$0\nu\beta\beta$ and EDMs: Energy Frontier Connections

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Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

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

DBD Topical Collaboration Meeting, February 2017

Goals For This Talk

- *Provide some context for the heavy particle exchange mechanism for $0\nu\beta\beta$ – decay*
- *Discuss some recent work on the interplay of $0\nu\beta\beta$ – decay and EDM searches with energy frontier searches*
- *Put the need for refined hadronic and nuclear matrix element computations in the broader BSM context*

0νββ-Decay: TeV Scale LNV

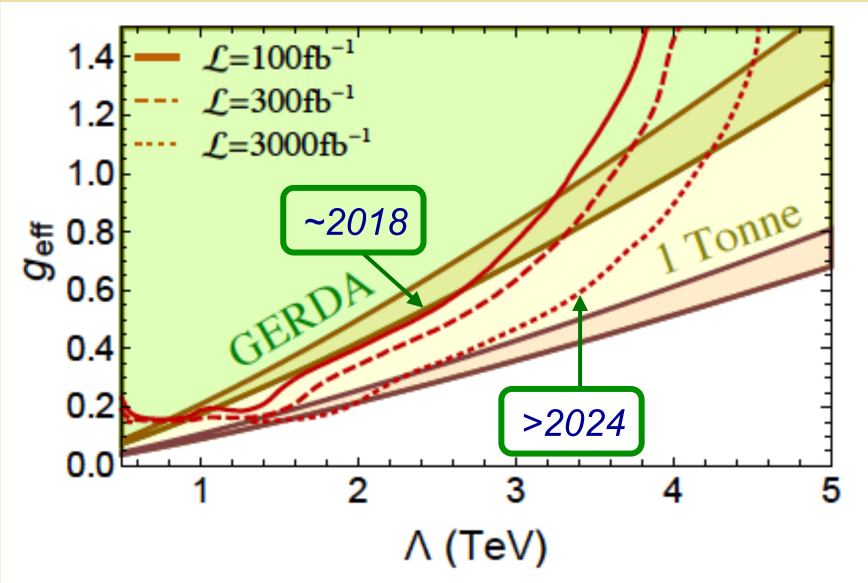
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

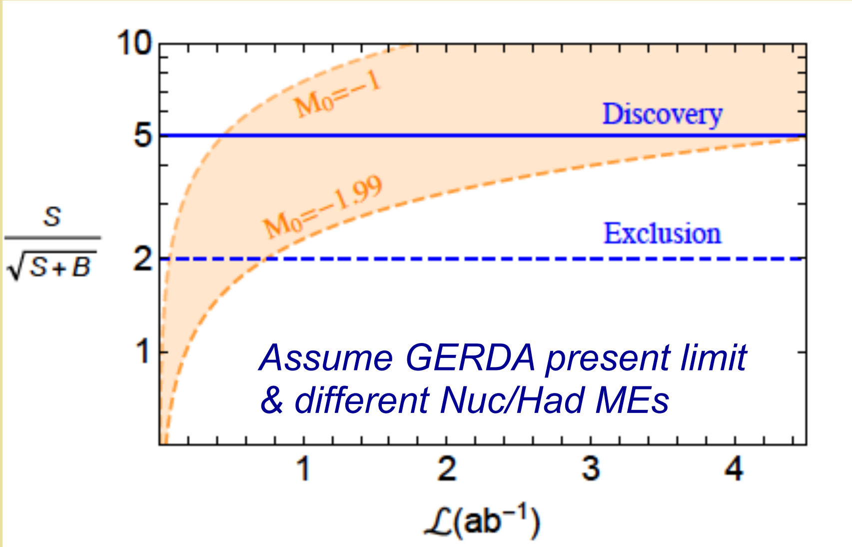
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV



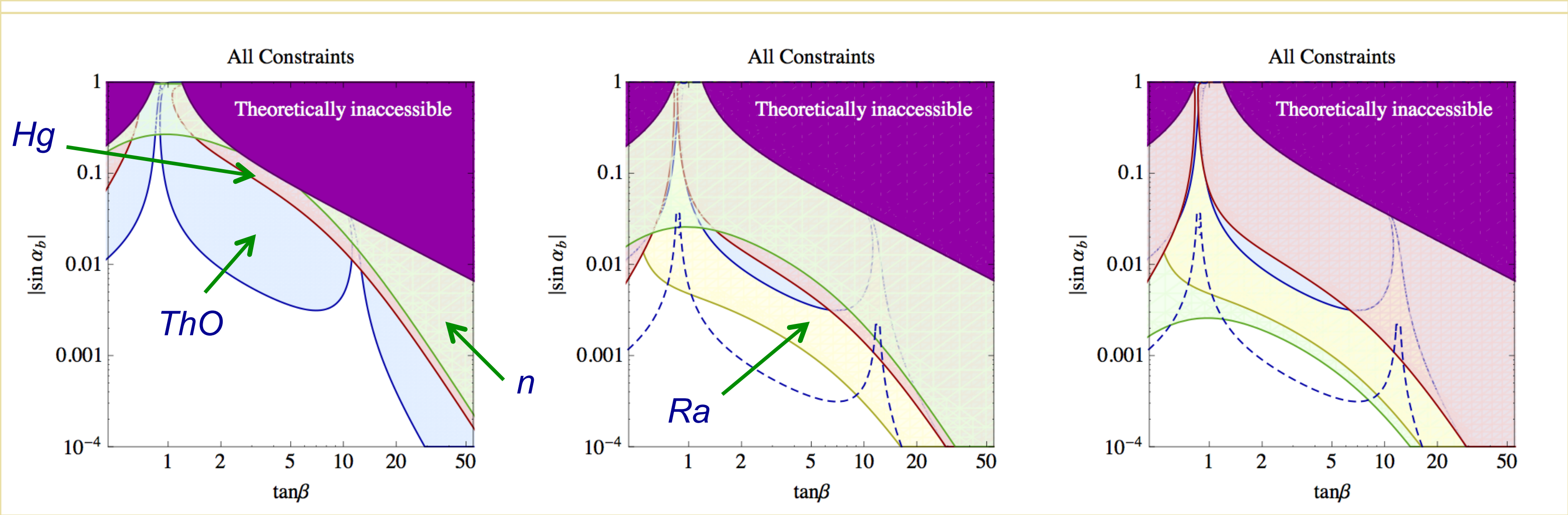


T. Peng, MRM, P. Winslow 1508.04444

Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra) [10^{-27} e cm]

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

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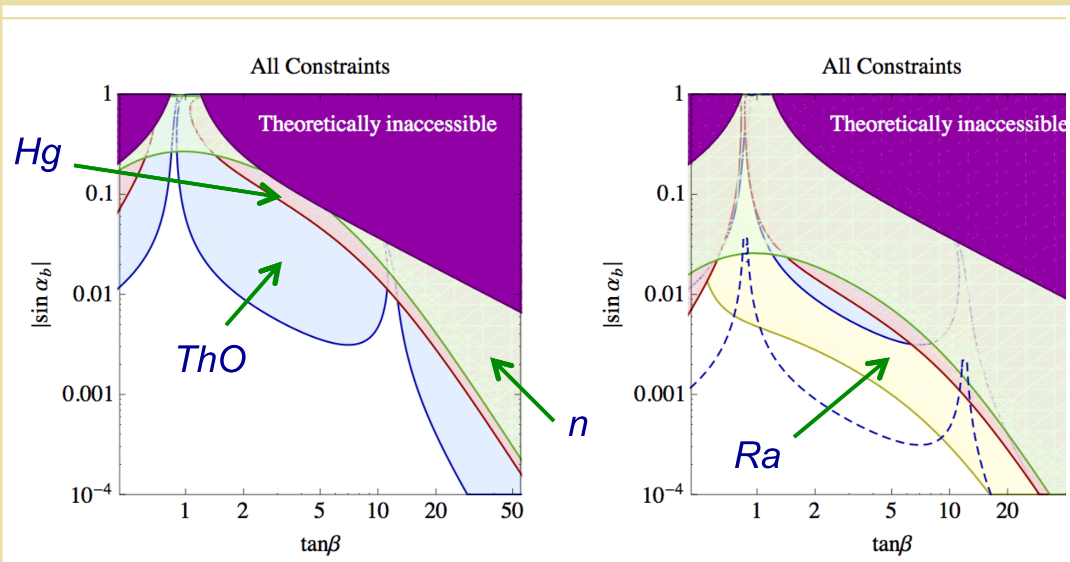

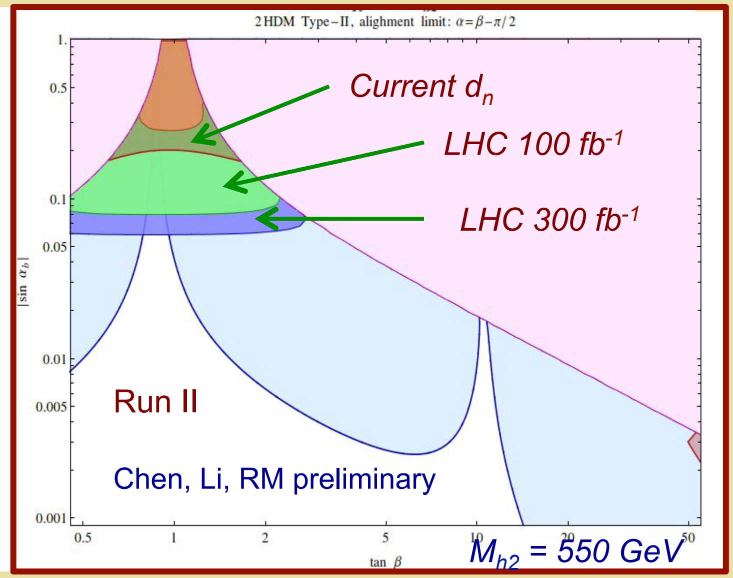

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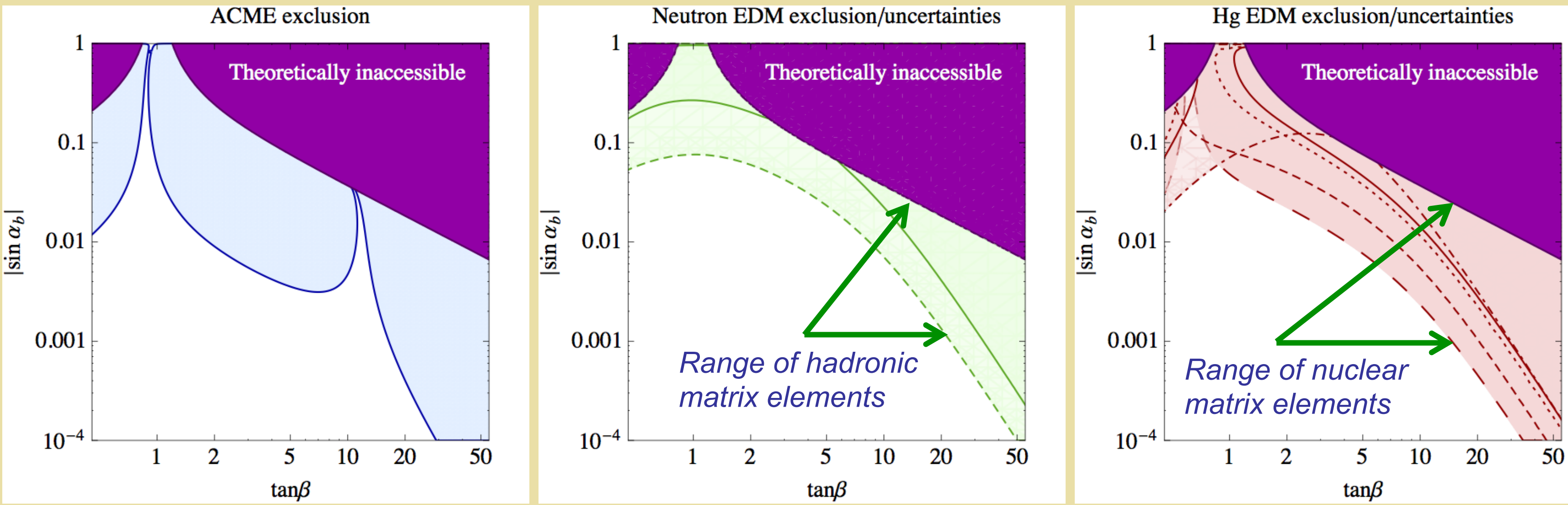
Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present

Challenge for Theory

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Outline

I. BSM Context

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

III. The "Standard Mechanism" : Lightning Review

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

V. EDMs & the LHC: Higgs Portal CPV

VI. Summary

VII. Back Up Slides: Sterile Neutrinos, $0\nu\beta\beta$ – Decay Effective Theory

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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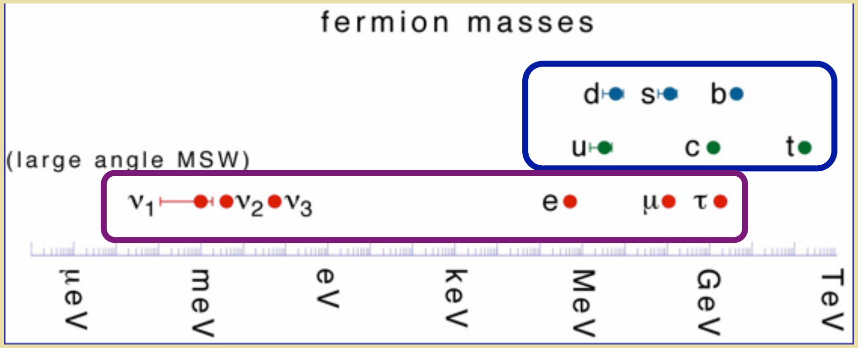

Partners

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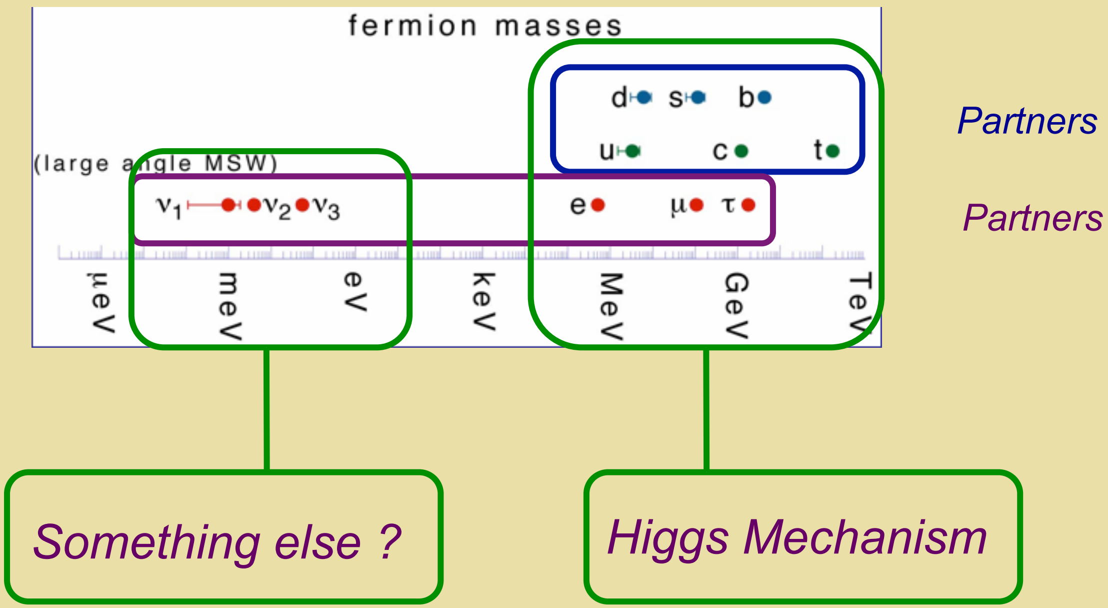

*Questions for Fundamental Physics**

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

****Partial List***

How "Natural" is m_ν ?

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

$v = 246$ GeV $\rightarrow$ $y \sim 10^{-12}$

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

$v = 246$ GeV
& $y \sim \mathcal{O}(1)$ $\rightarrow$ $\Lambda \sim 10^{14}$ GeV

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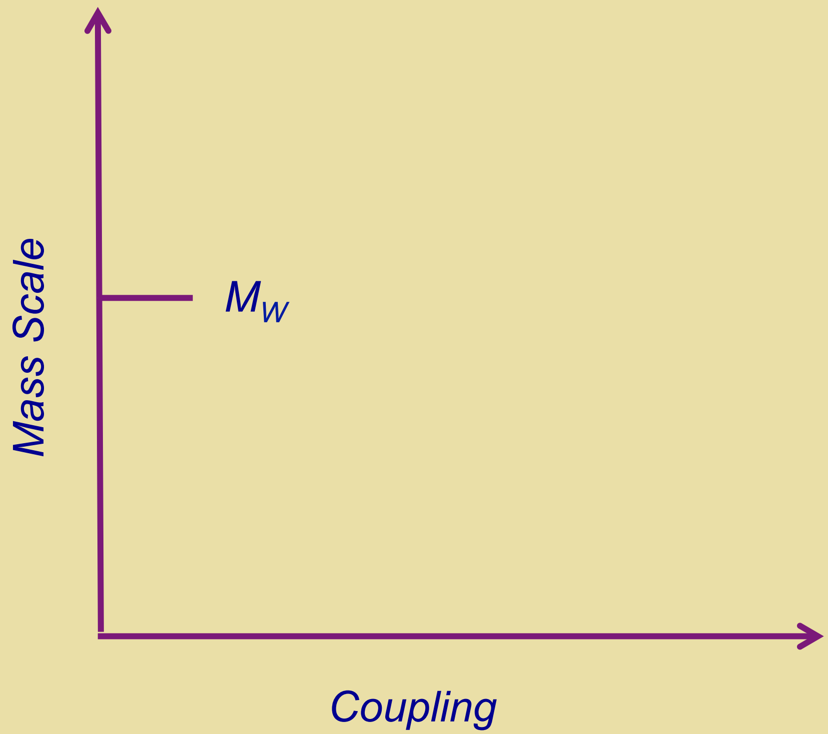
How reliable a guide is naturalness ?

BSM Physics: Where Does it Live ?



