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Double Beta and TeV Scale Physics

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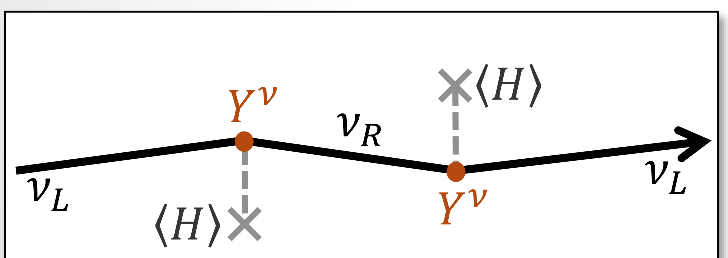
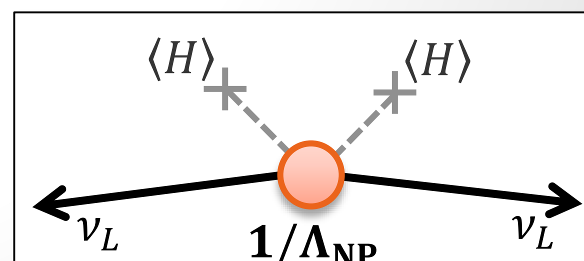
Dirac vs Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with $m_\nu/\Lambda_{EW} \approx 10^{-12}$ couplings to Higgs



Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation



Beta Decays and ν Mass

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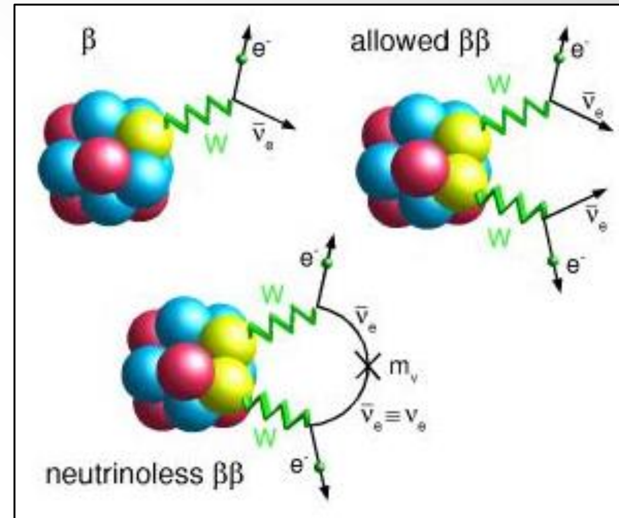
- Single beta decay

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

  - Tritium decay, KATRIN: $\boldsymbol{m_\beta \approx 0.2}$ **eV**
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy: $\boldsymbol{m_\beta \approx 0.05}$ **eV**
  - HOLMES: e^- capture in $^{163}\mathrm{Ho}$: $\boldsymbol{m_\beta \approx 0.1}$ **eV?**



- Allowed double beta ($2\nu\beta\beta$) decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

- Neutrinoless double beta ($0\nu\beta\beta$) decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

  - Violation of lepton number
  - Mediated by Majorana neutrinos

Three Active Neutrinos

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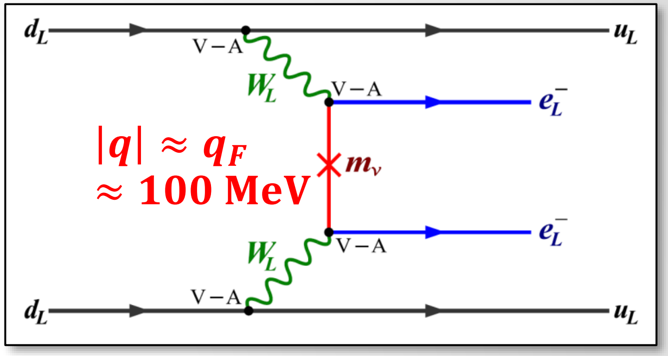
- Half-life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$



- Particle Physics

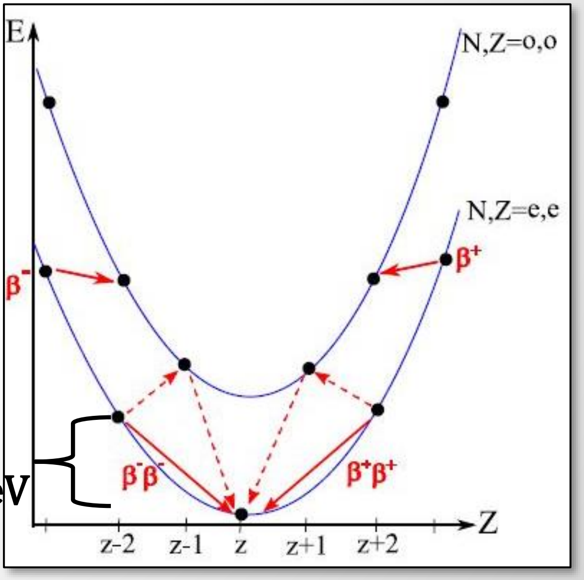
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$

$$T_{1/2}^{-1} \propto |m_{\beta\beta}|^2 q_F^2 G_F^4 Q^5$$

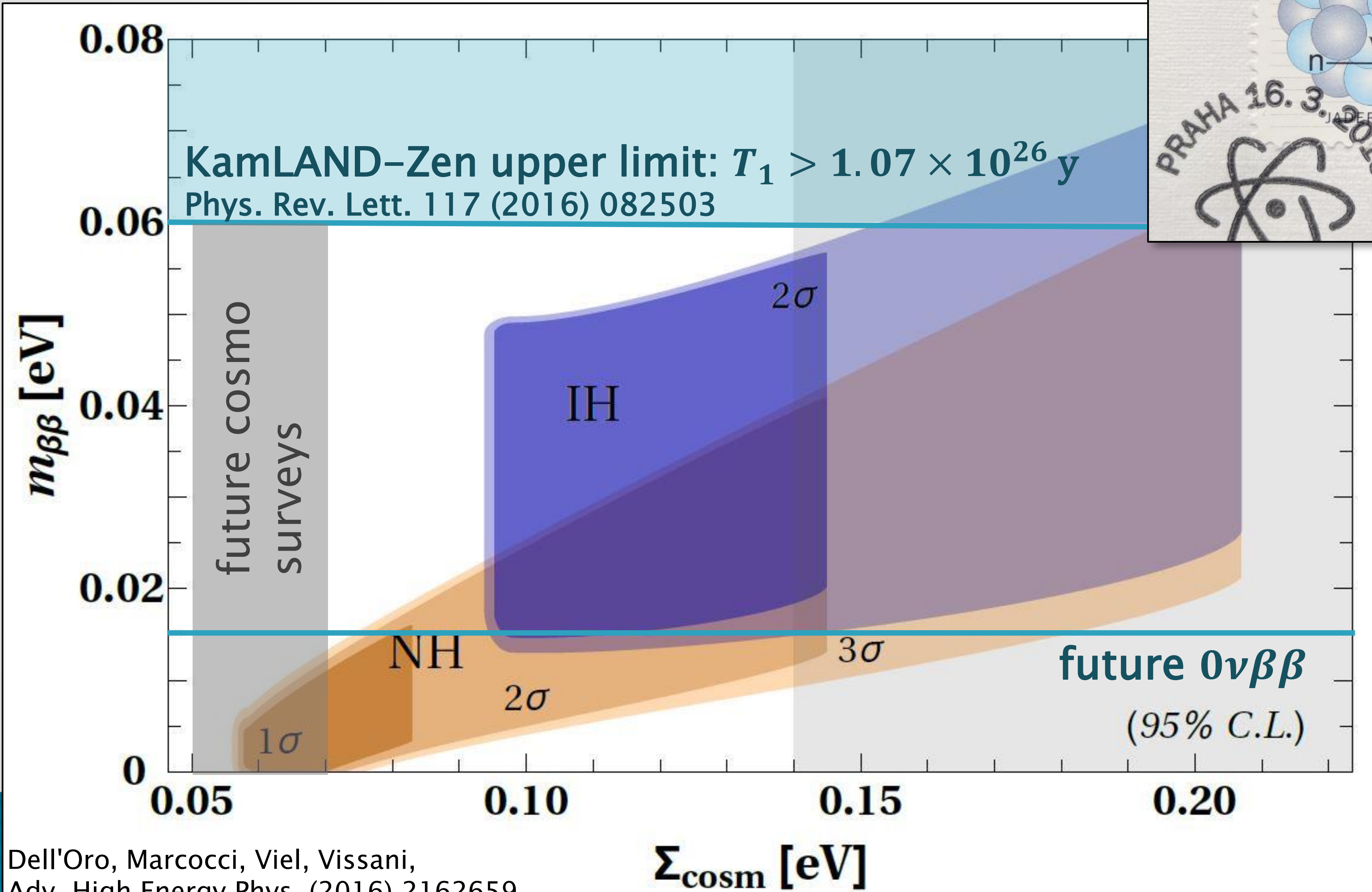
$$\frac{10^{25}\ \mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

