TeV Scale LNV: *$0\nu\beta\beta$-Decay & Colliders I*

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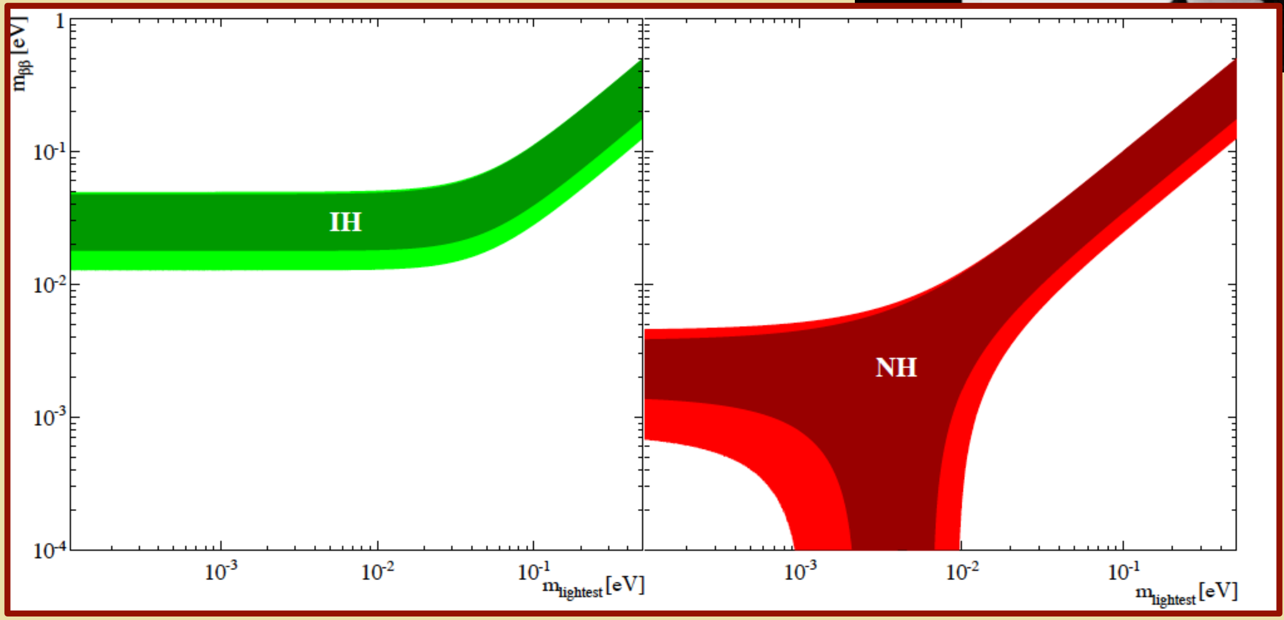
http://www.physics.umass.edu/acfi/

Collaborators: Tao Peng, Peter Winslow; V. Cirigliano, M. Graesser, M. Horoi, P. Vogel

ACFI Neutrino Workshop
July 2017

This talk: beyond the "poster child"



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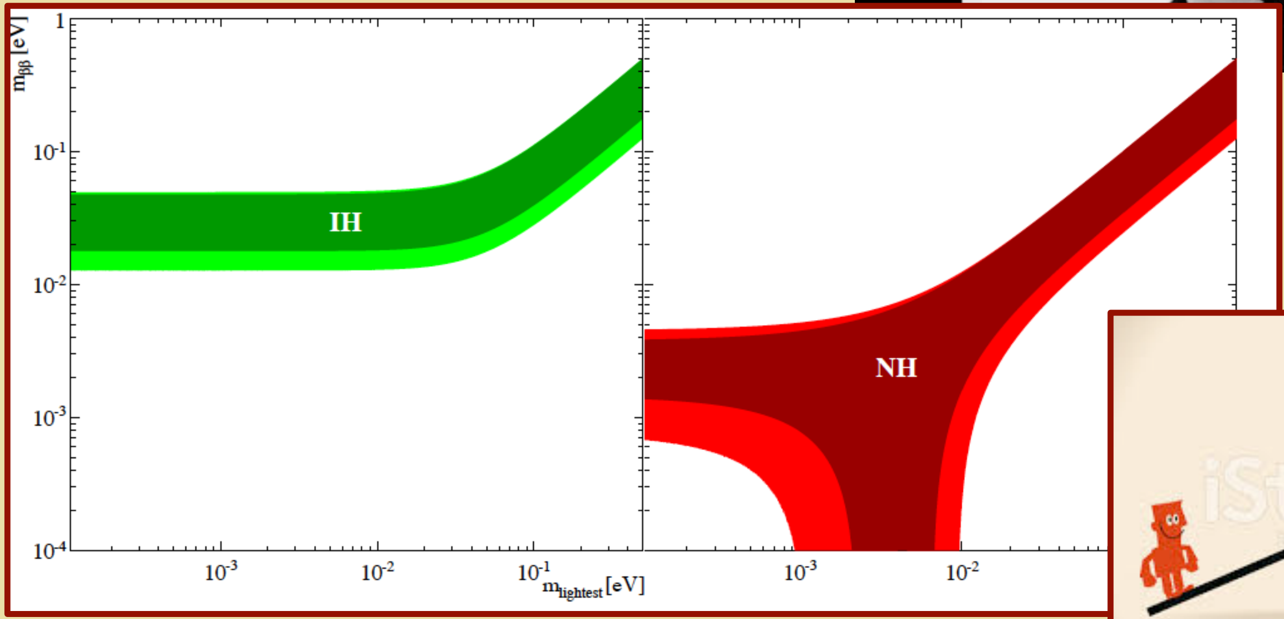


Themes for This Talk

Low-Energy / High-Energy Interplay

Discovery

"Diagnostic"

Low energy

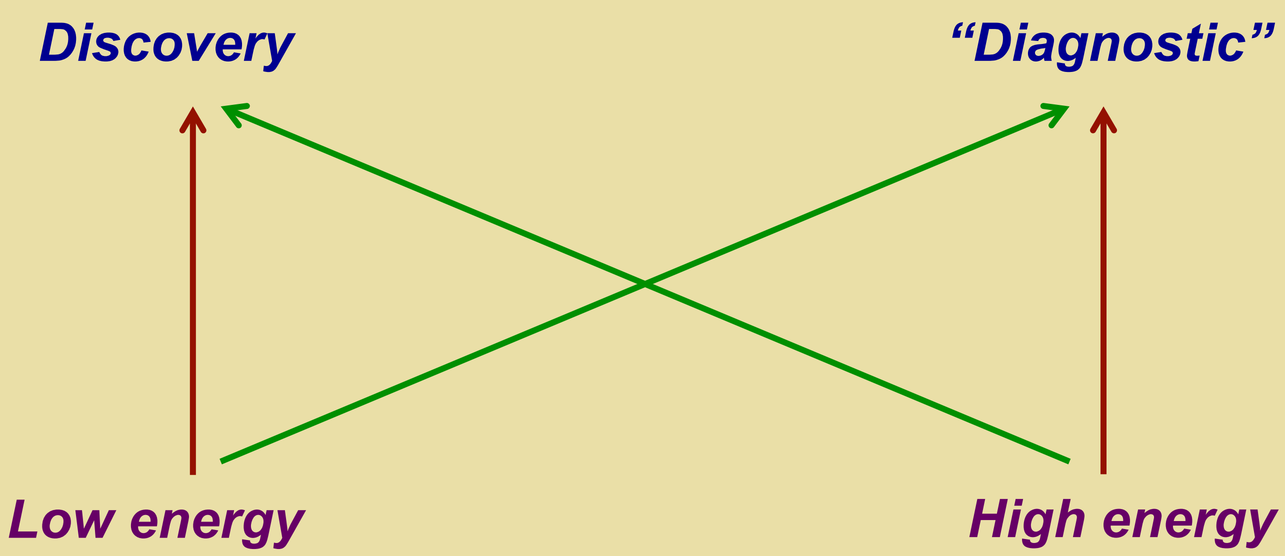
High energy

Low-Energy / High-Energy Interplay

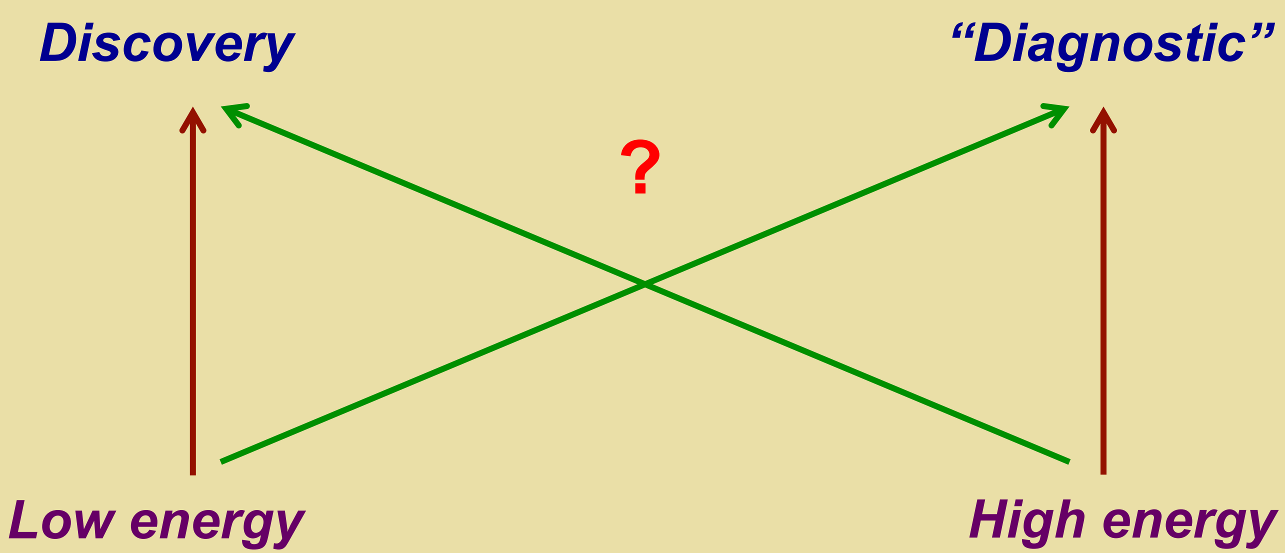
Discovery ***“Diagnostic”***

Low energy ***High energy***

Low-Energy / High-Energy Interplay



Low-Energy / High-Energy Interplay



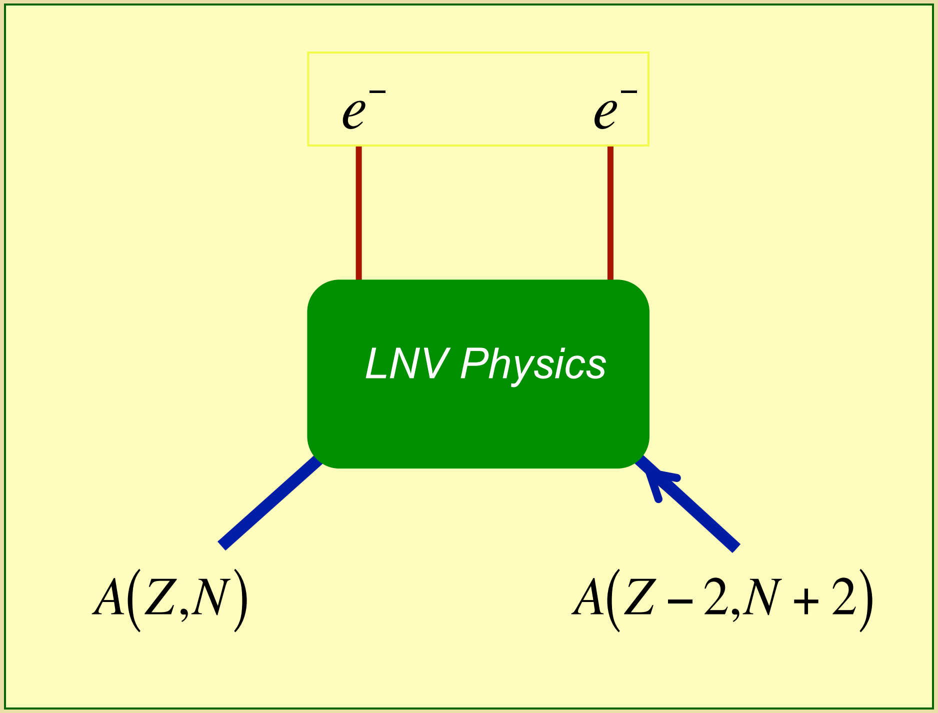
$0\nu\beta\beta$-Decay: LNV? Mass Term?

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

Dirac

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

Majorana



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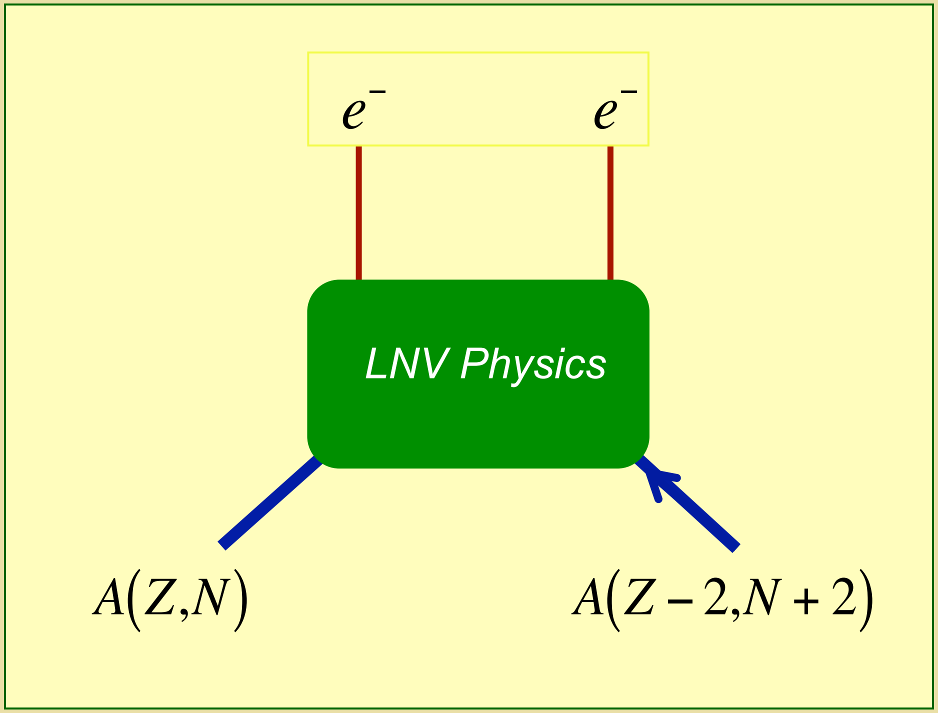
Impact of observation

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

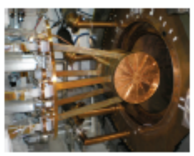


Ton Scale Experiments

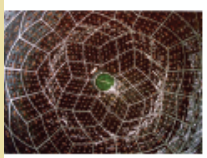
$0\nu\beta\beta$ decay Experiments - Efforts Underway

CUORE

EXO200



KamLAND Zen



Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	**100 kg - ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	**~ ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA

SNO+

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

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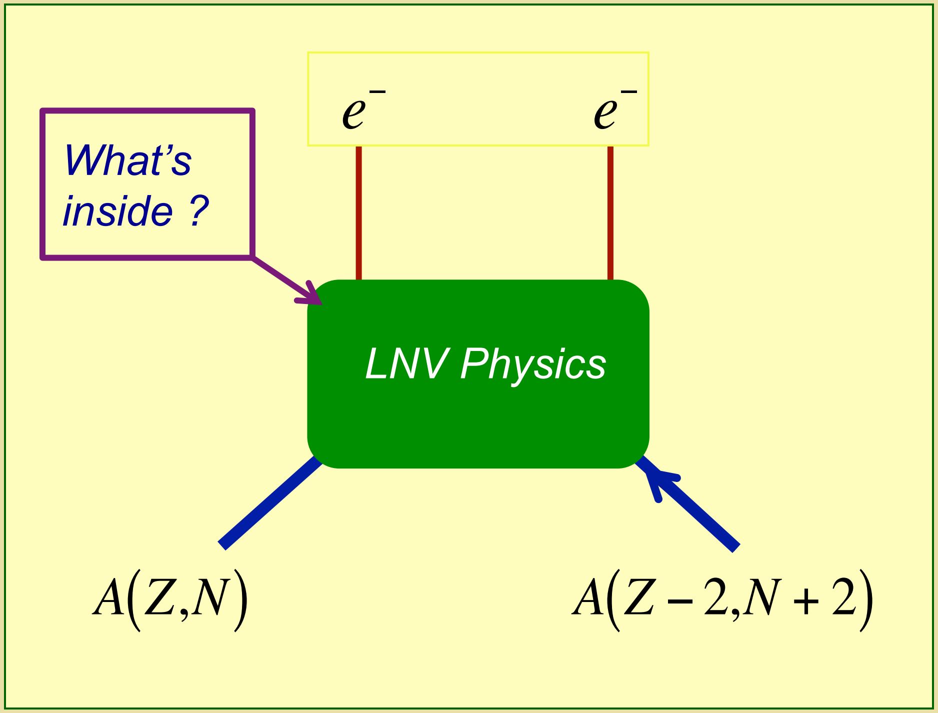
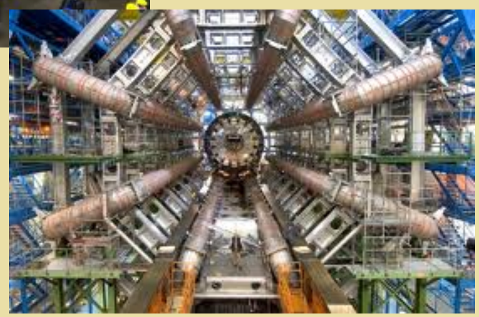


