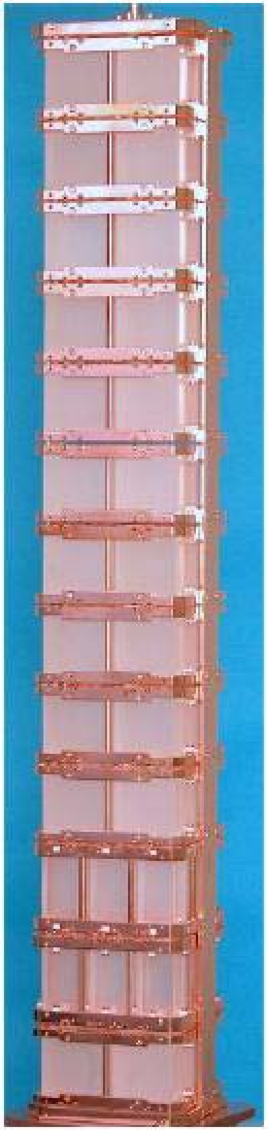
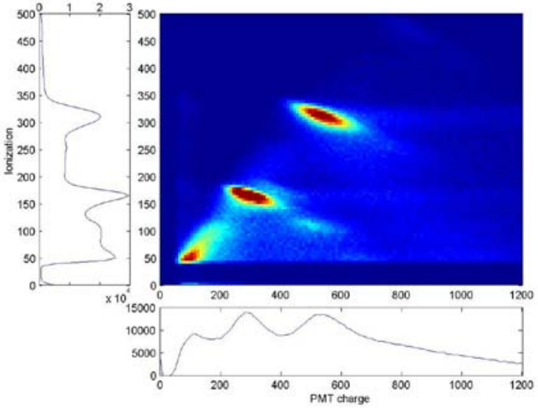
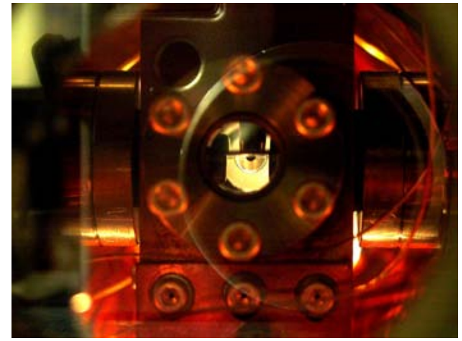
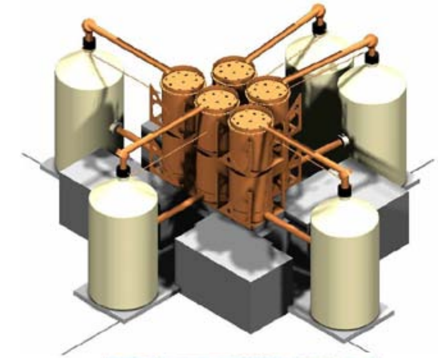


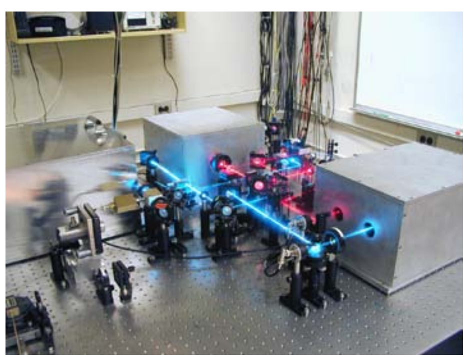


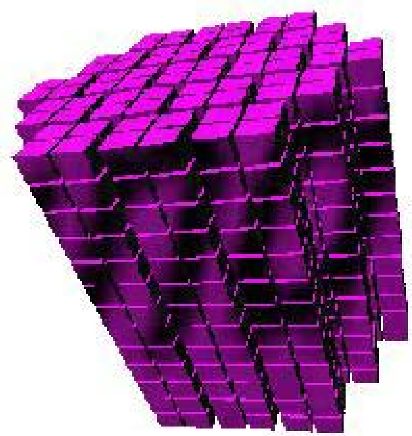




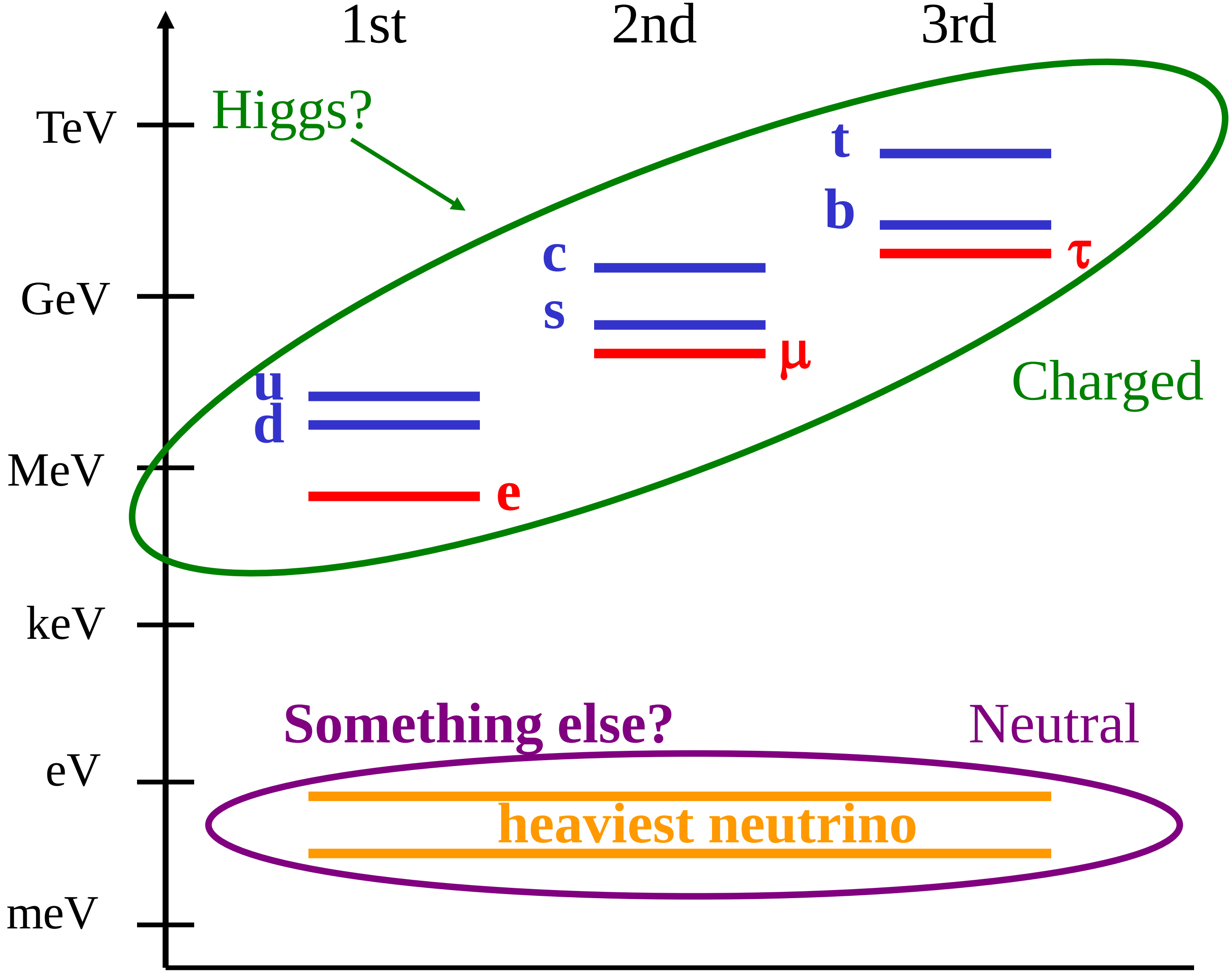
What’s so interesting about double beta decay?

Carter Hall
University of Maryland





Standard Model fermion mass spectrum



Neutrinos are the only electrically neutral fermions

Generation

Charge		1st	2nd	3rd
	1	e^+	μ^+	τ^+
	2/3	u	c	t
	1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Charge	0	ν_e	ν_μ	ν_τ
	-1/3	d	s	b
	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
	-1	e^-	μ^-	τ^-

Do neutrinos carry any charge?
What about lepton number?

Dirac and Majorana neutrinos

Dirac fermion: particle is charged, so $f \neq \bar{f}$ (e-, μ-, τ-, quarks).
A Dirac neutrino carries lepton number:

$$\nu : L = +1, \bar{\nu} : L = -1$$

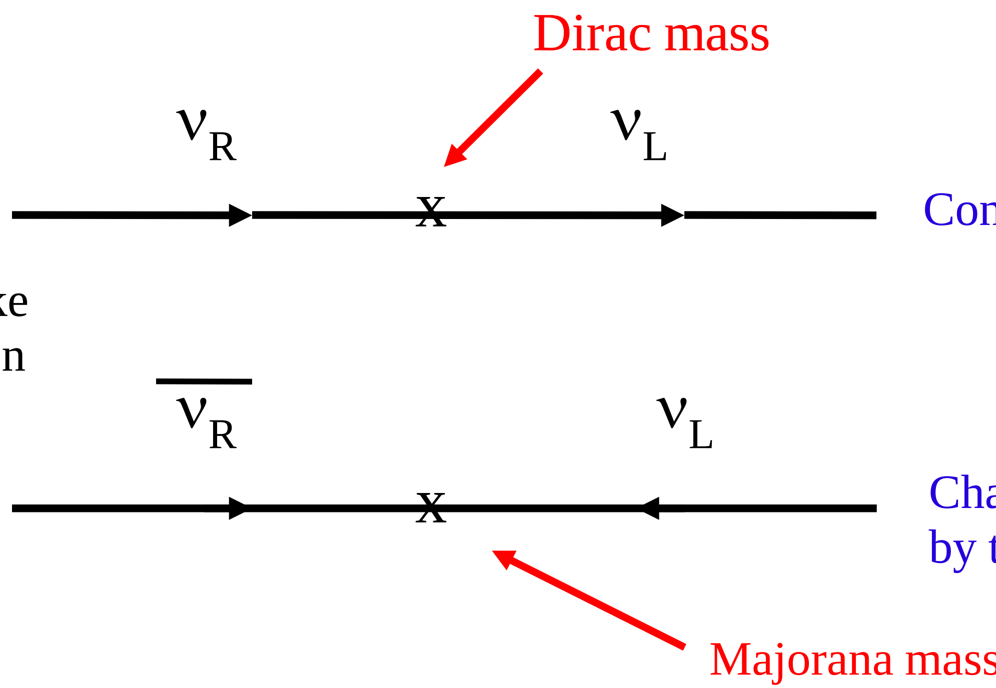
Majorana fermion: particle carries no charge, so $f = \bar{f}$

A Majorana neutrino cannot carry lepton number.

Does the neutrino carry lepton number?

Is the neutrino its own antiparticle?

Charge properties are closely related to mass



Conserves lepton number

Mass terms behave like an interaction between left-handed and right-handed fields

Changes lepton number by two units

Neutrinos may have Dirac masses, Majorana masses, or both.
But the Standard Model Higgs only generates Dirac terms.

