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Double Beta Decay and TeV Scale Physics

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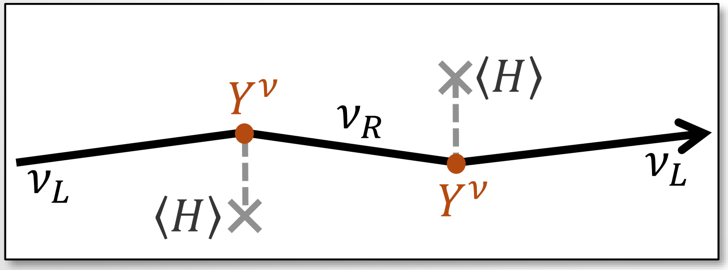
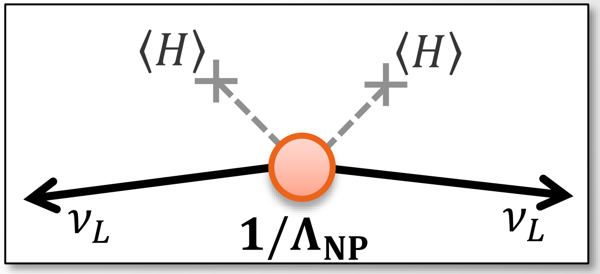
Dirac vs Majorana

- 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



Three Active Neutrinos

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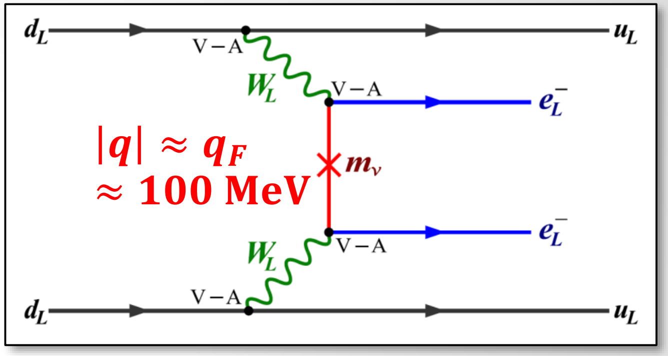
- Half-life

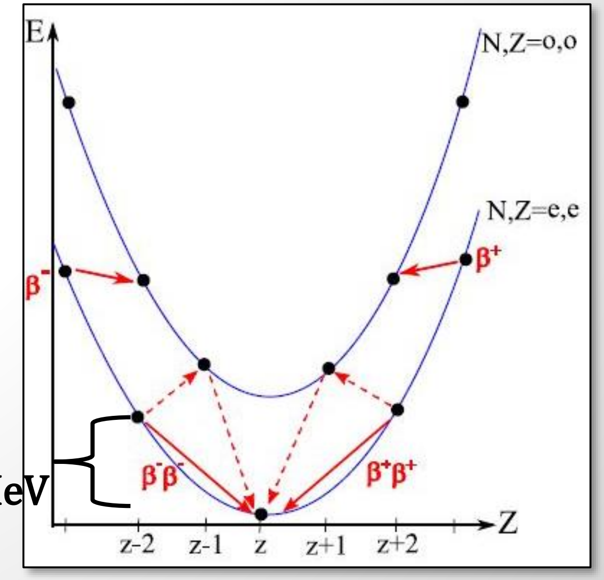
$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$

- 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 $M^{0\nu} \approx 1$



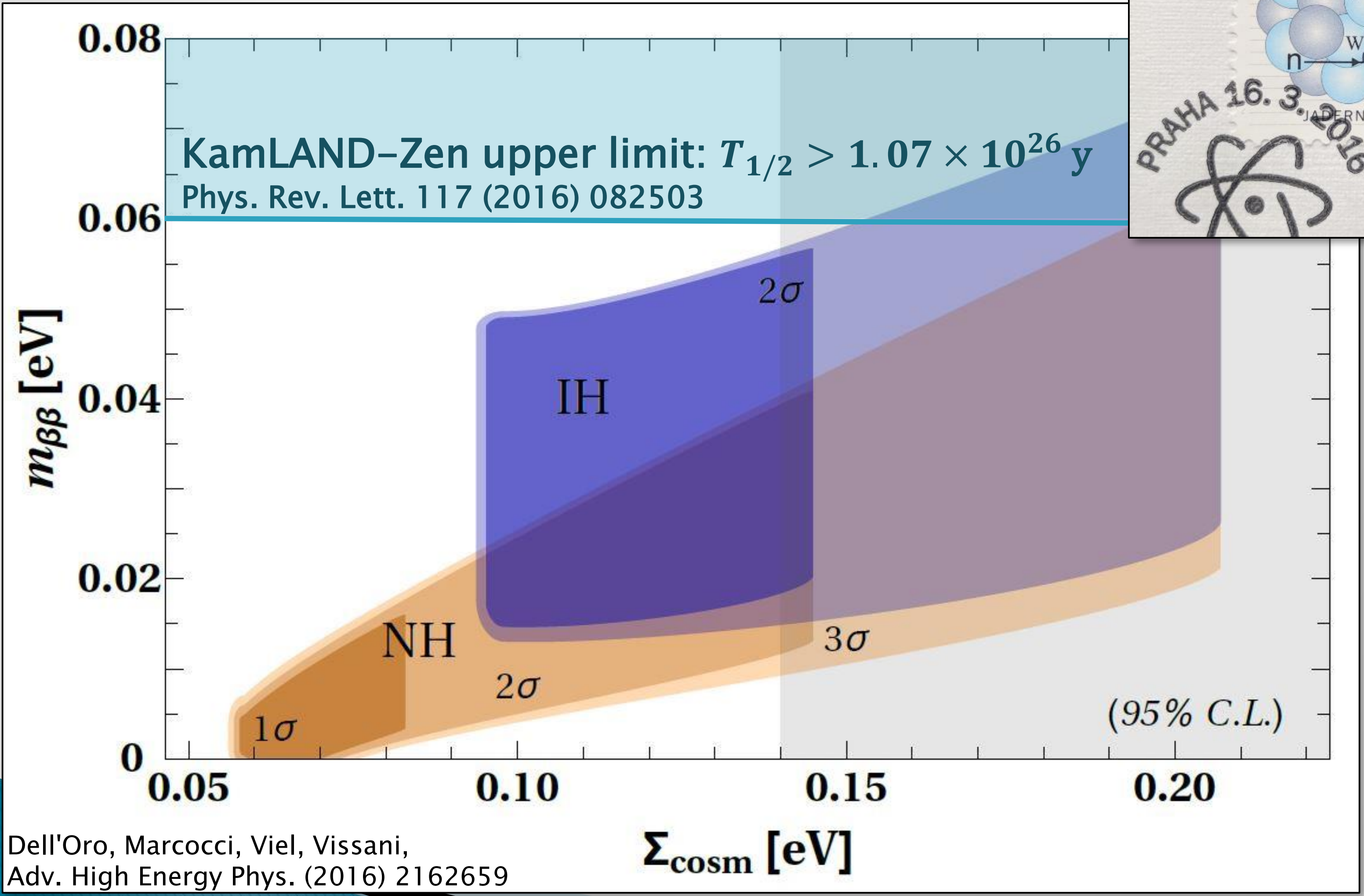
$$T_{1/2}^{-1} \propto |m_{\beta\beta}|^2 q_F^2 G_F^4 Q^5$$

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

$Q + 2m_e \approx$ 3–5 MeV

Three Active Neutrinos

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



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

Three Active Neutrinos

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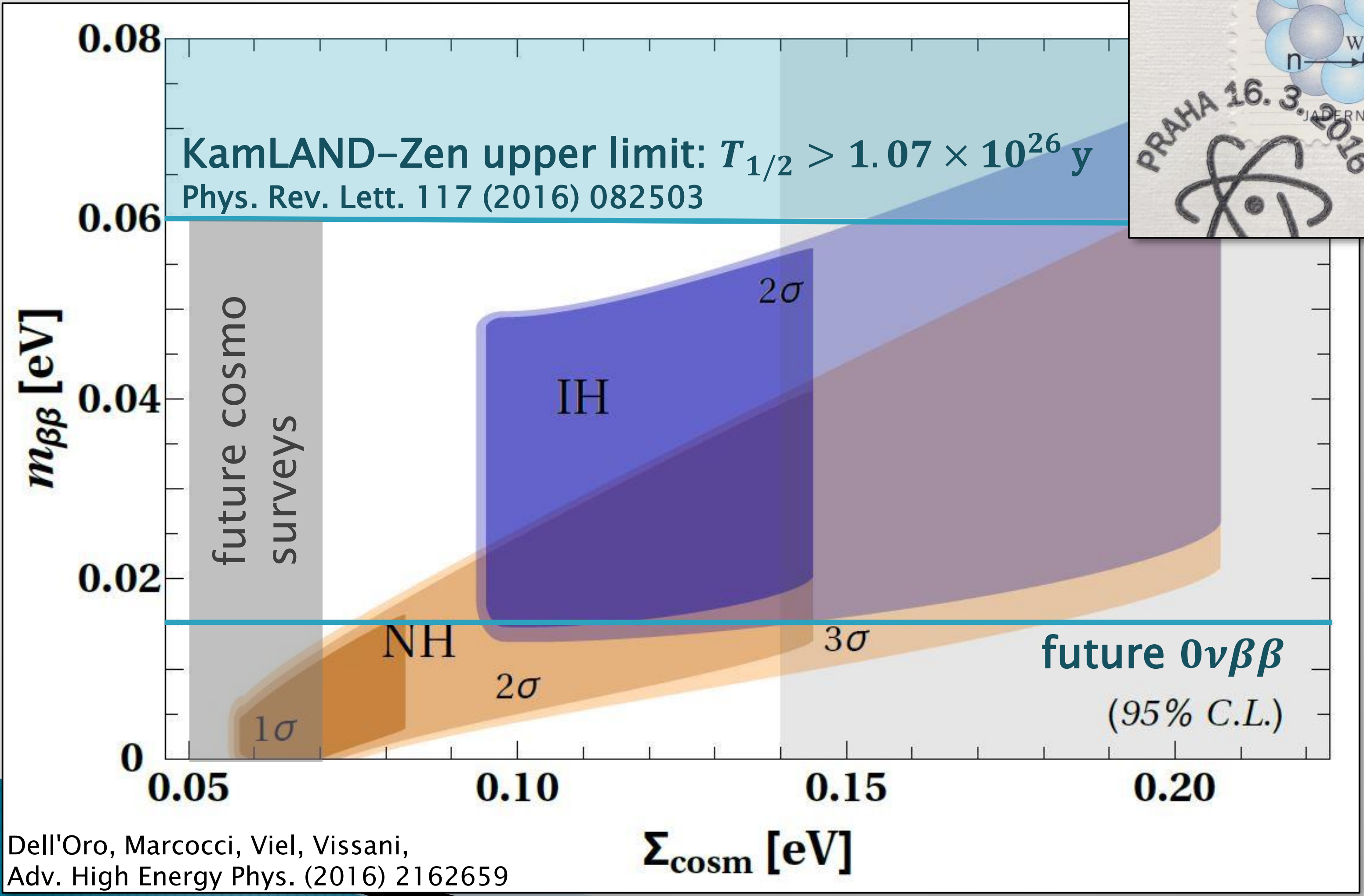