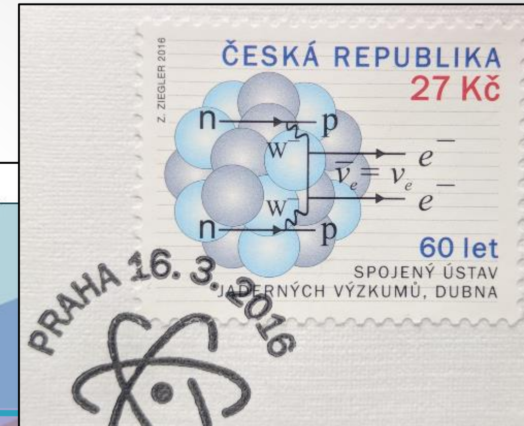
$Q + 2m_e$
$\approx$ 3–5 MeV



Three Active Neutrinos

- Effective $0\nu\beta\beta$ Mass





Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

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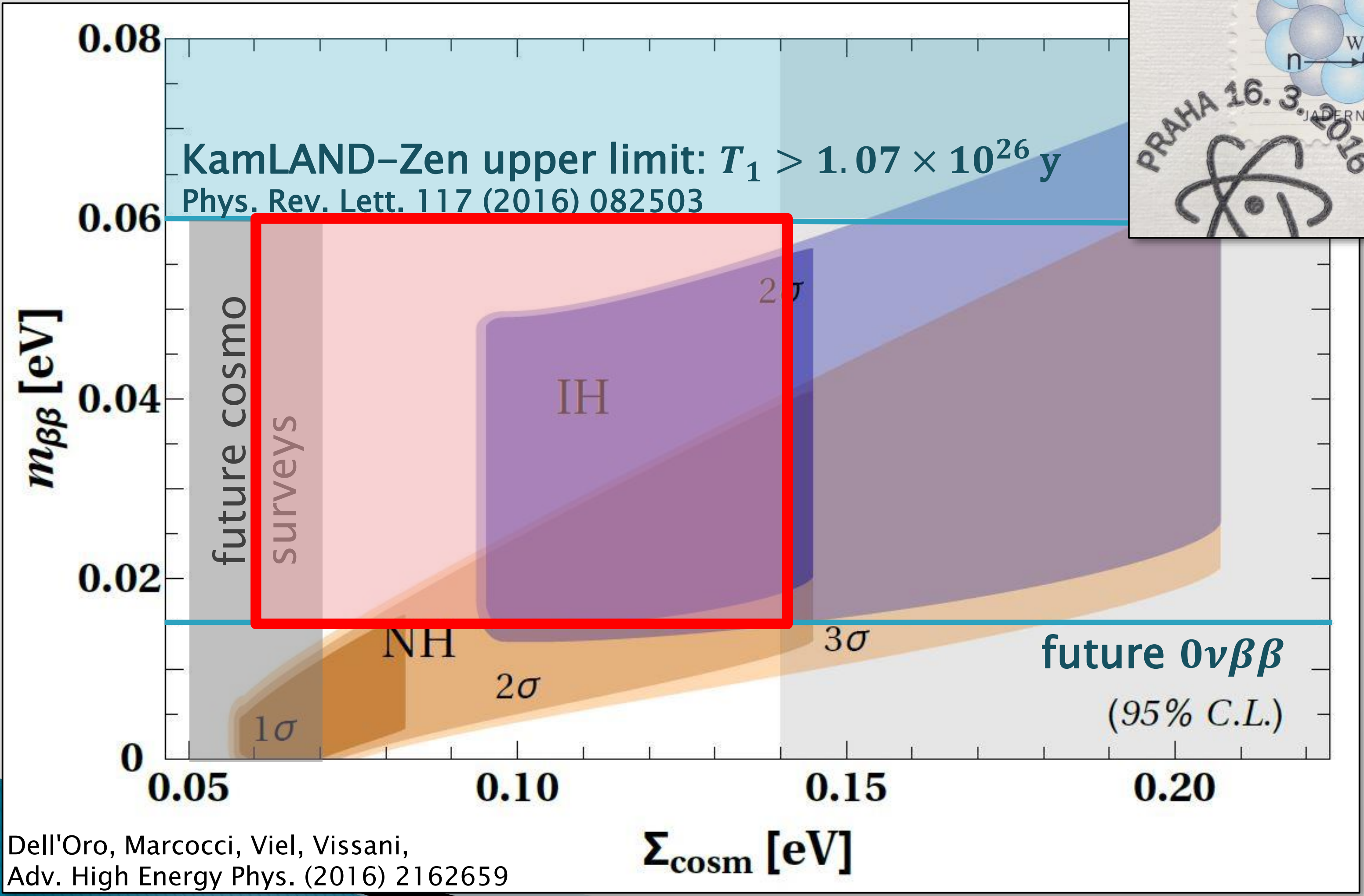

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New Physics and $0\nu\beta\beta$

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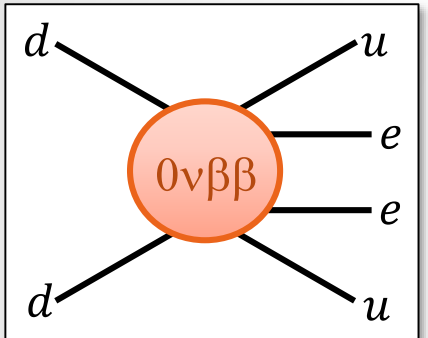
- Plethora of New Physics scenarios