The see-saw mechanism takes advantage of the Majorana terms to explain neutrino mass:

generated by the Higgs

Suppose m_{Dirac} ~ 100 GeV, like the top quark

and $m_{Majorana}$ ~ 10^{15} GeV

generated by some type of new physics at the Grand Unification energy scale

Then we would observe two Majorana neutrinos,

with $$m_1 \approx \frac{m_D^2}{M_{GUT}} \approx 10^{-2}\ \mathrm{eV}$$ like atmospheric ν oscillations

$$m_2 \approx M_{GUT}$$ too large to be seen directly

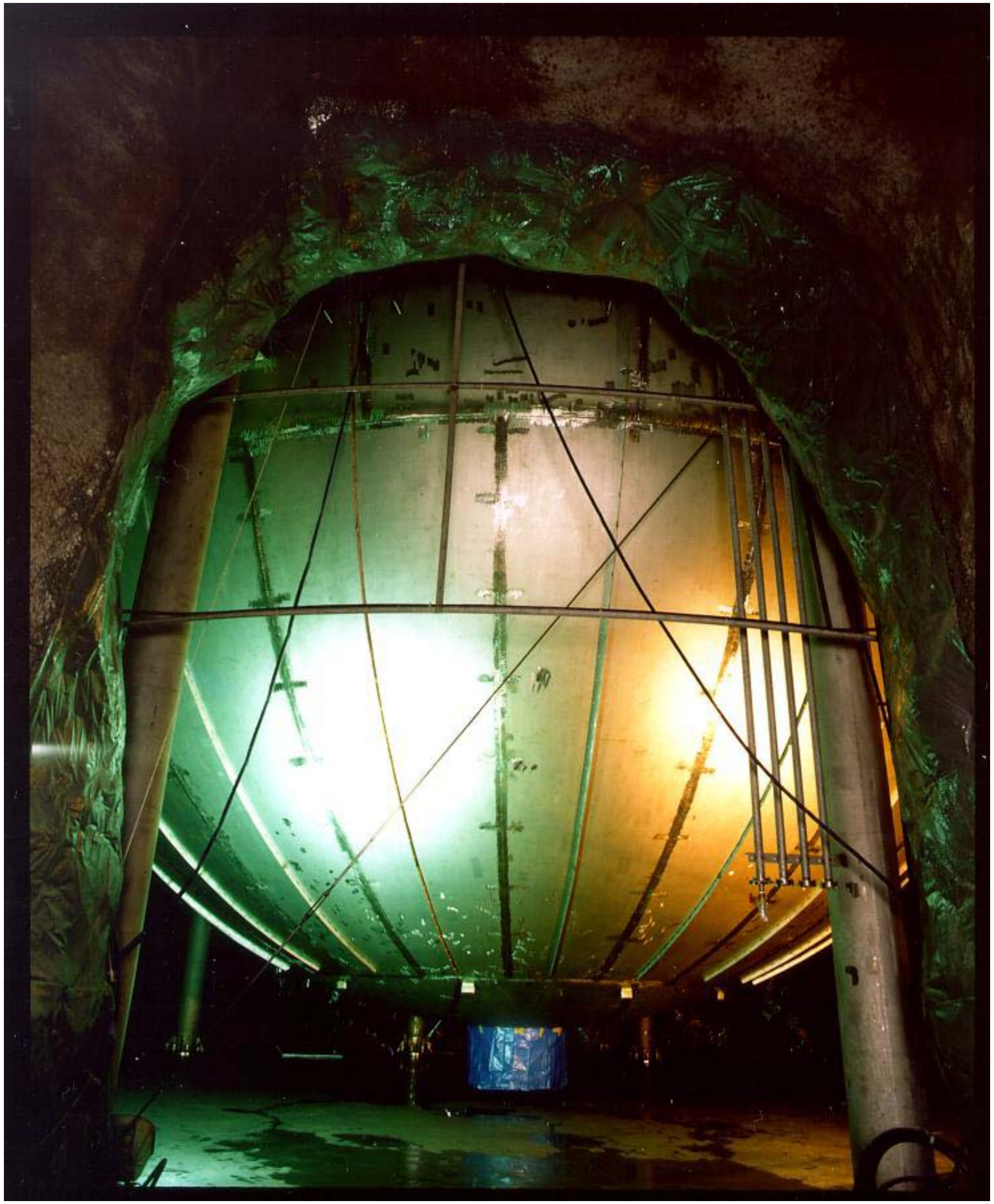
See-Saw mechanism predicts:

Light Majorana neutrinos and
Heavy GUT scale neutrinos (possible source of Leptogenesis)

But

Many models exist for both Dirac and Majorana neutrinos,
it’s up to the experimentalists to provide guidance.

Don't we already know that $\nu \neq \overline{\nu}$?

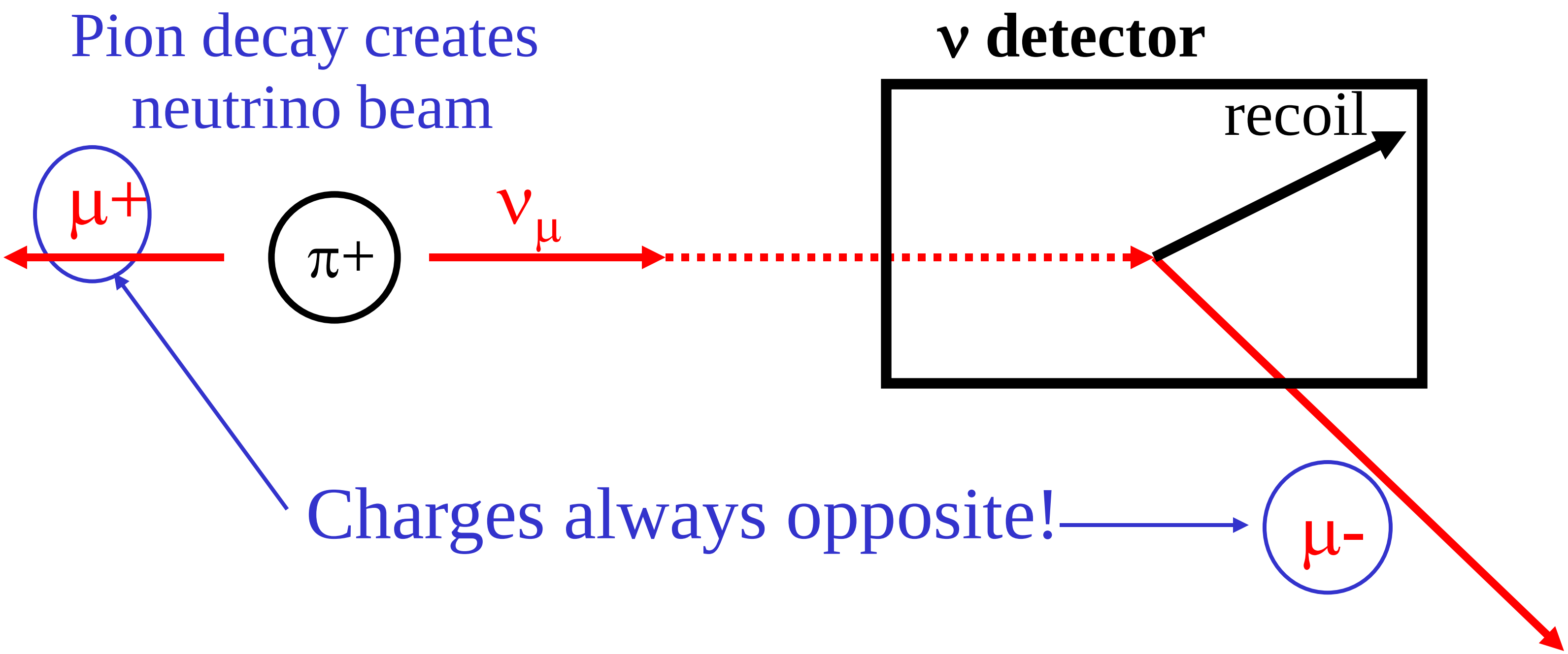


$$\overline{\nu}_e p \rightarrow e^+ n$$

Kamioka
Liquid Scintillator
Anti
Neutrino
Detector

Don't we already know that $\nu \neq \bar{\nu}$?

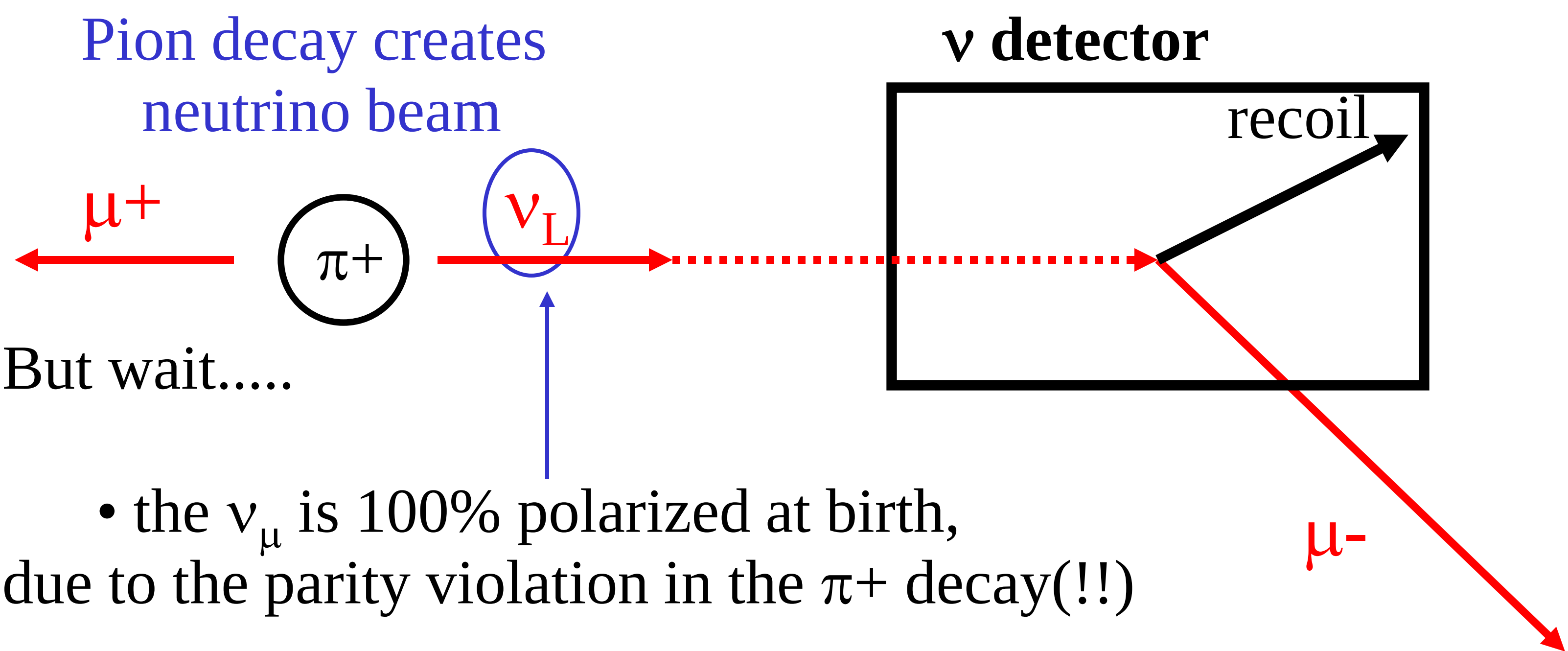
A typical neutrino scattering experiment:



"Easy" explanation: ν_μ carries a charge, "lepton number".
Lepton number is conserved in the detector, so only μ- is produced.

Don't we already know that $\nu \neq \bar{\nu}$?

A typical neutrino scattering experiment:



But wait.....