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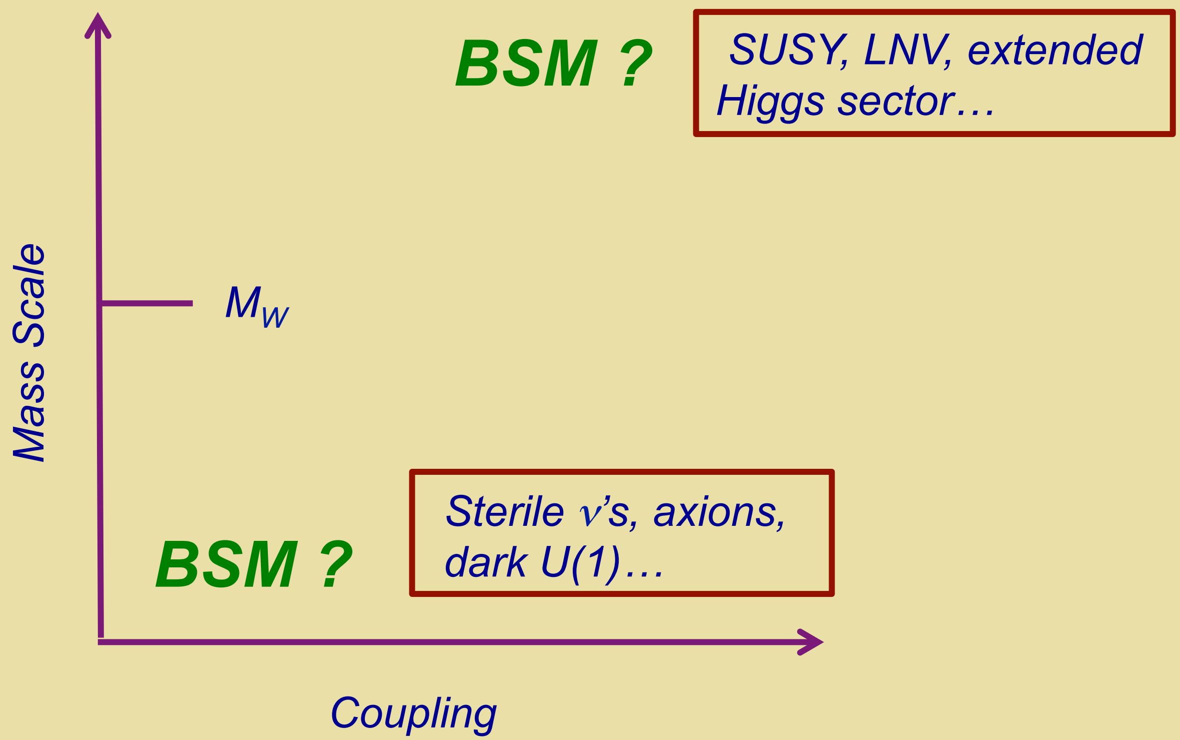

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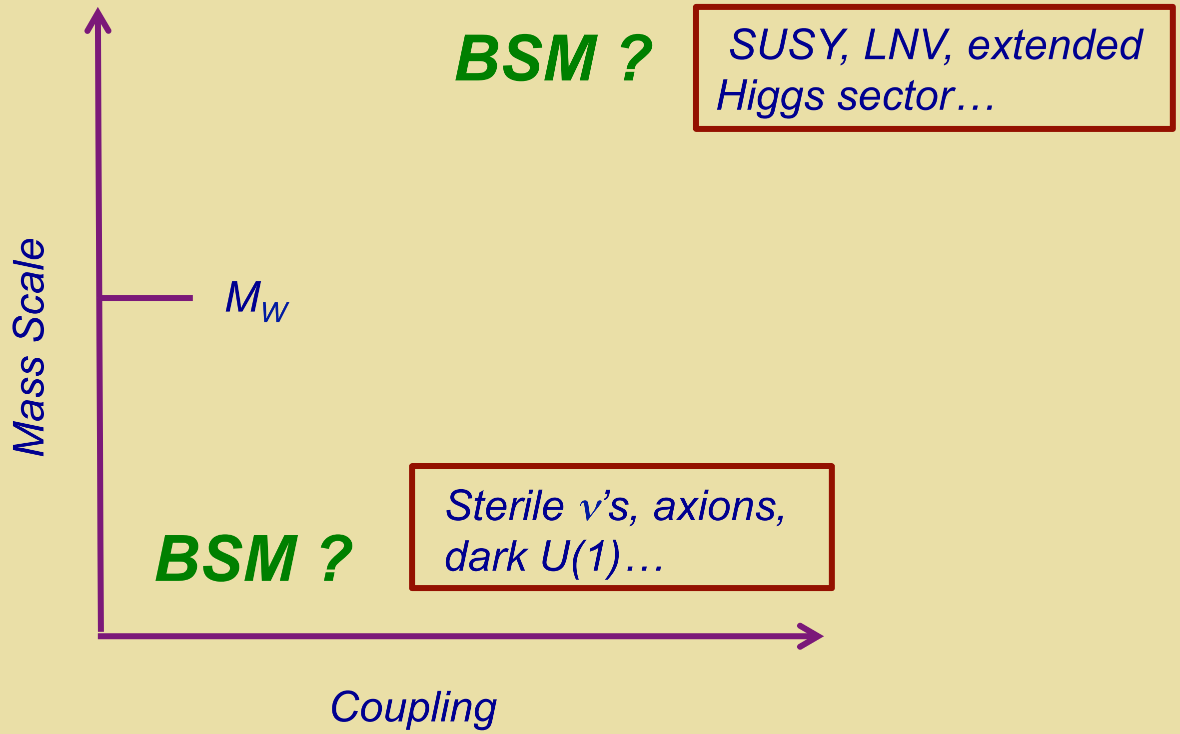


Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

*Questions for Fundamental Physics**

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

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

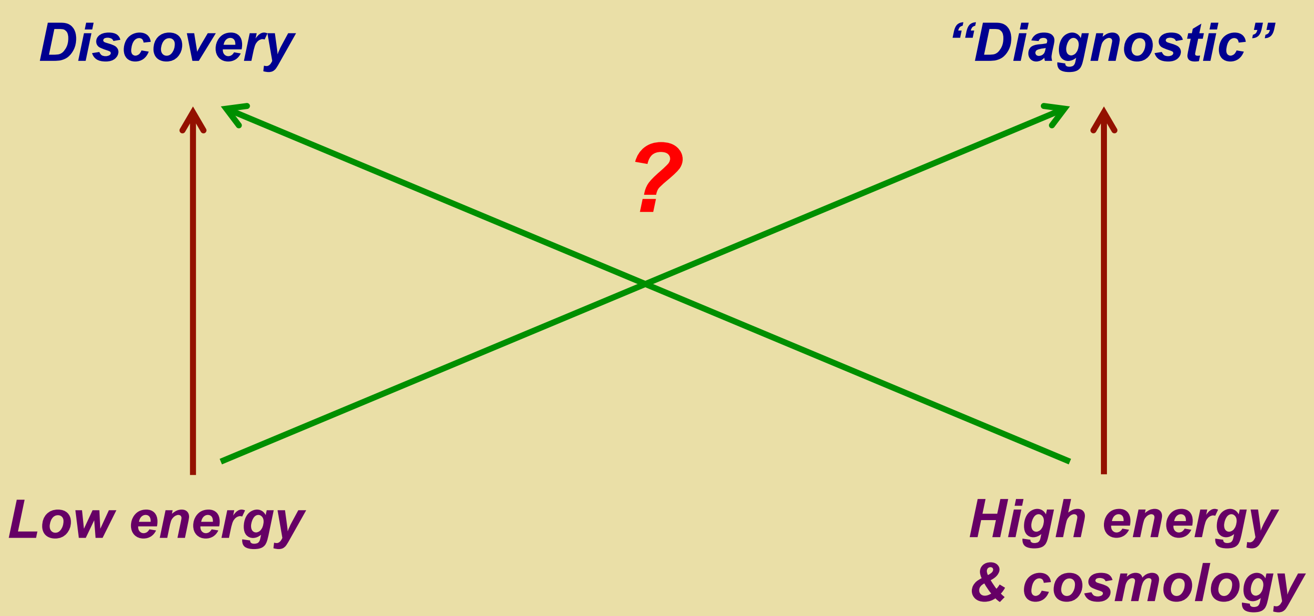
****Partial List***

Low-Energy / High-Energy Interplay

Discovery ↑ ***Low energy***

"Diagnostic" ↑ ***High energy & cosmology***

Low-Energy / High-Energy Interplay



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

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

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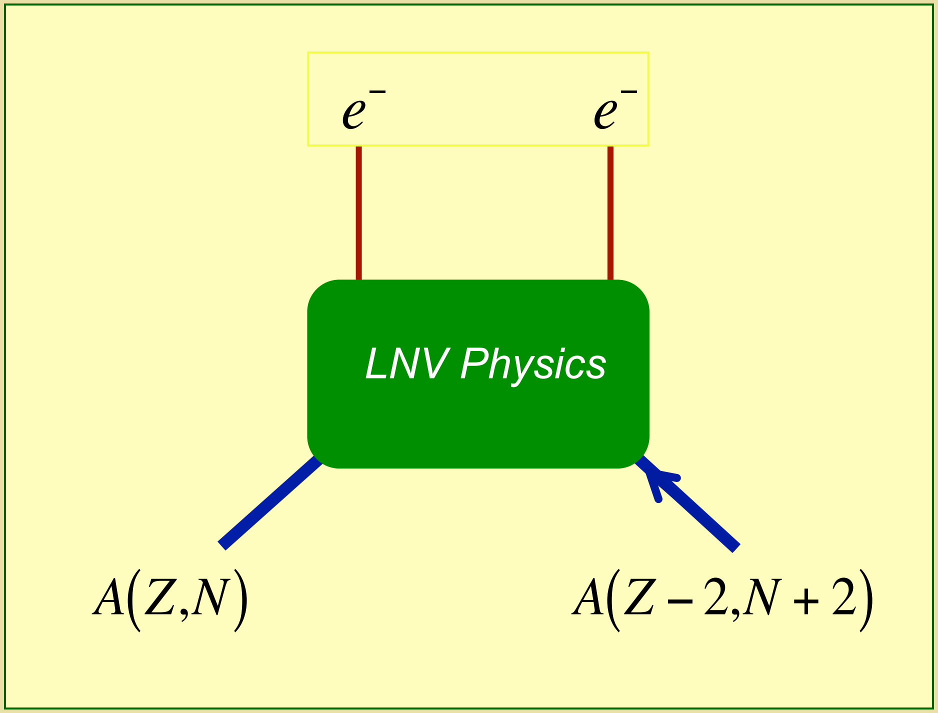

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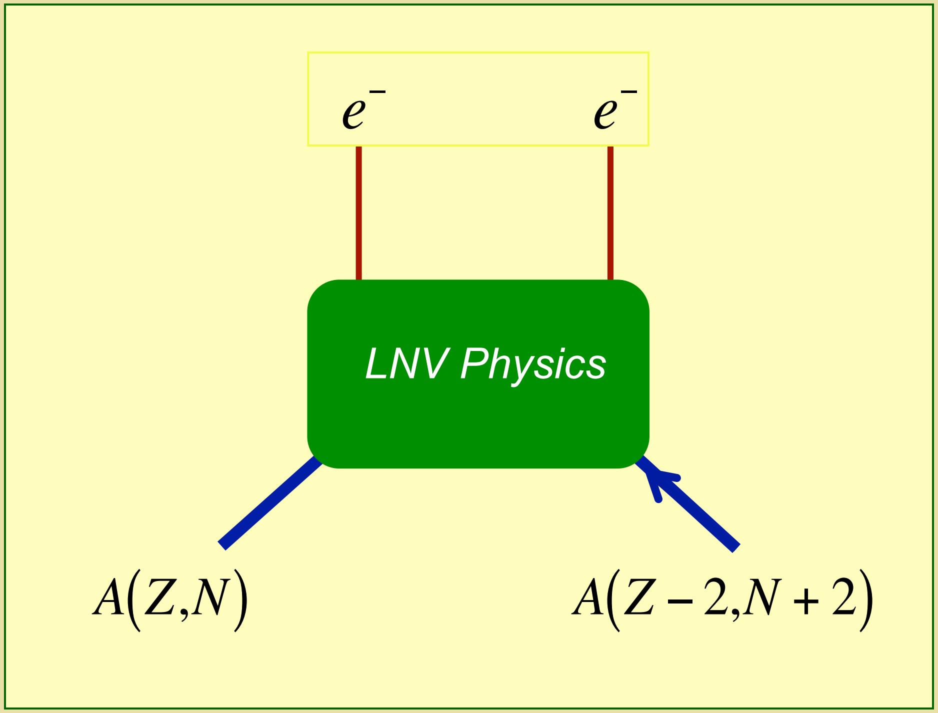
Majorana

Impact of observation

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



$0\nu\beta\beta$-Decay: Mechanisms

$A(Z,N) \rightarrow$ 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"

$0\nu\beta\beta$-Decay: "Standard" Mechanism

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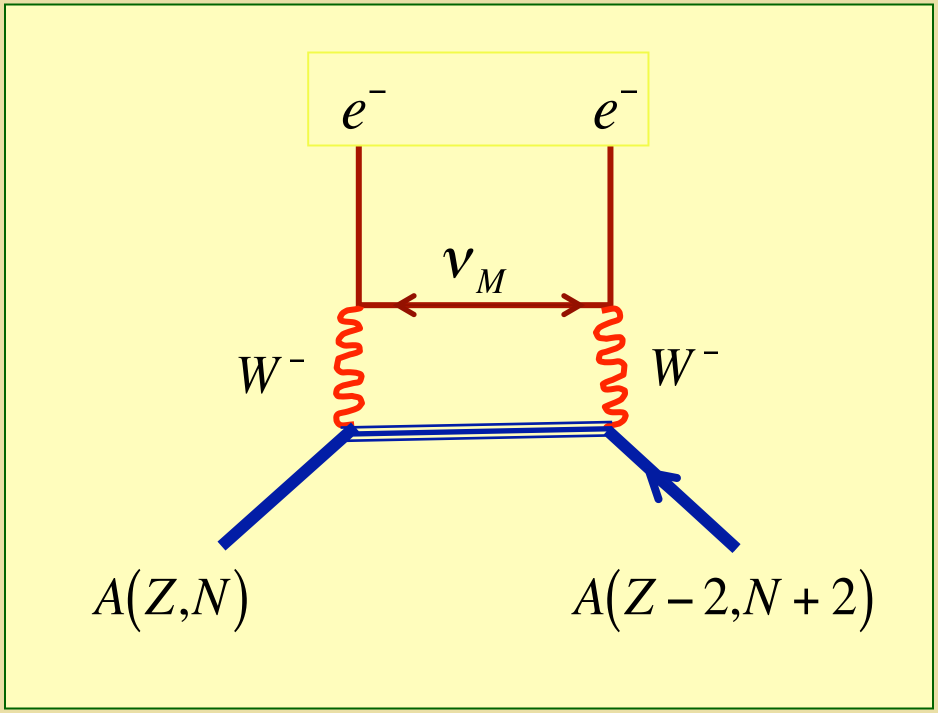
Majorana

"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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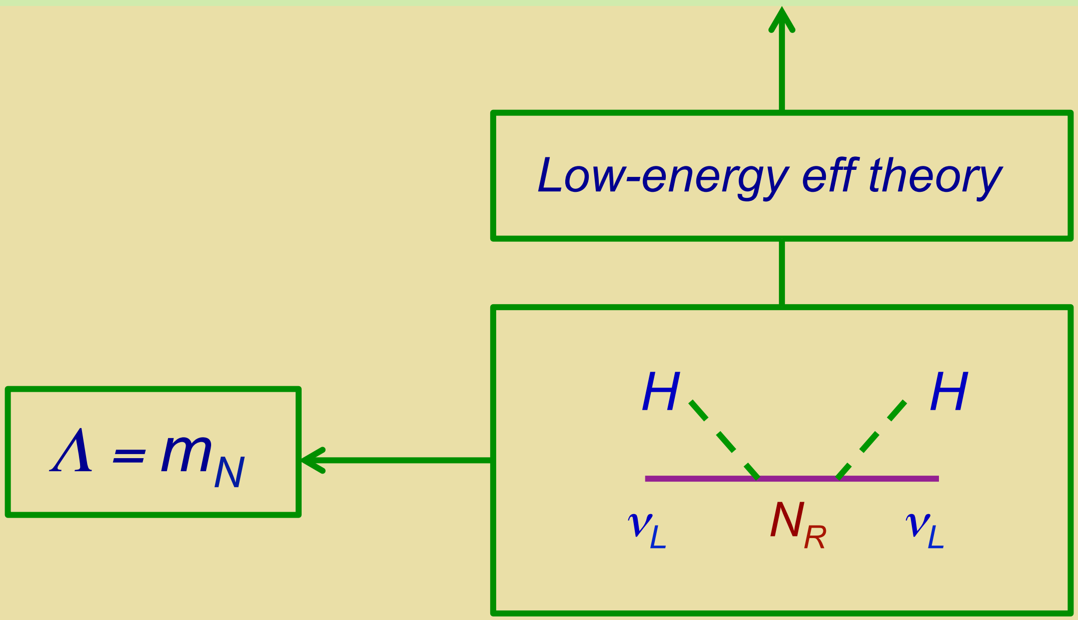

Neutrinos and the Origin of Matter

- *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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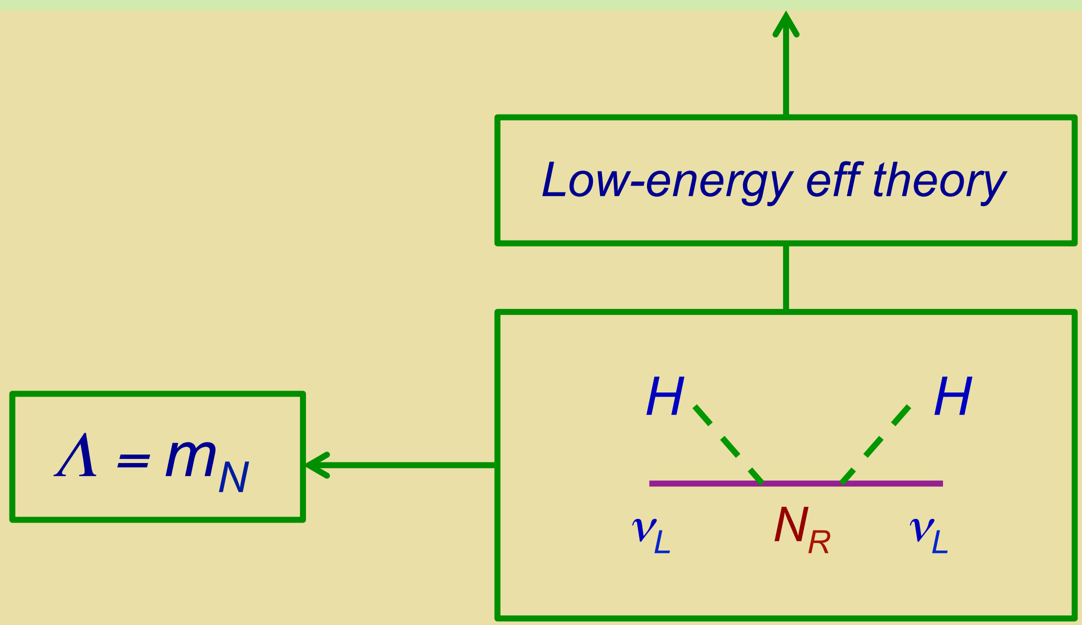

$0\nu\beta\beta$-Decay Sensitivity

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

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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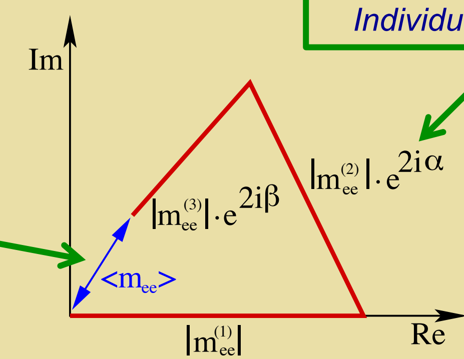
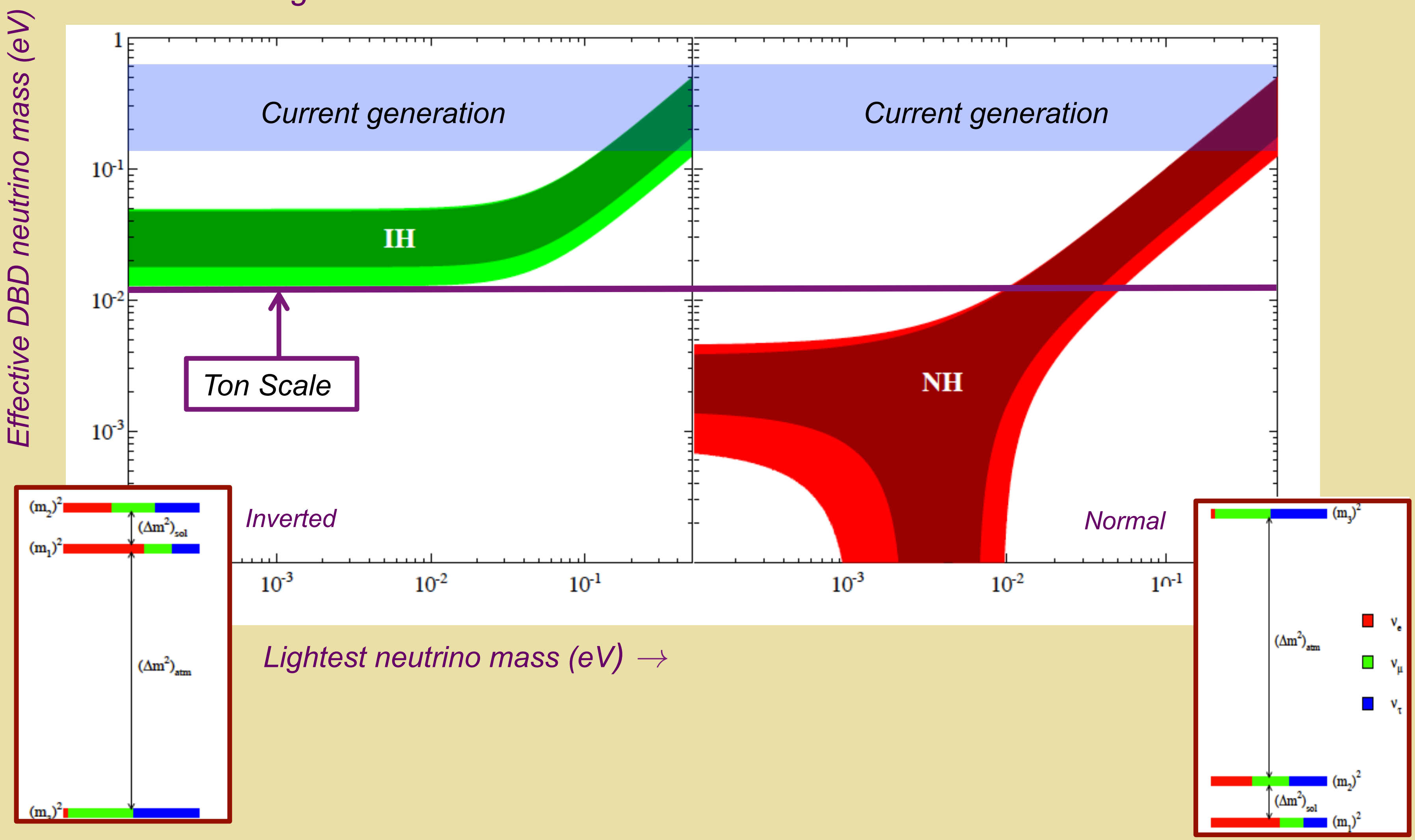
Individual contributions

