Minimal Flavor Violation
and
Neutrinoless Double β-Decay

Christopher Kolda

University of Notre Dame

*A lesson in how flavor symmetries in the **quark** sector can affect how we interpret possible signals in future $0\nu\beta\beta$ experiments.*

Based on B. Dudley and C. Kolda, Phys. Rev. D79:013014 (2009), arXiv:0810.2997 [hep-ph]

For last 10+ years, we have understood:

- Neutrinos have *mass*
- Neutrino flavor (and thus lepton flavor) is *not conserved*

What we still don't know is maybe more important:

- What is *absolute scale* of neutrino masses?
- Is there *CP violation* in lepton sector?
- Are neutrino masses *Dirac or Majorana* (or a combination)?
    - Is lepton number violated in nature?
    - Why are the masses so small?

Our choices:

- Extend SM spectrum with RH neutrinos and impose v. small Yukawa couplings
- *Extend SM Lagrangian to include dimension-5, LNV neutrino mass terms.*

Assume new physics at a scale Λ .

When heavy fields with masses $m \approx \Lambda$ are integrated out, we recover SM Lagrangian, plus new non-renormalizable interactions → effective theory.

At dimension-5, only one new term allowed which violates L or LF symmetries:

$$\mathcal{L}_5 = \frac{\kappa_{ij}}{\Lambda}(HL_i)(HL_j) \quad \longrightarrow \quad \kappa_{ij}\frac{v^2}{\Lambda}\nu_i\nu_j \qquad (v = \langle H \rangle = 175\,\mathrm{GeV})$$

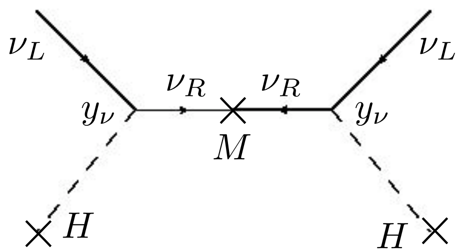
This term generates Majorana masses for neutrinos – violates LF and total L!

Assuming $m_{\nu,\max} \simeq \sqrt{\max(\Delta m^2)} \simeq 0.05\,\mathrm{eV}$ and $\kappa_{ij} \sim O(1)$:

$$\Lambda \approx 10^{14}\,\mathrm{GeV}$$

This is same operator generated by see-saw mechanism:

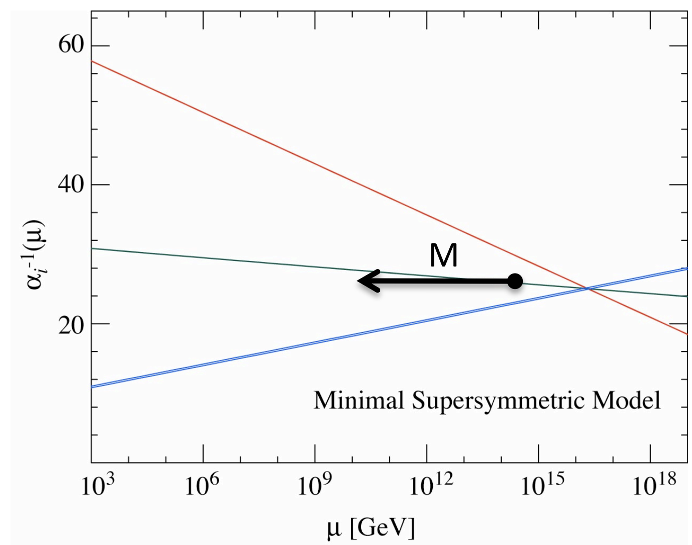
$$\mathcal{L} = y_\nu \bar{\nu}_L \nu_R H + M \nu_R \nu_R \quad \longrightarrow \quad \frac{(y_\nu v)^2}{M} \nu_L \nu_L$$



$$\text{If } y_\nu = 1 \quad \Rightarrow M \simeq 5 \times 10^{14}\,\text{GeV}$$

$$\text{If } y_\nu = y_e \quad \Rightarrow M \simeq 5\,\text{TeV}$$

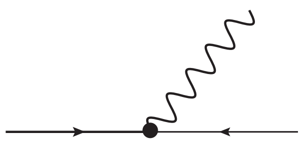
In either case, $M << M_{\text{GUT}}$ or M_{Pl}



If seesaw is correct, clear evidence for a new scale of physics BTSM.

At dimension-6, three important classes of operators appear (all LFV):

- Magnetic moment / transition operators



$$c_1 \bar{L}_i \sigma^{\mu\nu} e_j H B_{\mu\nu}, \quad c_2 \bar{L}_i \sigma^{\mu\nu} \tau^a e_j H W^a_{\mu\nu}$$

$\downarrow$ EWSB

$$\frac{e a_e}{4 m_e} \bar{e}_i \sigma^{\mu\nu} e_j F_{\mu\nu} + \frac{i}{2} d_e \bar{e}_i \sigma^{\mu\nu} \gamma_5 e_j F_{\mu\nu}$$

$$\left\{ \begin{array}{c} \mu \to e\gamma \\ \tau \to \mu\gamma \\ \tau \to e\gamma \\ \text{plus EDMs!} \end{array} \right.$$

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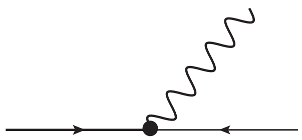

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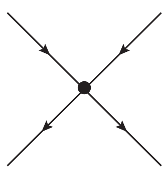
- Four lepton contact interactions



$$(\bar{L}_i \Gamma L_j)(\bar{L}_k \Gamma L_\ell)$$
$$(\bar{e}_i \Gamma e_j)(\bar{e}_k \Gamma e_\ell) \qquad \Gamma = 1\,, \gamma^\mu, \sigma^{\mu\nu}, \ldots$$
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$$\left\{ \begin{array}{c} \mu \to eee \\ \tau \to \mu\mu\mu \\ \tau \to \mu\mu e \\ \tau \to \mu ee \\ \tau \to eee \end{array} \right.$$

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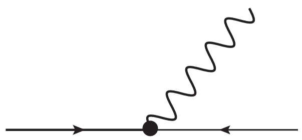

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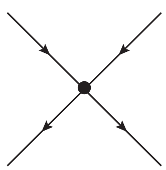

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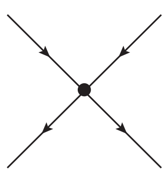
- Two lepton – two quark contact interactions



$$(\bar{L}_i \Gamma L_j)(\bar{q}_k \Gamma q_\ell)$$
$$(\bar{e}_i \Gamma e_j)(\bar{q}_k \Gamma q_\ell) \qquad \Gamma = 1\,, \gamma^\mu, \sigma^{\mu\nu}, \ldots$$
$$(\bar{L}_i \Gamma e_j)(\bar{q}_k \Gamma q_\ell)$$

$$\left\{ \begin{array}{c} \tau \to (e,\mu)\,\pi \\ \tau \to (e,\mu)\,\eta \\ \tau \to (e,\mu)\,\eta' \\ \tau \to (e,\mu)\,K_s \\ \cdots \\ \mu N \to e N \end{array} \right.$$

At what scale should we expect new LFV/LNV physics?