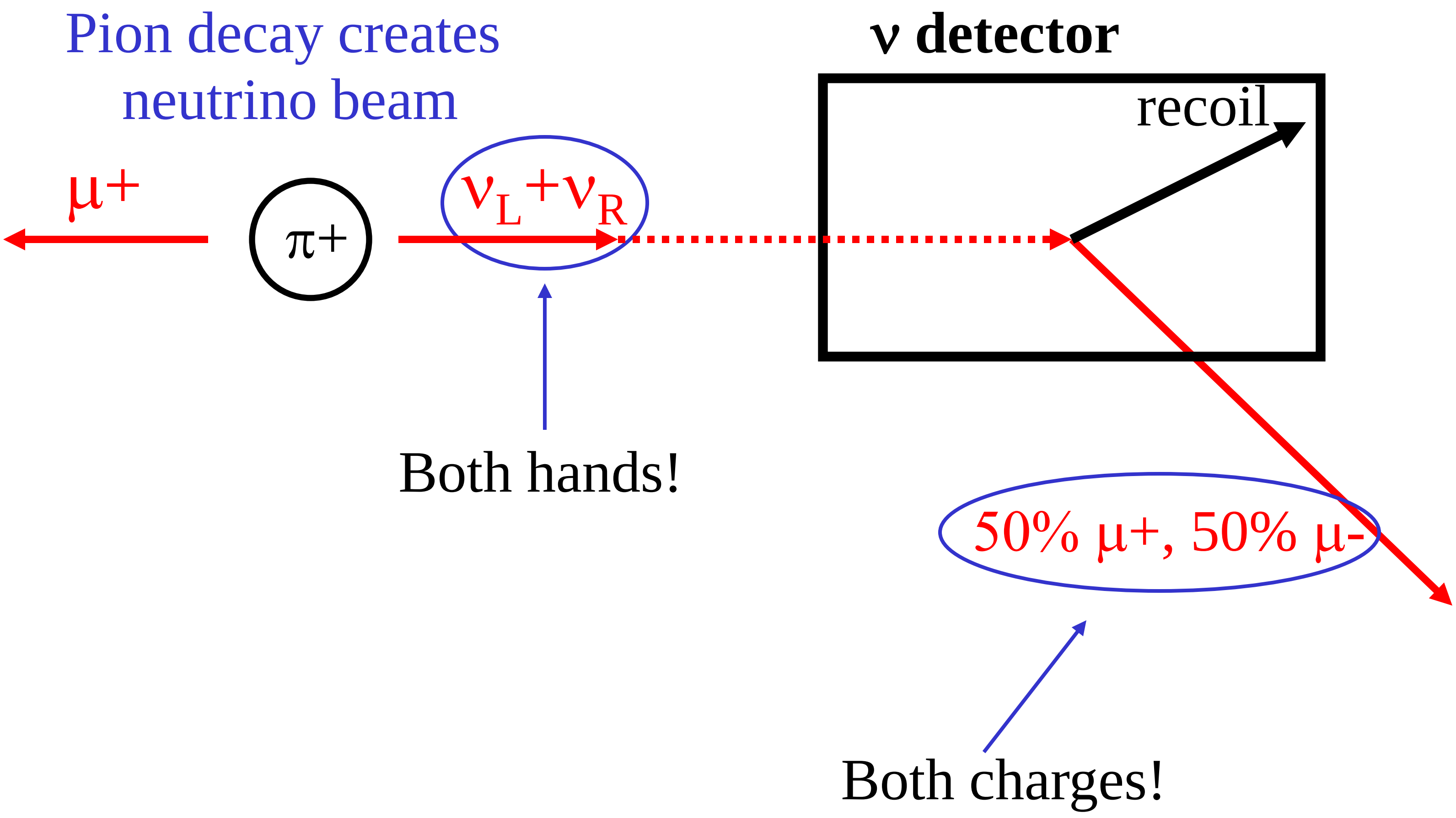
• the ν_μ is 100% polarized at birth,
due to the parity violation in the π+ decay(!!)

• parity violation in the detector allows the
ν_L to couple ONLY to μ- (and not μ+) in the final state.

Is Lepton number carried by the neutrino?
We can't tell because it is obscured by 100% parity violation.

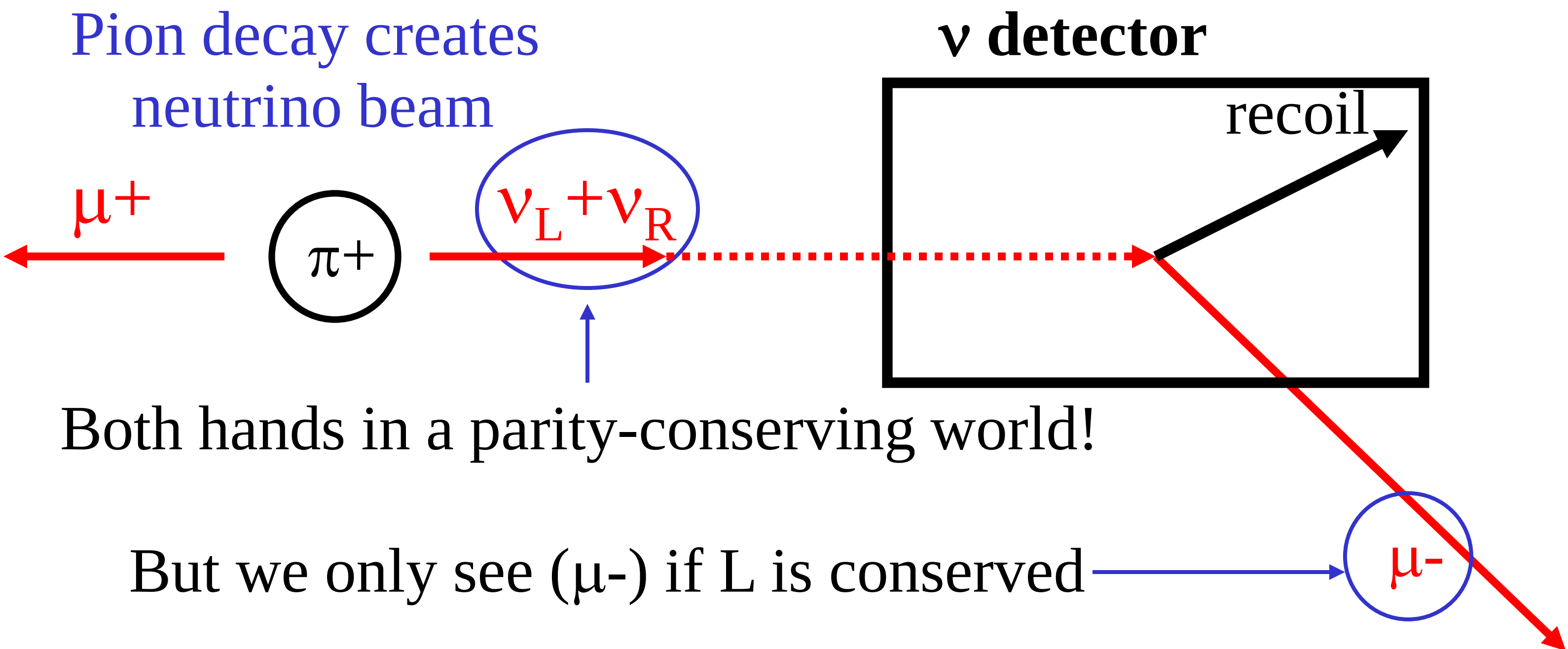
Imagine that parity were conserved

AND neutrinos did not carry lepton number



Imagine that parity were conserved

AND __neutrinos carry lepton number__

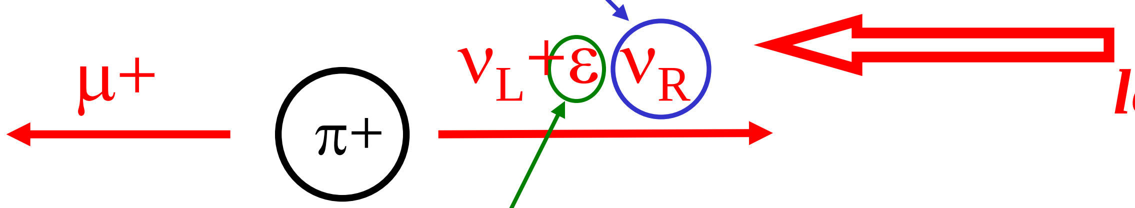


The absence of μ+ in the detector would confirm that lepton number is conserved, in a parity-conserving world.

In our world, the lack of μ+ tells us nothing about lepton number.

In our world, parity is violated 100%, BUT neutrinos have a small mass

Small mass creates small "wrong handed" component

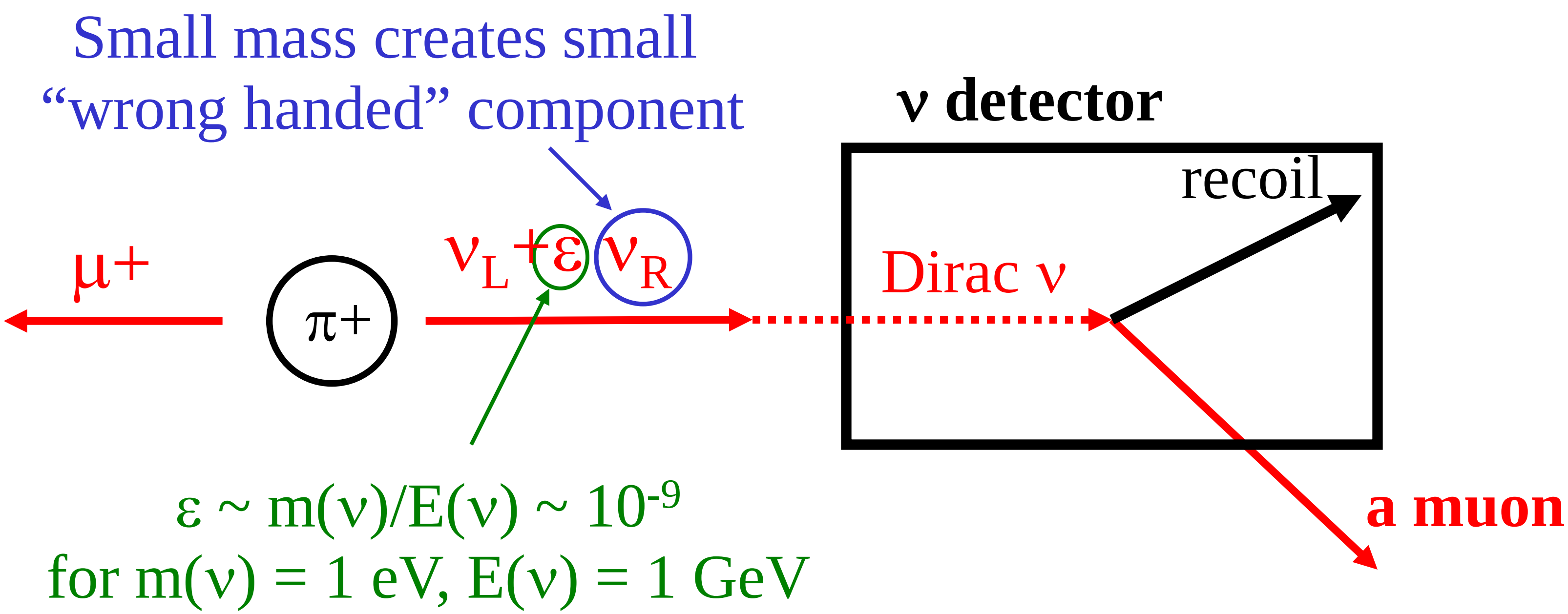


Does ν_R carry lepton number???

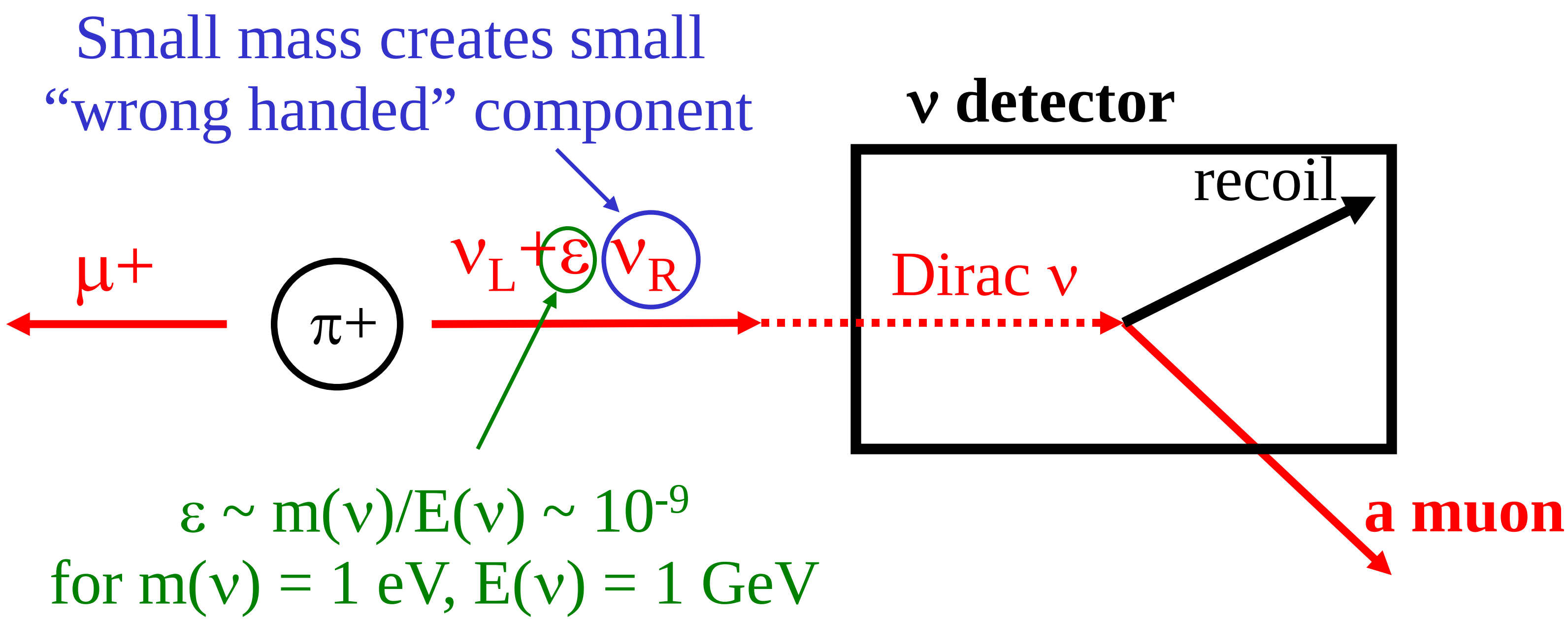
$\varepsilon \sim m(\nu)/E(\nu) \sim 10^{-9}$
for $m(\nu) = 1$ eV, $E(\nu) = 1$ GeV