All three light neutrinos participate $\rightarrow$ Rate governed by an effective mass



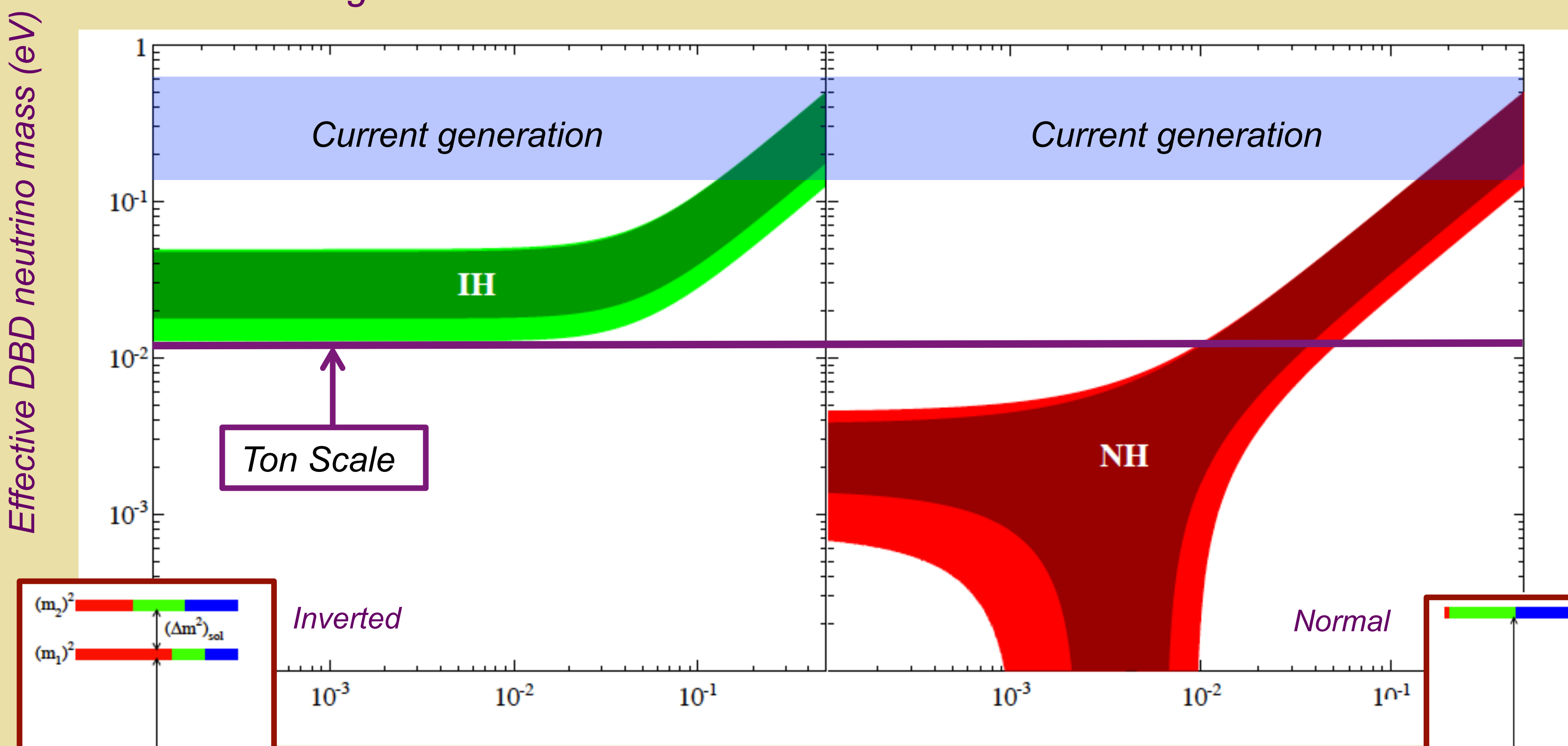
Why Might A "Ton-Scale" Exp't See It?

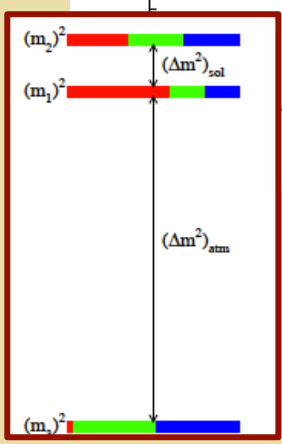
Three active light neutrinos

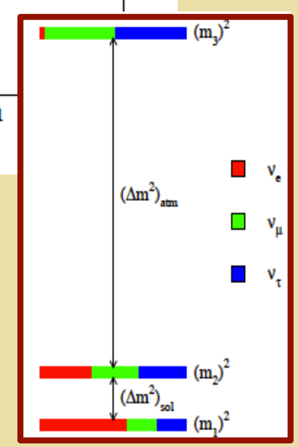


Interpreting the Result

Three active light neutrinos







Full implications require information on lightest mass & hierarchy

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

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

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

Two parameters: Effective coupling & effective heavy particle mass

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Dirac

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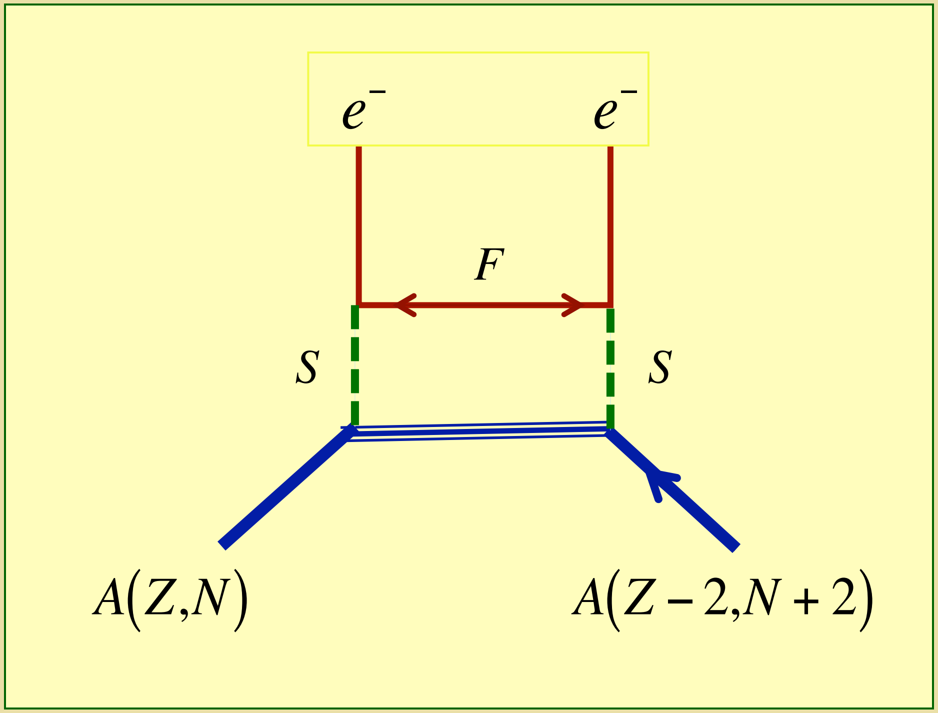
Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but 0νββ-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 ?

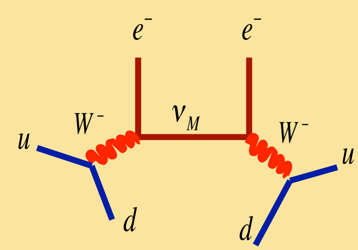
$$\frac{A_{\text{heavy}}}{A_{\text{light}}} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

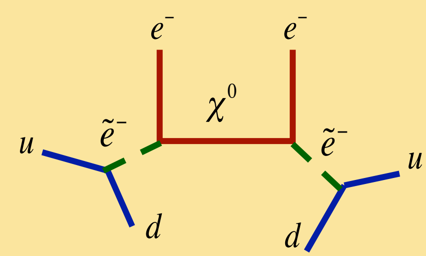
O(1) for Λ ~ TeV

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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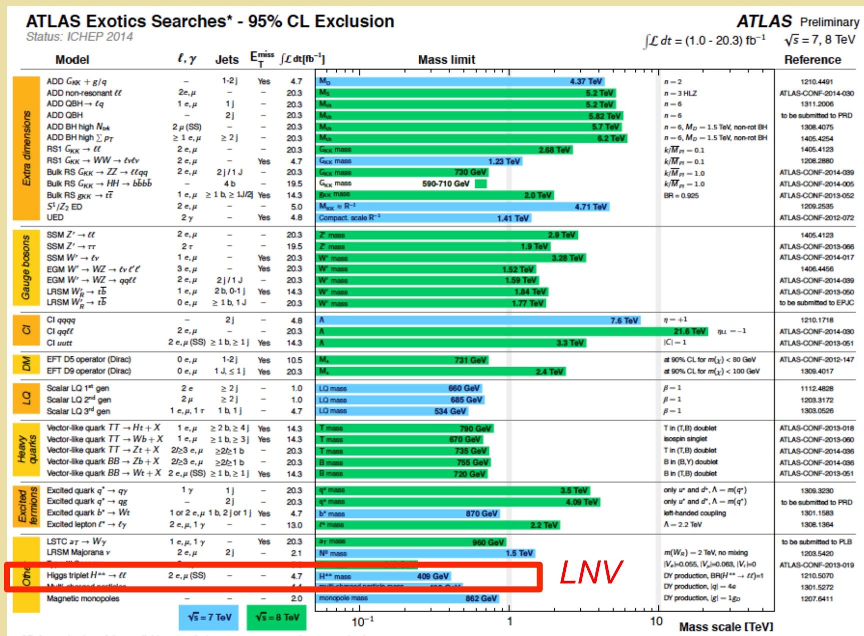
LNV at the LHC



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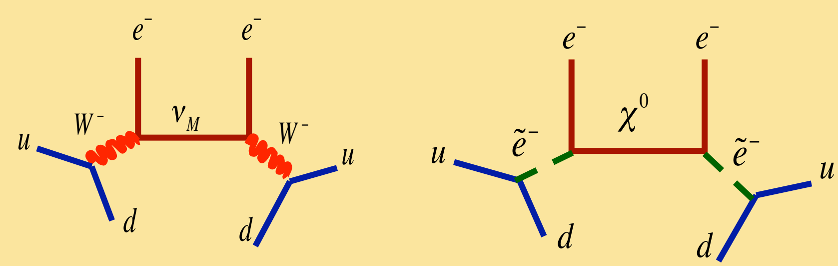

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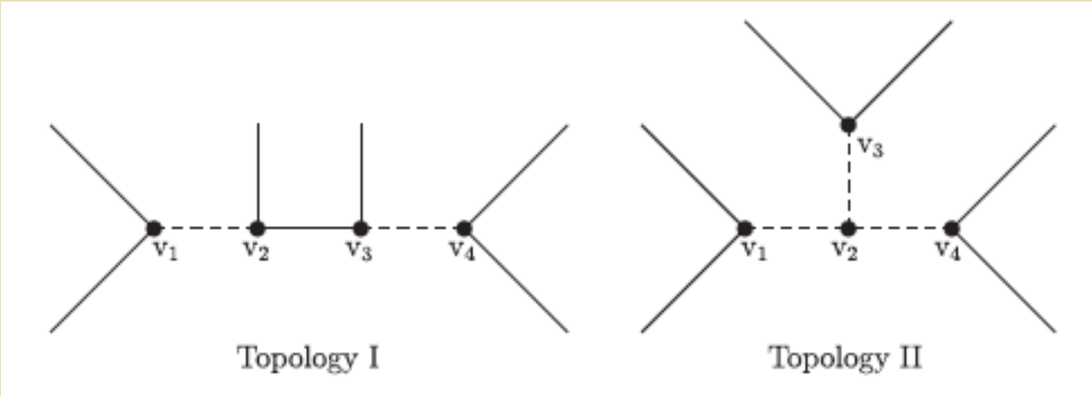
General Classification: Helo et al, PRD 88.011901, 88.073011



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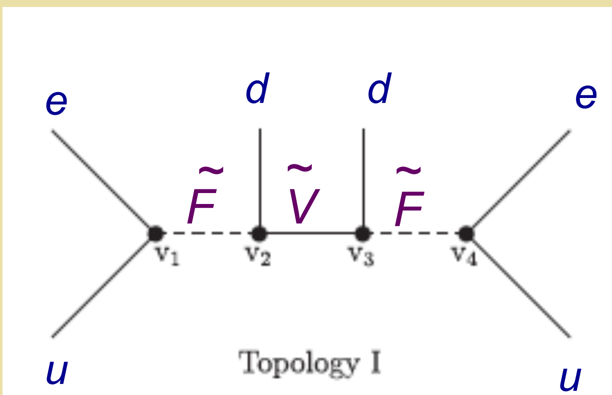

SUSY: R Parity-Violation

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

Gaugino $\tilde{g}$, χ *Majorana*

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

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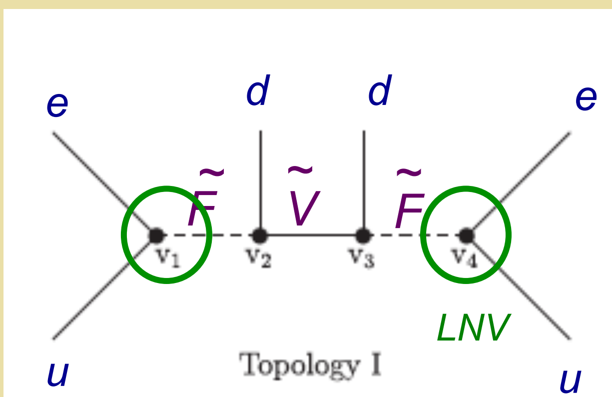

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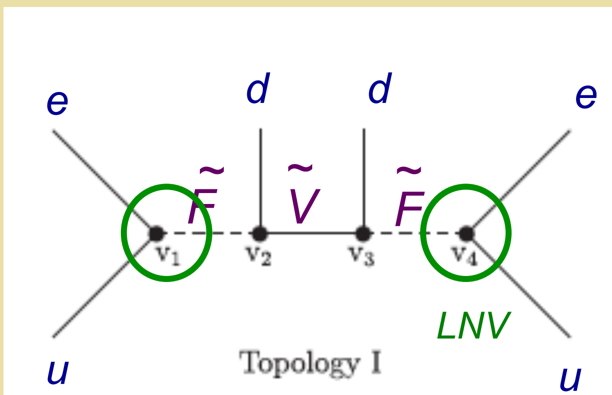

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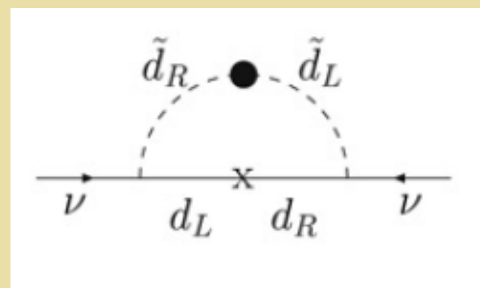

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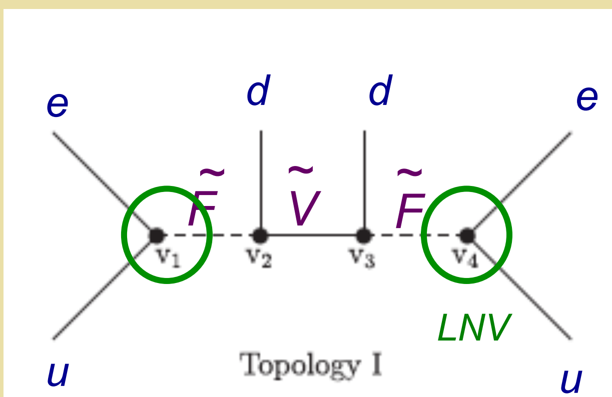

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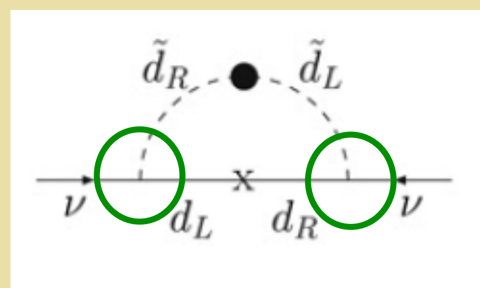

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$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \mathrm{h.c.}$$

Majorana

Other Models: Back Up Slides

$0\nu\beta\beta$-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

What can we learn from the LHC?

