# TeV Scale LNV: $0\nu\beta\beta$-Decay & the LHC

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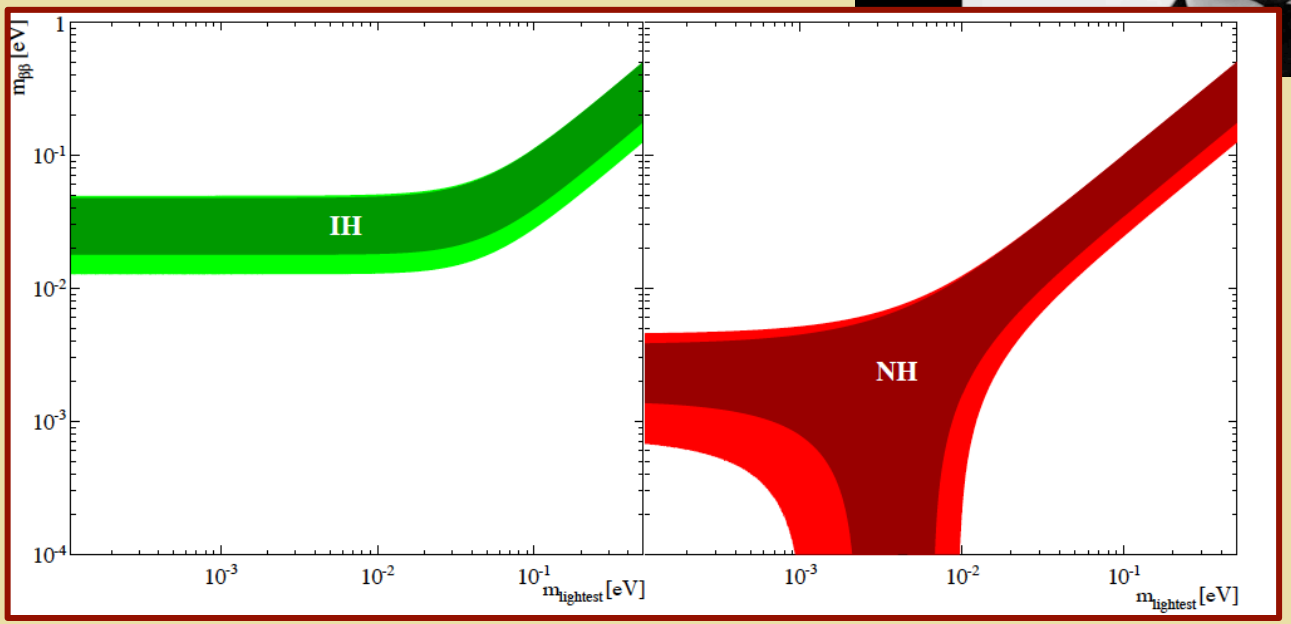
*U Mass Amherst*


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

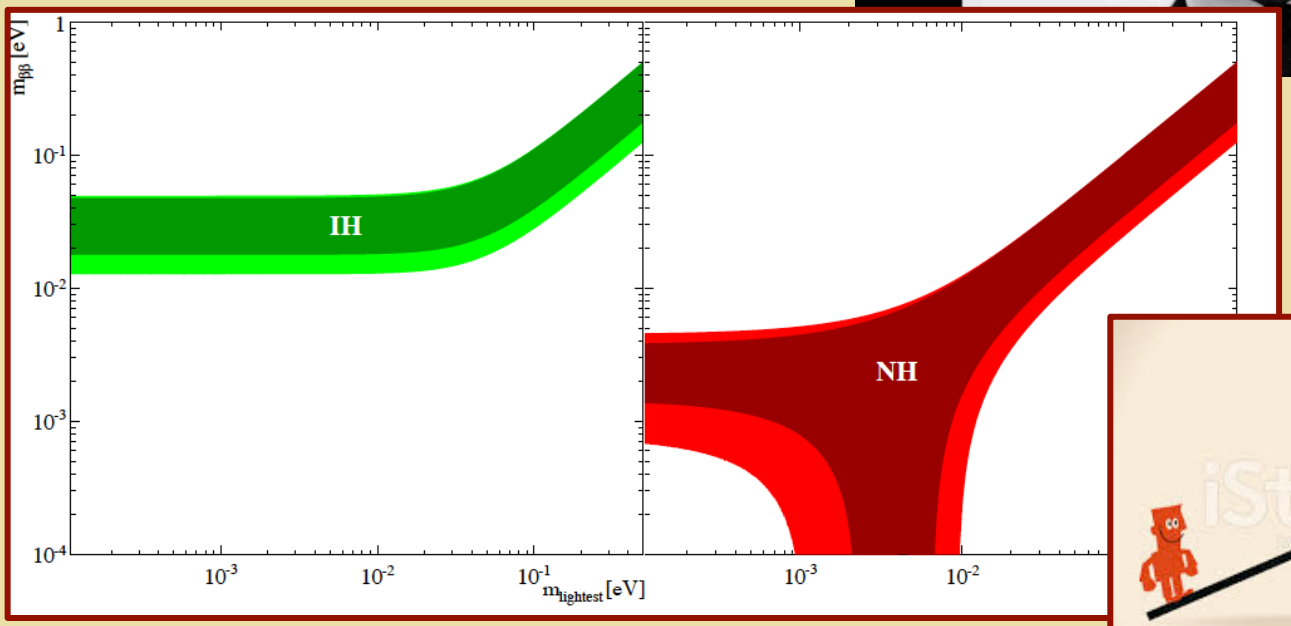
*Collaborators: Tao Peng, Peter Winslow; V. Cirigliano, M. Graesser, M. Horoi, P. Vogel*

INT $0\nu\beta\beta$-Decay Workshop
June 2017

# *This talk: beyond the "poster child"*

# *This talk: beyond the "poster child"*


# *Themes for This Talk*

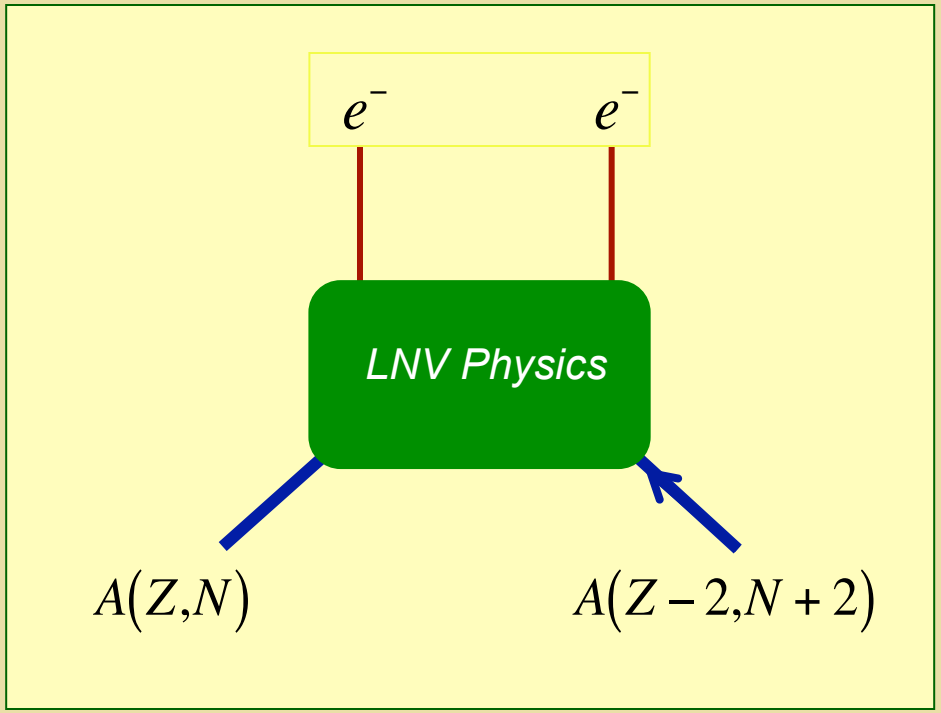
# $0\nu\beta\beta$-Decay: LNV? Mass Term?

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

*Dirac*

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

*Majorana*



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

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

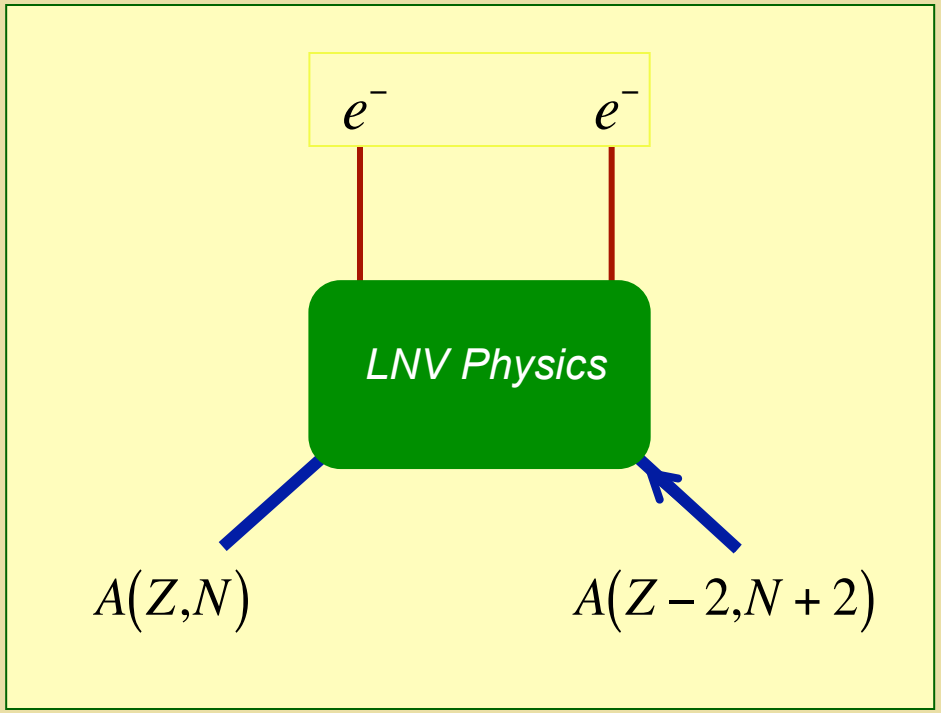
*Dirac*

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

*Majorana*

## Impact of observation

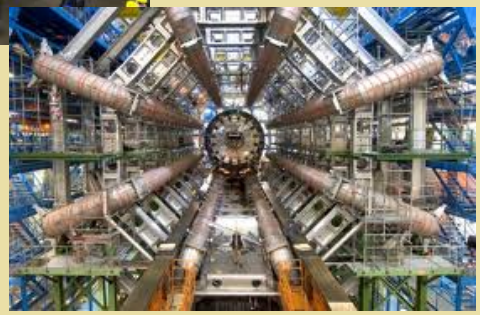
- *Total lepton number not conserved at classical level*
- *New mass scale in nature, $\Lambda$*
- *Key ingredient for standard baryogenesis via leptogenesis*



# LNV: Discoverable at the Energy Frontier

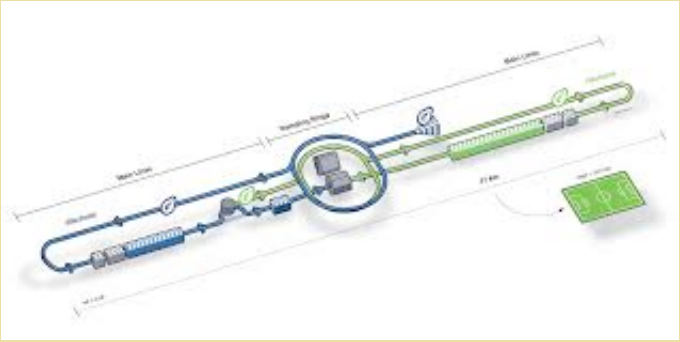
*LHC*

*ATLAS*

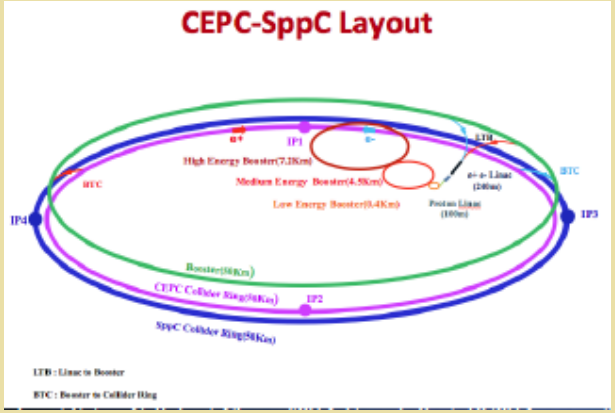


*CMS*

*International Linear Collider*



*Future Circular $e^+e^-$ & pp*

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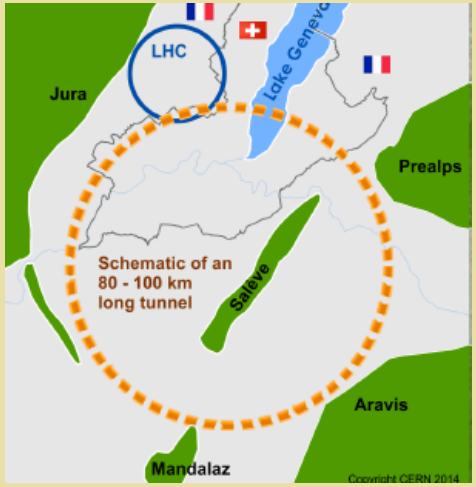