LNV: Discoverable at the Energy Frontier

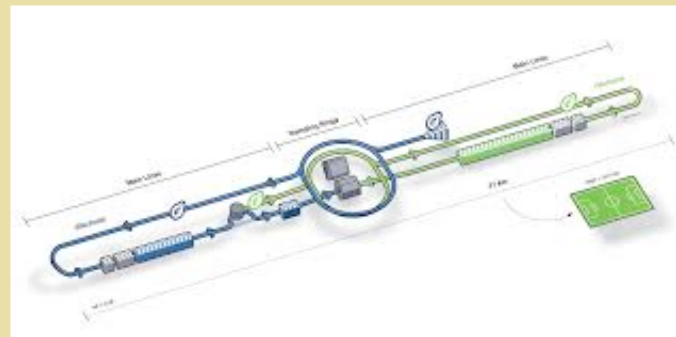
LHC

ATLAS

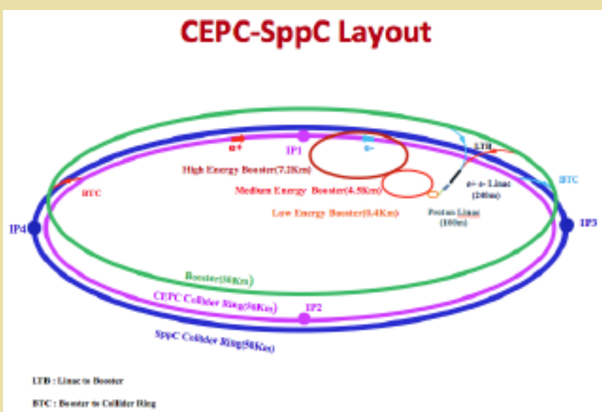
CMS



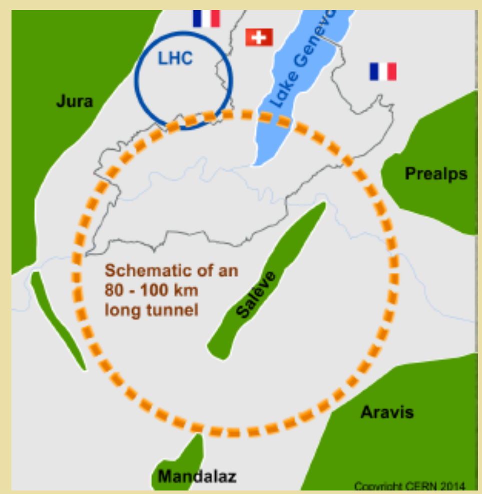
International Linear Collider



Future Circular e^+e^- & pp



Future Circular e^+e^- & pp



Thanks: S. Gascon-Shotkin

Outline

I. The "Standard Mechanism": High Scale LNV

II. TeV Scale LNV

III. Simplified Models: Connecting DBD & Colliders

IV. Summary

V. Sub Weak Scale LNV (back up)

I. “St’d Mechanism”: High Scale LNV

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **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*

LNV Mass Scale & $0\nu\beta\beta$-Decay

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

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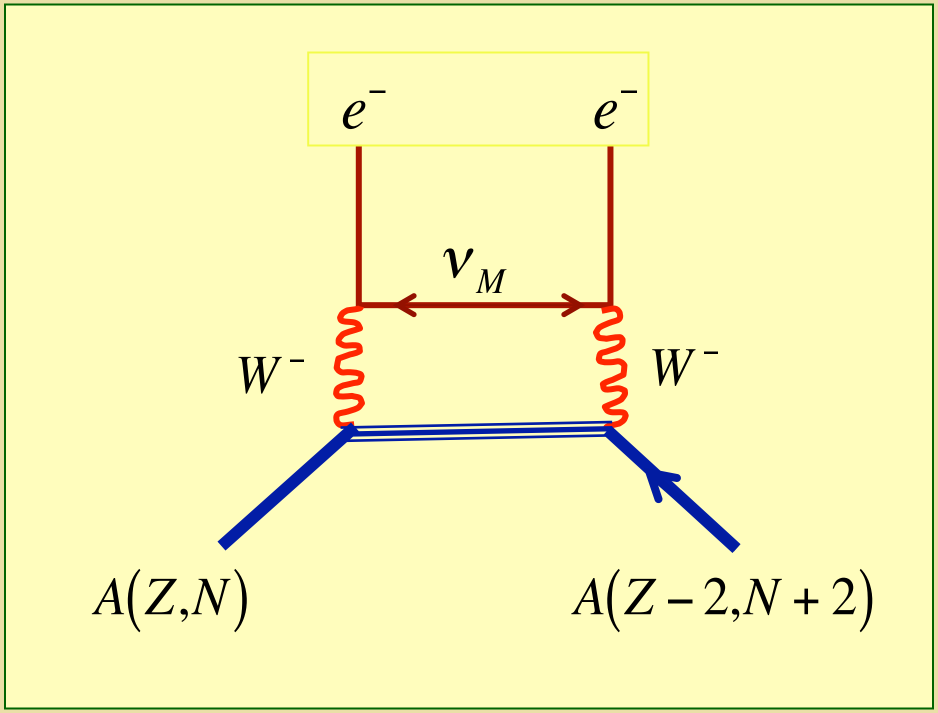
Dirac

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

Majorana

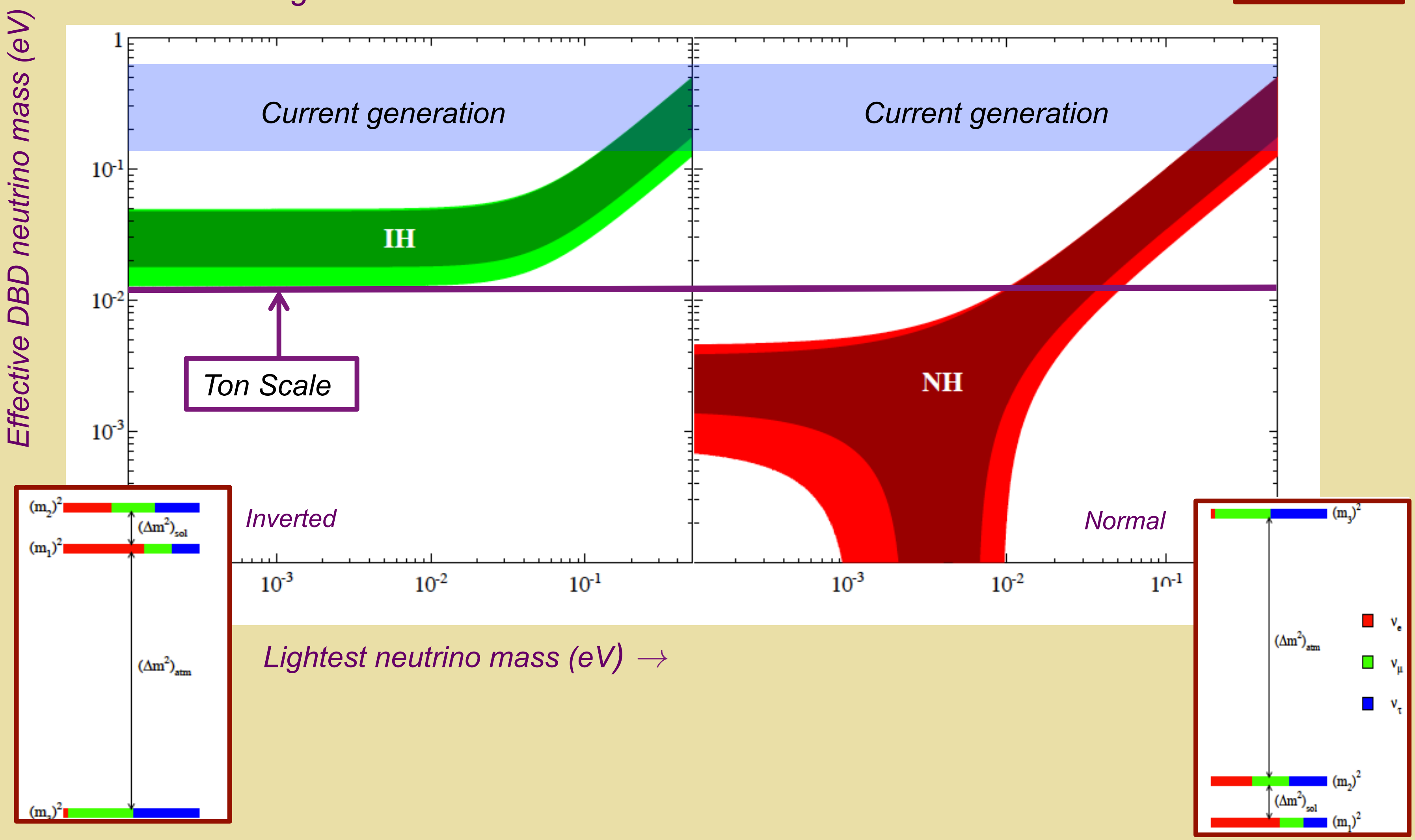
"Standard" Mechanism

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



High Scale LNV

Three active light neutrinos



Details

See F. Deppisch talk….

II. TeV Scale LNV

LNV Mass Scale & 0νββ-Decay

A(Z,N) → Underlying Physics → 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*

Two parameters: Effective coupling & effective heavy particle mass

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

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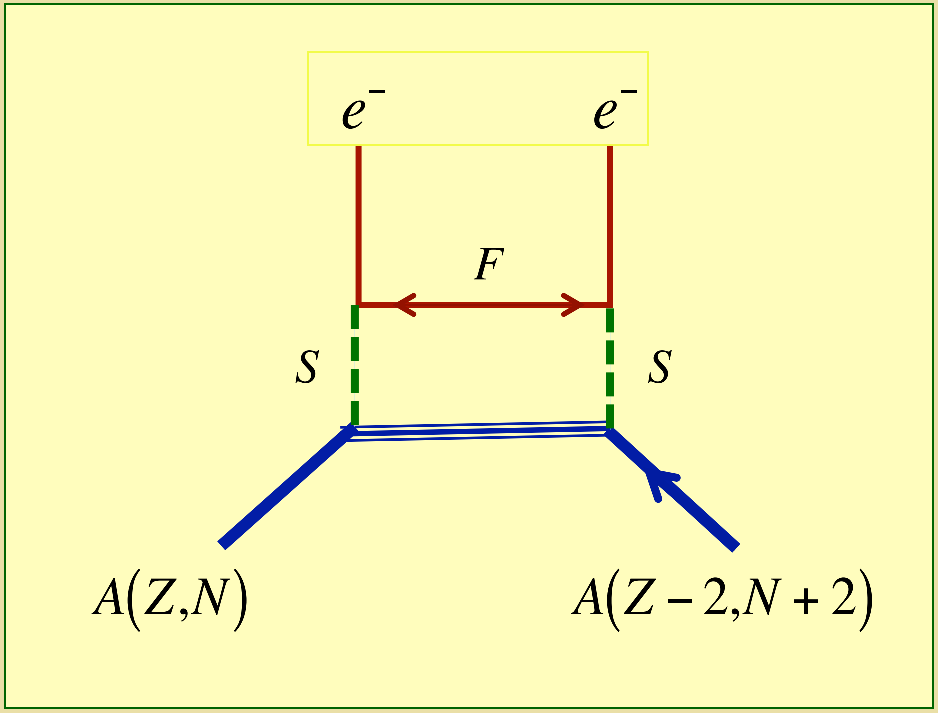
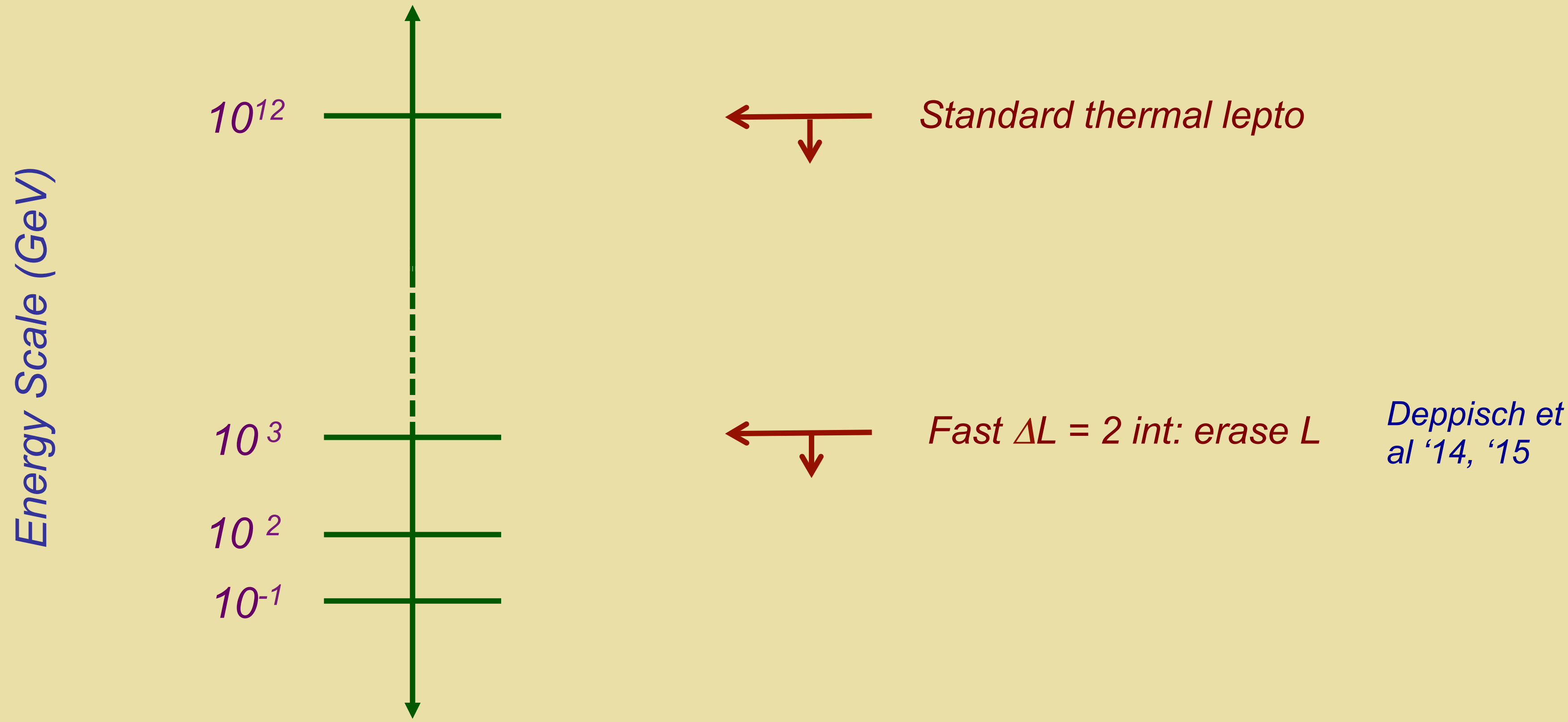
Majorana

TeV LNV Mechanism

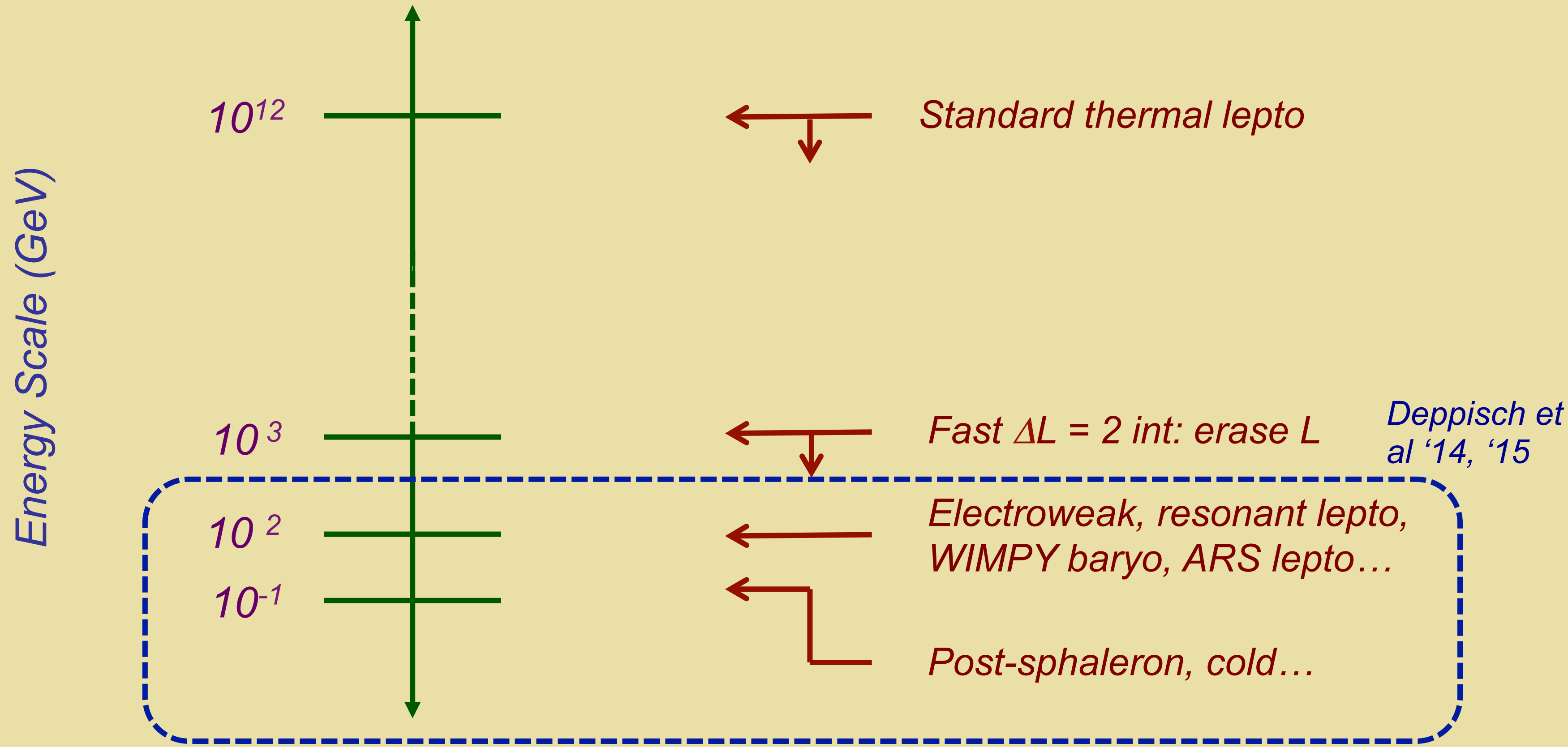
- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



TeV LNV & Leptogenesis



TeV LNV & Leptogenesis



Baryogenesis alternatives

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

General Classification: Helo et al, PRD 88.011901, 88.073011

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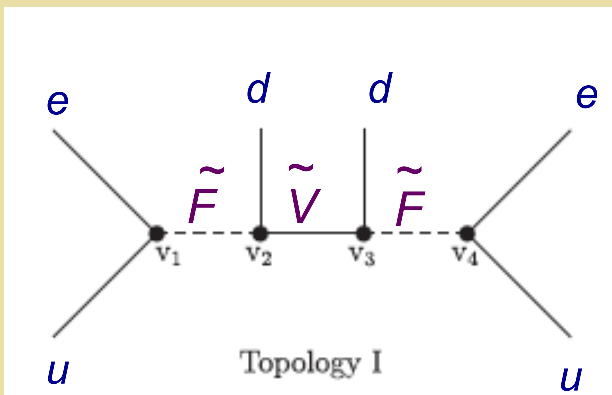