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

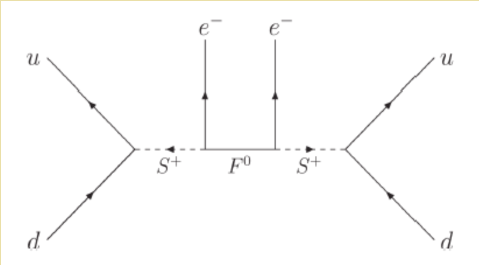
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

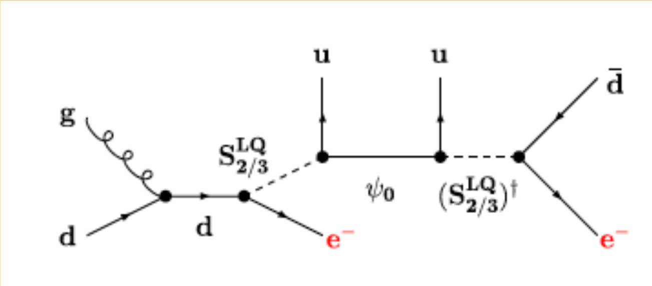
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

LHC Production



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



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

0νββ-Decay: TeV Scale LNV

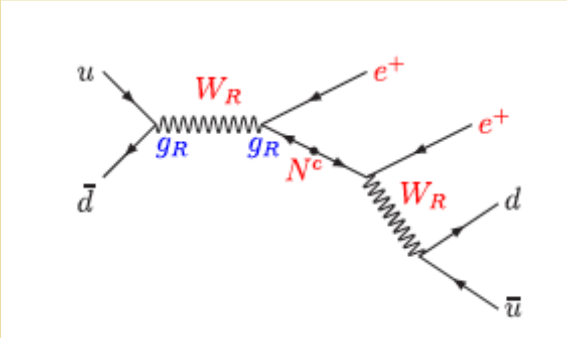
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

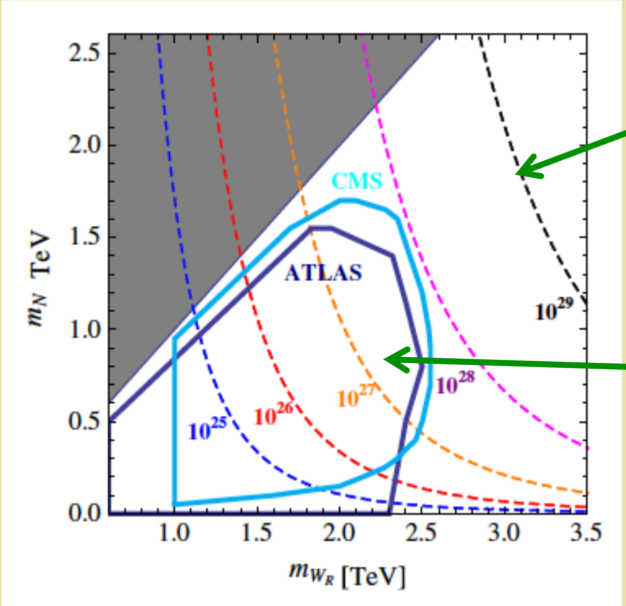
Dirac

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

Majorana

LHC Production & 0νββ-Decay





Helo et al, PRD 88.011901, 88.073011

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

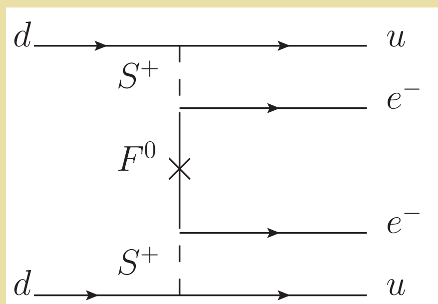
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; {\rm h.c.}$$

Dirac

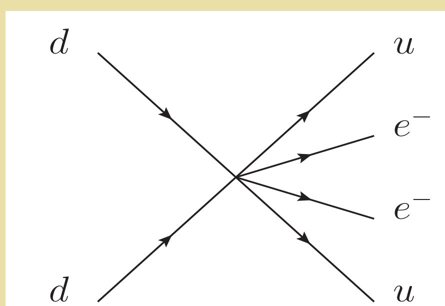
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; {\rm h.c.}$$

Majorana

LHC: pp $\to$ 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

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

0νββ-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

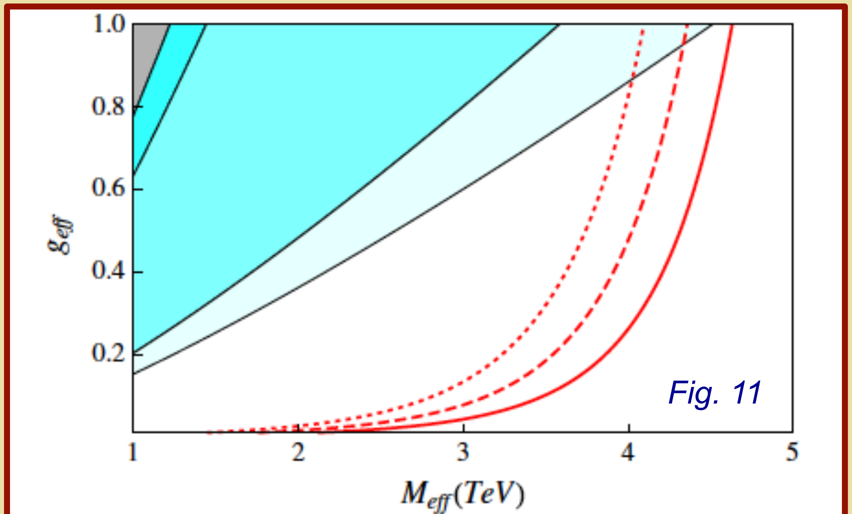
Helo et al claim:

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

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

$C_j = g_j$

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



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

0νββ-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

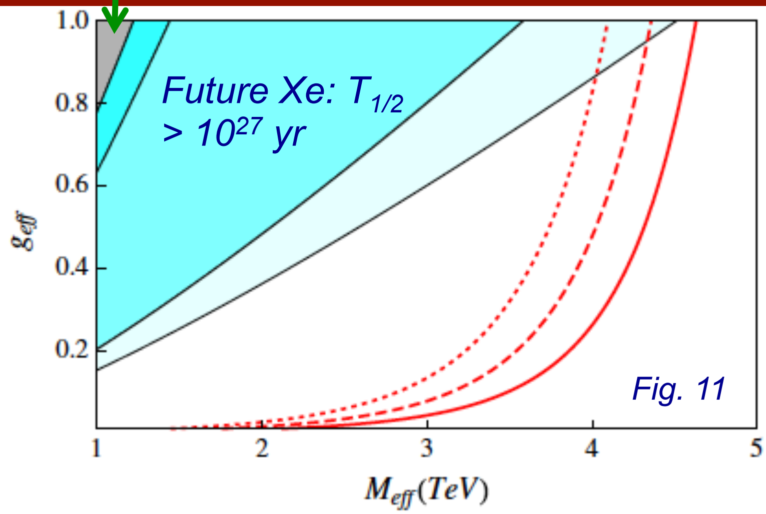
Helo et al claim:

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

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

EXO exclusion

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



$C_j = g_j$

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

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

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

Dirac

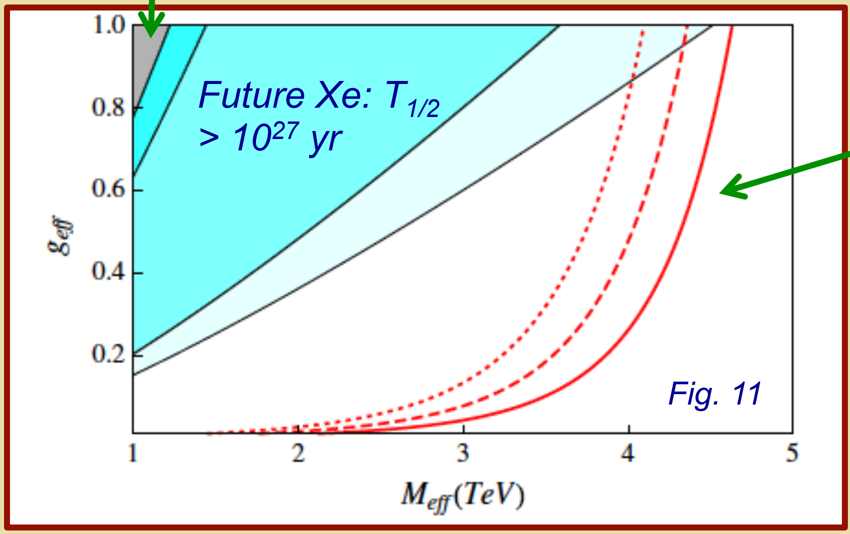
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Helo et al claim:

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

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

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

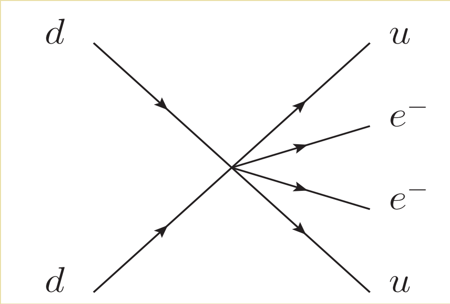
Dirac

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

Majorana

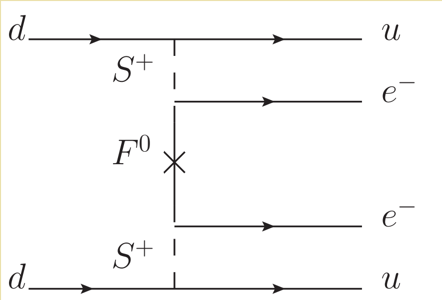
TeV Scale LNV

$0\nu\beta\beta$ - decay



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

LHC: pp $\rightarrow$ jj e⁻e⁻



Simplified models

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

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

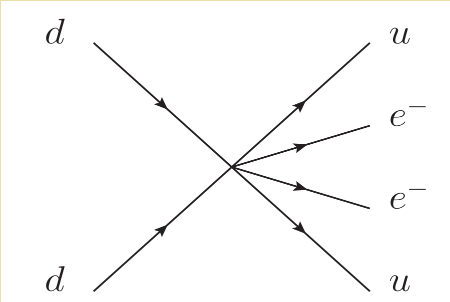
Dirac

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

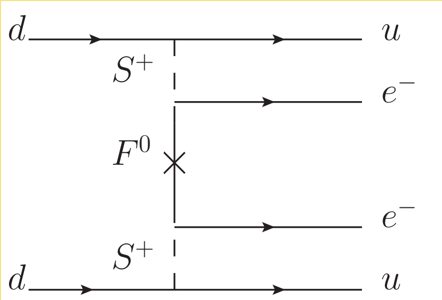
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



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



Effective operators:

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

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

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

0νββ-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

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

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*

$0\nu\beta\beta$-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*
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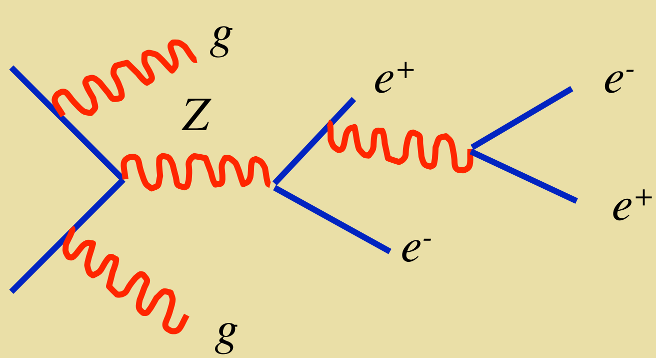


e^+ transfers most of p_T to conversion e^- ;
Z / γ^* + jets $\rightarrow$ apparent e^- e^- jj event

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

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

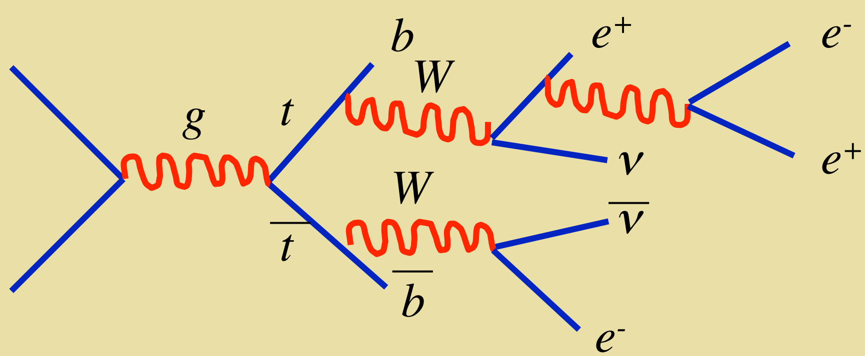
Dirac

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

Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*



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

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

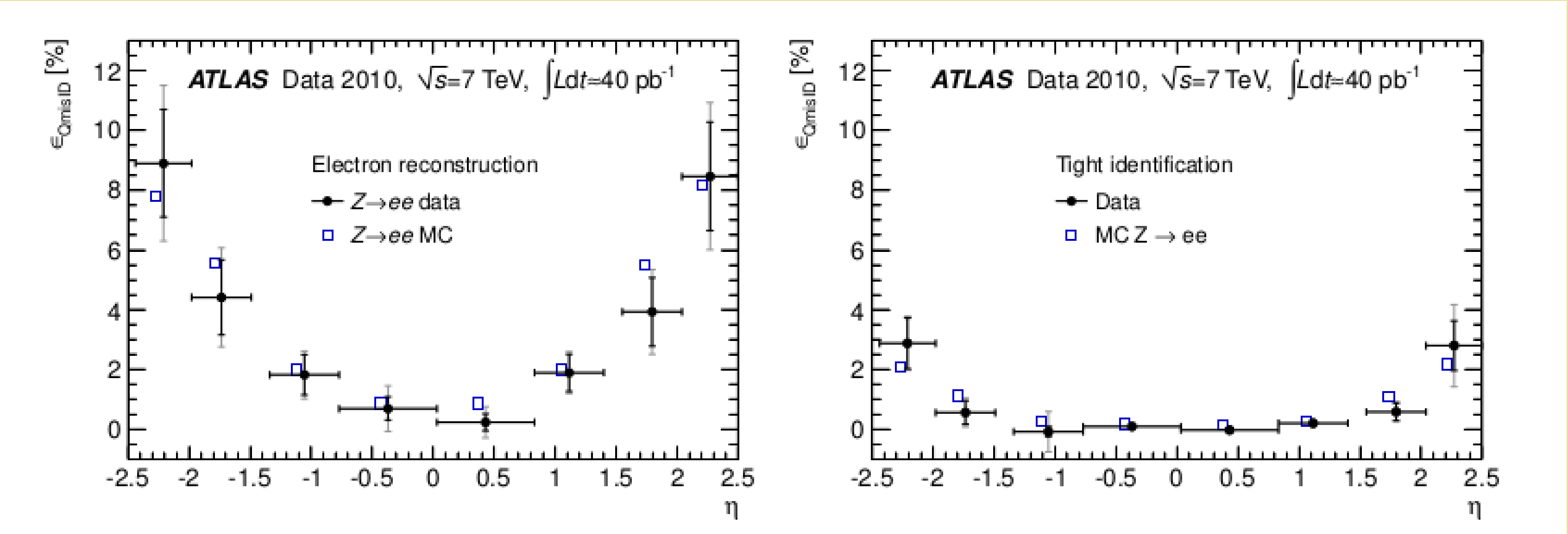
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

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

Majorana

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



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

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

Dirac

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

Majorana

Backgrounds: *Jet fakes*

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

$0\nu\beta\beta$-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*

- 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

0νββ-Decay: TeV Scale LNV

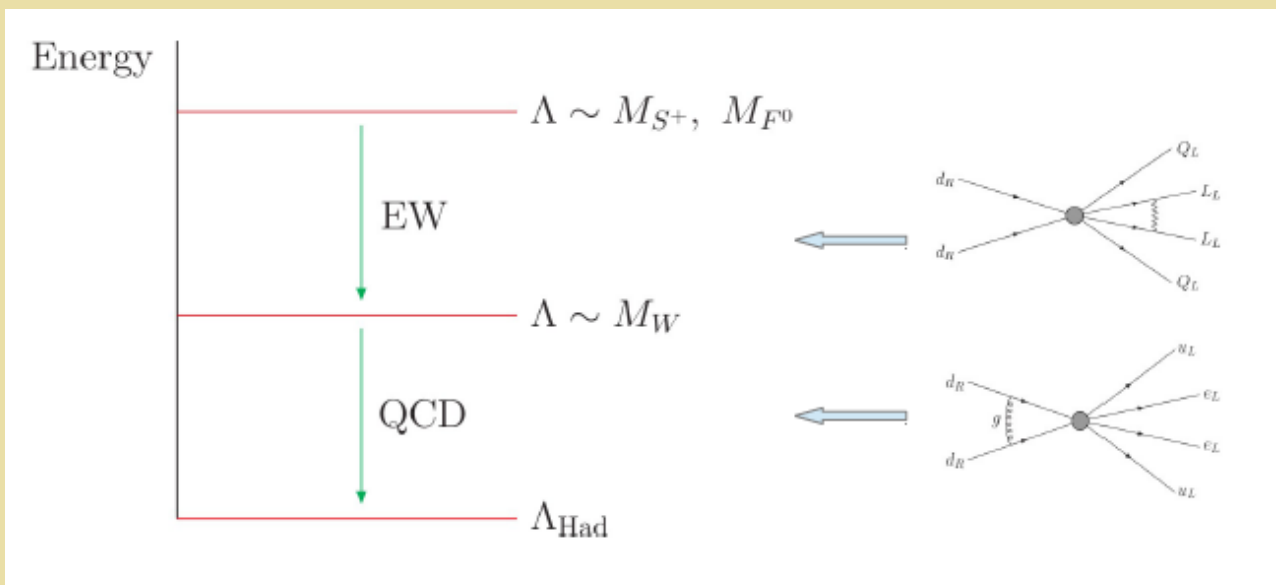
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

Low energy: *Running*



0νββ-Decay: TeV Scale LNV

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

Dirac

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

Majorana

Low energy: *QCD Running*

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

0νββ-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*

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

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

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

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

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

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

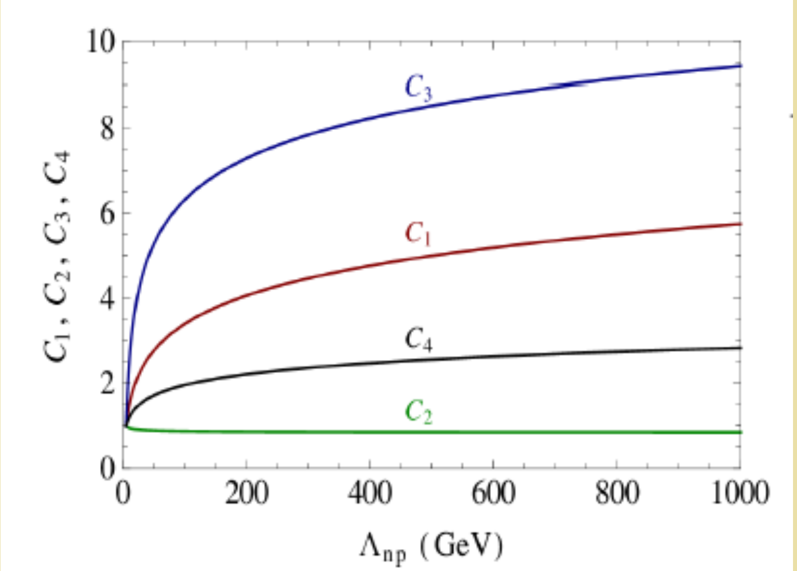
Dirac

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

Majorana

Low energy: *QCD Running*

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



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

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

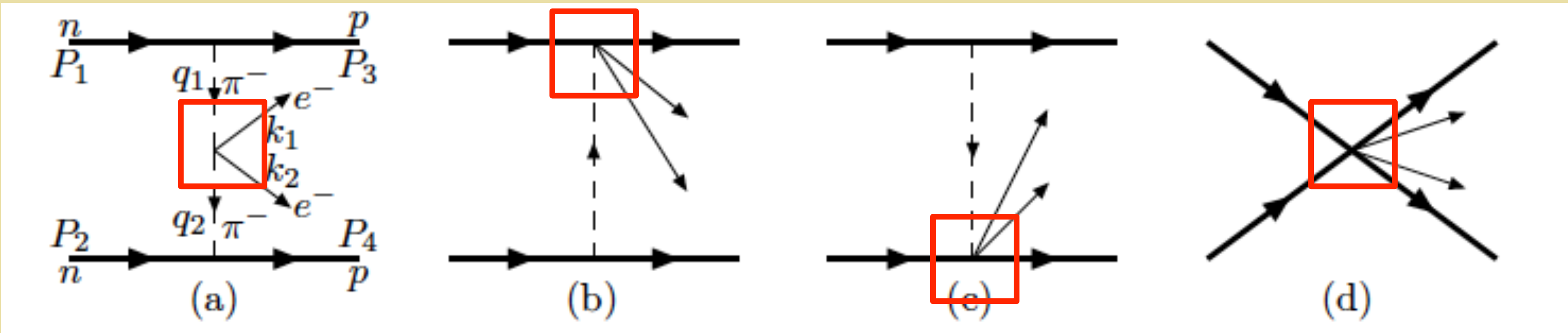
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