Assuming Majorana masses, neutrinos provide partial answer:

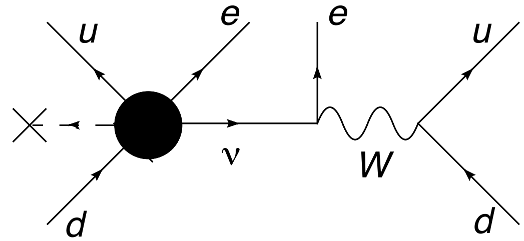
$$10^3\,\mathrm{GeV} < \Lambda < 10^{15}\,\mathrm{GeV}$$

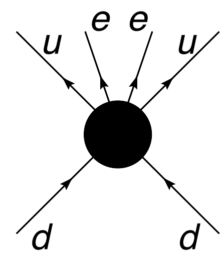
For radiative LFV decays ($\mu \to e\gamma$, etc):

$$1\,\mathrm{TeV} < \Lambda < 10\,\mathrm{TeV}$$

Next generation experiments probe LFV at level of (few – 60) TeV.

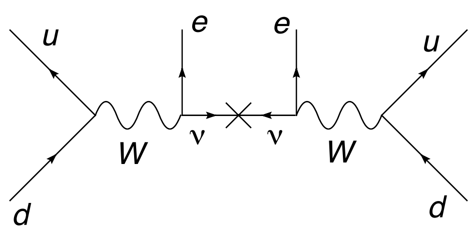
To observe LNV, must go to dimension 7 or 9 (or higher):

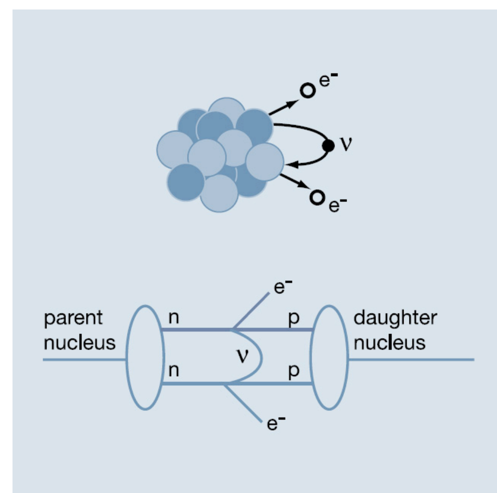




→Neutrinoless Double Beta-Decay!

Within Seesaw paradigm, $0\nu\beta\beta$ generated by exchange of a light, Majorana neutrino:





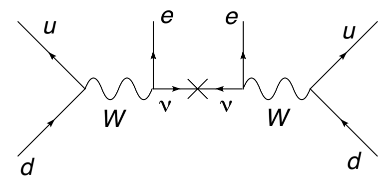
“Deep Science” report

$0\nu\beta\beta$ can (potentially) occur in even-even nuclei with energetically forbidden β-decays, but allowed double-β decays:

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

For neutrino-induced $0\nu\beta\beta$, lifetime depends on "effective" neutrino mass:

$$\Gamma \propto |\mathcal{M}_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$



Nuclear matrix elements   Effective neutrino mass

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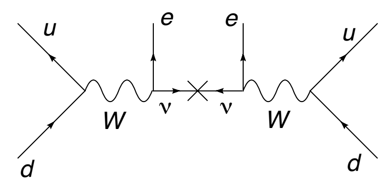
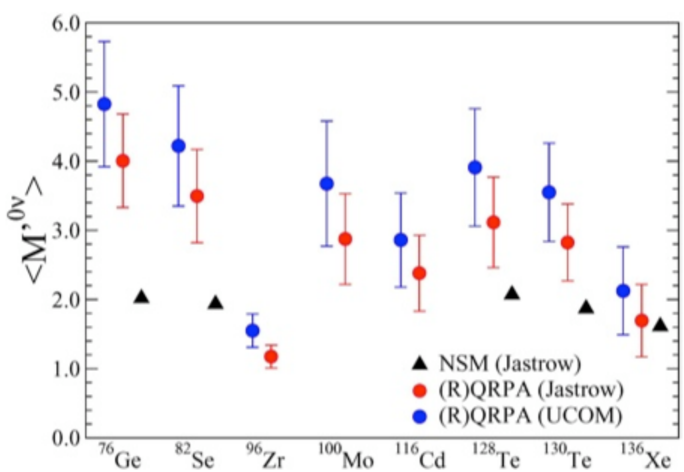


Nuclear matrix elements

Effective neutrino mass

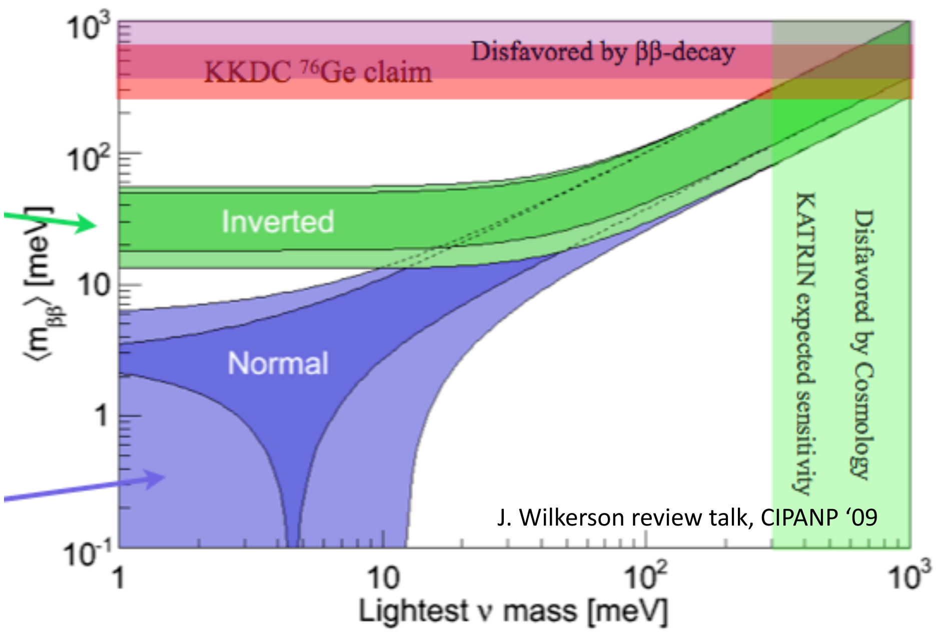
$$\langle m_{\beta\beta}\rangle = \left|\sum_i (U_{ei})^2\, m_{\nu,i}\right|$$

MNS matrix

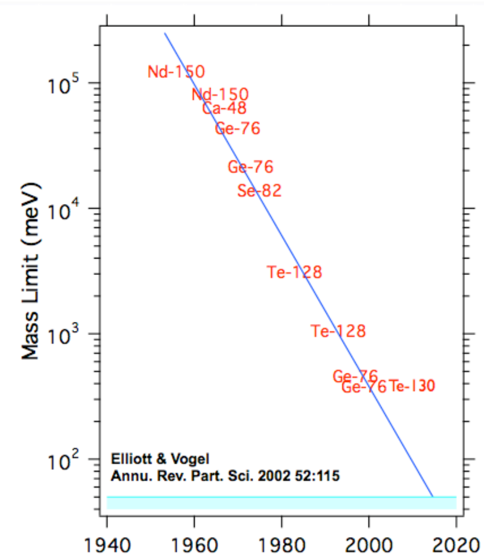


J. Wilkerson review talk, CIPANP '09

Given current understanding of neutrino masses/hierarchy, range of interest for $\langle m_{\beta\beta} \rangle$ is one (or more) orders below current $0\nu\beta\beta$ limits.

