$0\nu\beta\beta$ – Decay: Theory & Mechanism

M.J. Ramsey-Musolf

U Mass Amherst

http://www.physics.umass.edu/acfi/

ACFI Workshop, December 2015

Goals for this talk

- *Review the BSM context for $0\nu\beta\beta$-decay*
- *Review the different decay mechanisms & relationship to m_ν generation*
- *Illustrate complementarity with BSM searches at the high energy frontier*
- *Underscore the need for on-going developments in nuclear and hadronic structure*

Outline

I. BSM Context

II. LNV: $0\nu\beta\beta$ – Decay Mechanisms

III. The "Standard Mechanism"

IV. TeV Scale LNV: $0\nu\beta\beta$ – Decay & the LHC

V. Sterile Neutrinos

VI. Summary

I. The BSM Context

*Questions for Fundamental Physics**

- ***What is the origin of matter (luminous & dark) ?***
- ***Why are neutrino masses so small ?***
- ***Are fundamental interactions "natural" ?***

Partial List

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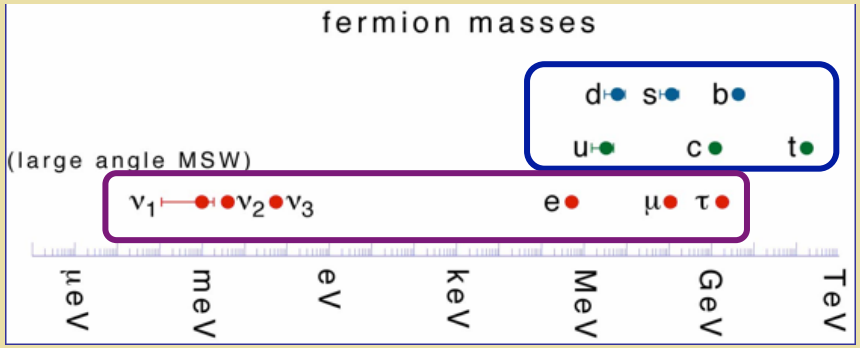

Partners

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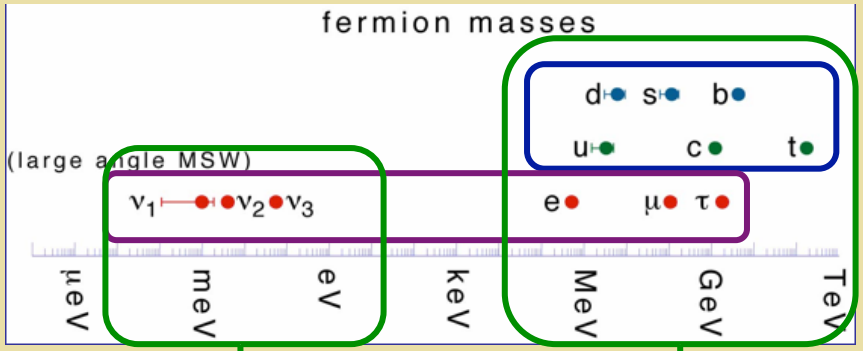

Partners

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Something else ?

Higgs Mechanism

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- ***What is the origin of matter (luminous & dark) ?***
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$0\nu\beta\beta$ Decay

***Partial List**

How "Natural" is m_ν ?

Dirac Mass: $m_\nu = y\, v$

$yv = 246\ \text{GeV} \rightarrow \quad y \sim 10^{-12}$

Majorana Mass: $m_\nu = y\, v^2 / \Lambda$

$yv = 246\ \text{GeV} \rightarrow \quad \Lambda \sim 10^{14}\ \text{GeV}$

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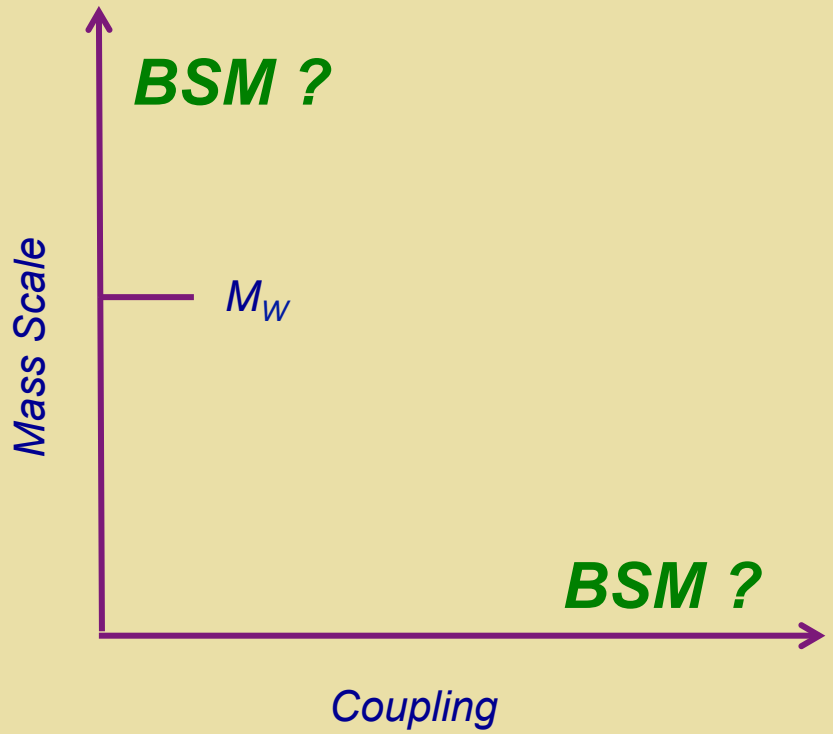
How reliable a guide is naturalness ?

BSM Physics: Where Does it Live ?



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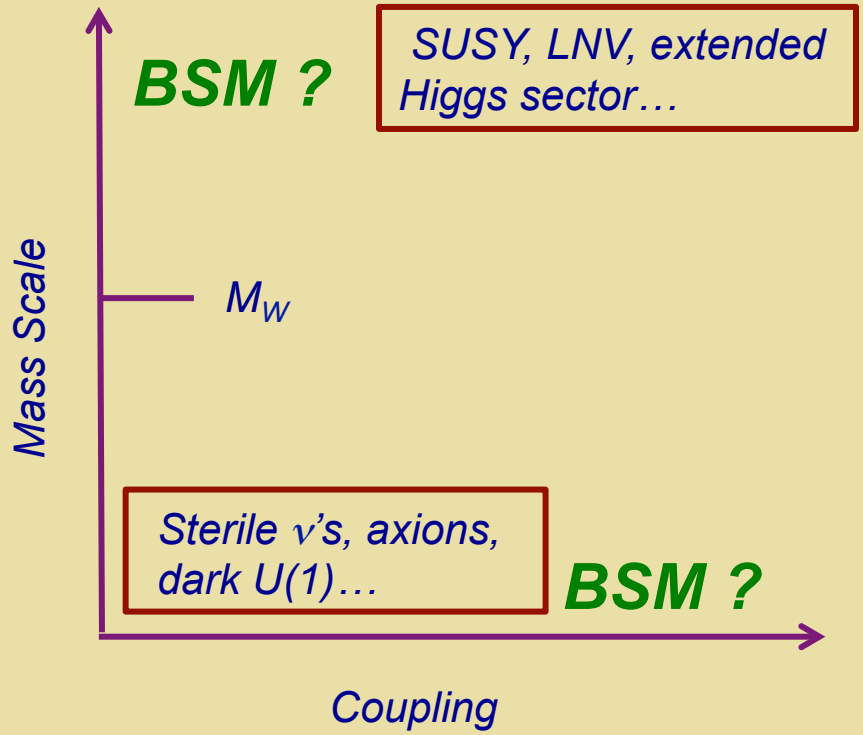

Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

*Questions for Fundamental Physics**

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Discovering answers requires studies at three frontiers: energy, intensity, & cosmic.

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Low-Energy / High-Energy Interplay

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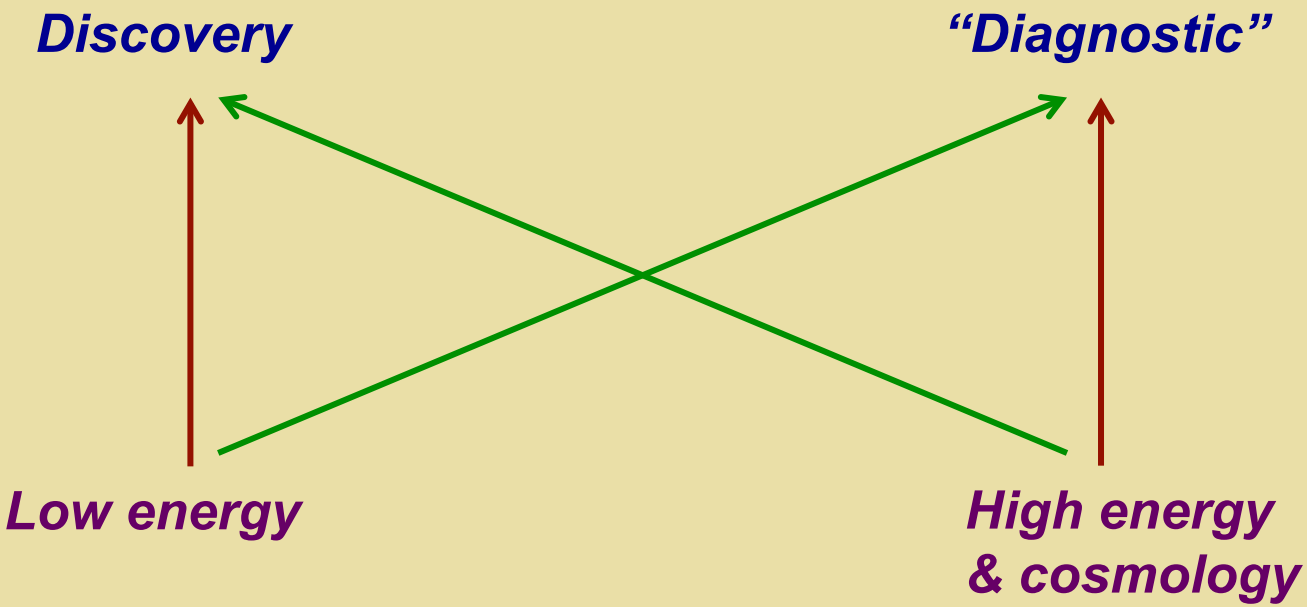

II. LNV: $0\nu\beta\beta$ – Decay Mechanisms

$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

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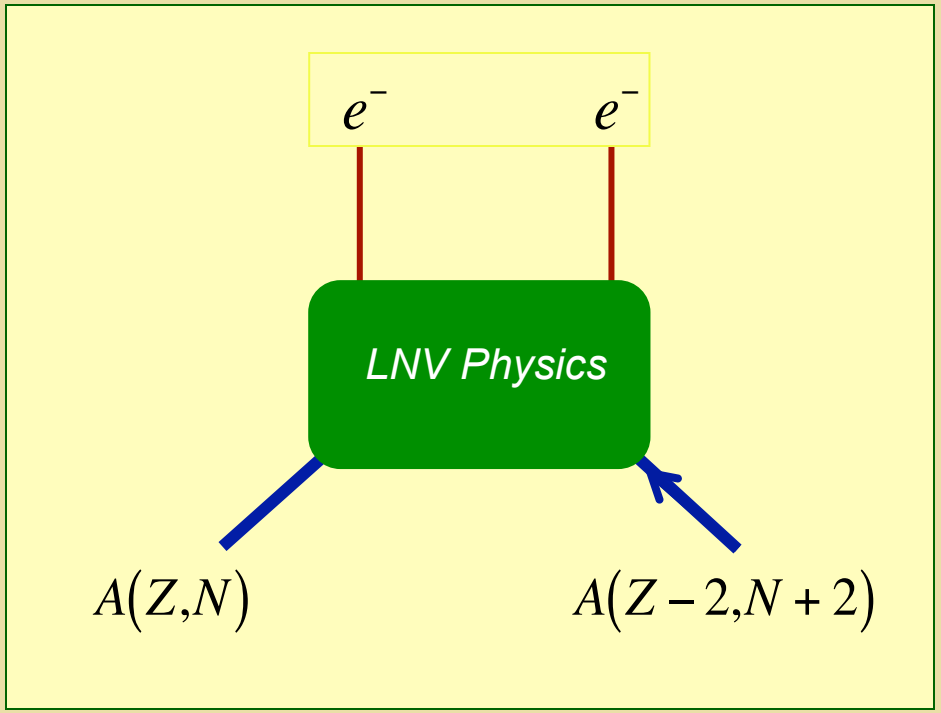

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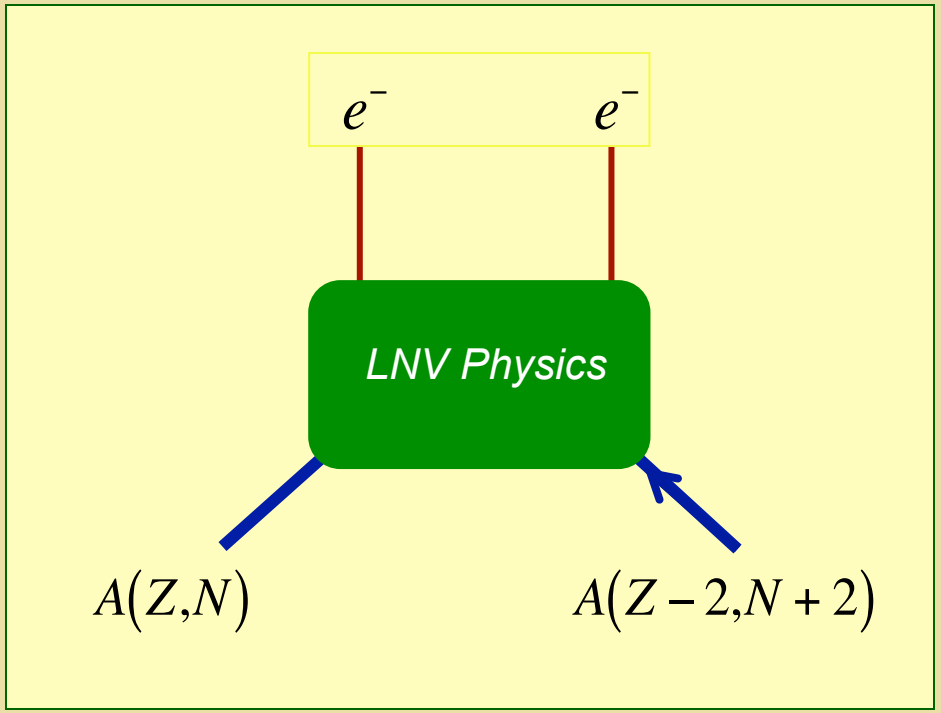
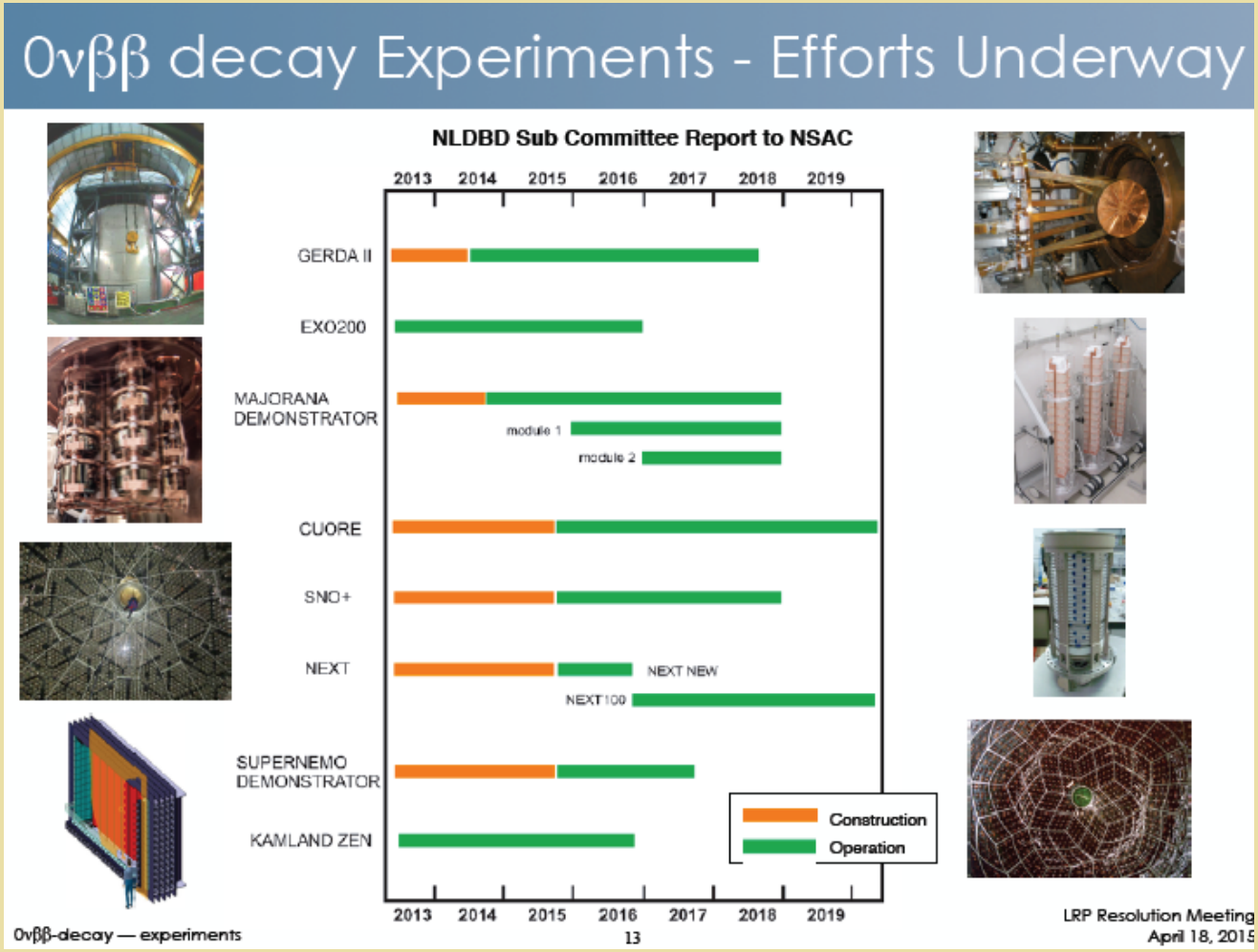
Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



Ton Scale Experiments



Thanks: J. Wilkerson

Why Might A "Ton-Scale" Exp't See It?

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

- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

III. The "Standard Mechanism"

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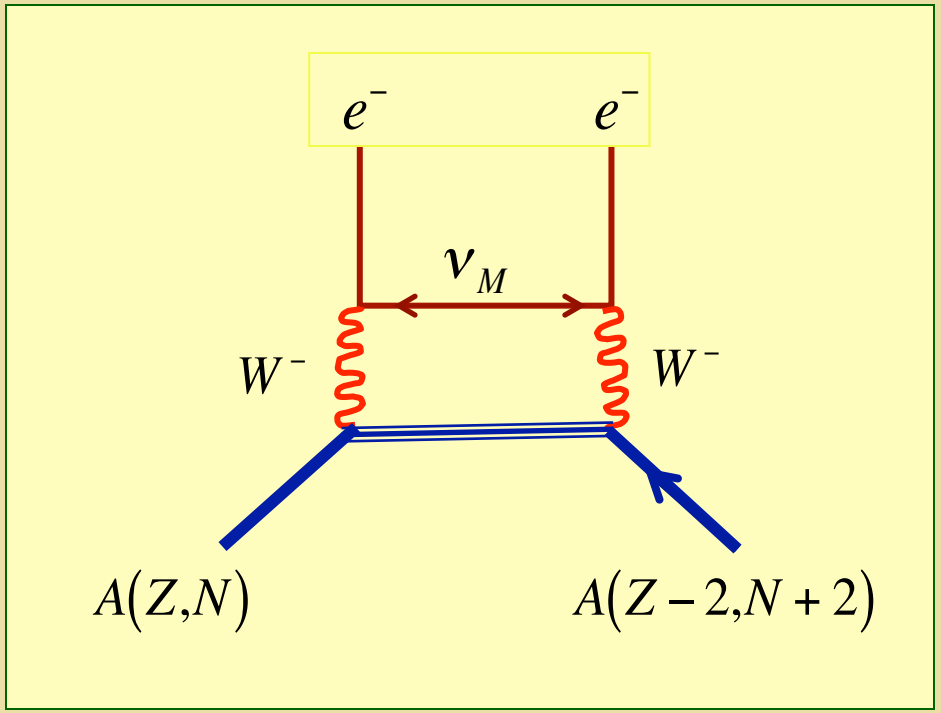
Majorana

"Standard" Mechanism

- *Light Majorana mass generated at the conventional see-saw scale: $\Lambda \sim 10^{12} - 10^{15}$ GeV*
- *3 light Majorana neutrinos mediate decay process*



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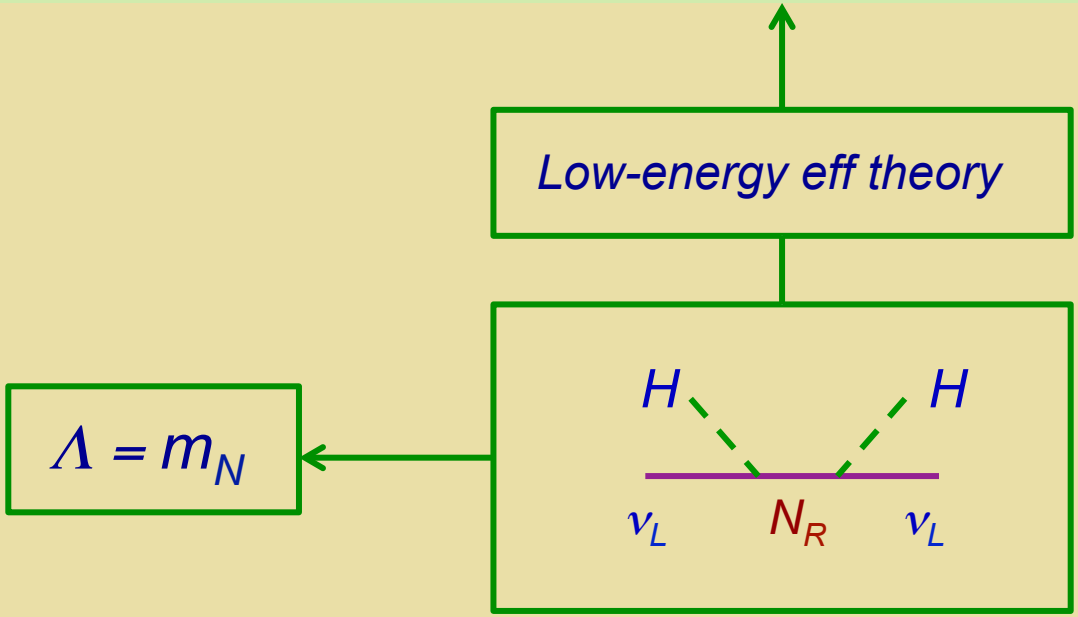