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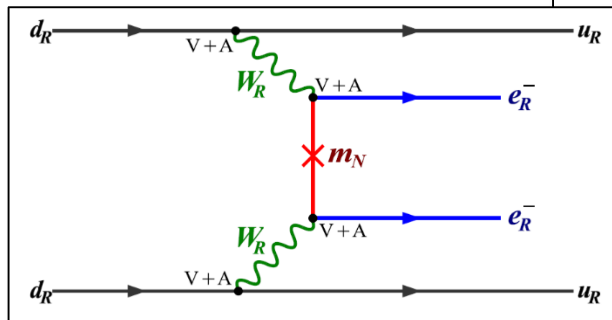
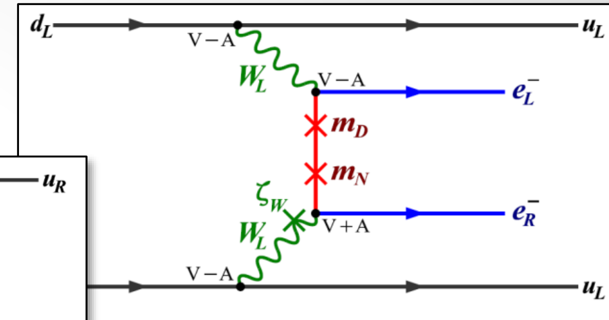
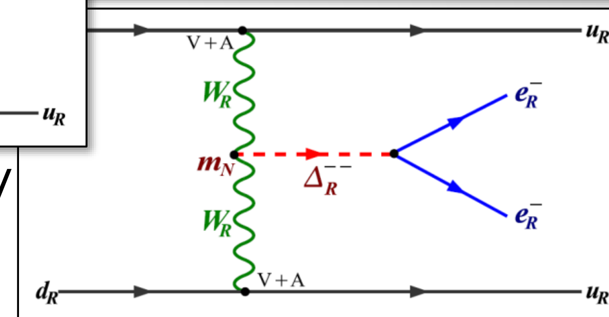
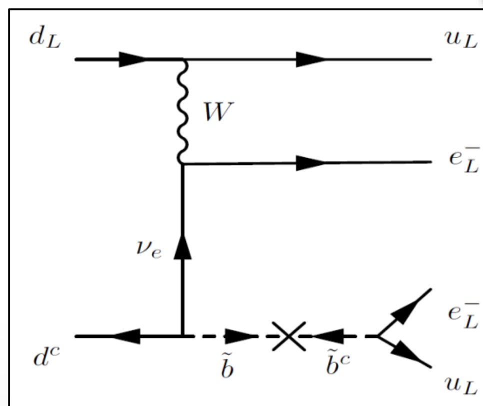
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

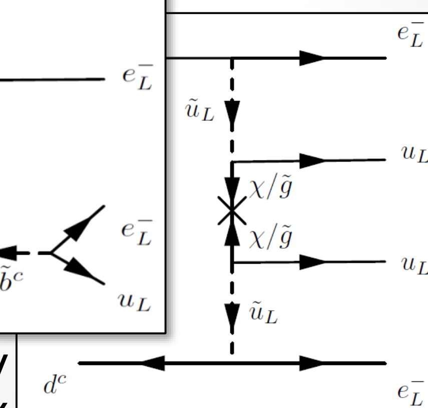






Left-Right Symmetry





R-Parity Violating SUSY

Extra Dimensions

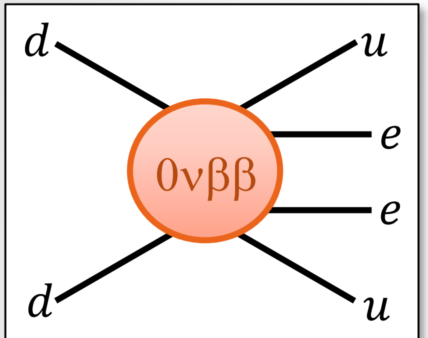
Majorons

Leptoquarks

...

New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios



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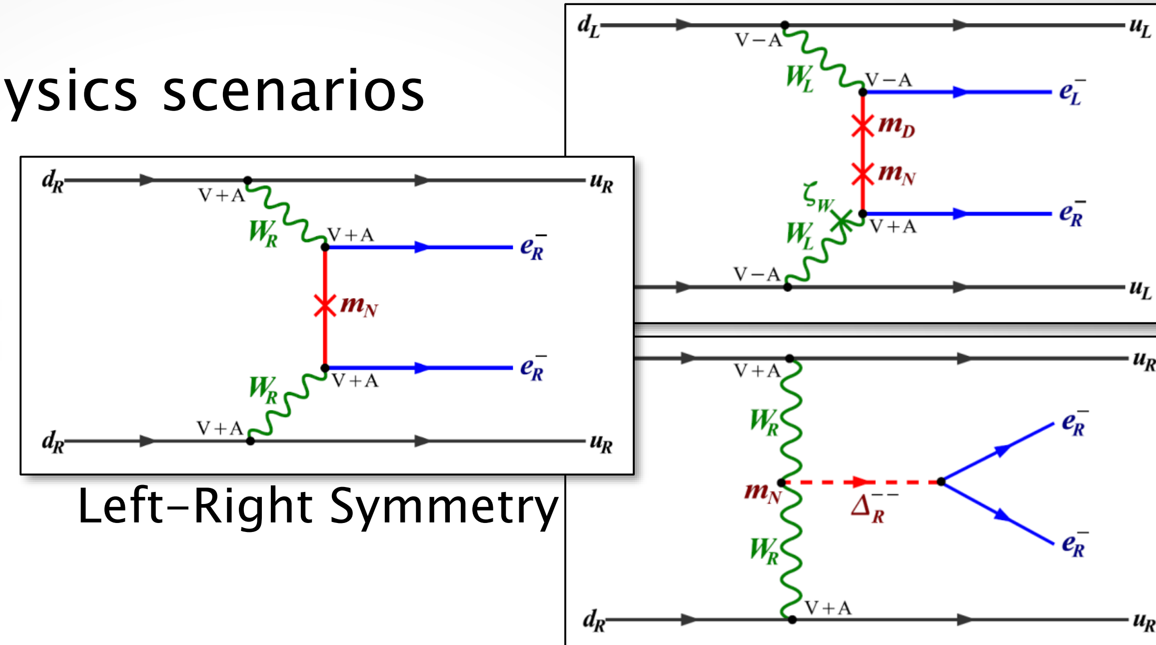
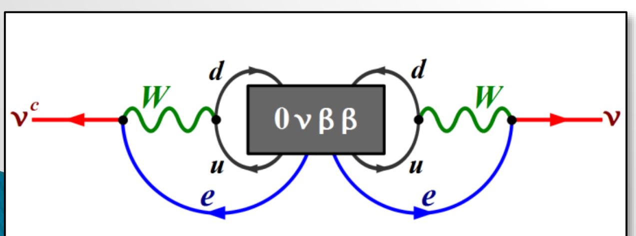
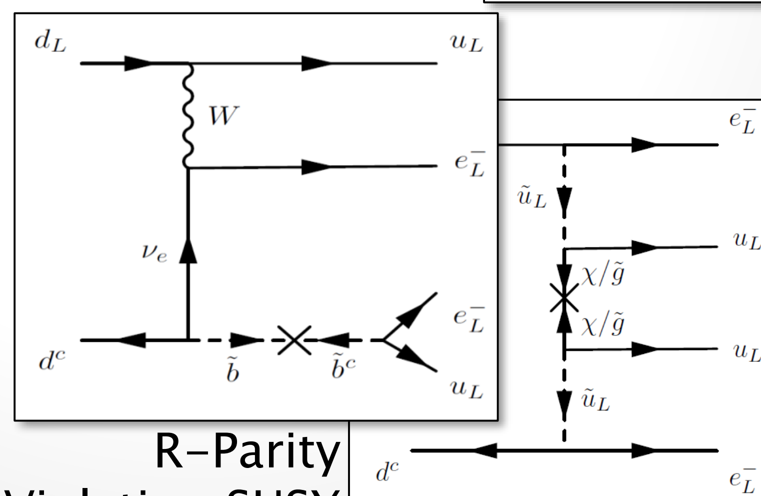


