay experiments, but with much higher rates, to test the calculated ground states.

Summary

Confirmation of 0νββ is only the beginning…

- Need to characterise the 0νββ spectrum; the shape and topology of the process will give clues to the underlying process.
- Precision oscillation measurements will constrain values of the (possible) Majorana phases.
- Need to improve nuclear matrix models to reduce uncertainty.
- If there are Majorana neutrinos in nature, we need to measure them elsewhere, and at higher energies (if possible) in order to understand where they fit in with current theory ⇒ colliders…
- …if not, there could be more exotic processes contributing to 0νββ

  ⇒ Get creative…