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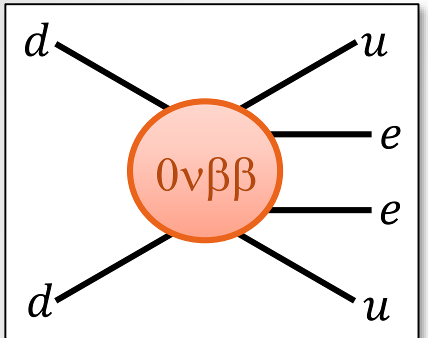
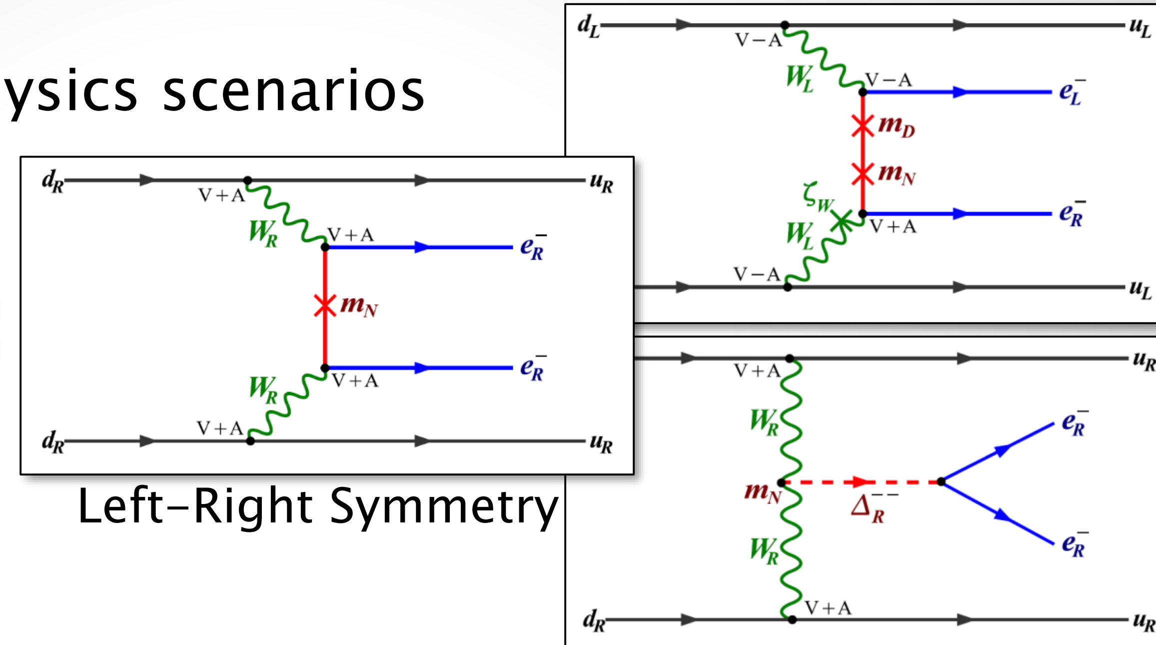
New Physics and $0\nu\beta\beta$

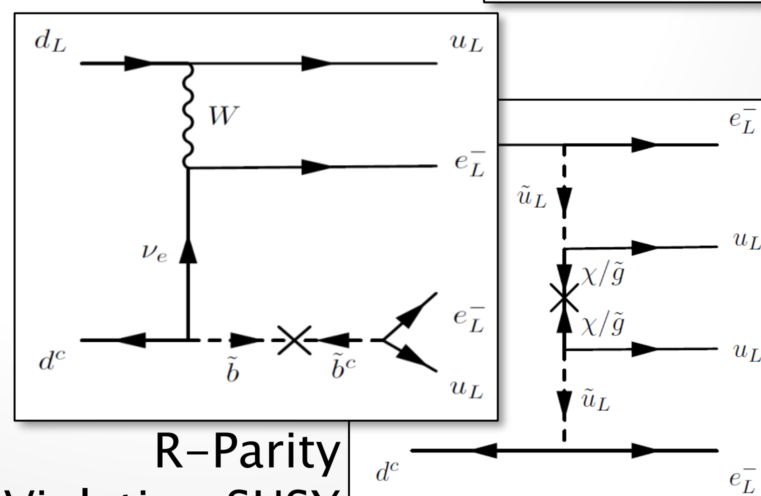
- Plethora of New Physics scenarios



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



Left-Right Symmetry

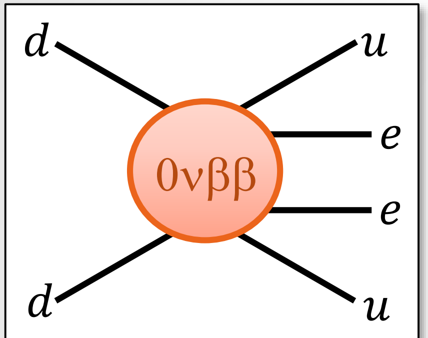


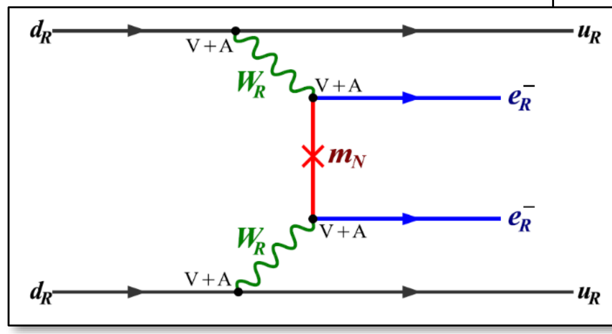
R-Parity Violating SUSY

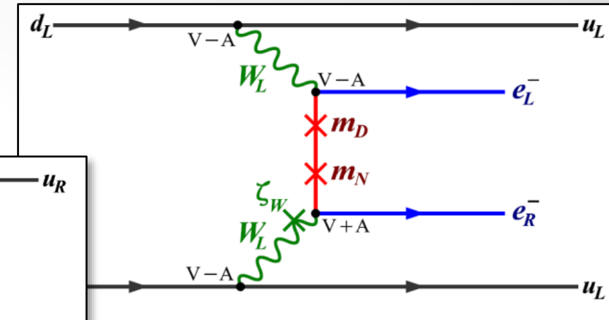
- Extra Dimensions
- Majorons
- Leptoquarks
- ...

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

- Examples in Left-Right Symmetry





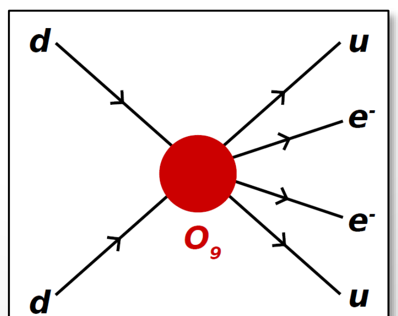


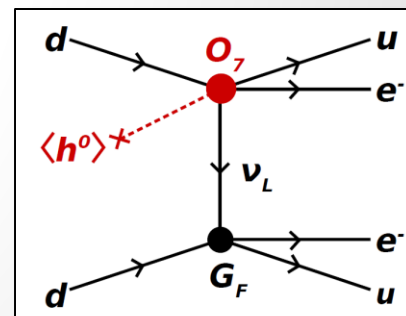
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

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

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

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





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

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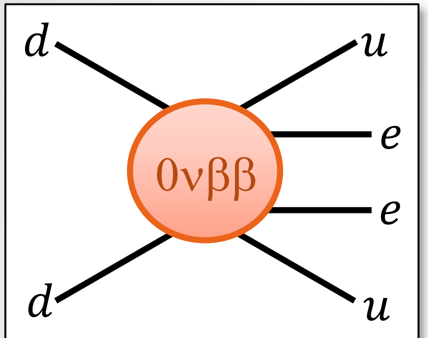