*Thanks: S. Gascon-Shotkin*

# *Outline*

*I. The BSM Context*

*II. High Scale LNV*

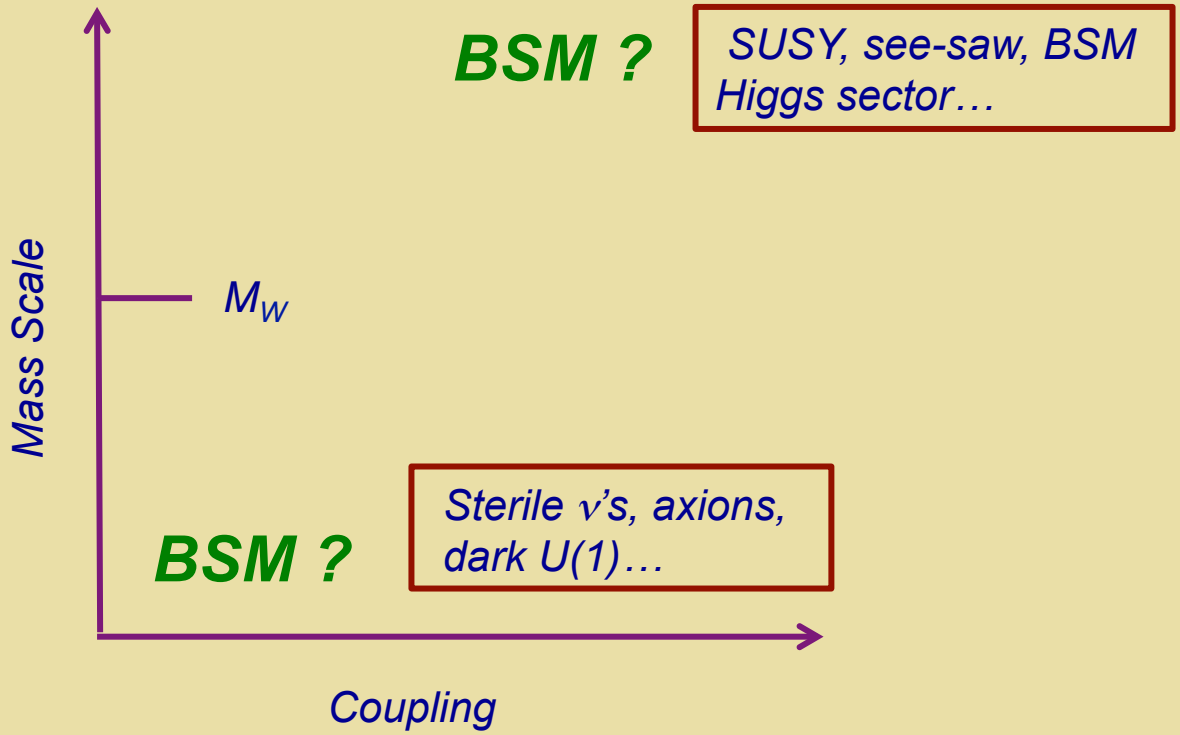
*III. TeV Scale LNV*

*IV. Sub Weak Scale LNV (time permitting)*

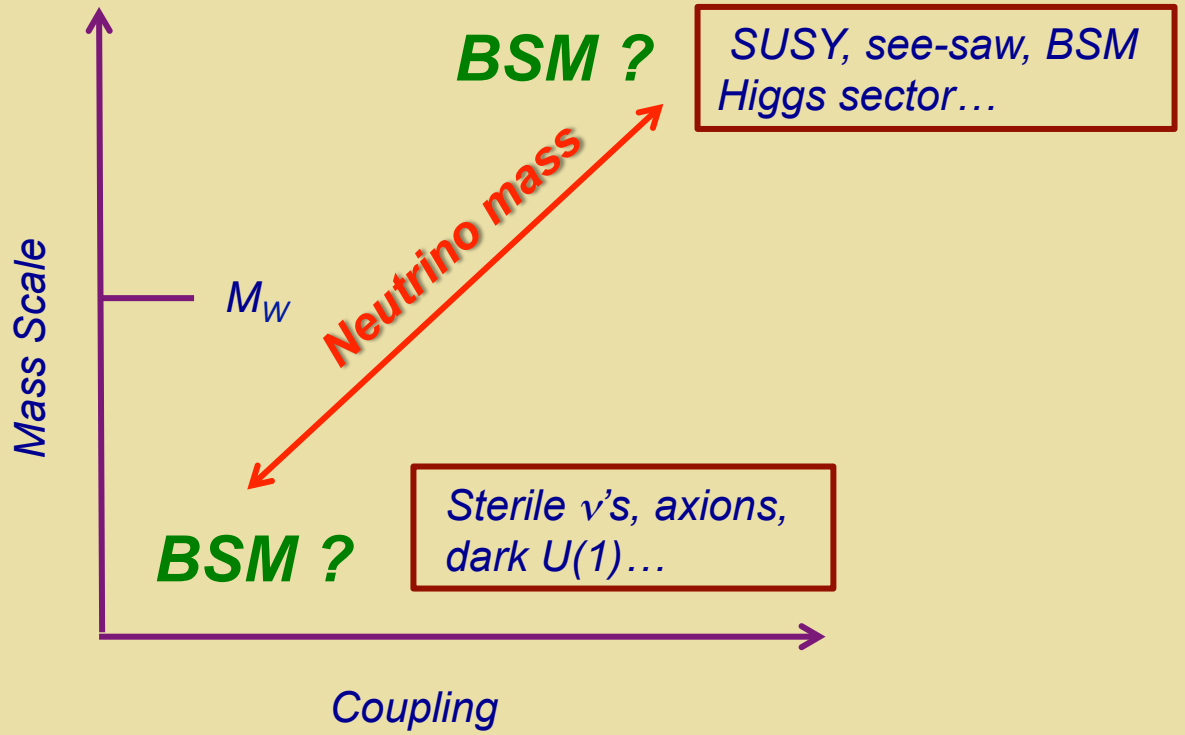
*V. Summary*

# *I. The BSM Context*

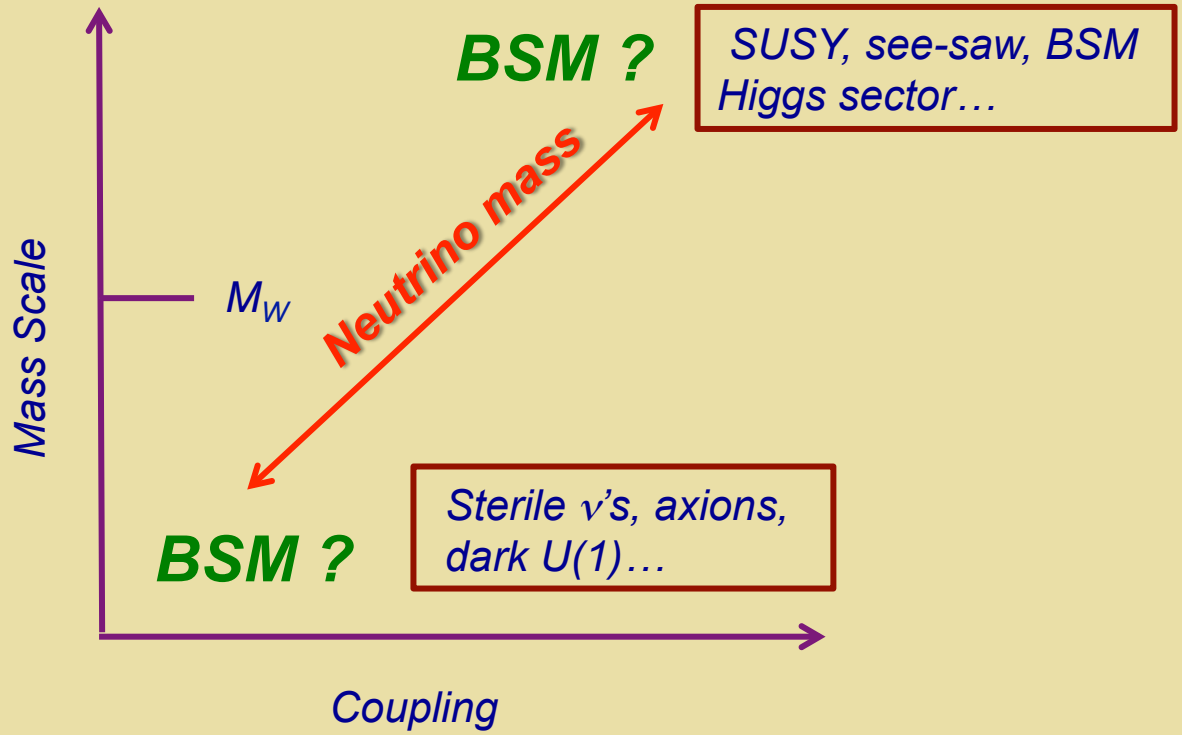
# BSM Physics: Where Does it Live ?