If it does, then it has $L = +1$, because it was created with a $\mu+$ (which has $L = -1$)

In our world, parity is violated 100%, BUT neutrinos have a small mass



In our world, parity is violated 100%, BUT neutrinos have a small mass



- Parity violation implies that ν_R should create μ+ in the detector.
- But L conservation forbids this, because this ν_R carries L = +1 (while μ+ has L = -1).
- In other words, this ν_R has no weak interactions! (sterile neutrino)

In our world, parity is violated 100%, BUT neutrinos have a small mass

Small mass creates small "wrong handed" component

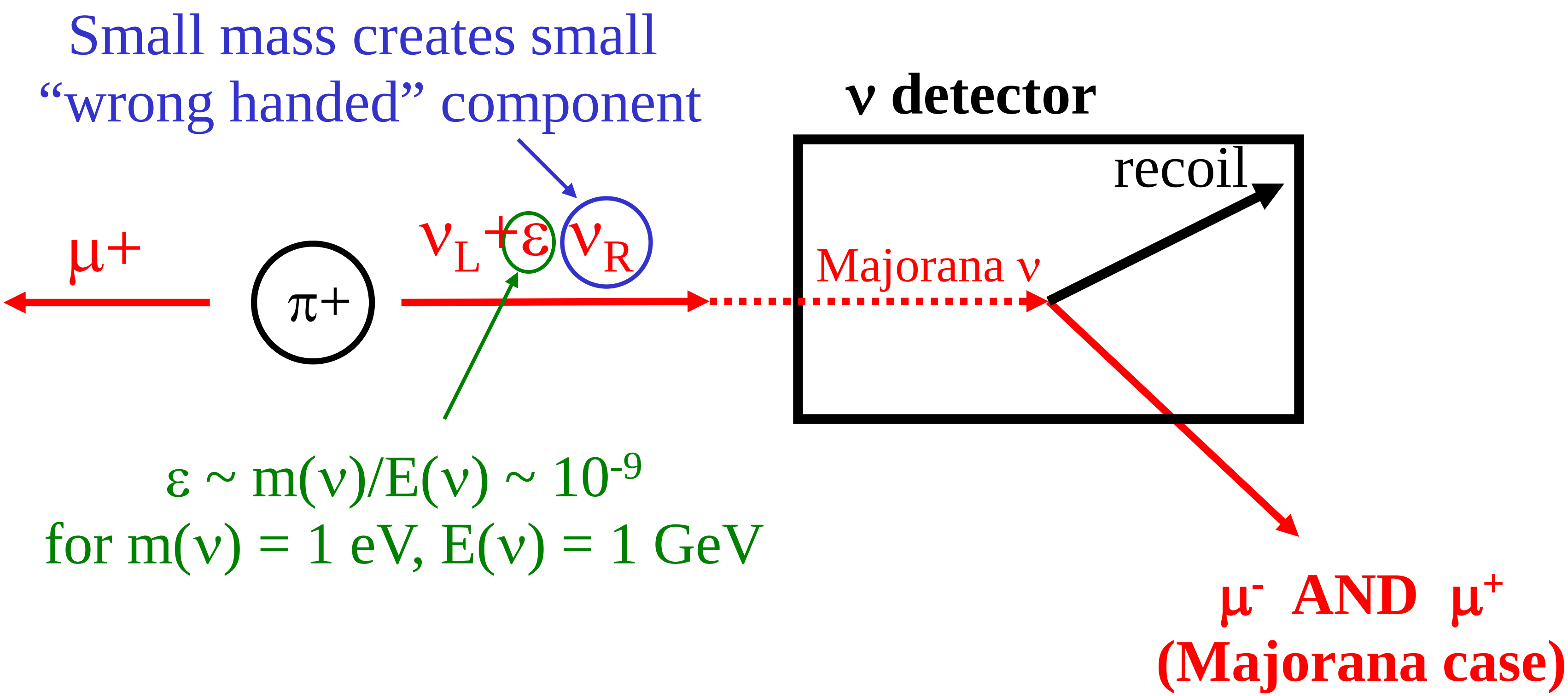
$\mu+$ $\pi+$ $\nu_L + \varepsilon\, \nu_R$

$\varepsilon \sim m(\nu)/E(\nu) \sim 10^{-9}$
for $m(\nu) = 1$ eV, $E(\nu) = 1$ GeV

Does ν_R carry lepton number???

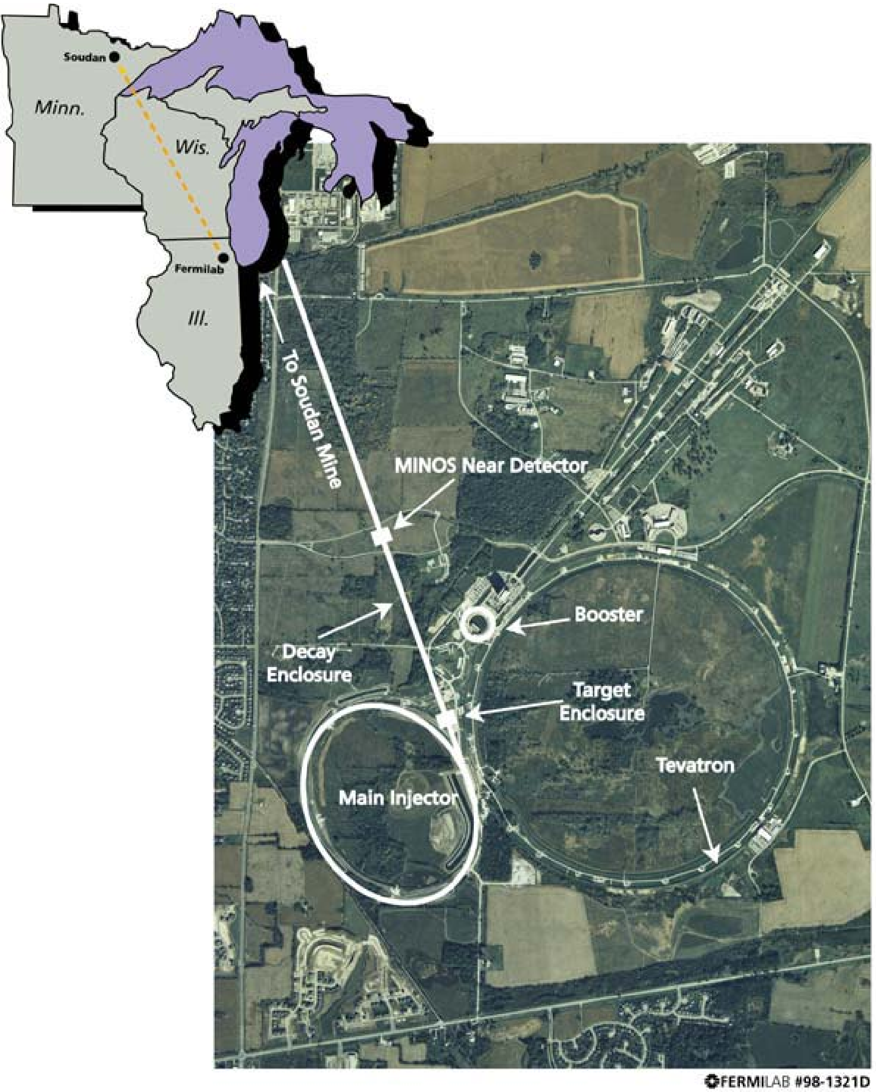
Suppose it does not! (Majorana neutrino)

In our world, parity is violated 100%, BUT neutrinos have a small mass



The appearance of μ+ in the detector would prove that ν is Majorana.

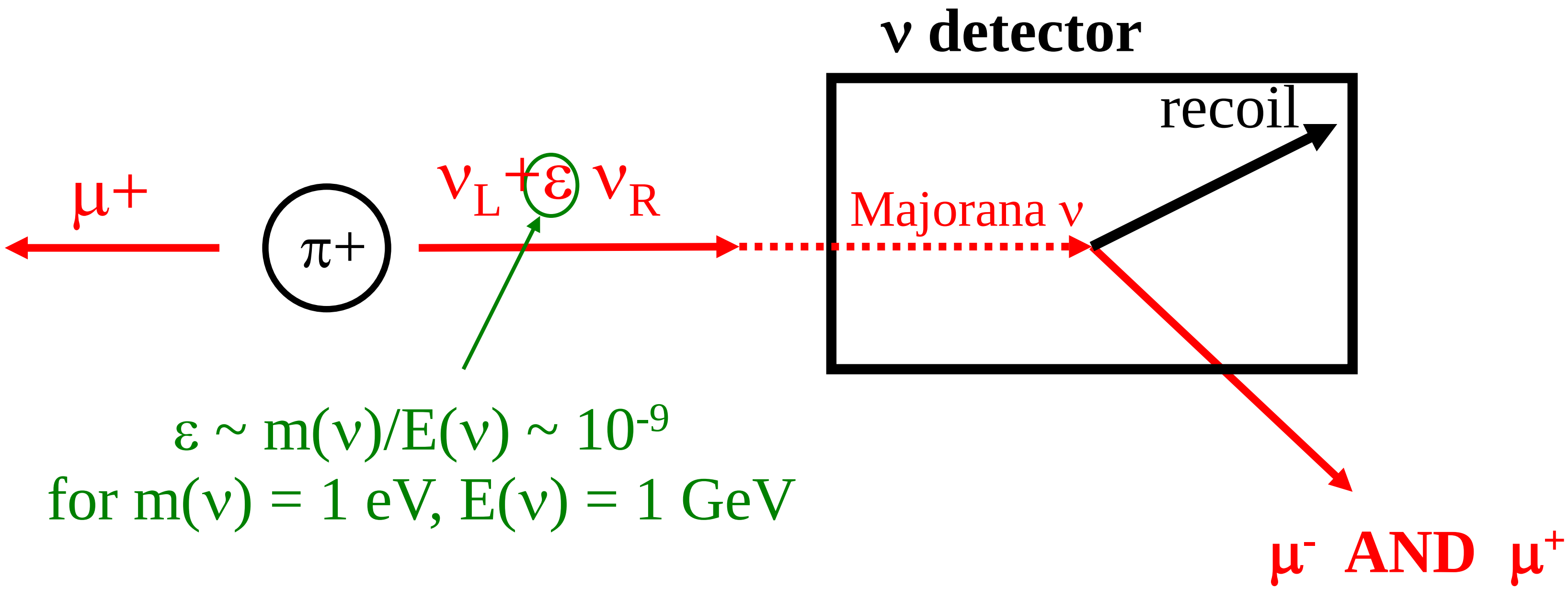
Let’s do the experiment!