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



Exploit Chiral Symmetry & EFT ideas

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

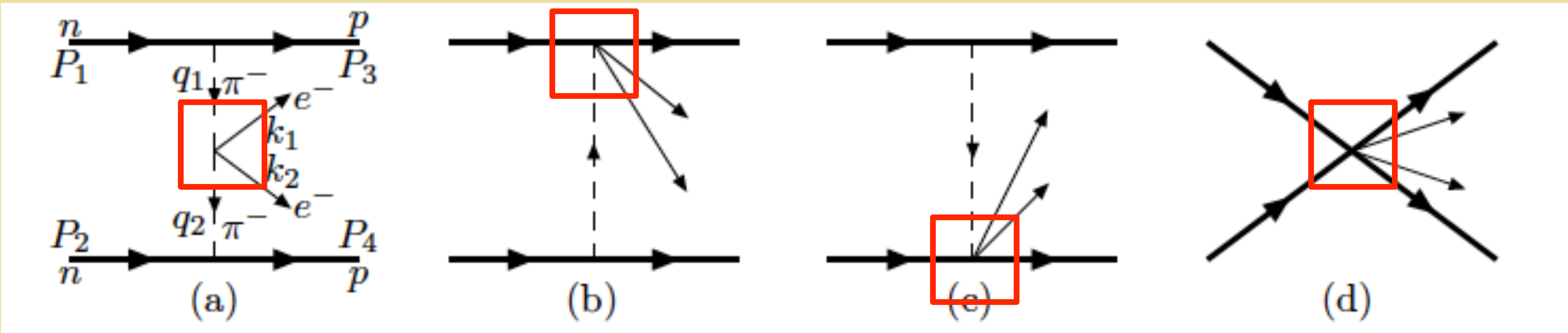
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

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



Our work

Helo et al

Exploit Chiral Symmetry & EFT ideas

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

Putting the pieces together

0νββ-Decay: TeV Scale LNV

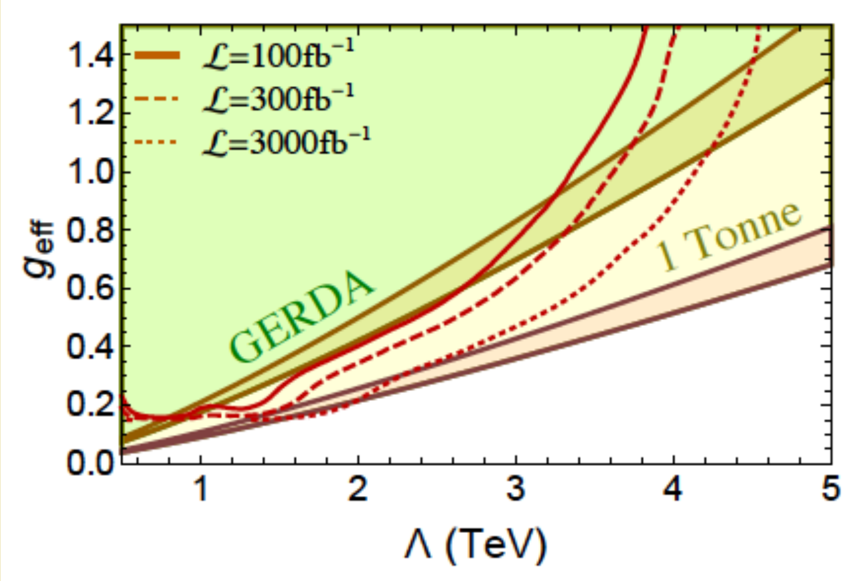
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444

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

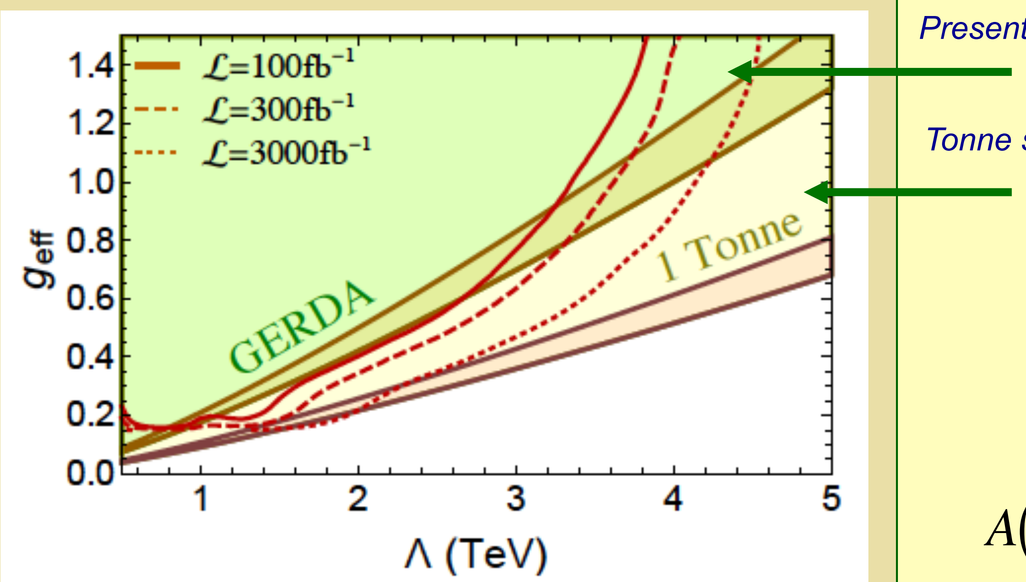
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

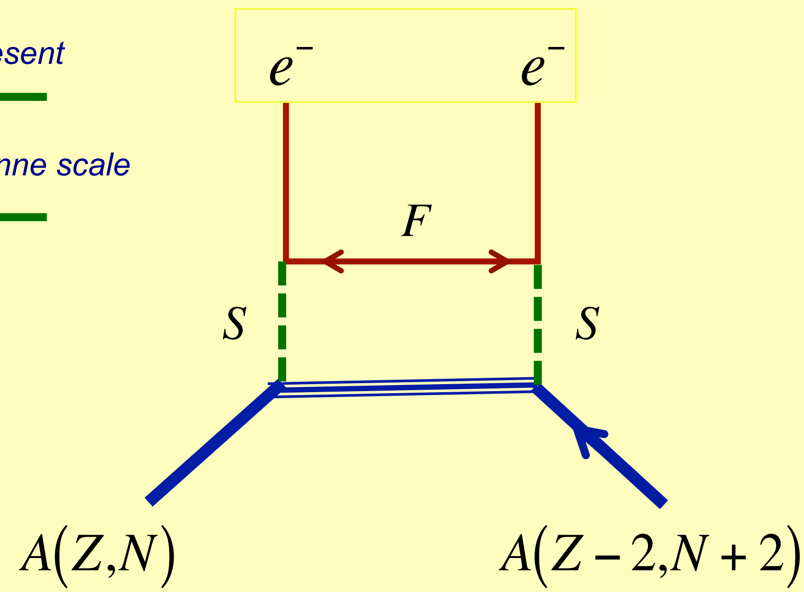
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

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

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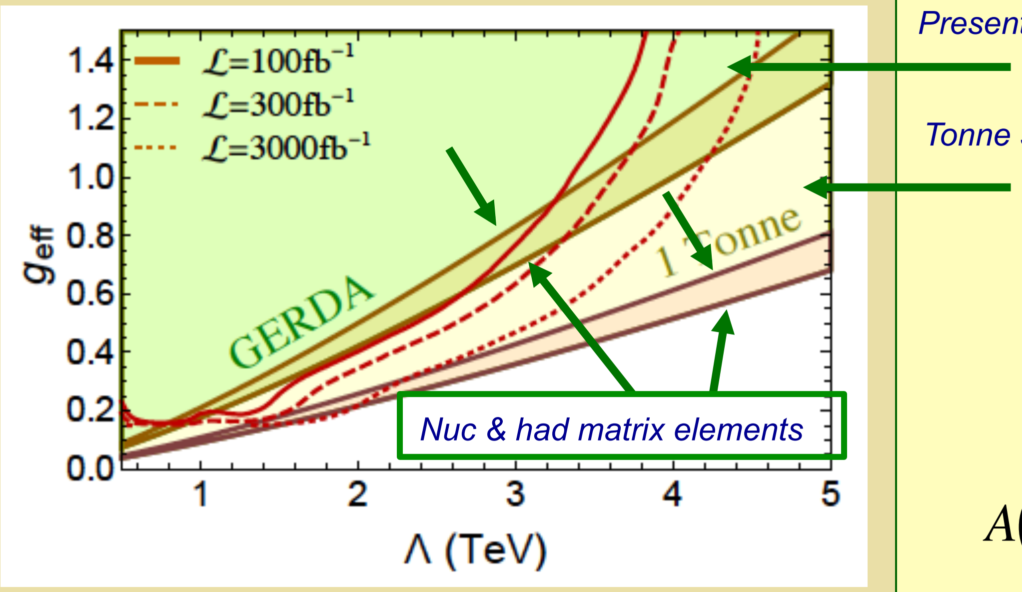
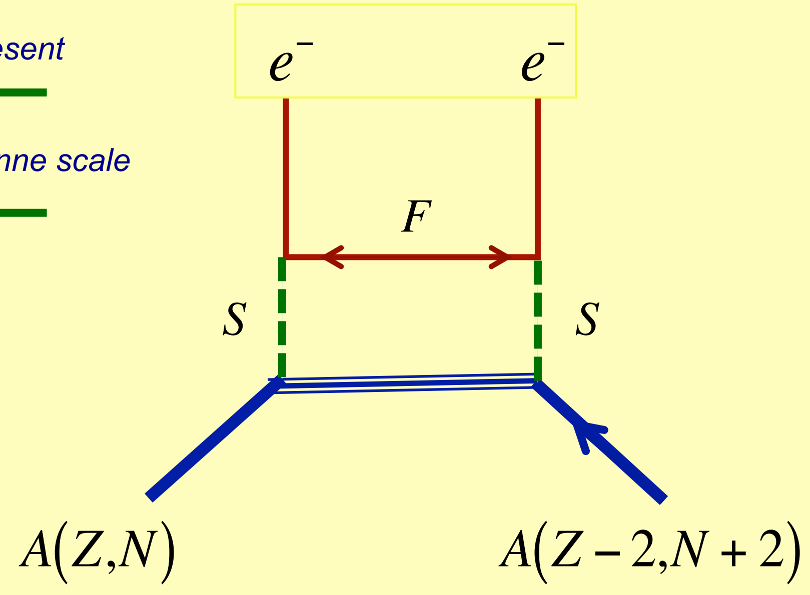
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

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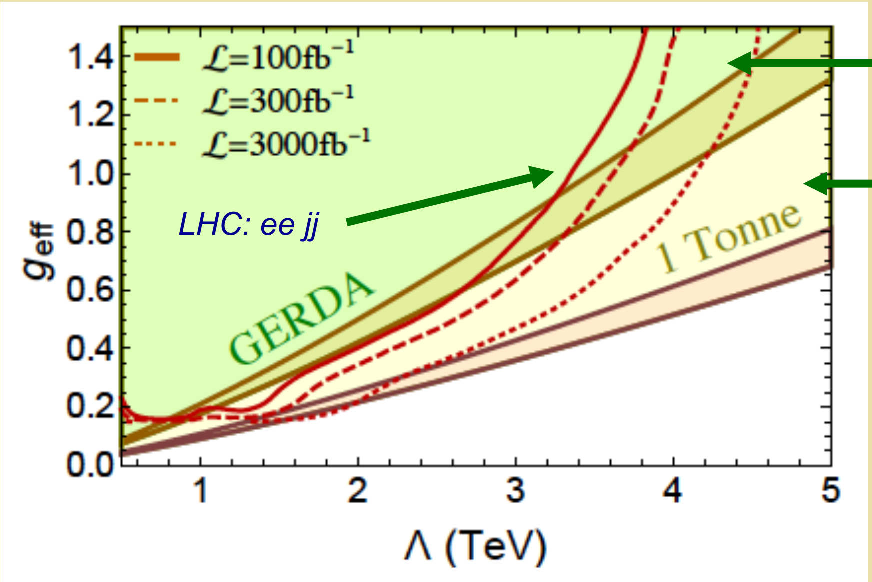
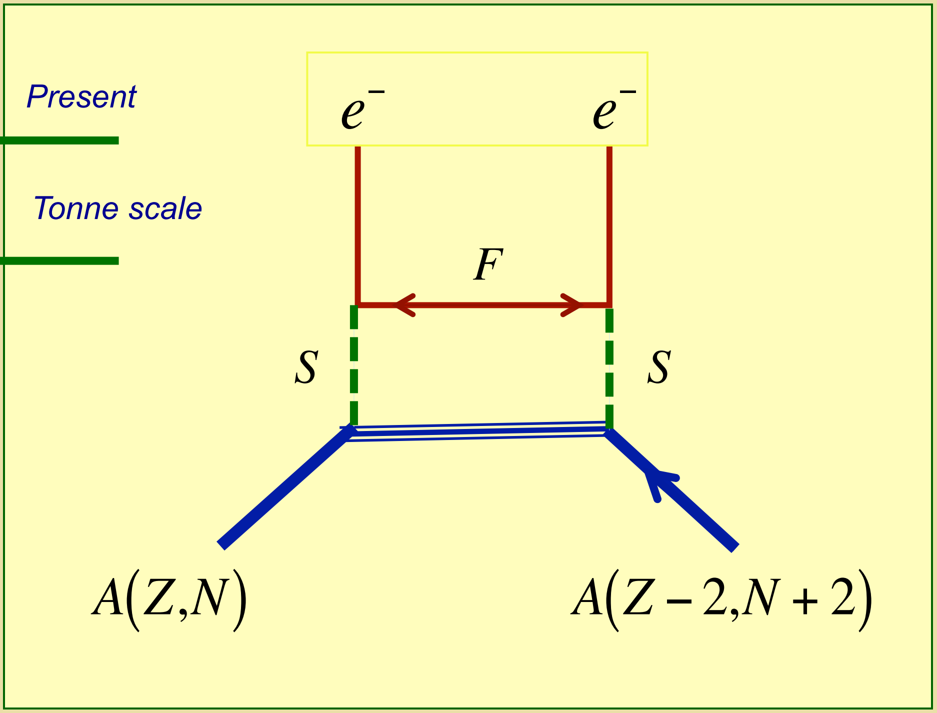
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

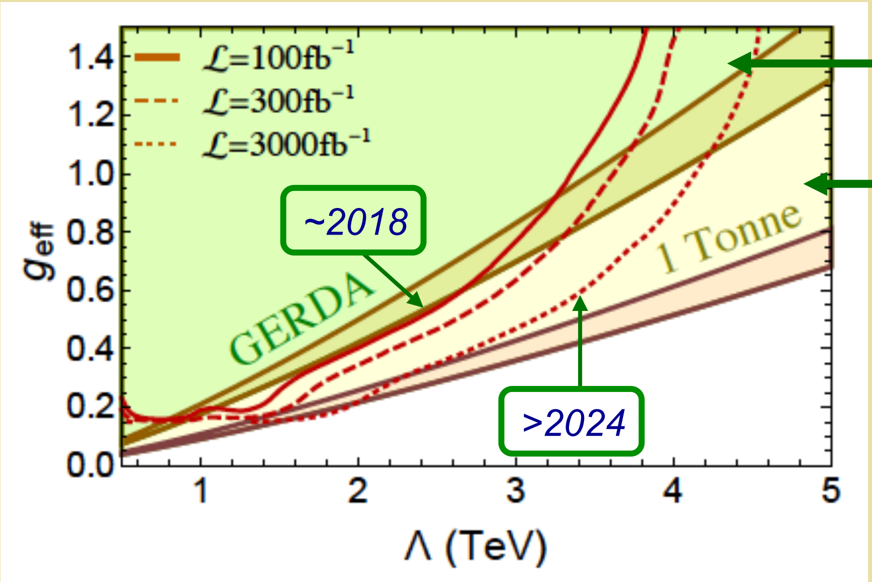
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV



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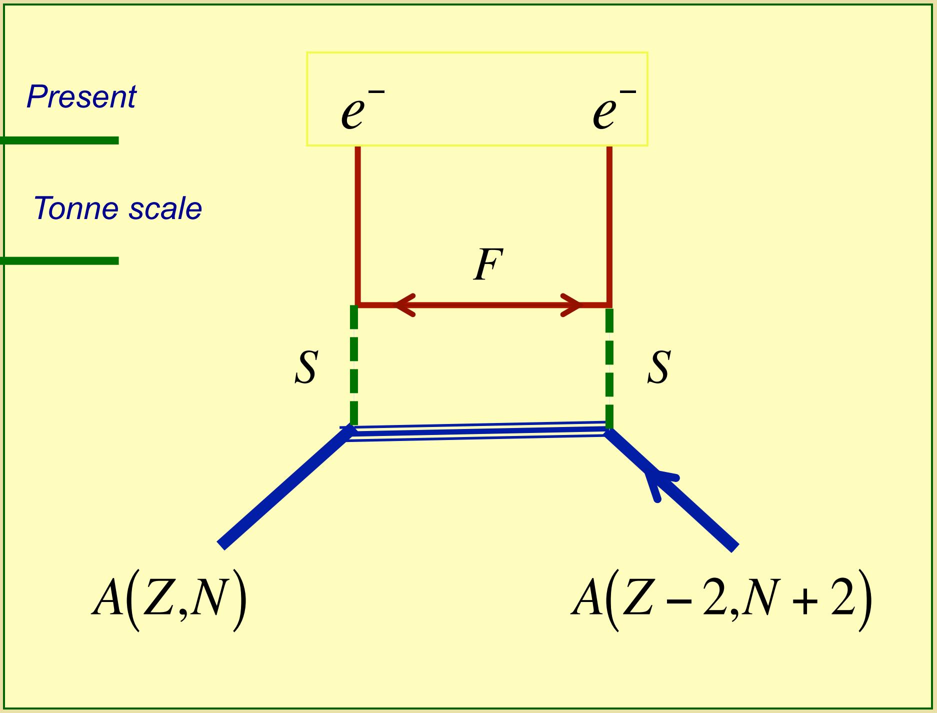

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

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Dirac

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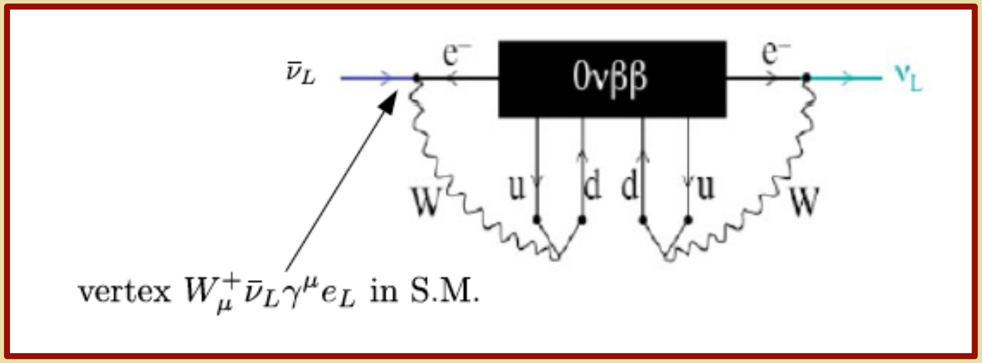
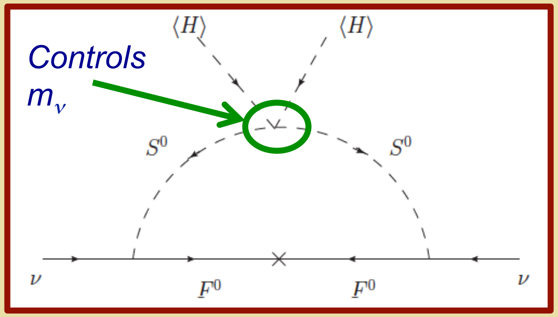
Majorana

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

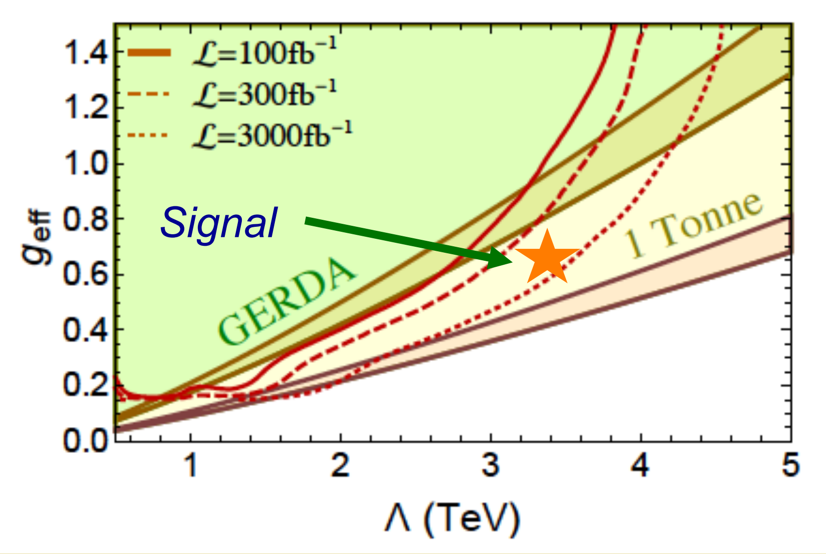
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