# BSM Physics: Where Does it Live ?



# BSM Physics: Where Does it Live ?




***Is the mass scale associated with $m_\nu$ far above $M_W$ ? Near $M_W$ ? Well below $M_W$ ?***

# 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*

# *II. 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*

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

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

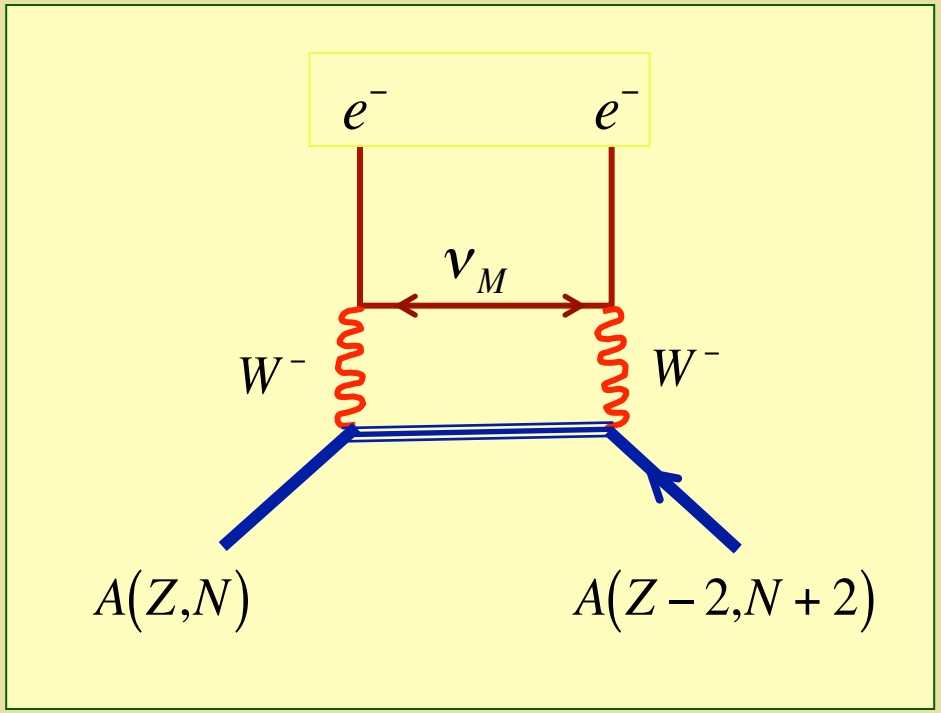
*Dirac*

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

*Majorana*

## "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*



# *Details*

***Essentially the rest of this workshop…***

# *III. TeV 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*

*Two parameters: Effective coupling & effective heavy particle mass*

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

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

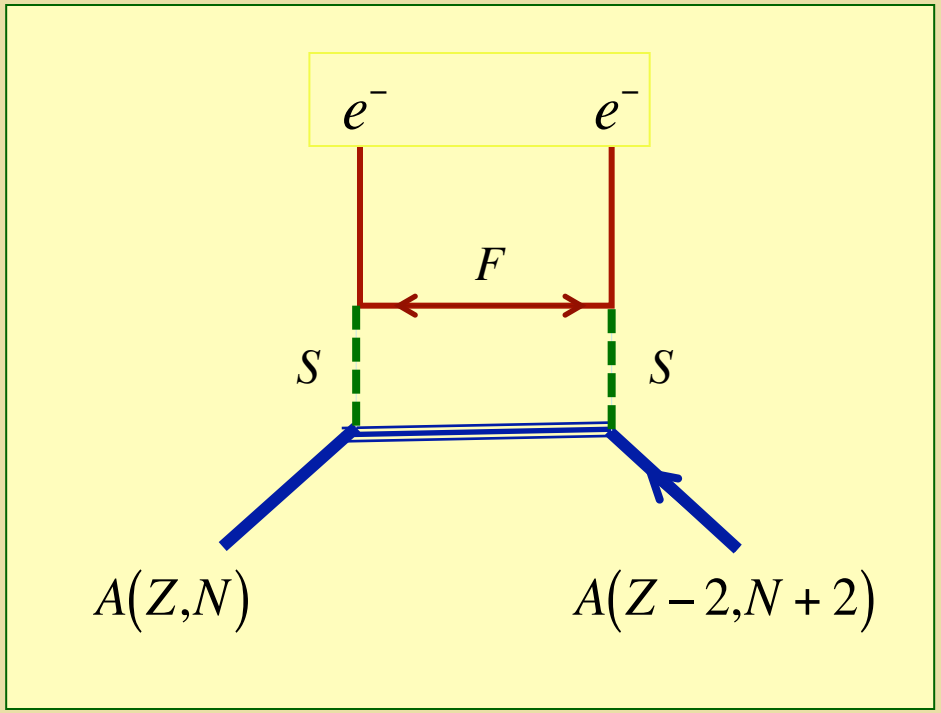
*Dirac*

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

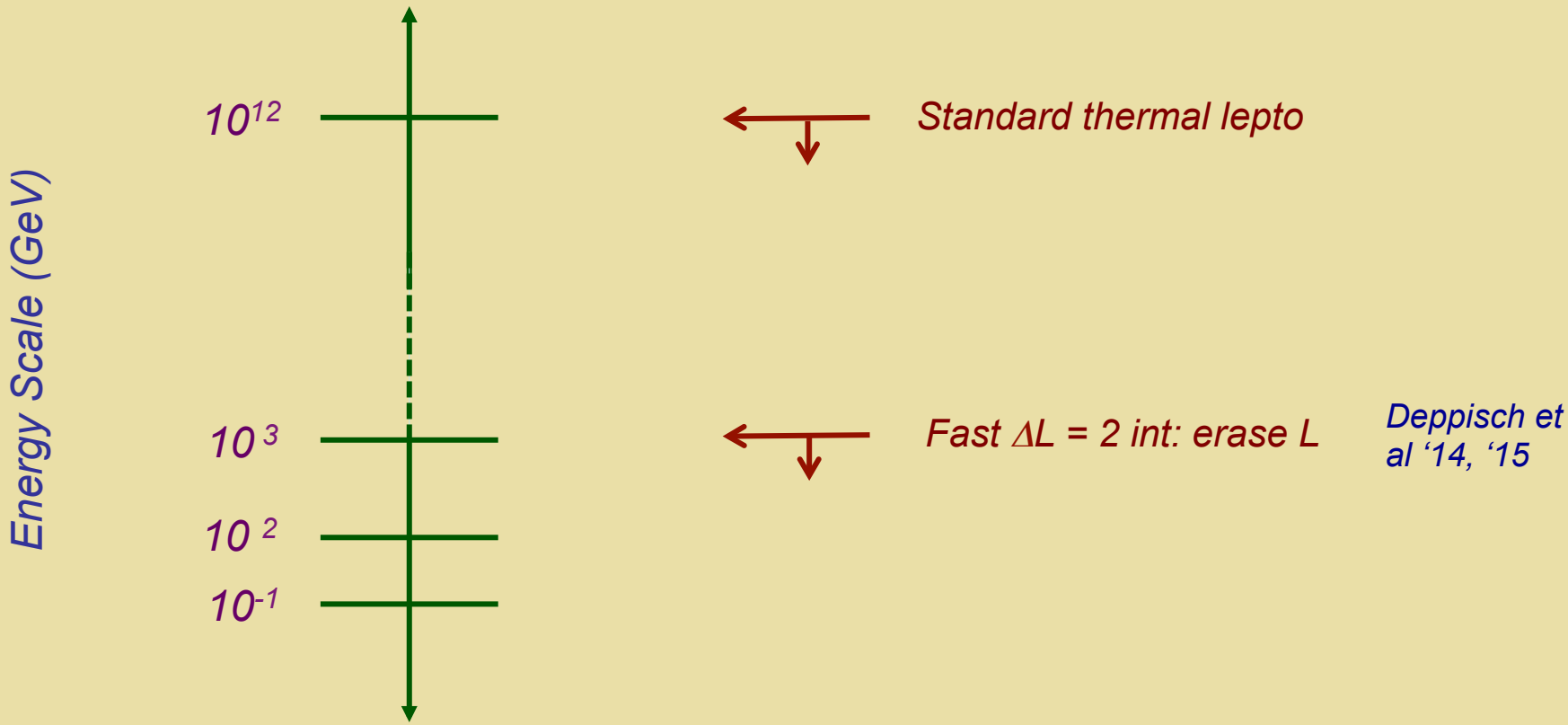
*Majorana*

## TeV LNV Mechanism

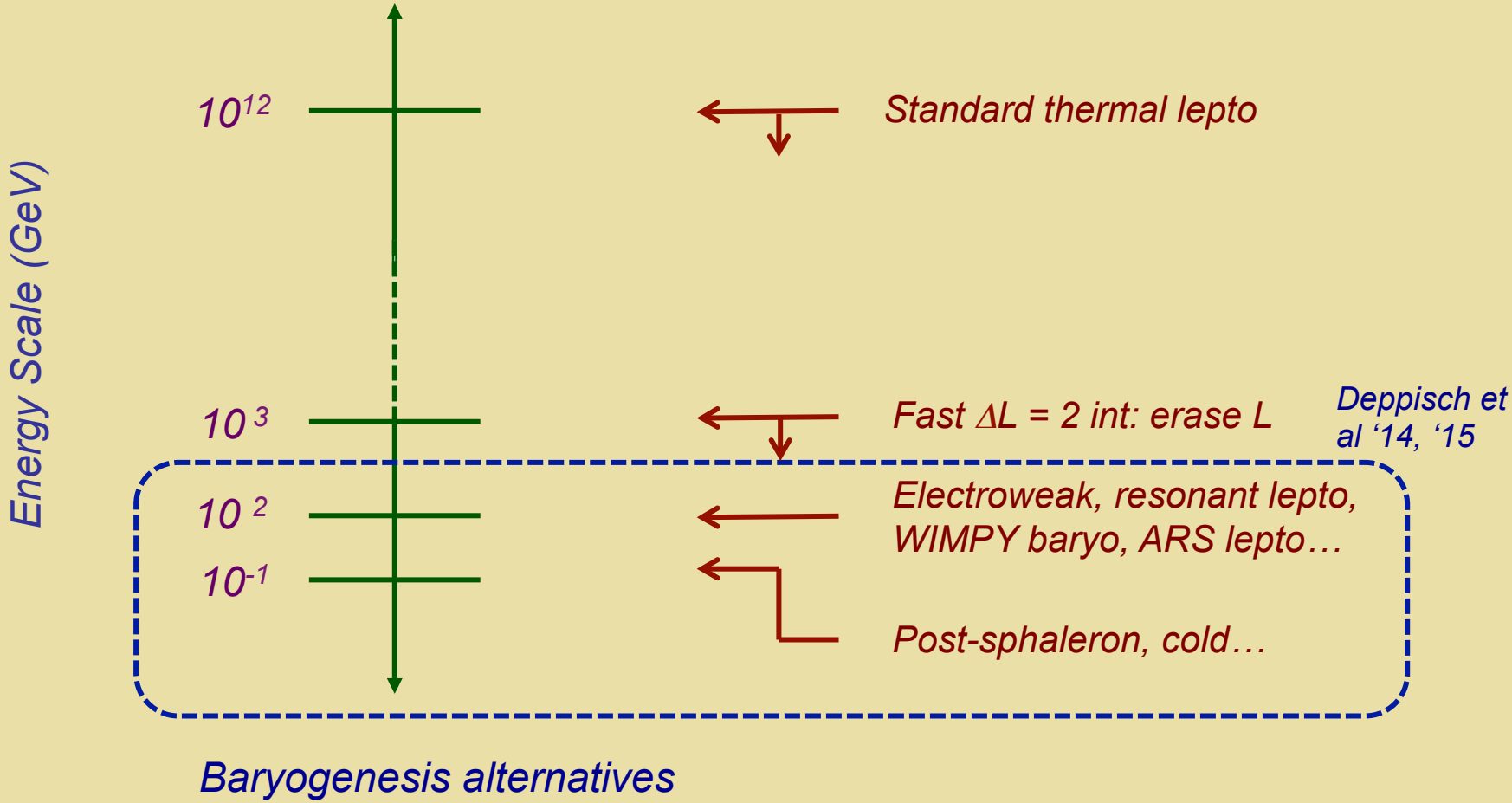
- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative $m_\nu$*
- *$m_{MIN}$ << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



# TeV LNV & Leptogenesis



# TeV LNV & Leptogenesis



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

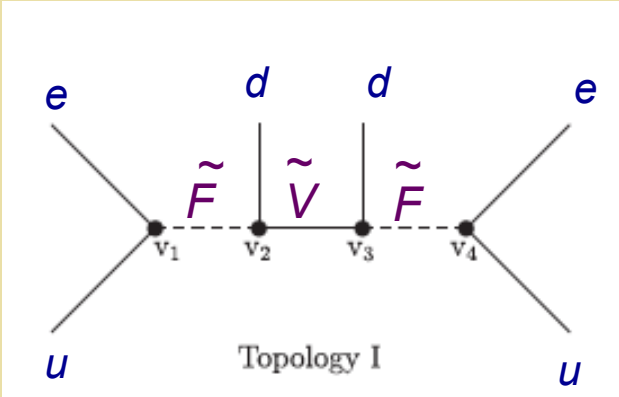
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; {\rm h.c.}$$

*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*




***SUSY: R Parity-Violation***

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

*Gaugino* $\tilde{g}$ , $\chi$ *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

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

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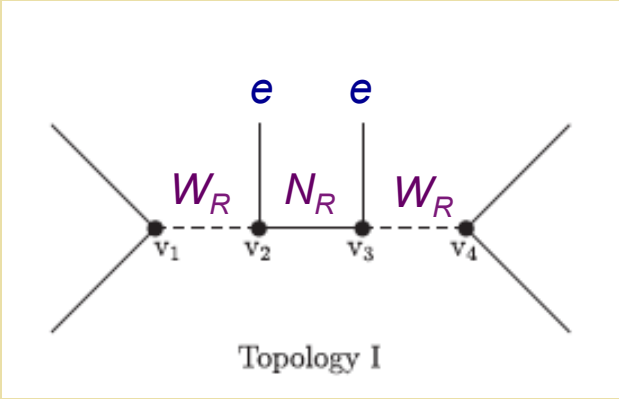