SUSY: R Parity-Violation

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

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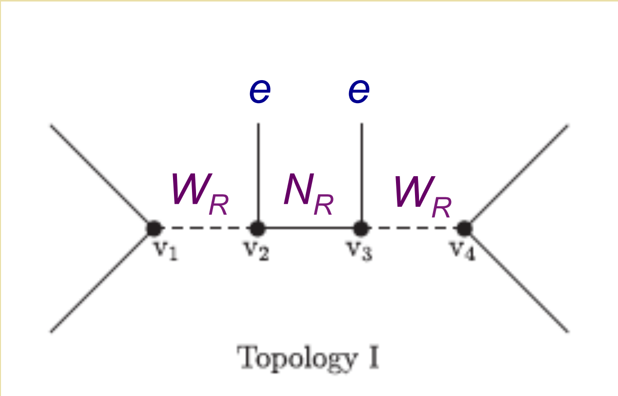

LRSM: Low-scale See-Saw

Mass: standard see-saw but TeV scale

+ many other diagrams

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

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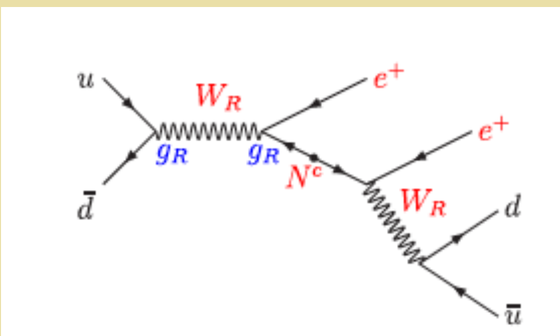
Majorana

LHC: SS Dilepton + Dijet

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



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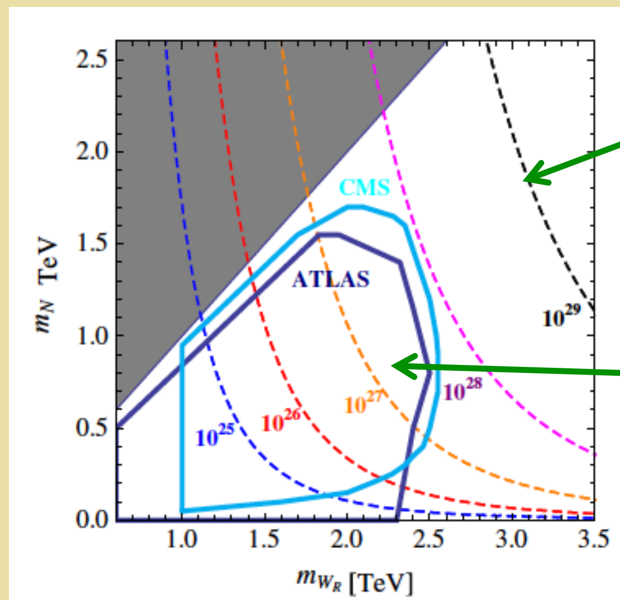

^{76}Ge $\tau(0\nu)$

LHC exclusion

III. Simplified Models

LNV Dog Race

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

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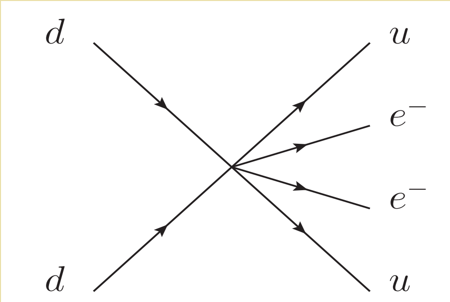
Majorana

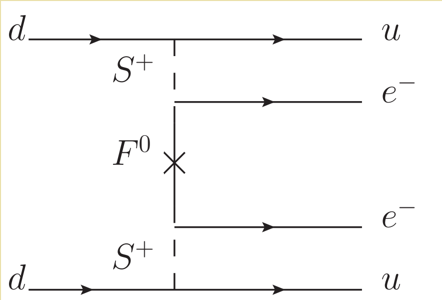
TeV Scale LNV

$0\nu\beta\beta$ - decay



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

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



Simplified models

Simplified Models: Illustrative Case

- ***General considerations for collider - $0\nu\beta\beta$ decay interface***

Simplified Models: Illustrative Case

$$\mathcal{L}_{\text{INT}} = g_1 \bar{Q}_i^a d^a S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$

S:	*(1, 2, ½)*	
F:	*(1, 0, 0)*	*Majorana*

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

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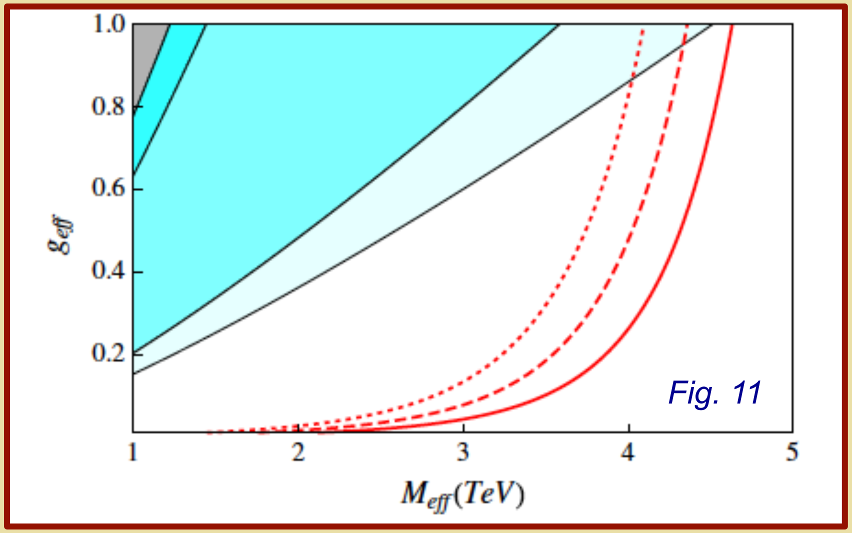
Majorana

Helo et al claim:

$$\mathcal{L}_{\text{INT}} = g_1 \bar{Q}_i^{\alpha} d^{\alpha} S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$

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



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

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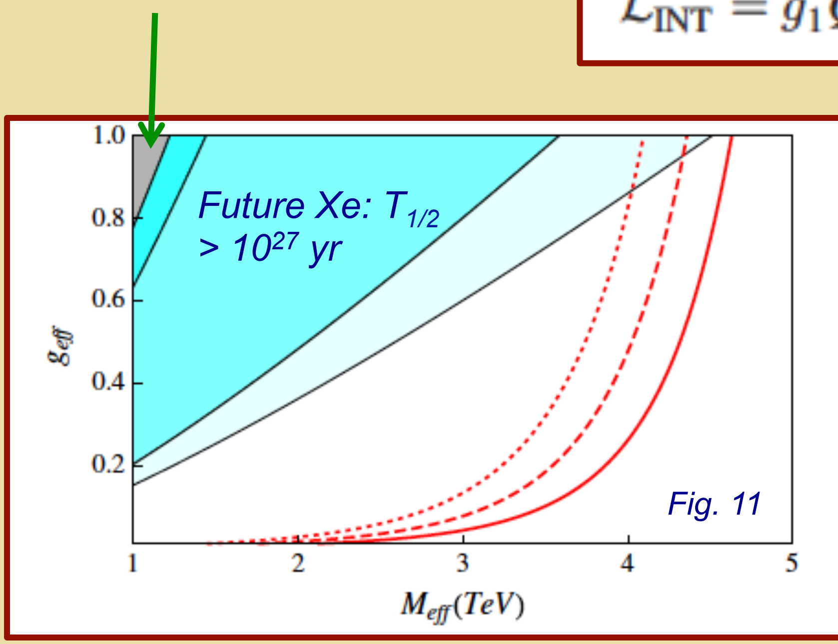

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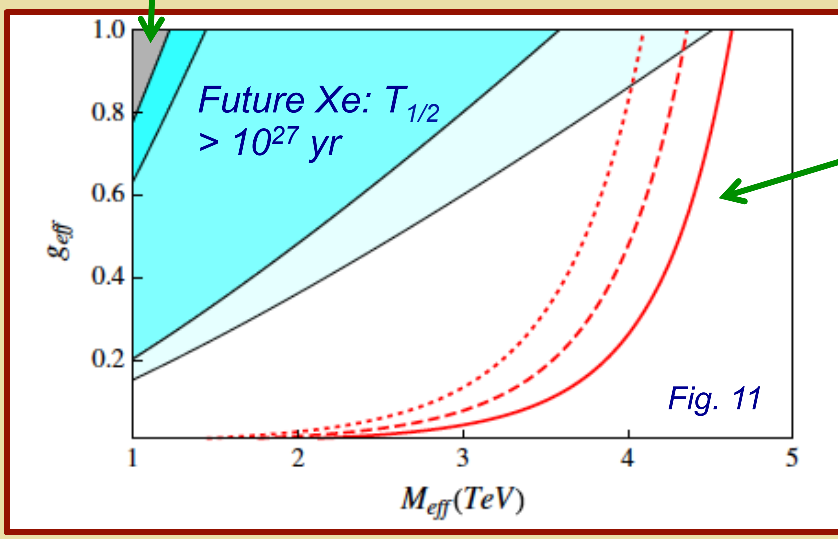

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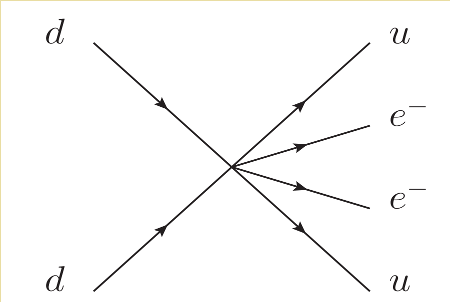
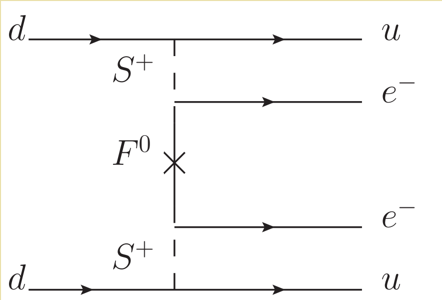
TeV Scale LNV

$0\nu\beta\beta$ - decay



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



Comparing $0\nu\beta\beta$ & LHC sensitivities (our work):

- *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

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Majorana

Backgrounds:

- *Charge flip*
- *Jet faking electron*

0νββ-Decay: TeV Scale LNV

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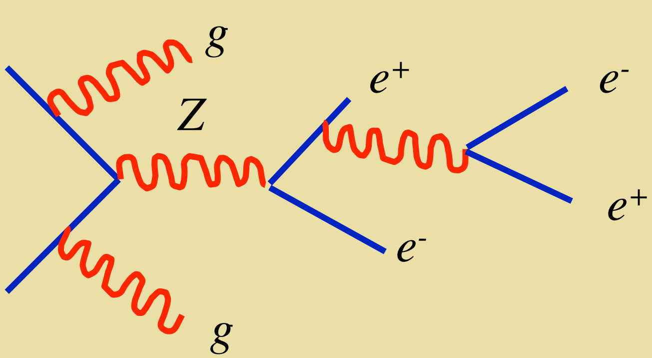

e^+ transfers most of p_T to conversion e^- ;
Z / γ^* + jets $\rightarrow$ apparent e^- e^- jj event

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

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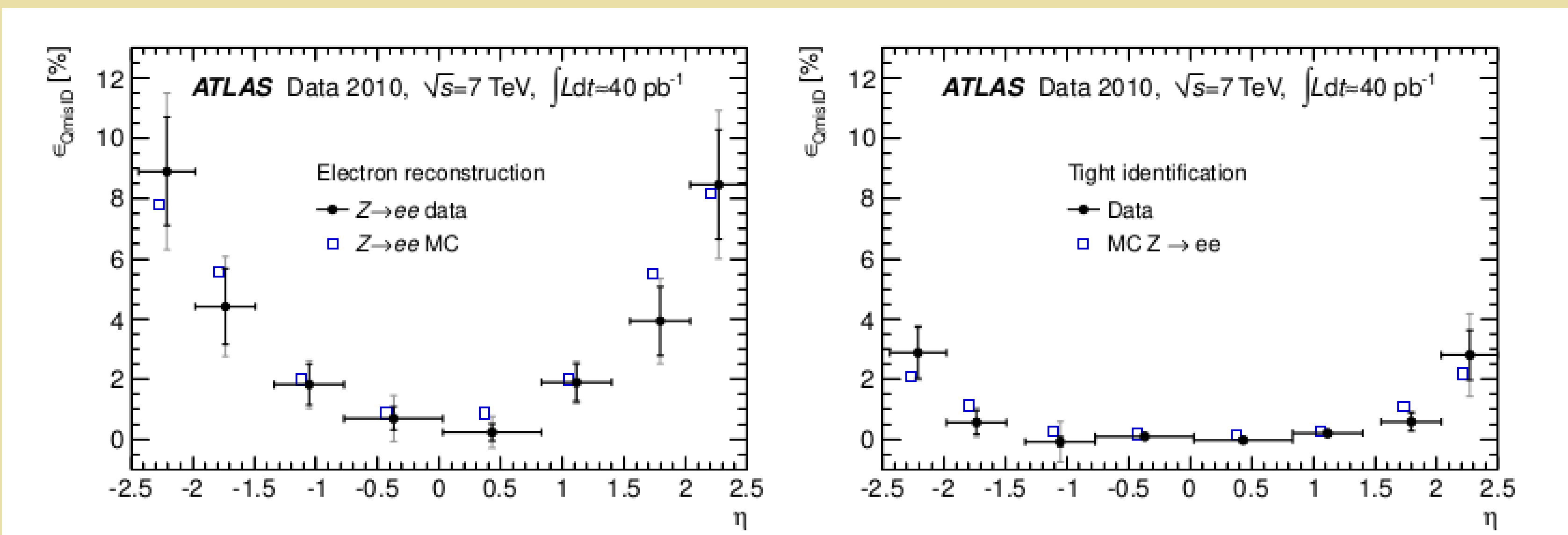
Majorana

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



0νββ-Decay: TeV Scale LNV

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Majorana

Backgrounds: *Jet fakes (e.g., π^+ looks like e^+)*

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

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

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Dirac

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Majorana

Backgrounds: *Cuts*

- H_T
- *MET*
- M_{ll}

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Dirac

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Majorana

Backgrounds: *Cuts*

σ(fb)	Signal	Backgrounds									$\frac{\mathbf{S}}{\sqrt{\mathbf{S+B}}}$ ($\sqrt{\text{fb}}$)
		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	3x10^{-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	3x10^{-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	2x10^{-5}	0.019	0.011	0.0738

T. Peng, MRM, P. Winslow 1508.04444

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

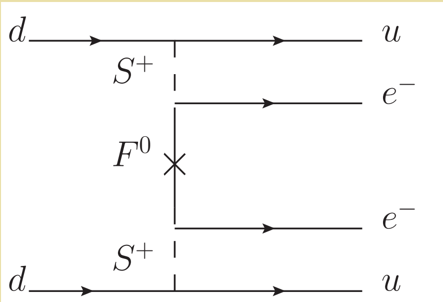
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

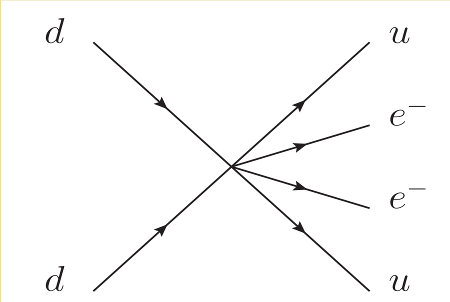
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Low energy: *Matching*



Match onto O_{eff} at Λ_{BSM}



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

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

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

0νββ-Decay: TeV Scale LNV

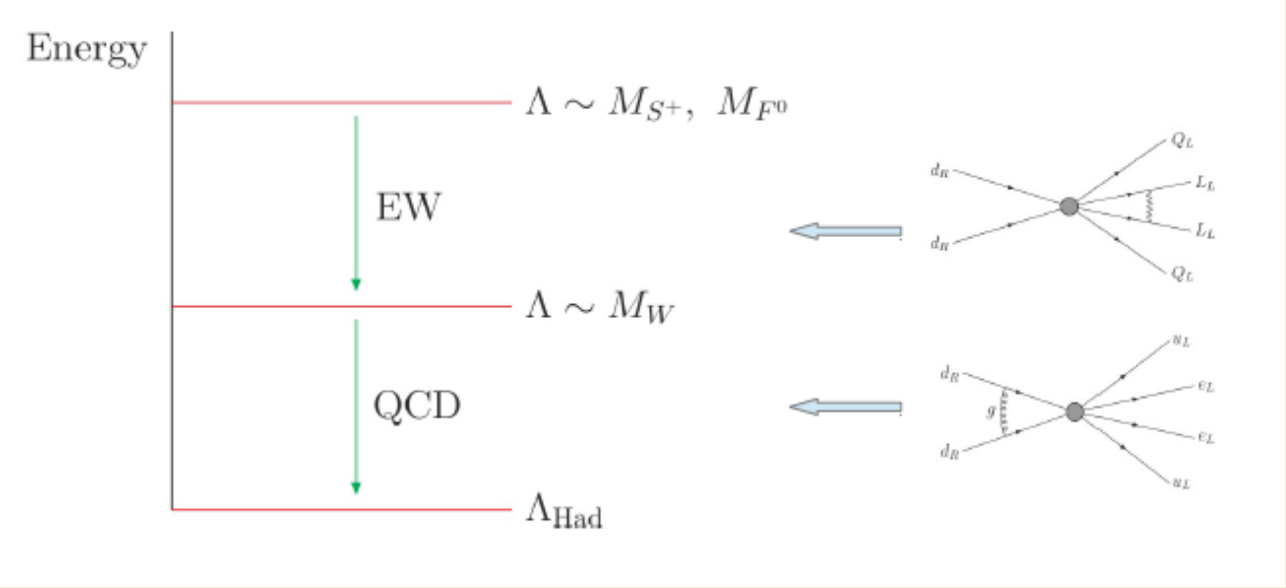
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

Low energy: *Running*



$0\nu\beta\beta$-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: *QCD Running*