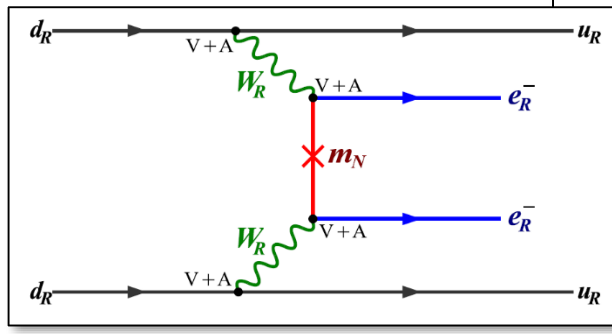

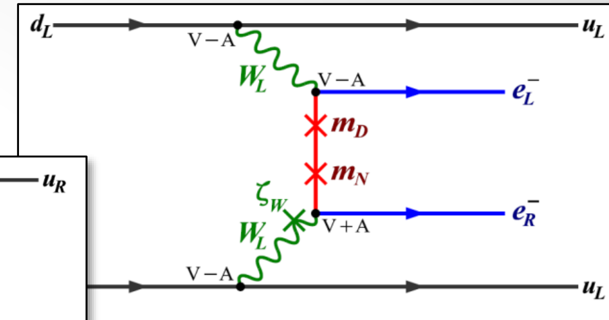

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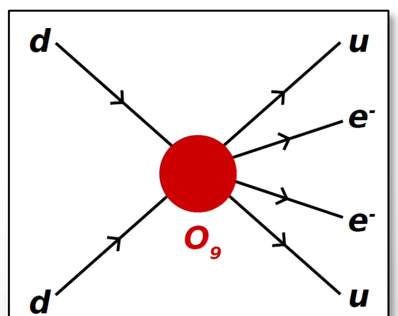
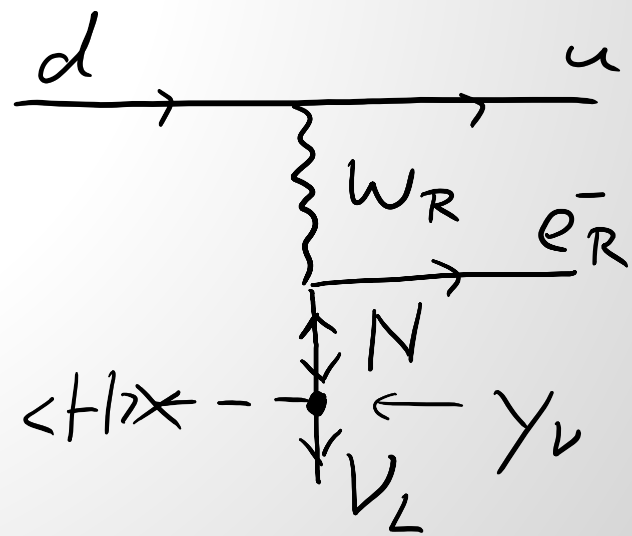
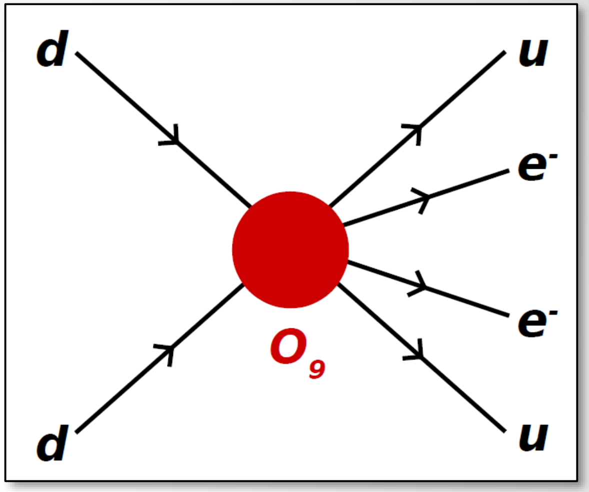




Short–Range Mechanisms

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



$$L = \frac{G_F^2}{2m_p}(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\nu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu})$$

Short-Range Mechanisms

- Evaluation of limits on short-range operators
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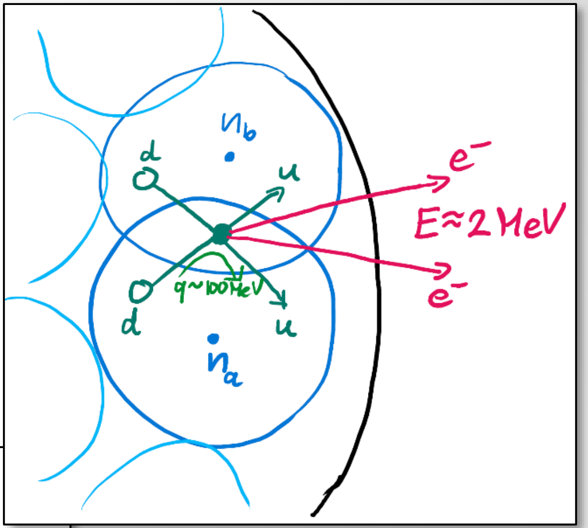
  - Nucleon currents



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

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

$$\langle p|\,\bar{u}\sigma^{\mu\nu}(1\pm\gamma_5)d\,|n\rangle = \bar{N}\tau^+\left[J^{\mu\nu}\pm\frac{i}{2}\epsilon^{\mu\nu\rho\sigma}J_{\rho\sigma}\right]N',$$

$$J^{\mu\nu} = F_{T_1}(q^2)\sigma^{\mu\nu} + i\frac{F_{T_2}(q^2)}{m_p}(\gamma^\mu q^\nu - \gamma^\nu q^\mu) + \frac{F_{T_3}(q^2)}{m_p^2}(\sigma^{\mu\rho}q_\rho q^\nu - \sigma^{\nu\rho}q_\rho q^\mu).$$

Short-Range Mechanisms

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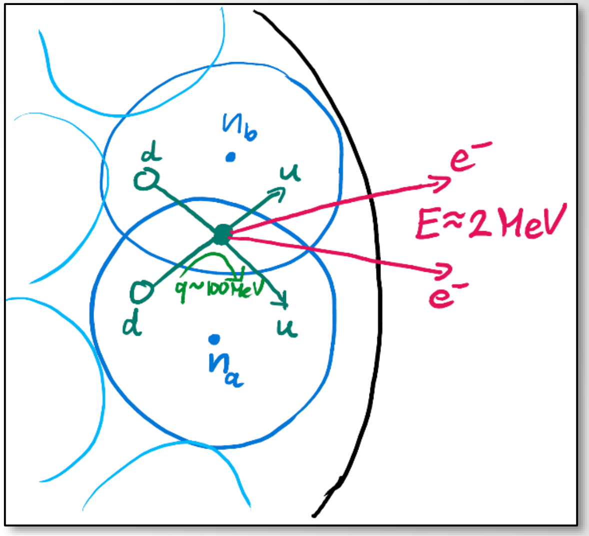
  - Nucleon currents
  - Nucleon form factors



$$F_S(q^2) = \frac{g_S}{(1+q^2/m_V^2)^2}, \qquad g_S = 1.0\ [42],$$

$$F_{PS}(q^2) = \frac{g_{PS}}{(1+q^2/m_V^2)^2}\frac{1}{1+q^2/m_\pi^2}, \qquad g_{PS} = 349\ [42],$$

$$F_V(q^2) = \frac{g_V}{(1+q^2/m_V^2)^2}, \qquad g_V = 1.0,$$

$$F_W(q^2) = \frac{g_W}{(1+q^2/m_V^2)^2}, \qquad g_W = 3.7,$$

$$F_A(q^2) = \frac{g_A}{(1+q^2/m_A^2)^2}, \qquad g_A = 1.27\ [43],$$

$$F_P(q^2) = \frac{g_P}{(1+q^2/m_A^2)^2}\frac{1}{1+q^2/m_\pi^2}, \qquad g_P = 4g_A\frac{m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right) = 231\ [44],$$

$$F_{T_i}(q^2) = \frac{g_{T_i}}{(1+q^2/m_V^2)^2}, \qquad g_{T_{1,2,3}} = 1.0, -3.3, 1.34\ [40].$$

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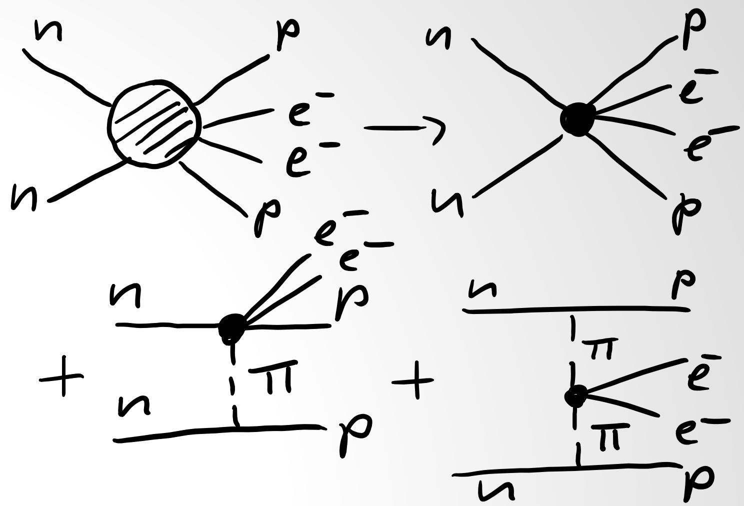

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Pion-mediated contributions

- 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)

