LEPTON NUMBER VIOLATION: SCALES AND MECHANISMS

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Lepton number

ν oscillations: first evidence of NP

↓

ν masses

some NP

↓

$$\frac{1}{\Lambda}\left(\bar{\ell}\phi\right)^2$$

↓

Majorana masses
(Λ large)

add ν_R

↓

Dirac masses

difficult to differentiate
→ $0\nu\beta\beta$ decay

"Standard" scenario:

NP → ν mass → $0\nu\beta\beta$ → $\Lambda \sim 10^6$ TeV ($m_D = m_\mu$)

An interesting alternative:

NP → $0\nu\beta\beta$ → ν mass → $\Lambda \sim 1$ TeV

$$\text{N.B.: } \Gamma_{SM}(0\nu\beta\beta) \equiv 0$$

Low-energy LNV effects

Write down all relevant effective operators exhibiting LNV … what *is* relevant?

- Choose the low energy fields

  What is the scalar sector like?

  Are there ν_R? How many?

-Decide whether the new physics is strongly or weakly coupled

  For strong coupling: some of the light fields should participate (in practice some of the hypotheticals e.g. ν_R)

- Do not use the effective theory above Λ!

- Operator hierarchies

  -Weakly coupled new physics: canonical dimension, loop or tree generated

  - Strongly coupled new physics: naïve dimensional analysis

N.B. loop-generated: for *all* models

tree-generated: there is *a* model

-Can determine the types of heavy physics that can generate any set of operators

  Testing the consistency of the resulting "reverse engineered" model(s) is straightforward, but tedious

Example

Low energy fields: SM (1 scalar isodoublet)

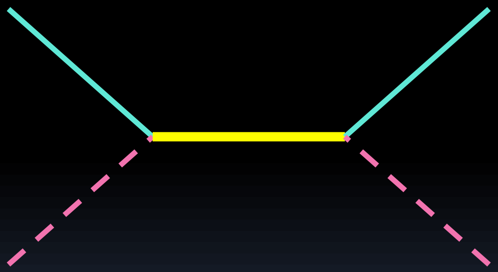
New physics: weakly coupled

Leading LNV operator (Weinberg):

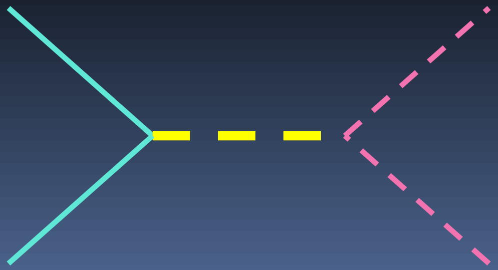
$$\frac{1}{\Lambda}\left(\bar{\ell}\phi\right)^2$$

Generated at tree level by

Fermion isosinglet: type I see-saw models
Fermion isotriplet: type III see-sew models



Boson isotriplet: type II see-saw models



LNV scale

Best limits: $0\nu\beta\beta$ decay - considered later

Other limits:

$$BR(Z \to p\ell) < 1.8 \times 10^{-6}\ 95\%\mathrm{CL}$$

$$\mathcal{L} = \frac{1}{\Lambda^4}(\bar{q}\tilde{\phi}\gamma^\mu e^c)(\bar{d}D_\mu u^c) \quad \Rightarrow \quad \Lambda_{\mathrm{LNV}} > 500\mathrm{GeV}$$

$$BR(\tau \to p\gamma) < 3.5 \times 10^{-6}\ 90\%\mathrm{CL}$$

$$\mathcal{L} = \frac{1}{\Lambda^4}(\bar{q}\tilde{\phi}\gamma^\mu e^c)(\bar{d}D_\mu u^c) \quad \Rightarrow \quad \Lambda_{\mathrm{LNV}} > 600\mathrm{GeV}$$

$$\left.\begin{array}{l} \tau \to \ell\pi\pi,\ \Lambda\pi \\ K^+ \to \pi^-\ell\ell \\ D^+ \to \pi^-\ell\ell,\ pe \\ \Xi^- \to p\mu\mu \end{array}\right\} \quad \Rightarrow \quad \Lambda_{\mathrm{LNV}} > O(100\mathrm{GeV})$$

N.B. These limits in general refer to different types of heavy physics

$0\nu\beta\beta$ decay

Of interest in probing

LNV

Structure of the ν mass sector

Best limit from the Heidelberg-Moscow experiment:

$$T_{1/2} = 1.8 \times 10^{25} \text{ years}$$

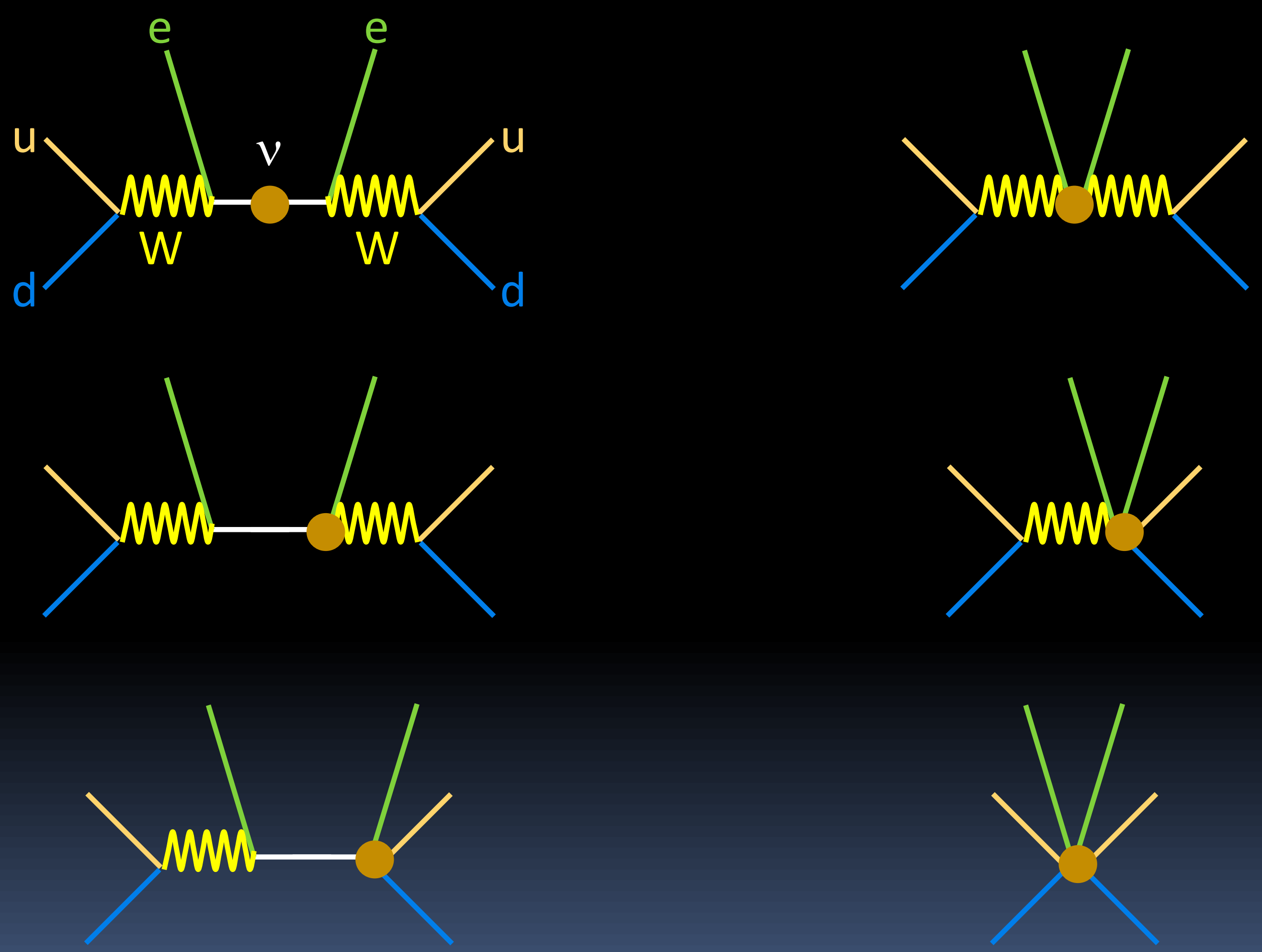
Violates B-L: absolutely forbidden in the SM

Next: what kinds of new physics can be responsible:

… What does the H-M experiment constrain?

… What will GENIUS-II probe?

Possible new physics effects:



Effective operators with no quarks:

vertex	effective operators	dim.	lepton chirality
$\nu\nu$	$(\bar\ell\tilde\phi)(\tilde\phi^T\ell^c)$	5	LL
$\nu e W$	$(\phi^\dagger D_\mu\tilde\phi)\left[\bar e\gamma^\mu(\tilde\phi^T\ell^c)\right]$	7	LR
$eeWW$	$(\phi^\dagger D^\mu\tilde\phi)(\phi^\dagger D_\mu\tilde\phi)(\bar e e^c)$	9	RR
	$(D^\mu\bar\ell\tilde\phi)(\tilde\phi^T D_\mu\ell^c)$, $(\phi^\dagger D_\mu\tilde\phi)(\bar\ell\epsilon D^\mu\ell^c)$, $(\bar\ell\tilde\phi)\partial^\mu(\tilde\phi^T D_\mu\ell^c)$	7	LL

Generated by the same heavy physics:

Discard dim 7

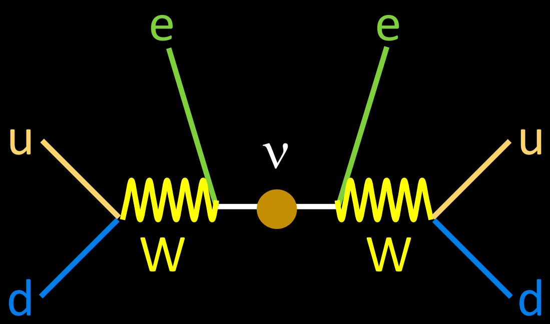
A given type of NP may generate any of the first 3 operators without generating the other 2 (at tree level)