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

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

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

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

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

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

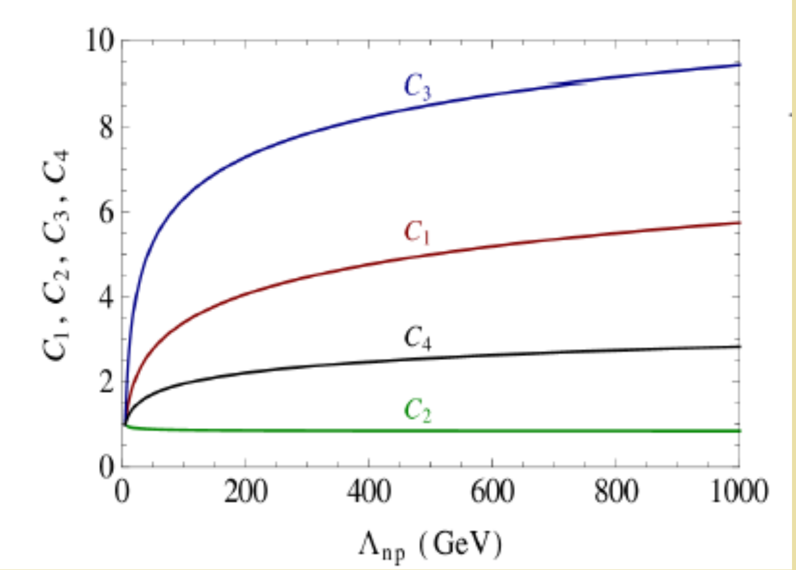
Dirac

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

Majorana

Low energy: *QCD Running*

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



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

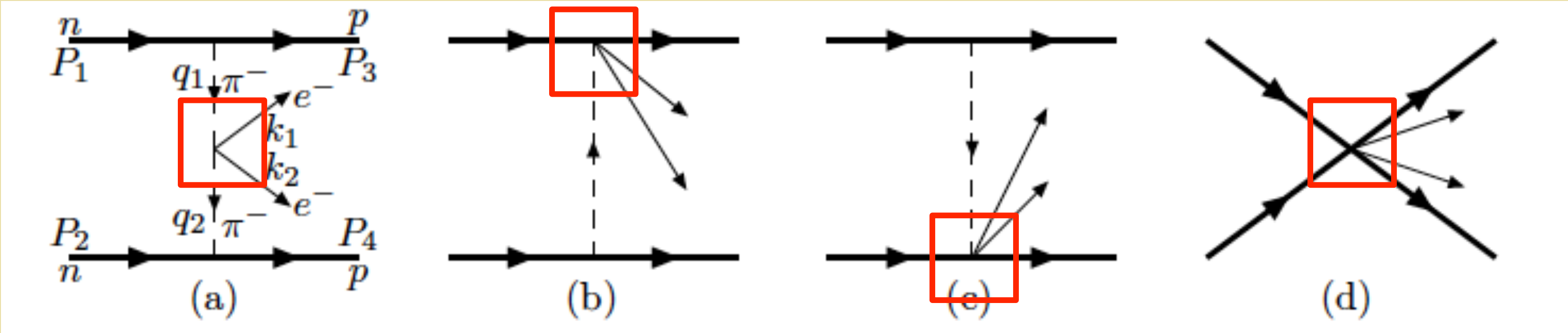
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

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*



Exploit Chiral Symmetry & EFT ideas

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

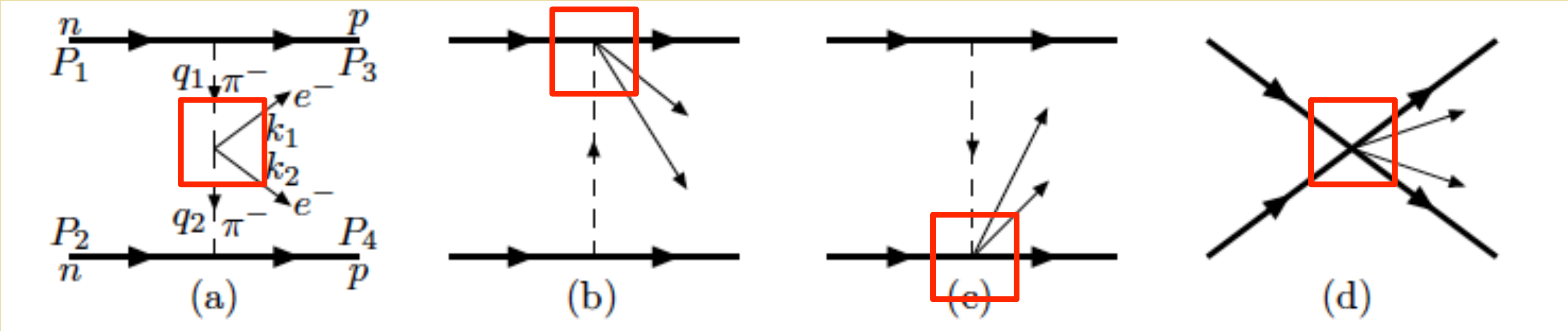
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

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*

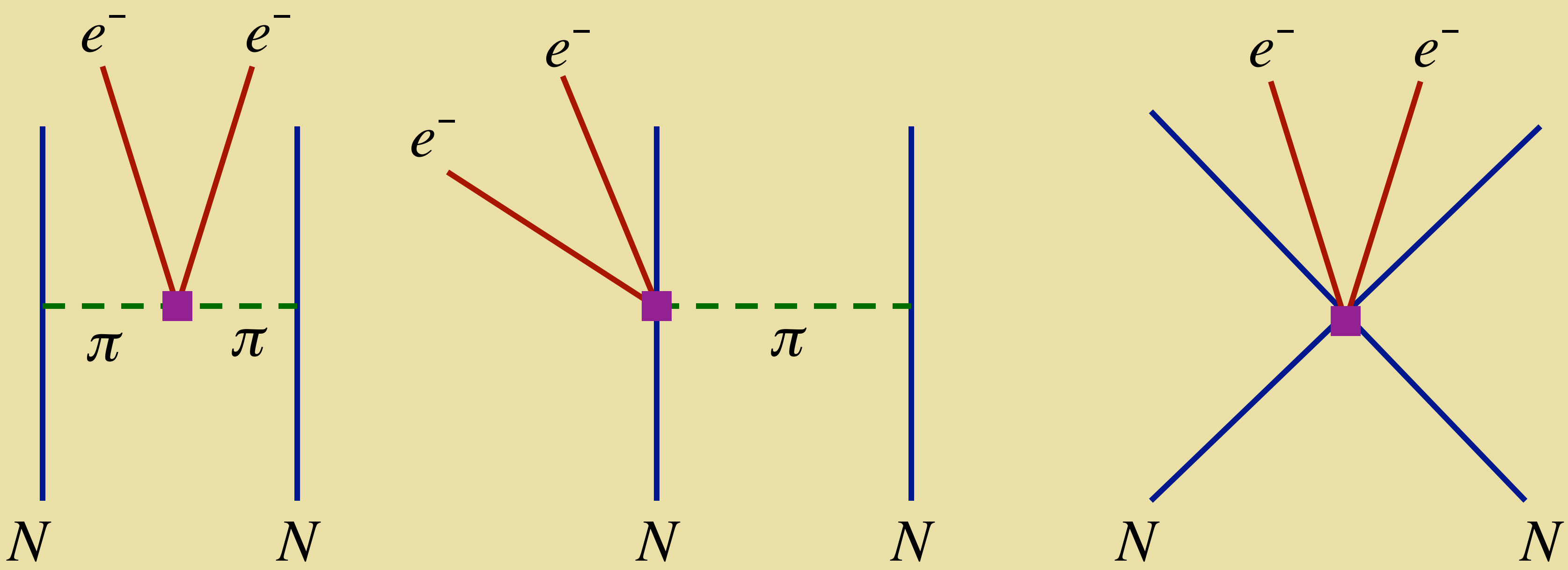


Our work

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

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

Operator classification

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

e.g.

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

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

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

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

Operator classification

$$\mathcal{O}^{ab}_{1+} \rightarrow (\bar{q}_L L^\dagger \tau^a \gamma^\mu L q_L)(\bar{q}_R R^\dagger \tau^b \gamma_\mu R q_R),$$

$$\mathcal{O}^{ab}_{2\pm} \rightarrow (\bar{q}_R R^\dagger \tau^a L q_L)(\bar{q}_R R^\dagger \tau^b L q_L) \pm (\bar{q}_L L^\dagger \tau^a R q_R)(\bar{q}_L L^\dagger \tau^b R q_R),$$

$$\mathcal{O}^{ab}_{3\pm} \rightarrow (\bar{q}_L L^\dagger \tau^a \gamma^\mu L q_L)(\bar{q}_L L^\dagger \tau^b \gamma_\mu L q_L) \pm (\bar{q}_R R^\dagger \tau^a \gamma^\mu R q_R)(\bar{q}_R R^\dagger \tau^b \gamma_\mu R q_R),$$

$$\mathcal{O}^{ab,\mu}_{4\pm} \rightarrow (\bar{q}_L L^\dagger \tau^a \gamma^\mu L q_L \mp \bar{q}_R R^\dagger \tau^a \gamma^\mu R q_R) \times (\bar{q}_L L^\dagger \tau^b R q_R - \bar{q}_R R^\dagger \tau^b L q_L),$$

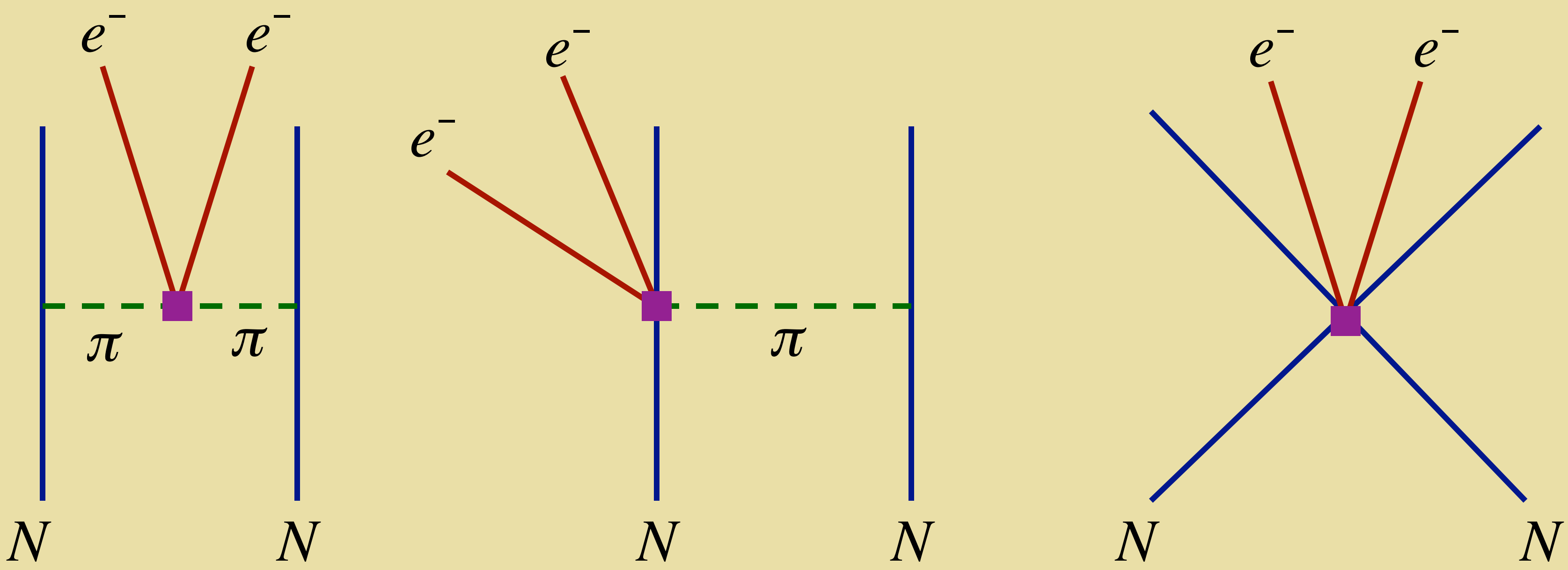
$$\mathcal{O}^{ab,\mu}_{5\pm} \rightarrow (\bar{q}_L L^\dagger \tau^a \gamma^\mu L q_L \pm \bar{q}_R R^\dagger \tau^a \gamma^\mu R q_R) \times (\bar{q}_L L^\dagger \tau^b R q_R + \bar{q}_R R^\dagger \tau^b L q_L).$$

Match onto hadronic operators using chiral transformation properties

Prezeau, MJRM, Vogel PRD 68 (2003) 034016

See also M. Graesser 1606.04549

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

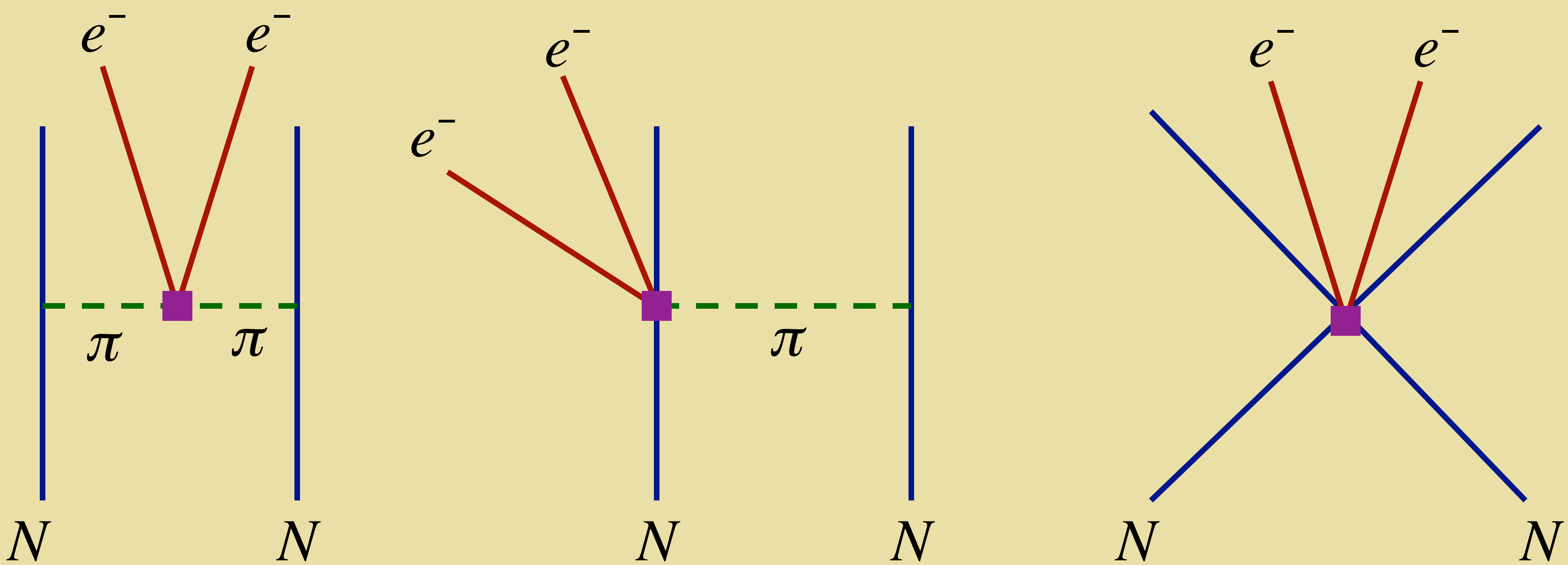


$K_{\pi\pi}\ p^{-2}$

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

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

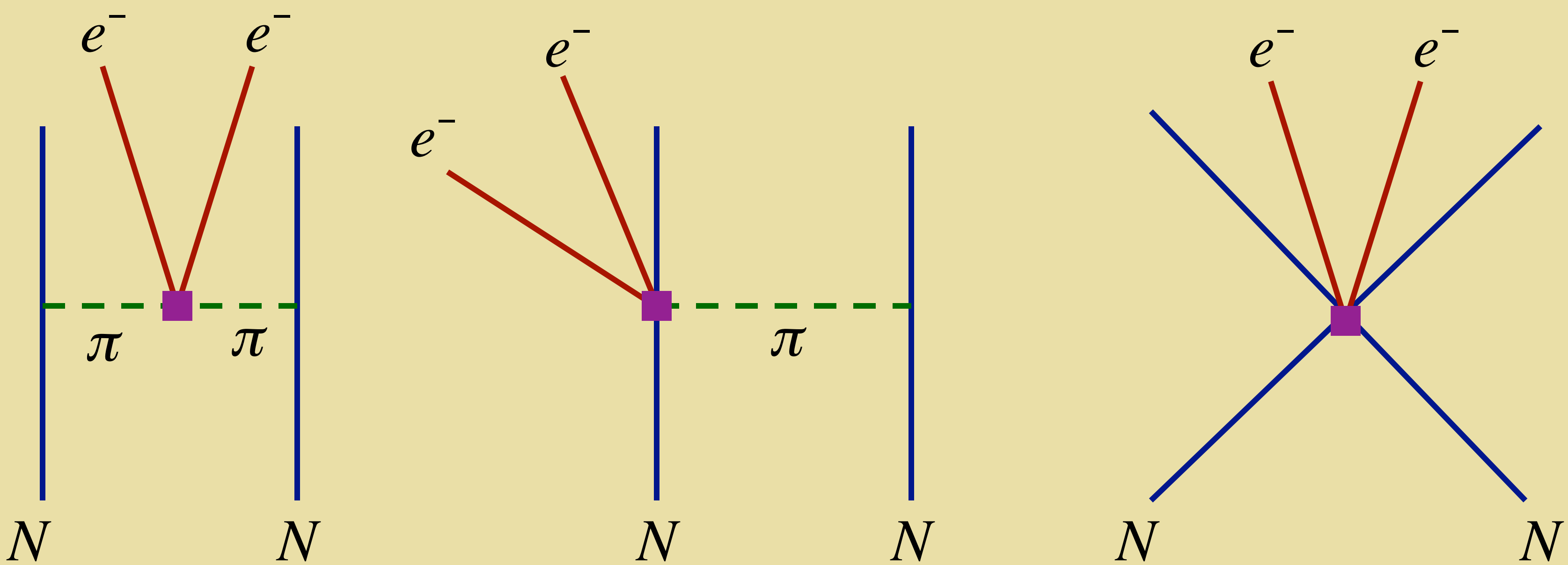
$0\nu\ \beta\beta$ - decay in effective field theory