Fermilab can create the neutrino beam

MINOS near detector measures the muon charge

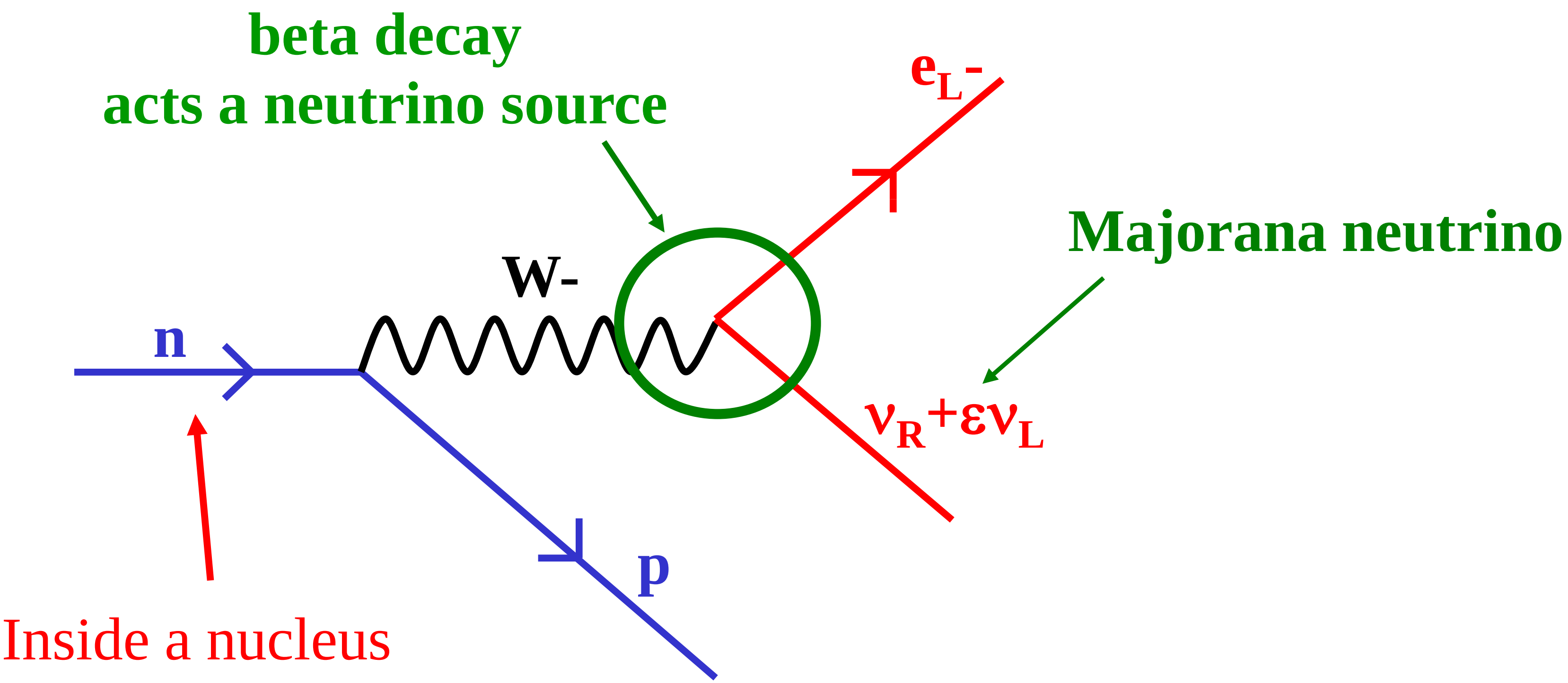
It can't be done(?!)



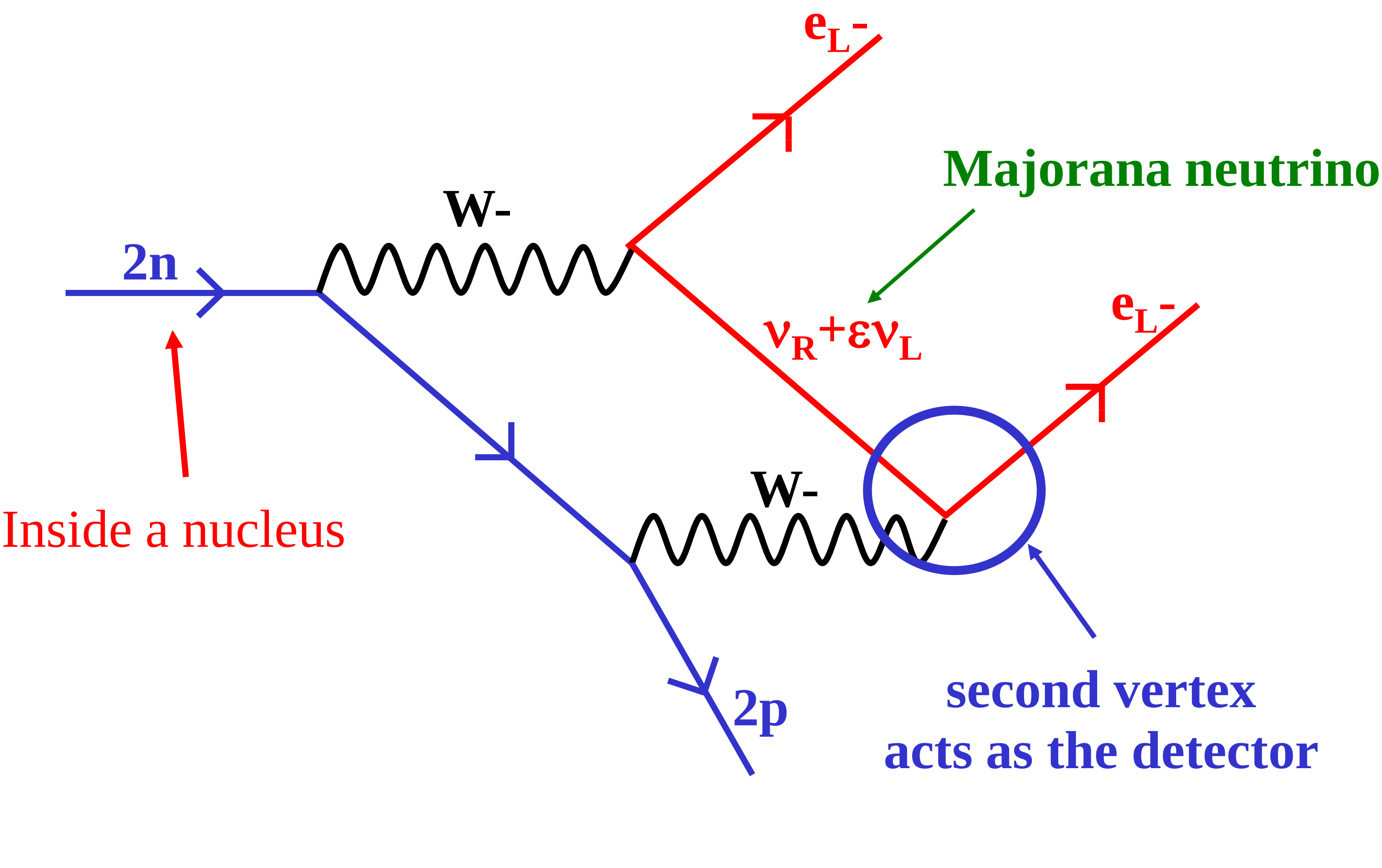
Severe chiral suppression!

- amplitude for μ+ is suppressed by **$\varepsilon \sim 10^{-9}$** relative to μ-
- cross section suppressed by **$\varepsilon^2 \sim 10^{-18}$**
- collect data at ~100 events/second → need a billion years!!!
- Cannot allow any fake μ+ in 10^{18} events

Use nuclear physics instead:



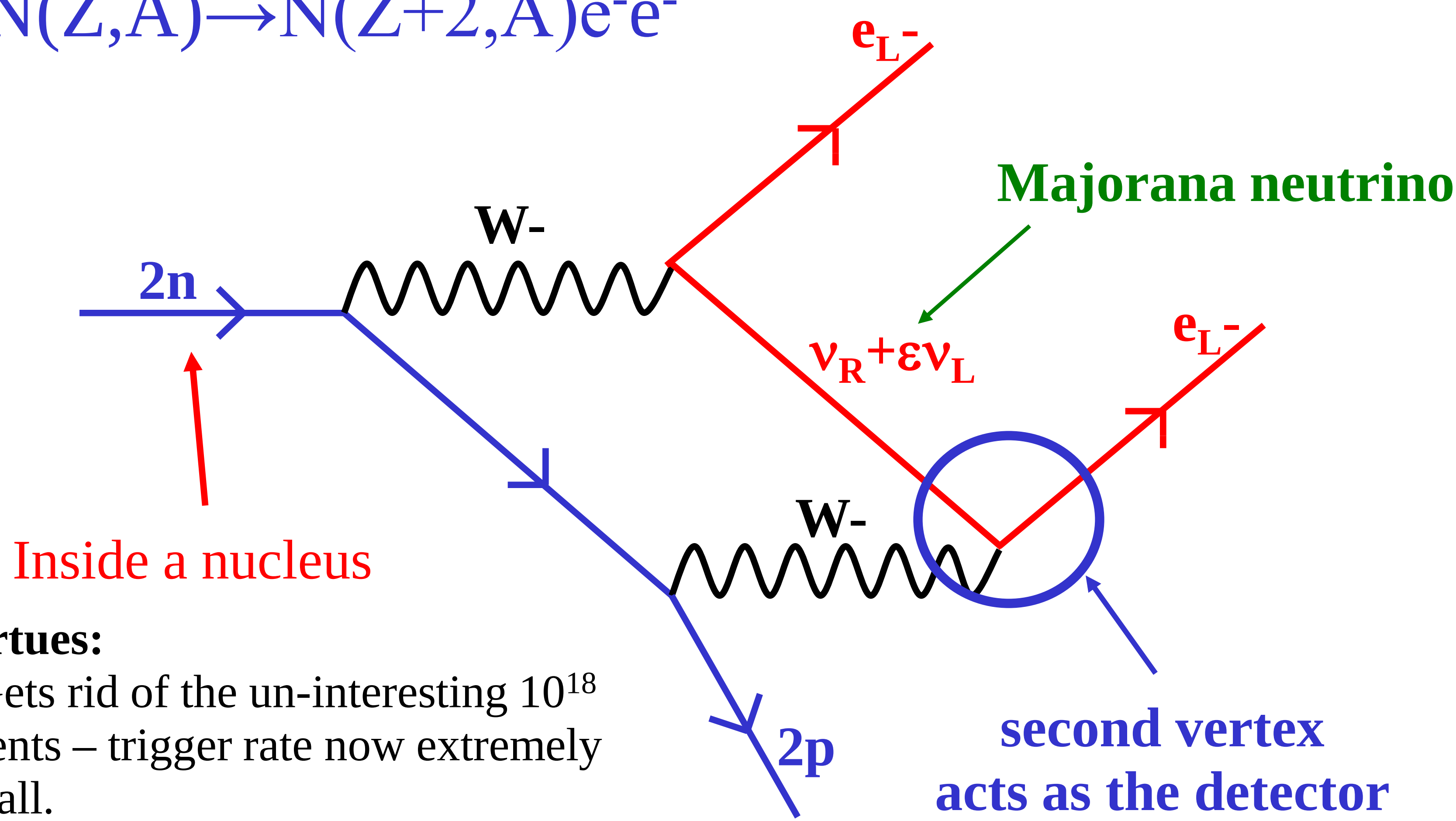
Use nuclear physics instead:



Neutrinoless Double Beta Decay ($\beta\beta0\nu$)