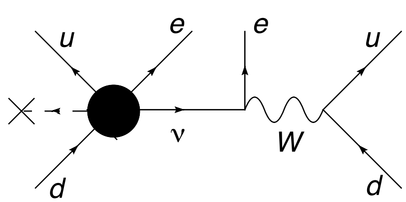


But experiments over next decade should extend reach down to 10's – 100's of meV.

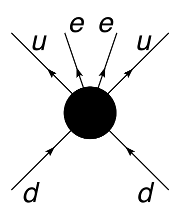


Observation of $0\nu\beta\beta$ means Lepton number is violated, but have we measured the Majorana neutrino mass?

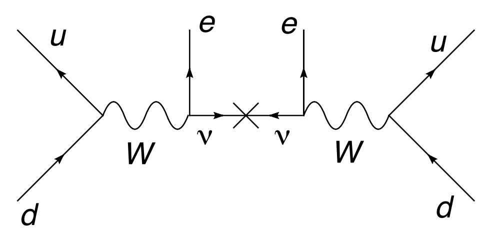
NOT NECESSARILY! New LNV operators at a scale Λ could produce $0\nu\beta\beta$ "directly" instead of through a Majorana neutrino.



or



instead of



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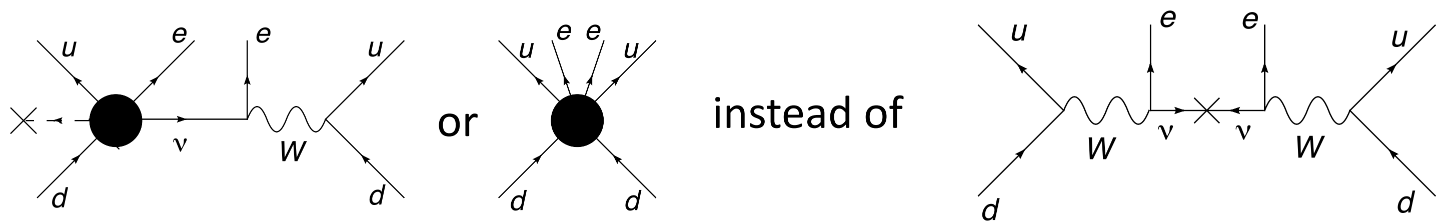
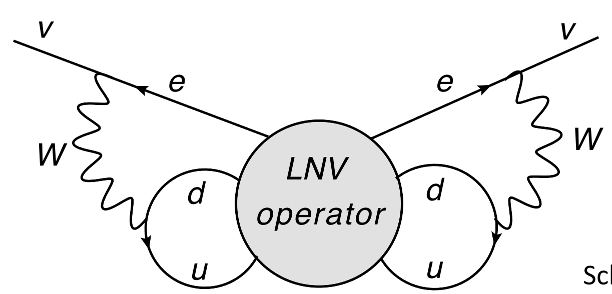


But even if $m_{\beta\beta}$ hasn't been measured, we will know that *neutrinos have a Majorana component to their masses!*



Schechter & Valle ('82)

A reported value of $m_{\beta\beta}$ maybe telling us Λ rather than a neutrino mass.

At dim-7, there are 5 operators which can generate $0\nu\beta\beta$ after EWSB:

$$\mathcal{L}_{d=7} = \frac{v}{\sqrt{2}\Lambda^3}\,[\lambda_{7,1}(\nu_e e)(u d^c) + \lambda_{7,2}(\nu_e \sigma^{\mu\nu} e)(u\sigma_{\mu\nu} d^c)$$
$$+\lambda_{7,3}(\nu_e e)(\bar{d}\bar{u}^c) + \lambda_{7,4}(\nu_e \sigma^{\mu\nu} e)(\bar{d}\sigma_{\mu\nu}\bar{u}^c)$$
$$+\lambda_{7,5}(\nu_e \sigma^{\mu}\bar{e}^c)(d^c\sigma_\mu \bar{u}^c)] + h.c.$$

$$\begin{cases} \psi = \text{LH-field} \\ \psi^c = \text{RH-field} \end{cases}$$

We define $m_{\beta\beta}^{\rm eff}$ as the value “reported” by some future $0\nu\beta\beta$ experiment. What is the true Λ that corresponds to the observation?

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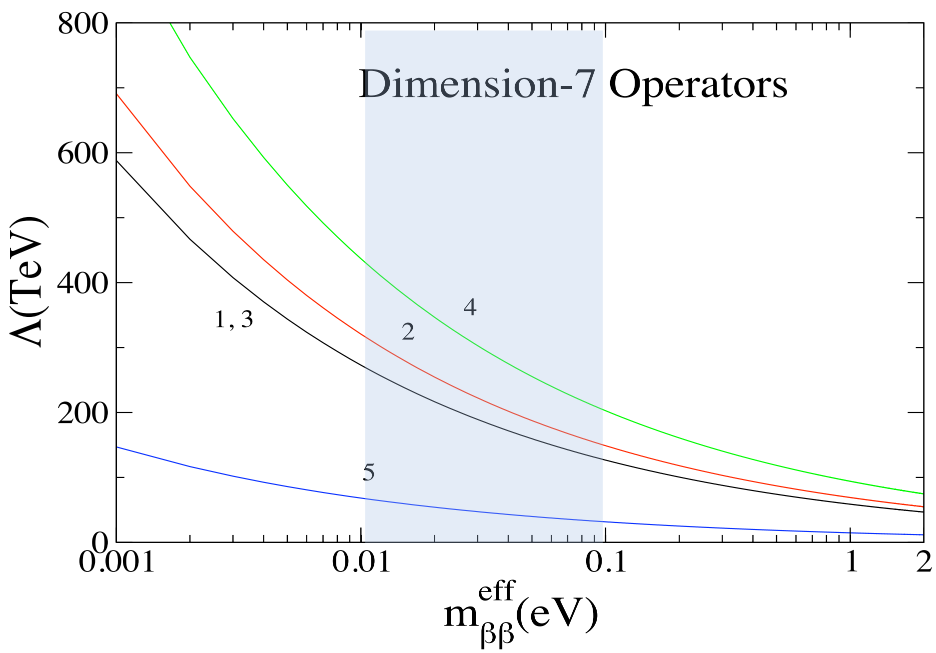