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

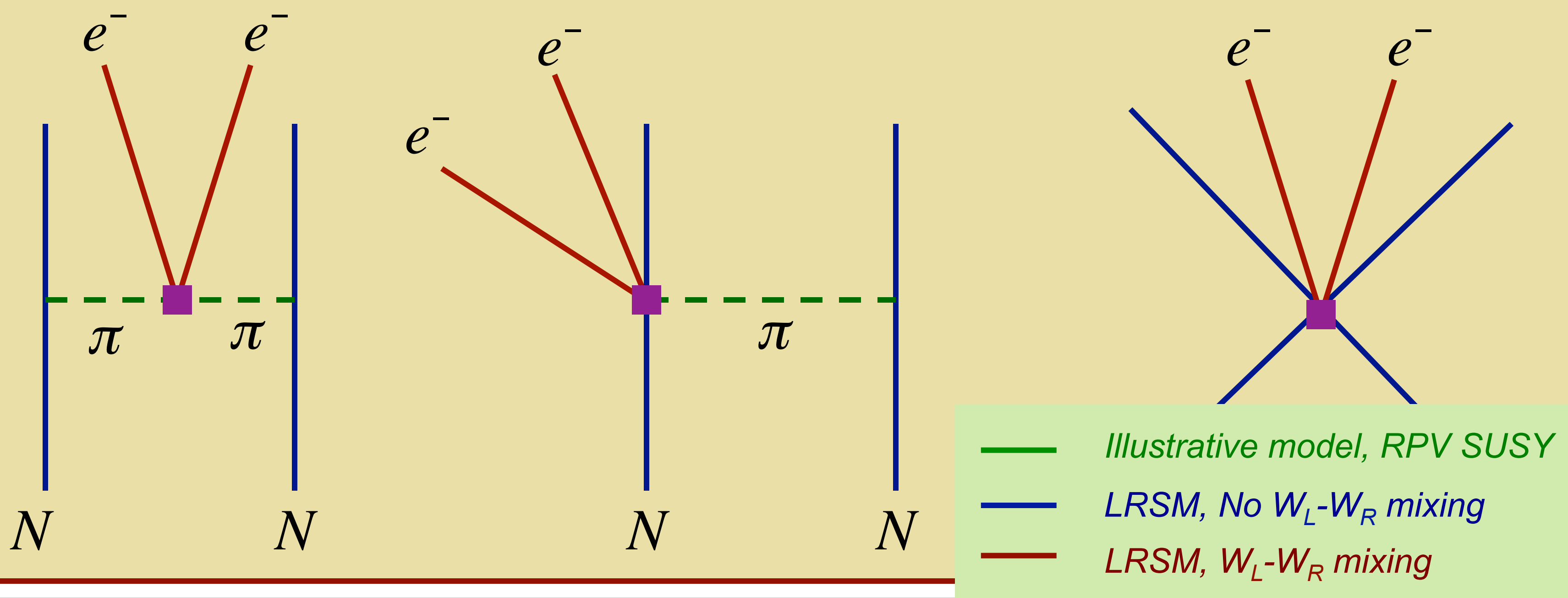
$\mathcal{O}(p^{-2})$ for $\hat{O}_{1+}^{++}$ $\quad$ $\mathcal{O}(p^{0})$ for $\hat{O}_{3+}^{++}$

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



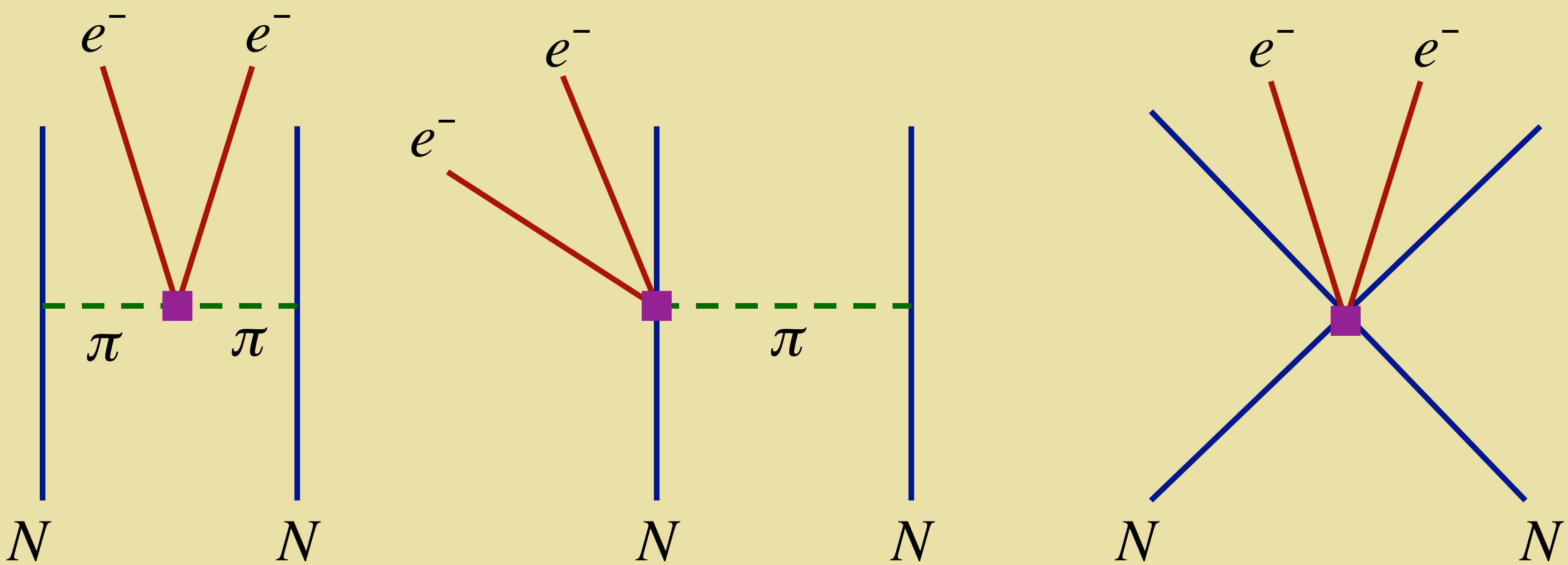
$0\nu\beta\beta$-decay ops.	$\mathcal{O}_{1+}^{\pm\pm}$	$\mathcal{O}_{2+}^{\pm\pm}$	$\mathcal{O}_{2-}^{\pm\pm}$	$\mathcal{O}_{3+}^{\pm\pm}$	$\mathcal{O}_{3-}^{\pm\pm}$	$\mathcal{O}_{4+}^{\pm\pm,\mu}$	$\mathcal{O}_{4-}^{\pm\pm,\mu}$	$\mathcal{O}_{5+}^{\pm\pm,\mu}$	$\mathcal{O}_{5-}^{\pm\pm,\mu}$
$\pi\pi ee$ LO	√	√	X	X	X	X	X	X	X
$\pi\pi ee$ NNLO	√	√	X	√	X	X	X	X	X
$NN\pi ee$ LO	X	X	√	X	X	√	√	√	√
$NN\pi ee$ NLO	X	√	X	√	X	√	√	√	√
$NNNNee$ LO	√	√	X	√	X	√	√	√	√

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



$0\nu\beta\beta$-decay ops.	$\mathcal{O}_{1+}^{\pm\pm}$	$\mathcal{O}_{2+}^{\pm\pm}$	$\mathcal{O}_{2-}^{\pm\pm}$	$\mathcal{O}_{3+}^{\pm\pm}$	$\mathcal{O}_{3-}^{\pm\pm}$	$\mathcal{O}_{4+}^{\pm\pm,\mu}$	$\mathcal{O}_{4-}^{\pm\pm,\mu}$	$\mathcal{O}_{5+}^{\pm\pm,\mu}$	$\mathcal{O}_{5-}^{\pm\pm,\mu}$
$\pi\pi ee$ LO	√	√	X	X	X	X	X	X	X
$\pi\pi ee$ NNLO	√	√	X	√	X	X	X	X	X
$NN\pi ee$ LO	X	X	√	X	X	√	√	√	√
$NN\pi ee$ NLO	X	√	X	√	X	√	√	√	√
$NNNNee$ LO	√	√	X	√	X	√	√	√	√

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



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

Hadronic matrix elements: M. Graesser talk

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

Rate

$$\frac{1}{T_{1/2}} = G_{01}\left(\frac{\mathrm{TeV}}{m_e}\right)^2\left(\frac{\Lambda_H}{\mathrm{TeV}}\right)^4\left(\frac{1}{18}\right)\left(\frac{v}{\mathrm{TeV}}\right)^8 \times\left(\frac{1}{g_A\cos\theta_C}\right)^4|M_0|^2\left[\frac{C_{\mathrm{eff}}^2}{(\Lambda/\mathrm{TeV})^{10}}\right],$$

$$G_{01} = (G_F\cos\theta_C)^4\left(\frac{\hbar c}{R}\right)^2\left(\frac{m_e^2 g_A^4}{32\pi^5\hbar\ln 2}\right)I(E_{\beta\beta}),$$

Rate

Hadronic matrix element *Nuclear matrix element*

$$\frac{1}{T_{1/2}} = G_{01}\left(\frac{\text{TeV}}{m_e}\right)^2\left(\frac{\Lambda_H}{\text{TeV}}\right)^4\left(\frac{1}{18}\right)\left(\frac{v}{\text{TeV}}\right)^8$$

$$\times\left(\frac{1}{g_A\cos\theta_C}\right)^4|M_0|^2\left[\frac{C_{\text{eff}}^2}{(\Lambda/\text{TeV})^{10}}\right],$$

$$G_{01} = (G_F\cos\theta_C)^4\left(\frac{\hbar c}{R}\right)^2\left(\frac{m_e^2 g_A^4}{32\pi^5\hbar\ln 2}\right)I(E_{\beta\beta}),$$

Phase space

Putting Pieces Together

0νββ-Decay: TeV Scale LNV

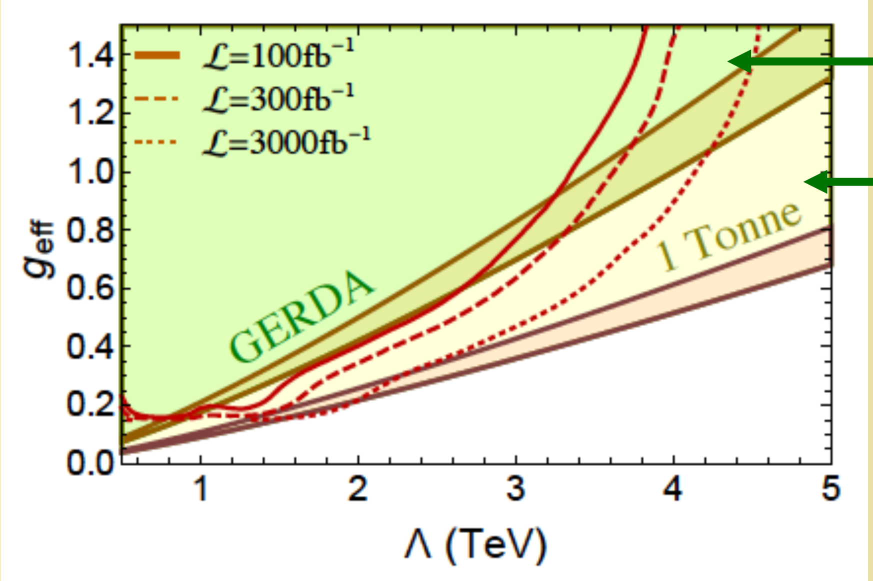
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

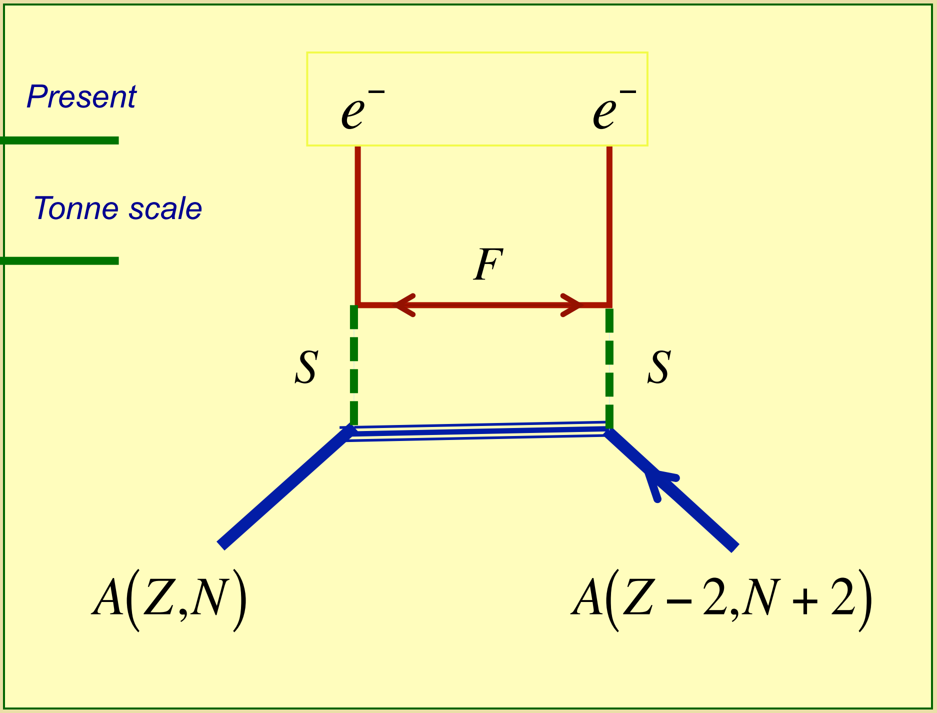
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

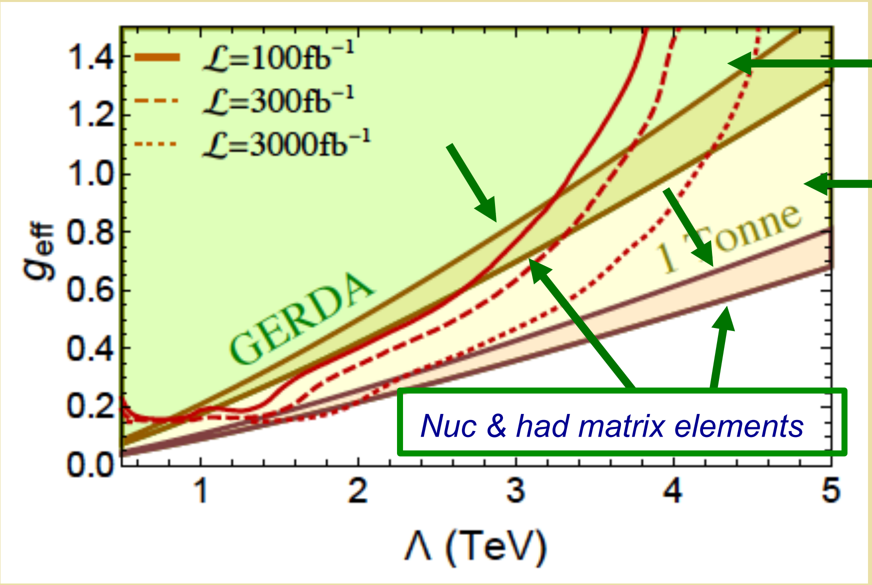
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

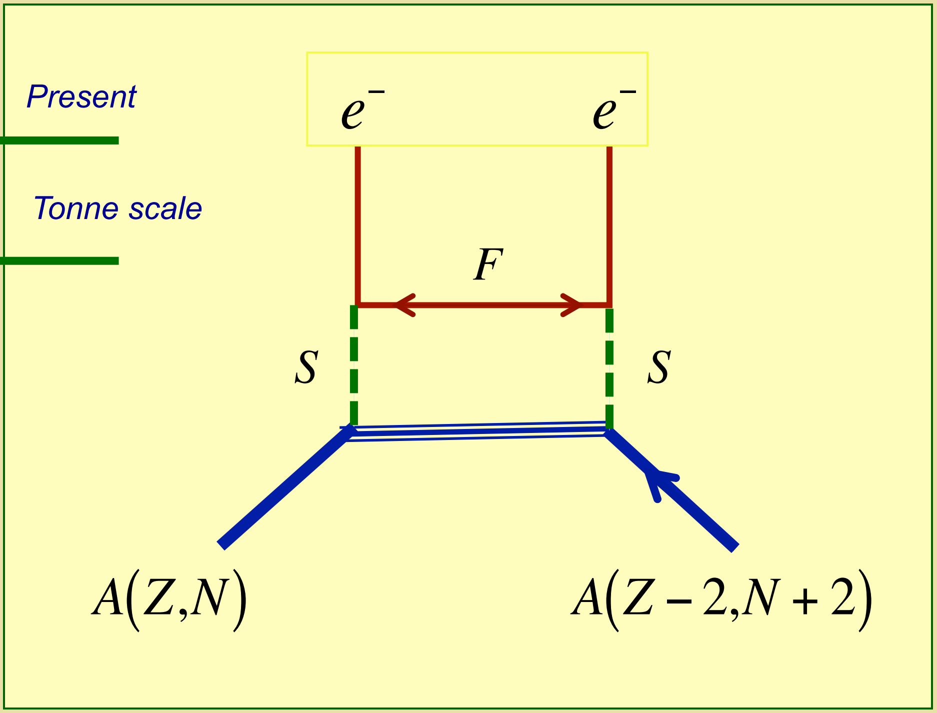
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





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

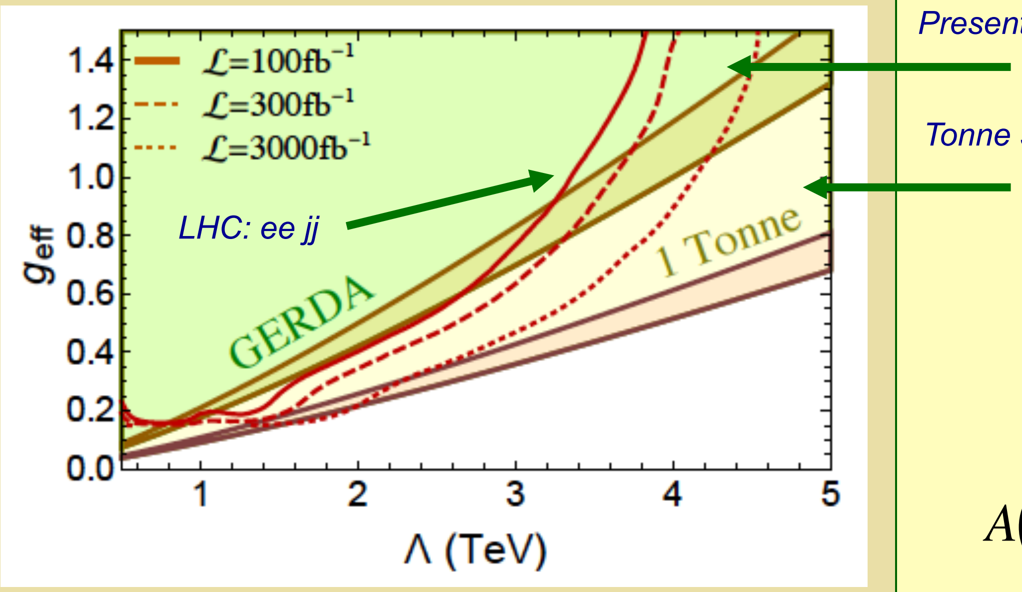
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

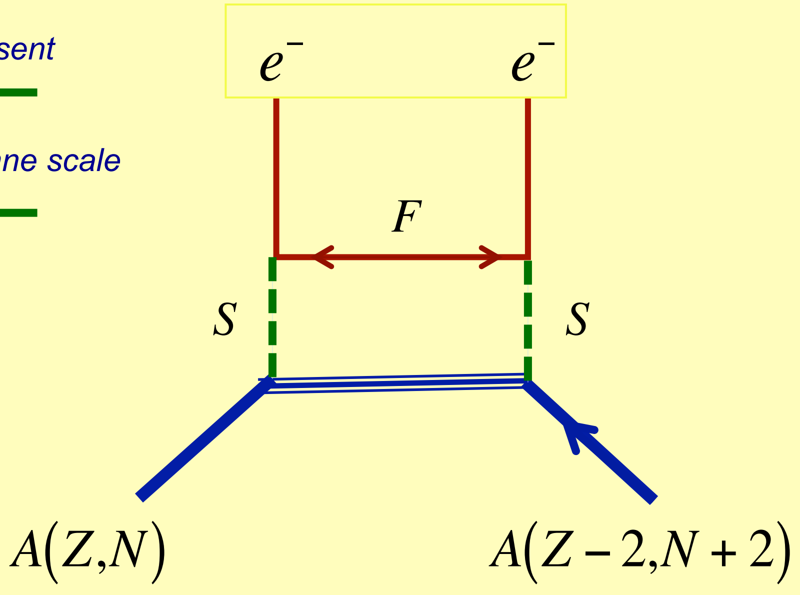
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