Forbidden if neutrino mass is Dirac only

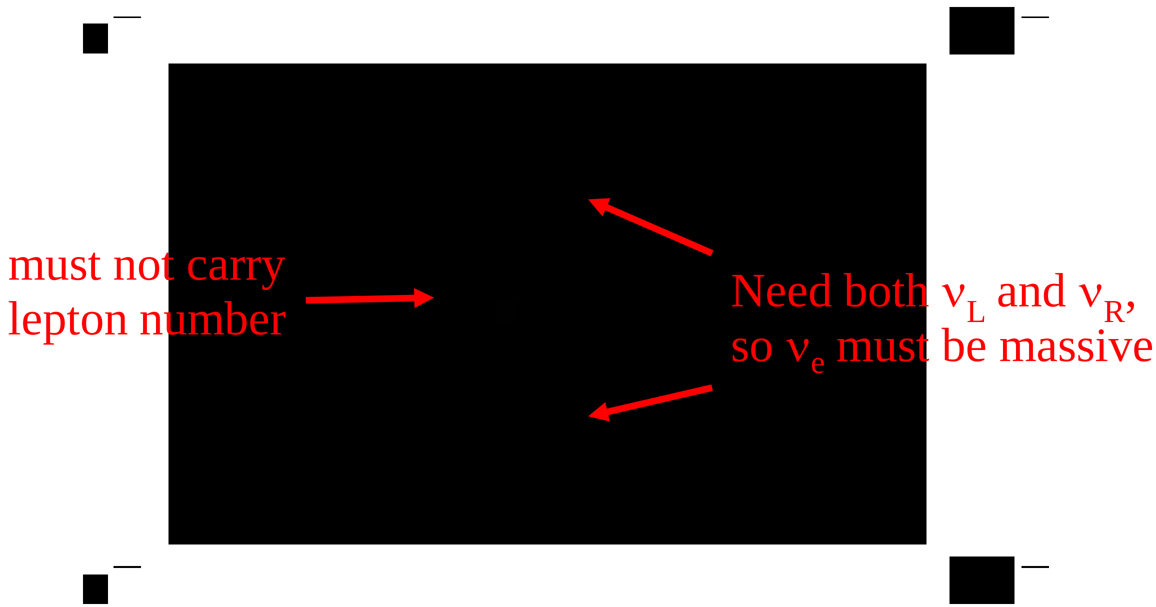
$N(Z,A) \rightarrow N(Z+2,A)e^-e^-$



Virtues:

- Gets rid of the un-interesting 10^{18} events – trigger rate now extremely small.
- Chiral suppression is still severe, but we can fight it with Avagadro’s number

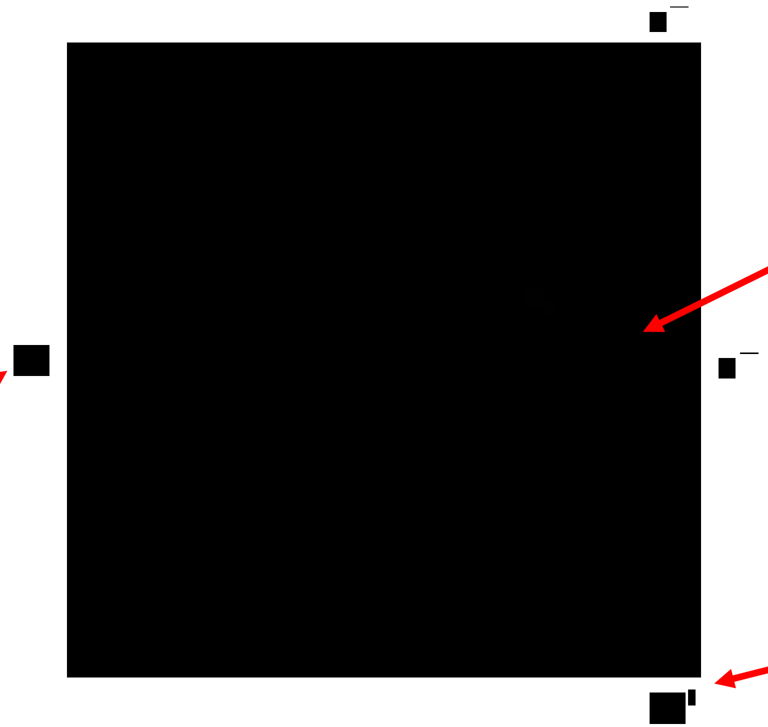
The equivalent HEP process is $e^- e^- \rightarrow W^- W^-$



If TeV scale Majorana neutrinos exist, this process could be used to discover them.

For the light neutrinos that we know and love, the rate is far too small.

“Neutrino mass mechanism” for double beta decay



amplitude ~ m(ν)/E(ν),
E(ν) ~ 100 MeV

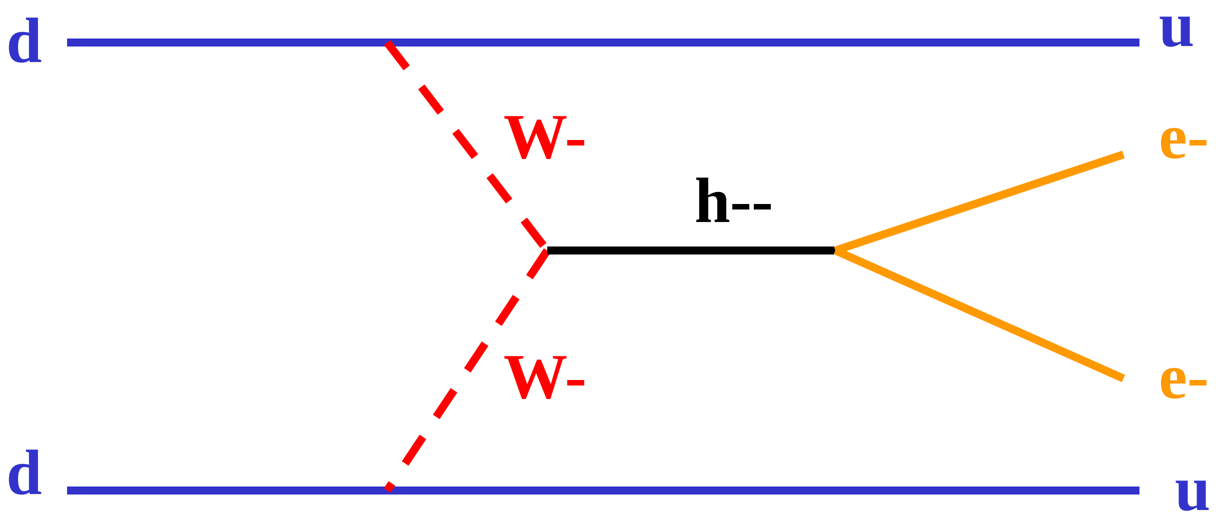
N(Z,A)

N(Z+2,A)

Neutrinoless Double Beta Decay (ββ0ν): N→N'e^-e^-

Many types of new physics lead to ββ0ν

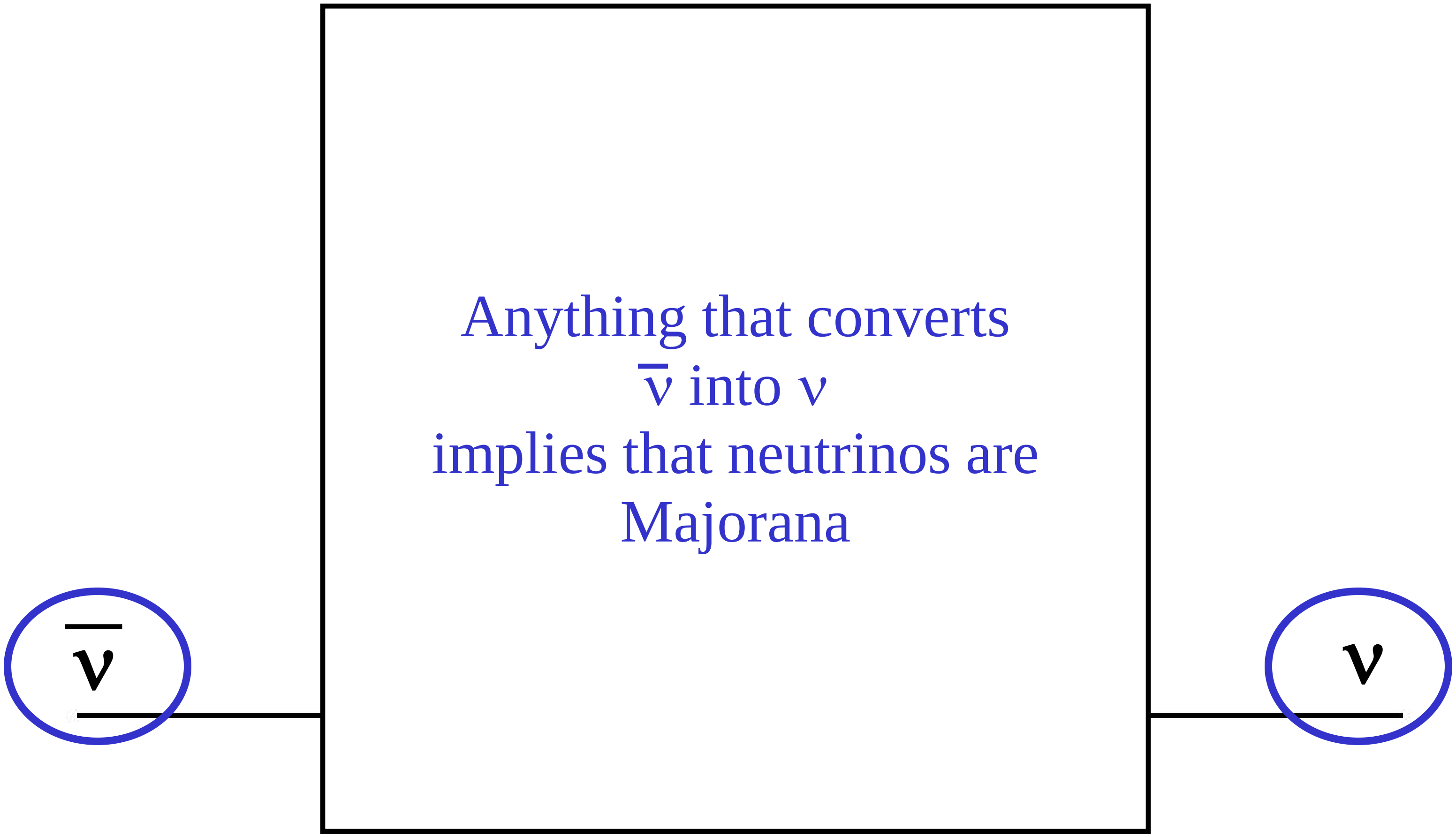
Right handed weak currents, leptoquarks,
supersymmetry, ect.,



"Doubly charged Higgs mechanism"
for double beta decay

Does this spoil neutrino physics interpretations of ββ0ν ?

Black box theorem guarantees that bb0n always implies Majorana ν's

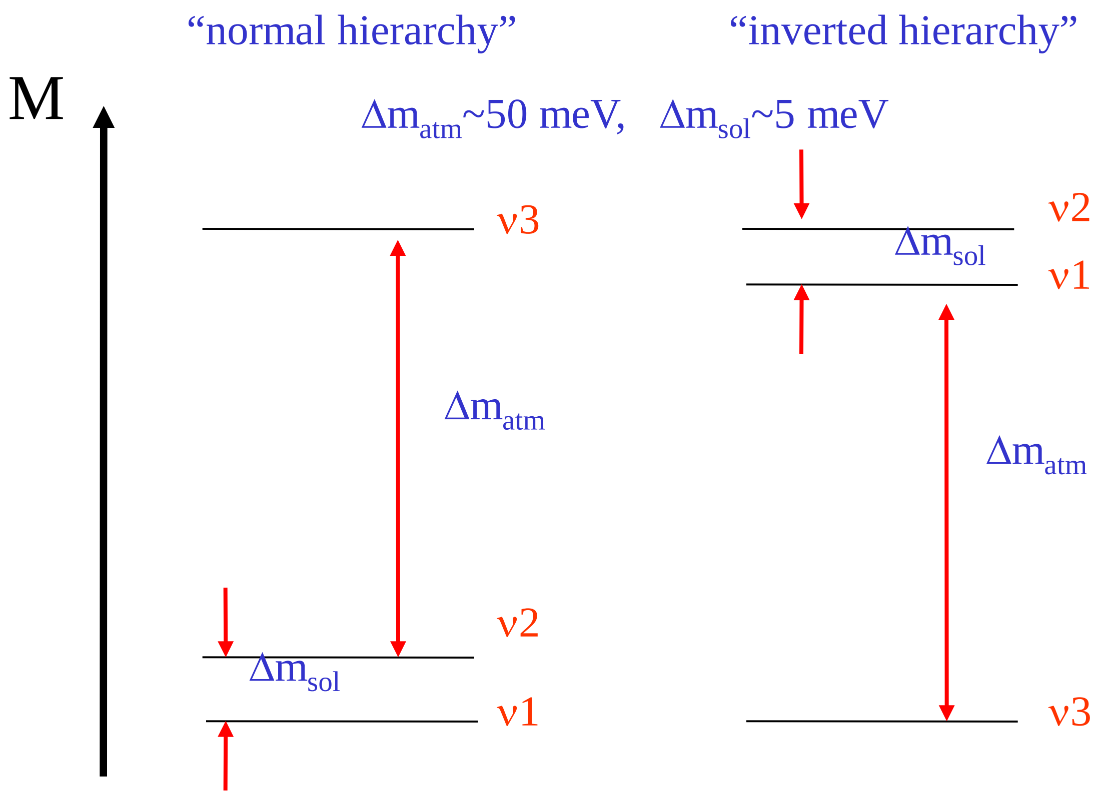


If we see ββ0ν, we know that Majorana neutrinos exist!