***LRSM: Type I See-Saw***

*Mass: standard see-saw but TeV scale*

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

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

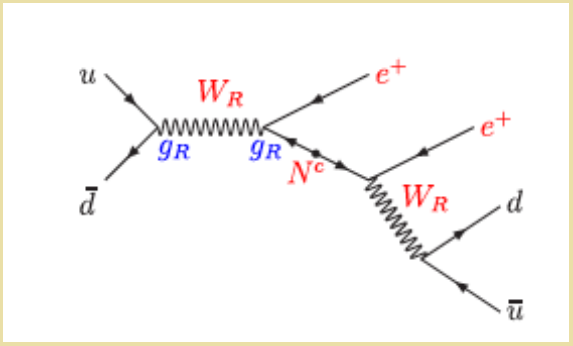
Dirac

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

Majorana

**LHC: SS Dilepton + Dijet**

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

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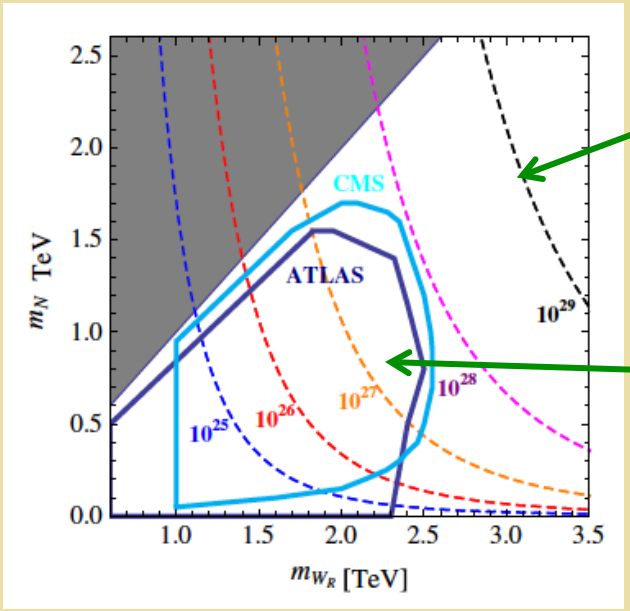


*$^{76}$Ge $\tau$ ($0\nu$)*

*LHC exclusion*

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

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

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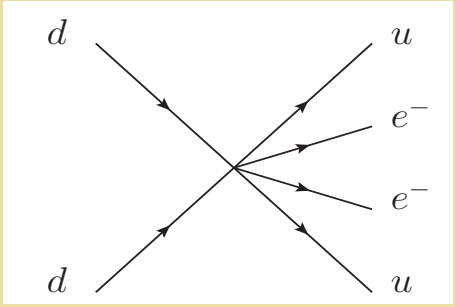
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \; + \; {\rm h.c.}$$

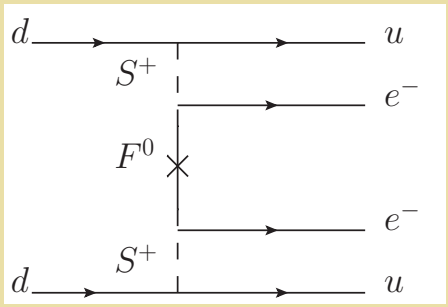
*Majorana*

**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***

# *Simplified Models: Illustrative Case*

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

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

# $0\nu\beta\beta$-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:*

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

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

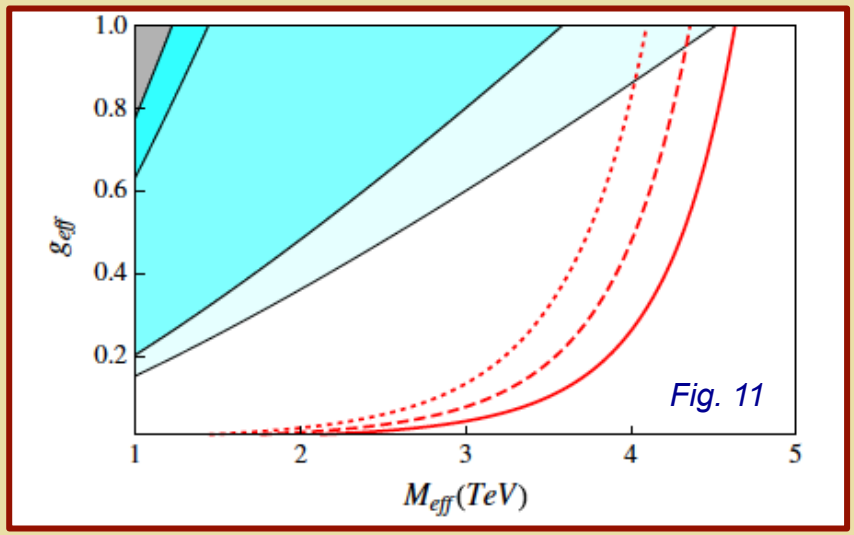



*Fig. 11*

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

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

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

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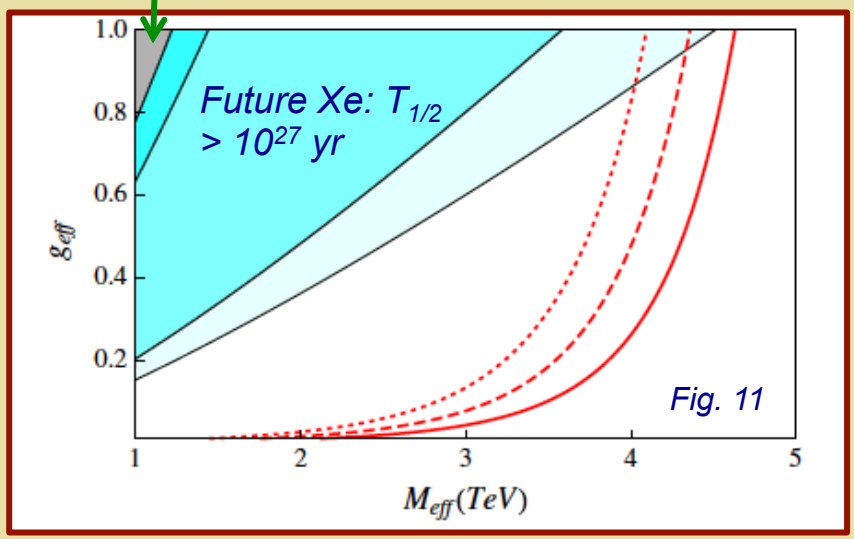


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$$M_{{\rm eff}(S)} = (m_S^4 m_\psi)^{1/5}$$

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

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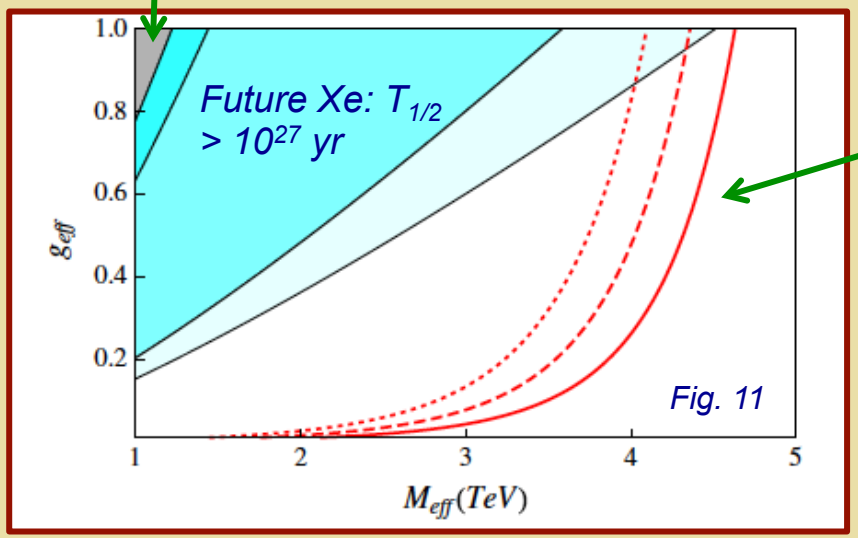
*EXO exclusion*




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

*LHC: pp → jj e⁻e⁻*

*300 fb⁻¹ :*

*< 3 events*

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

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

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

*Dirac*

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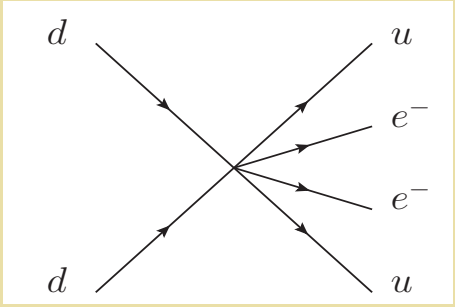
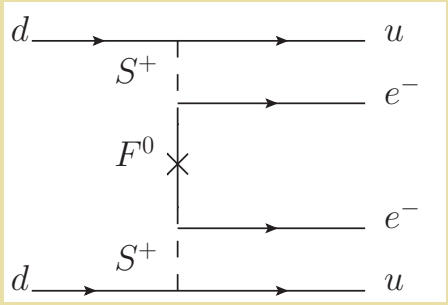
*Majorana*

*$0\nu\beta\beta$ - decay*




*LHC: pp → jj e⁻e⁻*




## TeV Scale LNV

*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

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

*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

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

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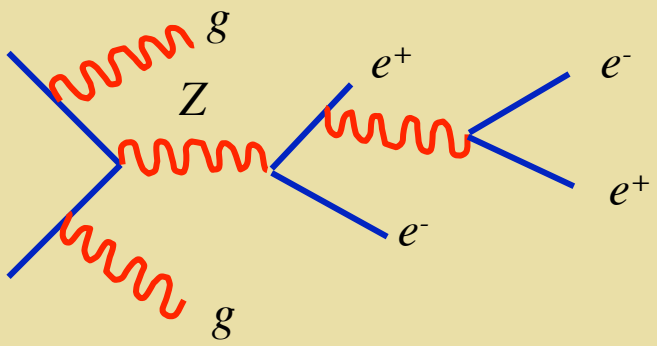
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

*Majorana*

*Backgrounds:*

- *Charge flip*
- *Jet faking electron*




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

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

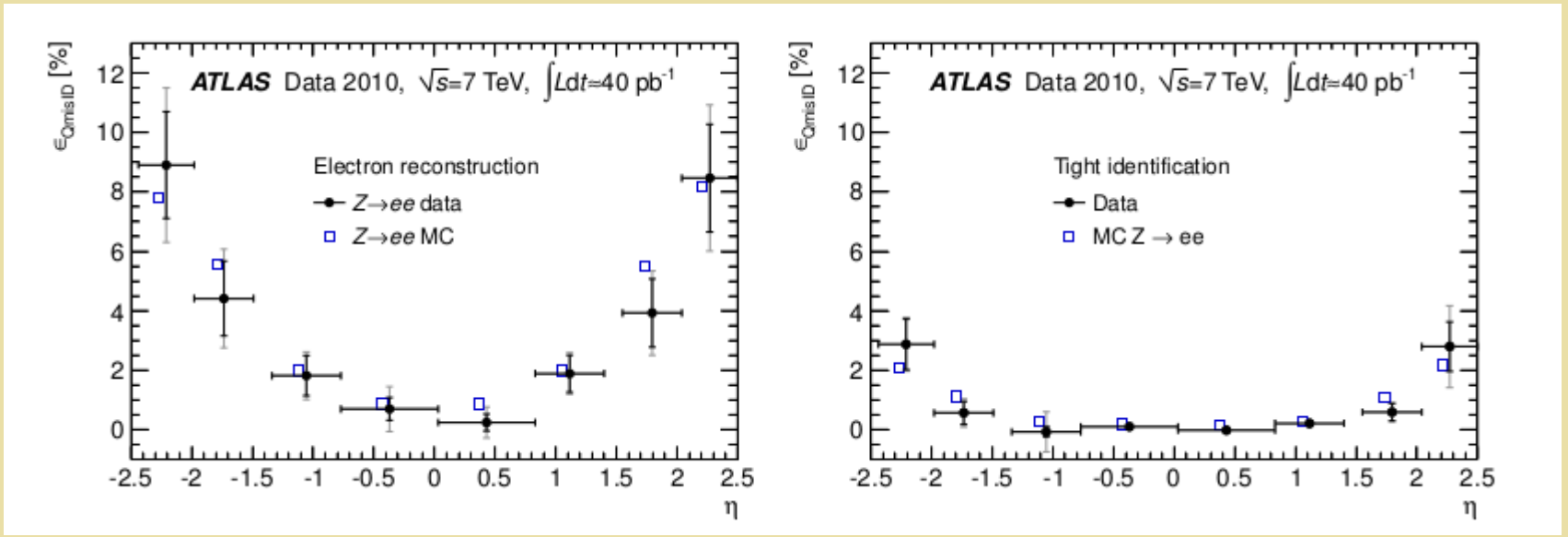
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

*Dirac*

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

*Majorana*

*Backgrounds:* *Bin in $\eta$ 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 (e.g., $\pi^+$ looks like $e^+$ )*