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

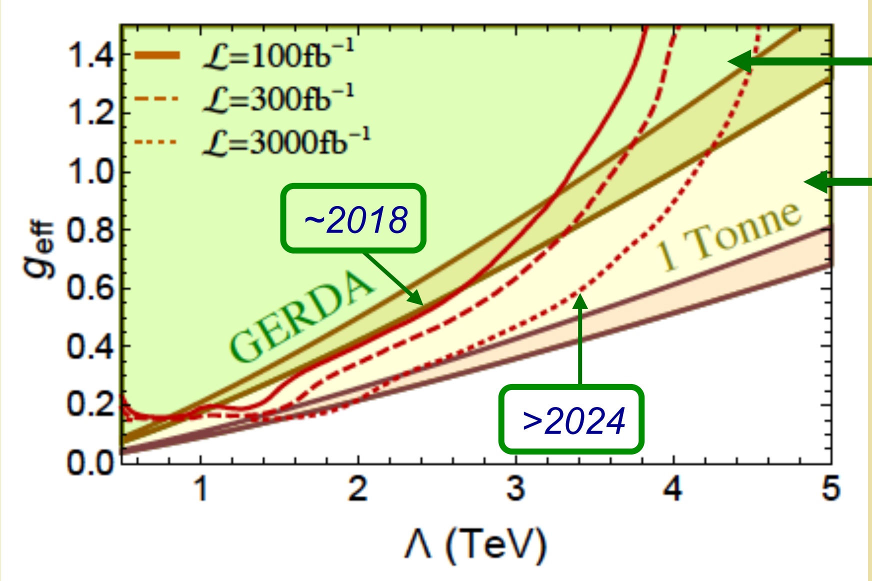
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

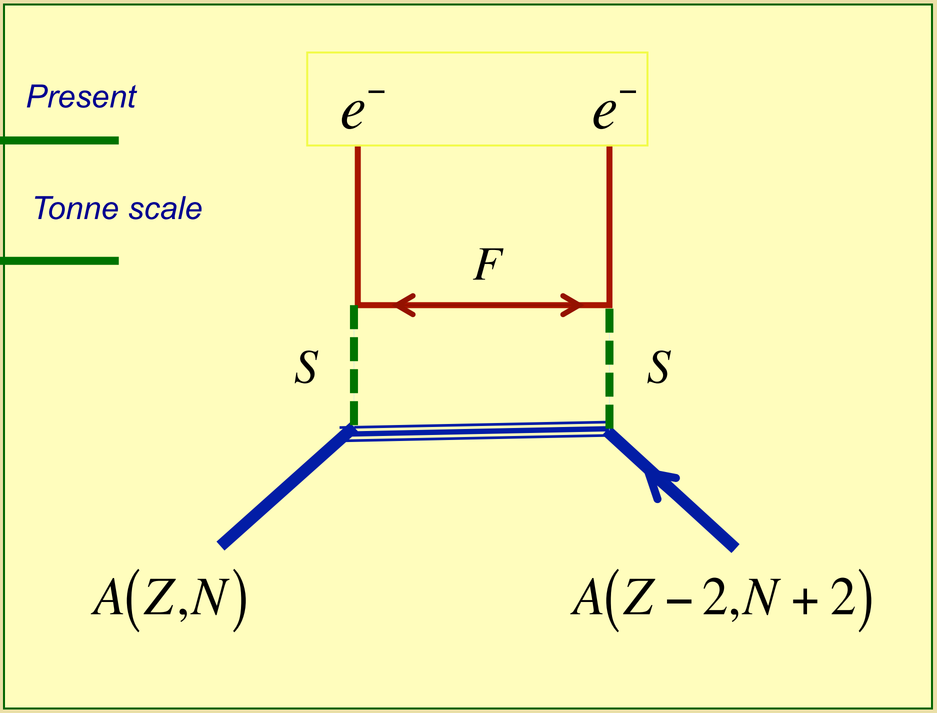
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





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

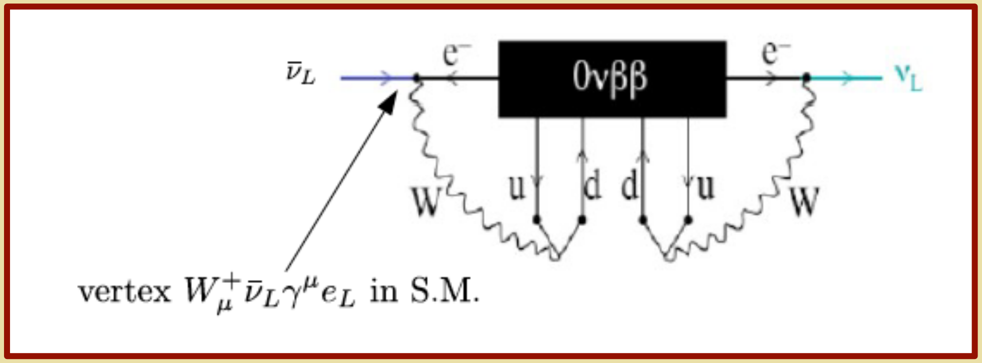
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

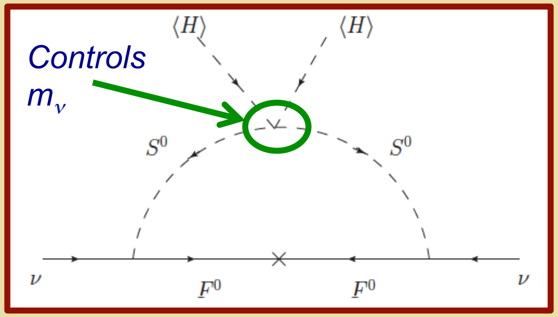
Dirac

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

Majorana

Implications for m_ν:





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

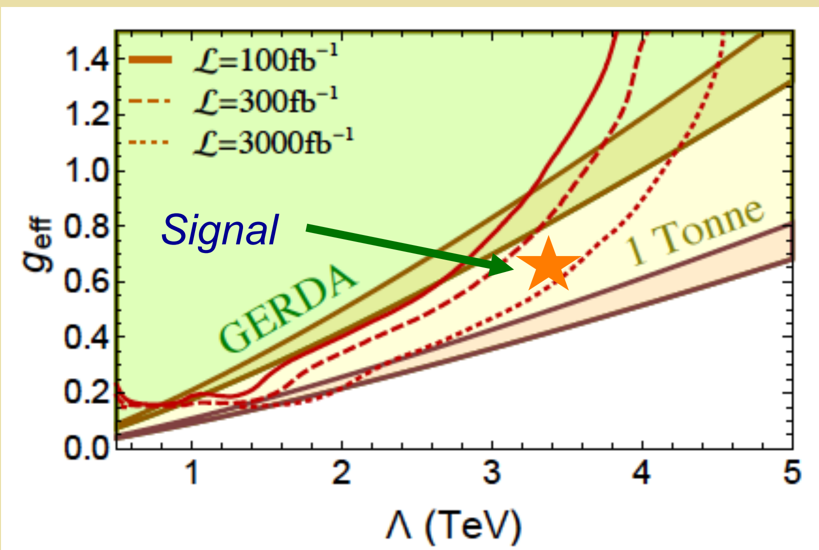
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R + \text{h.c.}$$

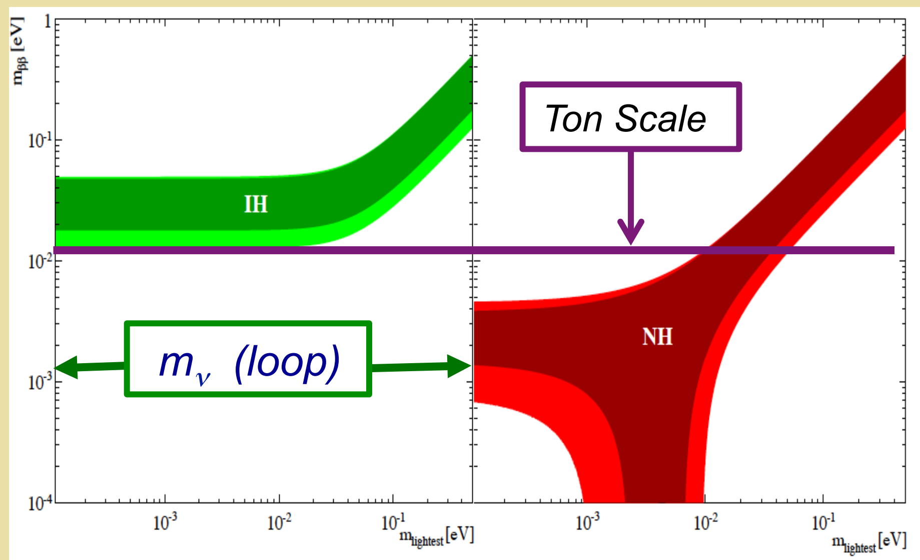
Dirac

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

Majorana

Implications for m_ν:





A hypothetical scenario

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

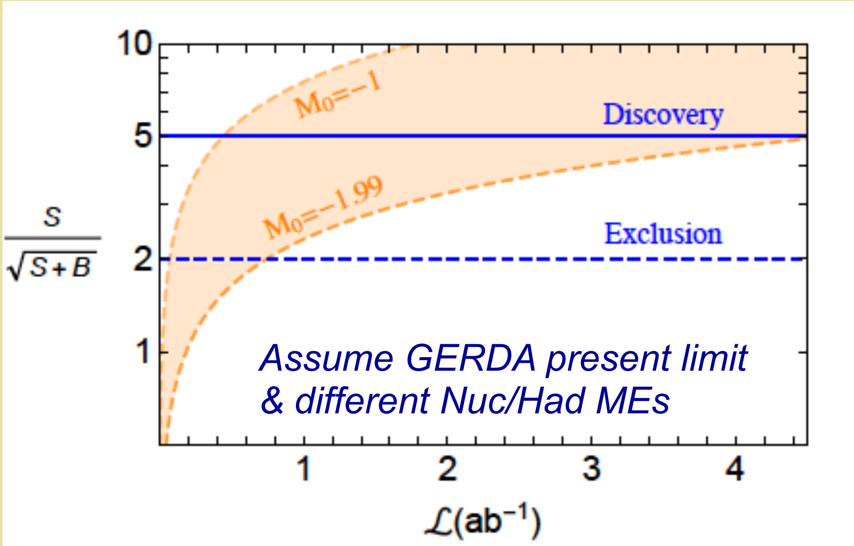
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

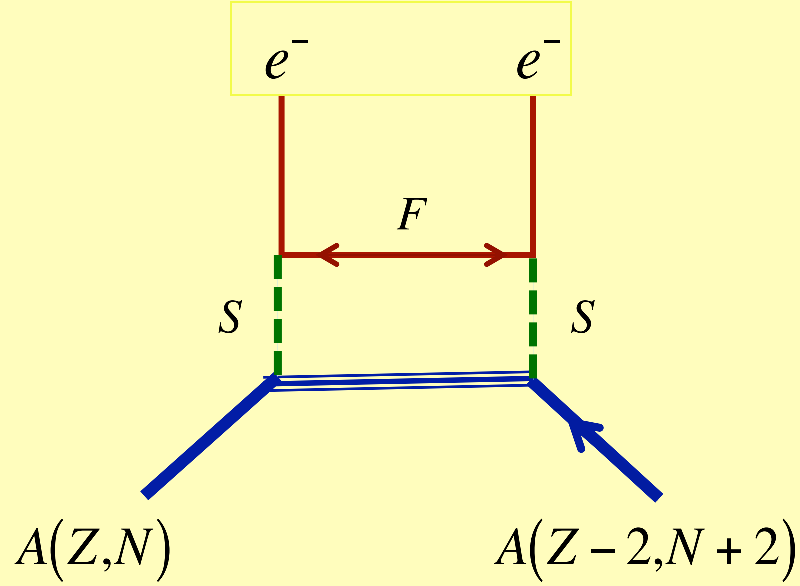
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





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0νββ / LHC Interplay: Matrix Elements

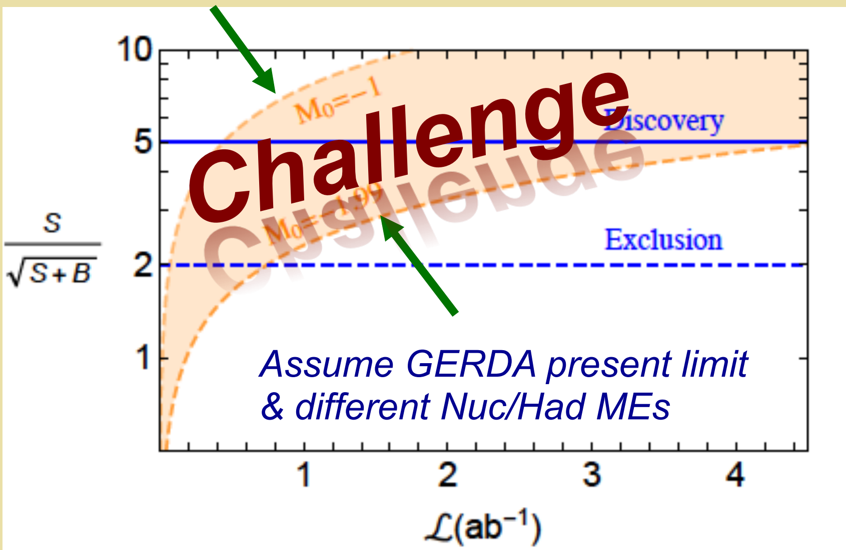
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

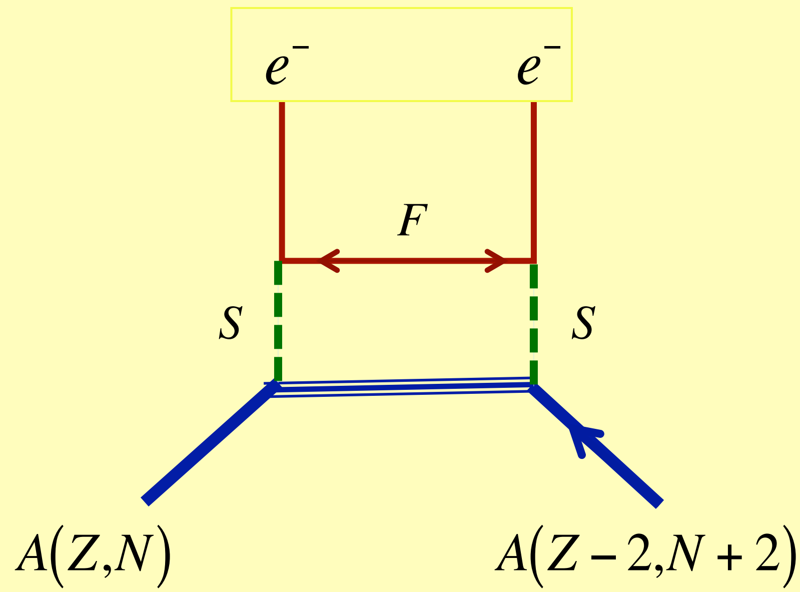
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





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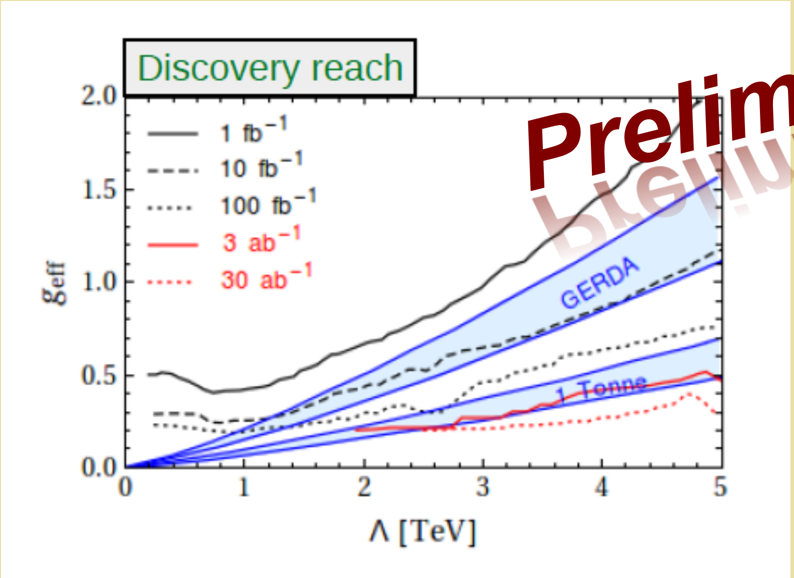
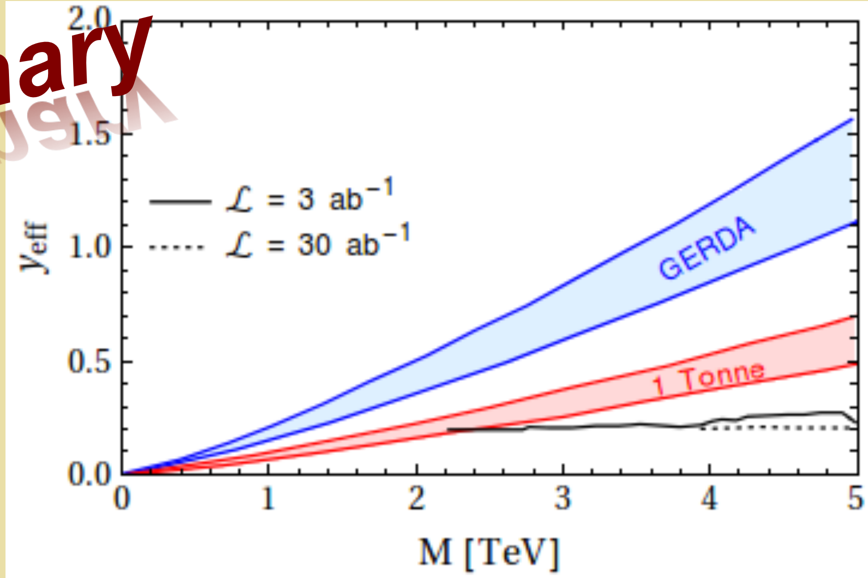
LNV: pp at 100 TeV