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*
- *Majorana neutrinos can decay to particles and antiparticles*
- *Rates can be slightly different (CP violation)*

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \bar{\ell} H^*)$$

- *Resulting excess of leptons over anti-leptons partially converted into excess of quarks over anti-quarks by Standard Model sphalerons*

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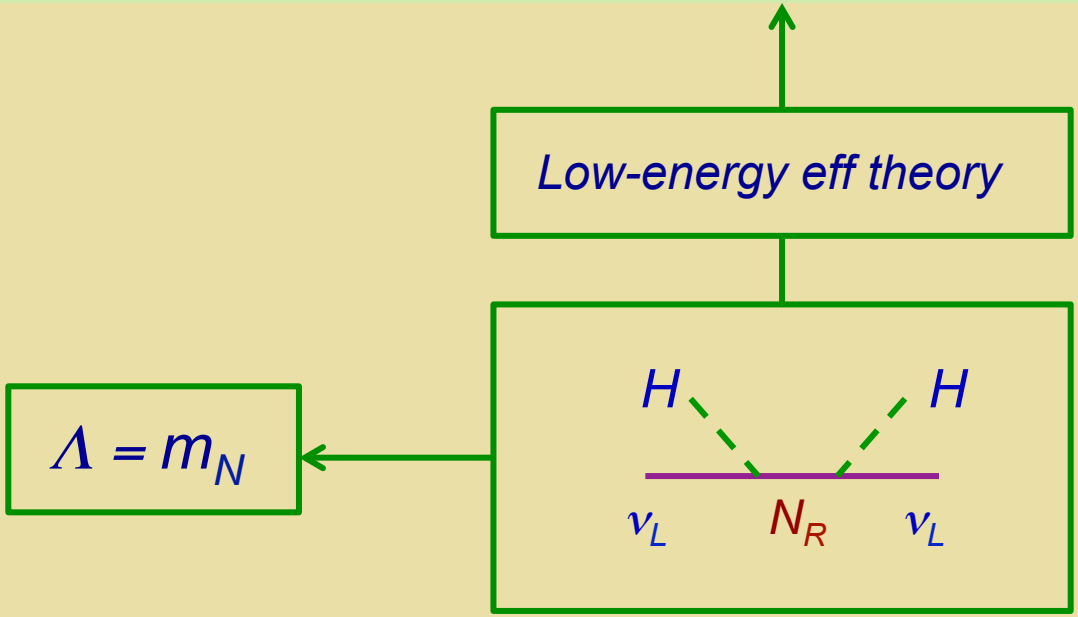

$0\nu\beta\beta$-Decay Sensitivity

2ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^- \overline{\nu}\,\overline{\nu}$

If own antiparticle, can be emitted then absorbed during decay

0ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^-$

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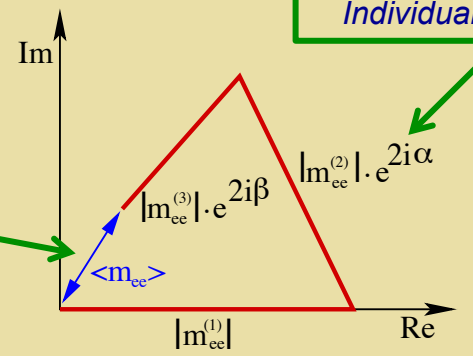
All three light neutrinos participate →
Rate governed by an effective mass

Individual contributions



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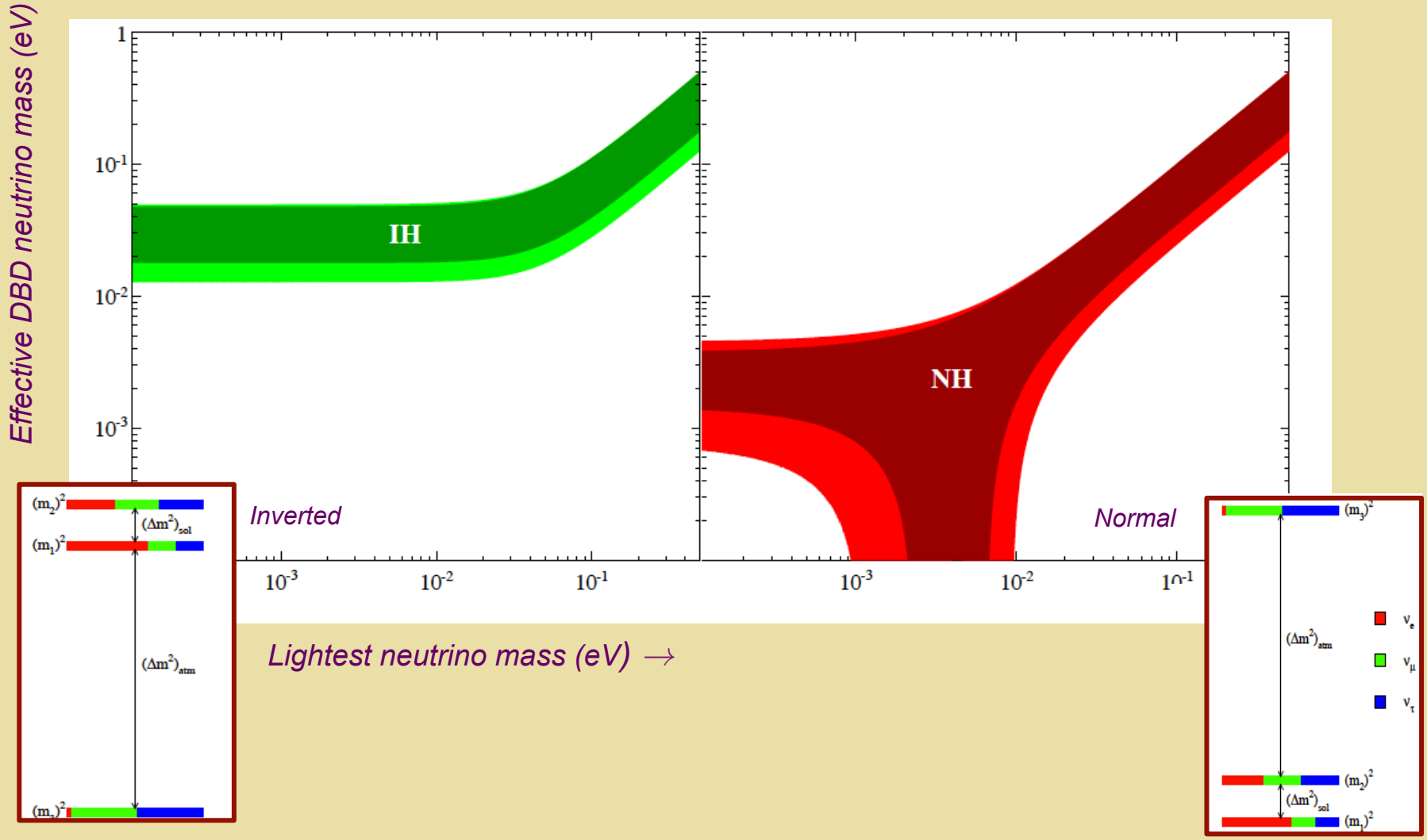
Three active light neutrinos



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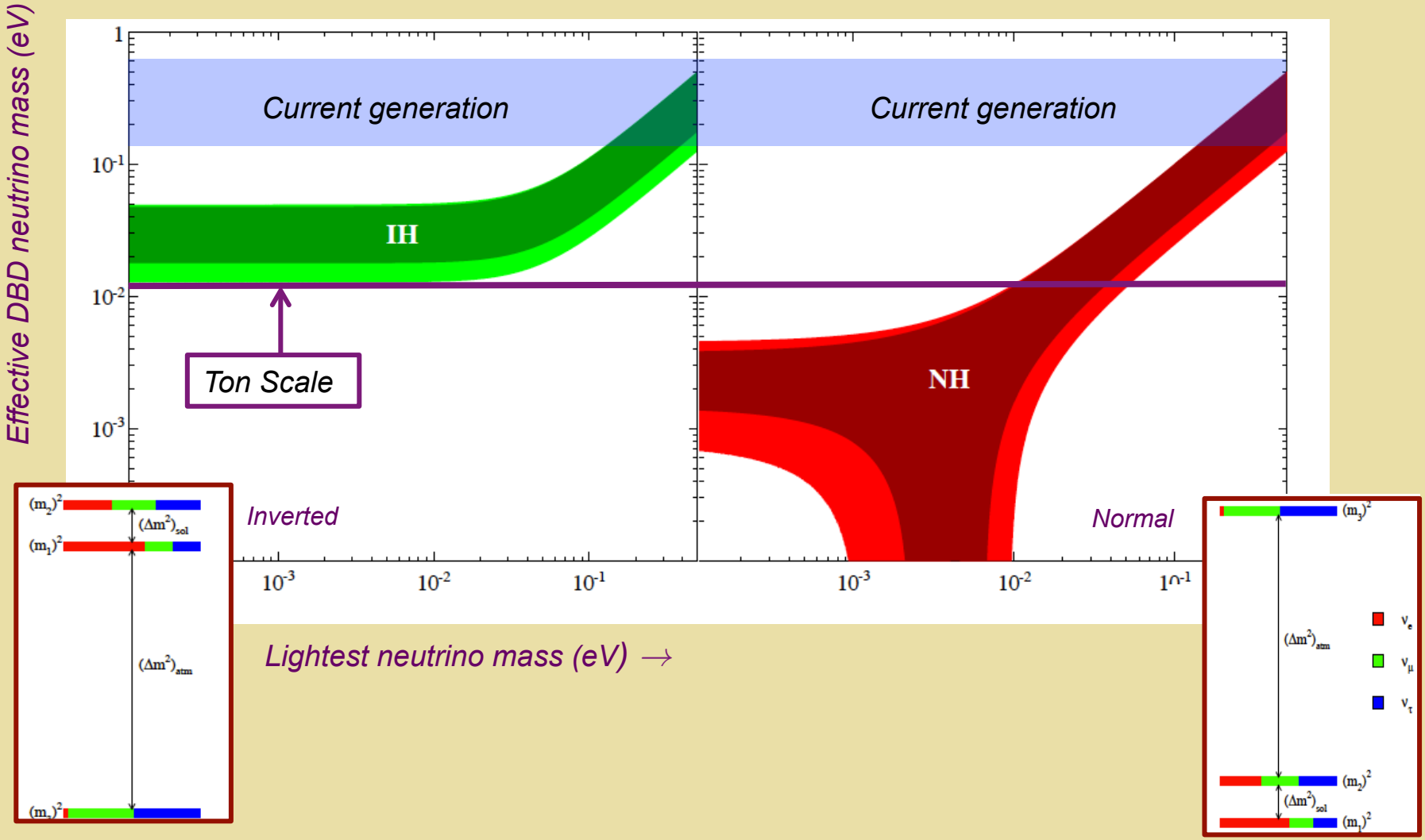
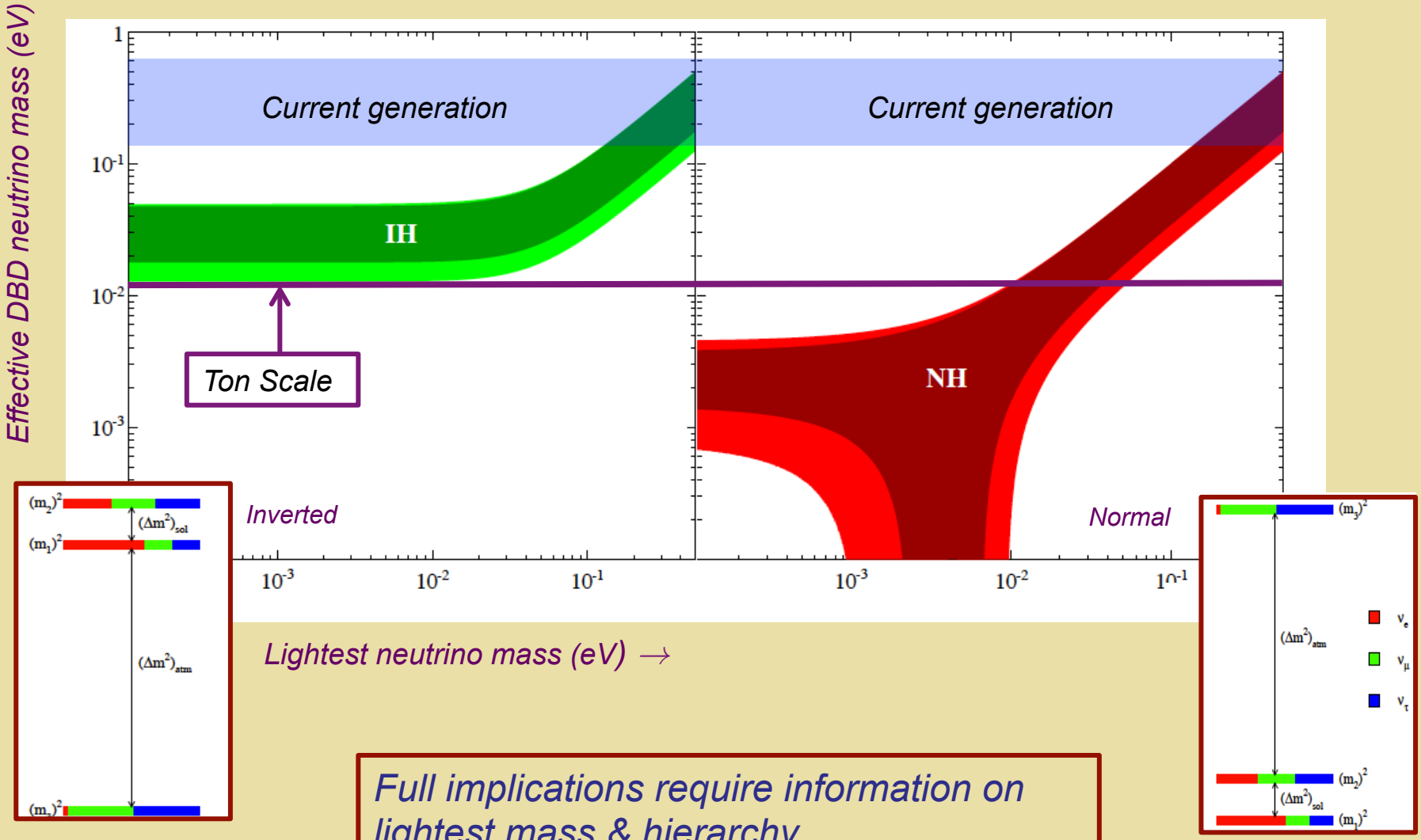