Left–Right Symmetry

- Neutrinos still Majorana





R–Parity Violating SUSY

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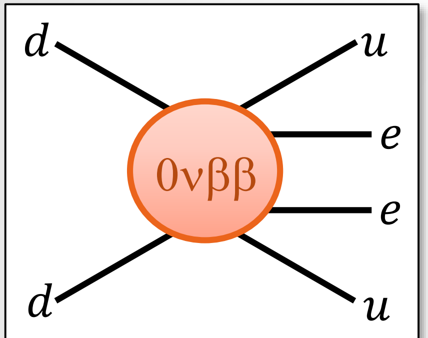
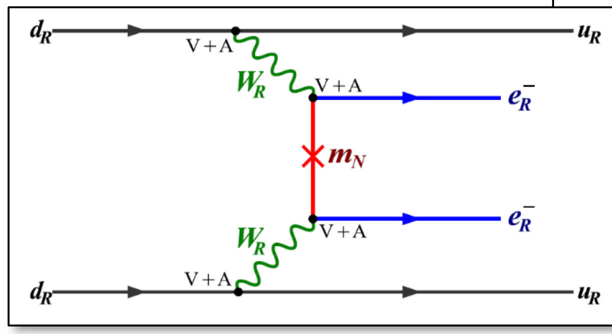
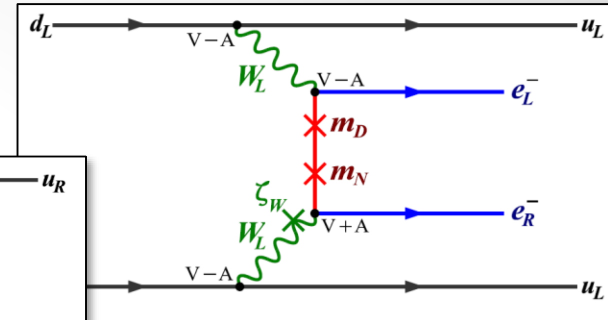
New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry





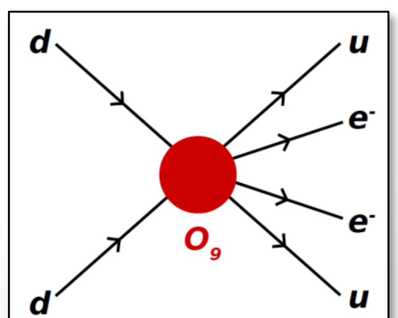


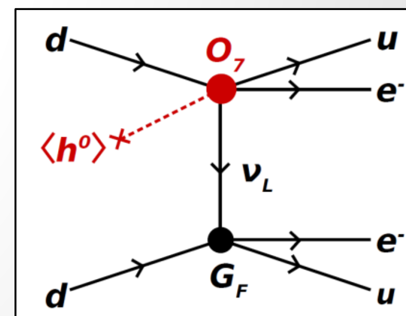
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan \zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale
- Limits on 6D and 9D eff. operators





New Physics and $0\nu\beta\beta$

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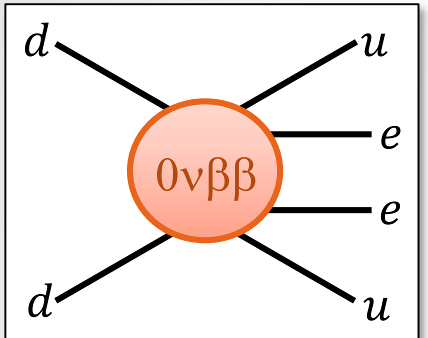

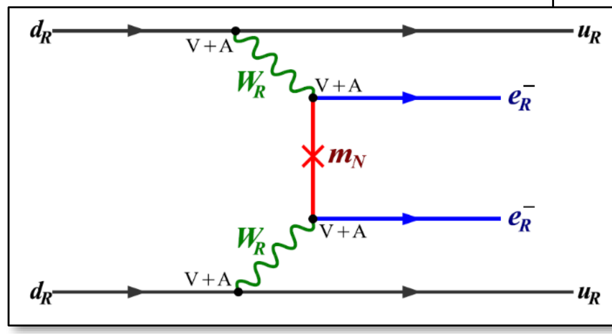

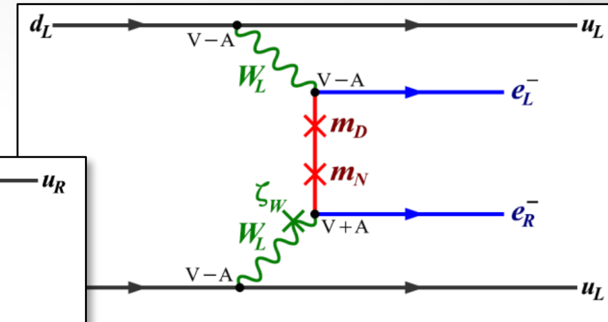

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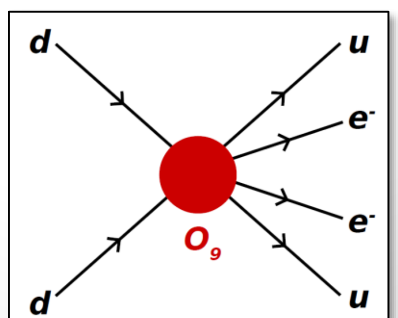
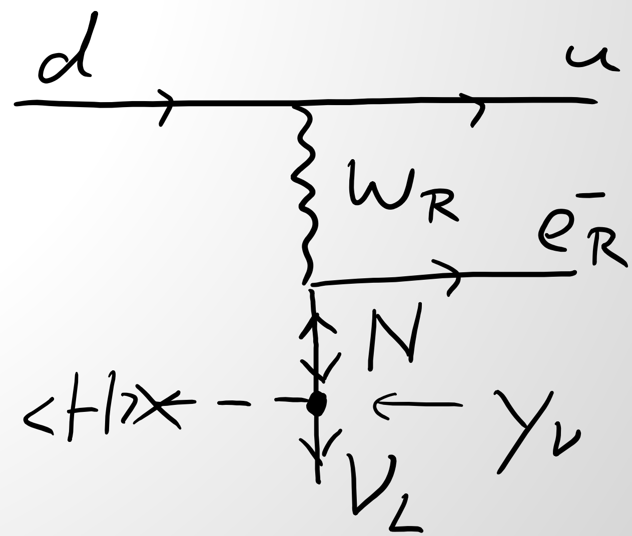
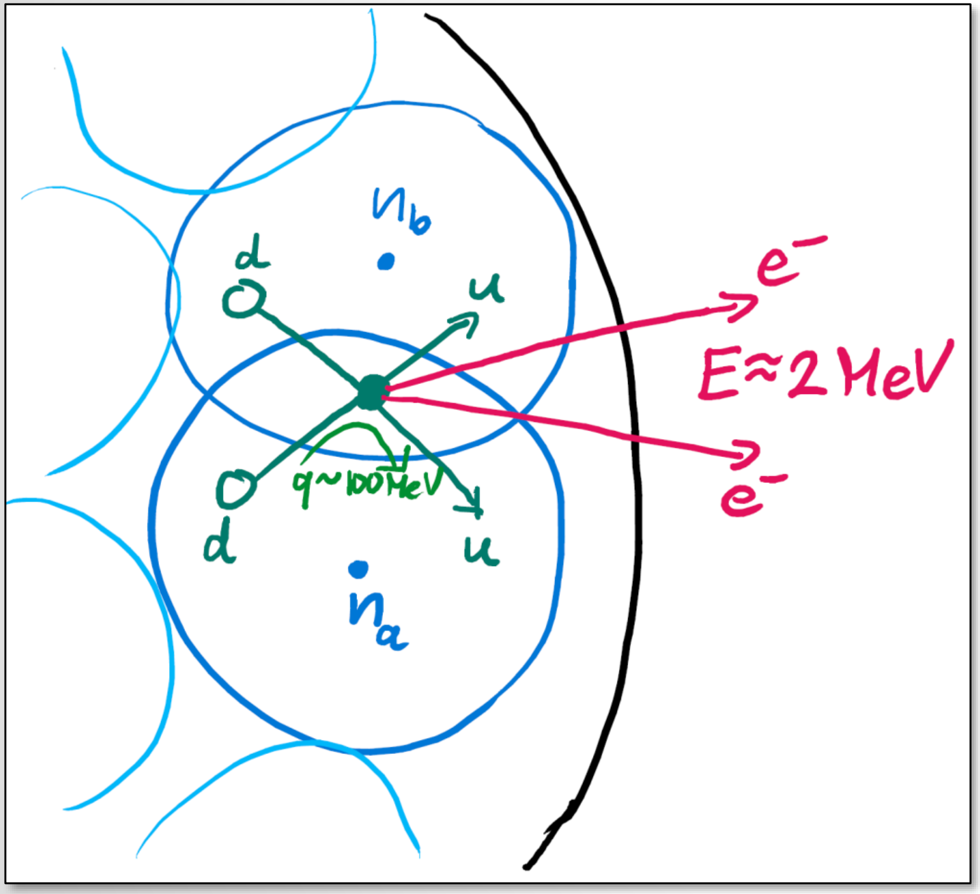