ν_e is a mixture of several mass states:

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

small



Neutrino oscillation experiments measure the Δm’s,
but not the absolute masses

The ββ0ν half-life depends directly on the absolute neutrino masses:

Decay rate

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|N^{\beta}\right|^{2}\left|\langle m_\nu \rangle\right|^{2}, \qquad \langle m_\nu \rangle = \sum_i U_{ei}^{2} m_i e^{i\alpha_i}$$

phase space

Nuclear Matrix Element

effective mass

mixing matrix (with phases)

mass eigenvalues

Majorana phases

Two caveats to ββ0ν as a mass measurement:

1) we must have a reliable calculation of the nuclear matrix element
2) the neutrino mass mechanism must dominate the decay

What ββ0ν can tell us about the neutrino mass scale

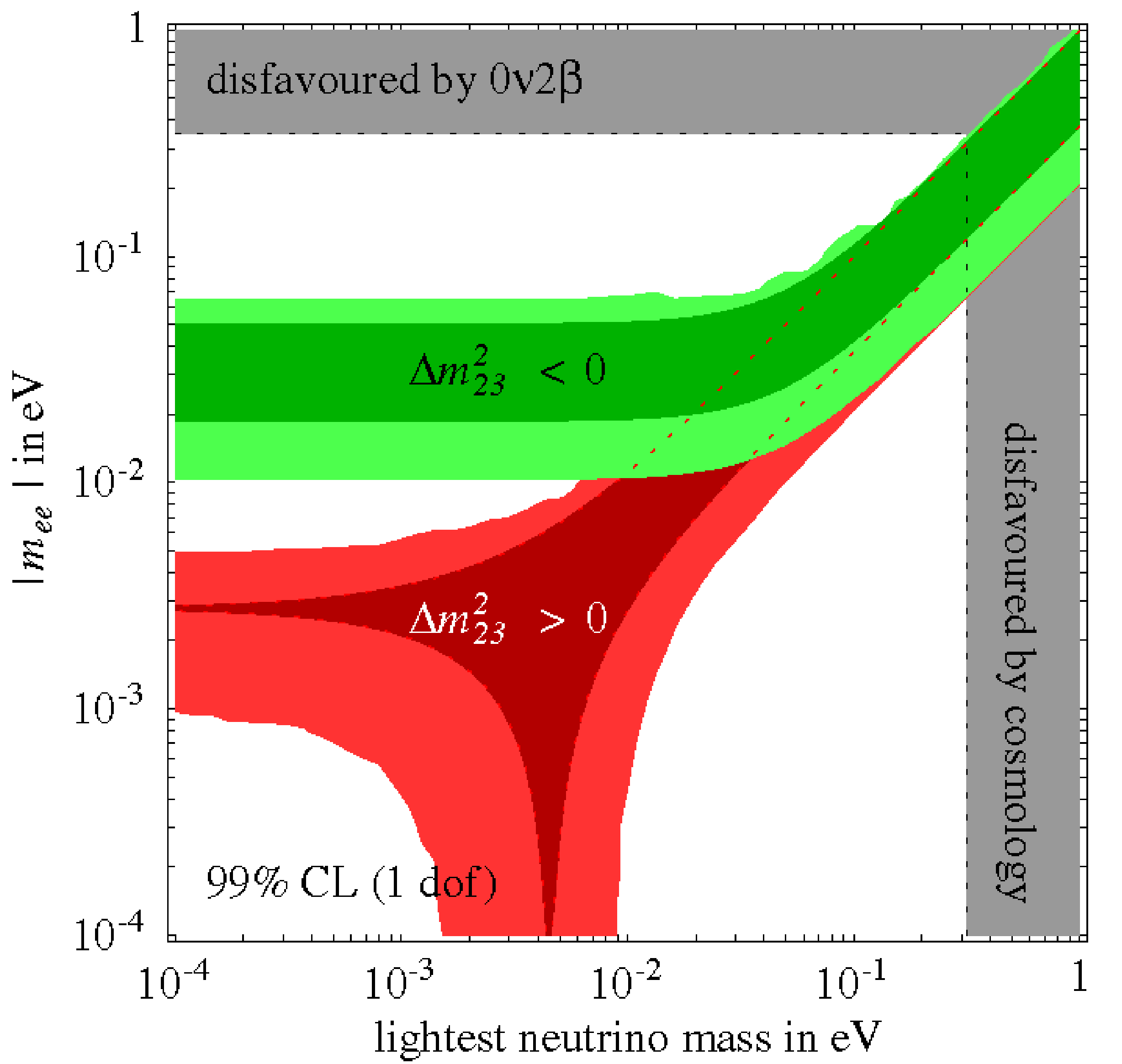
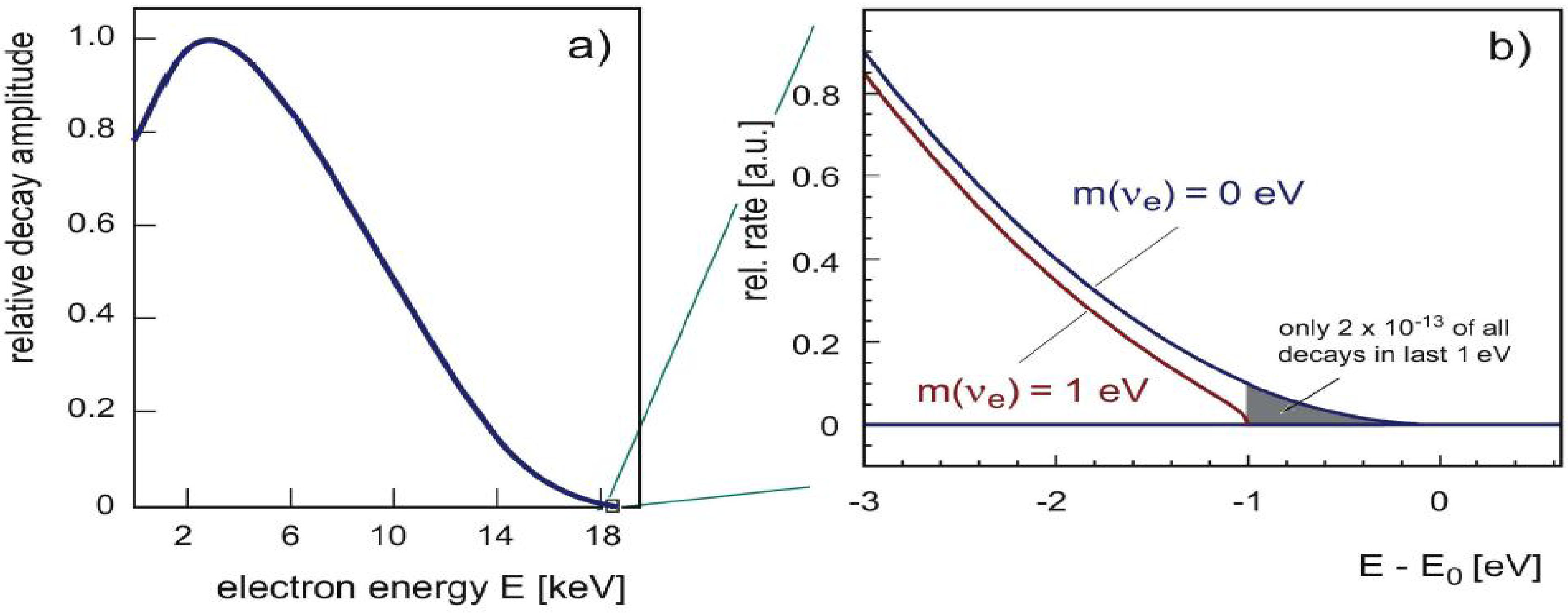


Figure from Strumia & Vissani, Nucl. Phys. B **726** 294 (2005)

Another way to measure the neutrino mass: Tritium beta decay ($^3H \rightarrow {}^3He\ e^- \nu_e$)



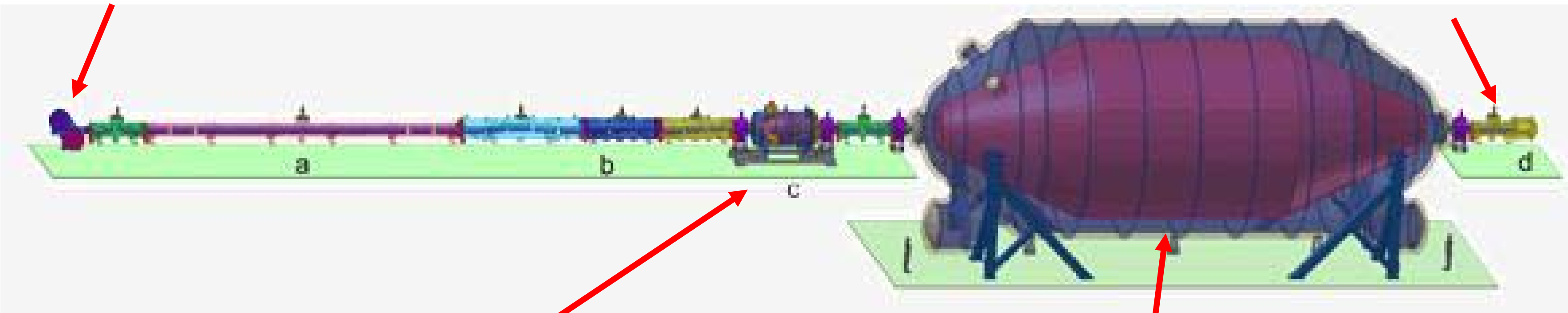
The electron energy spectrum should be slightly distorted due to the energy required to create the neutrino rest mass.

Current best limit: $m(\nu_e) < 2.2$ eV (Mainz & Troisk)

KATRIN: a new tritium neutrino mass experiment under construction in Karlsruhe, Germany

windowless, gaseous tritium source

electron counter



pre-spectrometer

10 m diameter beta spectrometer,
energy resolution = 1 eV.

Expected $m(\nu_e)$ sensitivity: 0.2 eV.