Interpreting the Result

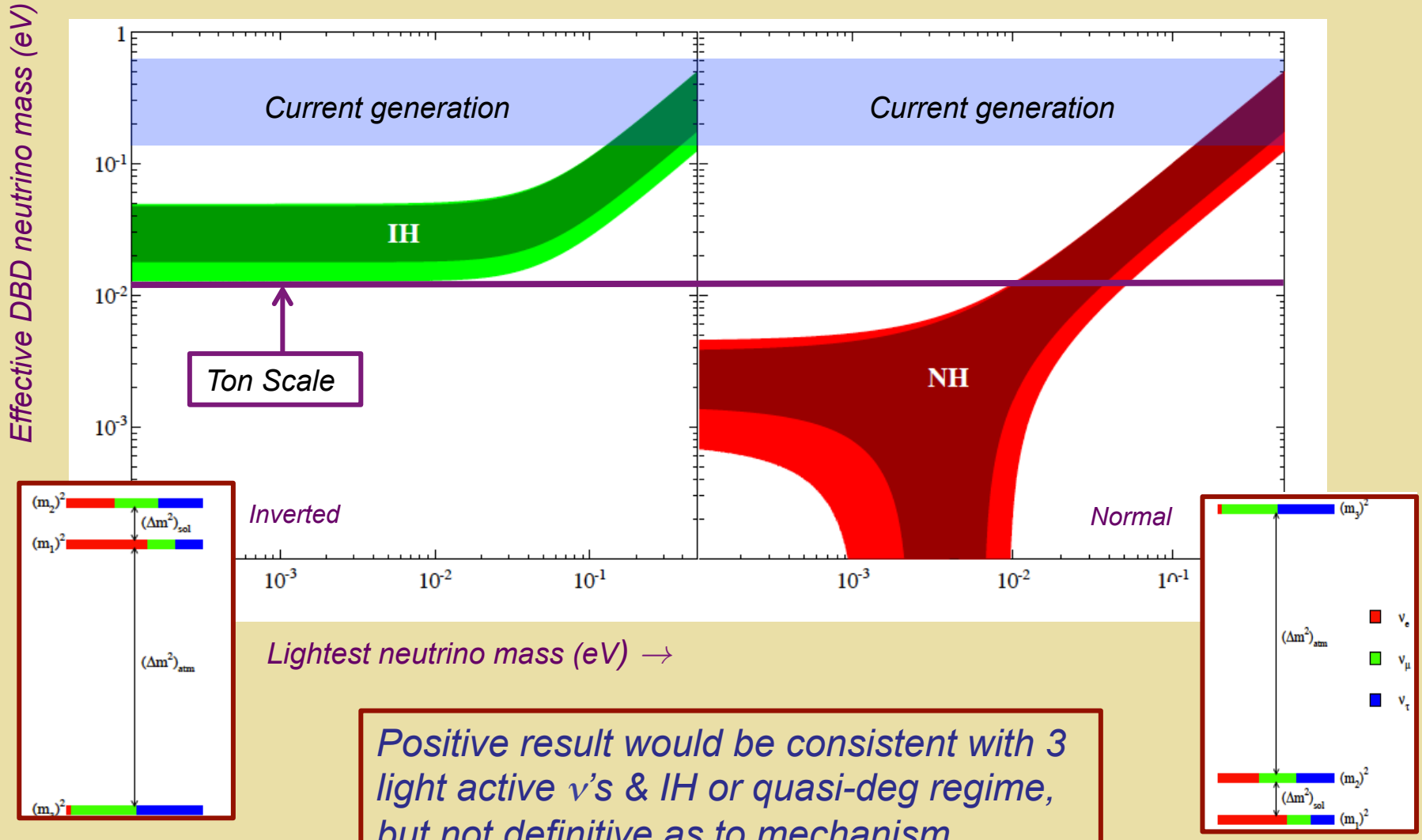
Three active light neutrinos



Full implications require information on lightest mass & hierarchy

Interpreting a Positive Result

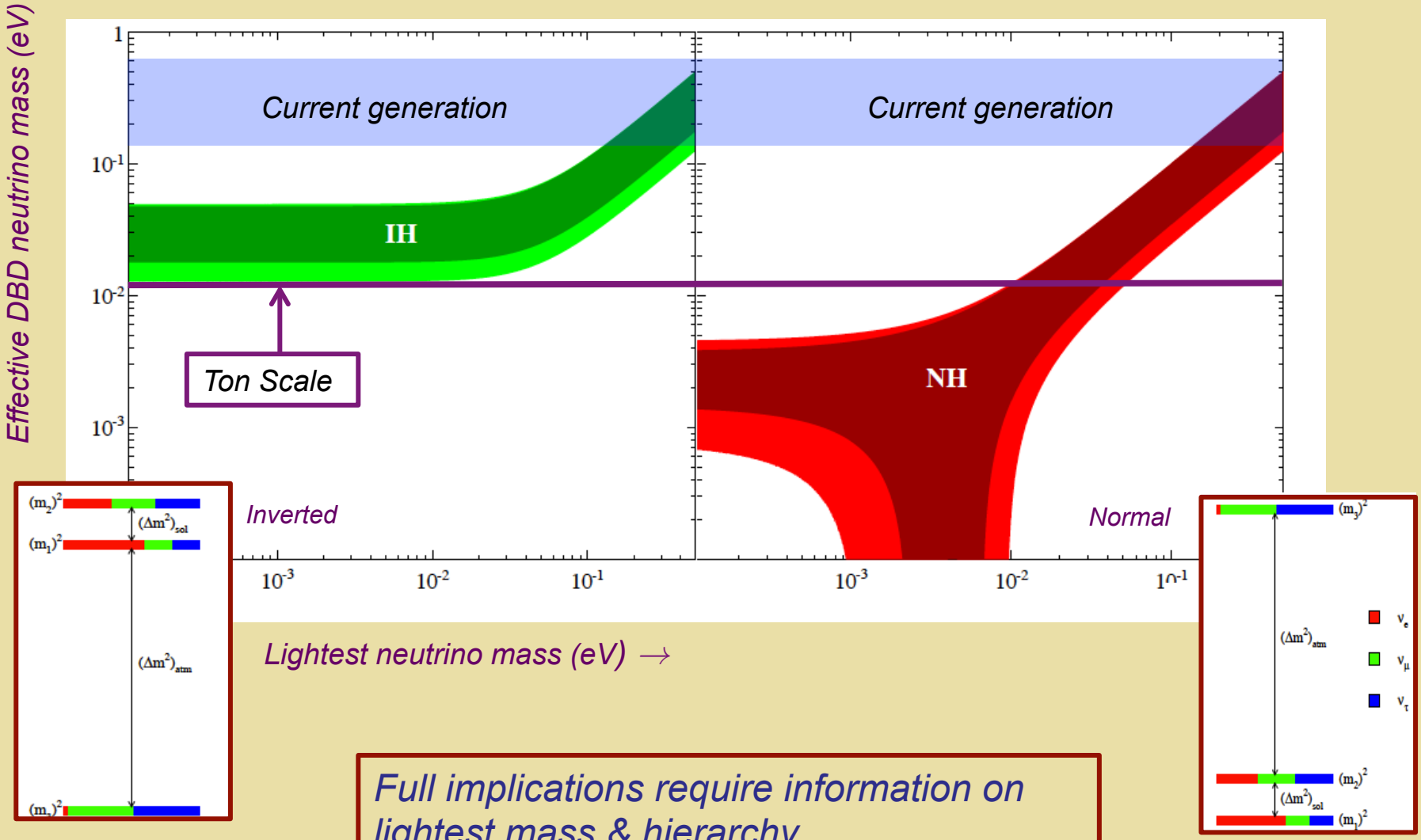
Three active light neutrinos



Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

Interpreting a Null Result

Three active light neutrinos



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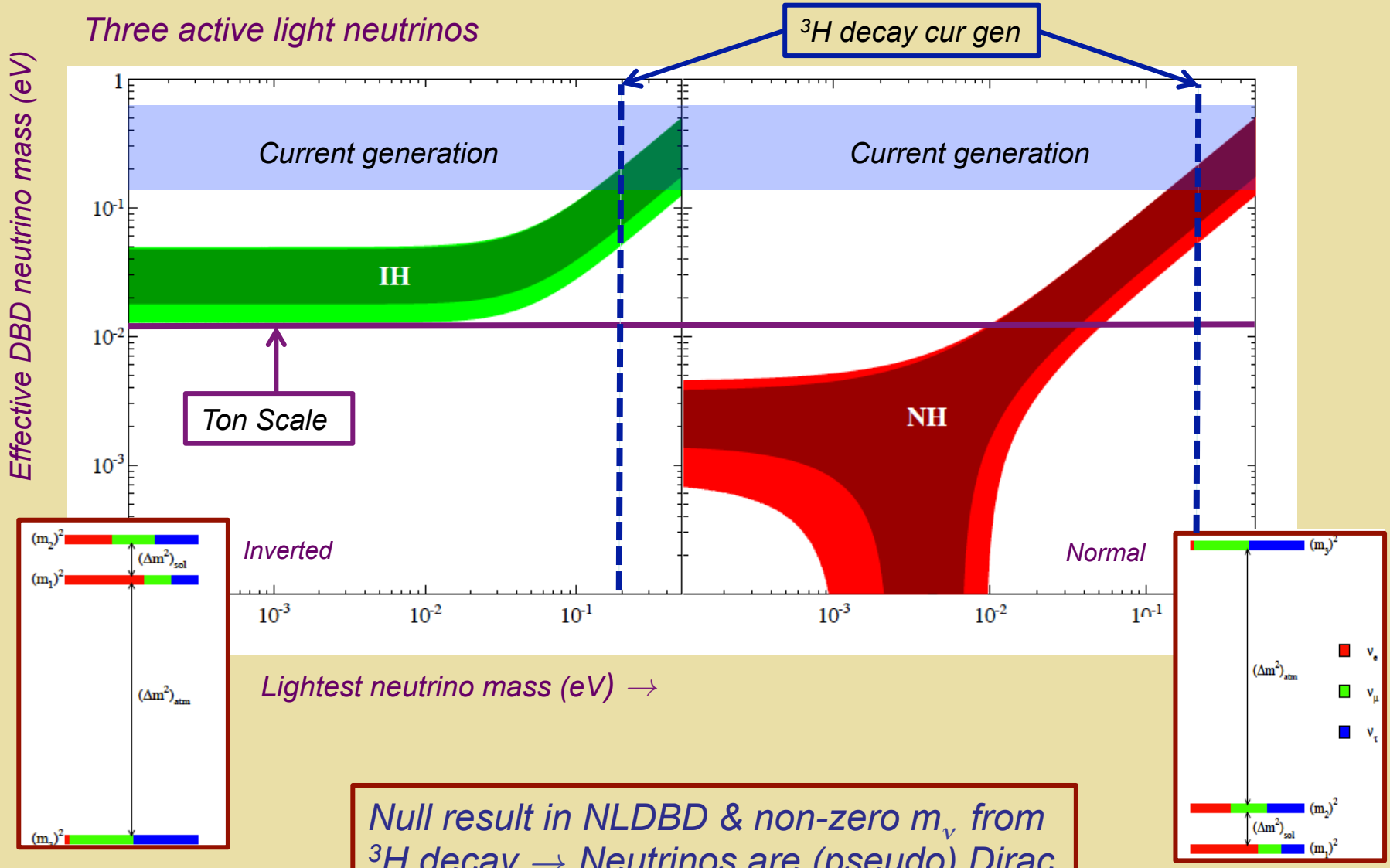

Null result in NLDBD & non-zero m_ν from ^{3}H decay → Neutrinos are (pseudo) Dirac

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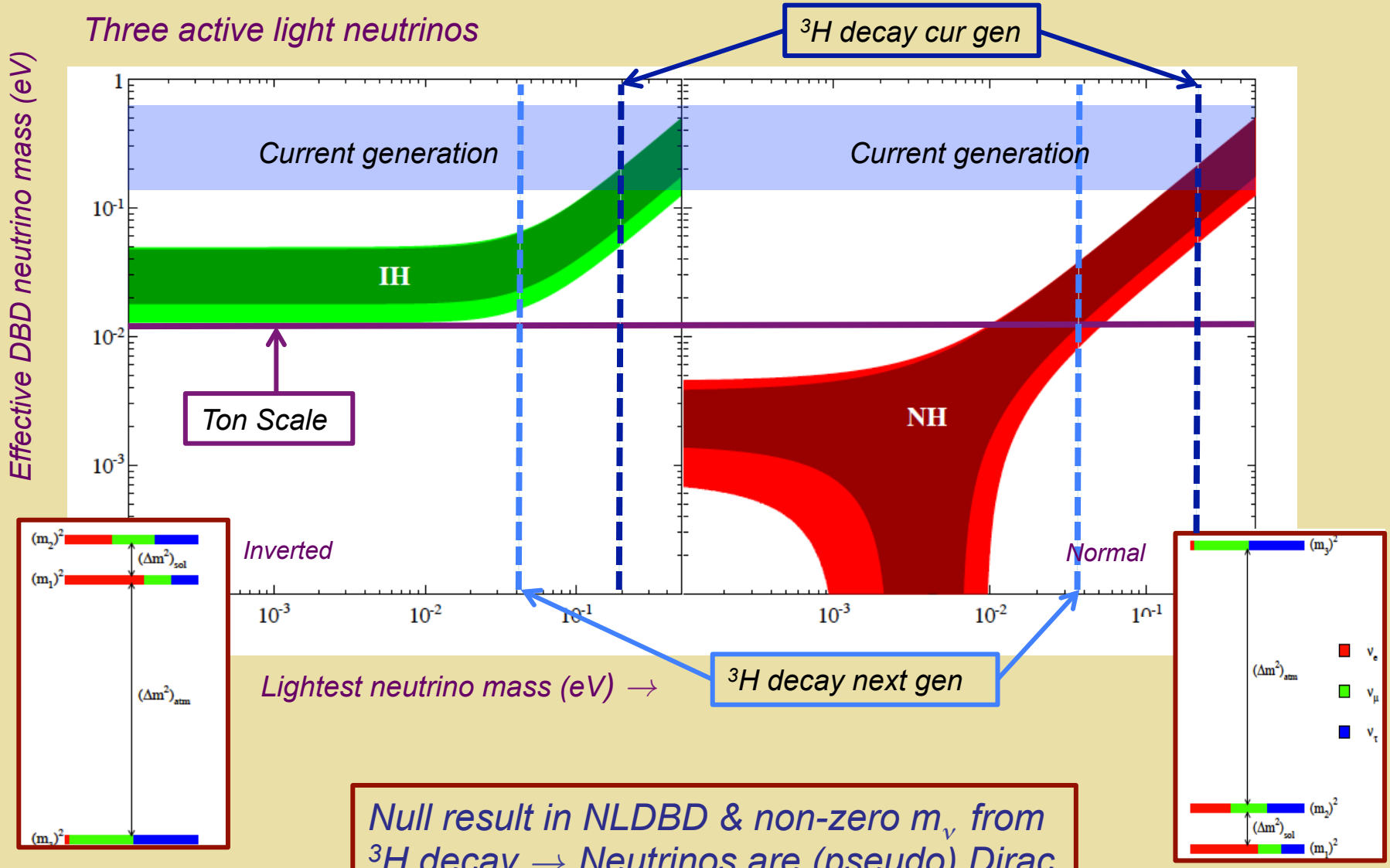

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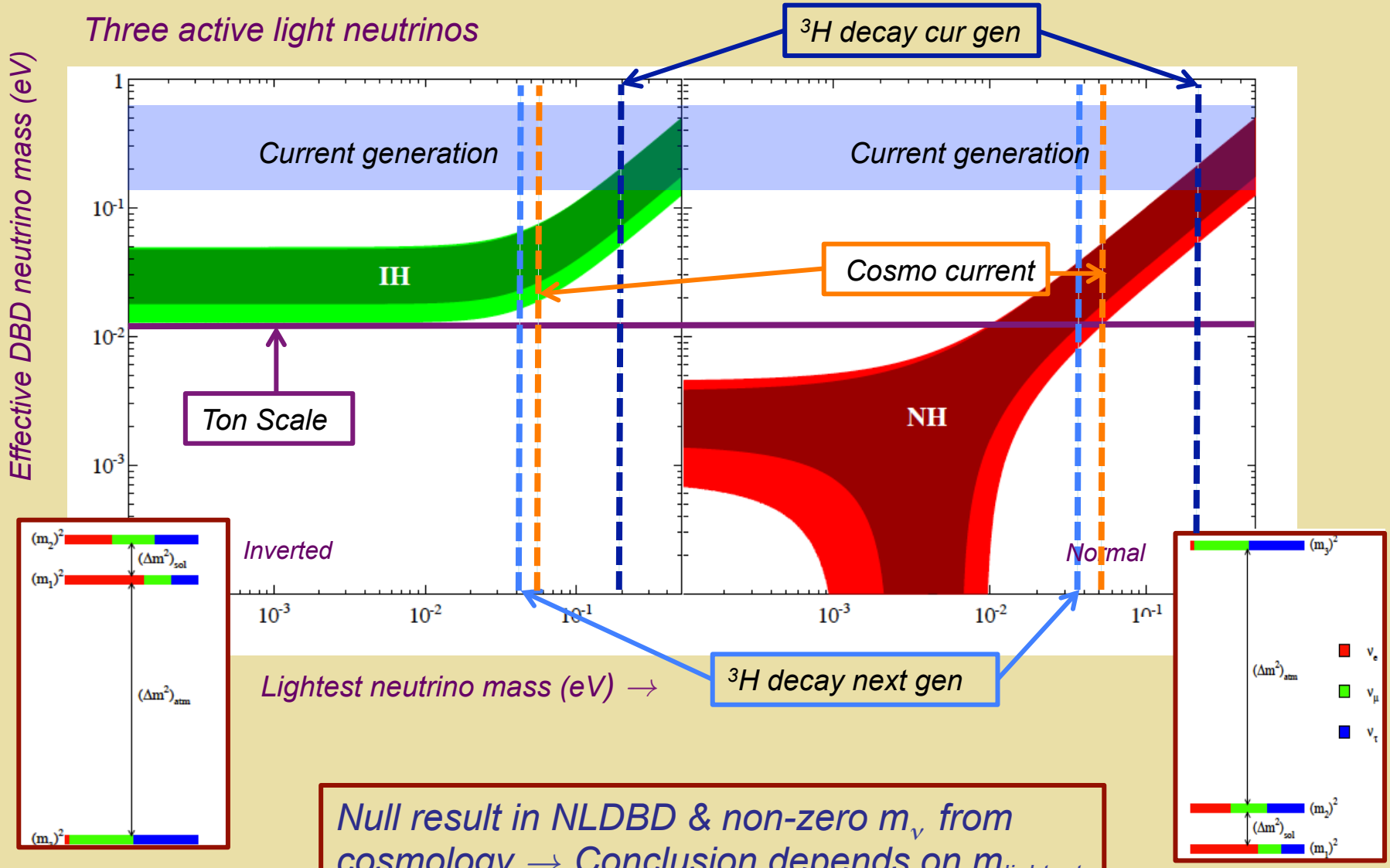

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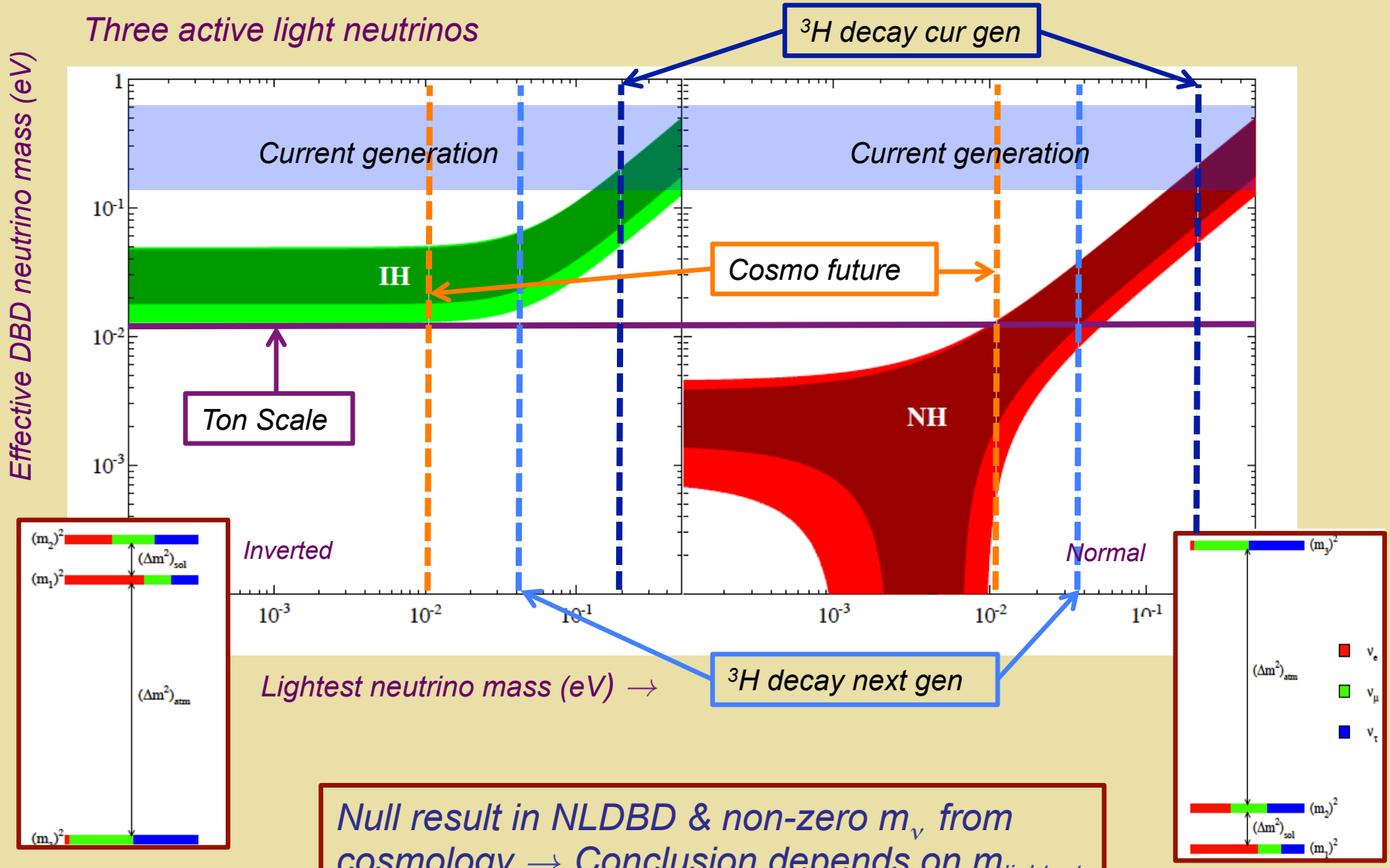

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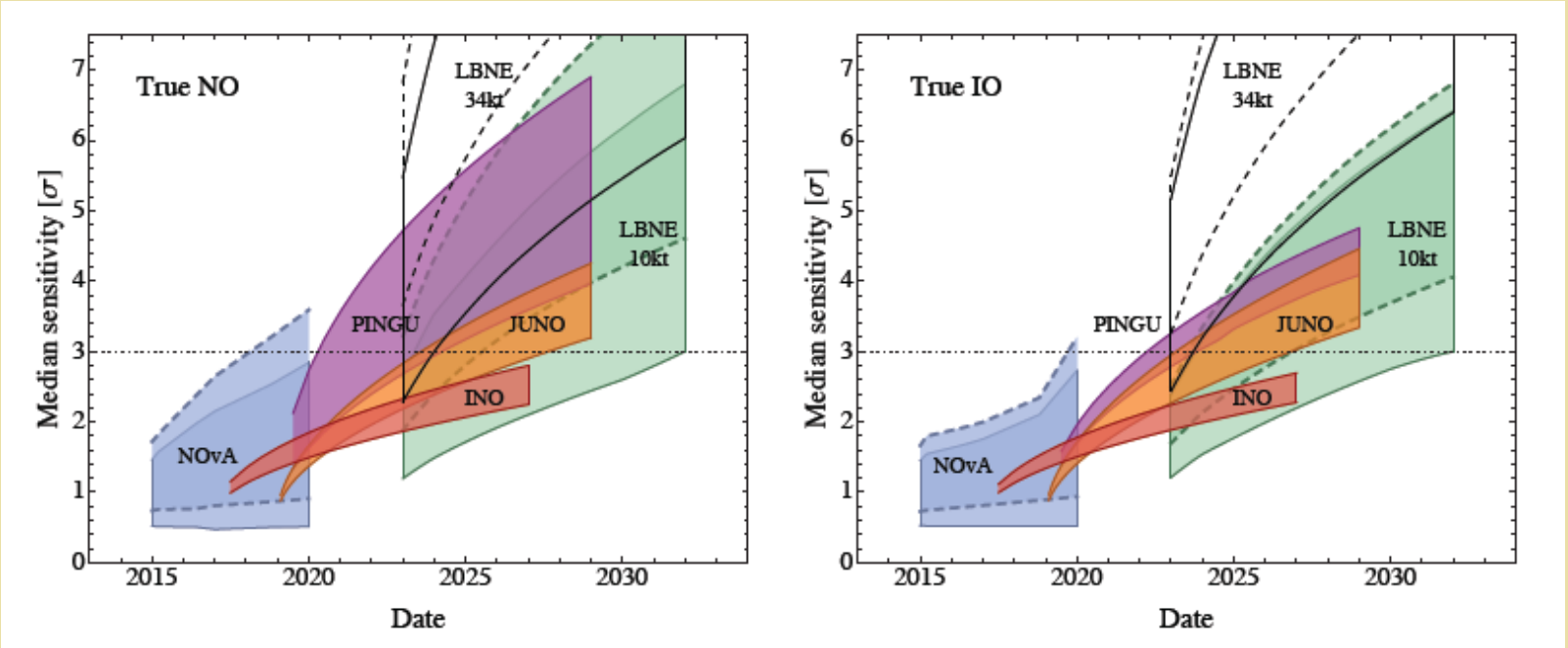
Neutrino Mass Hierarchy



Expected significance for rejecting wrong hierarchy hypothesis

Blennow et al, 1311.1822

Interpreting a Positive Result

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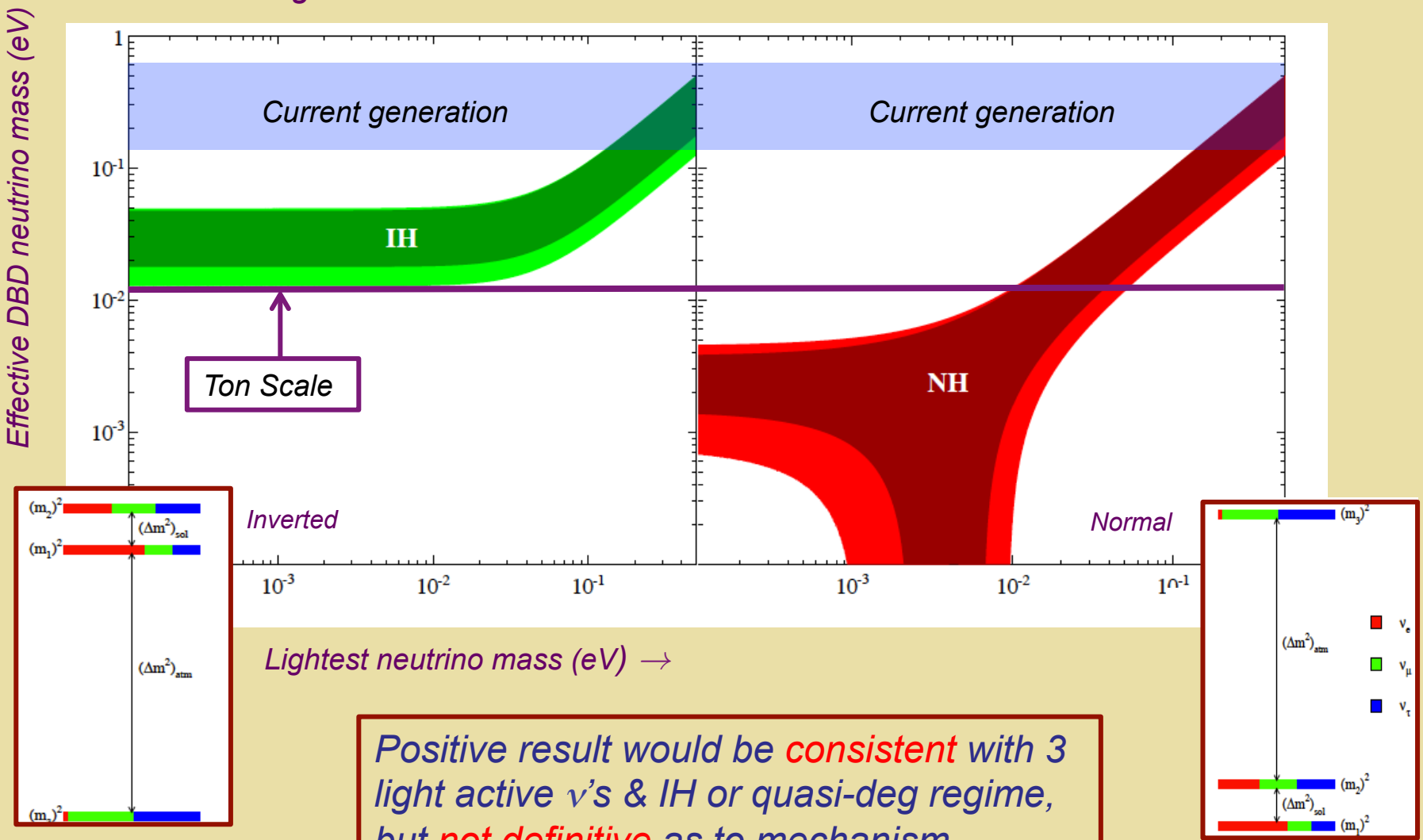