Short-Range Mechanisms



- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators
    (Paes et al. '01)
  - Nucleon currents

$$\langle p|\,\bar u(1\pm\gamma_5)d\,|n\rangle = \bar N\tau^+\left[F_S(q^2)\pm F_{PS}(q^2)\gamma_5\right]N',$$

$$\langle p|\,\bar u\gamma^\mu(1\pm\gamma_5)d\,|n\rangle = \bar N\tau^+\left[F_V(q^2)\gamma^\mu - i\frac{F_W(q^2)}{2m_p}\sigma^{\mu\nu}q_\nu\right]N' \pm \bar N\tau^+\left[F_A(q^2)\gamma^\mu\gamma_5 - \frac{F_P(q^2)}{2m_p}\gamma_5 q^\mu\right]N',$$

  - Form factors with enhancement for

$$F_{PS}(q^2) = \frac{g_{PS}}{(1+q^2/m_{PS}^2)^2}\frac{1}{1+q^2/m_\pi^2}, \qquad g_{PS} = 349$$

$$F_P(q^2) = \frac{g_A}{(1+q^2/m_A^2)^2}\frac{1}{1+q^2/m_\pi^2}\frac{4m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right)$$

Short-Range Mechanisms

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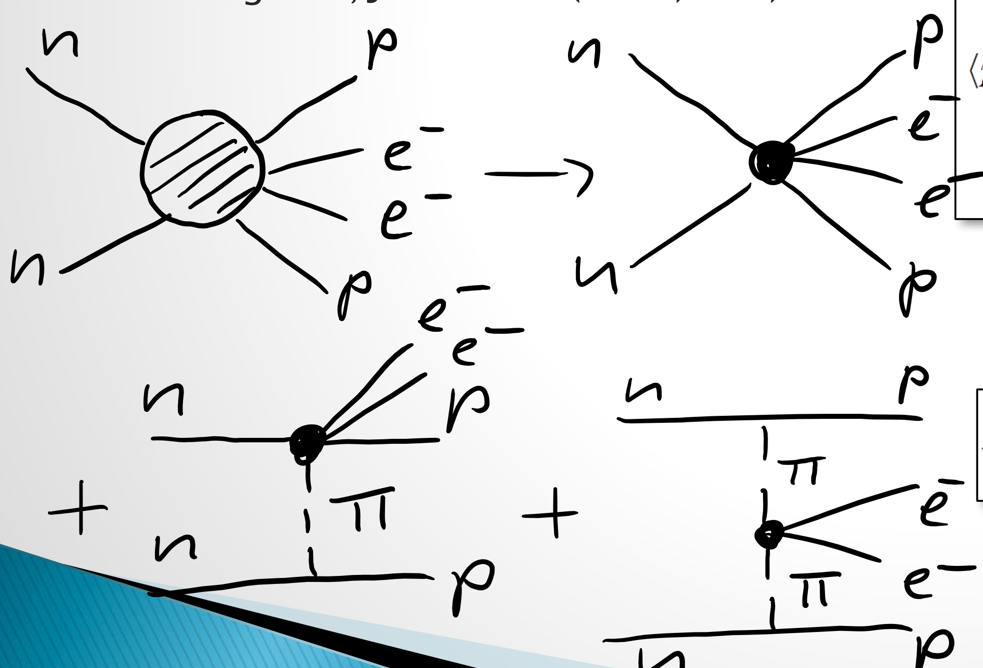
- Pion-mediated contributions
  - R-parity violating SUSY
    (Faessler, Kovalenko, Simkovic, Schwieger, Phys.Rev.Lett. 78 (1997) 183)
  - Chiral EFT with Pion-operators from Lattice QCD
    (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)



- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators
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  - Nucleon currents

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Short-Range Mechanisms

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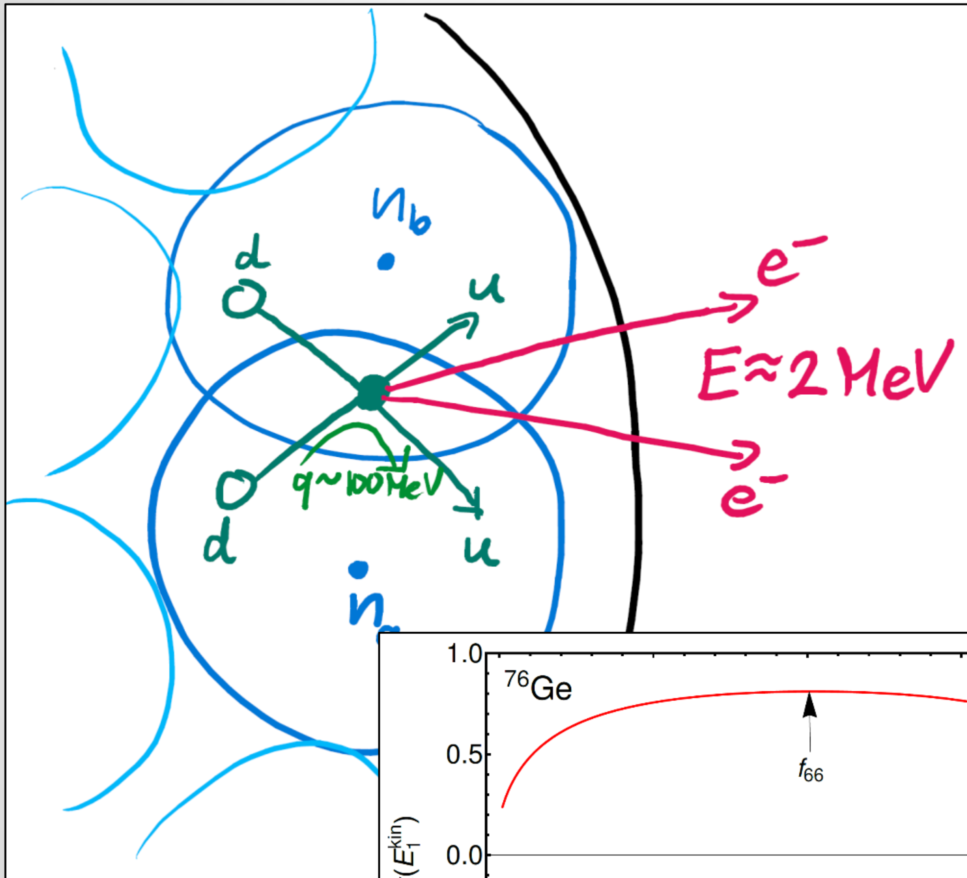
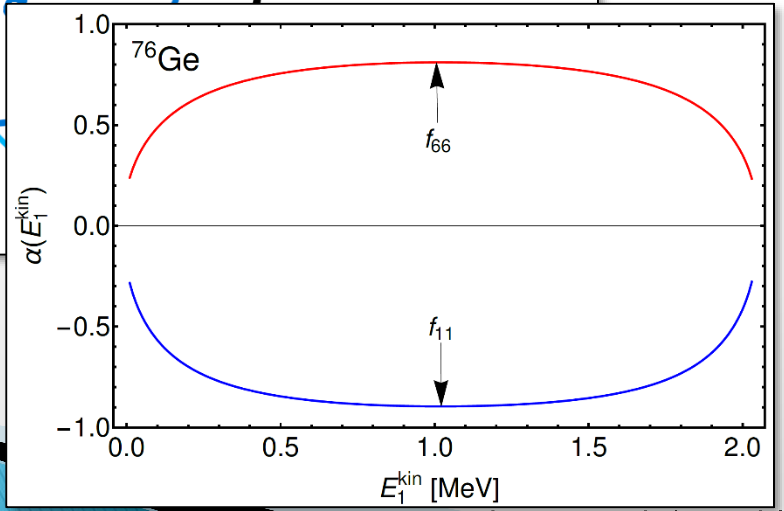
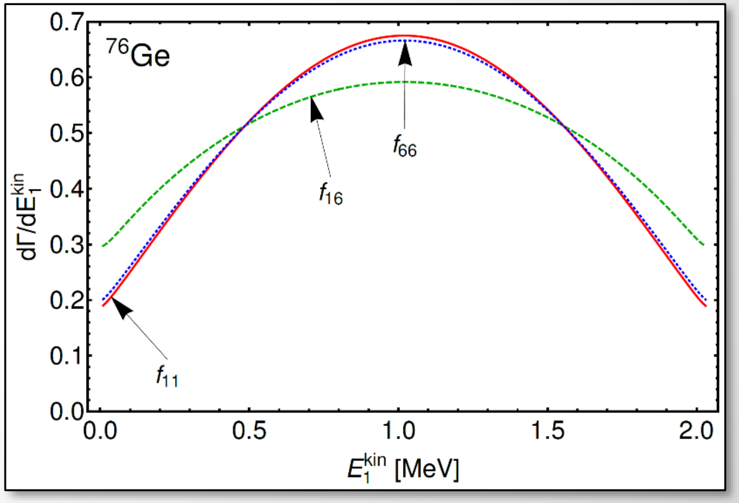


- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - Evaluation of additional NMEs
  - Numerical determination of e^- wavefunctions (nuclear Coulomb potential and e^- cloud screening ➔ e^- energy and angular distribution





Short-Range Mechanisms

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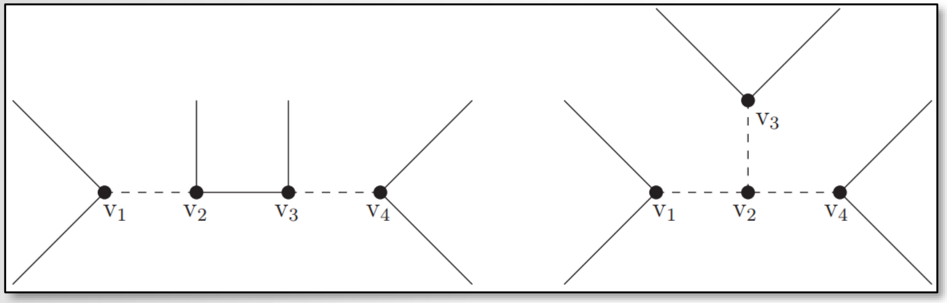


#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(-1, \mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$

Bonnet, Hirsch, Ota, Winter, JHEP 1303 (2013) 055

- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - Improved limits on effective interactions and NP scales

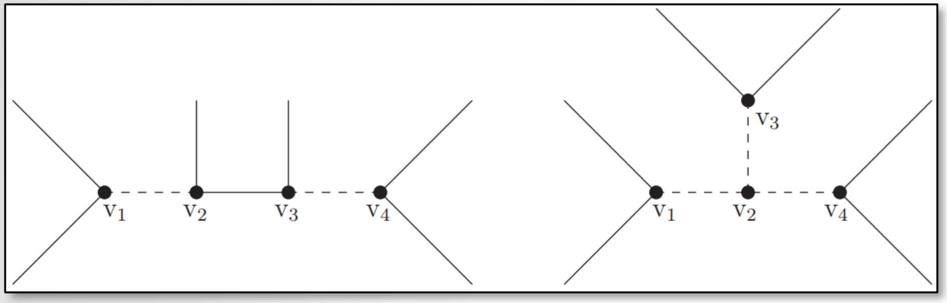
$$\frac{1}{\Lambda_{NP}^5} = \frac{G_F^2}{2m_p}\epsilon_i$$

including QCD RGE effects
(Mahajan, PRL 112, 031804; Gonzalez, Hirsch, Kovalenko, PRD 93, 013017)

		JJj		$J_{\mu\nu}J^{\mu\nu}j$	$J_\mu J^\mu j$		$J^\mu J_{\mu\nu}j^\nu$		$J_\mu J j^\mu$	
	$T_{1/2}^{exp}$ [y]	$\lvert c_1^{XX}\rvert$	$\lvert c_1^{LR}\rvert$	$\lvert c_2^{XX}\rvert$	$\lvert c_3^{XX}\rvert$	$\lvert c_3^{LR}\rvert$	$\lvert c_4^{XX}\rvert$	$\lvert c_4^{LR}\rvert$	$\lvert c_5^{XX}\rvert$	$\lvert c_5^{RL,LR}\rvert$
^{76}Ge	5.3×10^{25} [71]	0.62	0.36	88	160	260	580	400	25	12
^{130}Te	2.8×10^{24} [72]	1.4	0.83	200	350	580	1300	880	59	28
^{136}Xe	1.1×10^{26} [73]	0.24	0.14	32	72	130	250	190	9.6	4.7

$\times 10^{-10}$

Short-Range Mechanisms



- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - Improved limits on effective interactions and NP scales

$$= \frac{G_F^2}{2m_p}\epsilon_i$$

QCD RGE effects

Bonnet, Hirsch, Ota, Winter, JHEP 1303 (2013) 055

112, 031804; Gonzalez, nko, PRD 93, 013017)

#	Decomposition	Long Range?	Mediator $(U(1)_{\text{em}}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62,63]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65,66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60], LQ [65,66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	

$J_\mu J j^\mu$

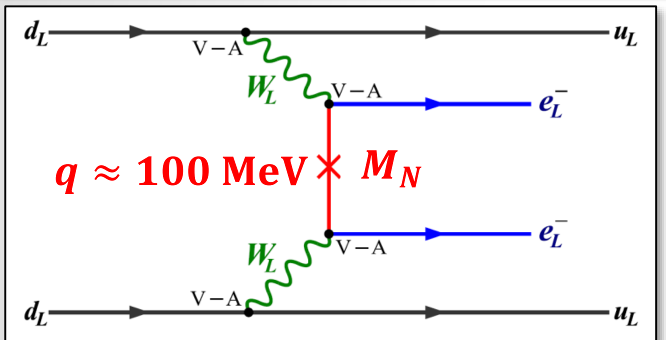
c_5^{XX}	$\lvert c_5^{RL,LR}\rvert$
25	12
59	28
9.6	4.7