Effective operators with quarks:

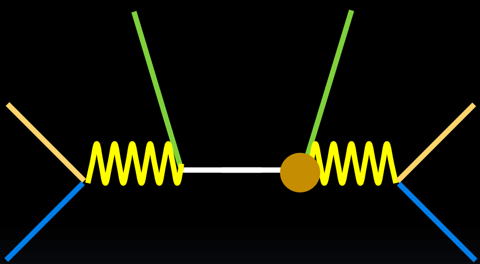
vertex	effective operators	dim.	lepton chirality
$\nu e \bar{u} d$	$(\bar{\ell} \epsilon D_\mu \ell^c)(\bar{u} \gamma^\mu d)$	7	LL
	$(\bar{\ell} \tilde{\phi} d)(\bar{u} e^c) +$ Fierz T.	7	LR
$eeW\bar{u}d$	$(\bar{\ell} \epsilon D_\mu \ell^c)(\bar{u} \gamma^\mu d)$	7	LL
	$(\phi^\dagger D_\mu \tilde{\phi})(\bar{\ell} \gamma^\mu e^c)\epsilon)\bar{q} d)$	7	LR
	$(\phi^\dagger D_\mu \tilde{\phi})(\bar{e} \gamma^\mu d)(\bar{u} e^c)$	7	LR
$ee\bar{u}\bar{u}dd$	$(\bar{e} \gamma^\mu d)(\bar{u} \gamma_\mu d)(\bar{u} e^c) \cdots$	9	LL, LR, RR

Operators, vertices & amplitudes:

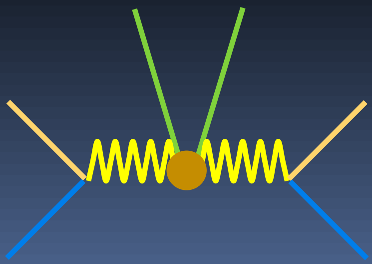
$$\text{Amplitude} \simeq \mathcal{A}/(Q^2 v^3)$$
$$\epsilon = v/\Lambda$$
$$\eta = Q/v \simeq 5.7 \times 10^{-4}$$



$$(\bar{\ell}\tilde{\phi})(\tilde{\phi}^T \ell^c) \rightarrow \mathcal{A} = \epsilon$$

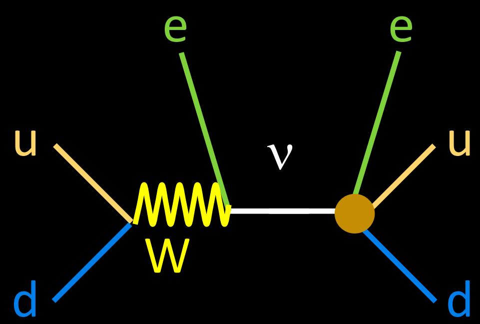


$$(\phi^\dagger D_\mu \tilde{\phi}) \left| \bar{e}\gamma^\mu (\tilde{\phi}^T \ell^c) \right| \rightarrow \mathcal{A} = \eta\epsilon^3$$

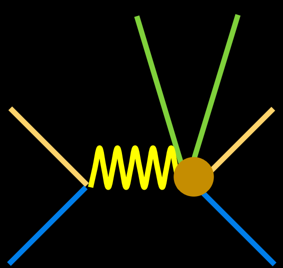


$$(\phi^\dagger D^\mu \tilde{\phi})^2 (\bar{e} e^c) \rightarrow \mathcal{A} = \eta^2 \epsilon^3$$

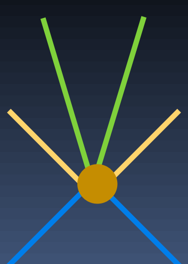
$$\text{Amplitude} \simeq \mathcal{A}/(Q^2 v^3)$$
$$\epsilon = v/\Lambda$$
$$\eta = Q/v \simeq 5.7 \times 10^{-4}$$



$$(\bar{\ell}\epsilon D_\mu \ell^c)(\bar{u}\gamma^\mu d) \to \mathcal{A} = \eta^2 \epsilon^3$$



$$(\bar{\ell}\epsilon D_\mu \ell^c)(\bar{u}\gamma^\mu d) \to \mathcal{A} = \eta \epsilon^3$$