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

# $0\nu\beta\beta$-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

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

*Dirac*

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

*Majorana*

*Backgrounds: Cuts*

| $\sigma$(fb) | Signal | Backgrounds | | | | | | | | | $\frac{S}{\sqrt{S+B}}$ ($\sqrt{\text{fb}}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diboson | | | Charge Flip | | Jet Fake | | | | |
| | | $W^-W^-$+2j | $W^-Z$+2j | ZZ+2j | $Z/\gamma^*$+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 |

*T. Peng, MRM, P. Winslow 1508.04444*

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

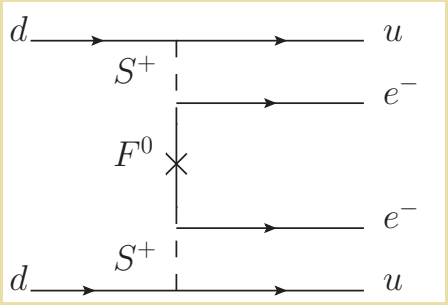
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

*Dirac*

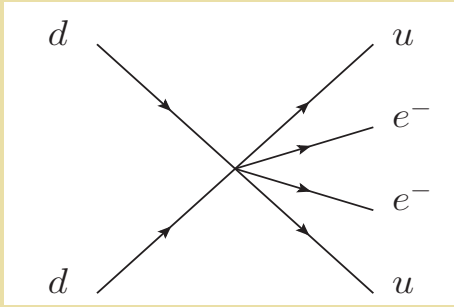
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

*Majorana*

*Low energy:* *Matching*




*Match onto $\mathcal{O}_{eff}$ at $\Lambda_{BSM}$*




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

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

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

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

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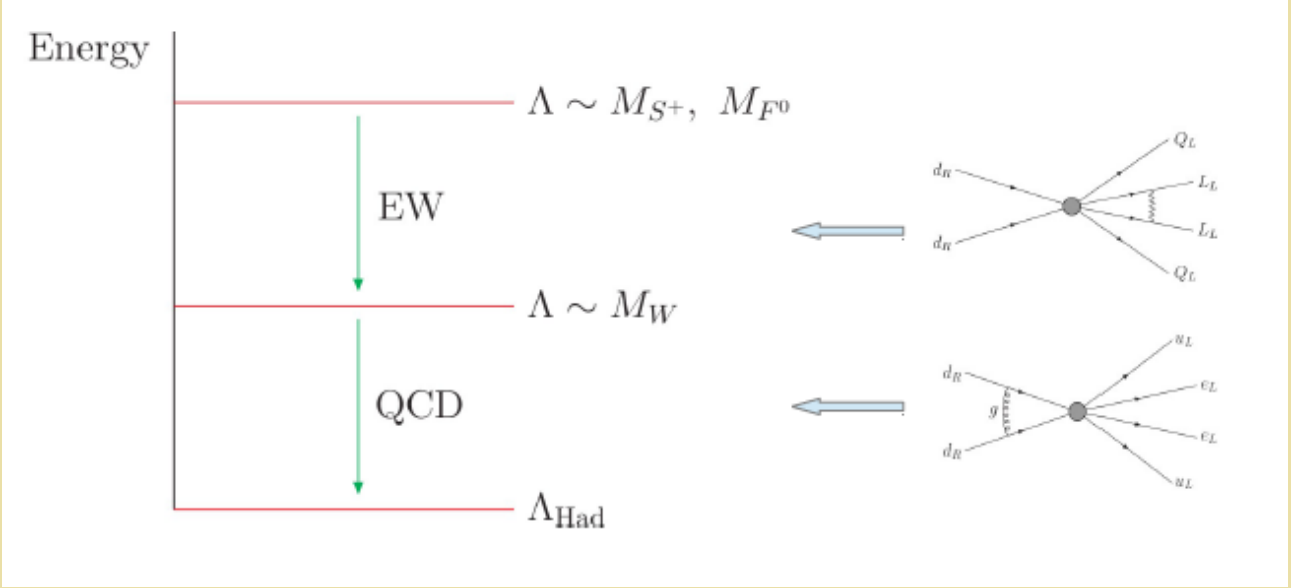
*Dirac*

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

*Majorana*

*Low energy:* *Running*



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

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*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*

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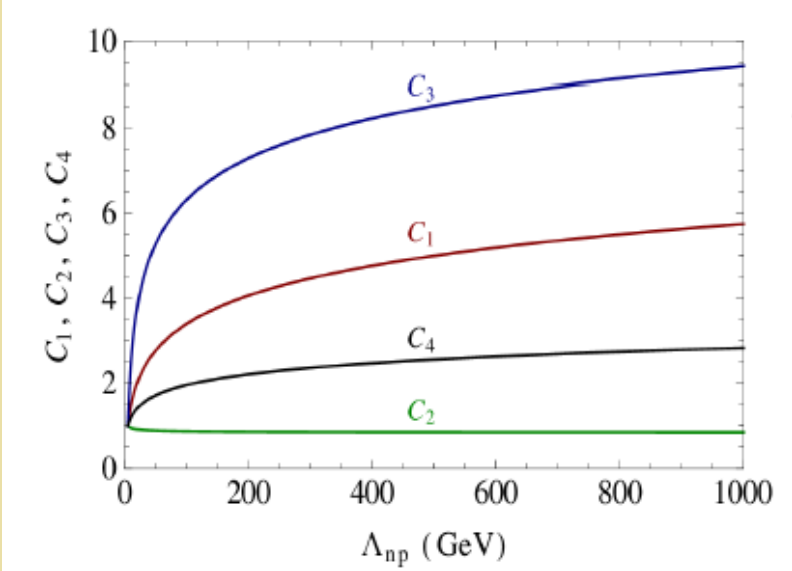


*Assuming $C_k$ = 1 at $\mu$ = 5 GeV → Effective DBD amplitude for $\mathcal{O}_1$ substantially weaker for given LHC constraints*

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

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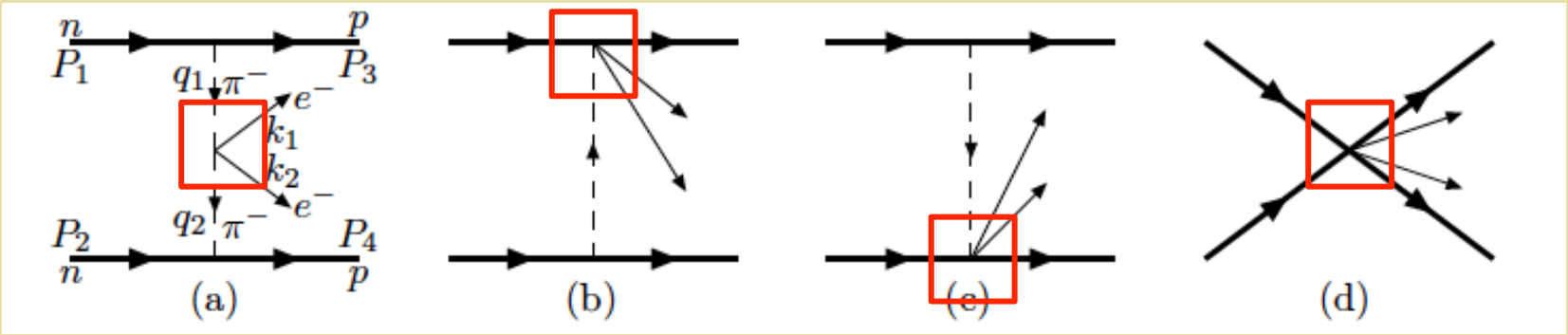
*Majorana*

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




*Exploit Chiral Symmetry & EFT ideas*

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

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

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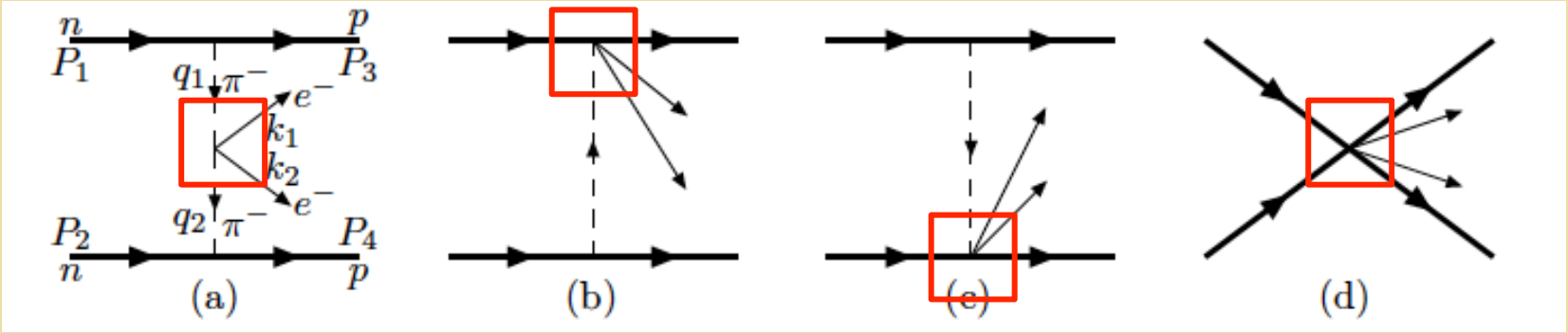
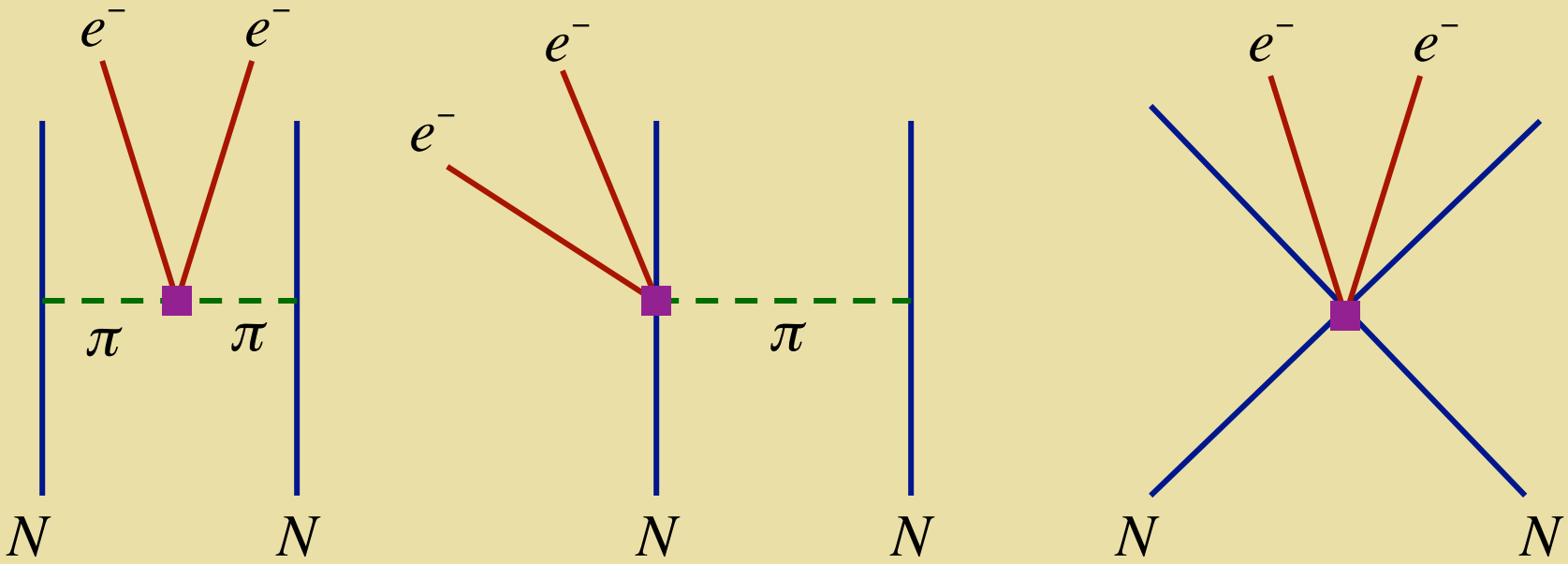