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$0\nu\beta\beta$-Decay: Nuclear Matrix Elements

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Dirac

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Majorana

Light ν_M exchange: can we determine m_ν

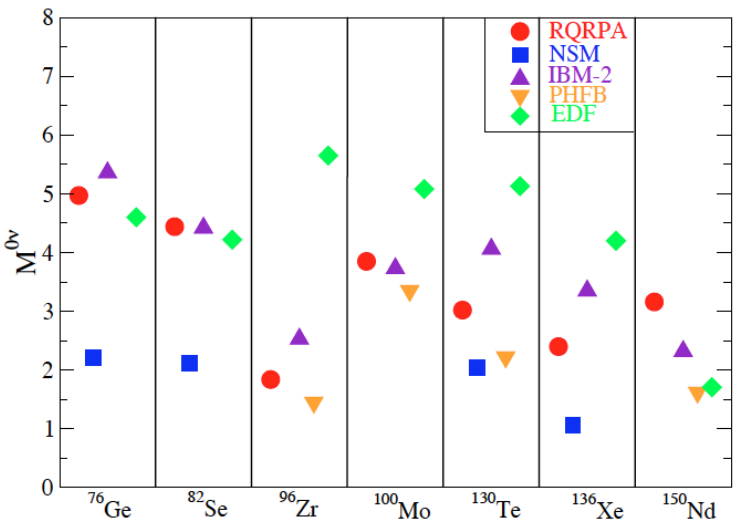
$$\frac{1}{T_{1/2}} = G^{0\nu}(E,Z)\left|M_{0\nu}\right|^2 \langle m_\nu^{\rm eff}\rangle^2$$

Shell Model vs. QRPA

Configs near Fermi surface

Levels above Fermi surface

P. Vogel



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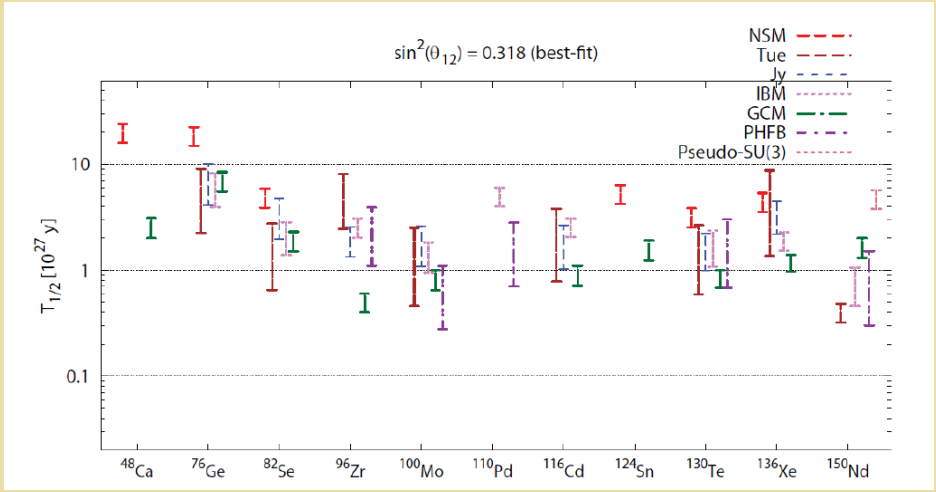

NSAC Subcommittee

IV. TeV-Scale LNV: $0\nu\beta\beta$ – Decay & The LHC

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Two parameters: Effective coupling & effective heavy particle mass

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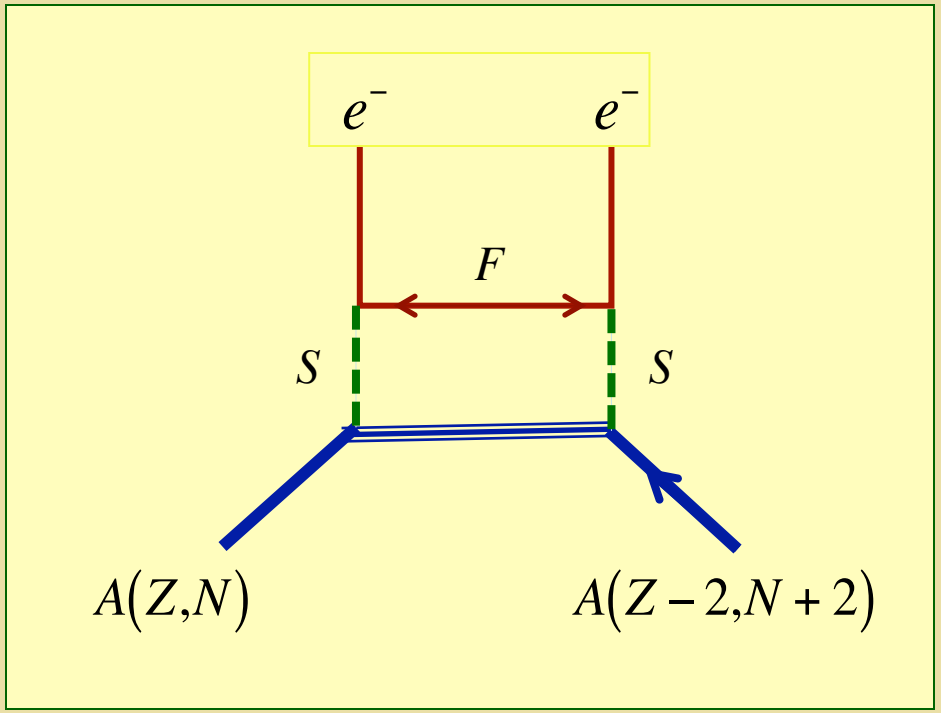
Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



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Majorana

Mechanism: does light ν_M exchange dominate ?

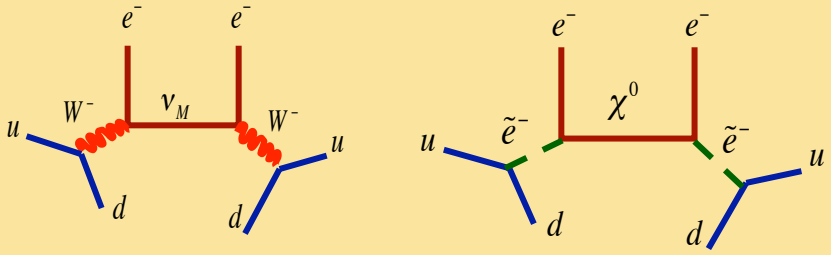
$$\frac{A_{\rm heavy}}{A_{\rm light}} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

O(1) for Λ ~ TeV

How to calc effects reliably ?
How to disentangle H & L ?

Theory Challenge: matrix elements + mechanism

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k \, e^{2i\delta}$$



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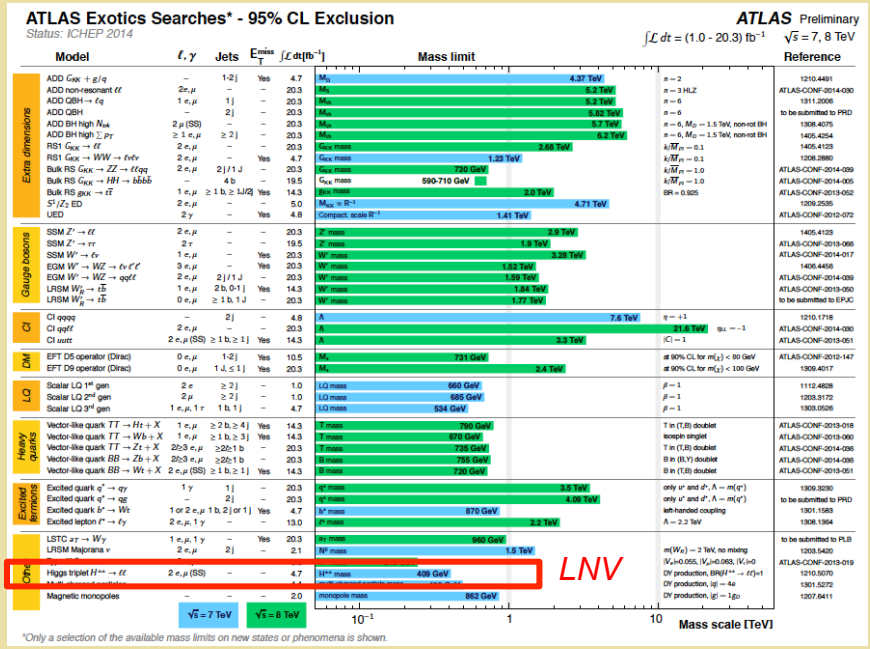
Majorana

LNV at the LHC



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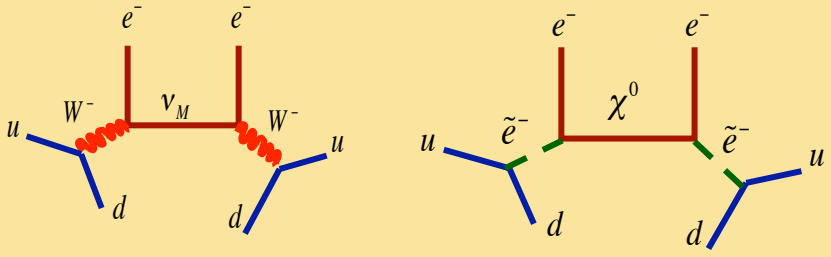

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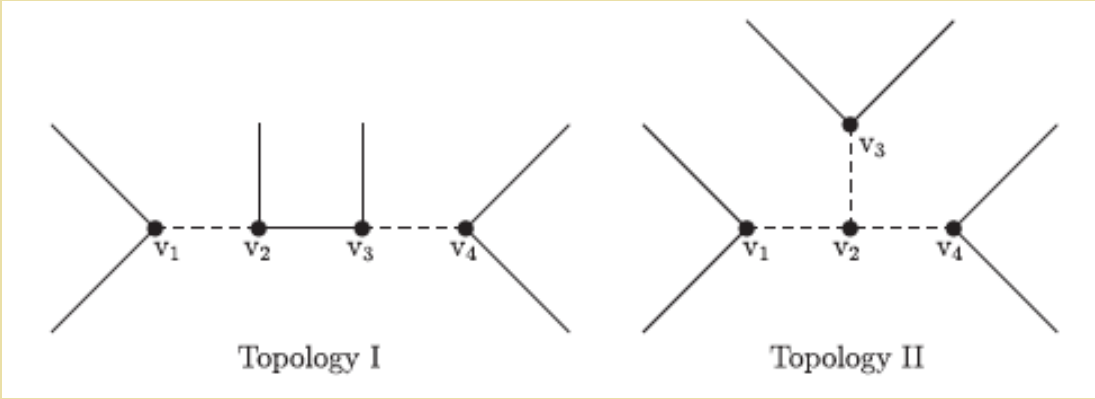
General Classification: Helo et al, PRD 88.011901, 88.073011



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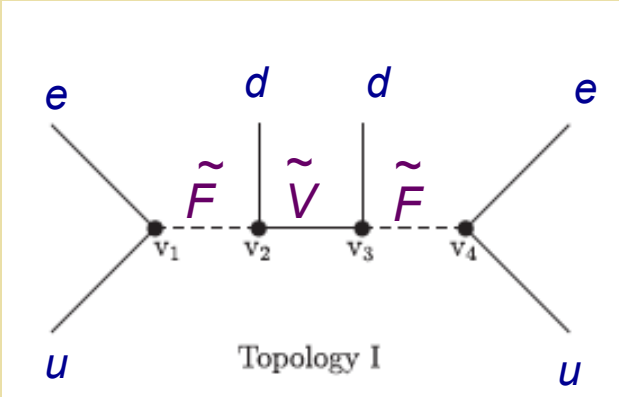


SUSY: R Parity-Violation

Sfermion $\tilde{q}$, $\tilde{l}$

Gaugino $\tilde{g}$, χ *Majorana*

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u,$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

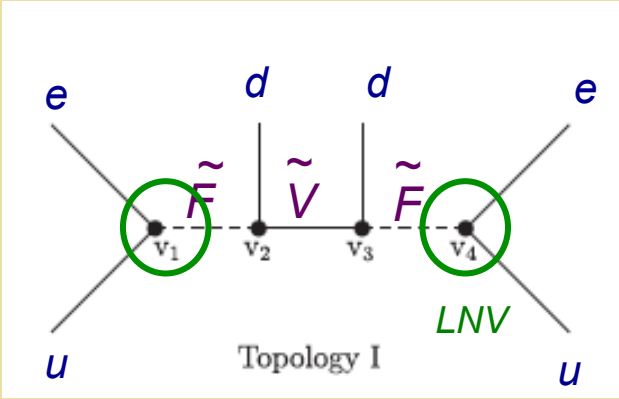
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



SUSY: R Parity-Violation

Sfermion $\tilde{q}$, $\tilde{l}$

Gaugino $\tilde{g}$, χ *Majorana*

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u,$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

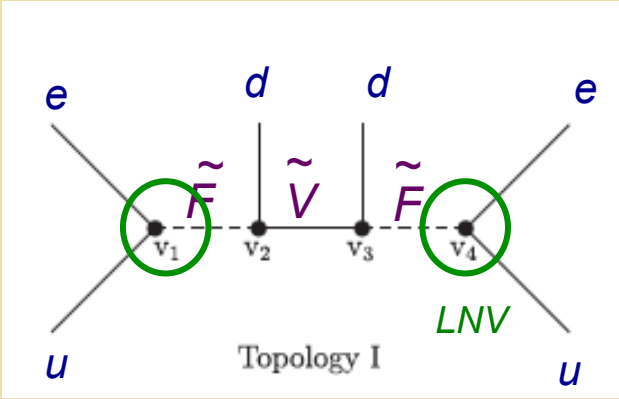
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



SUSY: R Parity-Violation

$$\lambda'_{111} \leq 2\times 10^{-4}\left(\frac{m_{\tilde{q}}}{100\,\text{GeV}}\right)^2\left(\frac{m_{\tilde{g}}}{100\,\text{GeV}}\right)^{1/2}$$

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u,$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

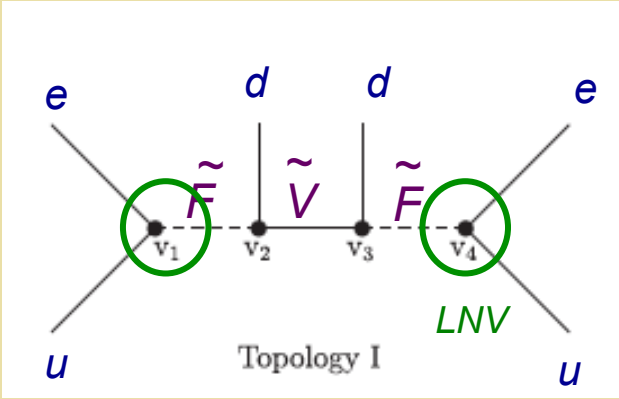
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

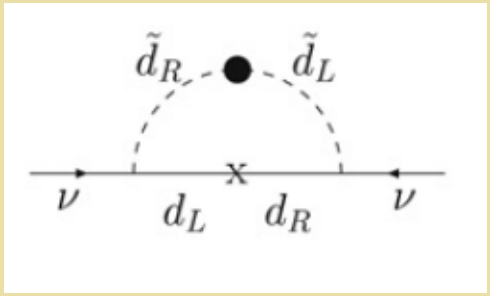
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



SUSY: R Parity-Violation



$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u,$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

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$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

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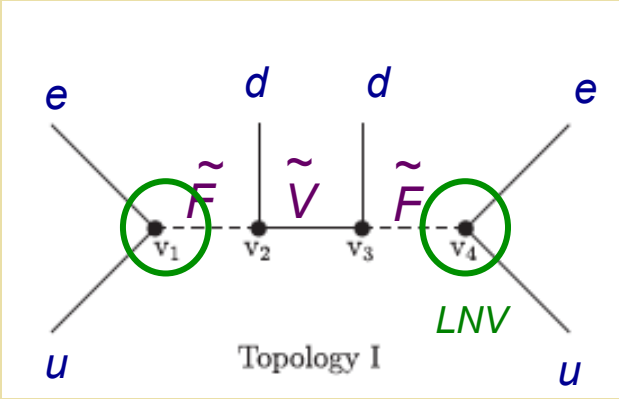
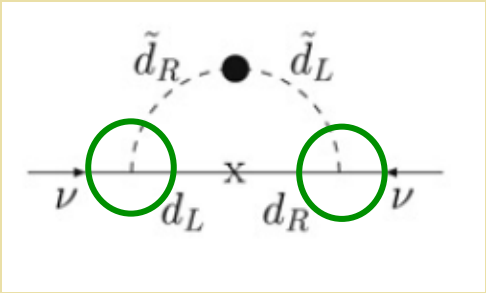


SUSY: R Parity-Violation



$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u,$$

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$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

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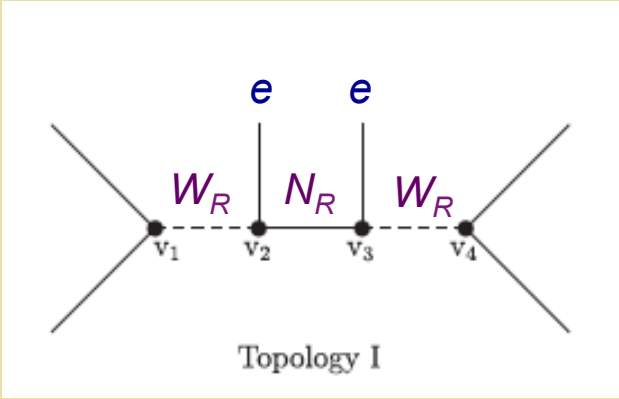
Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



LRSM: Type II See-Saw

$$\mathcal{L} = \frac{g}{2}h_{ij}\left[\bar{L}^{C_i}\varepsilon\Delta_L L^j\right] + (L \leftrightarrow R) + \text{h.c.}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

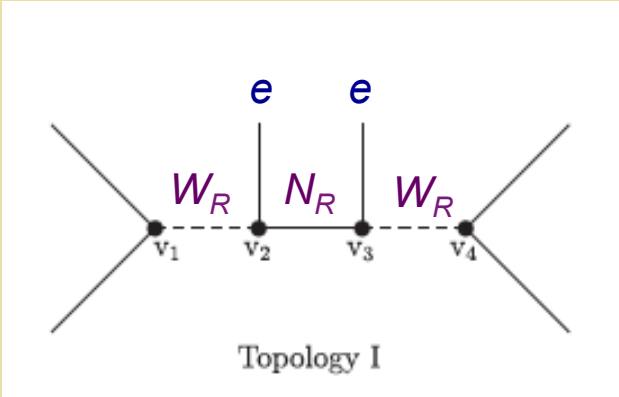
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



LRSM: Type I See-Saw

Mass: standard see-saw but TeV scale

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

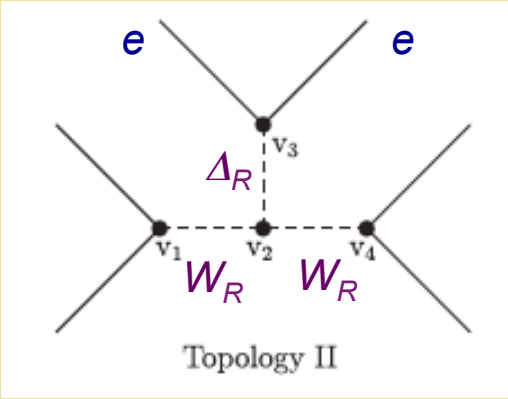
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011

LRSM: Type II See-Saw

$$\mathcal{L} = \frac{g}{2} h_{ij}\left[\bar{L}^{C_i}\varepsilon\Delta_L L^j\right] + (L \leftrightarrow R) + \text{h.c.}$$



$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

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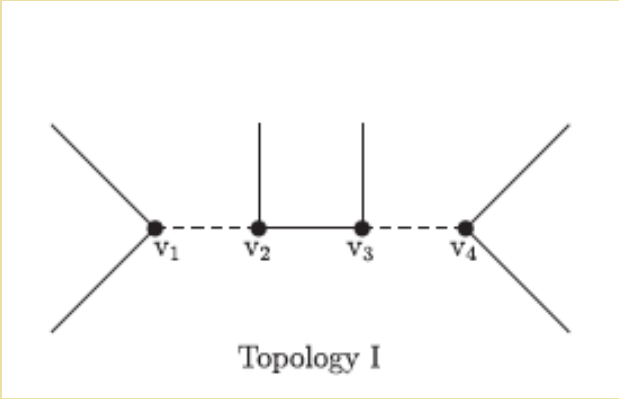


Topology I

Scalar Leptoquarks

Mass: like RPV SUSY (loop)

NLDBD: need Majorana fermion

$$\mathcal{L}_{F=0} = h^L_{1/2}\overline{u}_R\ell_L S^L_{1/2} + h^R_{1/2}\overline{q}_L\epsilon e_R S^R_{1/2} + \tilde{h}^L_{1/2}\overline{d}_R\ell_L\tilde{S}^L_{1/2}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

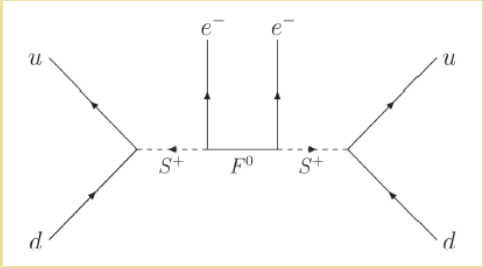
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

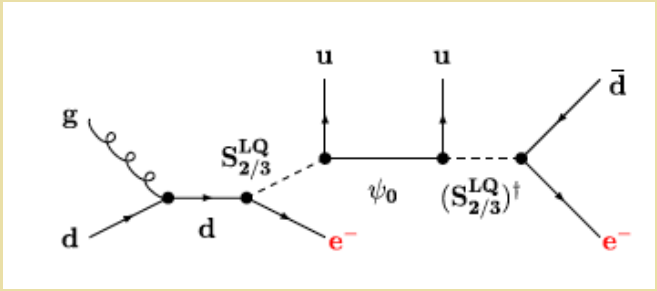
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