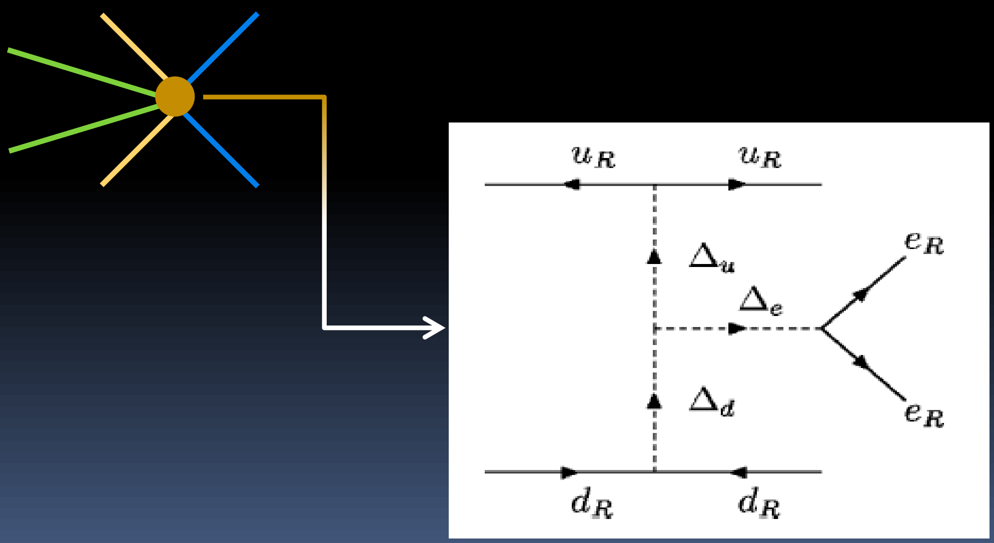
$$(\bar{e}\gamma^\mu d)(\bar{u}\gamma_\mu d)(\bar{u}e^c) \to \mathcal{A} = \eta^2 \epsilon^3$$

Limit: $\mathcal{A} < 1.5 \times 10^{-13}$ $\Rightarrow$

$\mathcal{A}$	$\Lambda_{\rm min}(\rm TeV)$
ϵ	10^{12}
$\eta\epsilon^3$	270
$\eta^2\epsilon^3$	$\mathbf{3}$

May have observable LHC effects

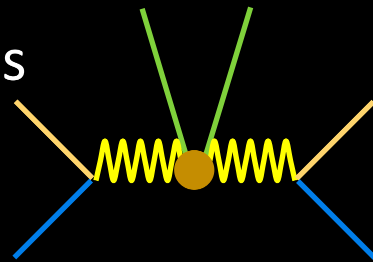
Example (Brahmachari & Ma):



Λ = O(TeV)

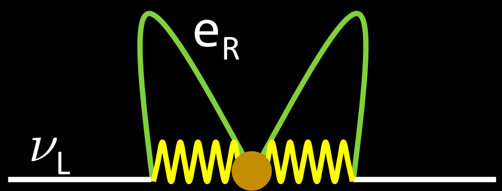
m_ν tiny: 4 loop effect (!)

For the contributions



$$\leftrightarrow \quad (\phi^\dagger D^\mu \tilde{\phi})^2 (\bar{e} e^c)$$

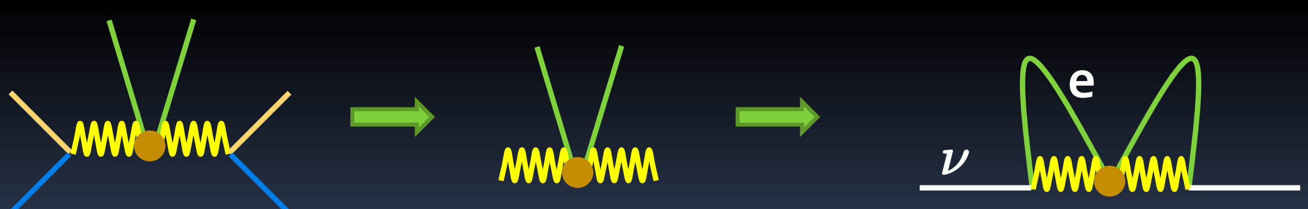
ν masses generated at 2 loops:



$$\rightarrow \quad (m_\nu)_{ij} \sim \frac{1}{\Lambda} \frac{m_i m_j}{2048\pi^4}$$

$$(m_\nu)_{ee} \sim 10^{-6}\text{eV}$$

Fit ν data? $\rightarrow$ Specific model

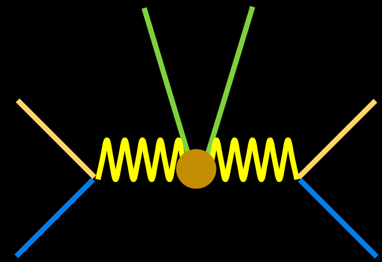


$$\sim \frac{g^2}{\Lambda}$$

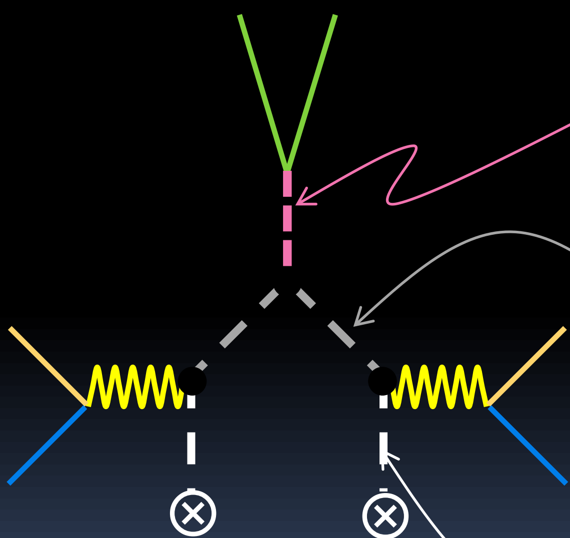
$$m_\nu \sim \frac{\Lambda^6}{(2\pi)^8 v^5}$$

Must take into account: gauge invariance & chirality!