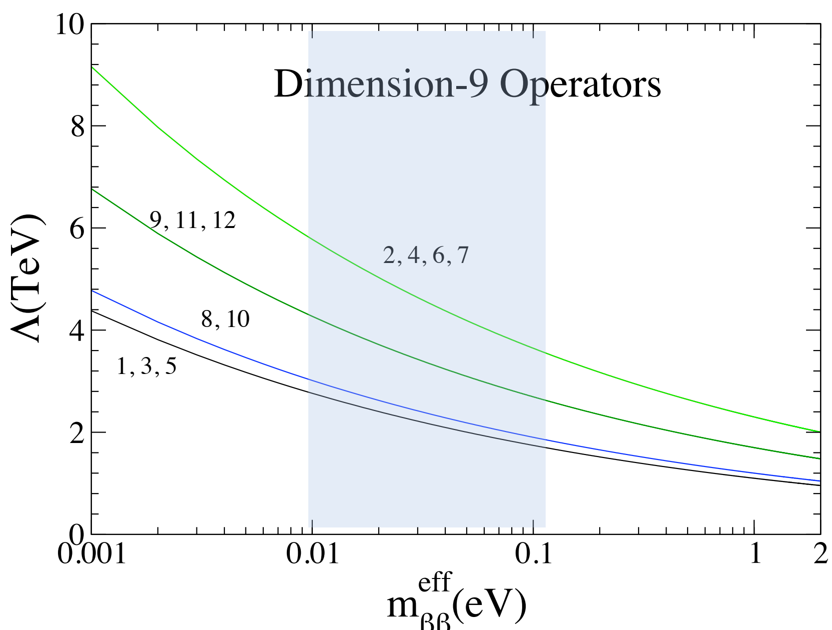
$$\left(m_{\beta\beta}^{\text{eff}}\right)^2 \propto \Gamma_{0\nu}$$

Next generation experiments sensitive to new physics at scales of 100's of TeV!!!

At dimension-9, there are 12 operators:

See also K.W. Choi, K.S. Jeong & W.Y. Song, '02

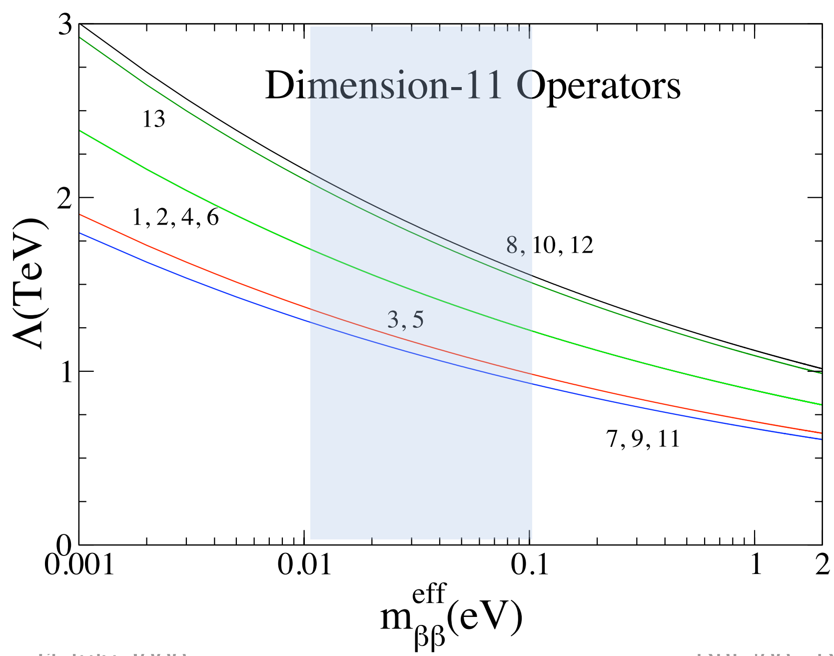
$$
\begin{aligned}
\mathcal{L}_{d=9} \quad = \quad & \frac{1}{\Lambda^5}\left[\lambda_{9,1}(ee)(ud^c)(ud^c) + \lambda_{9,2}(ee)(u\sigma^{\mu\nu}d^c)(u\sigma_{\mu\nu}d^c)\right. \\
& +\lambda_{9,3}(ee)(\bar{d}\bar{u}^c)(\bar{d}\bar{u}^c) + \lambda_{9,4}(ee)(\bar{d}\sigma^{\mu\nu}\bar{u}^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\
& +\lambda_{9,5}(ee)(ud^c)(\bar{d}\bar{u}^c) + \lambda_{9,6}(ee)(u\sigma^{\mu\nu}d^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\
& +\lambda_{9,7}(ee)(u\sigma^{\mu}\bar{d})(\bar{u}^c\sigma_{\mu}d^c) \\
& +\lambda_{9,8}(e\sigma^{\mu}\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)(ud^c) + \lambda_{9,9}(e\sigma^{\mu}e)(d^c\sigma^{\nu}\bar{u}^c)(u\sigma_{\mu\nu}d^c) \\
& +\lambda_{9,10}(e\sigma^{\mu}\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)(\bar{d}\bar{u}^c) + \lambda_{9,11}(e\sigma^{\mu}e)(d^c\sigma^{\nu}\bar{u}^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\
& \left.+\lambda_{9,12}(\bar{e}^c\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)(d^c\sigma^{\mu}\bar{u}^c)\right] + h.c.
\end{aligned}
$$



For dim-9 operators, next generation experiments sensitive to new physics at scales of 2 – 6 TeV.

At dimension-11, there are 13 *new & unique* operators (all involve 2 Higgs fields):