Short-Range Mechanisms

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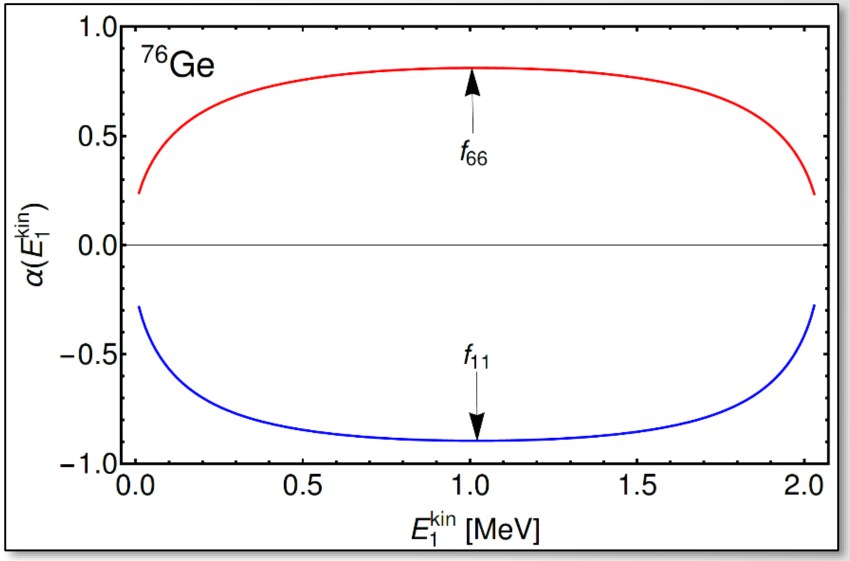
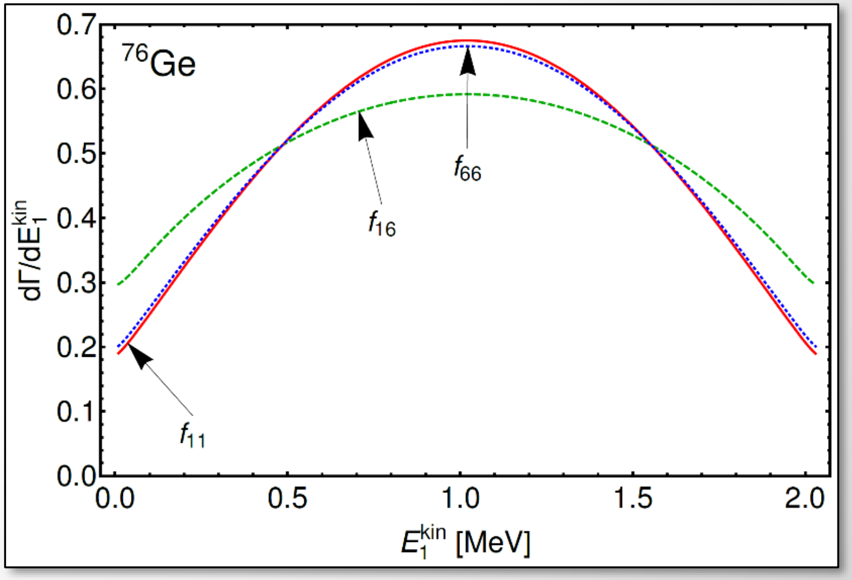
- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators (Paes et al. '01)
  - Nucleon currents
  - Nucleon form factors
  - Evaluation of additional NMEs
  - Numerical determination of e^- wavefunctions (nuclear Coulomb potential and e^- cloud screening Type equation here. energy and angular distribution





Nuclear Matrix Elements

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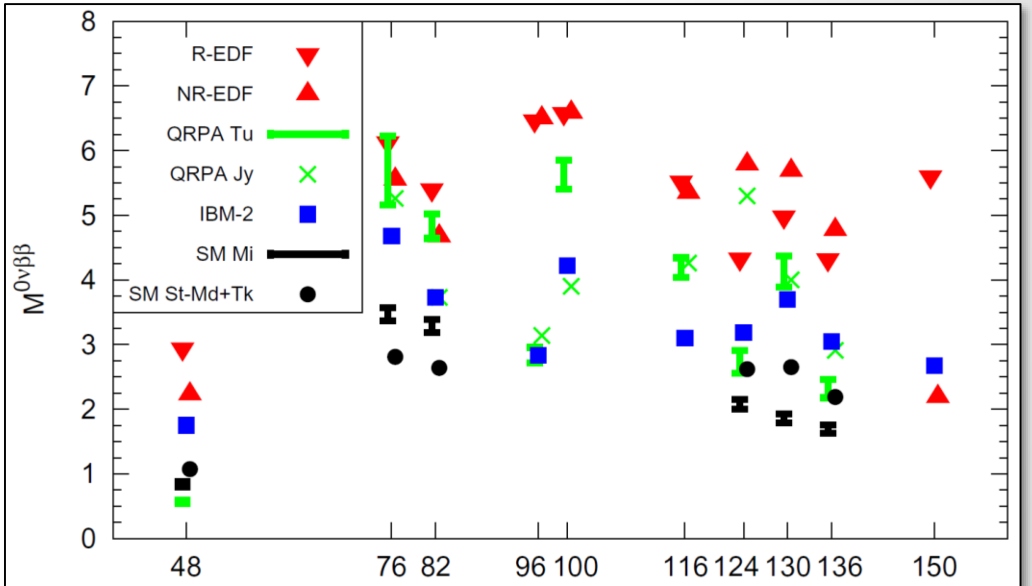
- Nuclear Matrix Element

$$M^{0\nu} = g_A^2\left(M_{GT} - \frac{g_V^2}{g_A^2}M_F + M_T\right)$$

  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models
  - Additional suppression of axial nucleon coupling g_A?



Menendez, arXiv:1605.05059

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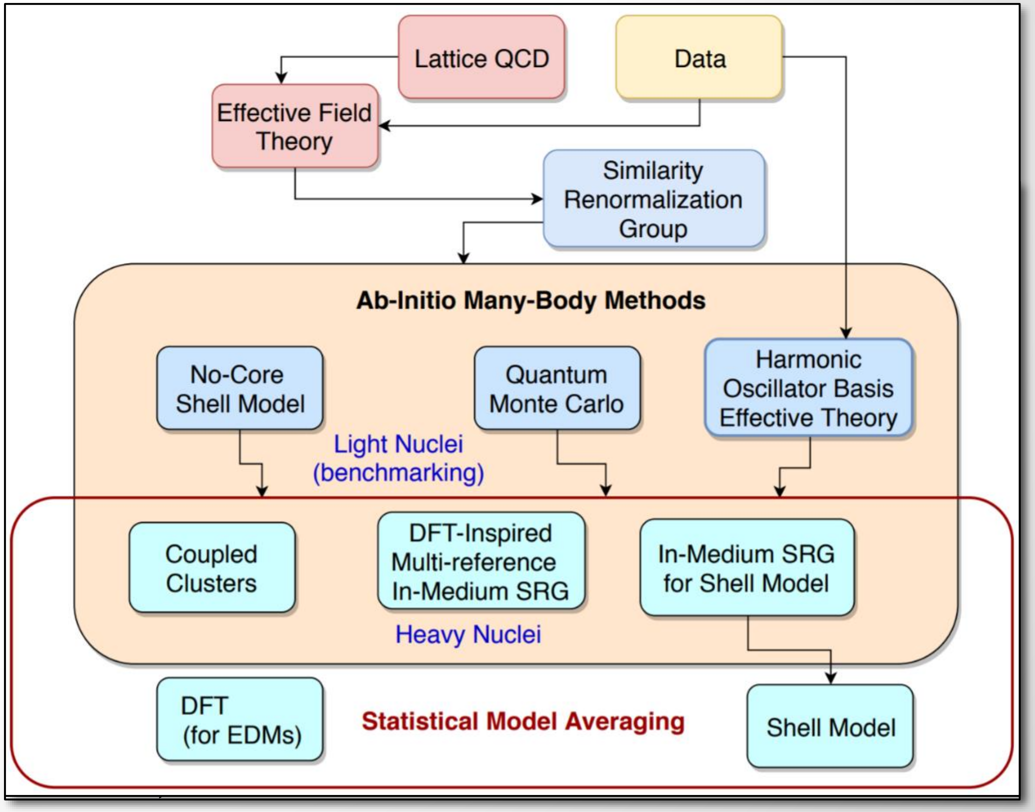
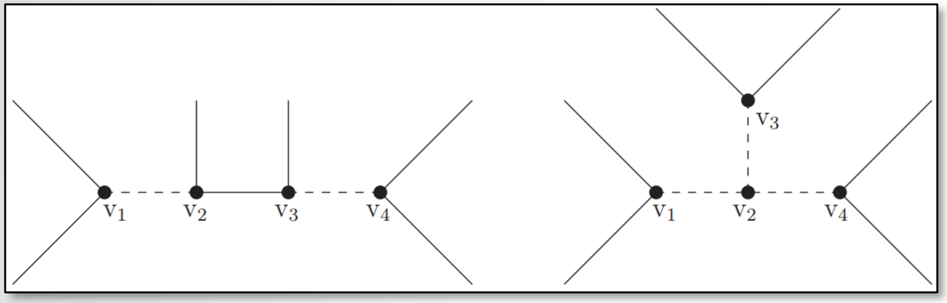
$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)$$

  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models
  - Additional suppression of axial nucleon coupling g_A?
- Strong theoretical and experimental effort to reduce uncertainty

J. Engel, Talk at ECT* Workshop
"Progress and Challenges in $0\nu\beta\beta$"
indico.ectstar.eu/event/33/timetable/#20190715



Short-Range Mechanisms



#	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

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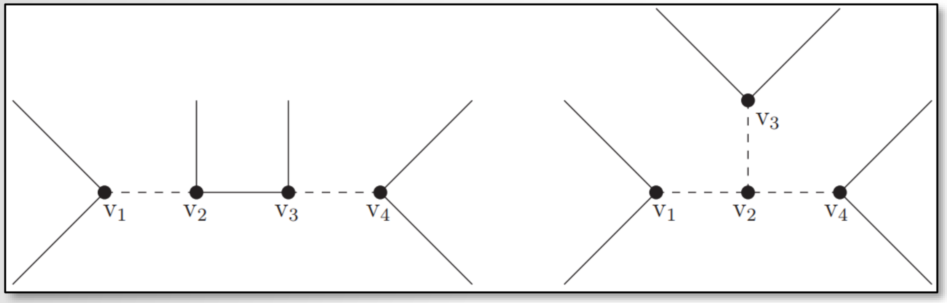


#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw,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

- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - Improved limits on effective interactio…s 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)