Testable model

Interested in generating  $\longleftrightarrow$ $(\phi^\dagger D^\mu \tilde{\phi})^2 (\bar{e} e^c)$

Many possibilities. We chose SM + 3 scalars:



k = Isosinglet, y=2

+ spontaneously broken L
(use a singlet σ)

χ = Isotriplet, y=1

Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + |Dk|^2 + |D\chi|^2 + \frac{1}{2}(\partial\sigma)^2 - V_0(\phi\times\phi^\dagger, |k|^2, \chi^\dagger\chi, \sigma)$$
$$- \left[\mu_k k^\dagger {\rm tr}\left(\chi^2\right) - \lambda_6 \sigma \phi^\dagger \chi \tilde{\phi} + {\rm H.c.}\right]$$
$$+ \left[Y_{rs}\bar{\ell}_r e_s \phi + g_{rs}\overline{e^c}_r e_s\, k + {\rm H.c.}\right]$$

N_ℓ conservation: no ν_L Maj. masses
N_e conservation: no $0\nu e_R e_R$ decay

Z_2 forbids $\chi-$lepton coupling (spont. broken by $\langle\sigma\rangle \neq 0$)

$Y \to 0$: N_ℓ and N_e decouple: $M_{\rm Maj}(\nu_L) = 0$
$\not{N}_e$ if $\mu_\kappa \cdot \lambda_6 \cdot g_{rs} \neq 0$: $0\nu\beta\beta \neq 0$

$$M_{\rm Maj}(\nu_L) \neq 0 \quad \Rightarrow \quad \mu_\kappa \cdot \lambda_6 \cdot g_{rs} \cdot Y \neq 0$$

Particle content:

$$\chi = \begin{pmatrix} \chi^+/\sqrt{2} & \chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix} \qquad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}.$$

$$k\,,\ \chi^{++} \to k_{1,2} \quad (\text{mixing} \propto \langle\chi\rangle)$$

$$\phi^+\,,\ \chi^+ \to H^+\,,\ G^+\,(\text{eaten})$$

$$\mathbf{Re}\chi^0\,, \mathbf{Re}\phi^0\,, \sigma \to h\,,\ h'\,,\ h''$$

$$\mathbf{Im}\chi^0\,, \mathbf{Im}\phi^0 \to A\,, G^0\,(\text{eaten})$$

- $\langle\chi\rangle \ll m_{\chi,k}$ and $|m_\chi - m_k| > \langle\phi\rangle : \quad k_1 \simeq k,\ k_2 \sim \chi^{++}$
- k : no WW coupling, $2(Z/\gamma)$ couplings OK
- χ : no ee coupling

Some bounds:

Process	Bound (90% CL)
$\mu^- \to e^+ e^- e^-$	$\lvert g_{e\mu} g_{ee} \rvert < 2.3 \times 10^{-5} (m_\kappa/\mathrm{TeV})^2$
$\tau^- \to e^+ e^- e^-$	$\lvert g_{e\tau} g_{ee} \rvert < 0.025 (m_\kappa/\mathrm{TeV})^2$
$\tau^- \to e^+ e^- \mu^-$	$\lvert g_{e\tau} g_{e\mu} \rvert < 0.017 (m_\kappa/\mathrm{TeV})^2$
$\tau^- \to e^+ \mu^- \mu^-$	$\lvert g_{e\tau} g_{\mu\mu} \rvert < 0.020 (m_\kappa/\mathrm{TeV})^2$
$\tau^- \to \mu^+ e^- e^-$	$\lvert g_{\mu\tau} g_{ee} \rvert < 0.019 (m_\kappa/\mathrm{TeV})^2$
$\tau^- \to \mu^+ e^- \mu^-$	$\lvert g_{\mu\tau} g_{e\mu} \rvert < 0.018 (m_\kappa/\mathrm{TeV})^2$
$\tau^- \to \mu^+ \mu^- \mu^-$	$\lvert g_{\mu\tau} g_{\mu\mu} \rvert < 0.025 (m_\kappa/\mathrm{TeV})^2$
$\mu^+ e^- \to \mu^- e^+$	$\lvert g_{ee} g_{\mu\mu} \rvert < 0.2 (m_\kappa/\mathrm{TeV})^2$

$$\langle\chi\rangle = \frac{\lambda_6 \langle\sigma\rangle \langle\phi\rangle^2}{m_\chi^2} \qquad \frac{\langle\chi\rangle}{\langle\phi\rangle} = \sqrt{\frac{1-\rho}{2}} \text{ (tree-level)}$$