LHC Production



LHC: pp → jj e⁻e⁻



LHC: pp → jjj e⁻e⁻

$0\nu\beta\beta$-Decay: TeV Scale LNV

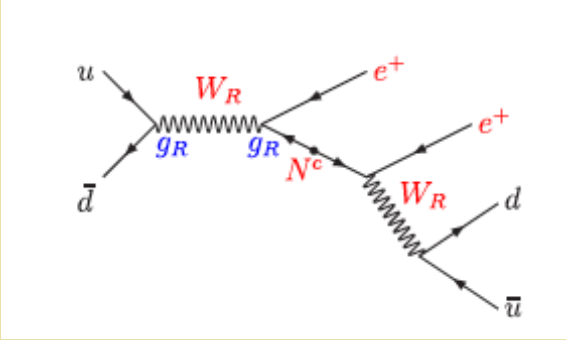
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

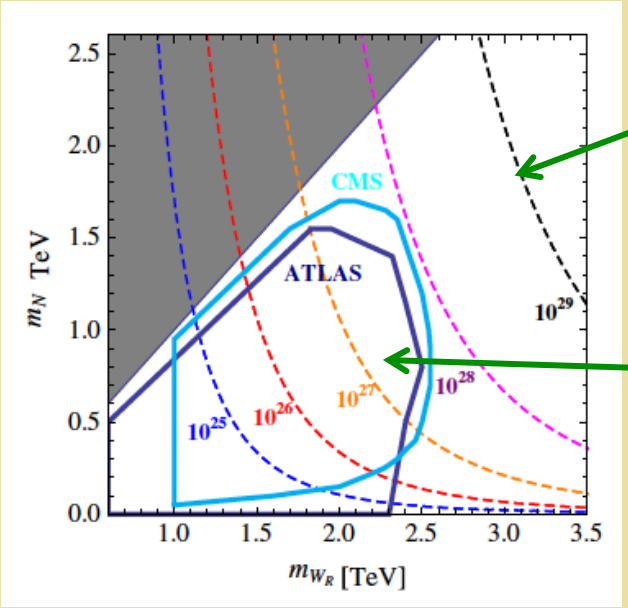
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

LHC Production & $0\nu\beta\beta$-Decay



Helo et al, PRD 88.011901, 88.073011



$0\nu\beta\beta$-Decay: TeV Scale LNV

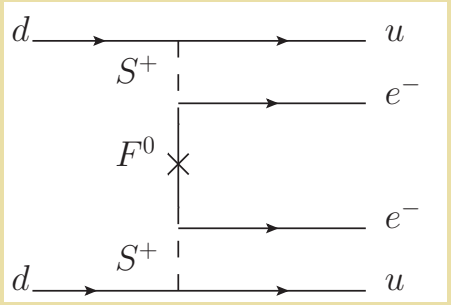
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

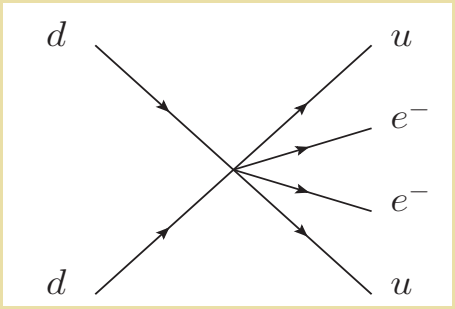
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

LHC: $pp \rightarrow$ jj $e^- e^-$



$0\nu\beta\beta$ - decay



Illustrative Simplified Model:

$$\mathcal{L}_{\rm eff} = C_1 \bar{Q}_L^\alpha d_{R\alpha} D + C_2 \epsilon^{ij} \bar{L}_L^i F D^{*j}$$

Y: -1/6 -1/3 1/2 | 1/2 0 -1/2

$D^T = (S^+ , S^0)$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

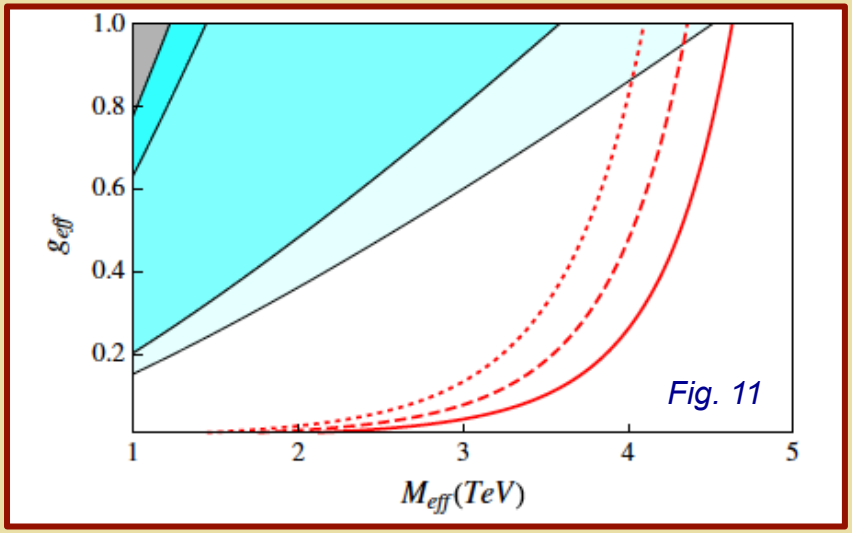
Helo et al claim:

$$\mathcal{L}_{\rm eff} = C_1 \bar{Q}_L^\alpha d_{R\alpha} D + C_2 \epsilon^{ij} \bar{L}_L^i F D^{*j}$$

Y -1/6 -1/3 1/2 1/2 0 -1/2

$C_j = g_j$

$g_{{\rm eff}(S)} = (g_1 g_2)^{1/2}$



$M_{{\rm eff}(S)} = (m_S^4 m_\psi)^{1/5}$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

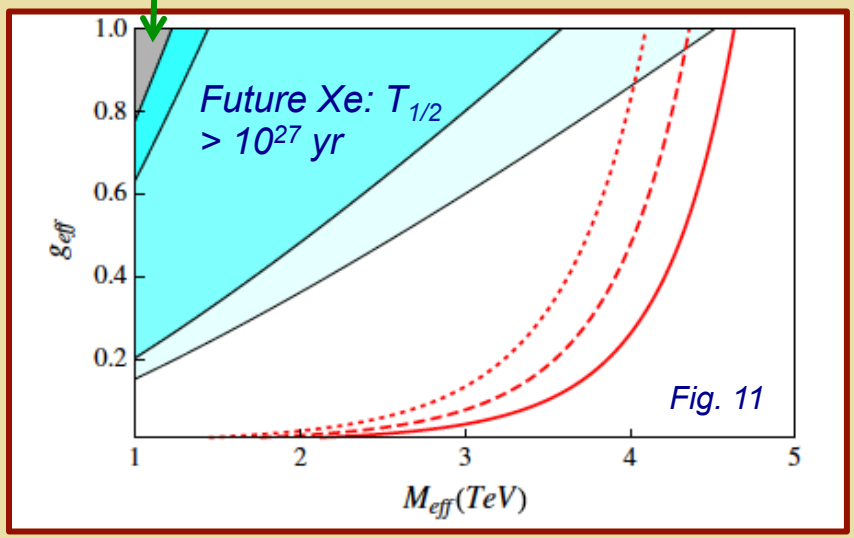
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Helo et al claim:

$$\mathcal{L}_{\rm eff} = C_1 \bar{Q}_L^\alpha d_{R\alpha} D + C_2 \epsilon^{ij} \bar{L}_L^i F D^{*j}$$

Y -1/6 -1/3 1/2 1/2 0 -1/2



$$g_{{\rm eff}(S)} = (g_1 g_2)^{1/2}$$

$$C_j = g_j$$

$$M_{{\rm eff}(S)} = (m_S^4 m_\psi)^{1/5}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

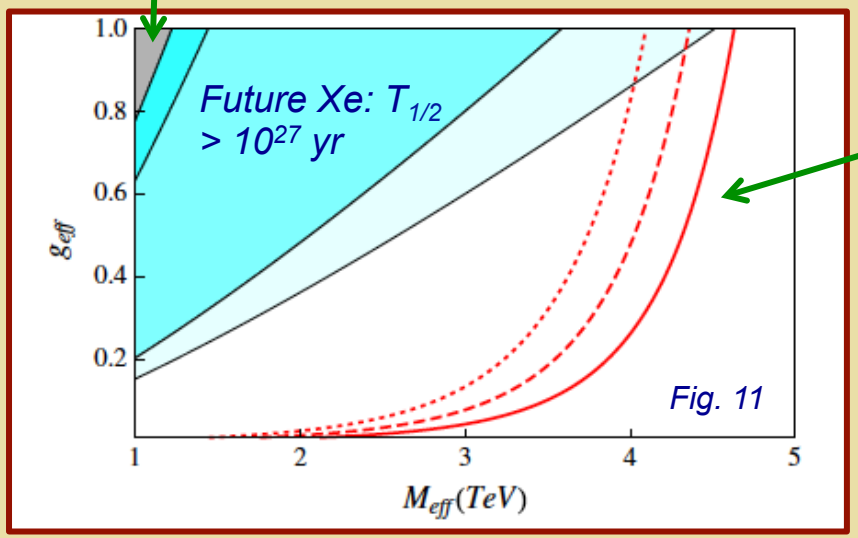
Majorana

Helo et al claim:

$$\mathcal{L}_{\rm eff} = C_1 \bar{Q}_L^\alpha d_{R\alpha} D + C_2 \epsilon^{ij} \bar{L}_L^i F D^{*j}$$

Y -1/6 -1/3 1/2 1/2 0 -1/2

EXO exclusion



LHC: pp → jj e⁻e⁻

300 fb⁻¹ :

— < 3 events

$$g_{{\rm eff}(S)} = (g_1 g_2)^{1/2}$$

$$C_j = g_j$$

$$M_{{\rm eff}(S)} = (m_S^4 m_\psi)^{1/5}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \; + \; {\rm h.c.}$$

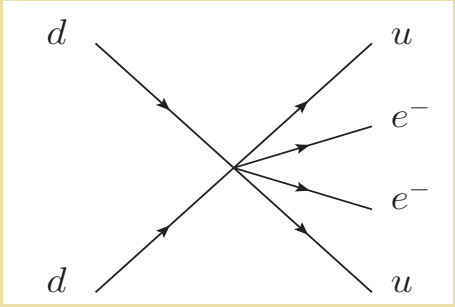
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \; + \; {\rm h.c.}$$

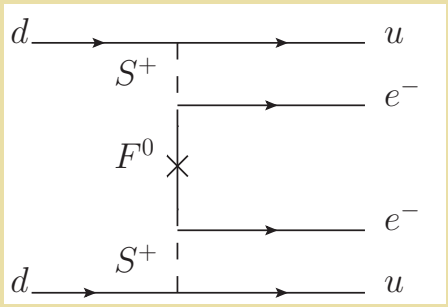
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp → jj e⁻e⁻



Can it be discovered with combination of $0\nu\beta\beta$ & LHC searches ?

Simplified models

$0\nu\beta\beta$-Decay: TeV Scale LNV

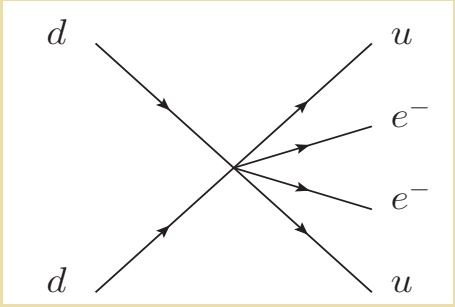
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

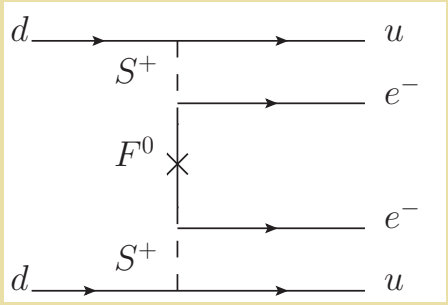
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

$0\nu\beta\beta$ - decay



LHC: pp → jj e⁻e⁻



TeV Scale LNV

Comparing $0\nu\beta\beta$ & LHC sensitivities:

- *LHC backgrounds*
- *Running effective op's to low energy*
- *Matching onto hadronic d.o.f.*
- *Long range NME contributions*

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

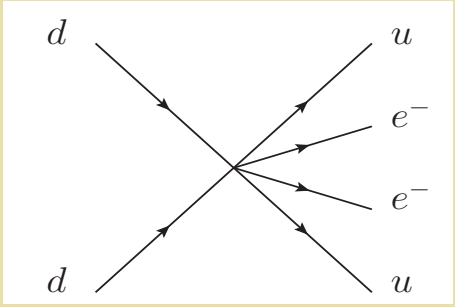
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

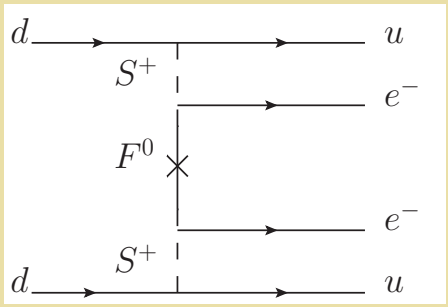
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp → jj e⁻e⁻



Effective operators:

$$\mathcal{L}^{\rm eff}_{\rm LNV} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + \text{h.c.}$$

$$\mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

$$g_{\rm eff} = C_1(\Lambda)^{1/4}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Our reanalysis:

- *Include backgrounds*
- *Incorporate QCD running*
- *Include long-distance contributions to nuclear matrix elements*

T. Peng, MJRM, P. Winslow, 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

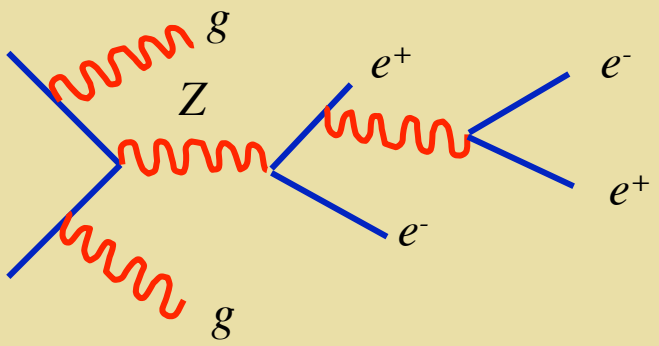
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*



e^+ transfers most of p_T to conversion e^- ;
Z / γ^* + jets $\rightarrow$ apparent e^- e^- jj event

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

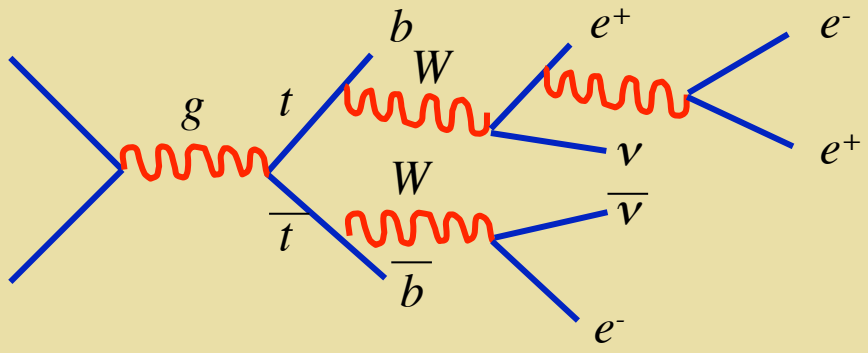
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*



e^+ transfers most of p_T to conversion e^- ;
b's not tagged → apparent e^- e^- jj event

72

$0\nu\beta\beta$-Decay: TeV Scale LNV

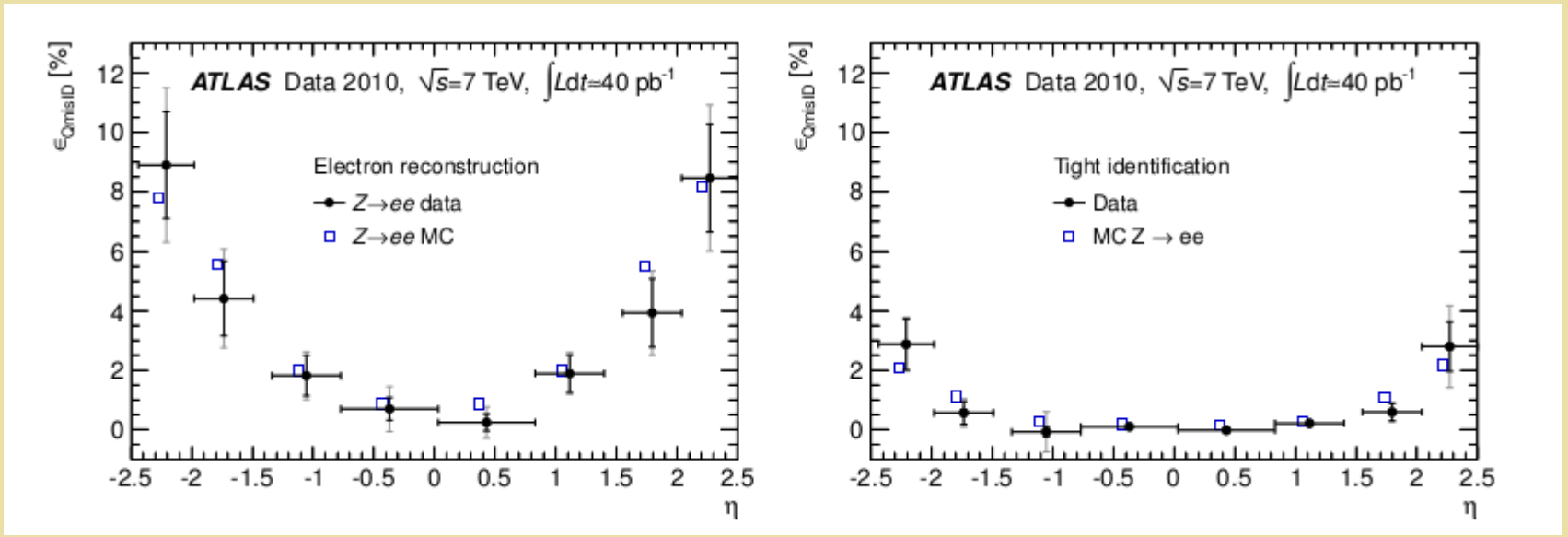
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Backgrounds: *Bin in η and apply charge flip prob*



$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Backgrounds: *Jet fakes*

$$\sigma_{JF} \text{ before cuts} = \sigma_{JF,MG+Pythia+PGS} \times (1/5000 \times 1/2)^{\#\text{ of jet-fakes}} \times \begin{pmatrix} \#\text{ of jets} \\ \#\text{ of jet-fakes} \end{pmatrix}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Backgrounds: *Cuts*

- H_T
- *MET*
- M_{ll}

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Backgrounds: *Cuts*

σ(fb)	Signal	Backgrounds									$\frac{S}{\sqrt{S+B}}$ ($\sqrt{\text{fb}}$)
		Diboson			Charge Flip		Jet Fake				
		W^-W^-+2j	W^-Z+2j	ZZ+2j	Z/γ^*+2j	$t\bar{t}$	$t\bar{t}$	$\bar{t}$+3j	W^-+3j	4j	
Before Cuts	0.142	0.541	6.682	0.628	903.16	68.2	6.7	0.45	15.09	362.352	0.0038
Signal Selection	0.091	0.358	4.66	0.435	721.7	28.9	2.37	0.22	11.73	72.03	0.0031
H_T(jets) > 650 GeV	0.054	0.04	0.187	0.015	5.6	0.266	0.025	0.0003	0.102	0.027	0.0213
$m_{\ell_1\ell_2} > 130$ GeV	0.039	0.029	0.105	0.008	0.163	0.127	0.024	$3\text{x}10^{-4}$	0.101	0.027	0.0493
$\not{E}_T < 40$ GeV	0.036	0.005	0.036	0.007	0.126	0.014	0.005	$3\text{x}10^{-5}$	0.03	0.017	0.0684
$(\eta_{j_{1,2}} - \eta_{\ell_{1,2}})_{max} < 2.2$	0.033	0.003	0.022	0.005	0.093	0.009	0.004	$2\text{x}10^{-5}$	0.019	0.011	0.0738

$0\nu\beta\beta$-Decay: TeV Scale LNV

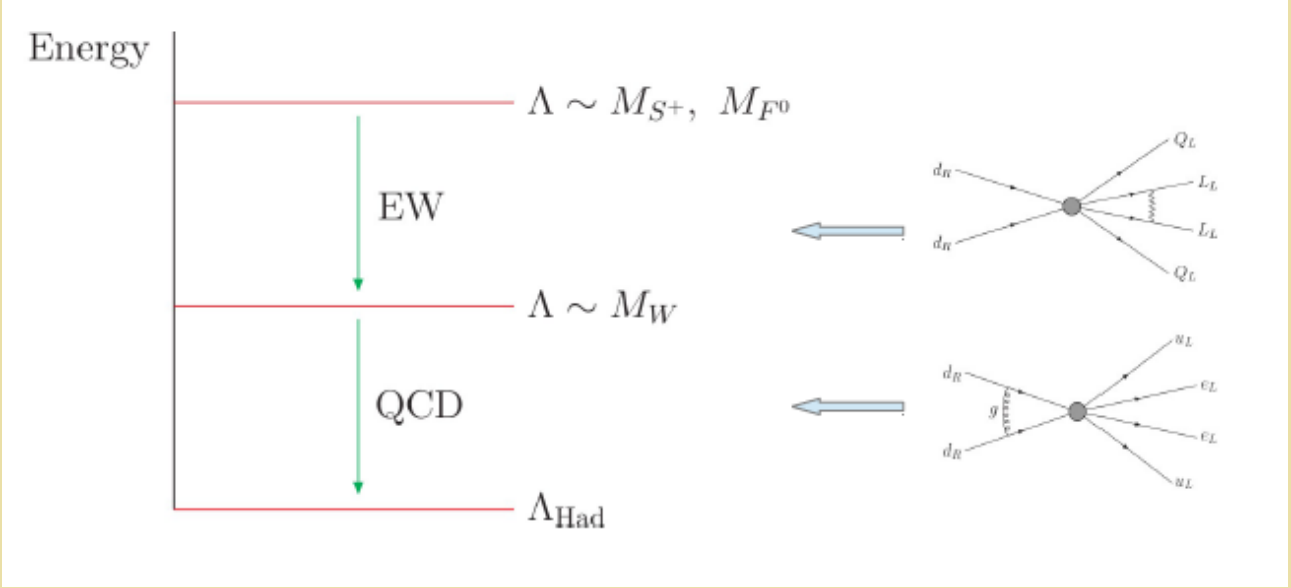
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

Low energy: *Running*



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$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