$J_\mu J j^\mu$

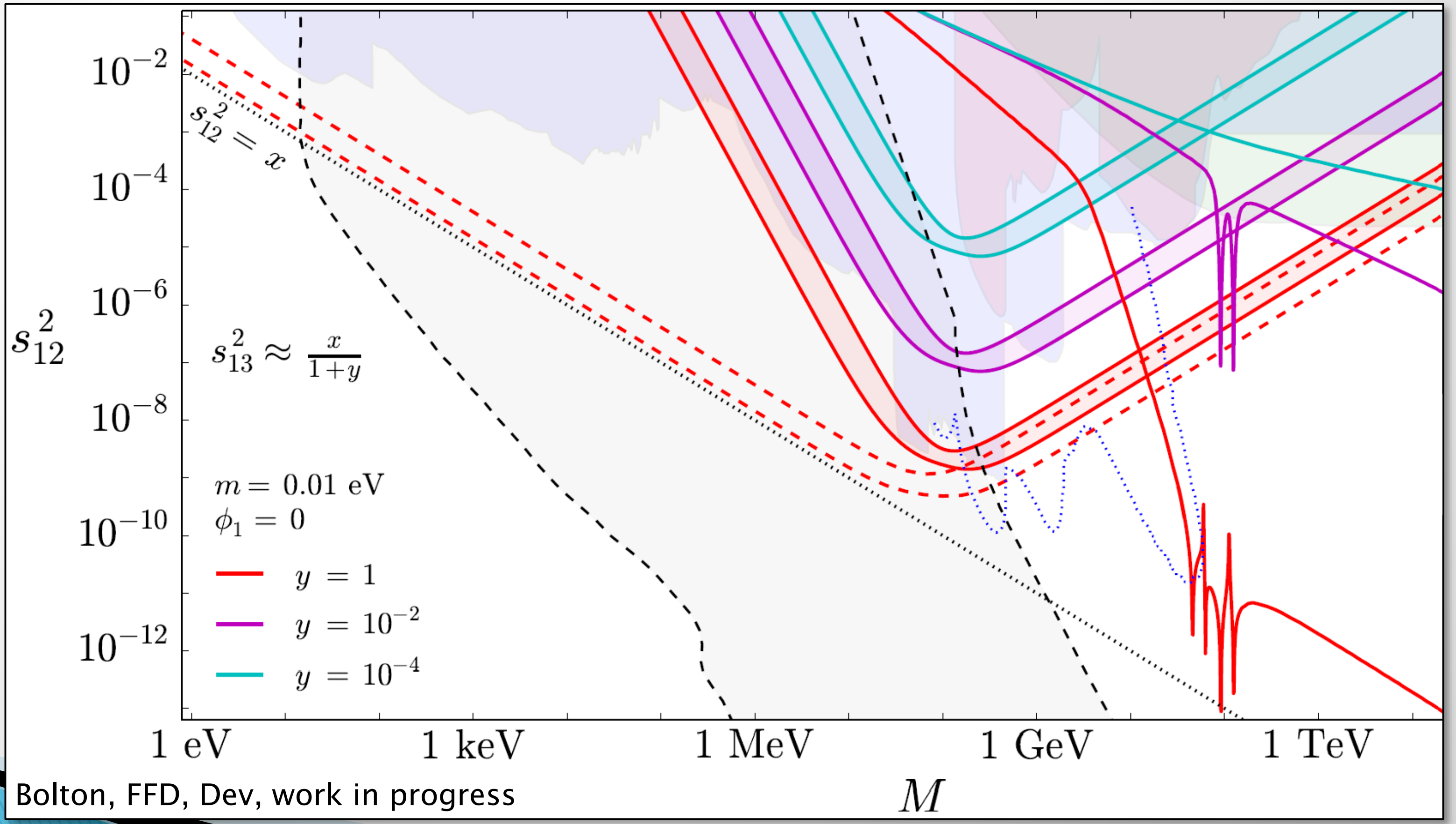
c_5^{XX}	$\lvert c_5^{RL,LR}\rvert$
25	12
59	28
9.6	4.7

$\times 10^{-10}$

Heavy Sterile Neutrinos

- with masses larger than ≈ 100 MeV

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



Interference with $m_{\beta\beta}$

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Same lepton current

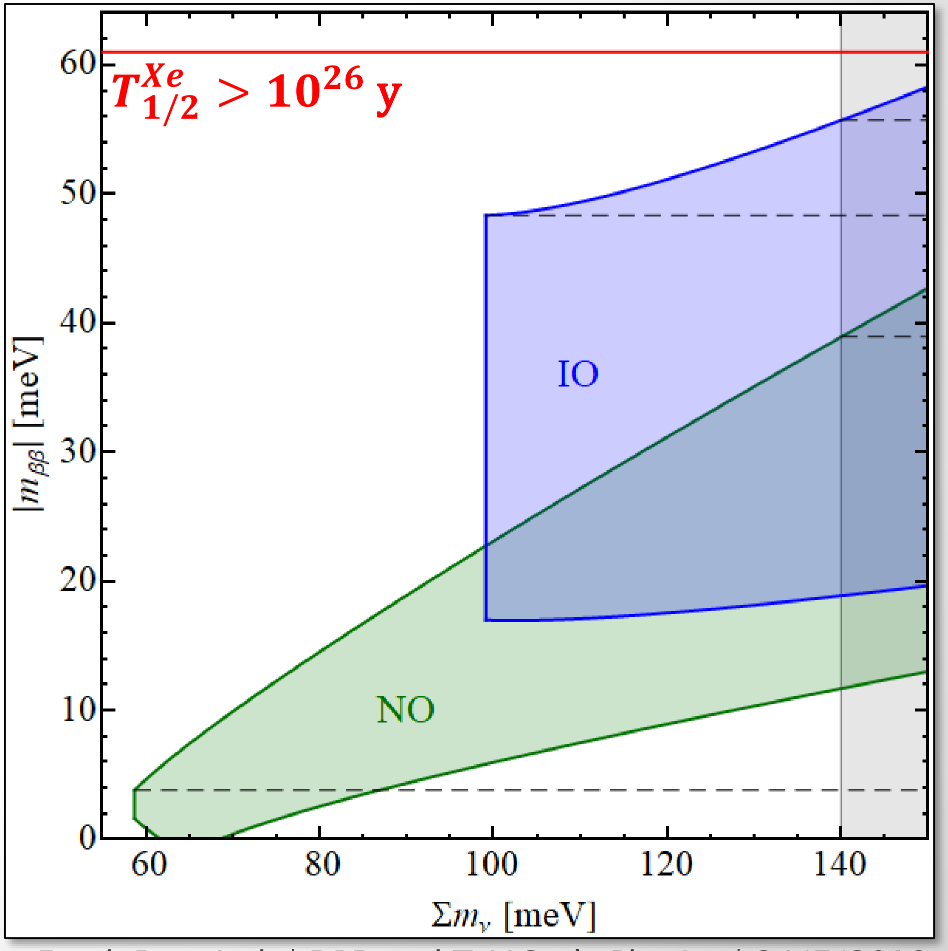
$$T_{1/2}^{-1} = G_\nu \left| \frac{m_{\beta\beta}}{m_e} \mathcal{M}_\nu + \epsilon \mathcal{M}_\epsilon \right|^2$$

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

Different currents

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

To constrain an exotic ϵ contribution, $m_{\beta\beta}$ has to be inferred independently, e.g. use upper limit on Σm_ν



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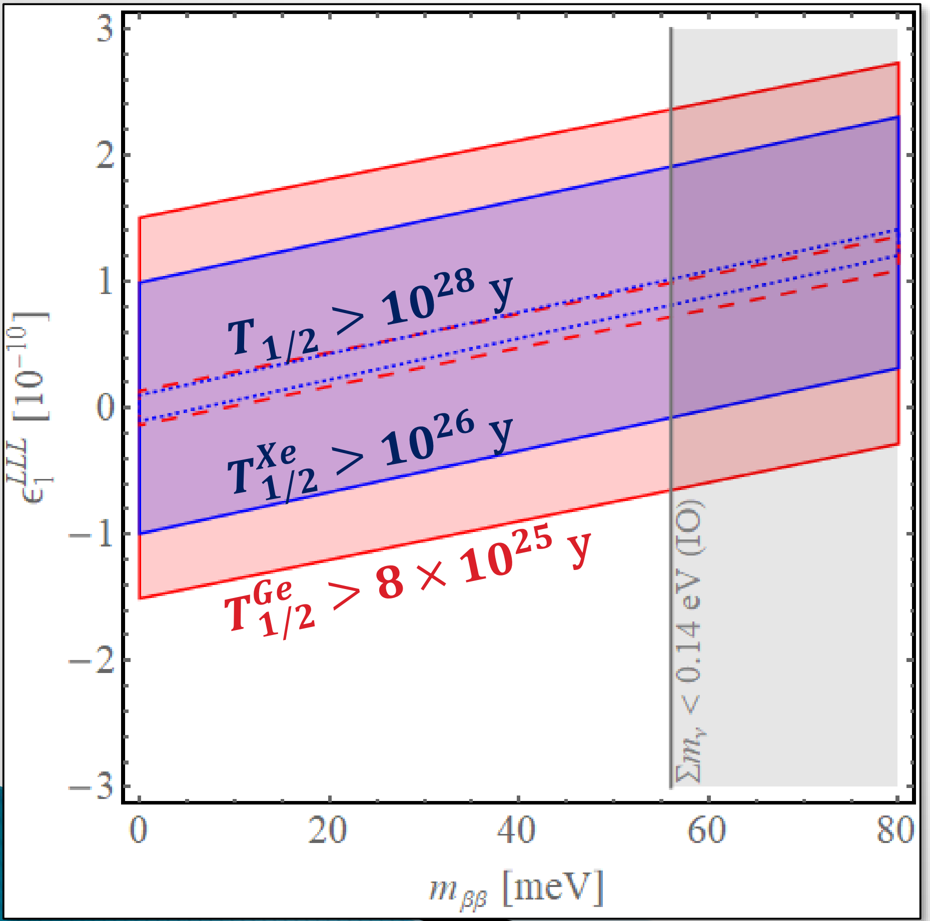