Loop corrections: opposite sign $\delta\rho|_{\text{loop}} \sim \left(\frac{m_\chi}{4\pi\langle\phi\rangle}\right)^2$

$$\text{Will take } \langle\chi\rangle < 10\text{GeV}$$

0νββ:

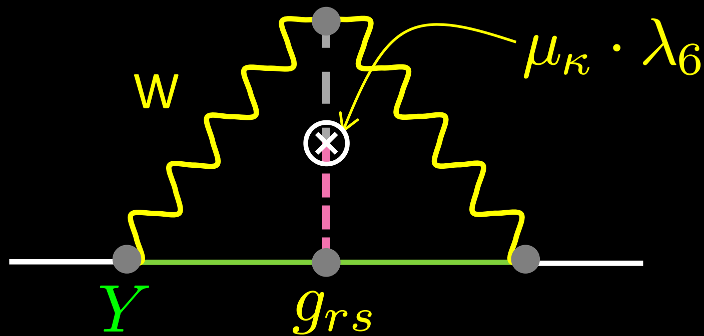
Integrate-out $\boldsymbol{\kappa}$ and χ :

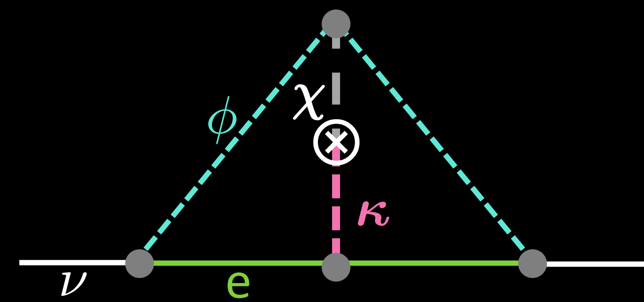
$$\mathcal{L}_{\text{eff}} = \frac{f}{\Lambda^5}(\phi^\dagger D\tilde{\phi})^2\bar{e}e^c = -\frac{g^2\mu_\kappa \langle\chi\rangle^2}{m_\chi^2 m_\kappa^2} g_{ee}^* \bar{e}e^c (W^-)^2 + \cdots$$

$$\Lambda^5 = \frac{m_\chi^4 m_k^2}{\mu_k} \qquad f = 2\left(\frac{m_\chi \langle\chi\rangle}{\langle\phi\rangle^2}\right)^2 = 2\left(\frac{\lambda_6 \langle\sigma\rangle}{m_\chi}\right)^2 \qquad \langle\chi\rangle = \frac{\lambda_6 \langle\sigma\rangle \langle\phi\rangle^2}{m_\chi^2}$$

$$6\times 10^{-10} \overset{\text{GEN}}{<} \frac{M_p}{\mu_k}\left(\frac{\mu_k \langle\chi\rangle}{m_k m_\chi}\right)^2 |g_{ee}| < 4\times 10^{-8} \;\; (90\% \text{ c.l.})$$

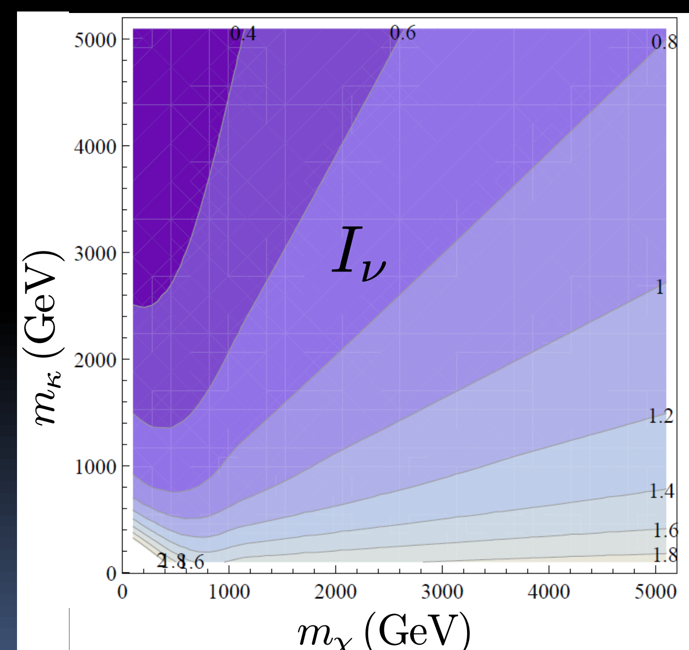
Majorana masses:





$$(m_\nu)_{rs} = \frac{G_F^2}{4\pi^4}\mu_k \langle\chi\rangle^2 \, m_r m_s g_{rs} \, I_\nu$$