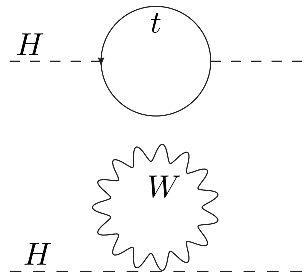
$$\begin{aligned}\mathcal{L}_{d=11} \quad = \quad & \frac{v^2}{2\Lambda^7}\Big[\lambda_{11,1}(ee)(u\sigma^\mu\bar{d})(u\sigma_\mu\bar{d}) + \lambda_{11,2}(ee)(d^c\sigma^\mu\bar{u}^c)(d^c\sigma_\mu\bar{u}^c) \\ & +\lambda_{11,3}(e\sigma^\mu\bar{e}^c)(u\sigma_\mu\bar{d})(ud^c) + \lambda_{11,4}(e\sigma^\mu\bar{e}^c)(u\sigma^\nu\bar{d})(u\sigma_{\mu\nu}d^c) \\ & +\lambda_{11,5}(e\sigma^\mu\bar{e}^c)(u\sigma_\mu\bar{d})(\bar{d}\bar{u}^c) + \lambda_{11,6}(e\sigma^\mu\bar{e}^c)(u\sigma^\nu\bar{d})(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\ & +\lambda_{11,7}(\bar{e}^c\bar{e}^c)(ud^c)(ud^c) + \lambda_{11,8}(\bar{e}^c\bar{e}^c)(u\sigma^{\mu\nu}d^c)(u\sigma_{\mu\nu}d^c) \\ & +\lambda_{11,9}(\bar{e}^c\bar{e}^c)(\bar{d}\bar{u}^c)(\bar{d}\bar{u}^c) + \lambda_{11,10}(\bar{e}^c\bar{e}^c)(\bar{d}\sigma^{\mu\nu}\bar{u}^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\ & +\lambda_{11,11}(\bar{e}^c\bar{e}^c)(ud^c)(\bar{d}\bar{u}^c) + \lambda_{11,12}(\bar{e}^c\bar{e}^c)(u\sigma^{\mu\nu}d^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\ & +\lambda_{11,13}(\bar{e}^c\bar{e}^c)(u\sigma^\mu\bar{d})(u\sigma_\mu\bar{d})\Big] + h.c.\end{aligned}$$



For dim-11 operators, next generation experiments sensitive to new physics at scales of 1 - 2 TeV.

Are there any good reasons to believe in new physics at TeV scale?

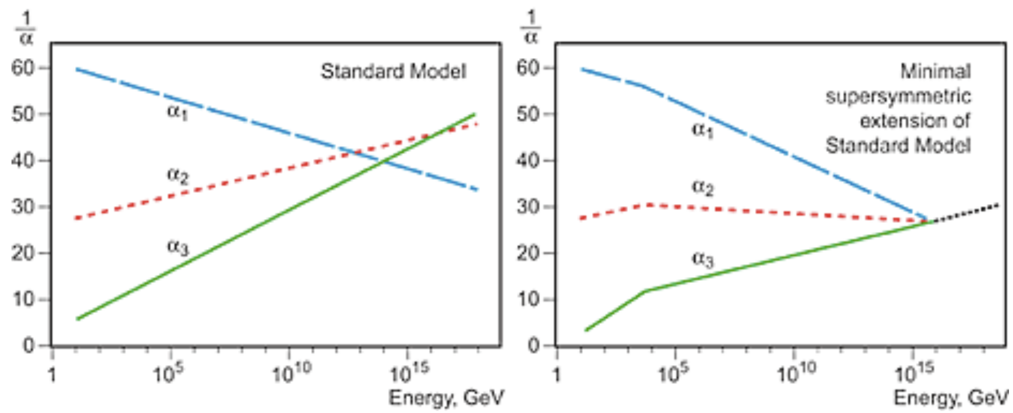
- Gauge hierarchy problem/fine-tuning problem



$$\delta m_H^2 \simeq \frac{1}{16\pi^2}\Lambda^2$$

$$\delta m_H^2 < (100\,\mathrm{GeV})^2 \implies \Lambda \lesssim 1\,\mathrm{TeV}$$

- GUT unification



- Dark matter

If dark matter is thermal, and $\sigma_{\mathrm{ann}} \simeq 1/m_{\mathrm{DM}}^2$ *, then:*

$$m_{\mathrm{DM}} \simeq 100 - 1000\,\mathrm{GeV}$$

But there are also some very good reasons **NOT** to believe in new TeV-scale physics:

→ *FLAVOR-CHANGING NEUTRAL CURRENTS*

Generic 4-quark, dimension-6 operators can generate large, new sources of FCNC's.

Example:

$$\frac{C}{\Lambda^2}(\bar{s}_L\gamma^\mu d_L)(\bar{s}_L\gamma_\mu d_L)$$ → K^0-$\overline{K^0}$ mixing!

If *C* is O(1) and real, $\Lambda \gtrsim 100\,\mathrm{TeV}$

If *C* is O(1) and complex, $\Lambda \gtrsim 1000\,\mathrm{TeV}$!

If these constraints apply universally (including leptons), it would be very difficult for new LNV operators to generate $0\nu\beta\beta$ at next generation experiments.

What conditions would allow new physics at TeV scale, consistent with all **quark flavor constraints**?

1. New physics is completely quark flavor-independent.

   Doesn't couple to fermions, or couples to fermions universally.
   Examples: singlet Higgs, or universal Z'
   Will alter SM predictions at $O(M_W/\Lambda)^n$ *only.*

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2. New physics that has non-trivial quark flavor physics, but only where we haven't looked yet.

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   Perhaps testable at LHCb or a future SuperB factory.

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3. New physics preserves approximate quark flavor symmetries of the SM.

   → ***Minimal Flavor Violation*** *(MFV)*

Minimal Flavor Violation (MFV)

D'Ambrosio, Giudice, Isidori, Strumia

In absence of fermion masses, Standard Model has a $U(3)^5$ flavor symmetry:

$$U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$
$$\times\, U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_E$$

$$= SU(3)_q^3 \times SU(3)_\ell^2 \times \ldots$$

The Yukawa couplings break the $SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)_{PQ} \times U(1)_E$, leaving only approximate symmetries.

As long as new physics preserves these approximate symmetries, no new large flavor-changing or LFV.

Easy to implement for quarks: treat Yukawa couplings/matrices as *spurions* that carry $SU(3)_q^3$-quantum numbers, broken when Yukawas get "vevs":

$$Y_u \sim (3, \bar{3}, 1)$$
$$Y_d \sim (3, 1, \bar{3})$$

under $SU(3)_Q \times SU(3)_U \times SU(3)_D$

For quark processes, MFV means:

- Most hadronic FCNC's receive only $O(M_W/\Lambda)^n$ corrections
  → GIM mechanism preserved!

- No new sources of CP violation. Corrections to SM scale as above.
  Example: no difference in CP asymmetries for $B_d \to \psi K_s,\ B_d \to \phi K_s$

- Specific exceptions only occur when new physics breaks $U(1)_{PQ}$.
  Example: minimal SUSY at large tanβ. Rate for $B_s \to \mu\mu$ *can be many orders above SM rate.*

In essence: *LL* interactions unsuppressed, all others (*LR, RL, RR*) suppressed by powers of Yukawa couplings.

Even though MFV is a restriction on quark interactions, it can impose severe constraints on lepton sector when coupling to quarks!