Cut based analysis

Machine learning

M. Graesser, T. Peng,
MJRM, P. Winslow in prog…

V. Summary

- ***LNV interactions responsible for m_ν may live at any scale from the conventional see-saw scale to the sub-GeV scale***
- ***TeV scale LNV is theoretically well-motivated and would have important implications for baryogenesis if it exists***
- ***$0\nu\beta\beta$-decay and collider searches provide complementary probes of this scenario***
- ***Fully exploiting this inter-frontier interface requires careful analysis of backgrounds, running, matching, and nuclear physics dynamics***

Back Up Slides

IV. Sub Weak Scale LNV

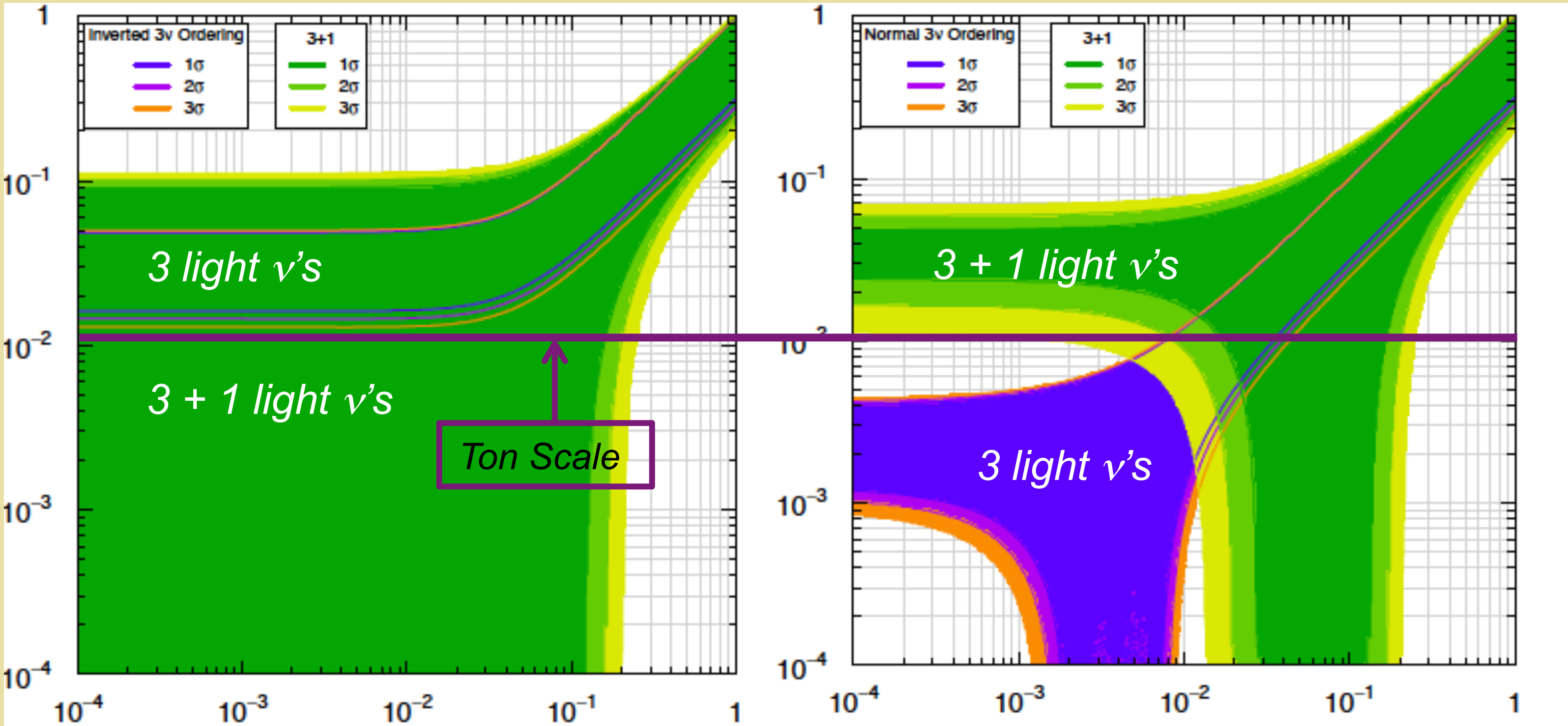
LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **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*

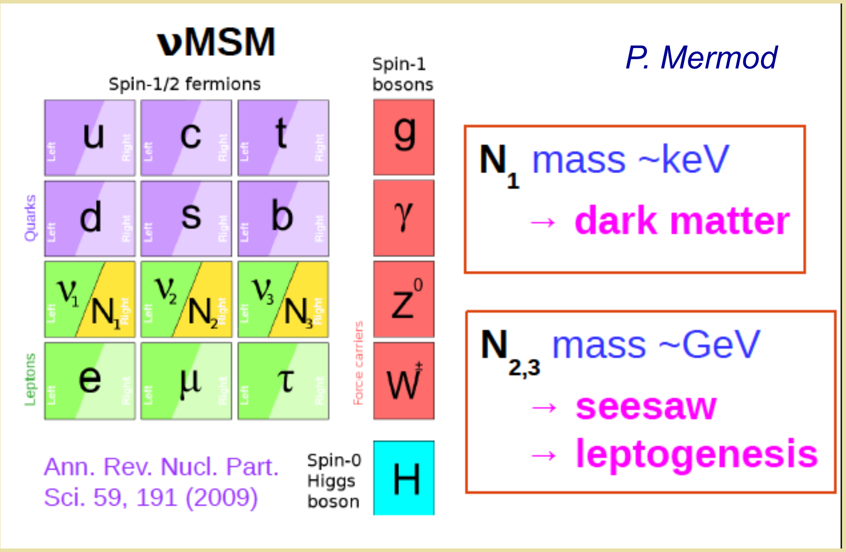
LNV Mass Scale & $0\nu\beta\beta$-Decay

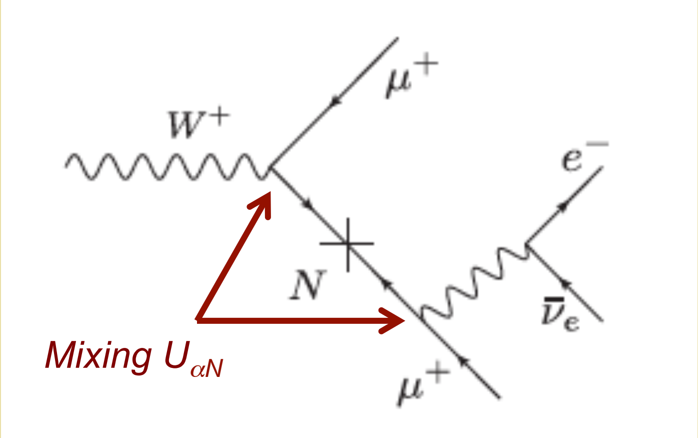
Effective DBD neutrino mass (eV) →

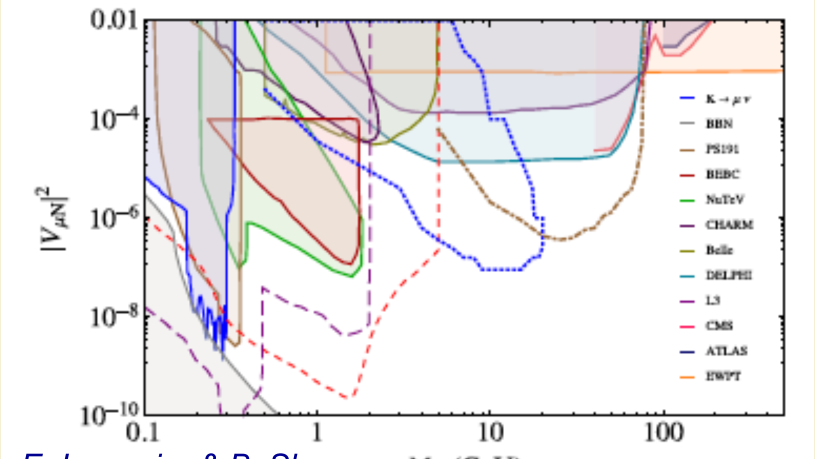


Lightest neutrino mass (eV) →

Sub Weak Scale LNV

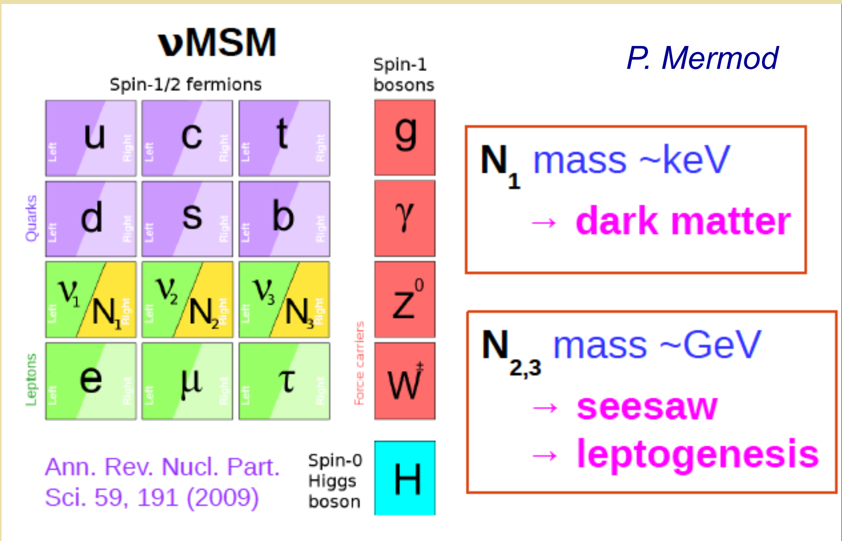


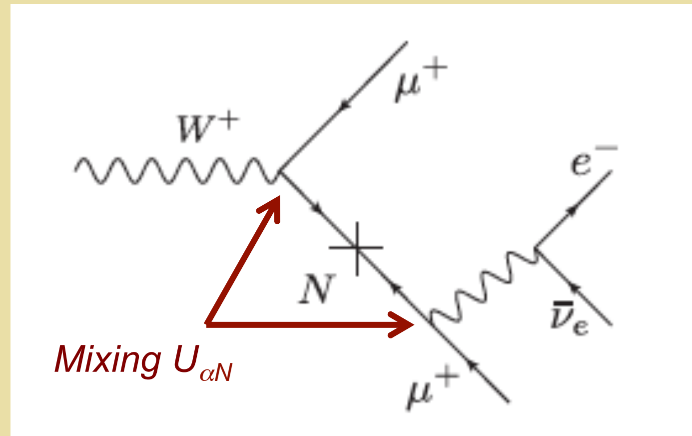


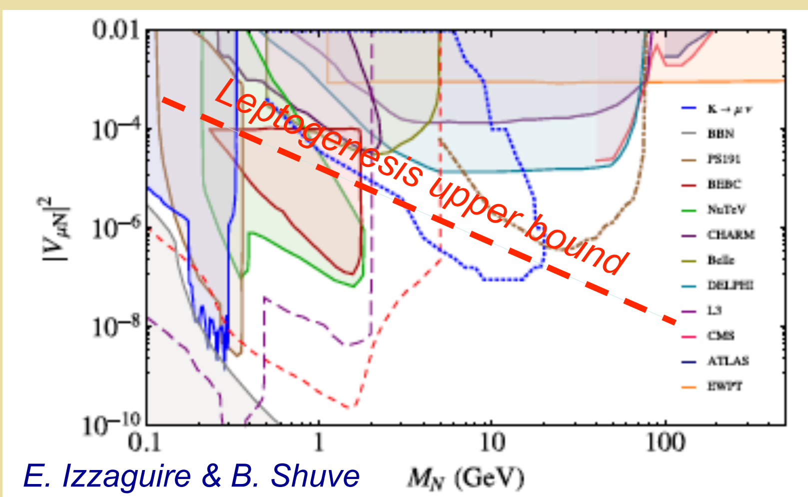


E. Izzaguire & B. Shuve

Sub Weak Scale LNV



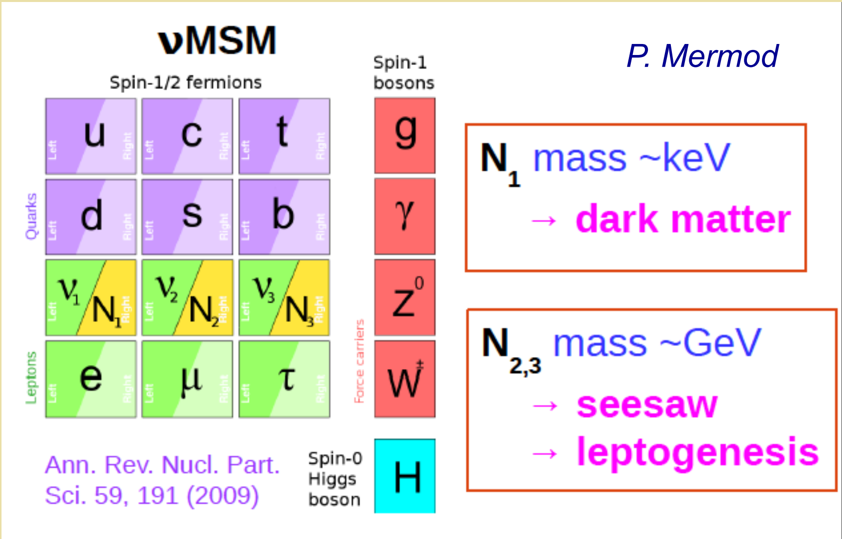


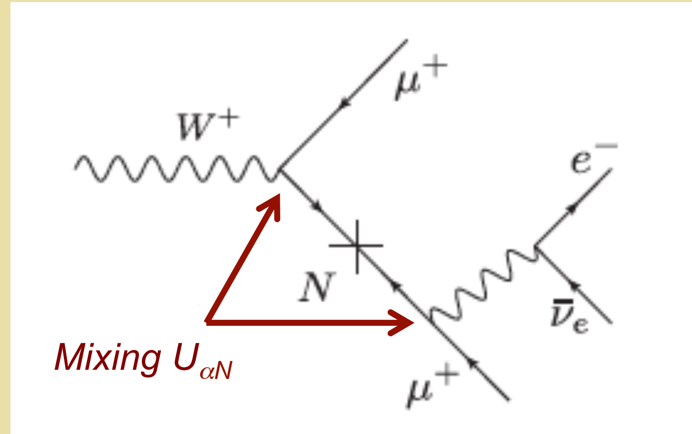


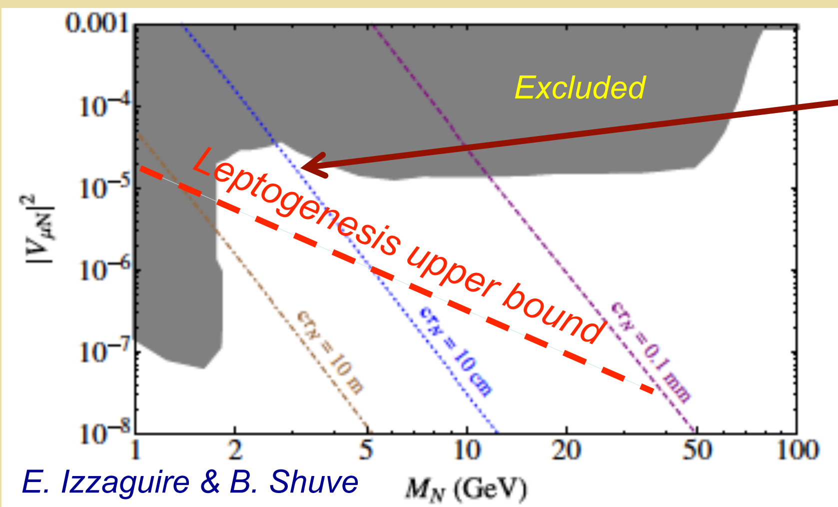
BAU from Leptogenesis

- *Drewes et al '16*
- *Lower bound < 10^{-10}*

Sub Weak Scale LNV



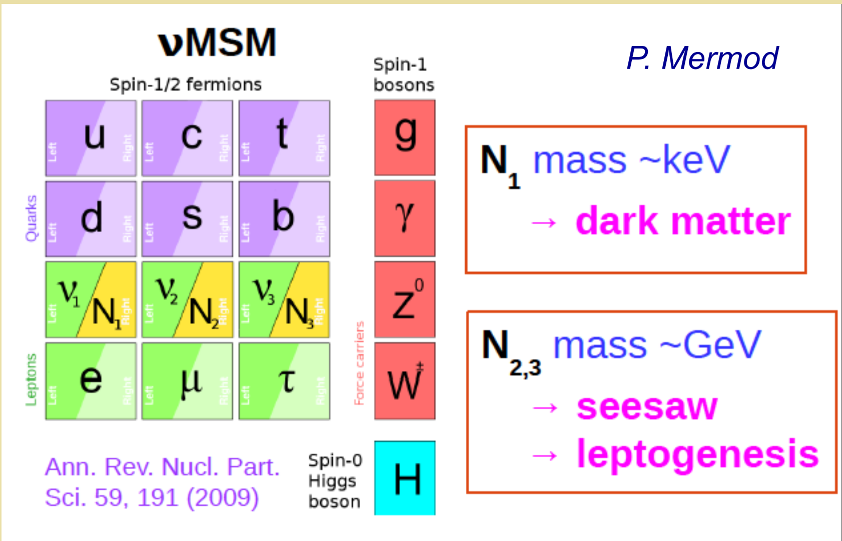


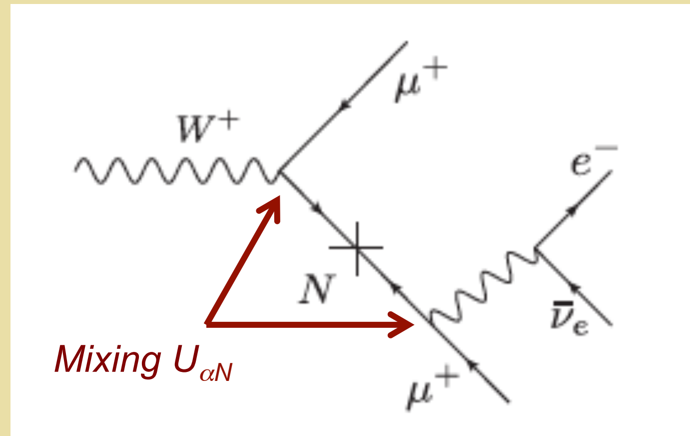


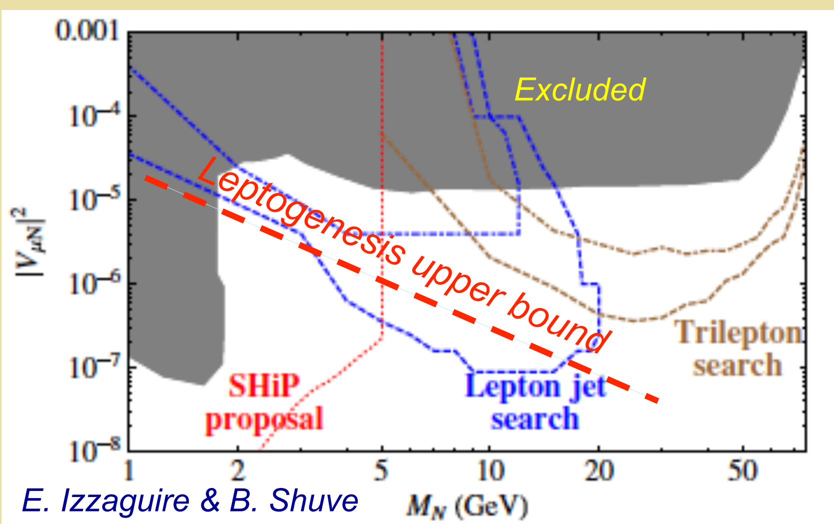
$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