$\times 10^{-10}$

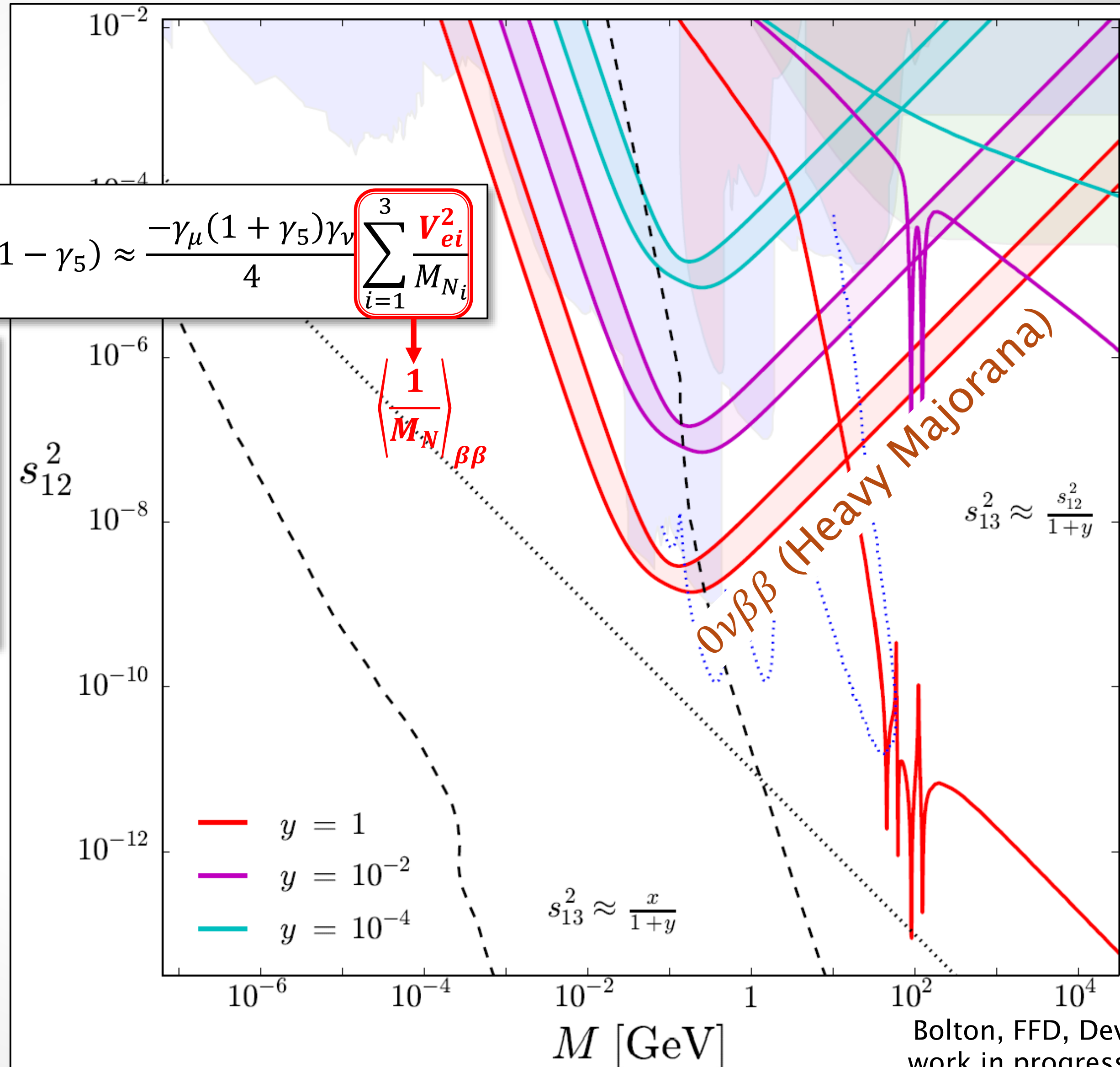
Heavy Sterile Neutrinos

- with masses larger than ≈ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\sum_{i=1}^{3}\frac{V_{ei}^2}{M_{N_i}}$$



- Different nuclear matrix elements
  - Short-range operator



Interference with $m_{\beta\beta}$

University College London

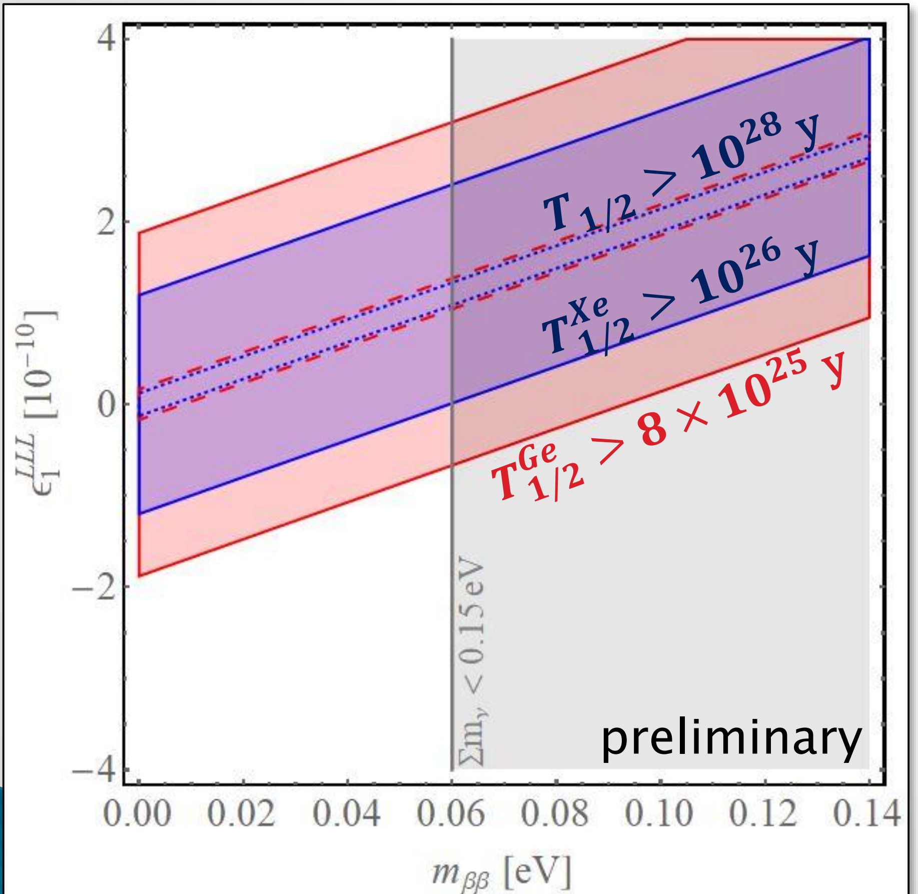
Same lepton current

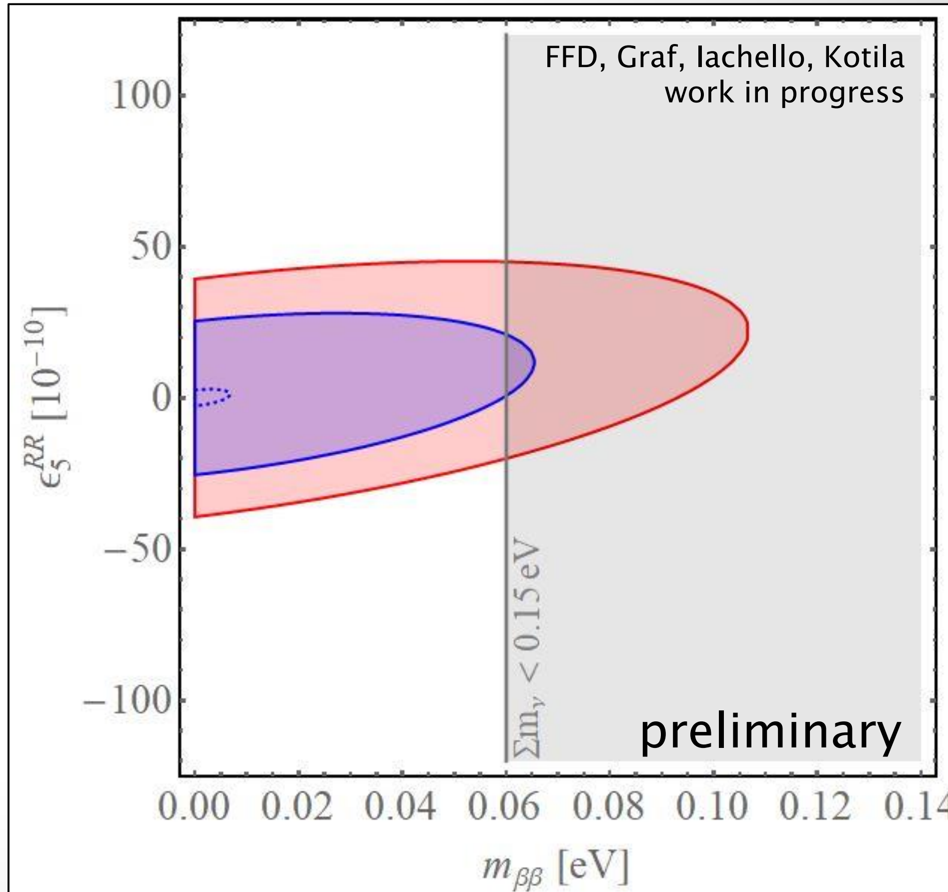
$$T_{1/2}^{-1} = G_\nu \left| \frac{m_{\beta\beta}}{m_e} \mathcal{M}_\nu + \epsilon \mathcal{M}_\epsilon \right|^2$$

e.g. heavy neutrino exchange
Mitra, Pascoli, Wong, Phys. Rev. D 90 (2014) 093005

Different currents

$$T_{1/2}^{-1} = \frac{|m_{\beta\beta}|^2}{m_e^2} |\mathcal{M}_\nu|^2 G_\nu + |\epsilon|^2 |\mathcal{M}_\epsilon|^2 G_\epsilon + 2Re\left[\frac{m_{\beta\beta}}{m_e} \epsilon^* \mathcal{M}_\nu \mathcal{M}_\epsilon^*\right] G_{\nu\epsilon}$$