Low energy: *QCD Running*

$$\begin{aligned}
\mathcal{O}_1 &= (\bar{u}_L d_R)(\bar{u}_L d_R)(\bar{e}_L e_R^c),\\
\mathcal{O}_2 &= (\bar{u}_L \sigma^{\mu\nu} d_R)(\bar{u}_L \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c),\\
\mathcal{O}_3 &= (\bar{u}_L t^a d_R)(\bar{u}_L t^a d_R)(\bar{e}_L e_R^c),\\
\mathcal{O}_4 &= (\bar{u}_L t^a \sigma^{\mu\nu} d_R)(\bar{u}_L t^a \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c).
\end{aligned}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

Low energy: *QCD Running*

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\mathcal{O}_3 &= (\bar{u}_L t^a d_R)(\bar{u}_L t^a d_R)(\bar{e}_L e_R^c),\\
\mathcal{O}_4 &= (\bar{u}_L t^a \sigma^{\mu\nu} d_R)(\bar{u}_L t^a \sigma_{\mu\nu} d_R)(\bar{e}_L e_R^c).
\end{aligned}$$

$$\gamma^{ij} = -\frac{\alpha_s}{2\pi}\begin{pmatrix} 8 & 0 & 0 & 1 \\ 0 & -8/3 & 48 & 0 \\ 0 & 2/9 & -1 & 5/12 \\ 32/3 & 0 & 20 & 19/3 \end{pmatrix}$$

$$\mathcal{L}_{\rm eff} = \sum_j \frac{C_j(\mu)}{\Lambda^5}\mathcal{O}_j(\mu) + h.c.,$$

$$\mu\frac{d}{d\mu}C = \gamma^T C$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

Low energy: *QCD Running*

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$$\mathcal{O}_3 = (\bar{u}_L t^a d_R)(\bar{u}_L t^a d_R)(\bar{e}_L e_R^c),$$
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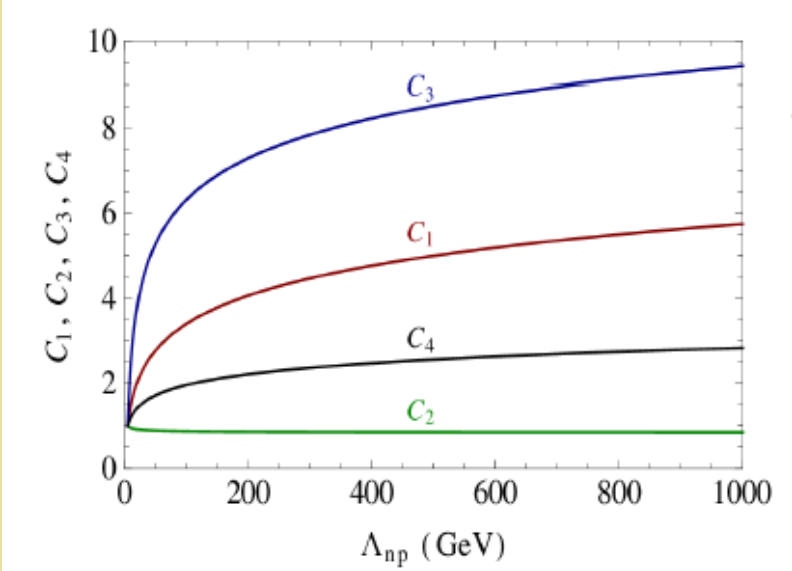


Assuming C_k = 1 at μ = 5 GeV → Effective DBD amplitude for $\mathcal{O}_1$ substantially weaker for given LHC constraints

$0\nu\beta\beta$-Decay: TeV Scale LNV

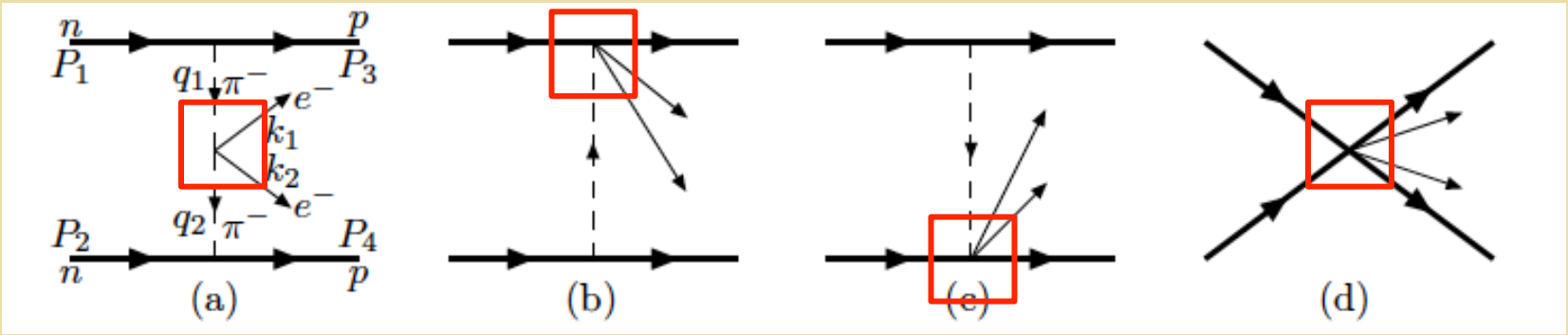
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Low energy: *Nuclear Matrix Elements: Long Range Effects*



Exploit Chiral Symmetry & EFT ideas

$0\nu\beta\beta$-Decay: TeV Scale LNV

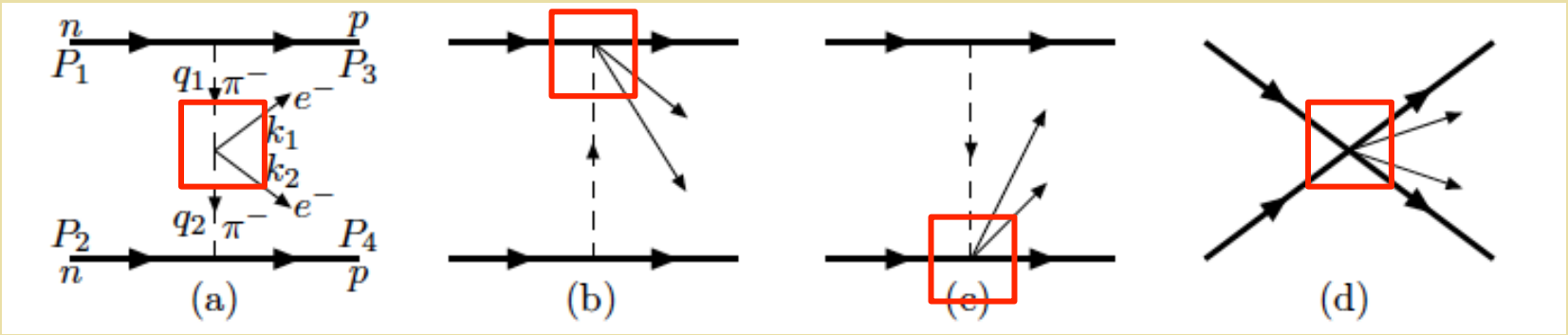
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; {\rm h.c.}$$

Majorana

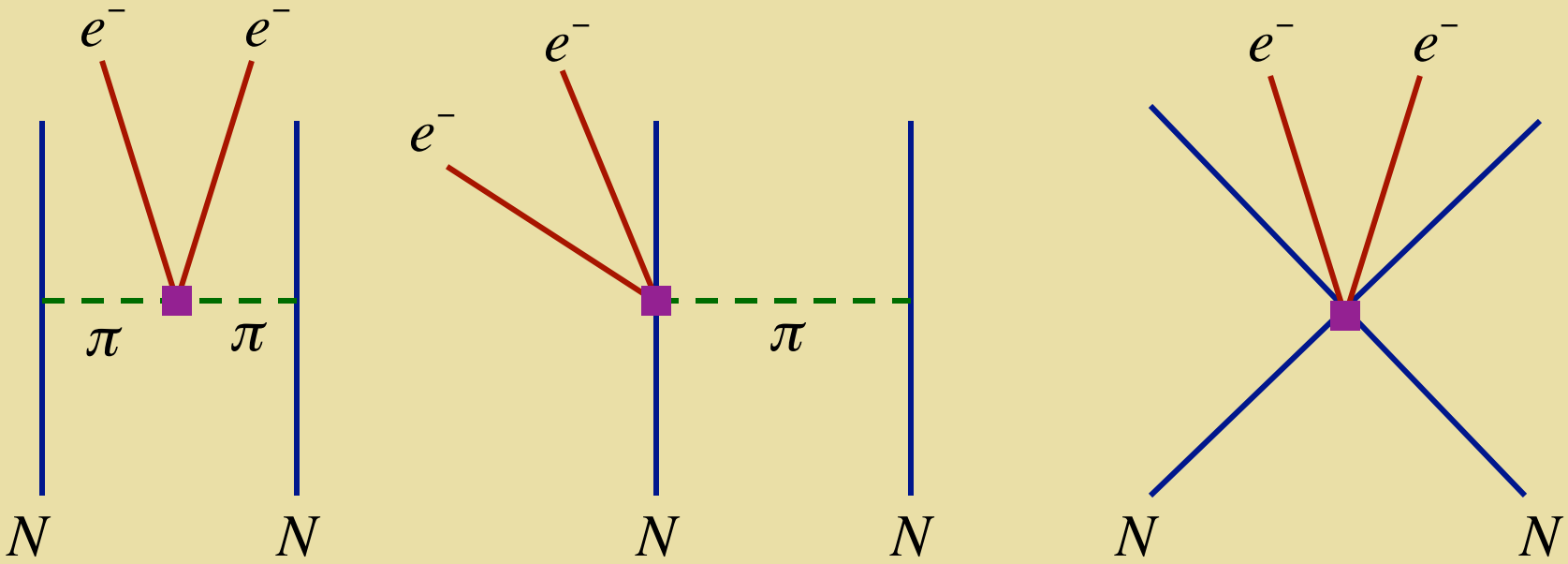
Low energy: *Nuclear Matrix Elements: Long Range Effects*



Our work *Helo et al*

Exploit Chiral Symmetry & EFT ideas

$0\nu\beta\beta$ - decay in effective field theory



Tractable nuclear operators

Systematic operator classification

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

0ν ββ - decay in effective field theory

Operator classification

$$\mu = M_{WEAK}$$

$$\mathcal{L}(q,e) = \frac{G_F^2}{\Lambda_{\beta\beta}} \sum_{j=1}^{14} C_j(\mu)\, \hat{O}_j^{++}\, \bar{e}\Gamma_j e^c \quad + \quad h.c.$$

e.g.

$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^a q_L \; \bar{q}_R \gamma_\mu \tau^b q_R$$

0ν ββ - decay: *a* = *b* = +

0ν ββ - decay in effective field theory

Operator classification

$$\mu = M_{WEAK}$$

$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^a q_L \; \bar{q}_R \gamma_\mu \tau^b q_R$$

Chiral transformations: $SU(2)_L$ x $SU(2)_R$

$$q_L \rightarrow L q_L \qquad q_R \rightarrow R q_R \qquad \begin{matrix} L \\ R \end{matrix} = \exp\left(i \vec{\theta}_{\begin{matrix} L \\ R \end{matrix}} \cdot \frac{\vec{\tau}}{2} P_{\begin{matrix} L \\ R \end{matrix}} \right)$$

$$\hat{O}_{1+}^{ab} \in (3_L, 3_R)$$

Parity transformations: $q_L \leftrightarrow q_R$

0ν ββ - decay: ***a = b = +***

$$\hat{O}_{1+}^{++} \leftrightarrow \hat{O}_{1+}^{++}$$

$0\nu\,\beta\beta$ - decay in effective field theory

Hadronic basis

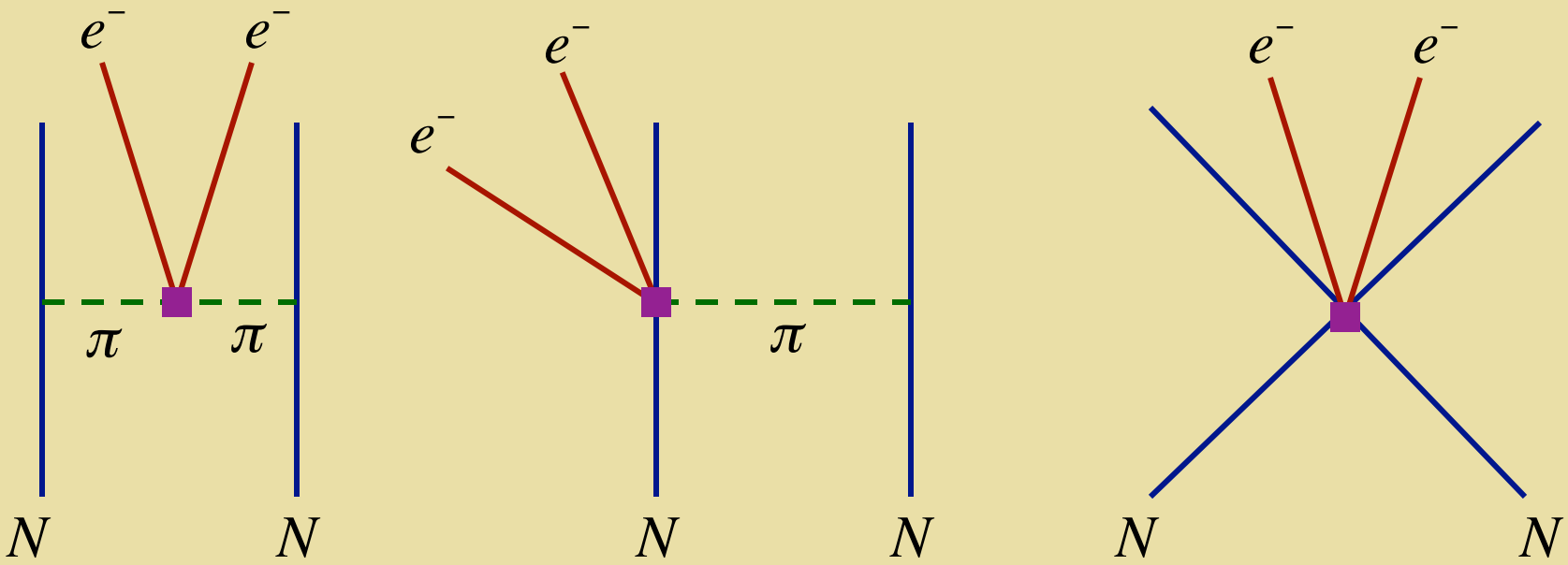
$$X_R^a = \xi\,\tau^a\,\xi^+\,,\quad X_L^a = \xi^+\,\tau^a\,\xi\,,\qquad \xi = \exp\left(i\vec{\tau}\cdot\vec{\pi}/2\right)$$

Chiral transformations

$$\hat{O}_{1+}^{++} \sim Tr\left(X_R^+\,X_L^+\right) \sim \frac{2}{F_\pi^2}\,\pi^-\,\pi^- + \cdots$$

No derivatives  $K_{\pi\pi} \sim O\,(p^0)$

$0\nu\ \beta\beta$ - decay in effective field theory



$K_{\pi\pi}\ p^{-2}$ $K_{\pi NN}\ p^{-1}$ $K_{NNNN}\ p^{0}$

$O(p^{-2})$ for $\hat{O}^{++}_{1+}$ $O(p^{0})$ for $\hat{O}^{++}_{3+}$

$0\nu\beta\beta$-Decay: TeV Scale LNV

Putting the pieces together

$0\nu\beta\beta$-Decay: TeV Scale LNV

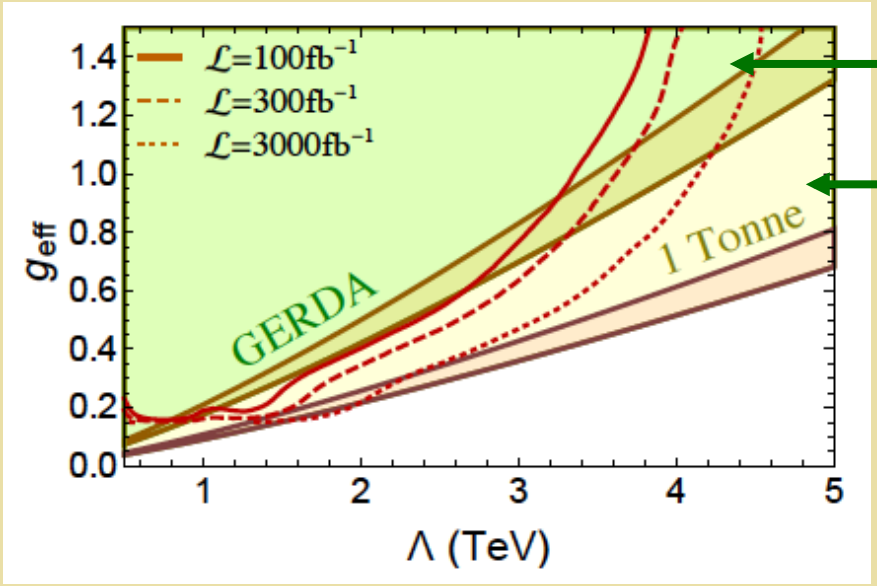
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

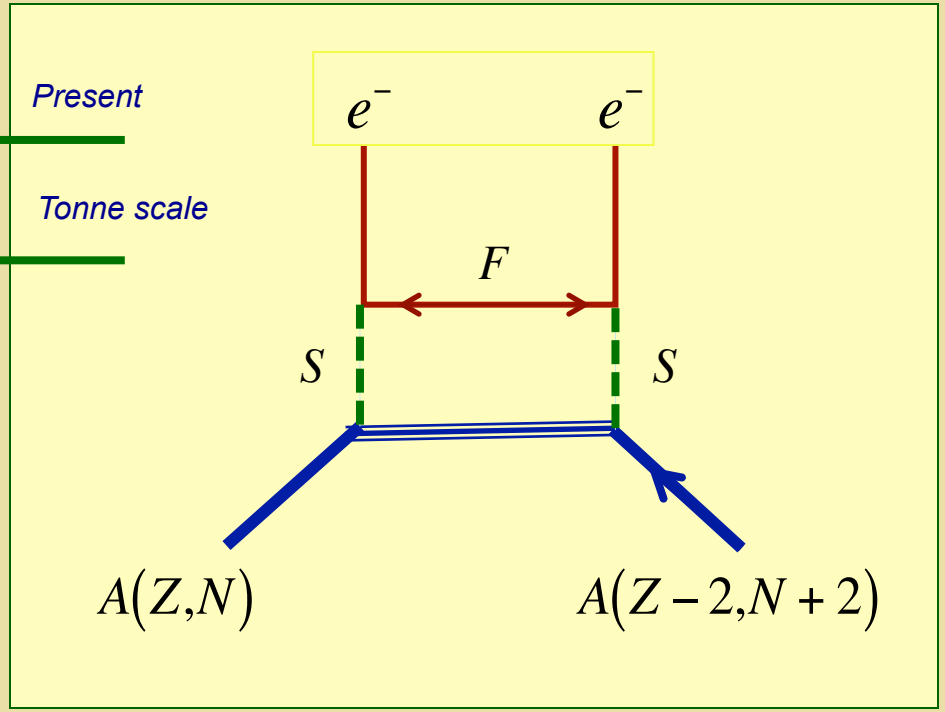
Majorana

Benchmark Sensitivity: TeV LNV



Present

Tonne scale



T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

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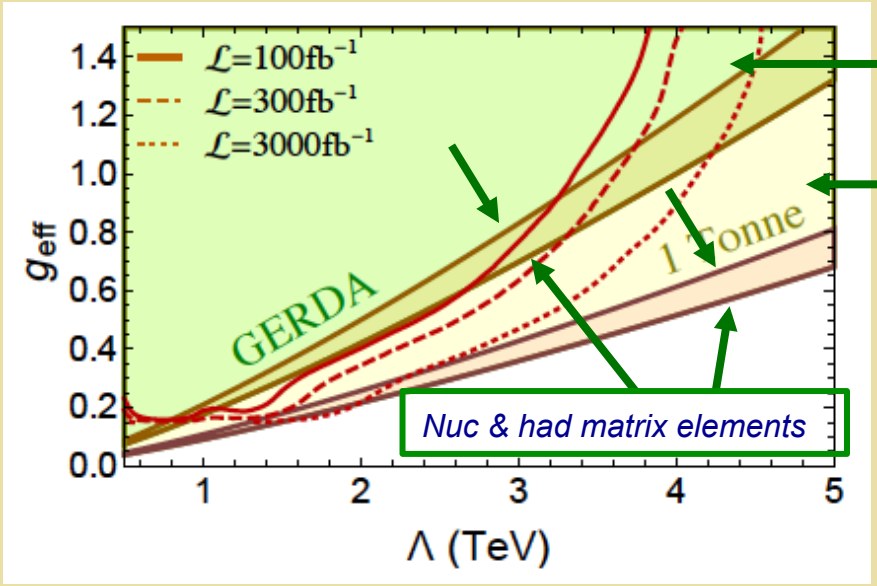
Majorana

Benchmark Sensitivity: TeV LNV



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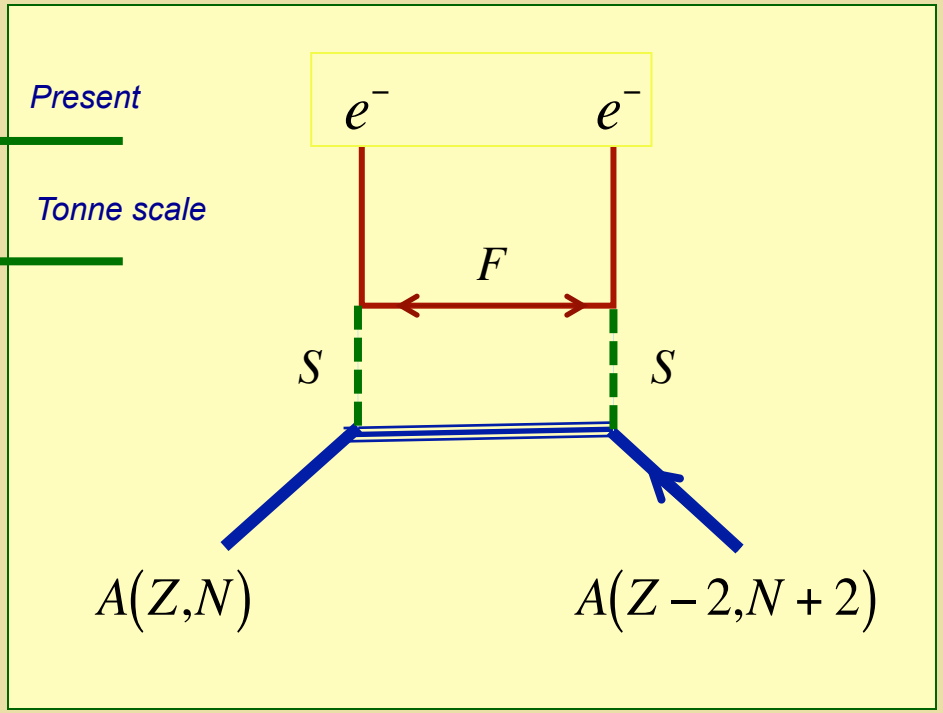