*Our work* *Helo et al*

*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

$$\mu = M_{WEAK}$$

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

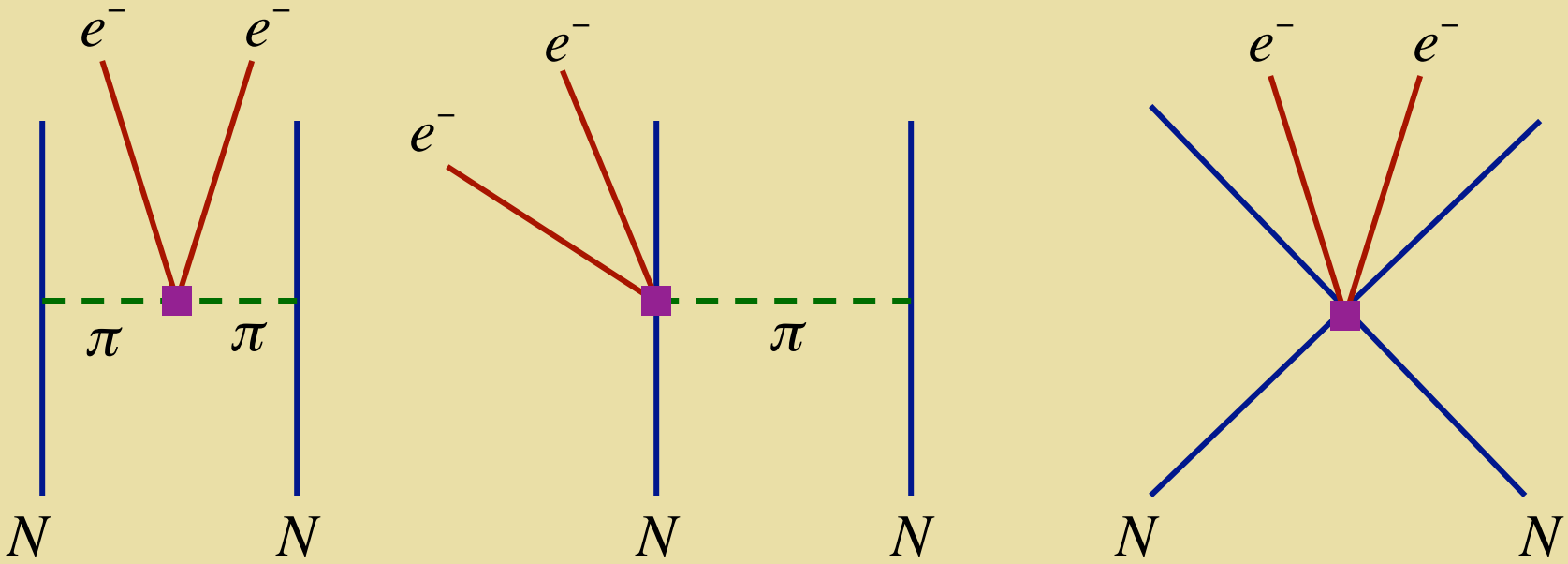
*e.g.*

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

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

*Prezeau, MJRM, Vogel*
*PRD 68 (2003) 034016*

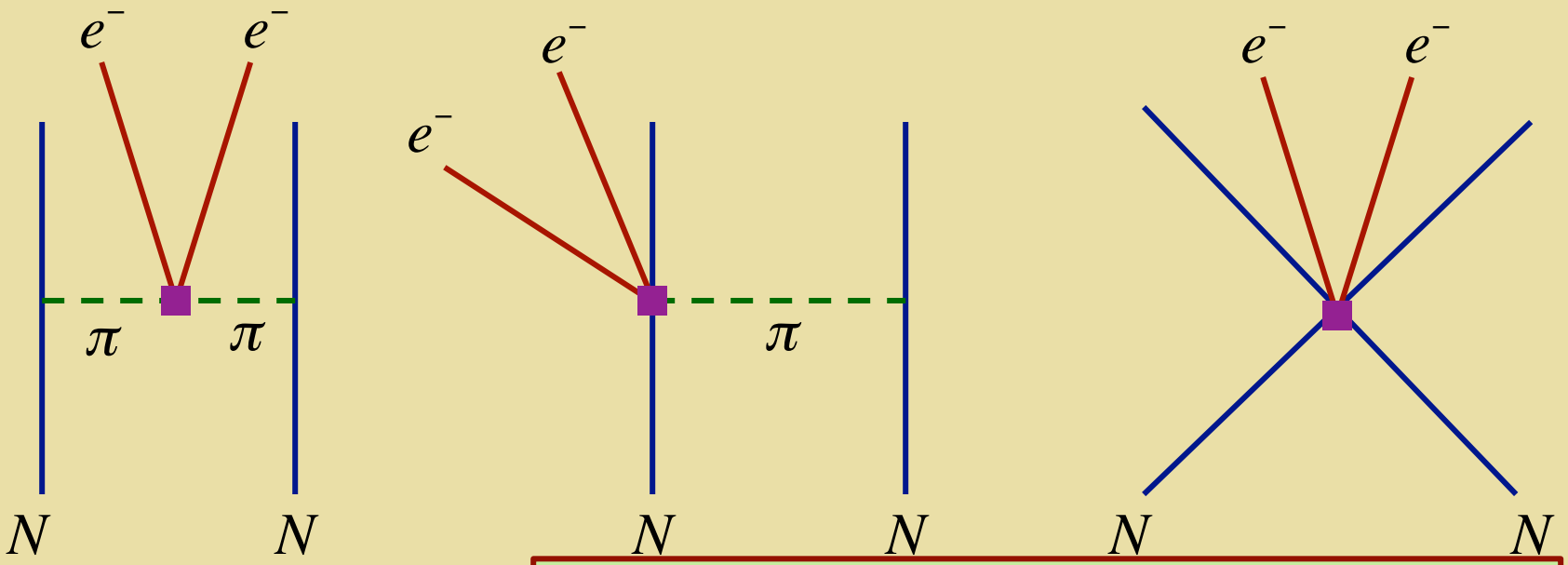
# $0\nu\,\beta\beta$ - decay in effective field theory




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

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

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




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

*Hadronic matrix elements: A. Nicholson, M. Graesser talks*

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

# *Putting Pieces Together*

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

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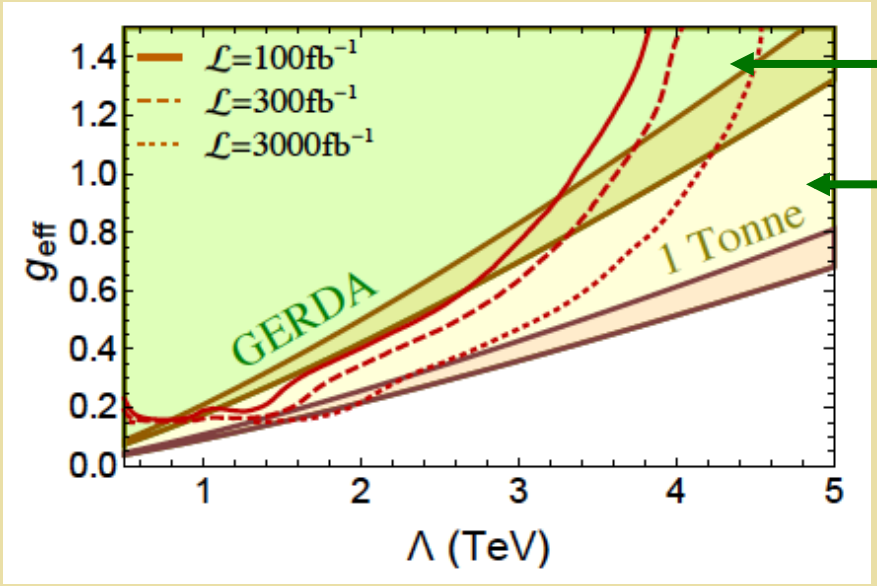
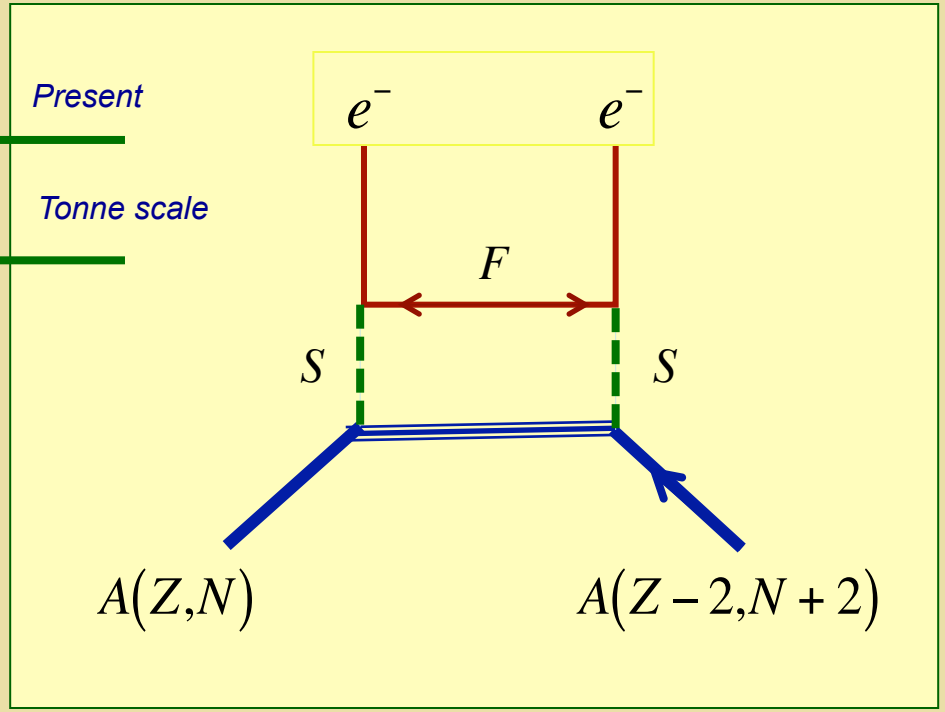
*Majorana*

**Benchmark Sensitivity: TeV LNV**




*Present*

*Tonne scale*




*T. Peng, MRM, P. Winslow 1508.04444*

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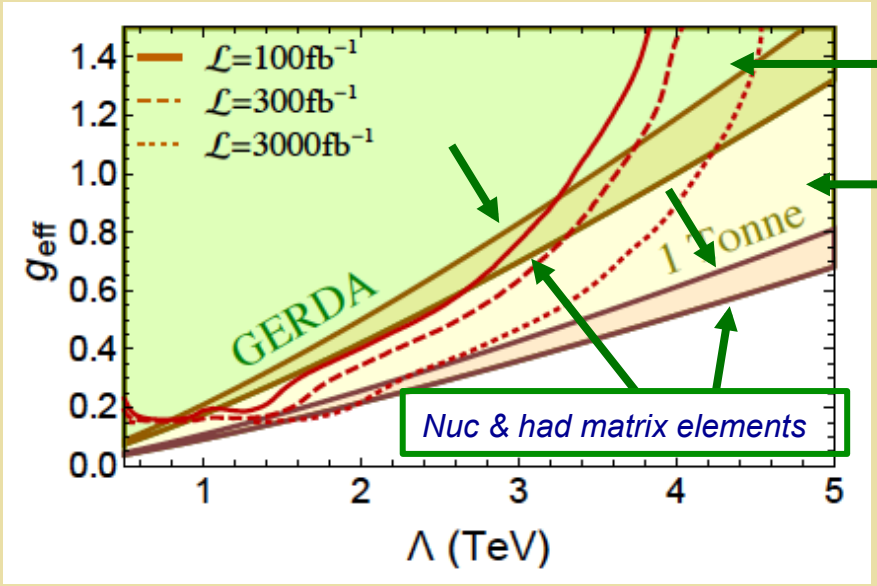
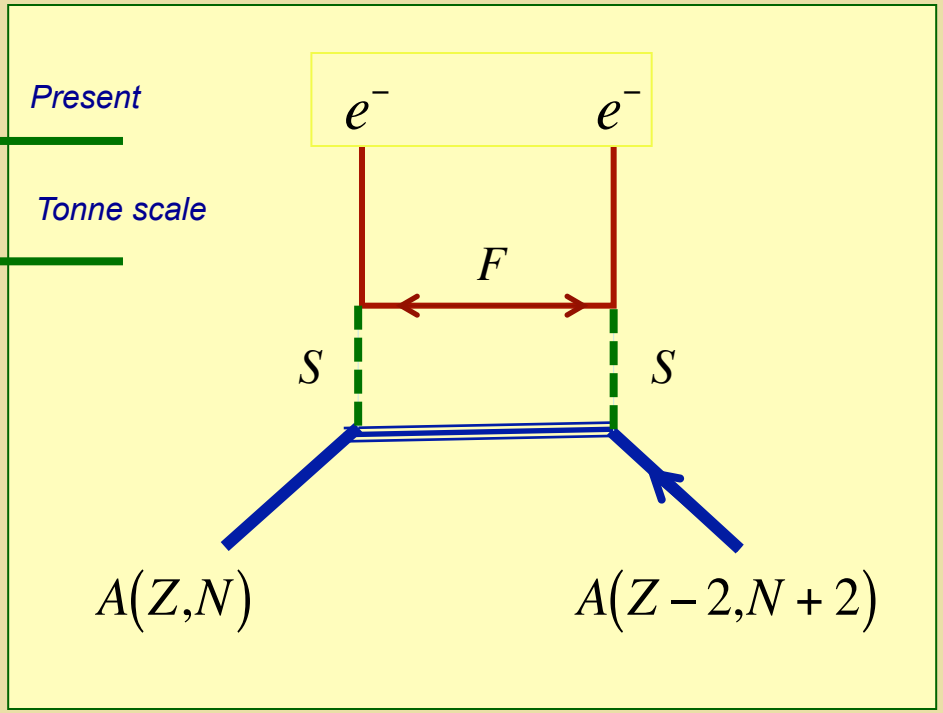