See also: Helo, Kovalenko & Hirsch

Sub Weak Scale LNV



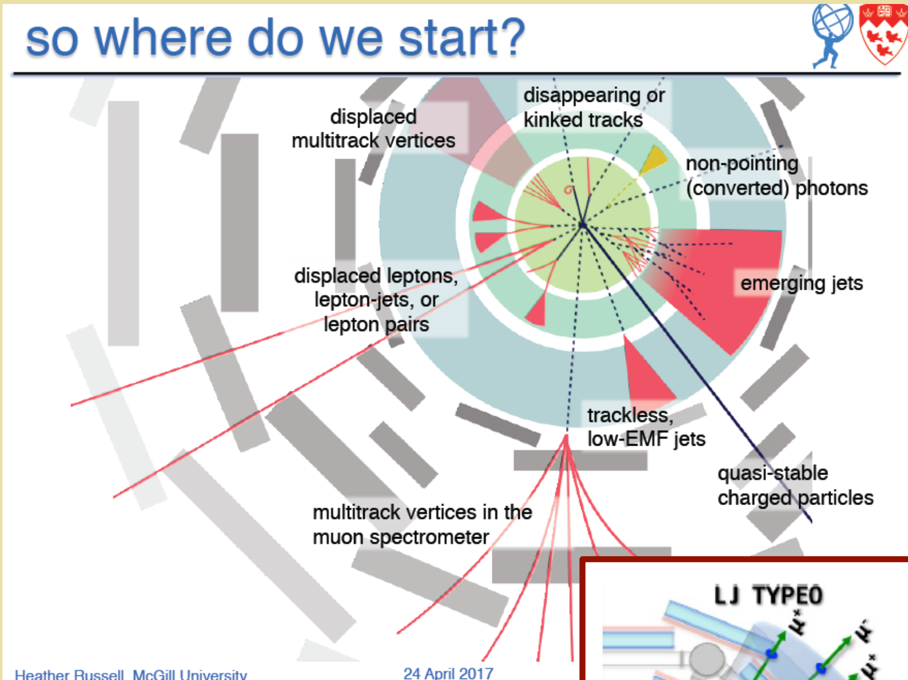




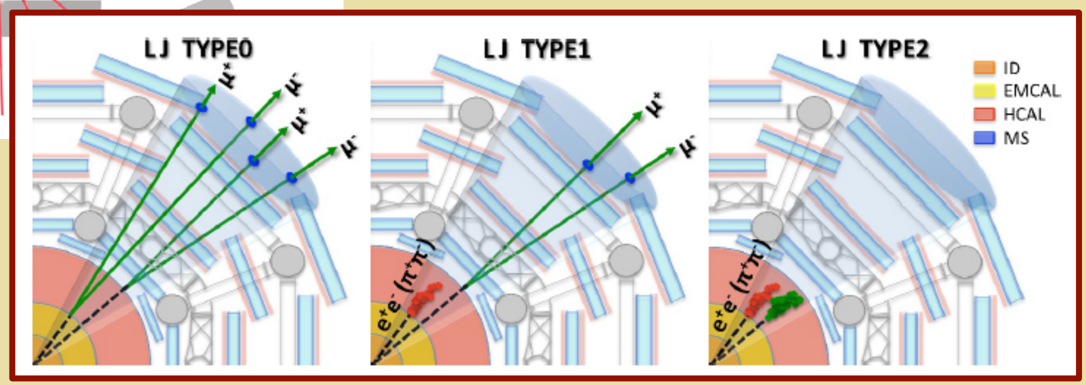
$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

- *Displaced LJ + μ*
- *3 resolved prompt leptons*

Displaced Lepton Jets



H. Russell, CERN LLP workshop, April 17



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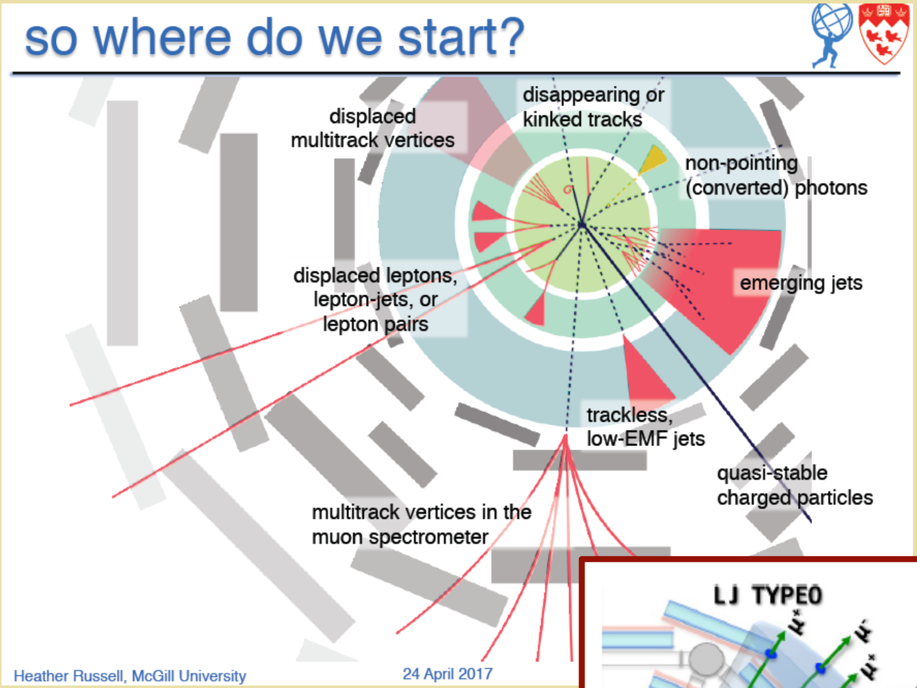
Displaced Lepton Jets



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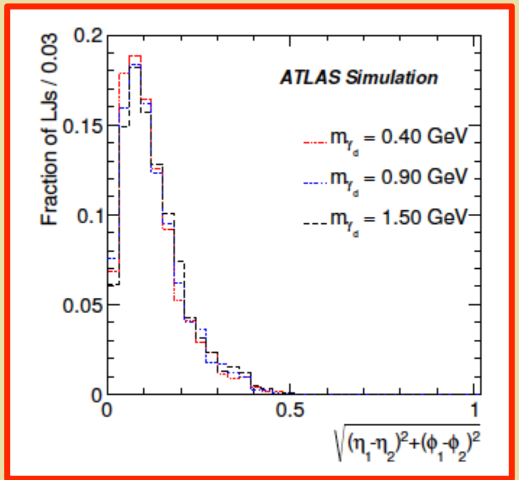

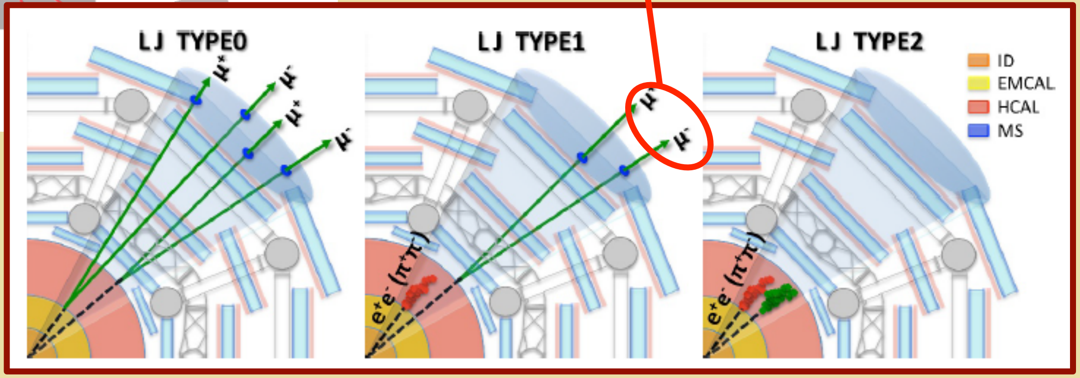

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Models

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

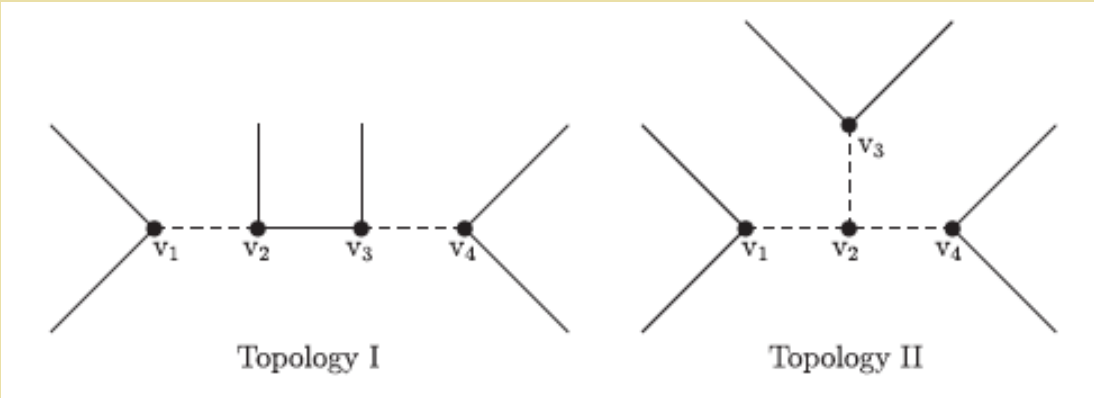
$$\mathcal{L}_{\mathrm{mass}} = y \bar{L} \tilde{H} \nu_R \ + \ \mathrm{h.c.}$$

Dirac

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

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



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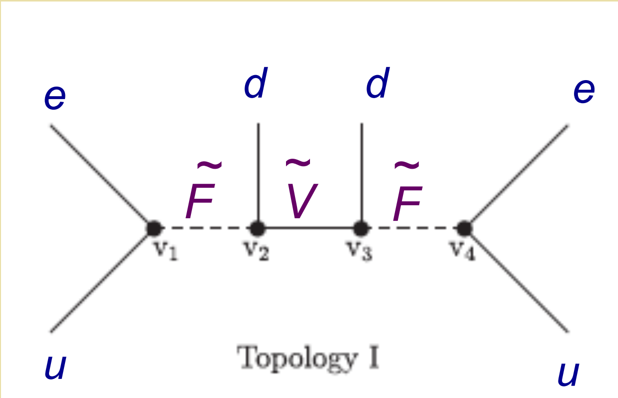

SUSY: R Parity-Violation

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

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

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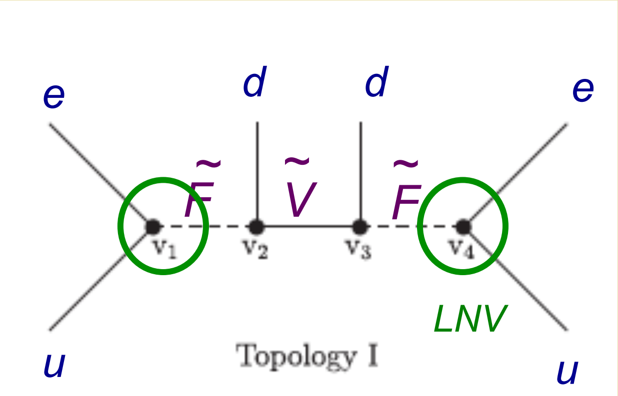

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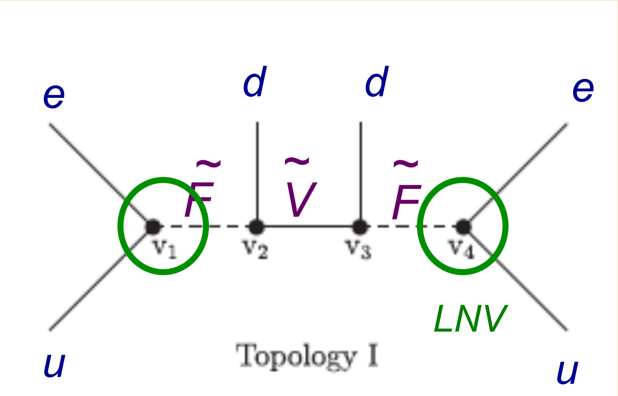

SUSY: R Parity-Violation

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

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

0νββ-Decay: TeV Scale LNV

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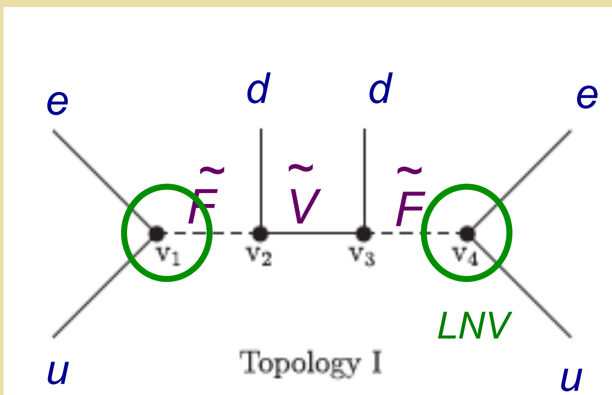

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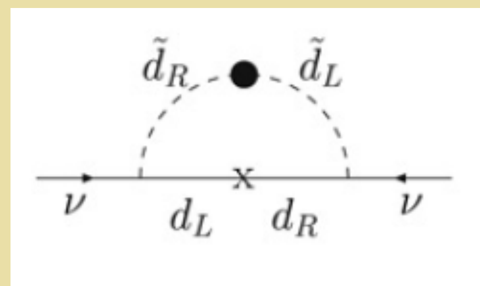

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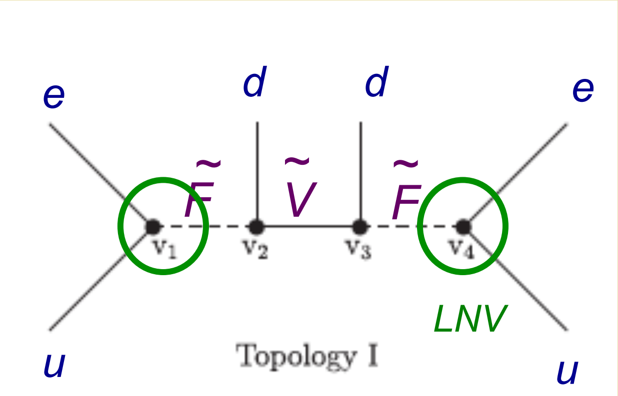

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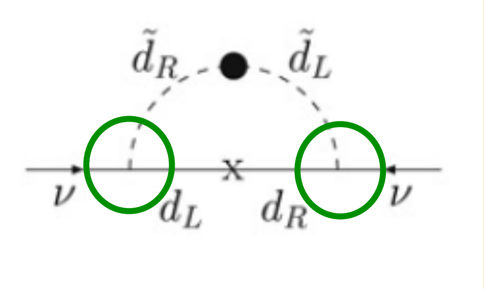

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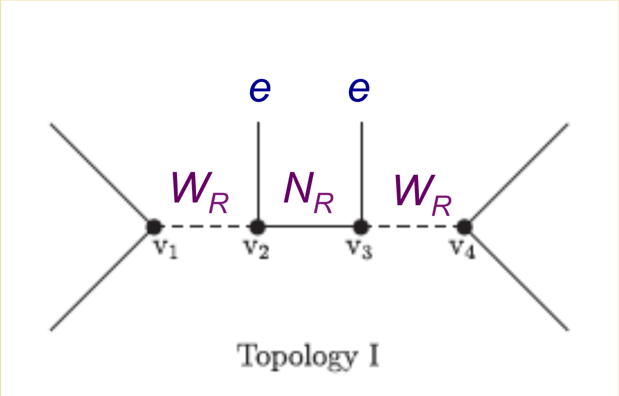


LRSM: Type I See-Saw

Mass: standard see-saw but TeV scale

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

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

Dirac

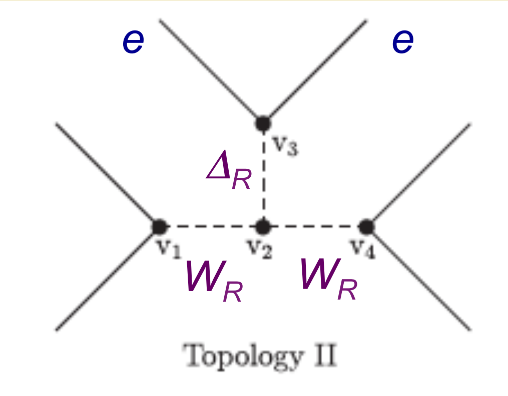
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011

LRSM: Type II See-Saw

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



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

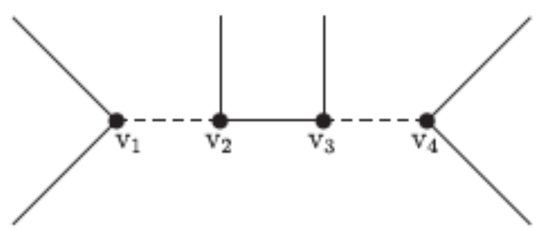
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

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



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

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

Dirac

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

Majorana

What can we learn from the LHC?

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

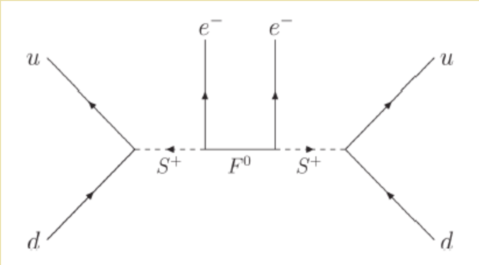
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

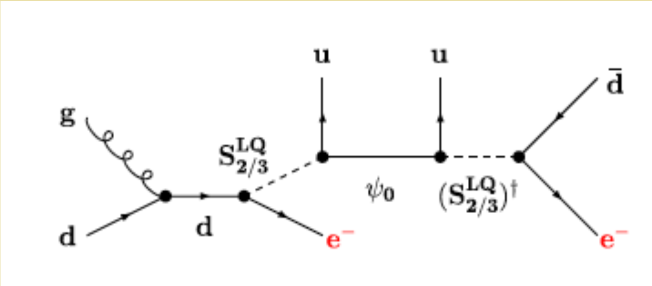
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

LHC Production



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



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