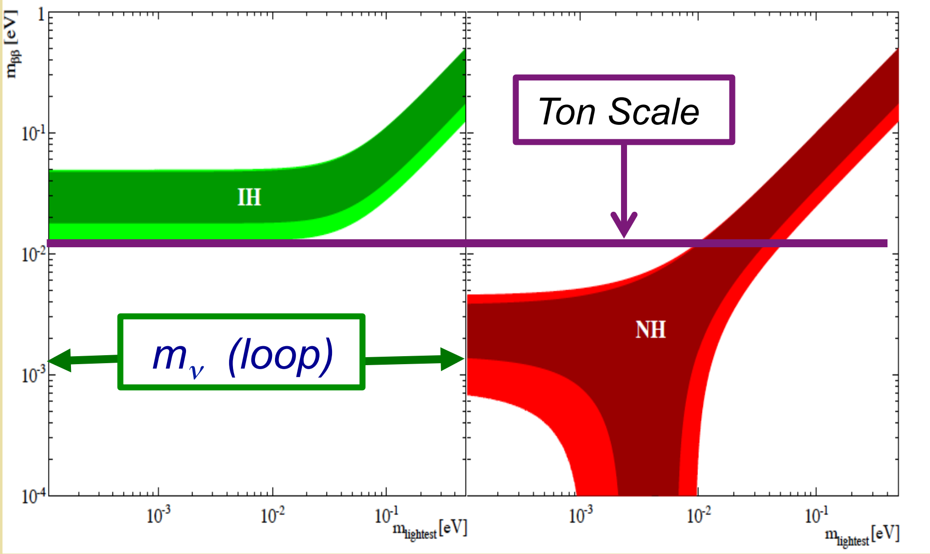
Dirac

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

Majorana

Implications for m_ν:





A hypothetical scenario

0νββ / LHC Interplay: Matrix Elements

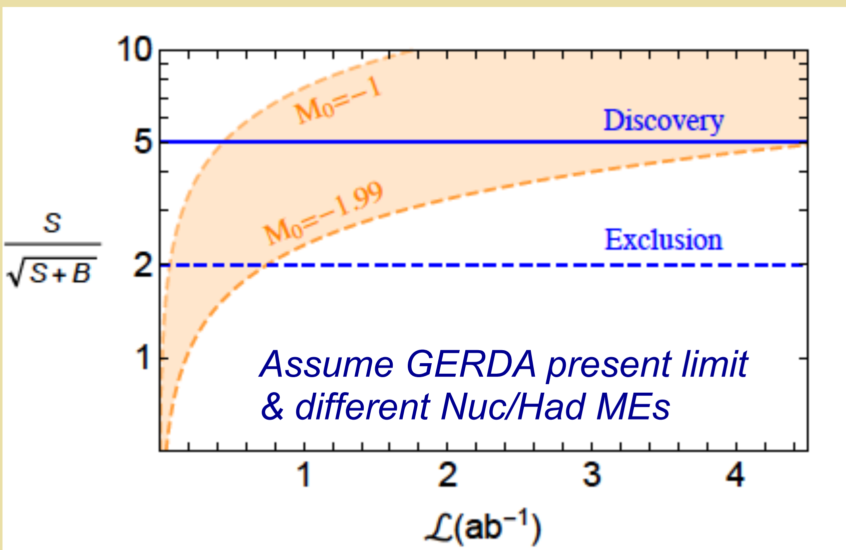
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

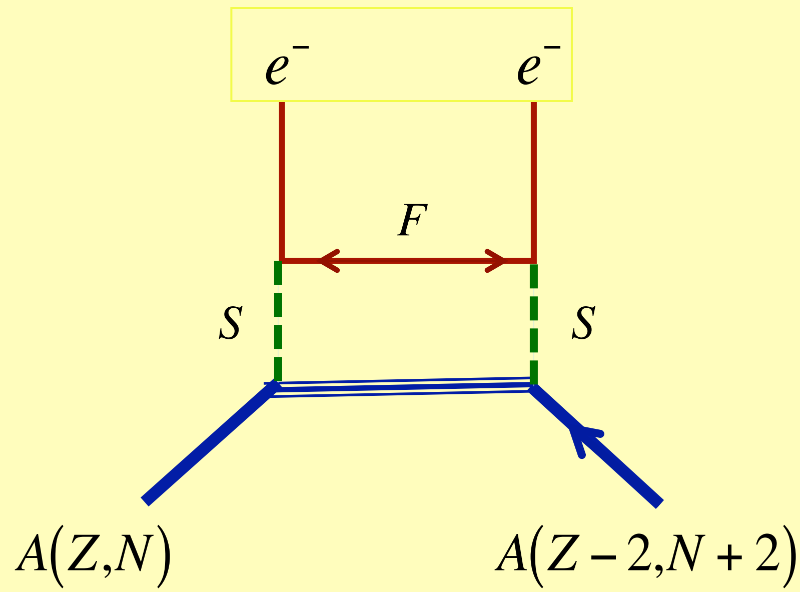
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

V. EDMs & the LHC: Higgs Portal CPV

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \ x\ \ \theta_{QCD} + d_n^{CKM}$$

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ x\ \ \theta_{QCD} + d_n^{CKM}$$

$$d_n^{CKM} = (1 - 6)\ x\ 10^{-32}\ e\ cm$$

C. Seng arXiv: 1411.1476

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \ \sin\phi\ \ x\ y_f\ F$$

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \boxed{\sin\phi}\ x\ y_f\ F$$

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \boxed{(\upsilon\,/\,\Lambda)^2}\ x\ \ \sin\phi\ \ x\ y_f\, F$$

BSM mass scale: TeV ? Much higher ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f F$$

BSM dynamics: perturbative? Strongly coupled?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f F$$

BSM dynamics: perturbative? Strongly coupled?

Hadronic & atomic systems: reliable SM calc's?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \boxed{(\upsilon / \Lambda)^2}\ x\ \boxed{\sin\phi}\ x\ \boxed{y_f F}$$

Need information from at least three "frontiers"

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm) \times \boxed{(\upsilon / \Lambda)^2} \times \boxed{\sin\phi} \times \boxed{y_f F}$$

Need information from at least three "frontiers"

- *Baryon asymmetry* — *Cosmic Frontier*
- *High energy collisions* — *Energy Frontier*
- *EDMs* — *Intensity Frontier*

EDM/LHC Complementarity

The Higgs Portal

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

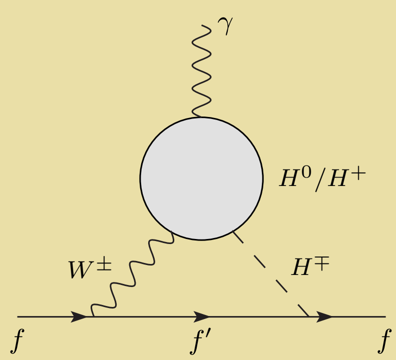
$\lambda_{6,7}$ *= 0 for simplicity*

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right],$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]$$

EWSB →

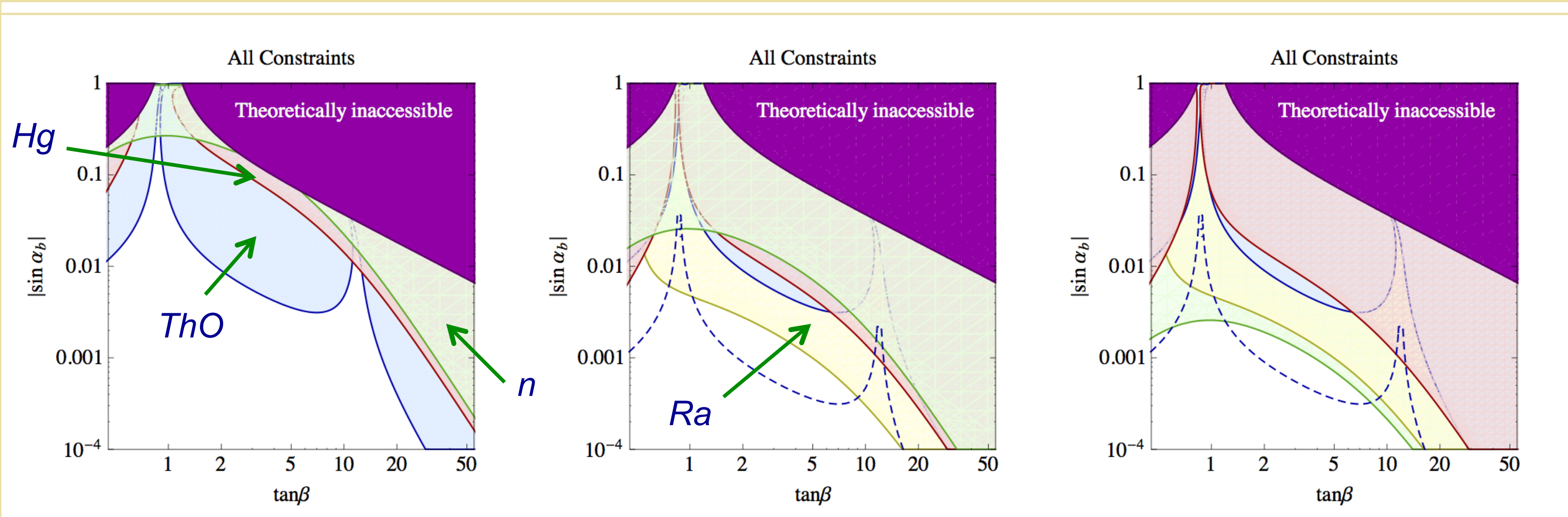
$$\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1$$



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present

Future:

- d_n x 0.1
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra) [10^{-27} e cm]

Future:

- d_n x 0.01
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra)

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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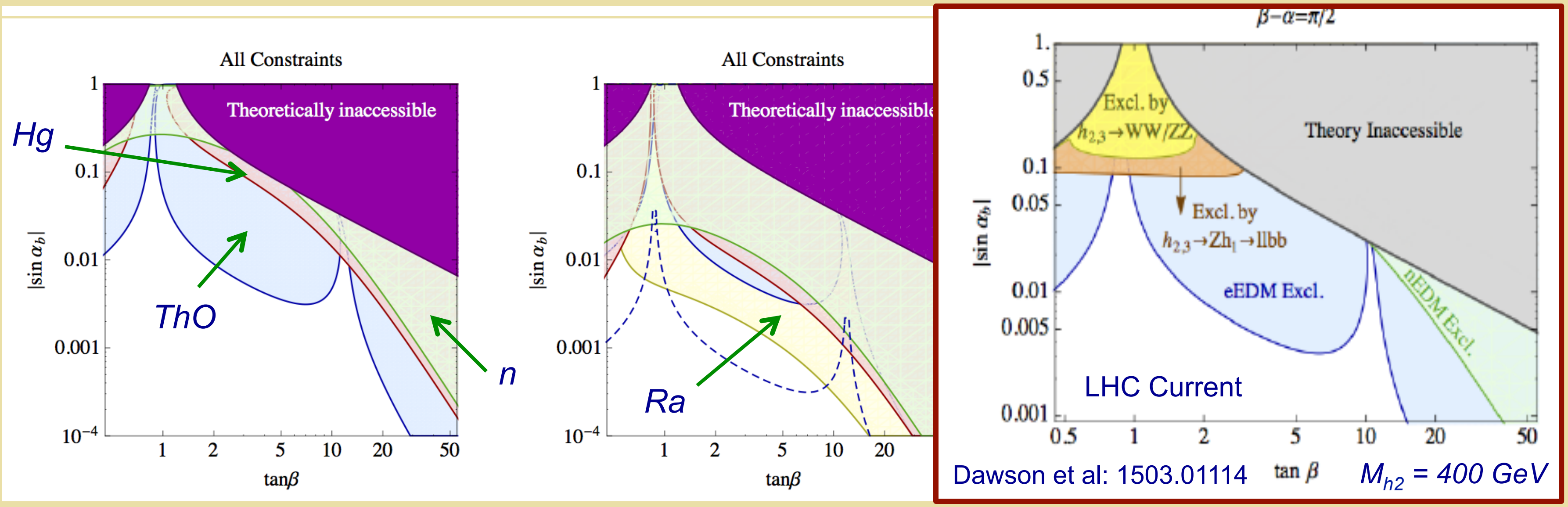

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Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

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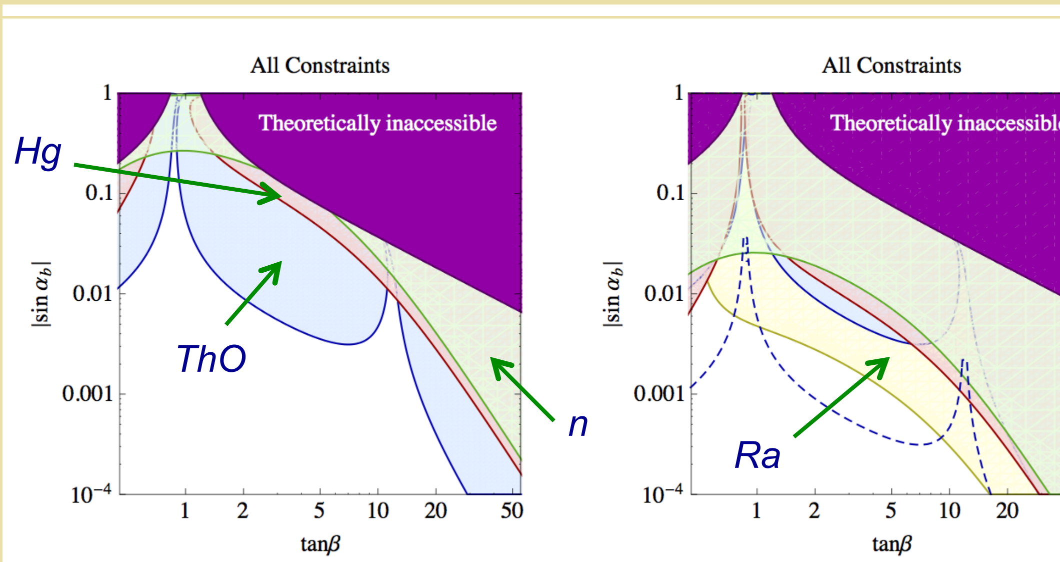

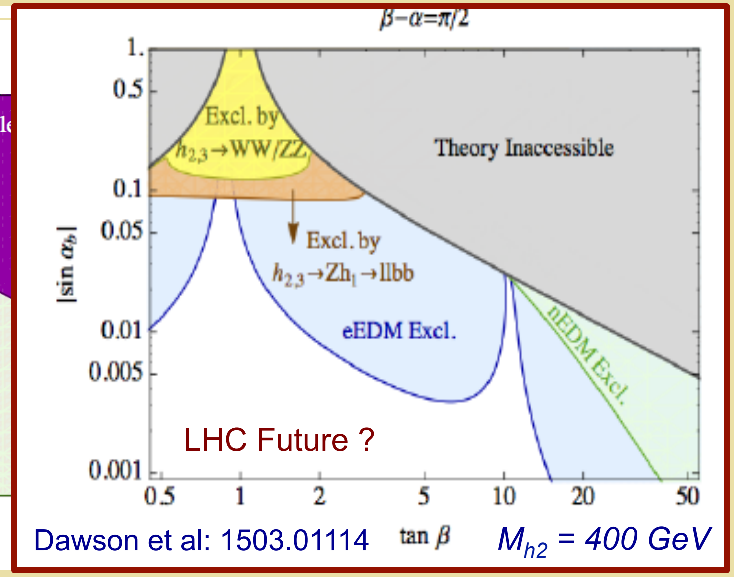

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Higgs Portal CPV: EDMs & LHC

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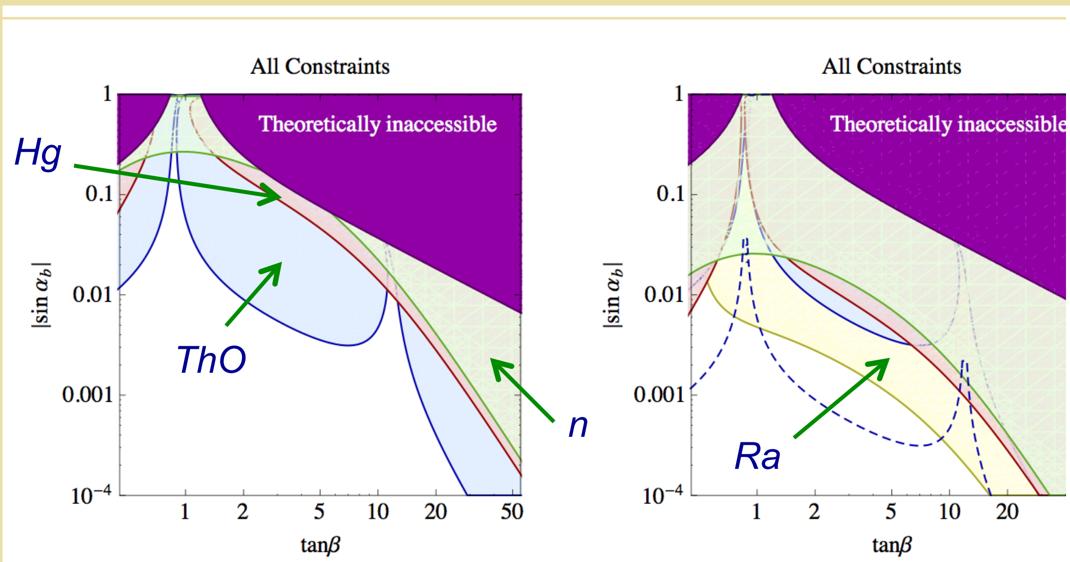

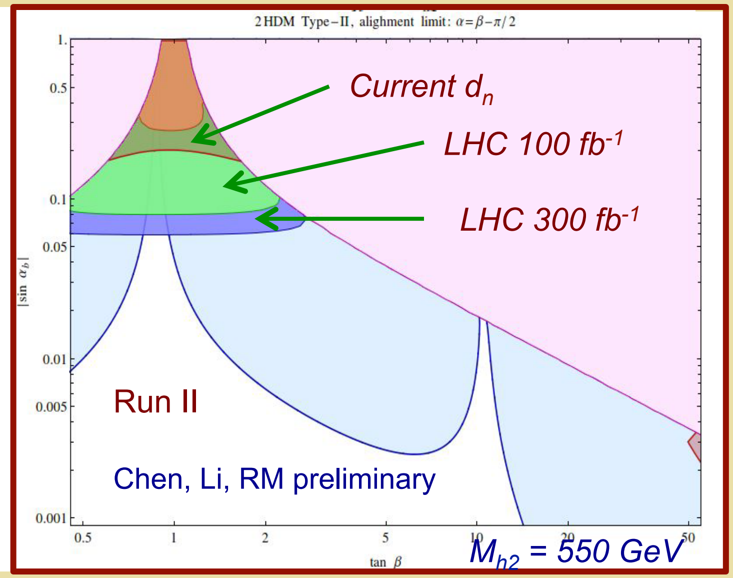

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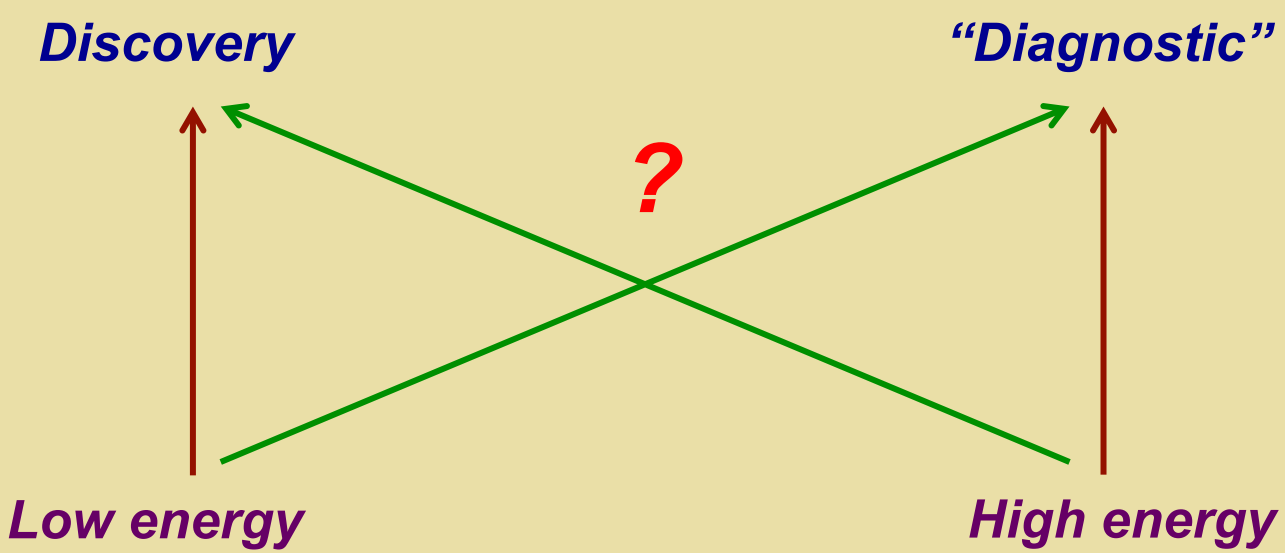
Inoue, R-M, Zhang: 1403.4257