Charged lepton masses



$$-7.5+2\left(\log m_k+\log m_\chi\right)\overset{\text{GEN}}{<}\log|m_{ee}|<-5.7+2\left(\log m_k+\log m_\chi\right)$$

$$\log\left[|m_{ee}||m_{e\mu}|\right]<-11.9+4\log\left(m_k\right)$$

$(m_{k,\chi}\ \text{in TeV})$

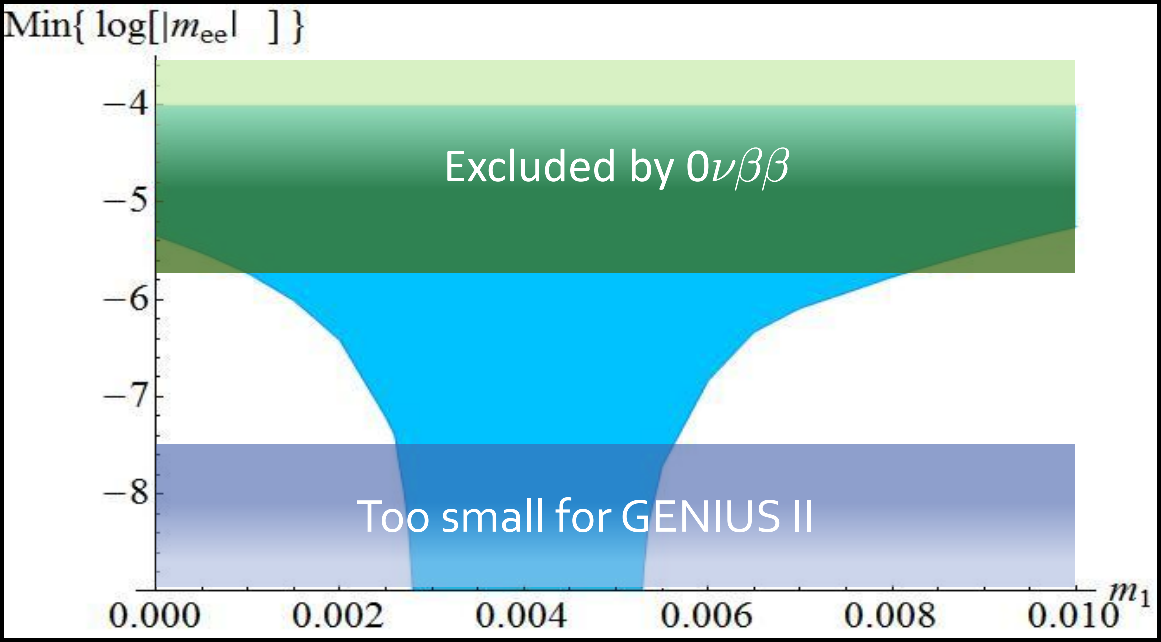
Consistent with the current data?

$$m_\nu = U\begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix}U^T$$

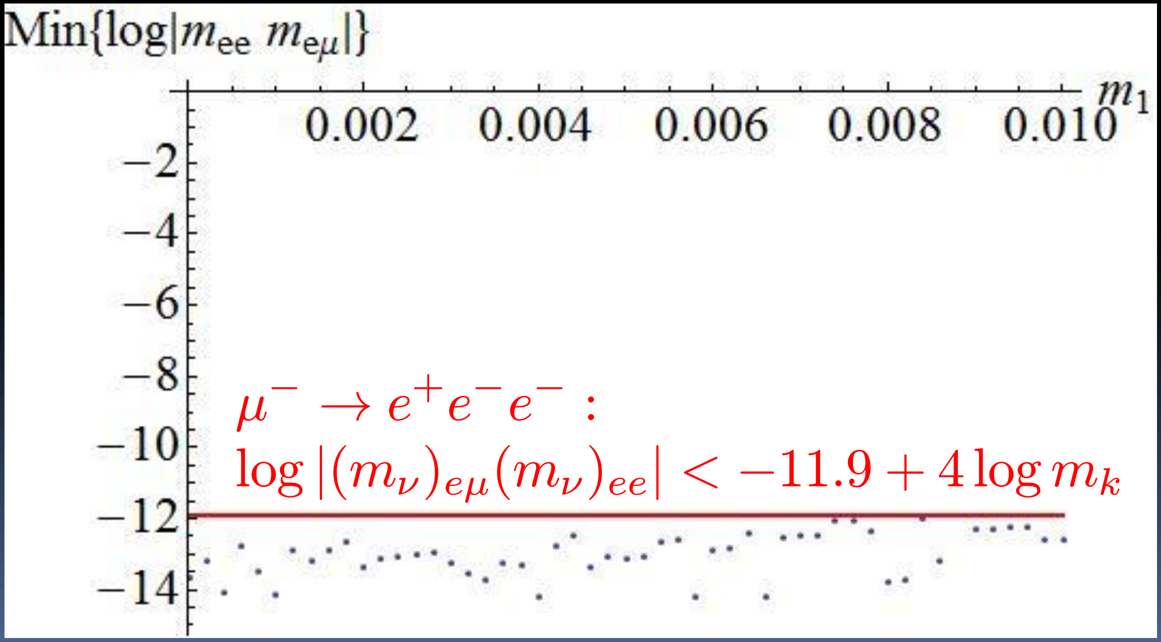
$$U=\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12}s_{13}e^{i\delta} & \\ -c_{23}s_{12}-s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12}-s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12}-c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12}-c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}\begin{pmatrix} e^{i\alpha_1/2} & & \\ & e^{i\alpha_2/2} & \\ & & 1 \end{pmatrix}$$