*T. Peng, MRM, P. Winslow 1508.04444*



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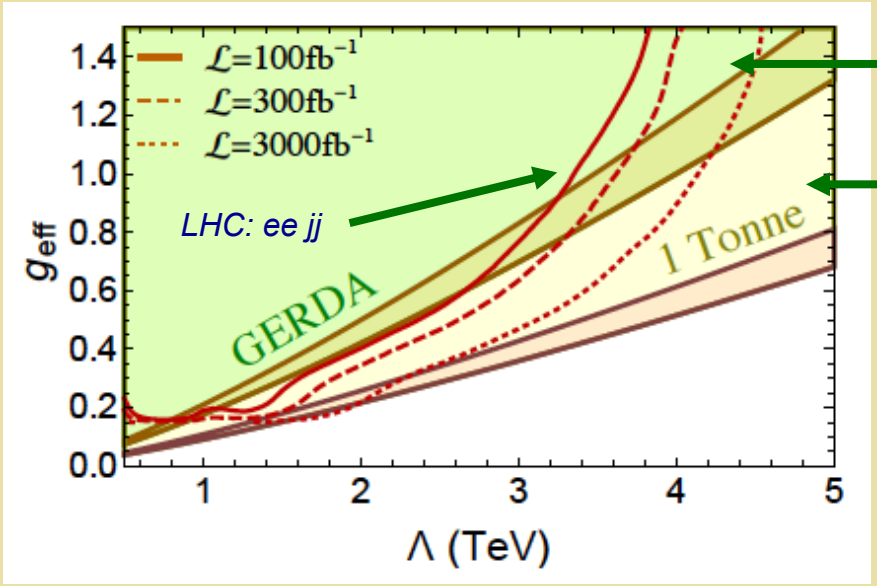
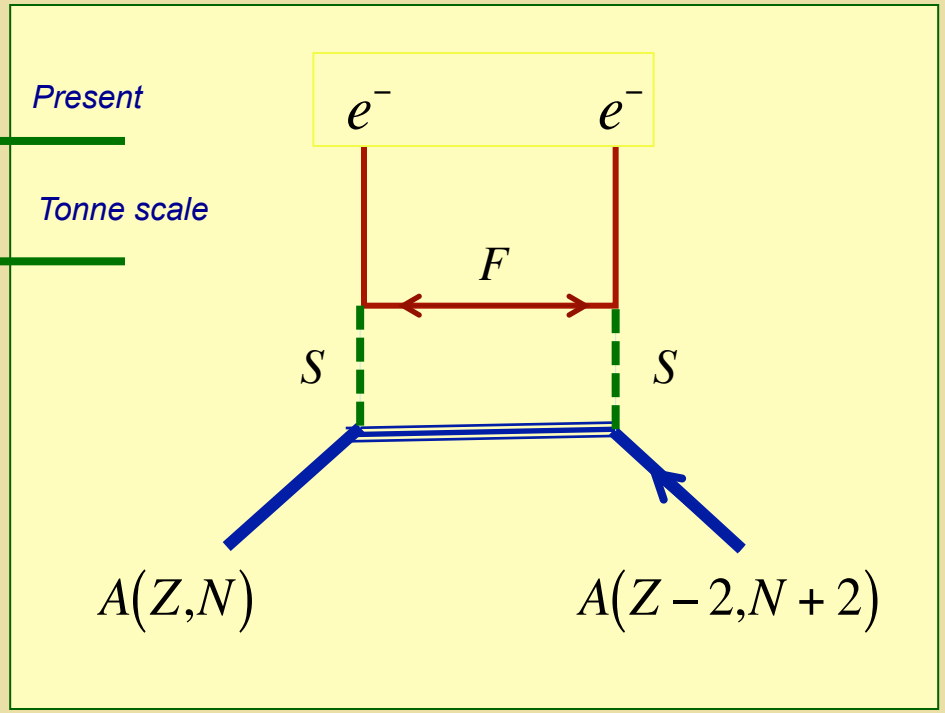



*T. Peng, MRM, P. Winslow 1508.04444*



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

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

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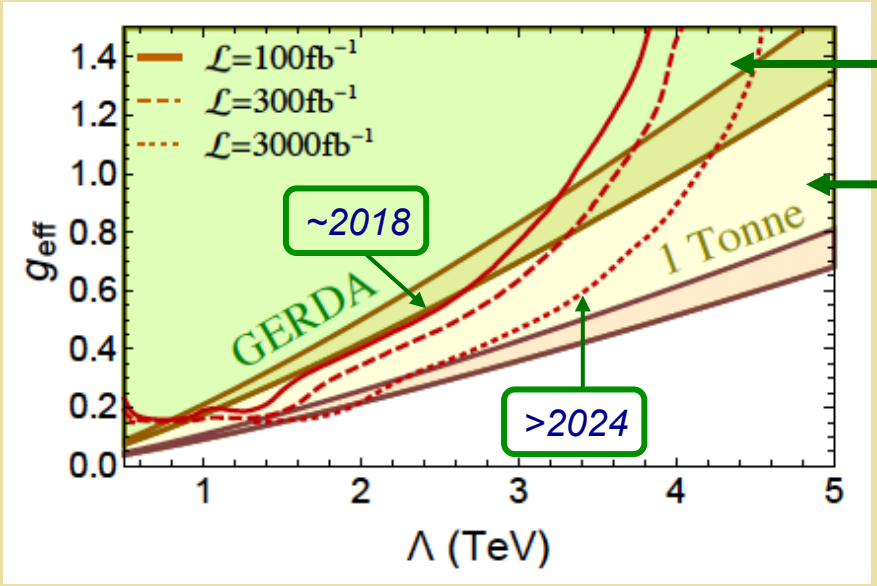
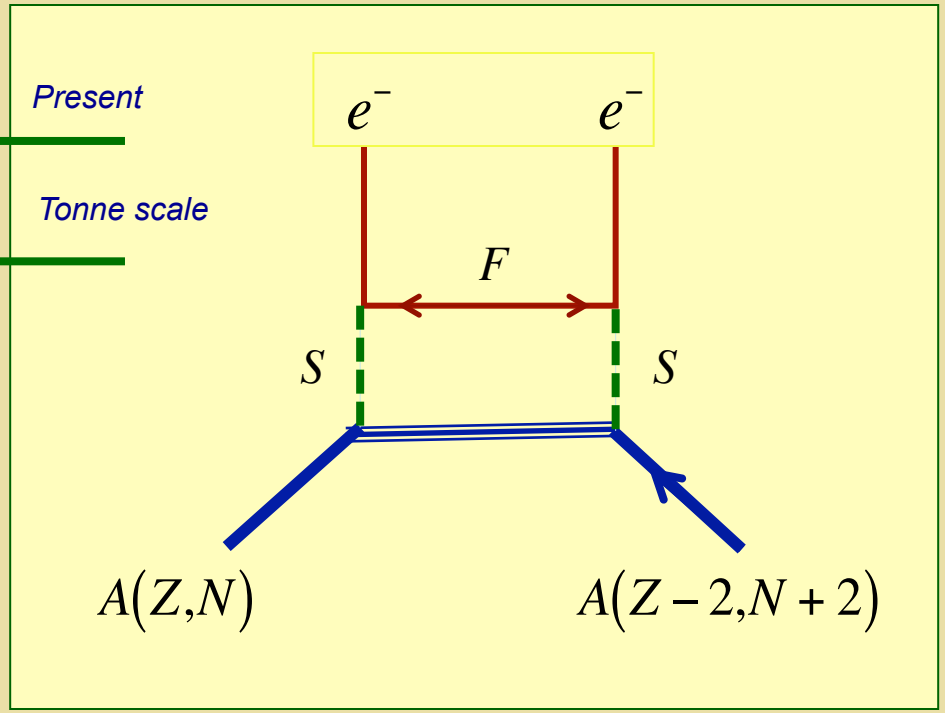
*Majorana*

**Benchmark Sensitivity: TeV LNV**




*T. Peng, MRM, P. Winslow 1508.04444*



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

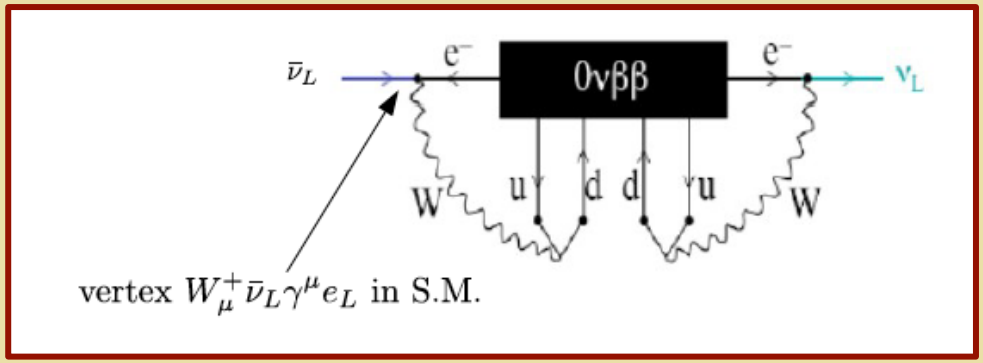
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; \text{h.c.}$$

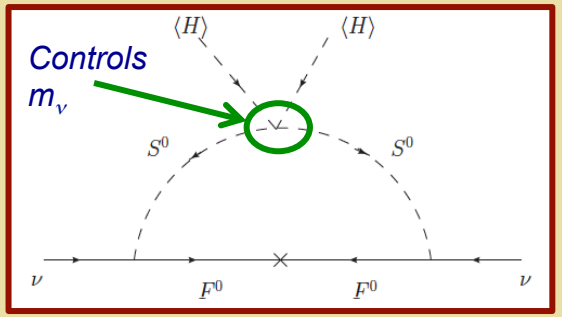
*Dirac*

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

*Majorana*

*Implications for $m_\nu$:*




*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 & $m_\nu$

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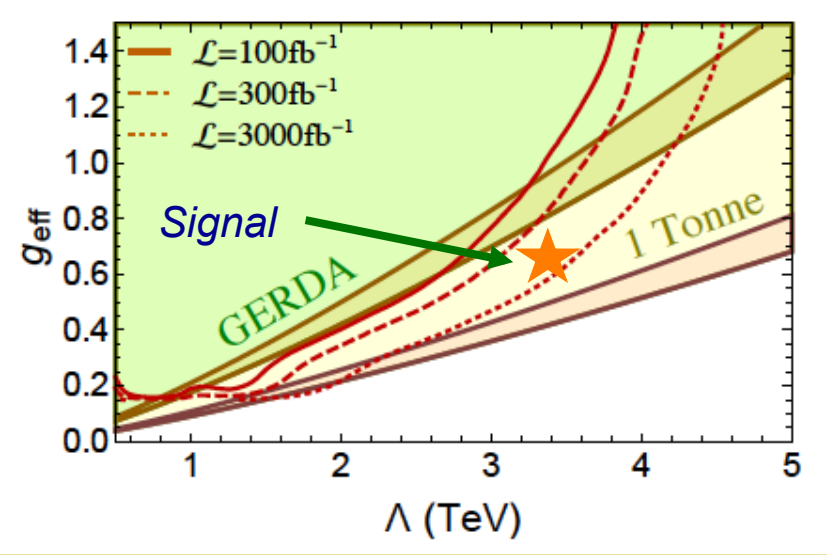
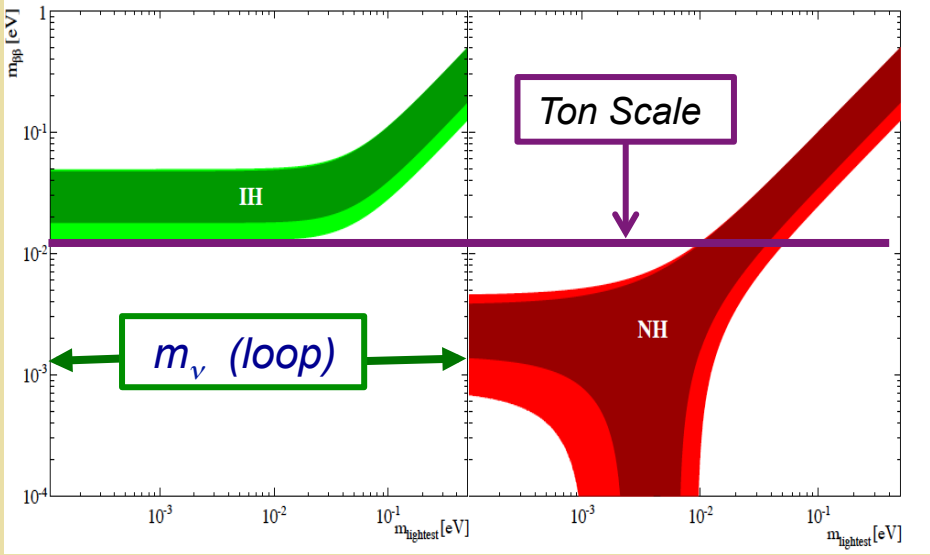
*Majorana*