Low-Energy / High-Energy Interplay

Higgs Portal CPV



Hadronic & Nuclear Matrix Elements

Hadronic Matrix Elements

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09 - 0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2 - 1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2 - 0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8 - 2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Engel, R-M, van Kolck '13

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	ρ_n^d	1.4	0.7–2.1
δ_q (EDM)	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$
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Update: Battacharya et al 2015

Engel, R-M, van Kolck '13

Nuclear Matrix Elements

$$S = a_0\, g\, \bar{g}_\pi^{(0)} + a_1\, g\, \bar{g}_\pi^{(1)} + a_2\, g\, \bar{g}_\pi^{(2)}$$

Nucl.	Best value		
	a_0	a_1	a_2
^{199}Hg	0.01	$\pm$ 0.02	0.02
^{129}Xe	−0.008	−0.006	−0.009
^{225}Ra	−1.5	6.0	−4.0

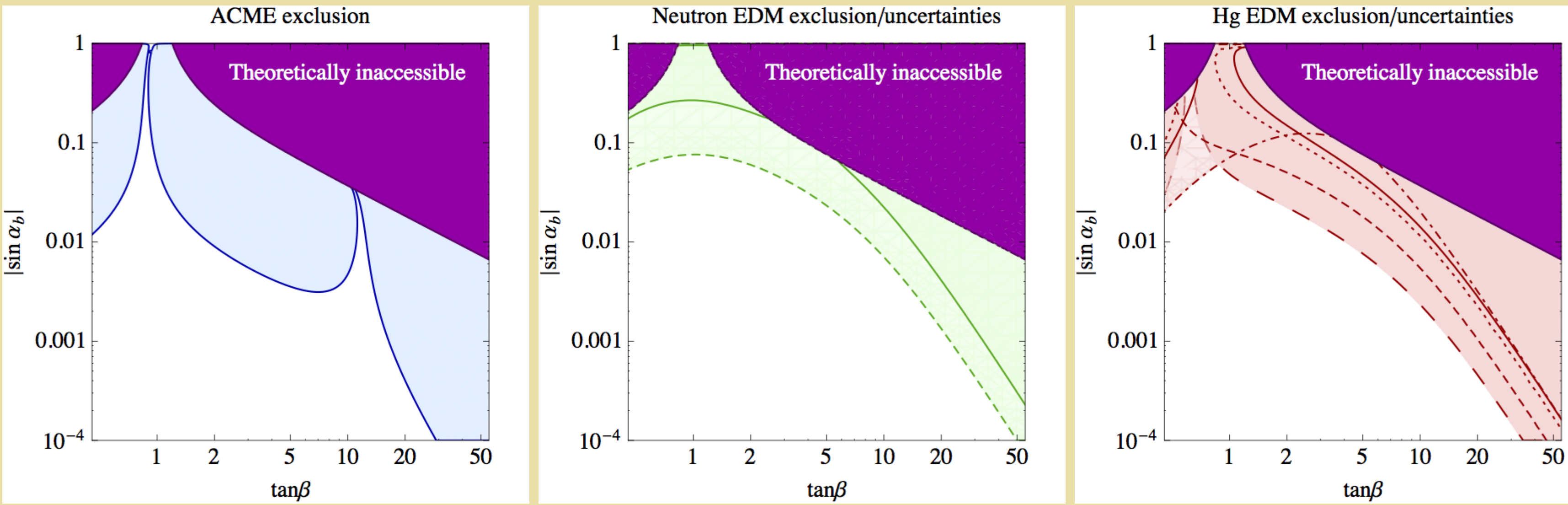
Range		
a_0	a_1	a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

Engel, R-M, van Kolck ‘13

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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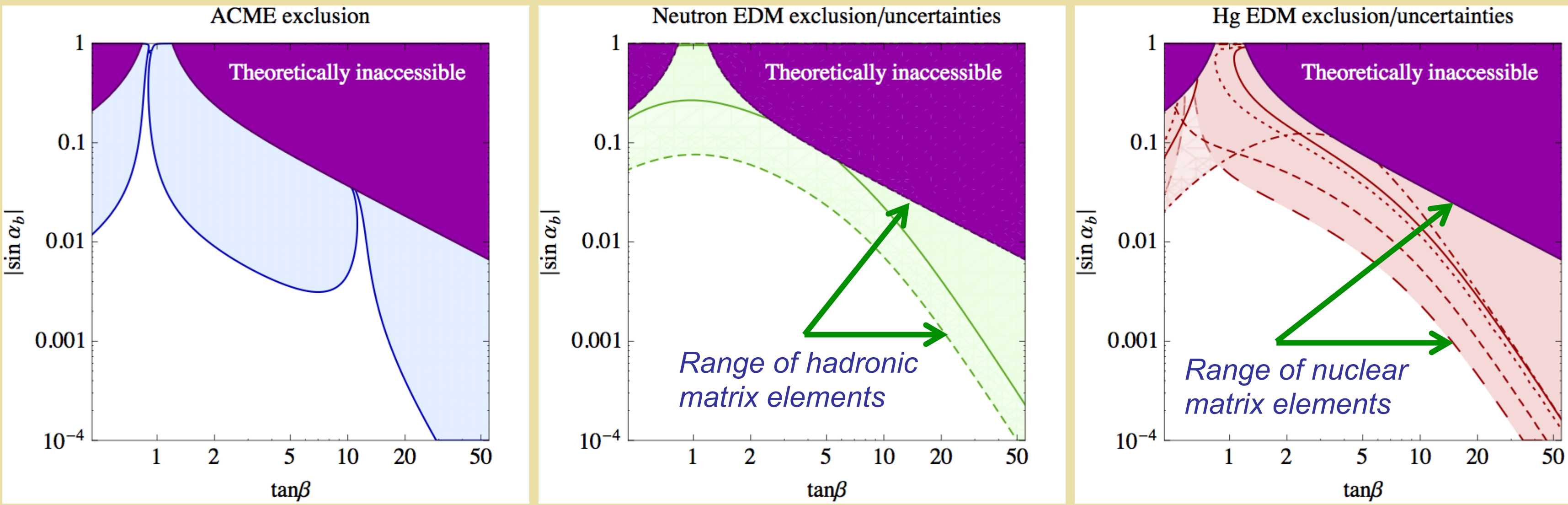

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Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

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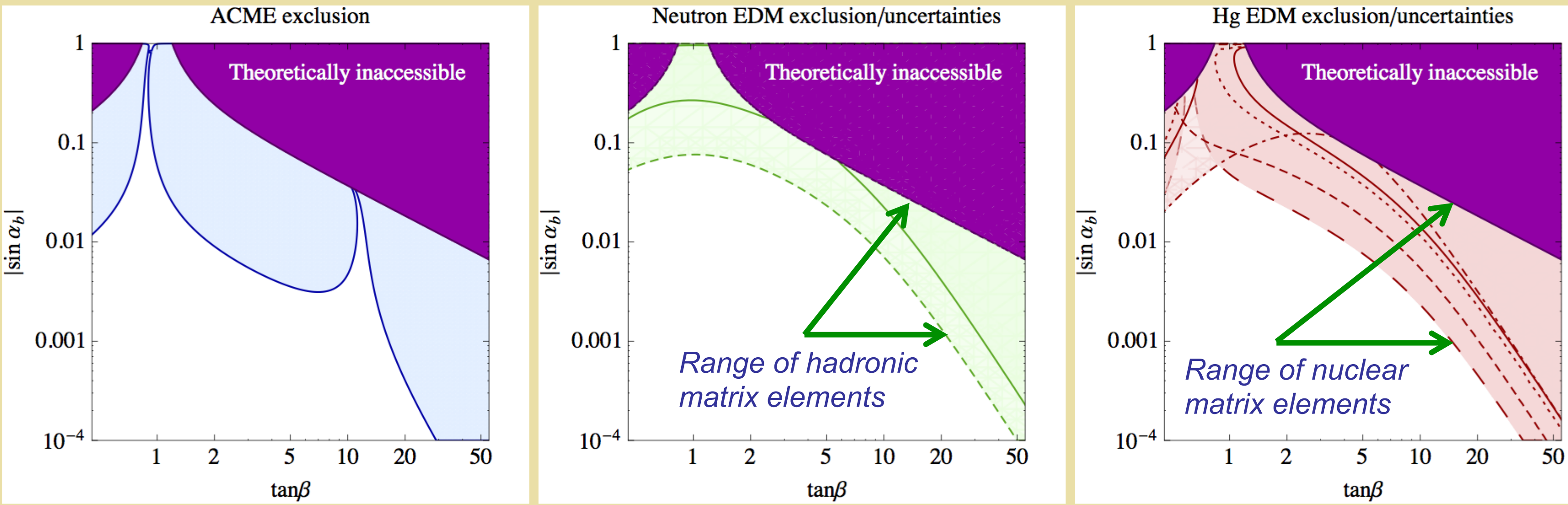


Present

Challenge for Theory

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

VI. Summary & Outlook

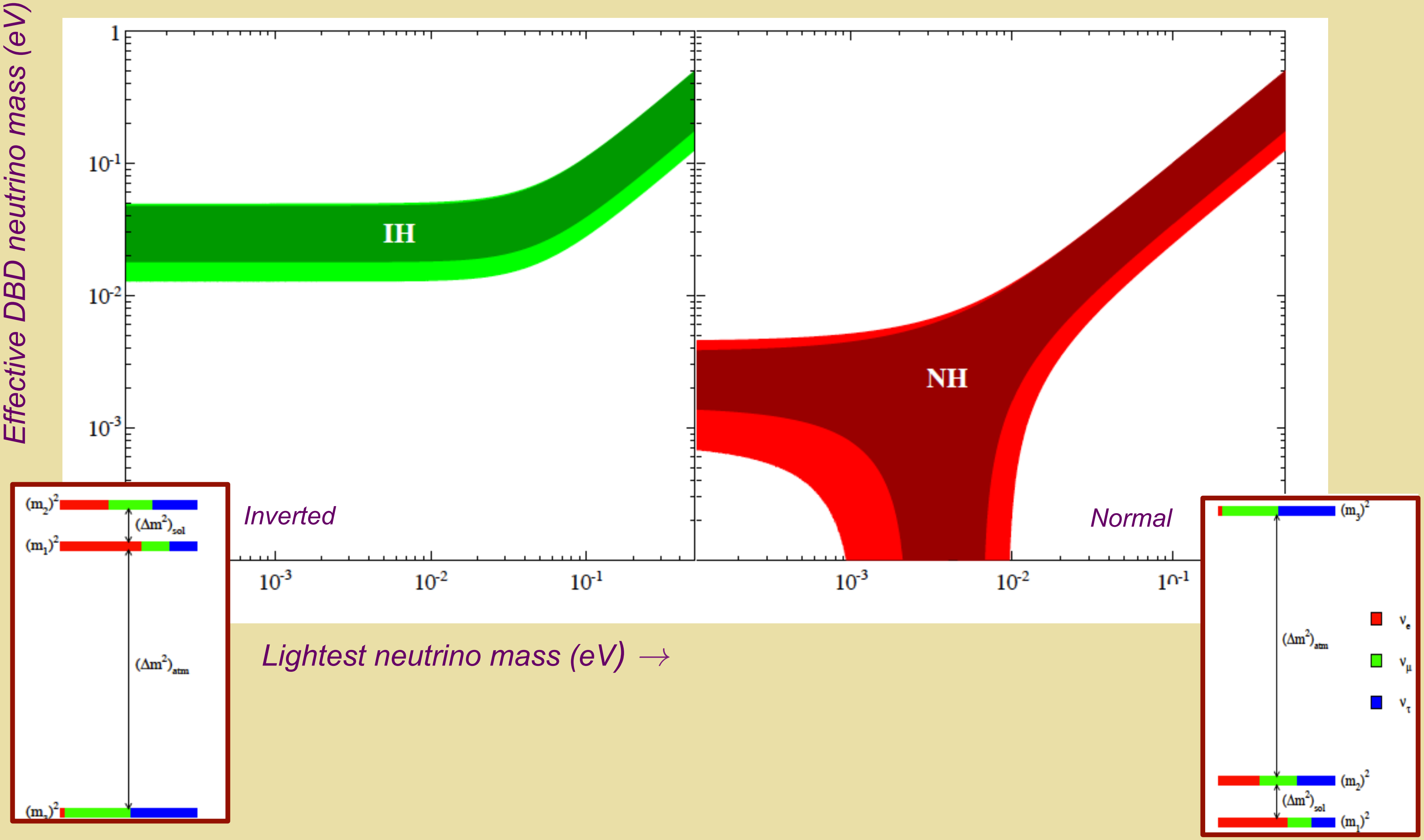
- *There exist a variety of well-motivated neutrino mass mechanisms associated with LNV interactions ranging from low- to high-scales*
- *$0\nu\beta\beta$-decay and LHC searches provide complementary probes of TeV scale LNV*
- *EDM and LHC searches can provide complementary probes of BSM CPV*
- *LHC results may provide a powerful diagnostic for interpreting a non-zero $0\nu\beta\beta$-decay and/or EDM observation*
- *Refined hadronic & nuclear ME computations are essential to this inter-frontier complementarity*

VII. Back Up Slides

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

Three active light neutrinos

Effective DBD neutrino mass (eV)



Lightest neutrino mass (eV) →

0νββ-Decay: TeV Scale LNV

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Dirac

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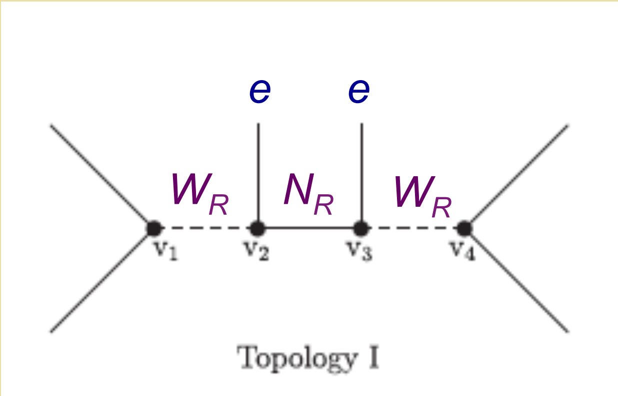
Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



LRSM: Type I See-Saw

Mass: standard see-saw but TeV scale

0νββ-Decay: TeV Scale LNV

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

Dirac

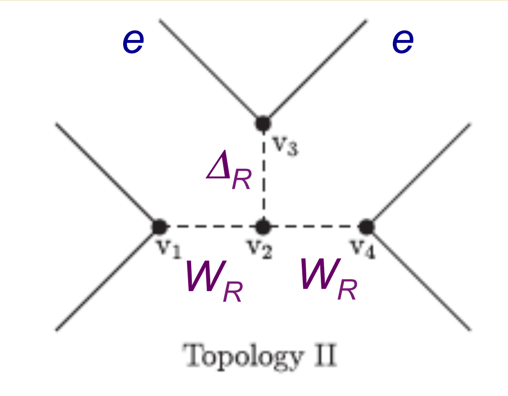
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011

LRSM: Type II See-Saw

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



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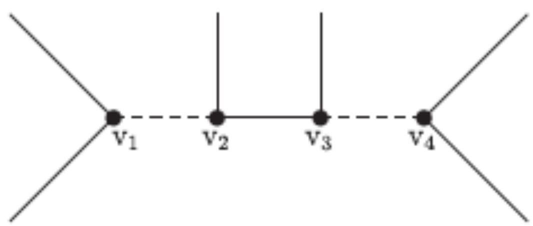


Topology I

Scalar Leptoquarks

Mass: like RPV SUSY (loop)

NLDBD: need Majorana fermion

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

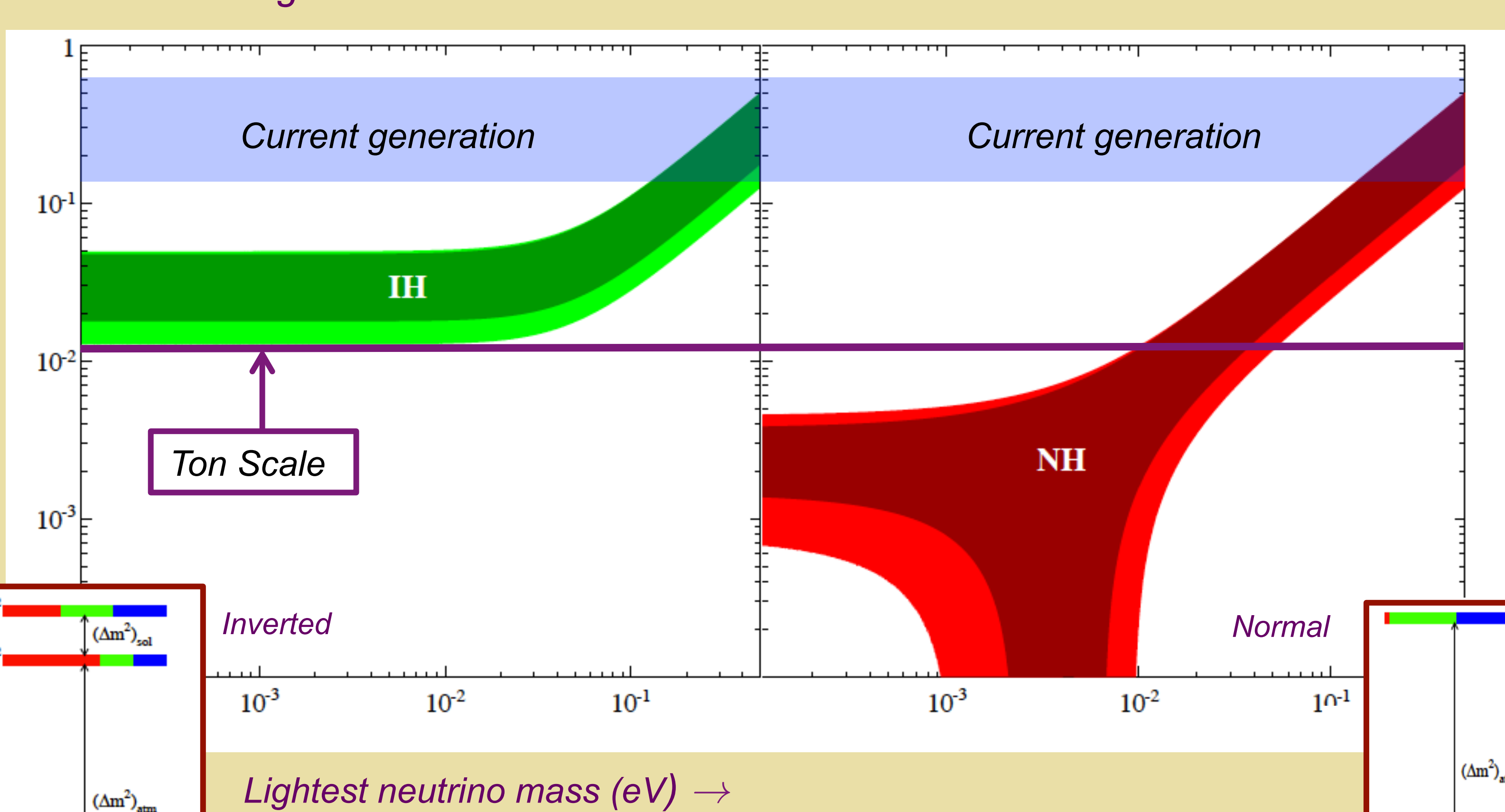
Why Might A "Ton-Scale" Exp't See It?