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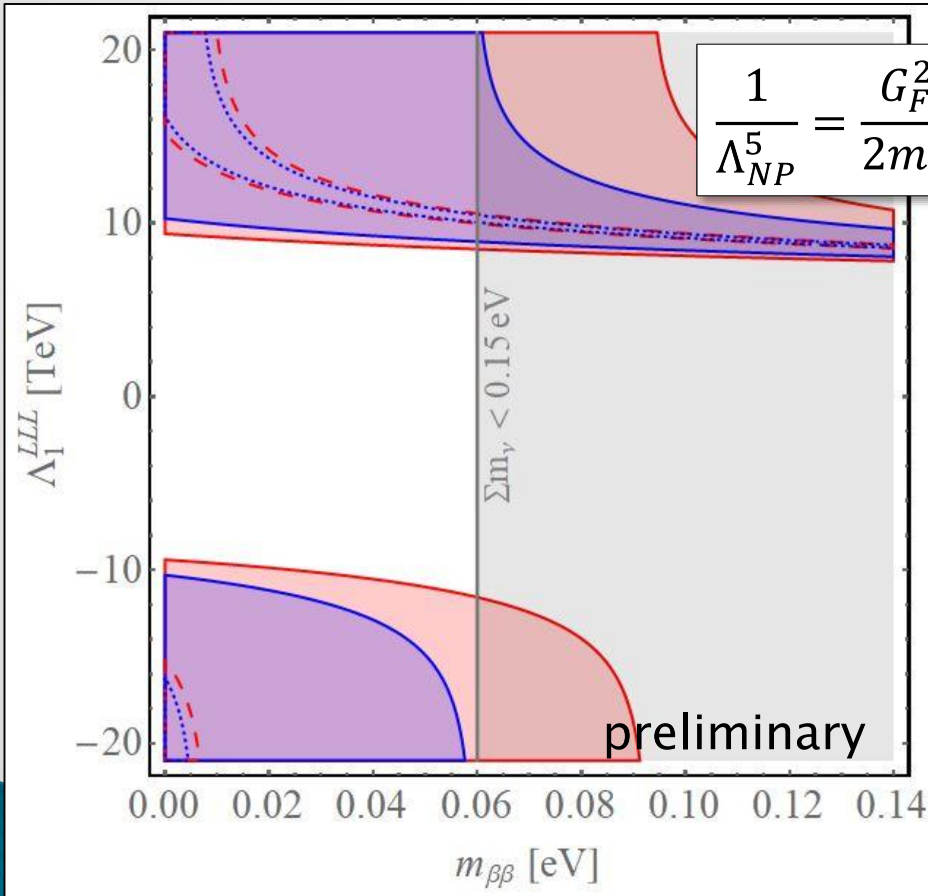
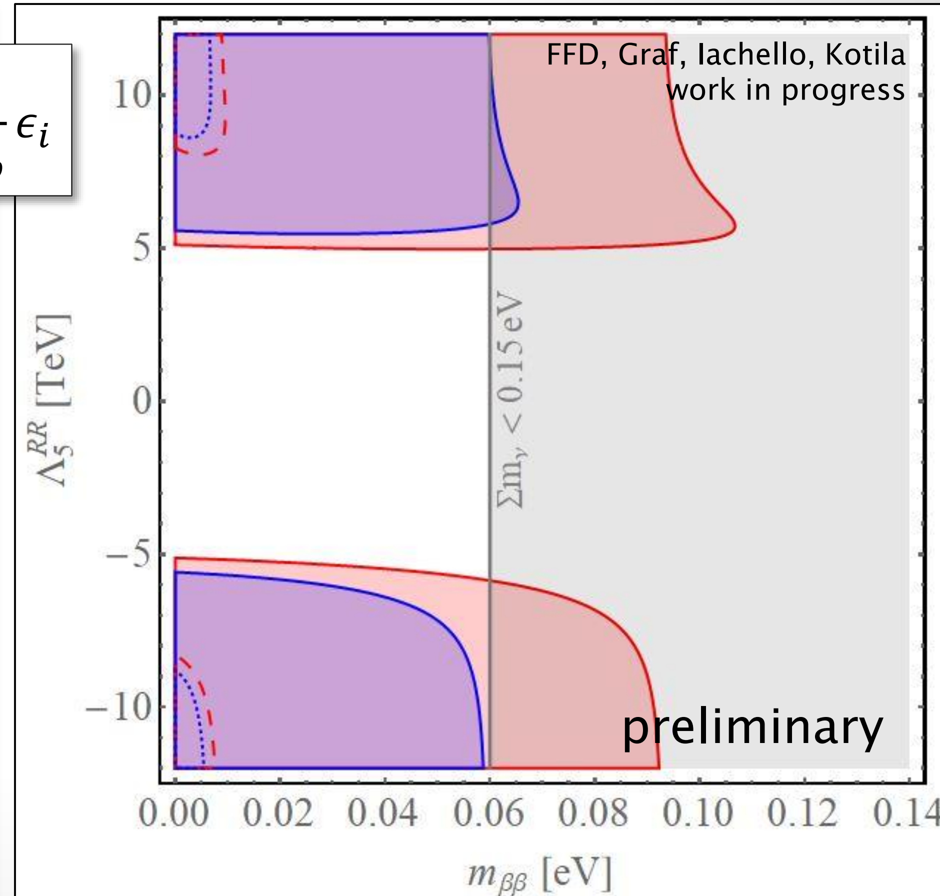
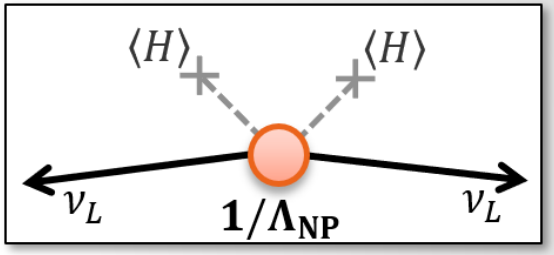
$$\frac{1}{\Lambda_{NP}^5} = \frac{G_F^2}{2m_p}\epsilon_i$$





Conclusion

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
  - Determination of absolute mass scale



$$\frac{T_{1/2}^{0\nu\beta\beta}}{10^{28}\ \mathrm{y}} \approx \left(\frac{\Lambda_{NP}}{10^{15}\ \mathrm{GeV}}\right)^2$$

- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - New LNV physics at the LHC scale?
  - Standard Mass Mechanism?
    - 5-dim operator from LNV at GUT scale
  - Experimentally and theoretically challenging
- **Importance of probing LNV around the TeV scale**
  - E.g. searches for heavy neutral leptons at the LHC
  - Can we rule out mechanisms of neutrino mass generation?
  - Impact on baryon asymmetry of the Universe
    (FFD, Harz, Hirsch, Phys. Rev. Lett. 112 (2014) 221601)