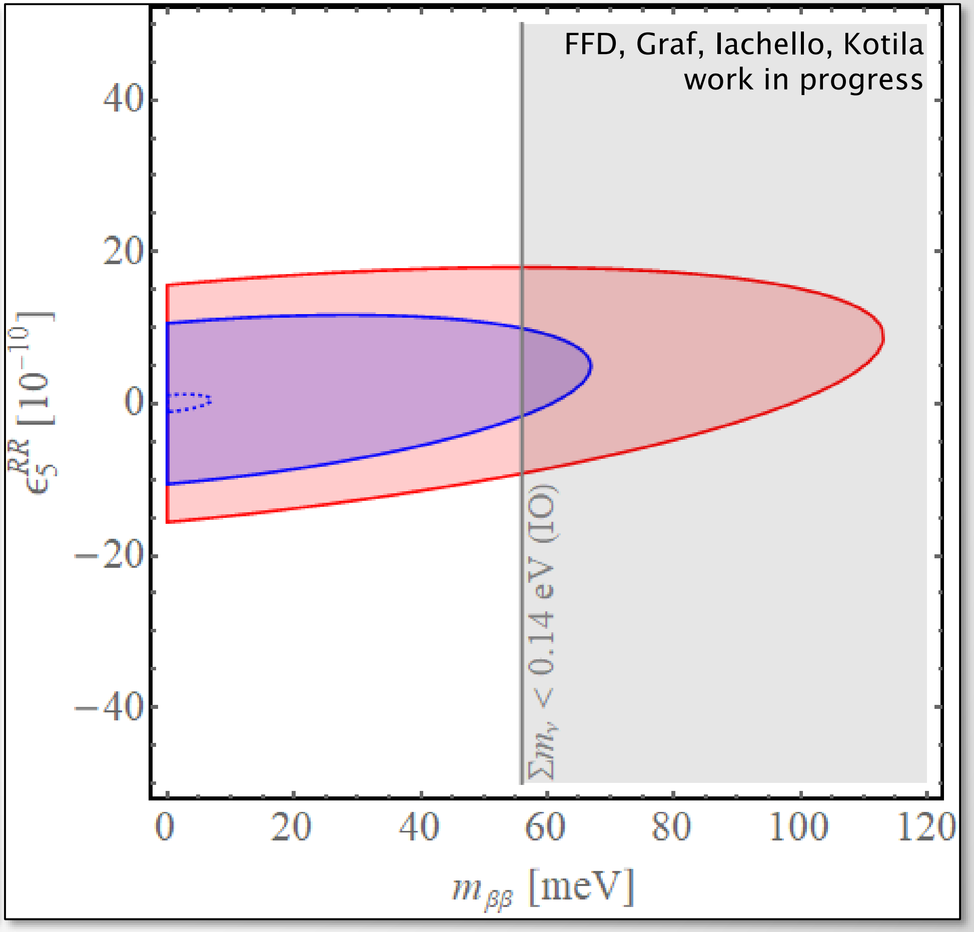

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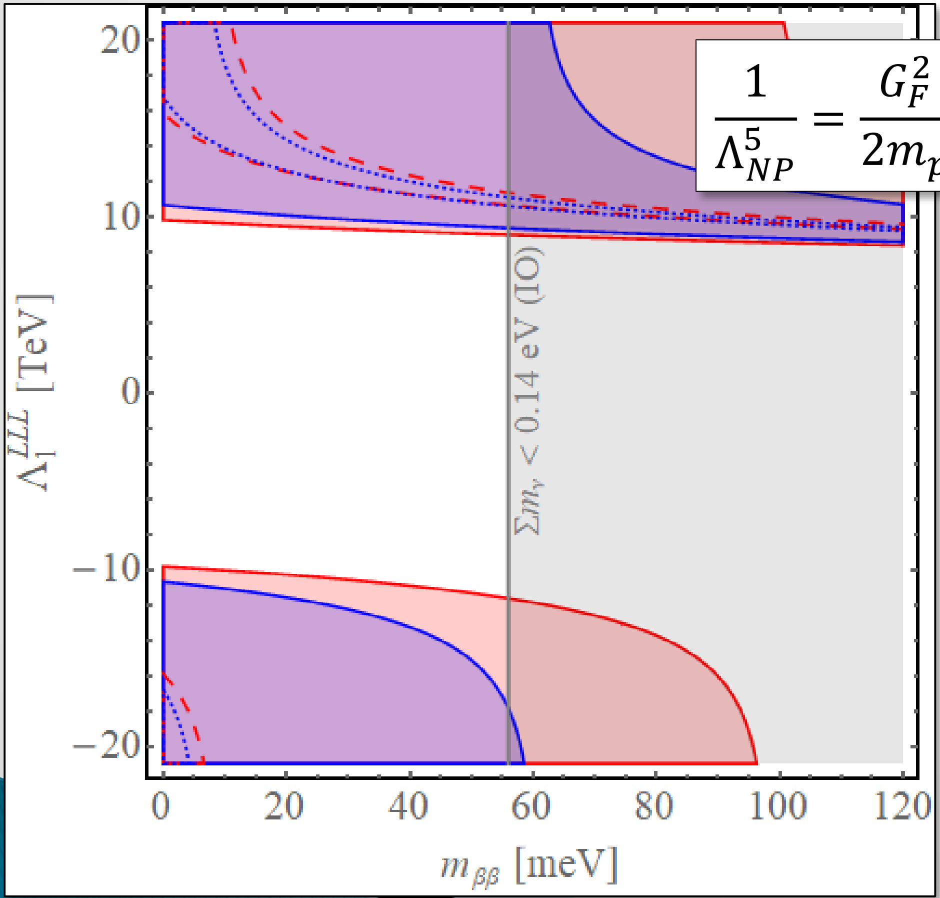
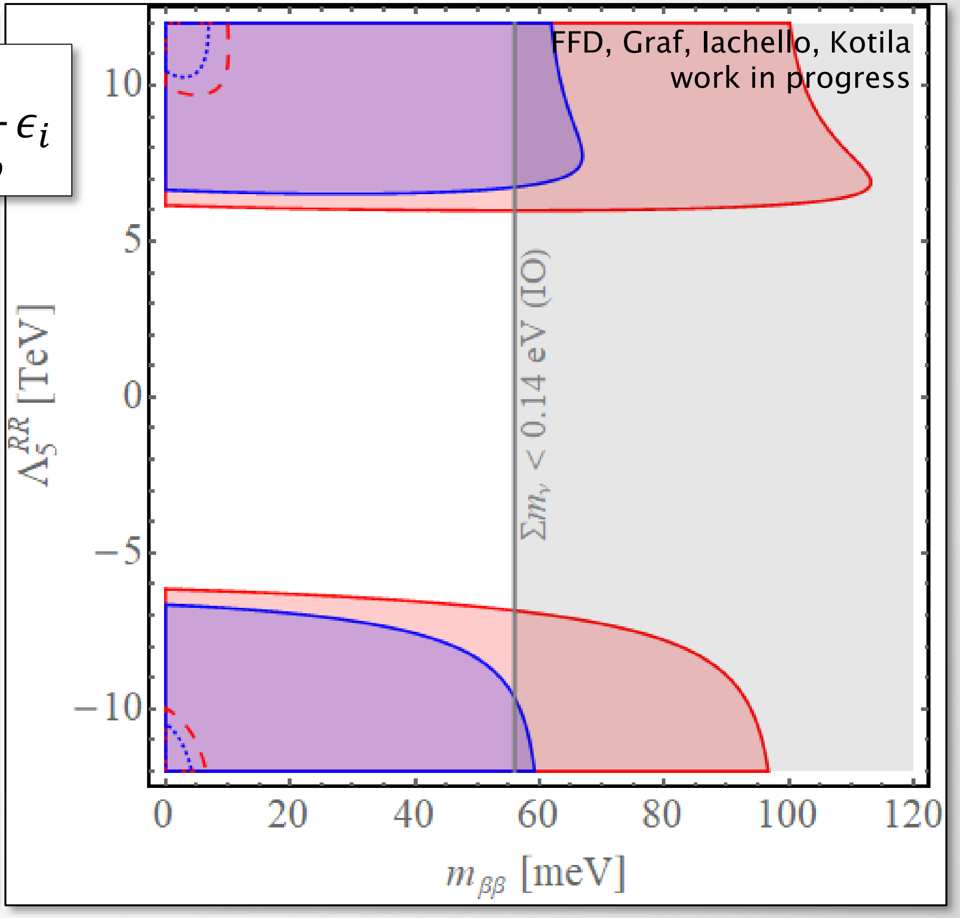
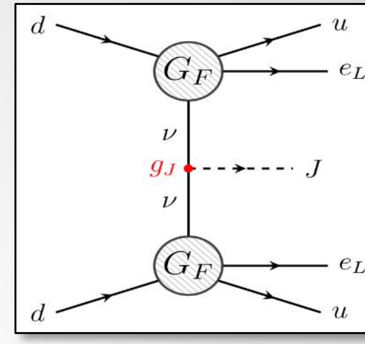


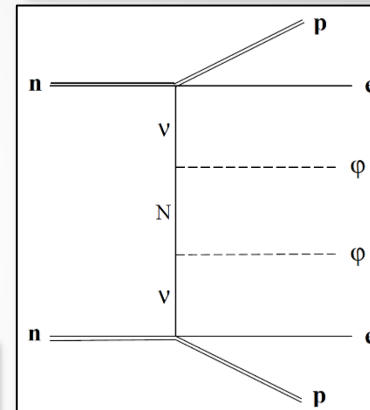
$$\frac{1}{\Lambda_{NP}^5} = \frac{G_F^2}{2m_p} \epsilon_i$$

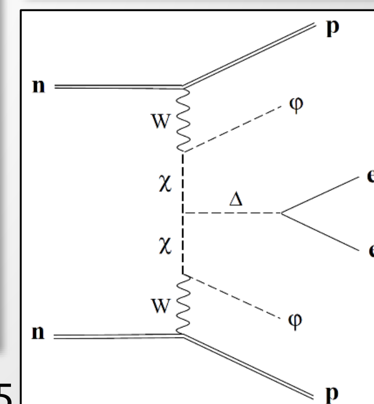


Majorons and MLPs

- Emission of one or more neutral bosons
  - Majoron model of neutrino mass generation
  - "Majoron-like" boson J with coupling to ν, e.g. $g_{ij}\bar{\nu}_i\gamma_5\nu_j J$