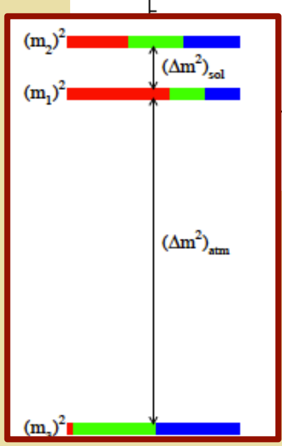
$A(Z,N) \rightarrow$ **Underlying Physics** $\rightarrow A(Z+2, N-2) + e^- e^-$

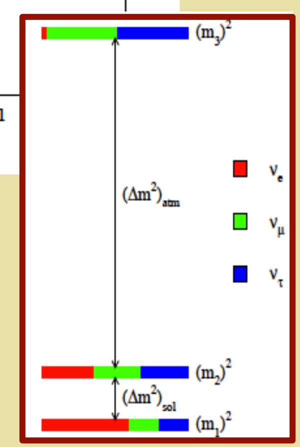
- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

Interpreting a Positive Result

Three active light neutrinos





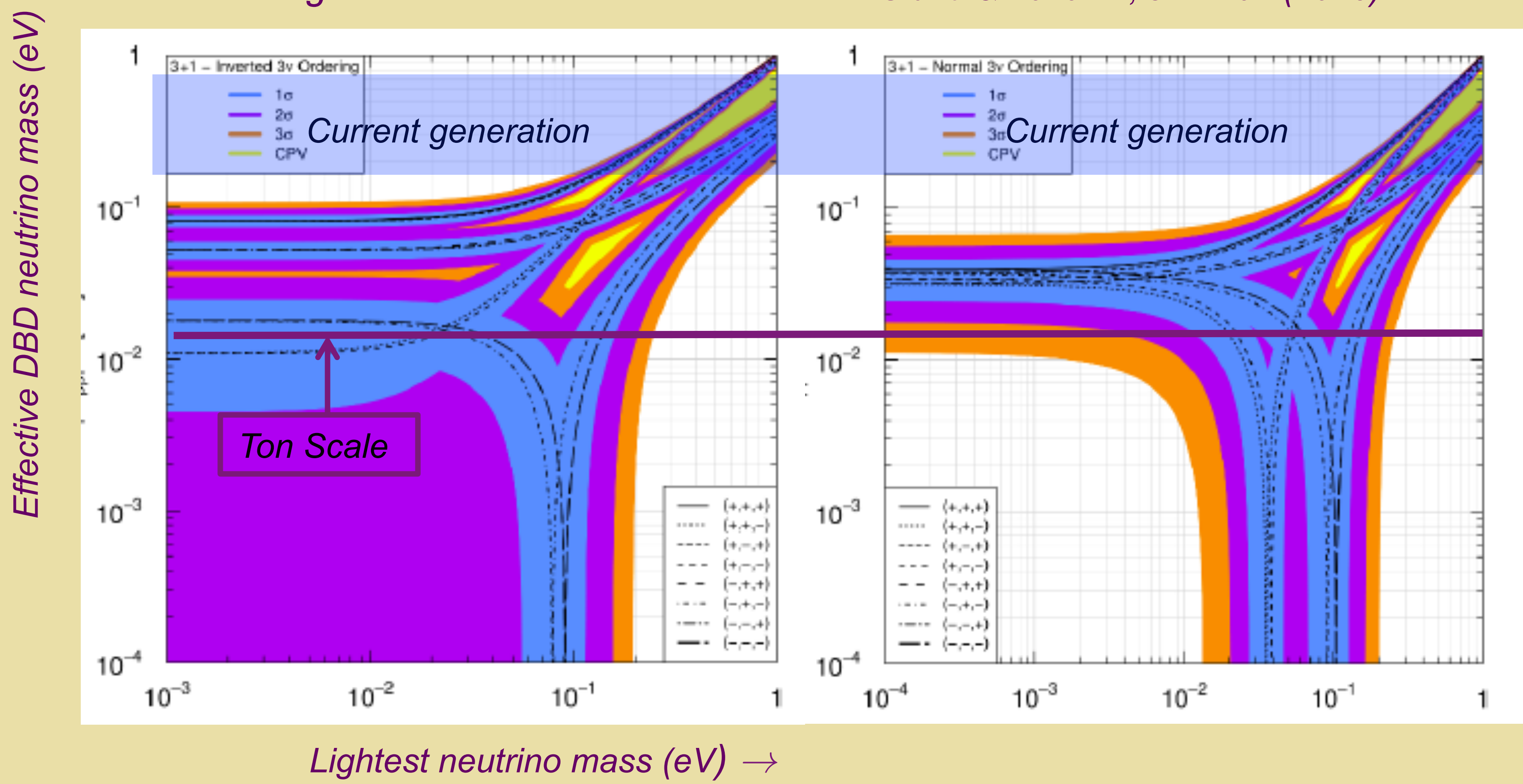


Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

Interpreting a Positive Result

3+1 active light neutrinos

Giunti & Zavanin, JHEP07 (2015) 171



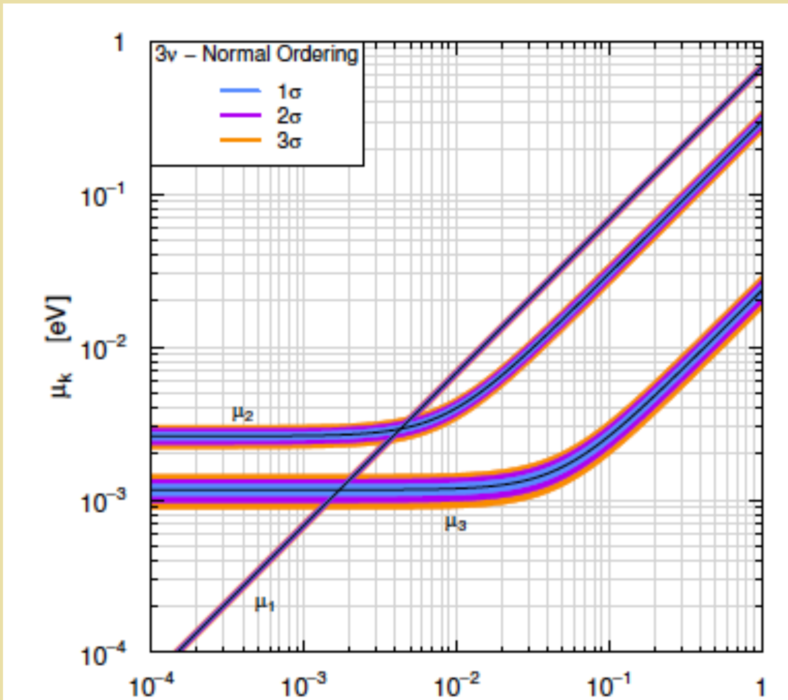
Positive result would be consistent with 3+1 light active ν's & NH, IH, or quasi-deg regime, but not definitive as to mechanism

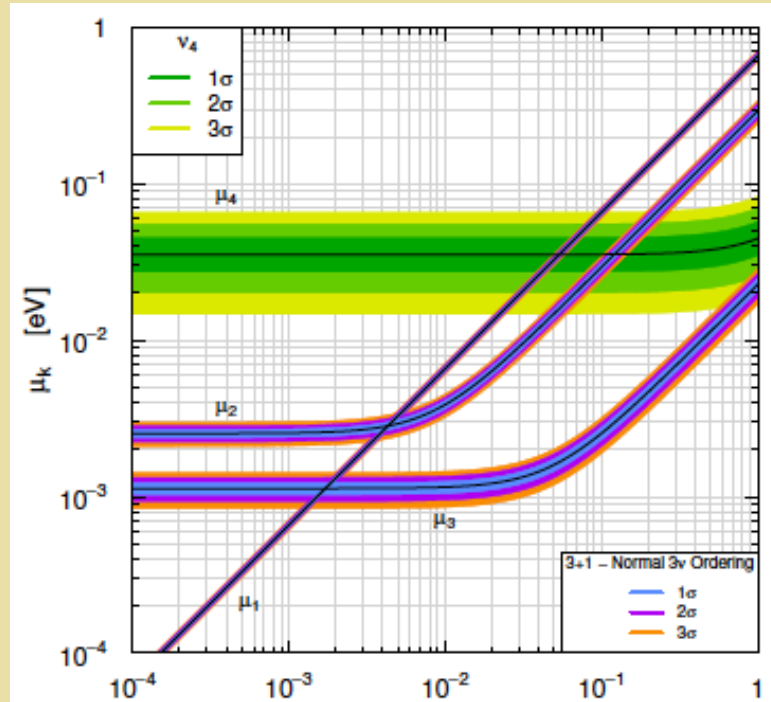
Sterile Neutrinos & $0\nu\beta\beta$−Decay

3 active light neutrinos

3+1 active light neutrinos

Effective DBD neutrino mass (eV)





Lightest neutrino mass (eV) →

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

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

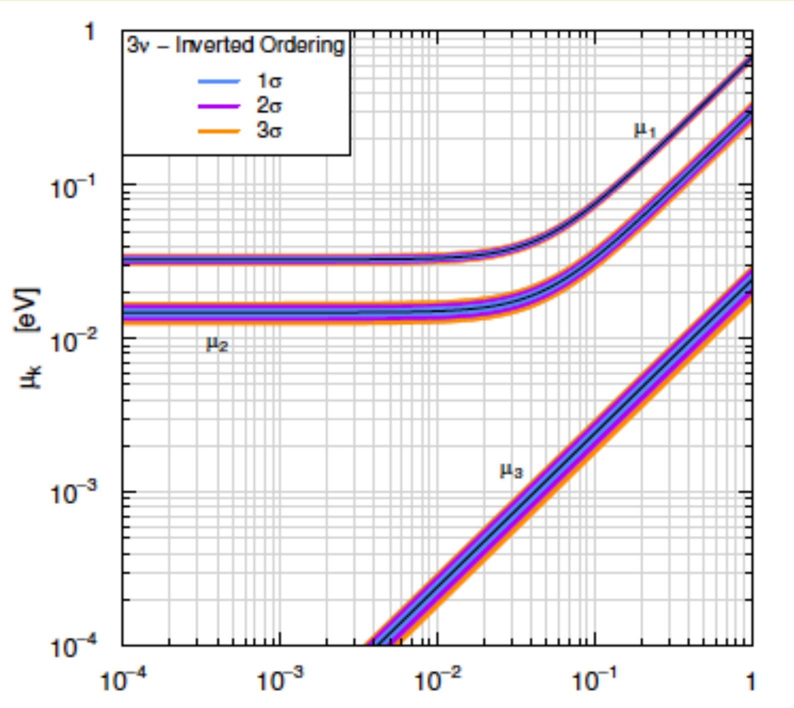
Giunti & Zavanin, JHEP07 (2015) 171

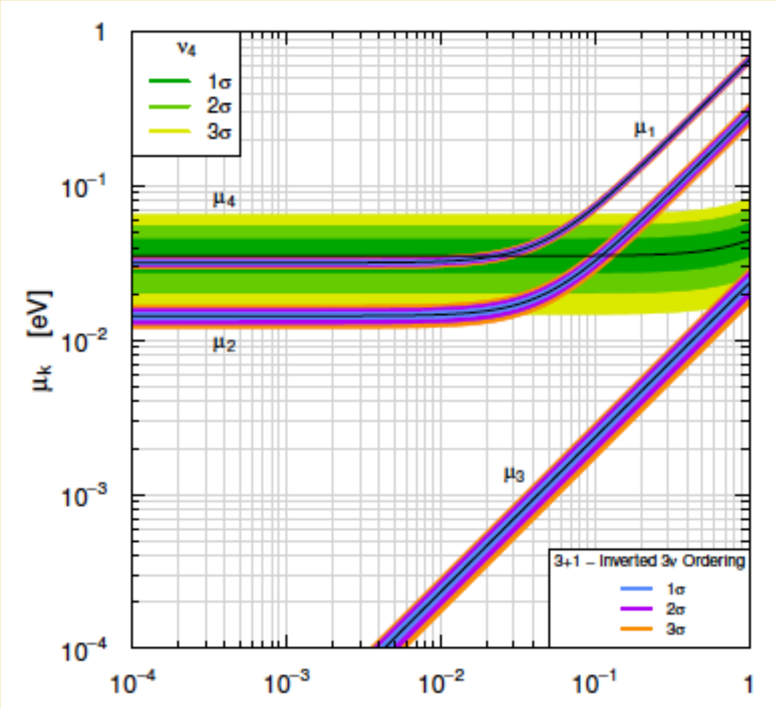
Sterile Neutrinos & $0\nu\beta\beta$–Decay

3 active light neutrinos

3+1 active light neutrinos

Effective DBD neutrino mass (eV)





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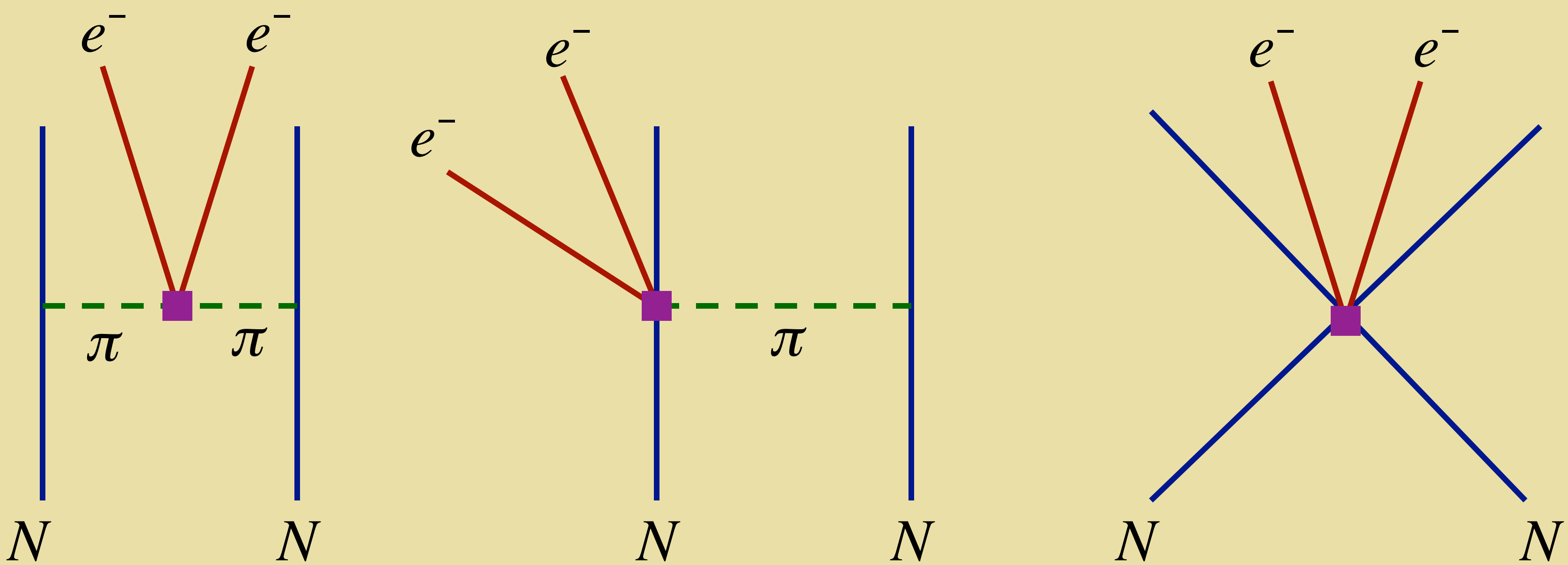
Giunti & Zavanin, JHEP07 (2015) 171

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



Tractable nuclear operators

Systematic operator classification

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

$0\nu\ \beta\beta$ - 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.

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

$0\nu\ \beta\beta$ - decay: *a* = *b* = +

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

Operator classification

$$\mu = M_{WEAK}$$

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

Chiral transformations: $SU(2)_L \times SU(2)_R$

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

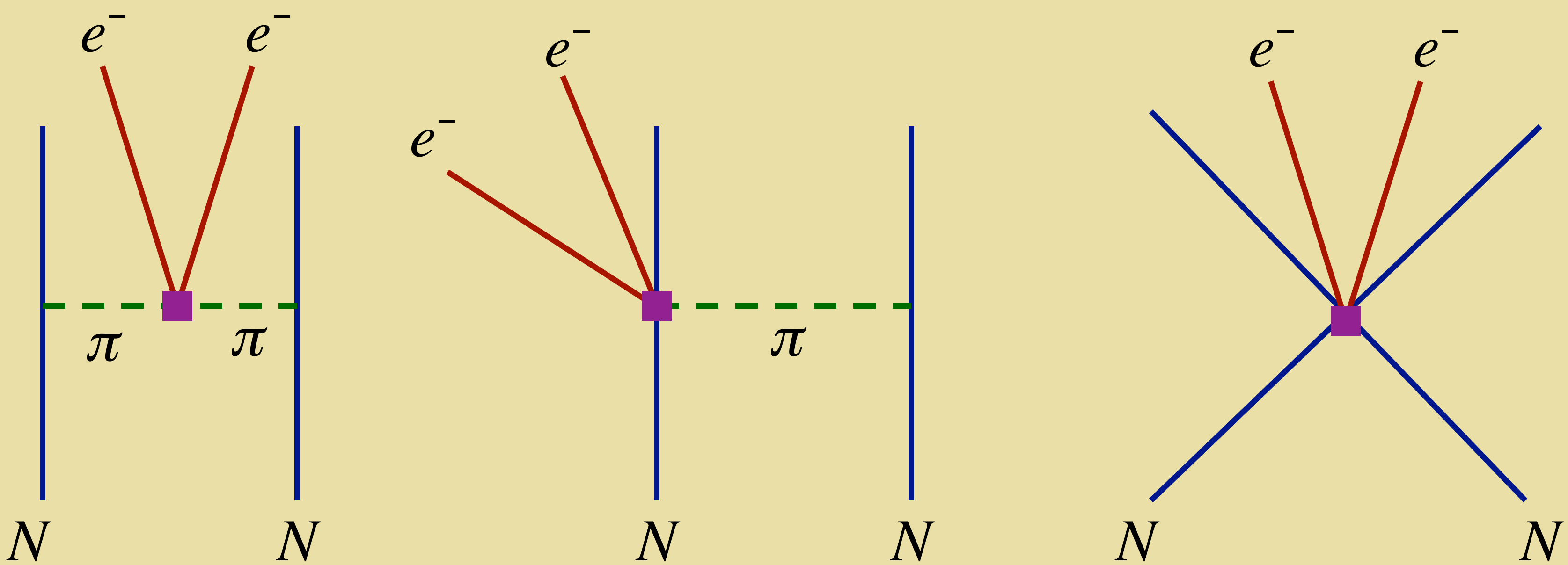
$$\hat{O}^{ab}_{1+} \in (3_L, 3_R)$$

Parity transformations: $q_L \leftrightarrow q_R$

$0\nu\ \beta\beta$ - decay: ***a = b = +***

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

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



$K_{\pi\pi}\ p^{-2}$

$K_{\pi NN}\ p^{-1}$

$K_{NNNN}\ p^{0}$

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