Look again at the dimension-7 0νββ operators:

$$\mathcal{L}_{d=7} = \frac{v}{\sqrt{2}\Lambda^3}\,[\lambda_{7,1}(\nu_e e)(ud^c) + \lambda_{7,2}(\nu_e\sigma^{\mu\nu}e)(u\sigma_{\mu\nu}d^c) + \lambda_{7,3}(\nu_e e)(\bar{d}\bar{u}^c) + \lambda_{7,4}(\nu_e\sigma^{\mu\nu}e)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) + \lambda_{7,5}(\nu_e\sigma^{\mu}\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)] + h.c.$$

LR

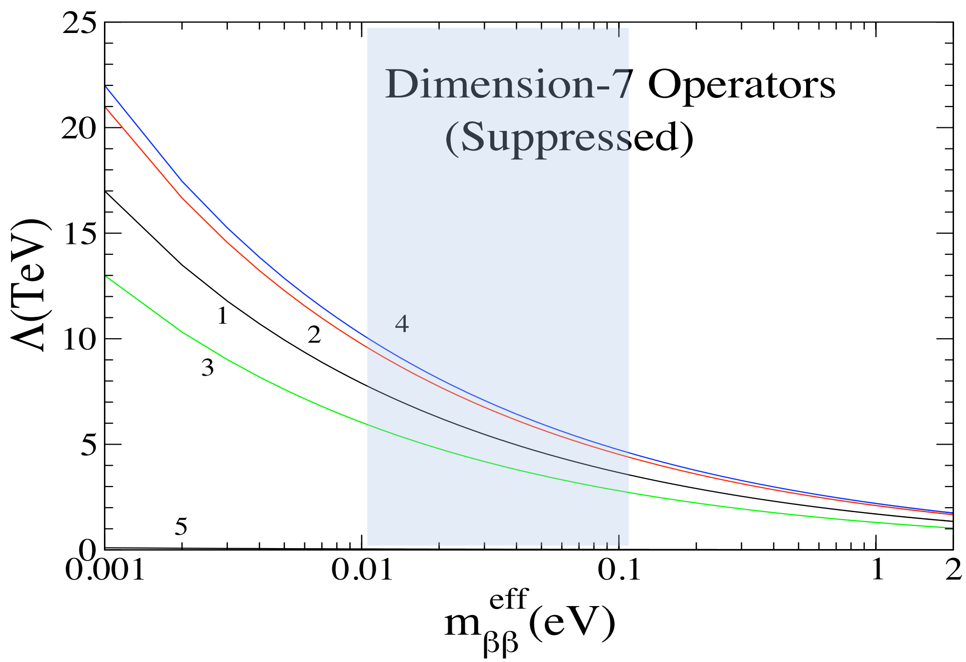
LR

RR

Even though quarks are all 1st generation, all dim-7 terms break SM quark flavor symmetries. By MFV, they must be suppressed by powers of Yukawas:

$$\lambda_{7,1}, \lambda_{7,2} \quad \propto Y_D^\dagger \quad \sim y_d$$
$$\lambda_{7,3}, \lambda_{7,4} \quad \propto Y_U \quad \sim V_{ud} y_u$$
$$\lambda_{7,5} \quad \propto Y_U Y_D^\dagger \quad \sim V_{ud} y_u y_d$$

Now 0νββ experiments probe only 3 – 10 TeV range, not 100's of TeV !



Now the dimension-9 operators:

$$
\begin{aligned}
\mathcal{L}_{d=9} \;=\; \frac{1}{\Lambda^5}\,[\lambda_{9,1}(ee)(ud^c)(ud^c) &+ \lambda_{9,2}(ee)(u\sigma^{\mu\nu}d^c)(u\sigma_{\mu\nu}d^c) \\
+\lambda_{9,3}(ee)(\bar{d}\bar{u}^c)(\bar{d}\bar{u}^c) &+ \lambda_{9,4}(ee)(\bar{d}\sigma^{\mu\nu}\bar{u}^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\
+\lambda_{9,5}(ee)(ud^c)(\bar{d}\bar{u}^c) &+ \lambda_{9,6}(ee)(u\sigma^{\mu\nu}d^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\
+\lambda_{9,7}(ee)(u\sigma^{\mu}\bar{d})(\bar{u}^c\sigma_{\mu}d^c) & \\
+\lambda_{9,8}(e\sigma^{\mu}\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)(ud^c) &+ \lambda_{9,9}(e\sigma^{\mu}e)(d^c\sigma^{\nu}\bar{u}^c)(u\sigma_{\mu\nu}d^c) \\
+\lambda_{9,10}(e\sigma^{\mu}\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)(\bar{d}\bar{u}^c) &+ \lambda_{9,11}(e\sigma^{\mu}e)(d^c\sigma^{\nu}\bar{u}^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\
+\lambda_{9,12}(\bar{e}^c\bar{e}^c)(d^c\sigma_{\mu}\bar{u}^c)(d^c\sigma^{\mu}\bar{u}^c)] &+ h.c.
\end{aligned}
$$

only *LL* term

RR *LR*

Leading to the following suppressions:

$\lambda_{9,1},\lambda_{9,2}$	$\lambda_{9,3},\lambda_{9,4}$	$\lambda_{9,5},\lambda_{9,6},\lambda_{9,7}$	$\lambda_{9,8},\lambda_{9,9}$	$\lambda_{9,10},\lambda_{9,11}$	$\lambda_{9,12}$
$Y_D^{\dagger\,2}$	Y_U^2	$Y_U Y_D^\dagger$	$Y_D^{\dagger 2} Y_U$	$Y_U^2 Y_D^\dagger$	$Y_D^{\dagger 2} Y_U^2$
y_d^2	$V_{cd}V_{us}y_c y_u$	$V_{ud}y_u y_d$	$V_{ud}y_u y_d^2$	$V_{cd}V_{us}y_c y_u y_d$	$V_{cd}V_{us}y_c y_u y_d^2$

And dimension-11:

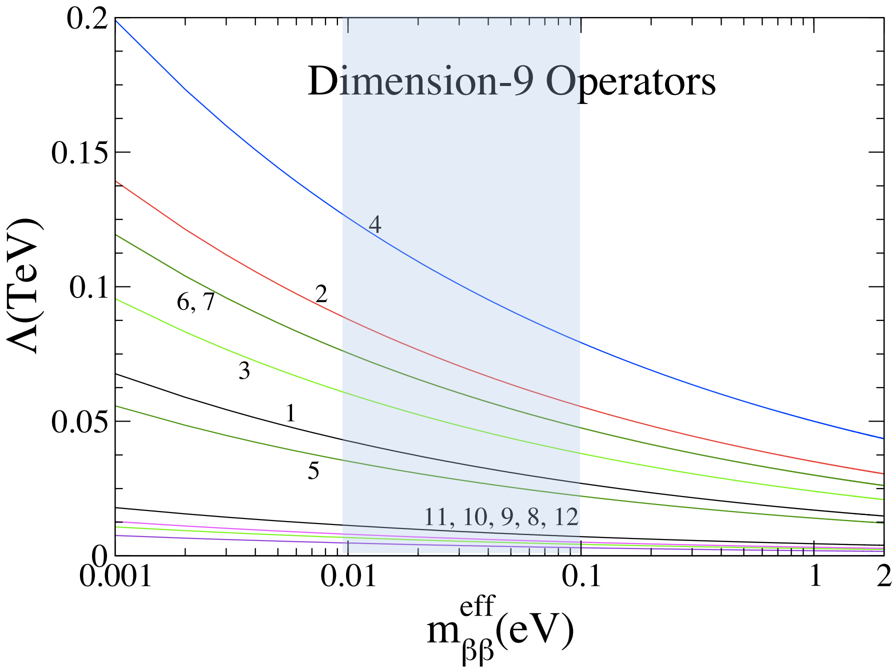
LL

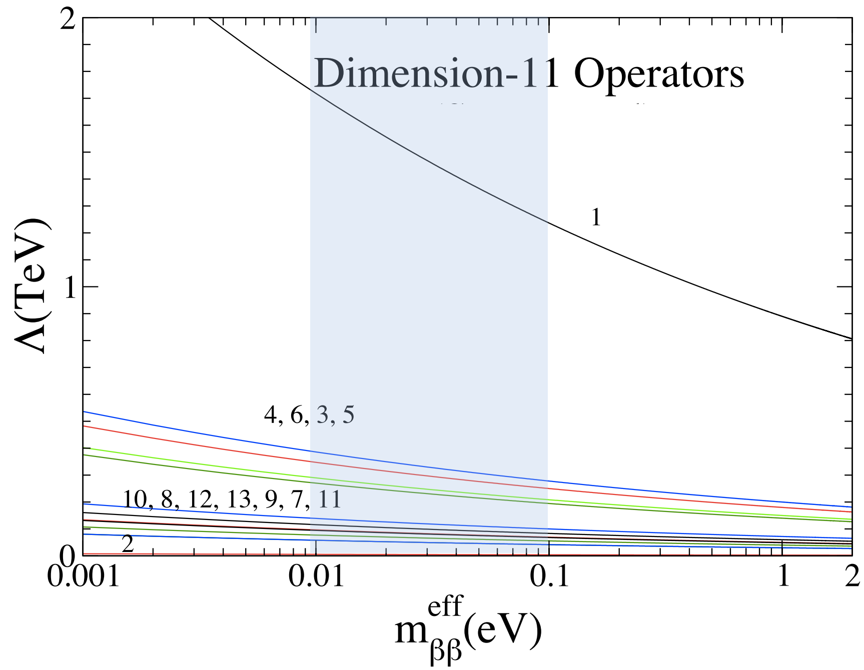
$$\begin{aligned}\mathcal{L}_{d=11} \quad = \quad & \frac{v^2}{2\Lambda^7}\Big[\lambda_{11,1}(ee)(u\sigma^\mu\bar{d})(u\sigma_\mu\bar{d}) + \lambda_{11,2}(ee)(d^c\sigma^\mu\bar{u}^c)(d^c\sigma_\mu\bar{u}^c) \\ & +\lambda_{11,3}(e\sigma^\mu\bar{e}^c)(u\sigma_\mu\bar{d})(ud^c) + \lambda_{11,4}(e\sigma^\mu\bar{e}^c)(u\sigma^\nu\bar{d})(u\sigma_{\mu\nu}d^c) \\ & +\lambda_{11,5}(e\sigma^\mu\bar{e}^c)(u\sigma_\mu\bar{d})(\bar{d}\bar{u}^c) + \lambda_{11,6}(e\sigma^\mu\bar{e}^c)(u\sigma^\nu\bar{d})(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\ & +\lambda_{11,7}(\bar{e}^c\bar{e}^c)(ud^c)(ud^c) + \lambda_{11,8}(\bar{e}^c\bar{e}^c)(u\sigma^{\mu\nu}d^c)(u\sigma_{\mu\nu}d^c) \\ & +\lambda_{11,9}(\bar{e}^c\bar{e}^c)(\bar{d}\bar{u}^c)(\bar{d}\bar{u}^c) + \lambda_{11,10}(\bar{e}^c\bar{e}^c)(\bar{d}\sigma^{\mu\nu}\bar{u}^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\ & +\lambda_{11,11}(\bar{e}^c\bar{e}^c)(ud^c)(\bar{d}\bar{u}^c) + \lambda_{11,12}(\bar{e}^c\bar{e}^c)(u\sigma^{\mu\nu}d^c)(\bar{d}\sigma_{\mu\nu}\bar{u}^c) \\ & +\lambda_{11,13}(\bar{e}^c\bar{e}^c)(u\sigma^\mu\bar{d})(d^c\sigma_\mu\bar{u}^c)\Big] + h.c.\end{aligned}$$

Leading to the following suppressions:

$\lambda_{11,1}$	$\lambda_{11,2}$	$\lambda_{11,3}, \lambda_{11,4}$	$\lambda_{11,5}, \lambda_{11,6}$	$\lambda_{11,7}, \lambda_{11,8}$	$\lambda_{11,9}, \lambda_{11,10}$	$\lambda_{11,11}, \lambda_{11,12}, \lambda_{11,13}$
1	$Y_D^{\dagger 2} Y_U^2$	$Y_D^\dagger$	Y_U	$Y_D^{\dagger 2}$	Y_U^2	$Y_D^\dagger Y_U$
1	$V_{cd}V_{us}y_c y_u y_d^2$	y_d	$V_{ud}y_u$	y_d^2	$V_{cd}V_{us}y_c y_u$	$V_{ud}y_u y_d$

These suppress the scales associated with $0\nu\beta\beta$ at dim-9 and -11:



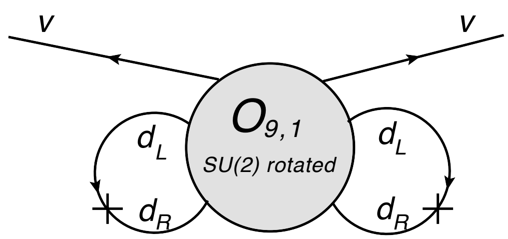


Physics associated with $0\nu\beta\beta$ must sit at or near TeV-scale in order to provide signal in next generation experiments, UNLESS signal due to an actual Majorana mass!

There is another constraint on these operators because they will induce Majorana neutrino masses in loops. If mass is too large, will contradict atmospheric neutrino data, or even cosmological data.

For example: $\mathcal{O}_{9,1} = (ee)(ud^c)(ud^c) \quad \xrightarrow{\mathrm{SU(2)}} \quad (\nu\nu)(dd^c)(dd^c)$

Induces neutrino mass at 2-loops



$$m_\nu \approx \frac{\lambda_{9,1}}{\Lambda^5} \times \frac{1}{(16\pi^2)^2} \times (\Lambda^2)^2 \times m_d^2 \quad \propto \frac{m_d^2}{\Lambda}$$

See also DeGouvea & Jenkins, '07

If $\lambda \sim 1$, and we demand all $m_\nu \lesssim 0.05\,\mathrm{eV}$, then we must have $\Lambda \gtrsim 20\,\mathrm{GeV}$.