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

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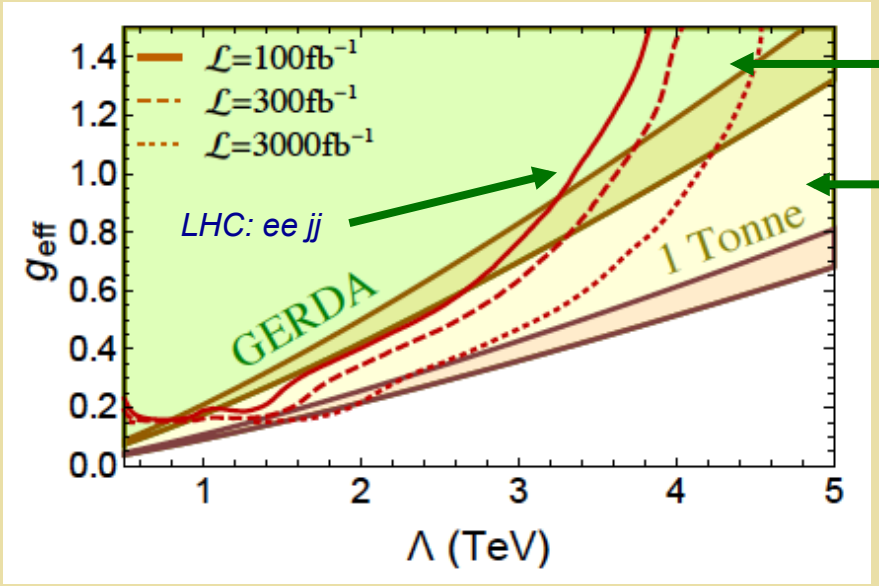
Majorana

Benchmark Sensitivity: TeV LNV



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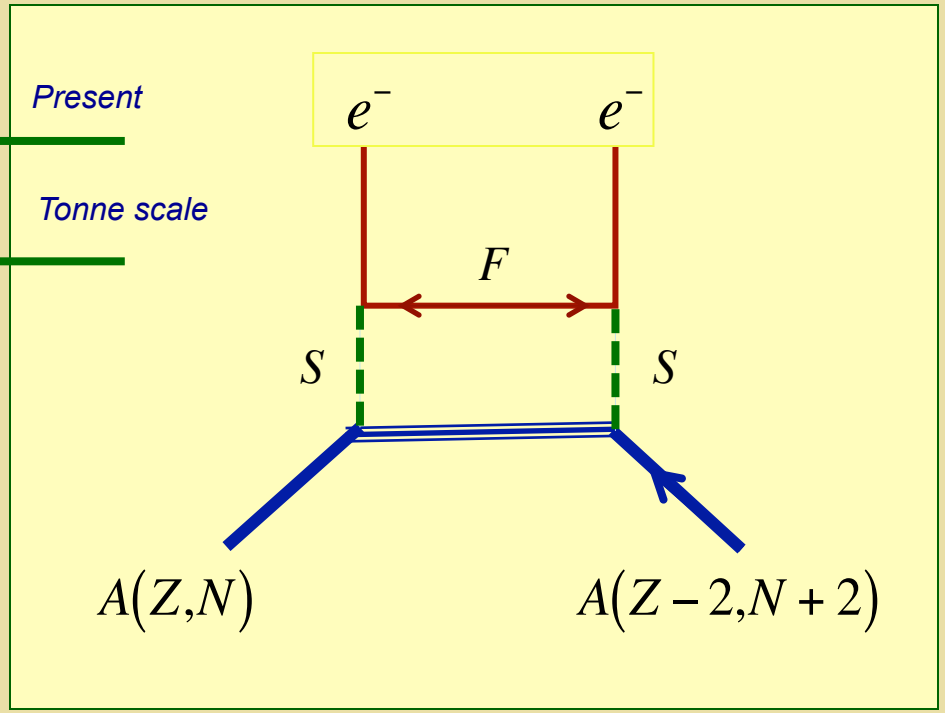

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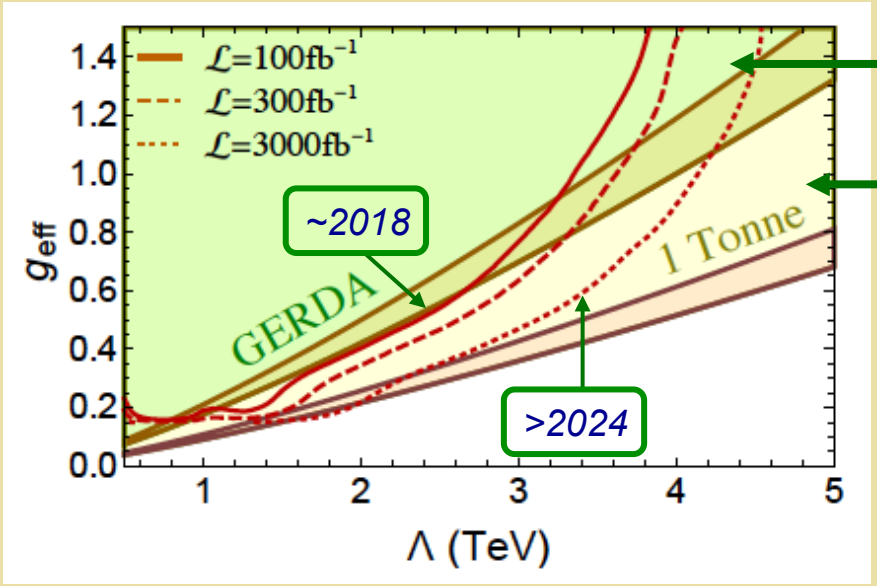
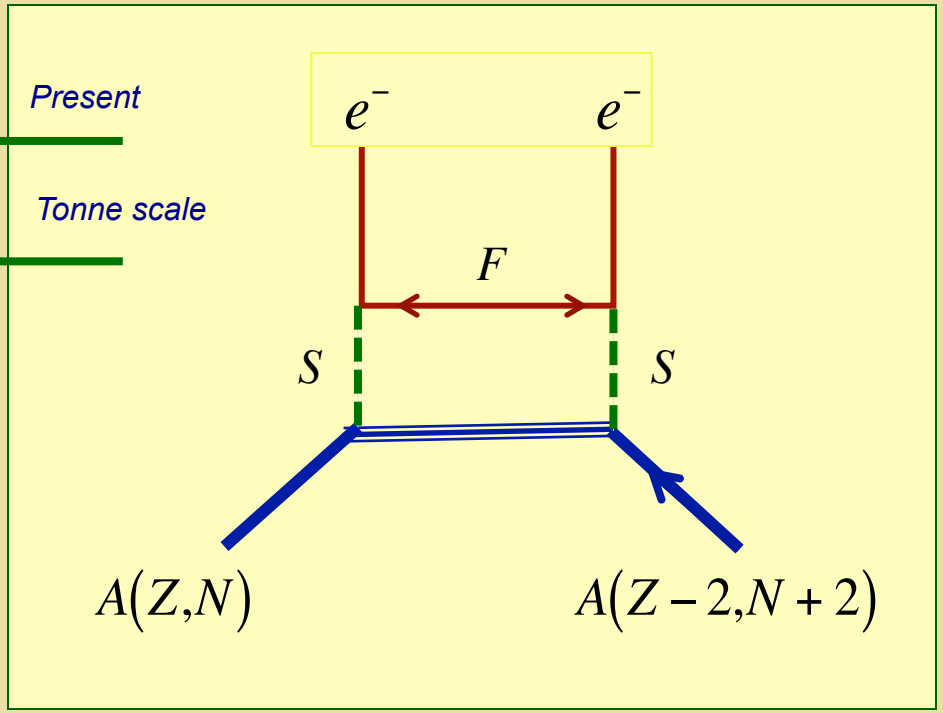
Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

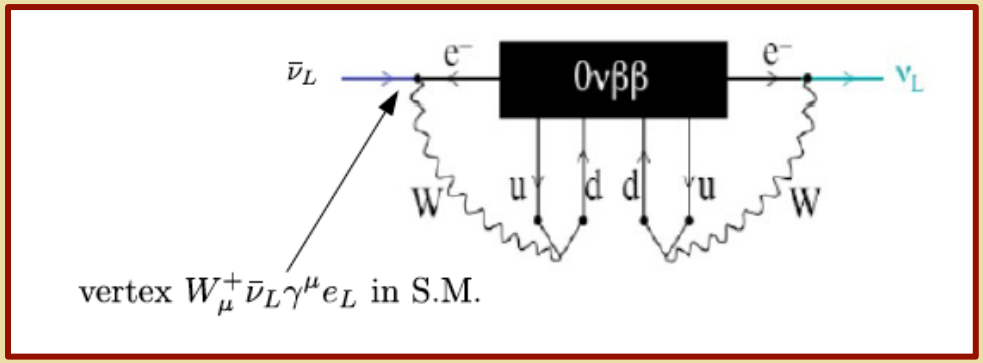
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

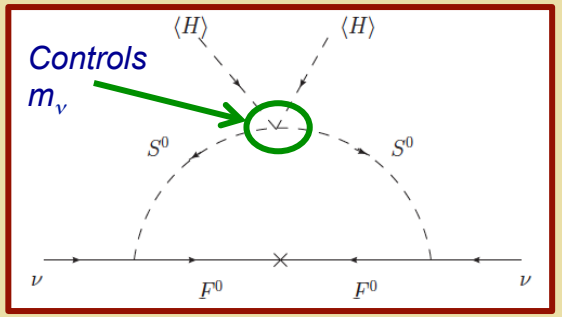
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; \text{h.c.}$$

Majorana

Implications for m_ν:





Schecter-Valle: non-vanishing Majorana mass at (multi) loop level

Simplified model: possible (larger) one loop Majorana mass

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

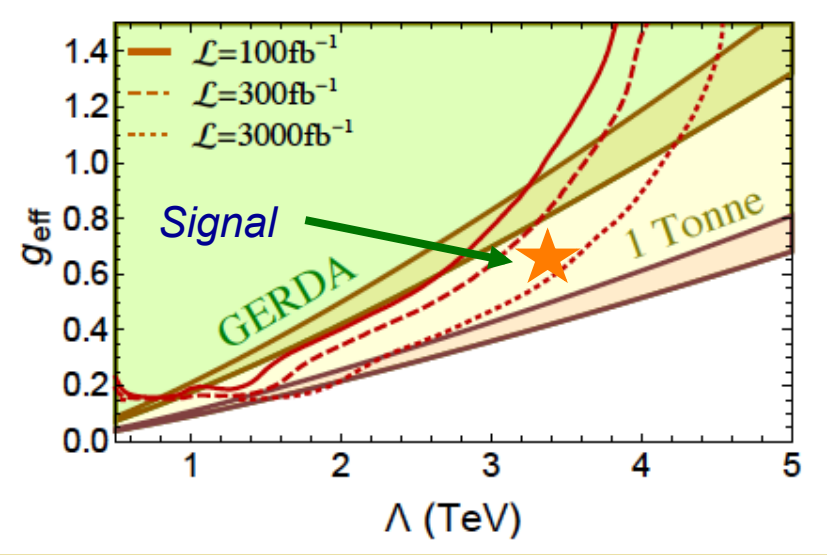
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; {\rm h.c.}$$

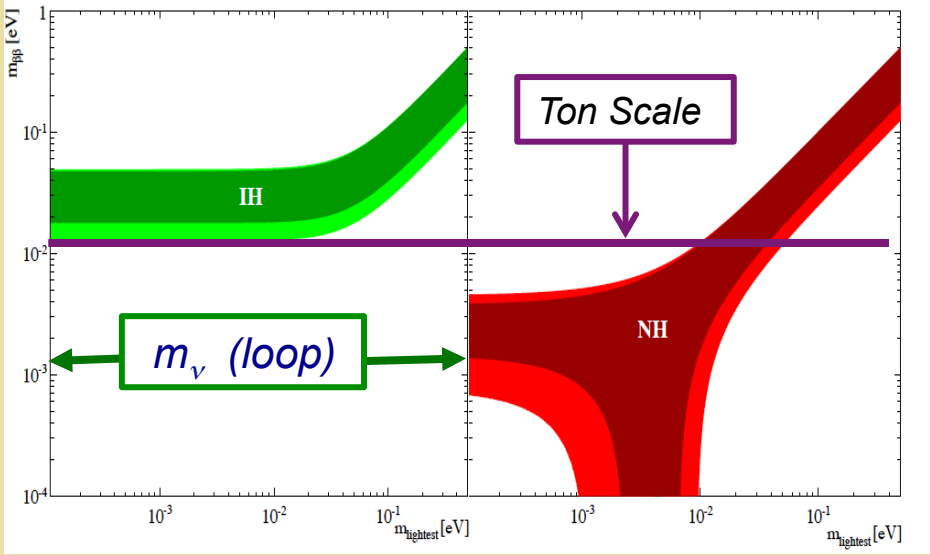
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; {\rm h.c.}$$

Majorana

Implications for m_ν:

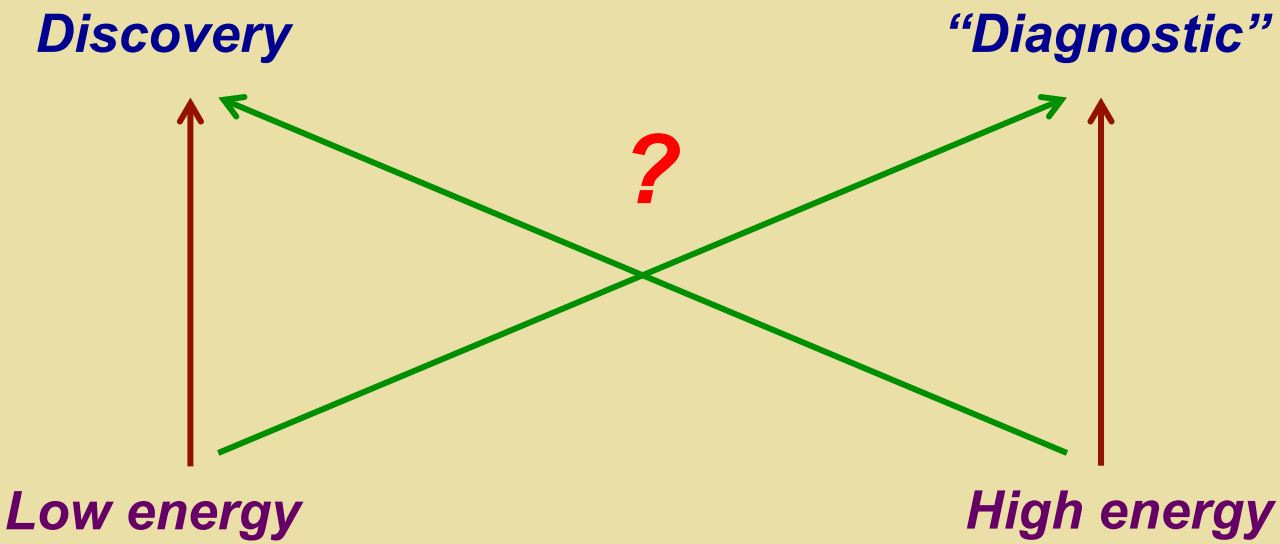




A hypothetical scenario

Low-Energy / High-Energy Interplay

TeV LNV



$0\nu\beta\beta$ / LHC Interplay: Matrix Elements

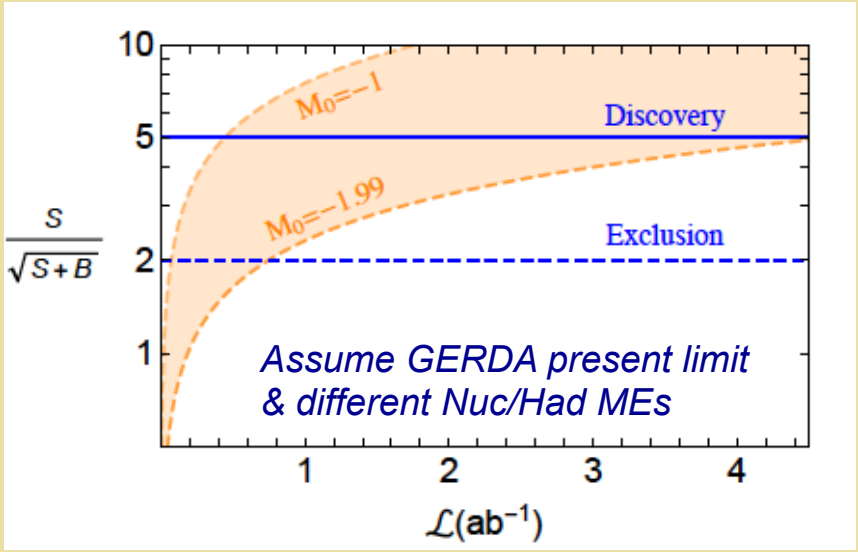
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

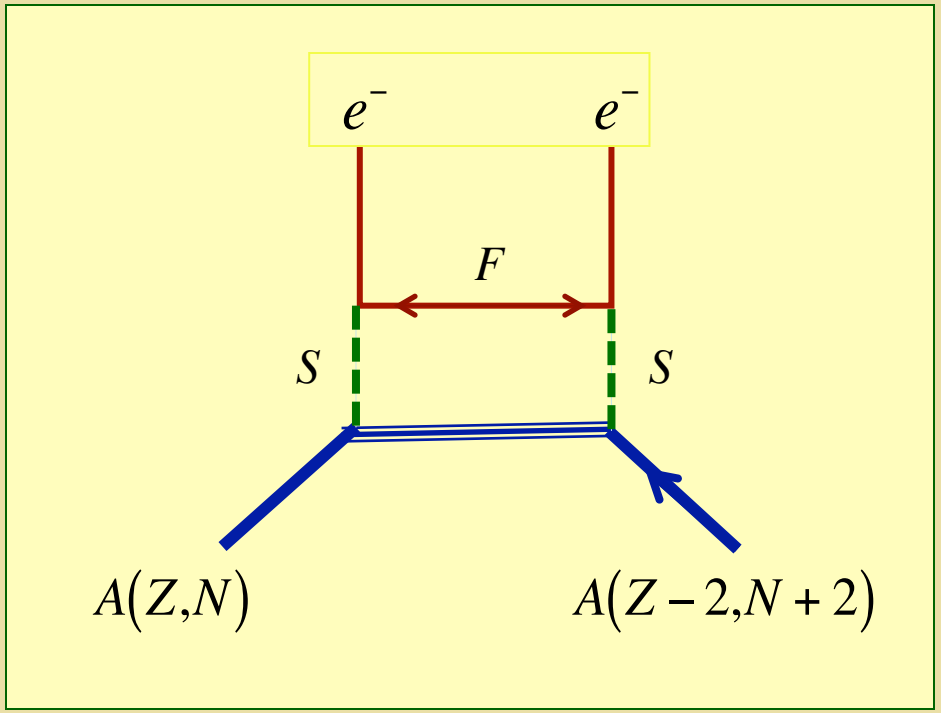
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



V. Sterile Neutrinos

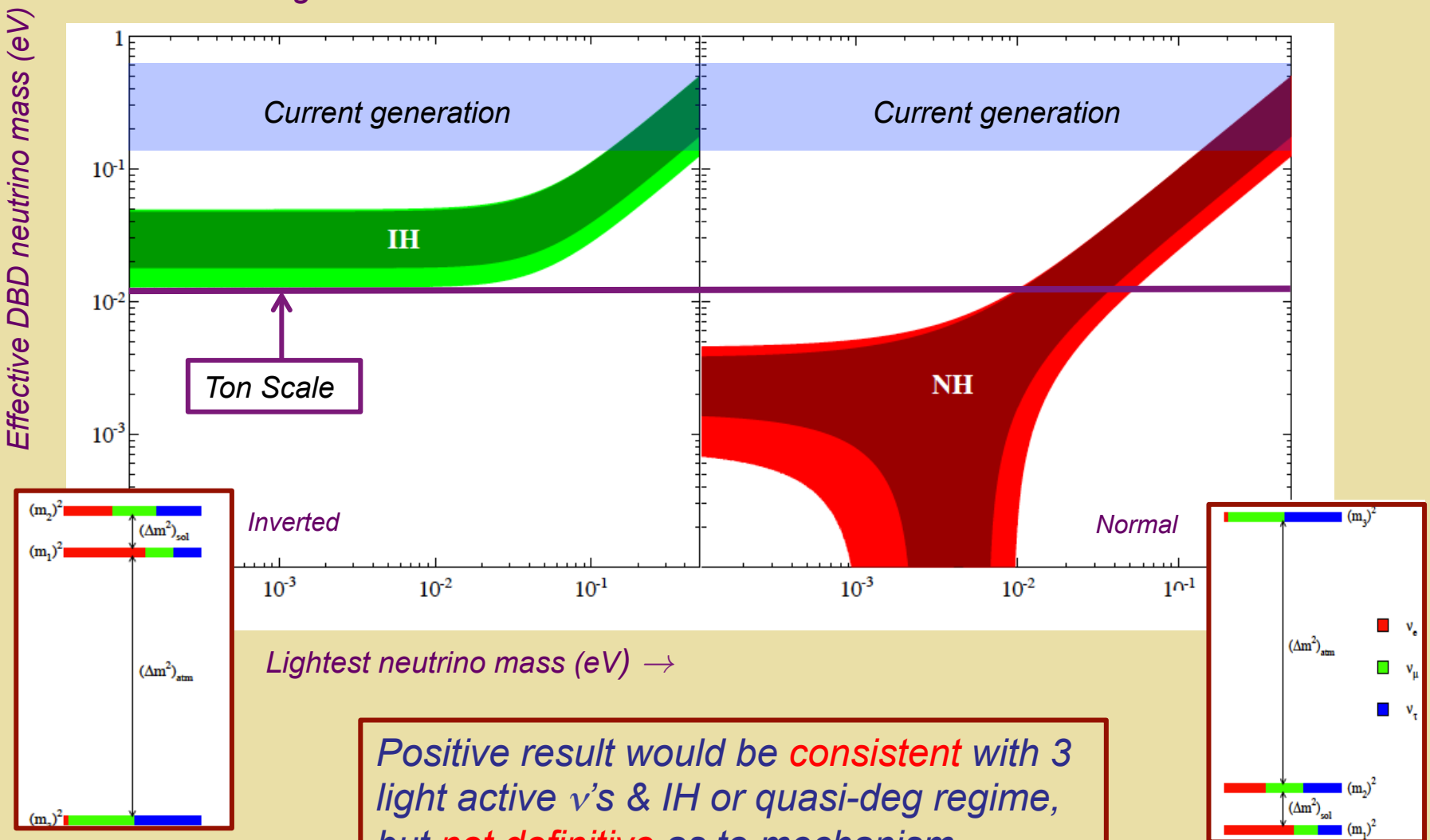
Why Might A "Ton-Scale" Exp't See It?