*Implications for $m_\nu$:*




*A hypothetical scenario*

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

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

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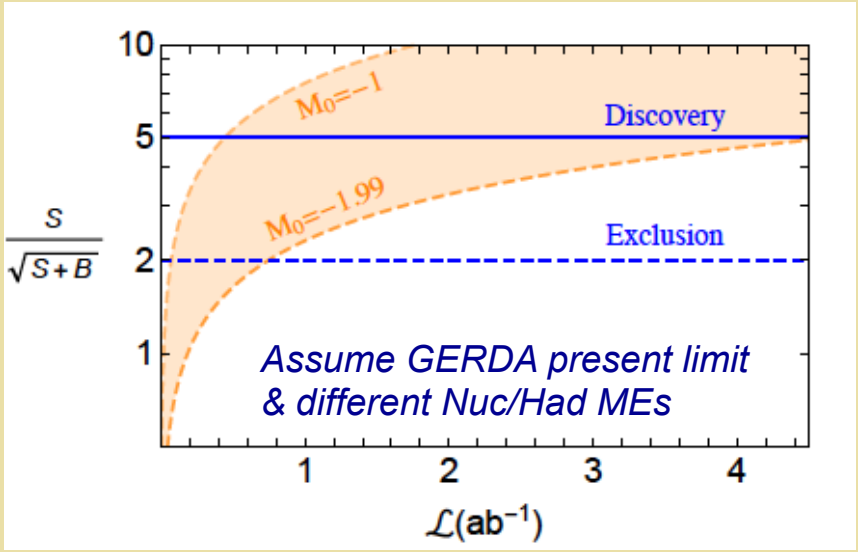
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ \text{h.c.}$$

*Majorana*

**Benchmark Sensitivity: TeV LNV**

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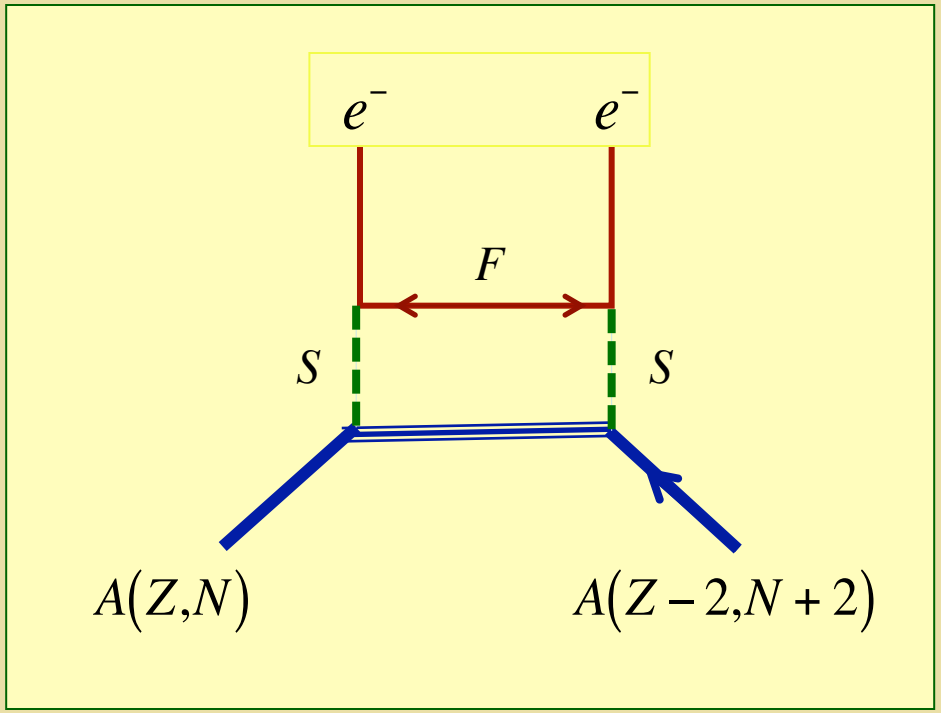

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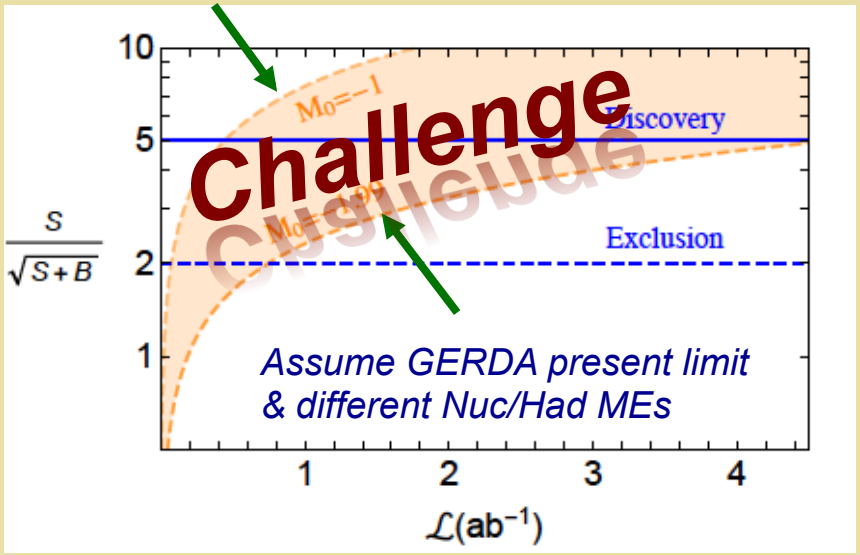
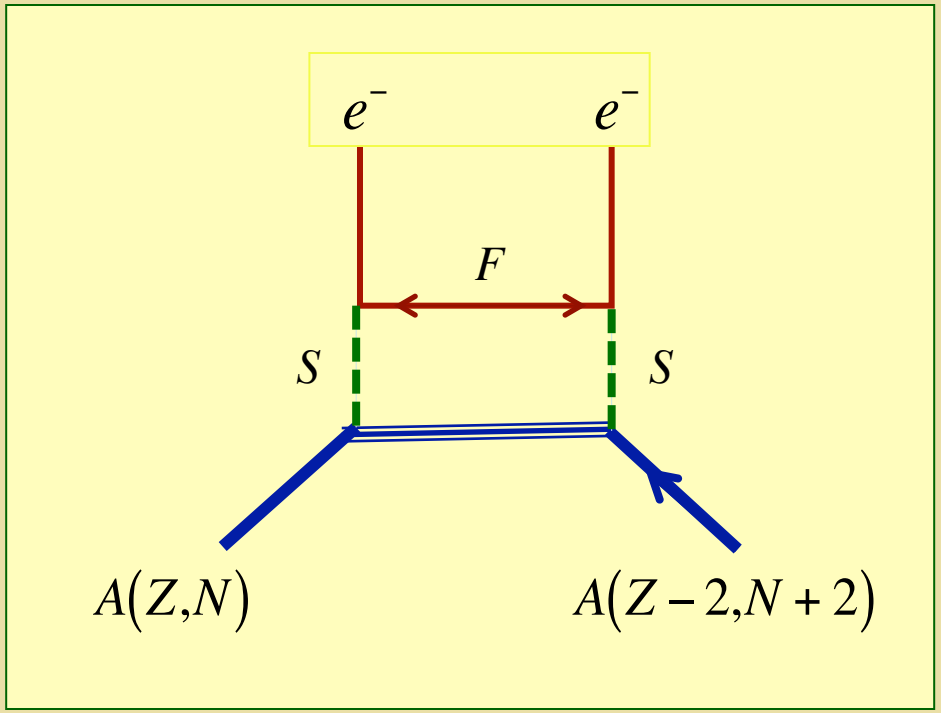
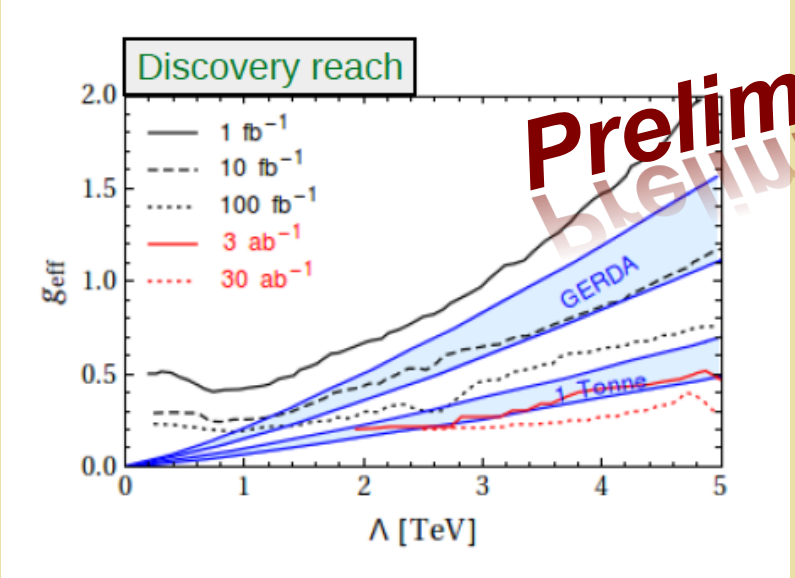
**Benchmark Sensitivity: TeV LNV**

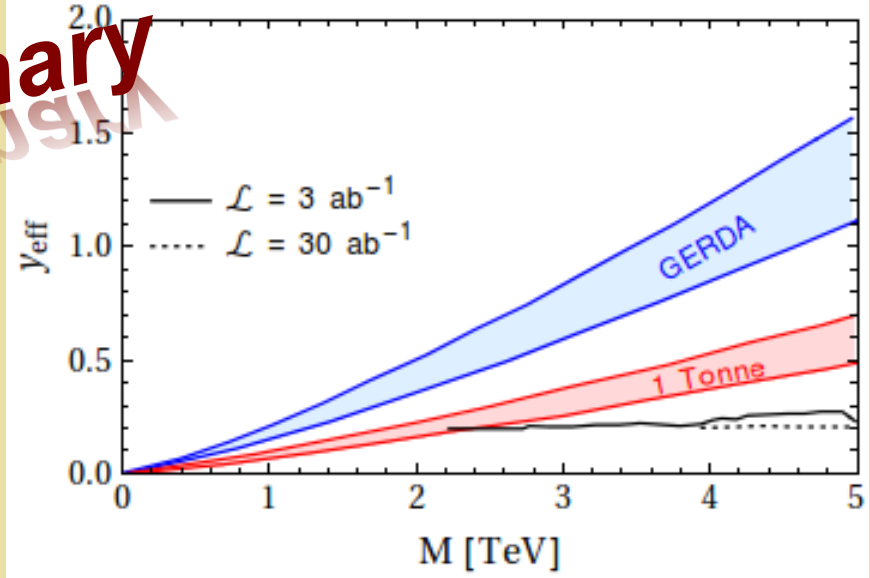



*T. Peng, MRM, P. Winslow 1508.04444*



# 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 $m_\nu$ 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 poses new challenges for hadronic & nuclear structure theory***