ββ0ν and Tritium experiments are complementary:

ββ0ν measures:

$$\left|\langle m(\nu_e)\rangle\right|^2 = \left|\sum_i U_{ei}^2 m_i e^{i\alpha_i}\right|^2$$

coherent sum

Tritium measures:

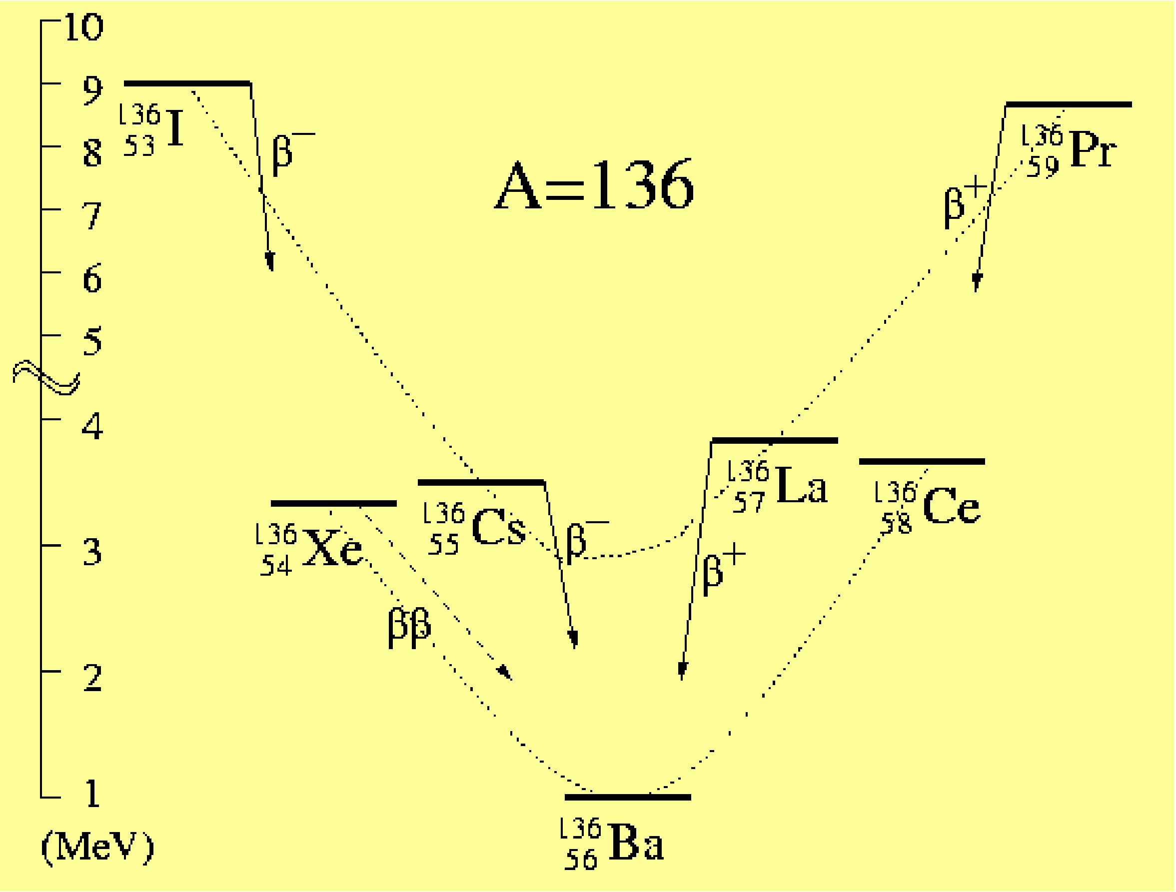
$$m^2(\nu_e) = \sum_i \left|U_{ei}\right|^2 m_i^2$$

incoherent sum

To prove neutrinos are Majorana, we need to see a ββ0ν signal.

To prove neutrinos are Dirac, we need a tritium signal AND show that ββ0ν is absent.

Choosing a double beta decay source isotope:



N(Z,A)→N(Z+2,A)e^-e^-: daughter nucleus must have a smaller mass than the parent for the decay to occur.

To extract the neutrino mass from the bb0n half-life, we need to know the nuclear matrix element

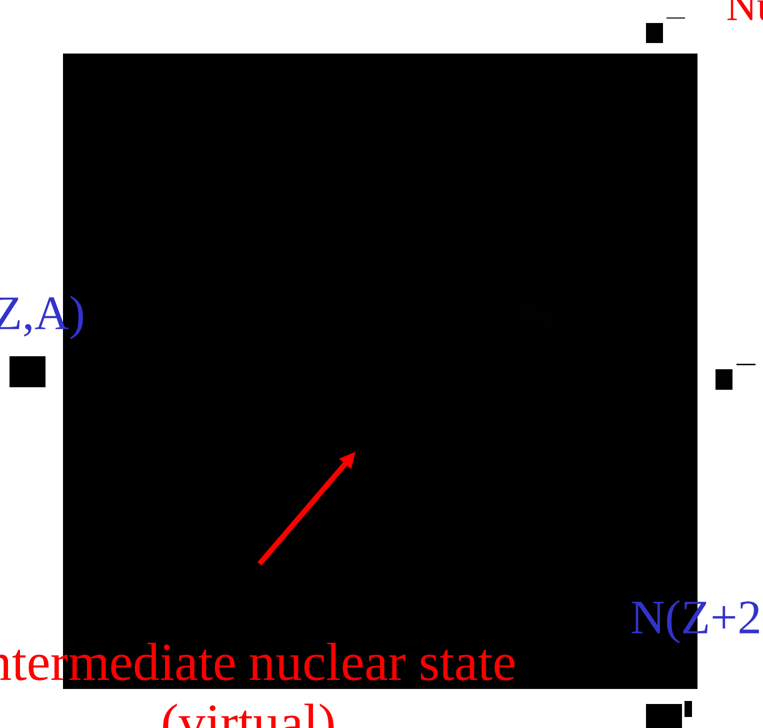
Decay rate

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \left|\langle m_\nu \rangle\right|^2,$$

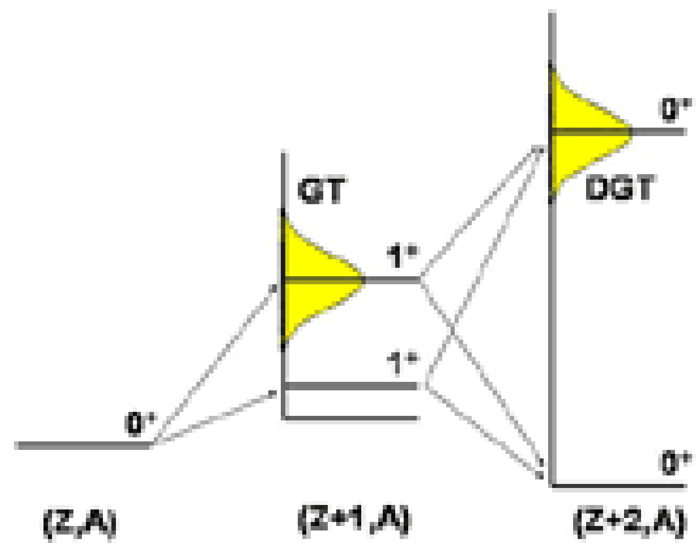
phase space

Nuclear Matrix Element

effective mass



Intermediate nuclear state (virtual)



Nuclear many-body calculations

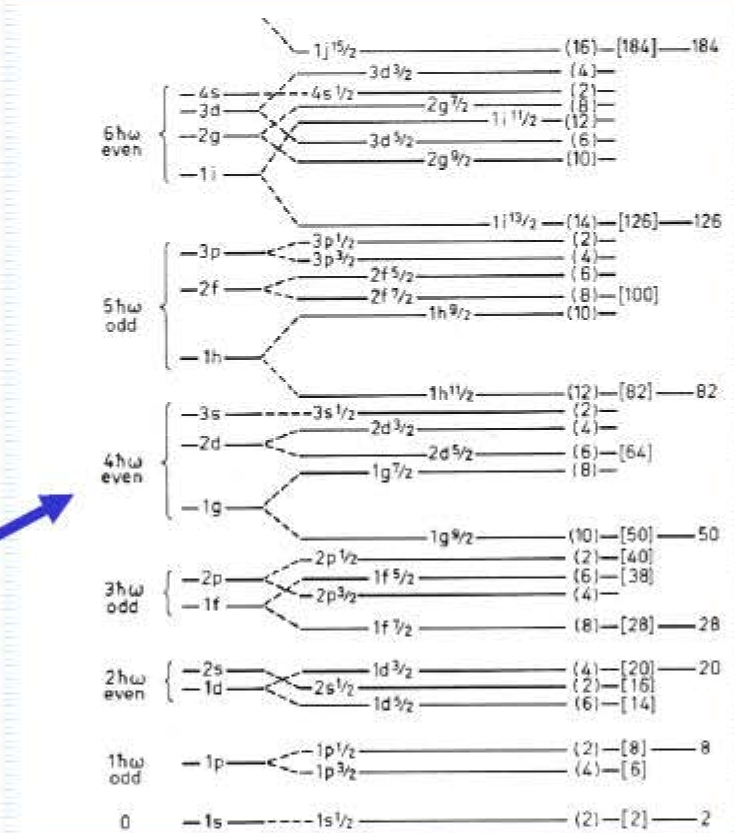
Model space

- *Start with the many-body Hamiltonian*

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2m} + \sum_{i<j} V_{NN}\left(\vec{r}_i - \vec{r}_j\right)$$

- *Introduce a mean-field U to yield basis*

$$H = \sum_i \left(\frac{\vec{p}_i^{\,2}}{2m} + U(r_i) \right) + \underbrace{\sum_{i<j} V_{NN}\left(\vec{r}_i - \vec{r}_j\right) - \sum_i U(r_i)}_{\text{Residual interaction}}$$

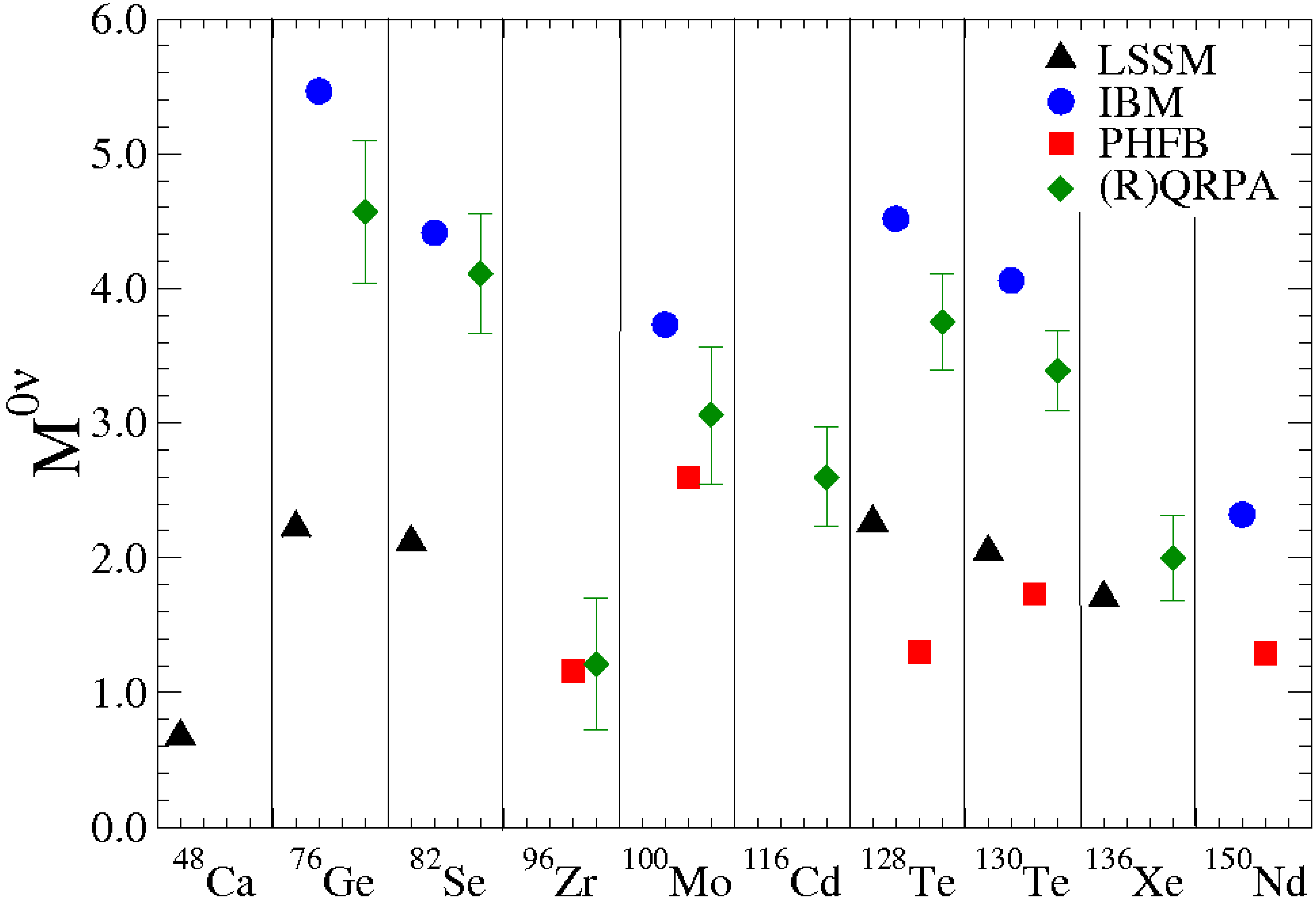


- *The mean field determines the shell structure*
- *In effect, nuclear-structure calculations rely on perturbation theory*

The success of any nuclear structure calculation depends on the choice of the mean-field basis and the residual interaction!

From F. Simkovic, Neutrino 2010

Calculation differ by about a factor of two, but not all calculations are equally valid



LSSM: nuclear shell model

QRPA: quasi-particle random phase approximation

From F. Simkovic, Neutrino 2010