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

- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

Interpreting a Positive Result

Three active light neutrinos

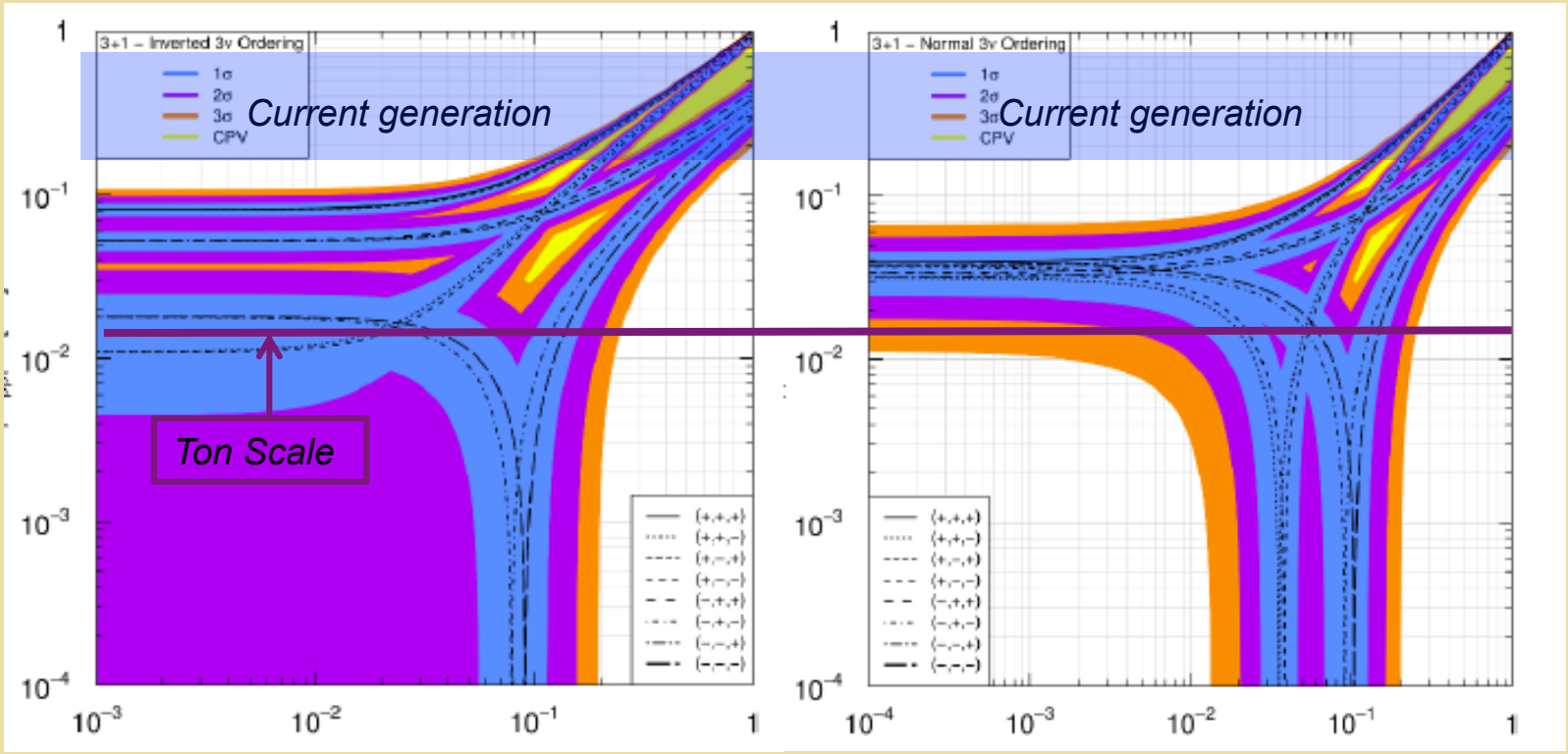


Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

Interpreting a Positive Result

3+1 active light neutrinos

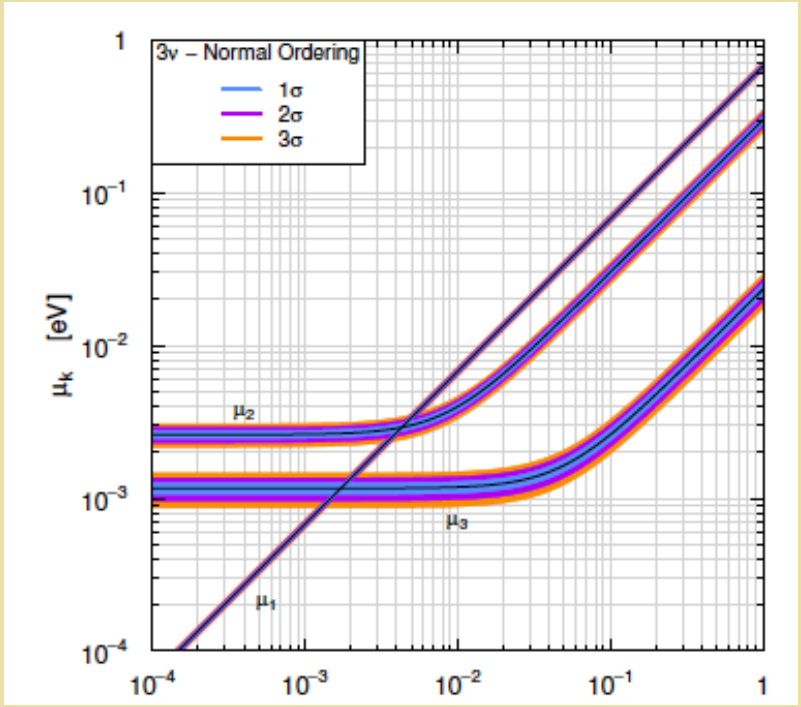
Giunti & Zavanin, JHEP07 (2015) 171



Positive result would be consistent with 3+1 light active ν's & NH, IH, or quasi-deg regime, but not definitive as to mechanism

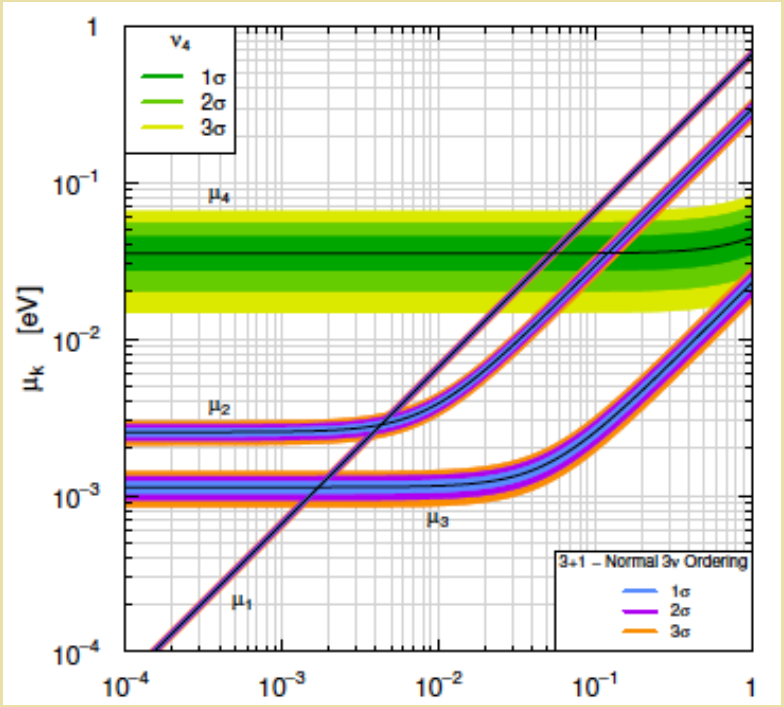
Sterile Neutrinos & $0\nu\beta\beta$-Decay

3 active light neutrinos



$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3}\right|$$

3+1 active light neutrinos

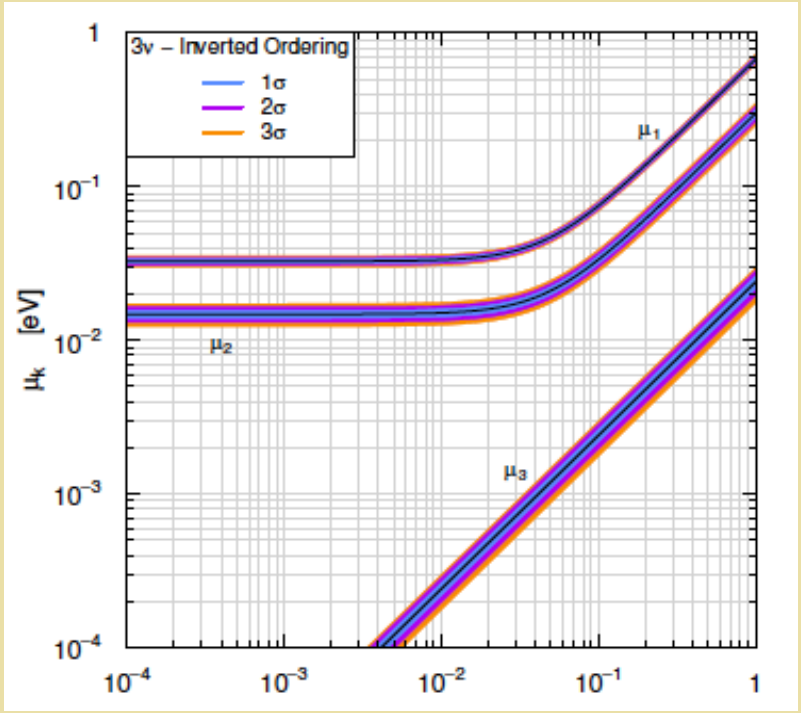


$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3} + \mu_4 e^{i\alpha_4}\right|$$

Giunti & Zavanin, JHEP07 (2015) 171

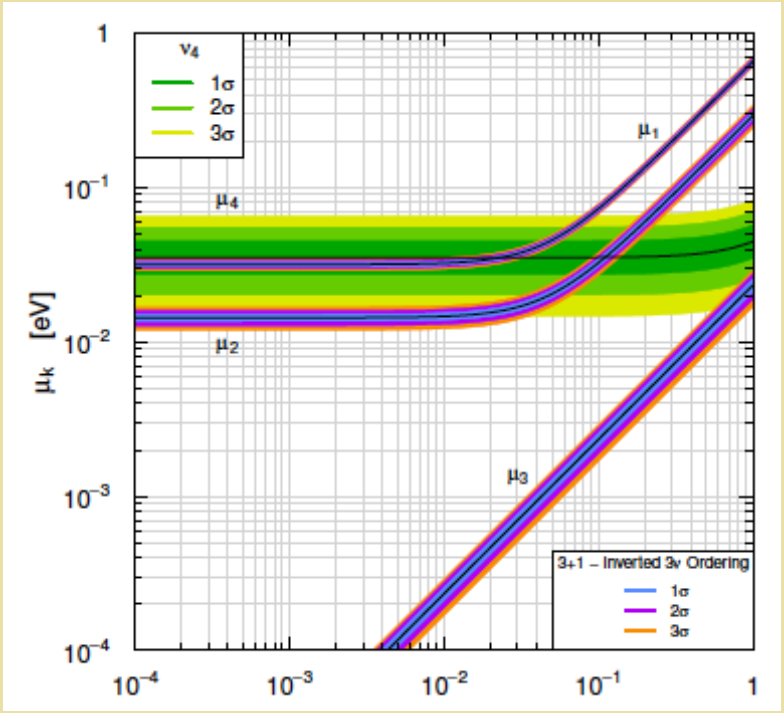
Sterile Neutrinos & $0\nu\beta\beta$-Decay

3 active light neutrinos



$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3}\right|$$

3+1 active light neutrinos



$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3} + \mu_4 e^{i\alpha_4}\right|$$

Giunti & Zavanin, JHEP07 (2015) 171

VI. Summary & Outlook

- *Determining the mechanism and BSM mass scale associated with neutrino mass generation is a key challenge for nuclear physics, high energy physics, & cosmology*

- *There exist a variety of well-motivated mechanisms associated with low- to high-scales*

- *"Naturalness" is a useful guiding theoretical consideration but not definitive*

- *Results from $0\nu\beta\beta$-decay, in combination with results from kinematic mass measurements, oscillation studies, LHC LNV searches, & cosmology are vital to addressing this fundamental puzzle*

Back Up Slides

$0\nu\beta\beta$-Decay: LNV? Mass Term?

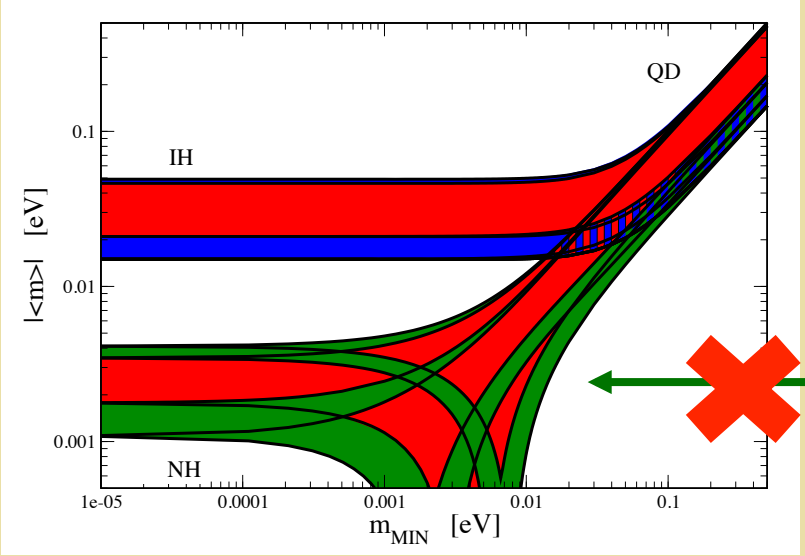
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

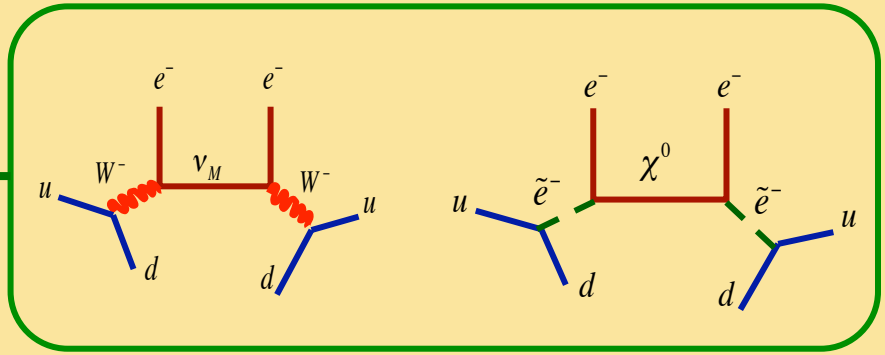
Majorana

Benchmark Sensitivity



Theory Challenge: matrix elements + mechanism

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k \, e^{2i\delta}$$



Heavy ν_M or other heavy LNV

$0\nu\beta\beta$-Decay: TeV Scale LNV

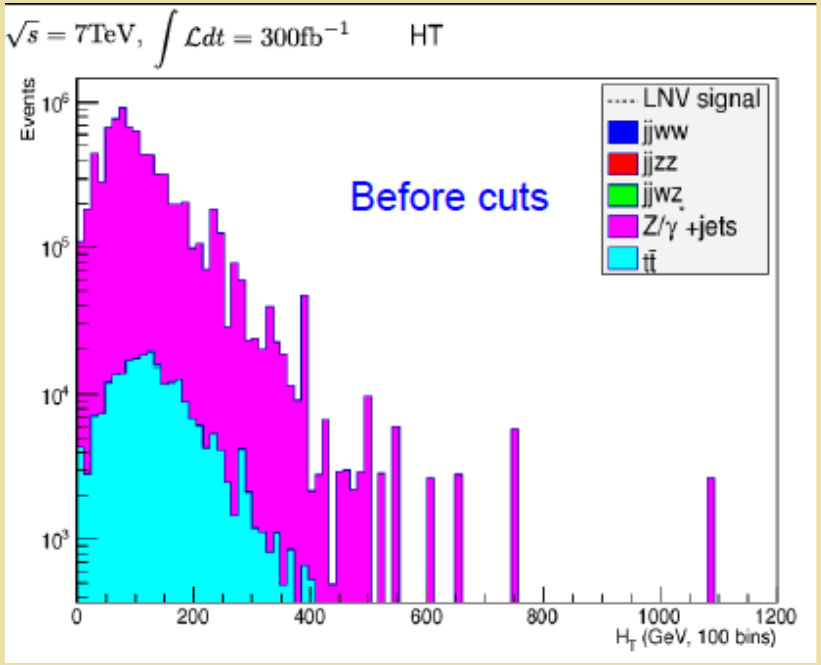
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Backgrounds: *Cuts*



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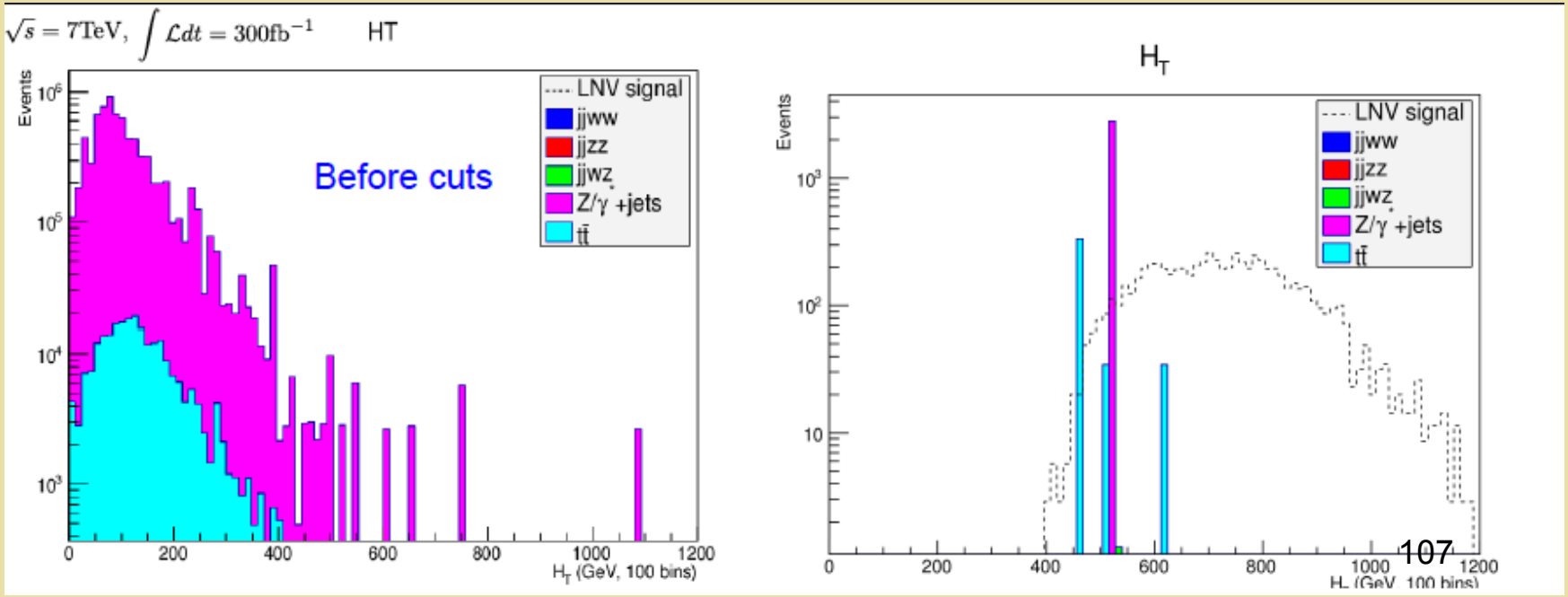

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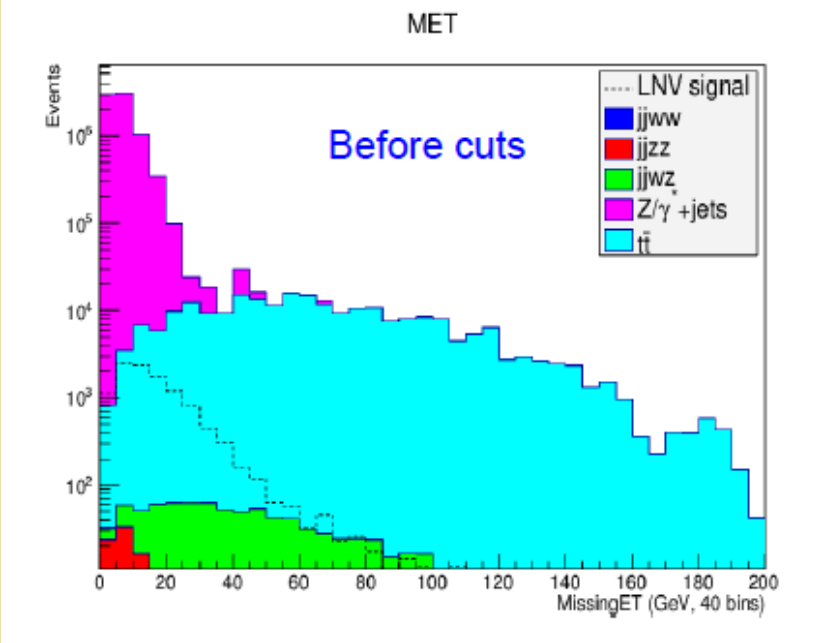

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