GERDA, Eur. Phys. J. C75 (2015) 9, 416

Model	n	Mode	Goldstone boson	L	$T_{1/2}^{0\nu\chi}$ $[10^{23}\text{yr}]$	$\mathcal{M}^{0\nu\chi}$	$G^{0\nu\chi}$ $[\text{yr}^{-1}]$	$\langle g\rangle$
IB	1	χ	no	0	>4.2	$(2.30-5.82)$	$5.86\cdot10^{-17}$	$<(3.4-8.7)\cdot10^{-5}$
IC	1	χ	yes	0	>4.2	$(2.30-5.82)$	$5.86\cdot10^{-17}$	$<(3.4-8.7)\cdot10^{-5}$
ID	3	$\chi\chi$	no	0	>0.8	$10^{-3\pm1}$	$6.32\cdot10^{-19}$	$<2.1^{+4.5}_{-1.4}$
IE	3	$\chi\chi$	yes	0	>0.8	$10^{-3\pm1}$	$6.32\cdot10^{-19}$	$<2.1^{+4.5}_{-1.4}$
IF	2	χ	bulk field	0	>1.8	–	–	–
IIB	1	χ	no	-2	>4.2	$(2.30-5.82)$	$5.86\cdot10^{-17}$	$<(3.4-8.7)\cdot10^{-5}$
IIC	3	χ	yes	-2	>0.8	0.16	$2.07\cdot10^{-19}$	$<4.7\cdot10^{-2}$
IID	3	$\chi\chi$	no	-1	>0.8	$10^{-3\pm1}$	$6.32\cdot10^{-19}$	$<2.1^{+4.5}_{-1.4}$
IIE	7	$\chi\chi$	yes	-1	>0.3	$10^{-3\pm1}$	$1.21\cdot10^{-18}$	$<2.2^{+4.9}_{-1.4}$
IIF	3	χ	gauge boson	-2	>0.8	0.16	$2.07\cdot10^{-19}$	$<4.7\cdot10^{-2}$

Bamert, Burgess, Mohapatra '95

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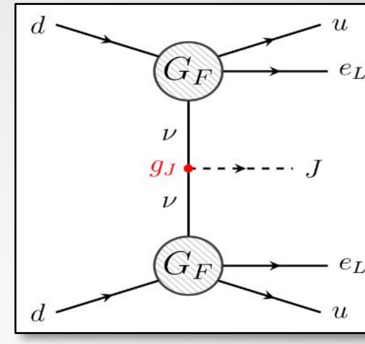
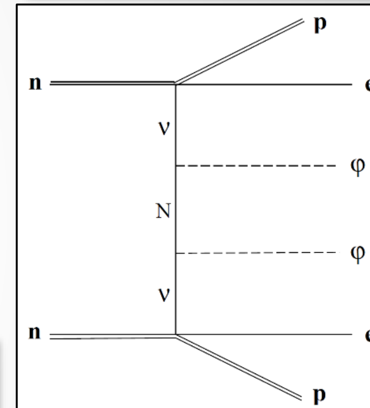
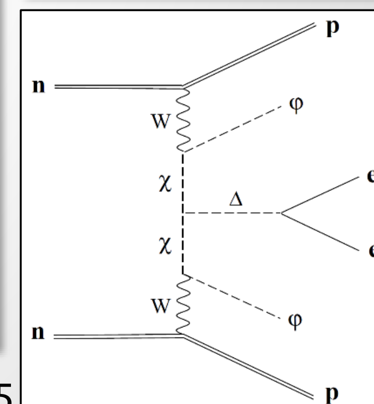
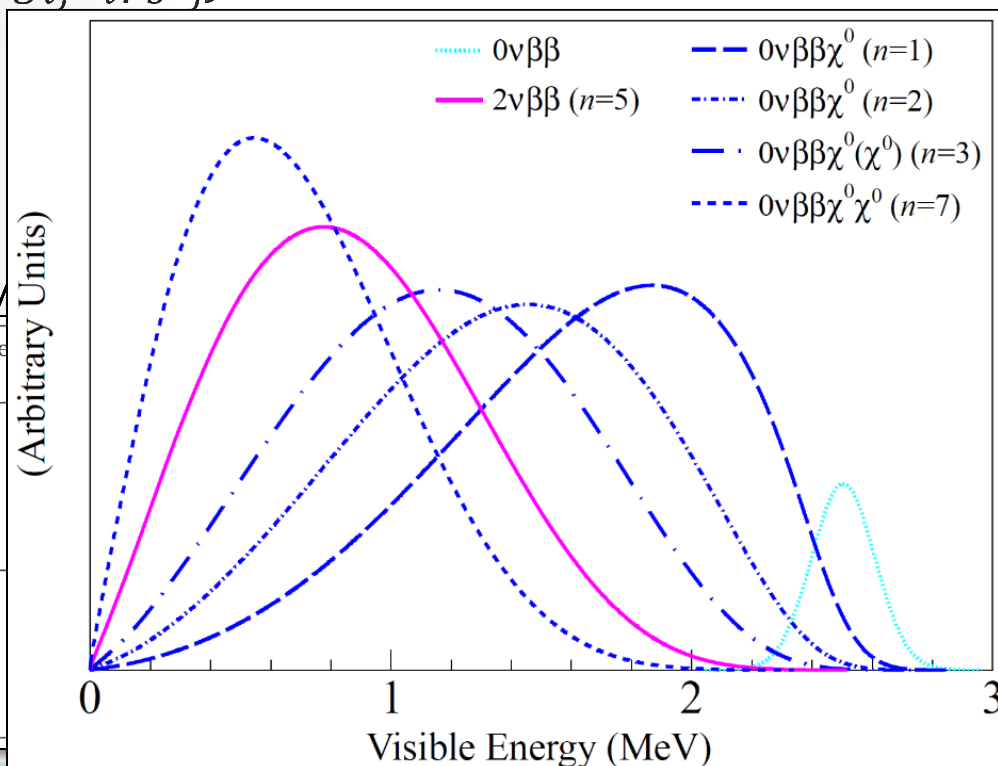






GERDA, Eur. Phy

Model	n	Mode	⟨g⟩
IB	1	χ	$.4-8.7)\cdot 10^{-5}$
IC	1	χ	$.4-8.7)\cdot 10^{-5}$
ID	3	$\chi\chi$	$< 2.1^{+4.5}_{-1.4}$
IE	3	$\chi\chi$	$< 2.1^{+4.5}_{-1.4}$
IF	2	χ	–
IIB	1	χ	$.4-8.7)\cdot 10^{-5}$
IIC	3	χ	$< 4.7\cdot 10^{-2}$
IID	3	$\chi\chi$	$< 2.1^{+4.5}_{-1.4}$
IIE	7	$\chi\chi$	$< 2.2^{+4.9}_{-1.4}$
IIF	3	χ	$< 4.7\cdot 10^{-2}$



Bamert, Burgess, Mohapatra '95

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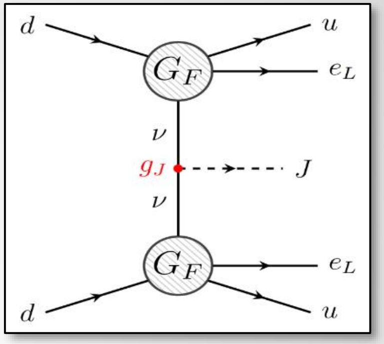
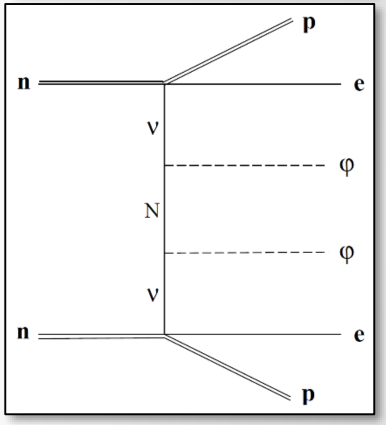
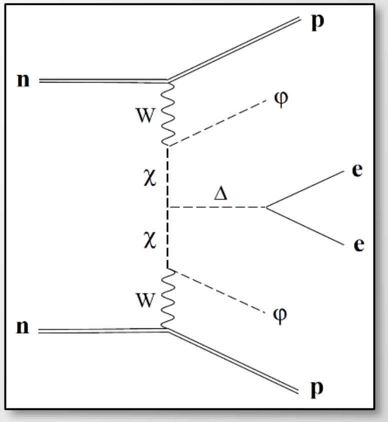
  - Light scalar associated with Weinberg-like operator (Blum, Nir, Shavit, Phys. Lett. B785 (2018) 354)

$$\mathcal{L}_{d=6} = -\frac{\mathcal{Y}_{\alpha\beta}}{\Lambda^2}\phi(HL_\alpha)(HL_\beta)$$







Bamert, Burgess, Mohapatra '95

Majorons and RH Currents

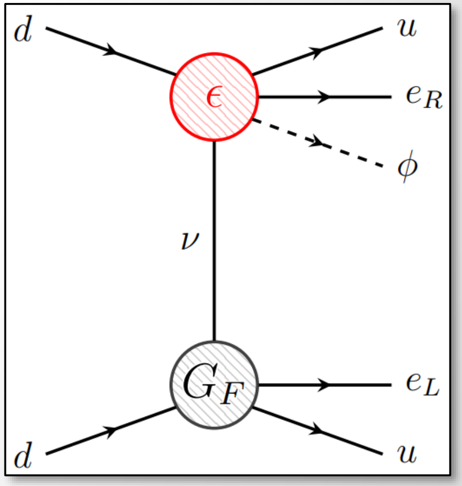
University College London

- Effective RH lepton currents with massless scalar ϕ
  (R. Cepedello, FFD, L. González, C. Hati, M. Hirsch, Phys. Rev. Lett. 122 (2019) 181801)