$$\Delta m^2_{21}=7.64^{+0.19}_{-0.18}\times 10^{-5}\text{eV}^2 \qquad \Delta m^2_{31}=(2.45\pm 0.09)\times 10^{-3}\text{eV}^2$$

$$s^2_{12}=0.316\pm 0.016 \qquad s^2_{23}=0.51\pm 0.06 \qquad s^2_{13}=0.017^{+0.007}_{-0.009}$$



$$m_{k,\chi} = 1\text{TeV}$$



Conclusions

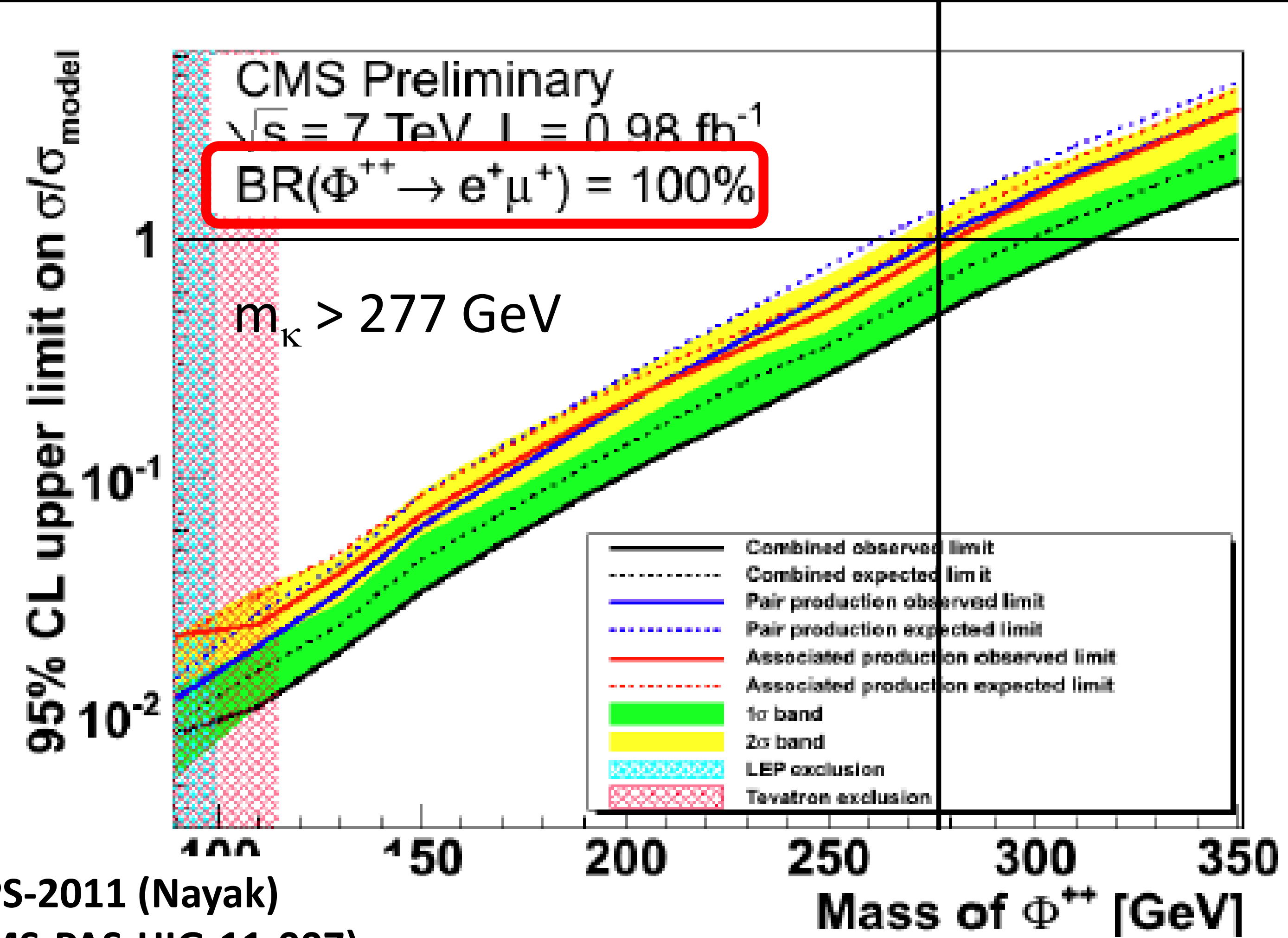
LNV effects can have a light scale
... consistent with ν data and the $0\nu\beta\beta$ constraint

The scale can be low enough to be probed at the LHC

k and χ^{++} probed at LEP and Tevatron:
$m_{k,\chi} > 100$ GeV

Phenomenology: in progress
some initial LHC limits already available

At the LHC: $qq \to Z\,\gamma \to k\,k$: $m_k >$ few $\times$ 100 GeV



EPS-2011 (Nayak)
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