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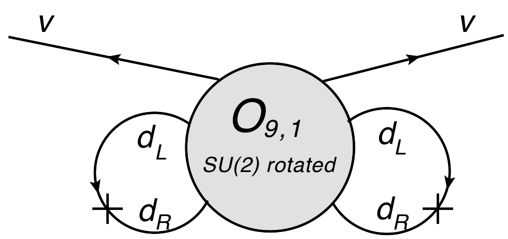

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If $\lambda \sim 1$, and we demand all $m_\nu \lesssim 0.05\,\mathrm{eV}$, then we must have $\Lambda \gtrsim 20\,\mathrm{GeV}$.

But MFV flavor symmetries relate this diagram to one with *b*-quarks in loops, replacing $m_d \to m_b$ in neutrino mass calculation, but also suppressing it by a further y_b^2.

$$\Lambda \gtrsim 10^4\,\mathrm{GeV}$$

Lesson:

Operators which produce observable $0\nu\beta\beta$ signals may be ruled out because they induce large (and excluded) neutrino masses.

Operators which can survive must produce a $0\nu\beta\beta$ signal without too much MFV suppression (allowing Λ to be as large as possible) while requiring large suppressions when inducing neutrino masses.

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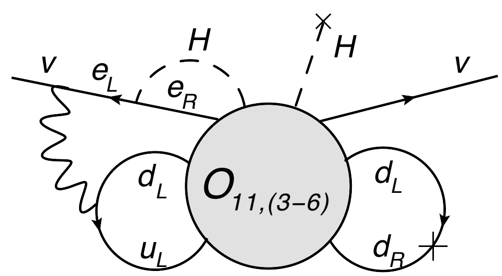
Only four operators satisfy both criteria:

$$\mathcal{O}_{11,(3,4,5,6)} \sim (e\sigma^\mu \bar{e}^c)(q\sigma^\nu \bar{q})(q\Gamma_{\mu\nu} q^c) \qquad \Gamma_{\mu\nu} = \delta_{\mu\nu} \text{ or } \sigma_{\mu\nu}$$

LL LR

(would be suppressed if MFV extended to leptons)

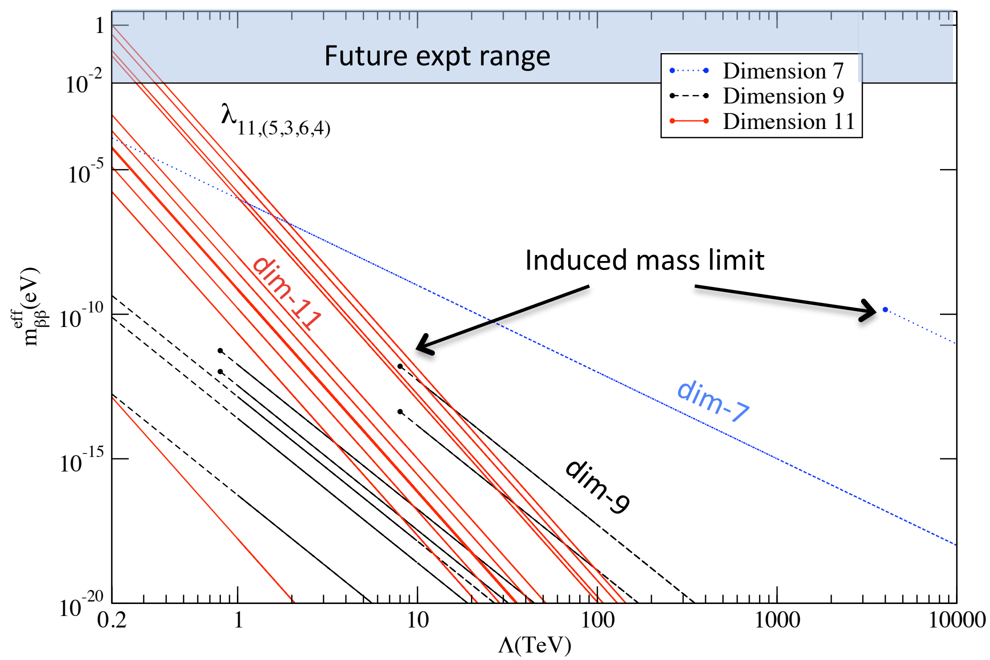
Neutrino mass induced at 4-loops → too small to constrain the operators.



$$m_\nu \approx \frac{g^2}{(16\pi^2)^4} \frac{m_e m_d}{\Lambda} \times y_d$$

MFV suppression

“Summary” of results:

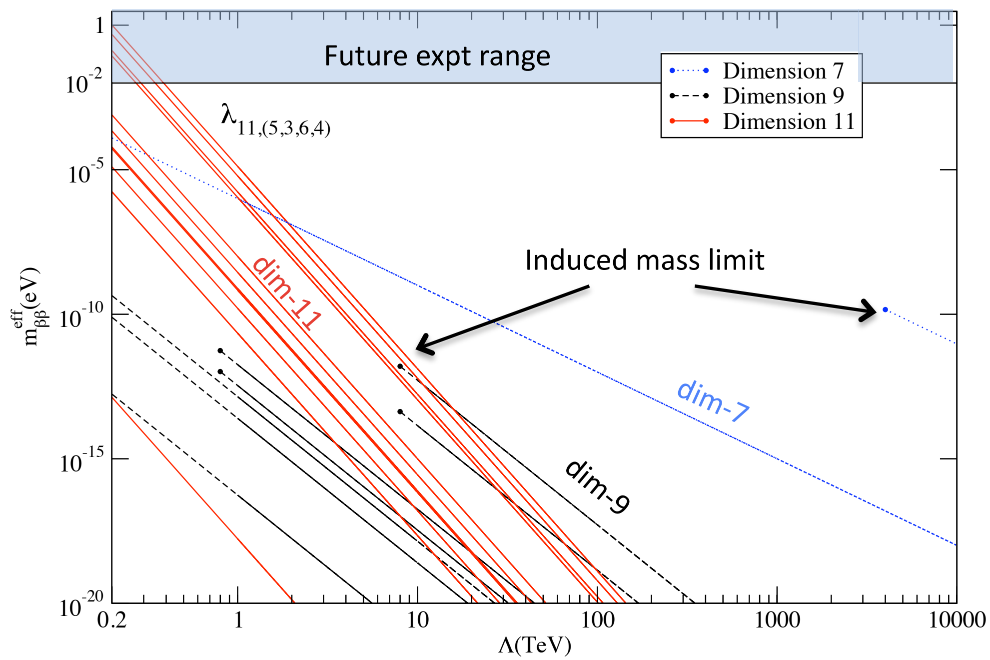


Four dim-11 operators can produce observable $0\nu\beta\beta$ without inducing neutrino masses above atmospheric bound.

All four require cutoffs below 500 GeV in order to produce sizable $0\nu\beta\beta$

→ we can hope to see this physics at the LHC!

“Summary” of results:



Conversely, it is very likely that a positive signal in a $0\nu\beta\beta$ experiment would be a measurement of Majorana neutrino masses -- especially if LHC finds no evidence for new physics that may be LNV.

Validity of this result rests on assumption of Minimal Flavor Violation in quark sector!