$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu}\phi \right) + \text{h.c.}$$

- Giving rise to long-range contribution to $0\nu\beta\beta\phi$ decay

$$\mathcal{M} = \epsilon_{RX}^\phi \frac{(G_F \cos\theta_C)^2}{\sqrt{2} m_p} \sum_N \int d^3x d^3y \int \frac{d^3q}{2\pi^2\omega} \phi(\mathbf{y}) e^{i\mathbf{q}(\mathbf{x}-\mathbf{y})} \times \left\{ \left[\frac{J_{LX}^{\rho\sigma}(\mathbf{x},\mathbf{y}) u_{\rho\sigma}^L(E_1\mathbf{x}, E_2\mathbf{y})}{\omega + \mu_N - \frac{1}{2}(E_1 - E_2 - E_\phi)} - \frac{J_{XL}^{\rho\sigma}(\mathbf{x},\mathbf{y}) u_{\rho\sigma}^R(E_1\mathbf{x}, E_2\mathbf{y})}{\omega + \mu_N - \frac{1}{2}(E_1 - E_2 + E_\phi)} \right] - \left[E_1 \leftrightarrow E_2 \right] \right\}$$



  - No suppression with ν mass
- Calculation follows long-range η and λ modes
  (Doi, Kotani, Takasugi, Prog. Theor. Phys. Suppl. 83 (1985) 1)

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University College London

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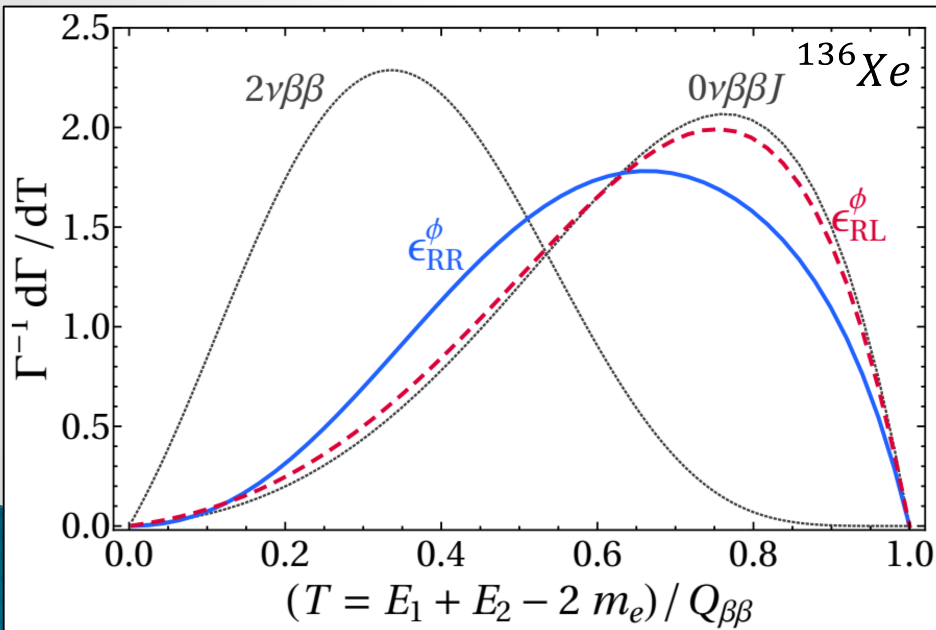
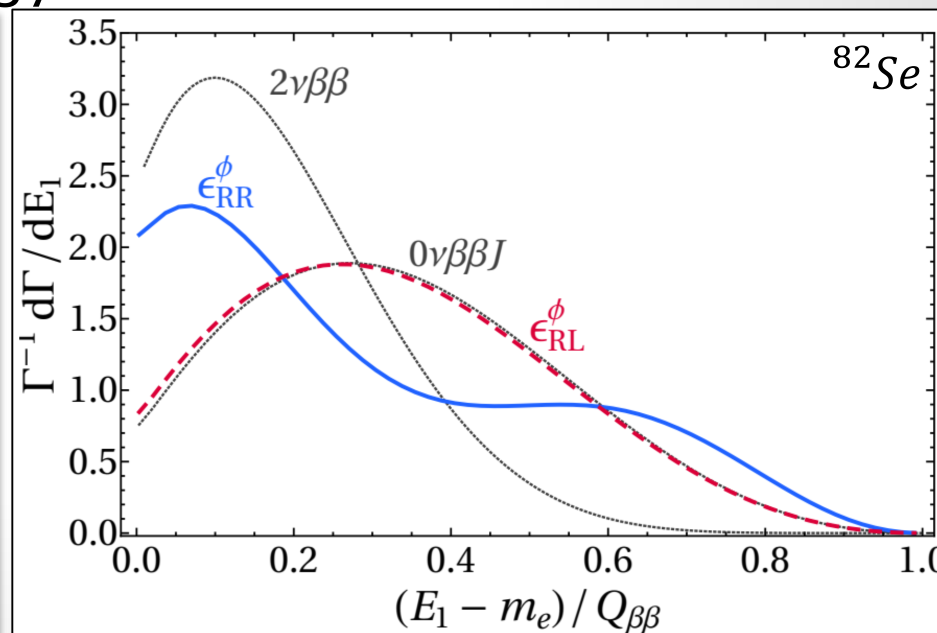
- Non-standard electron energy distributions

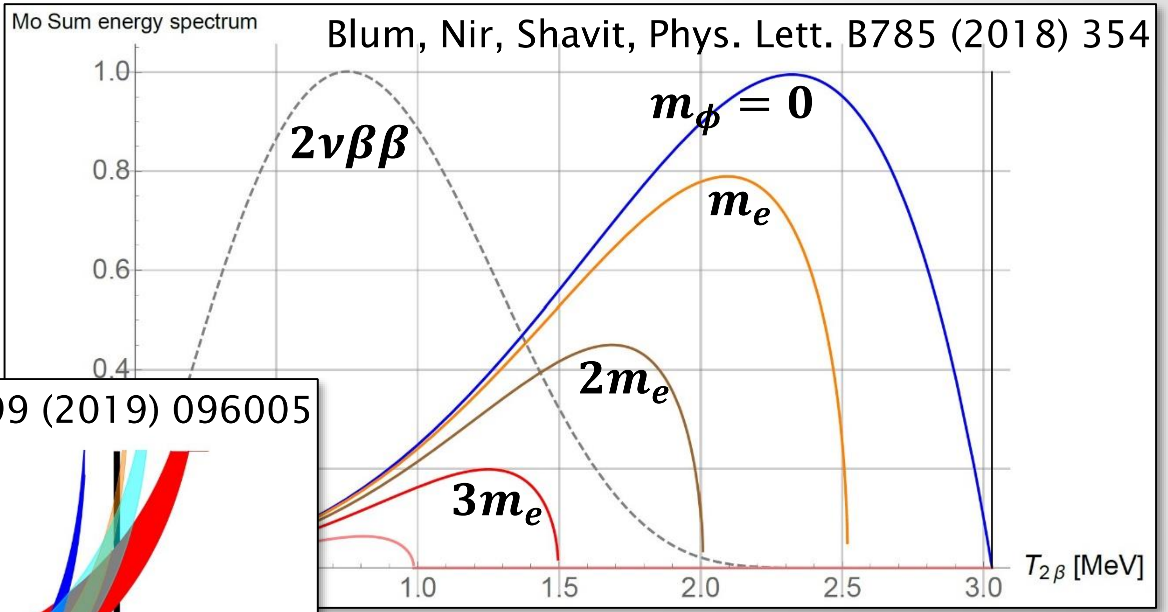


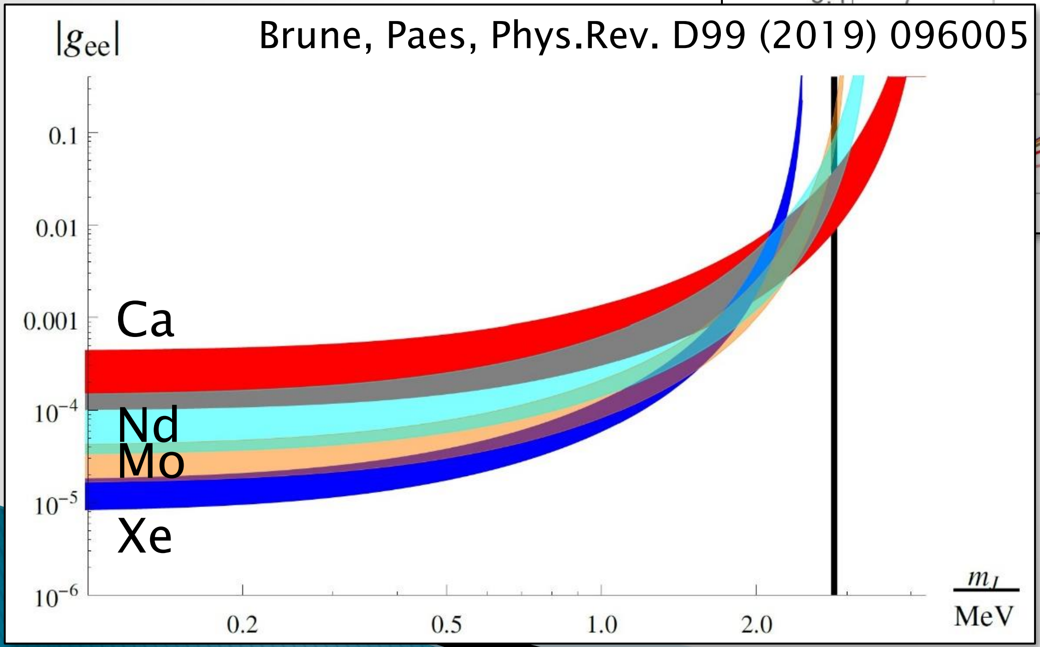


Majorons and RH Currents

University College London

- Sensitivity modification for massive ϕ
  - Suppression of phase space
  - Decrease of $S/\sqrt{B}$

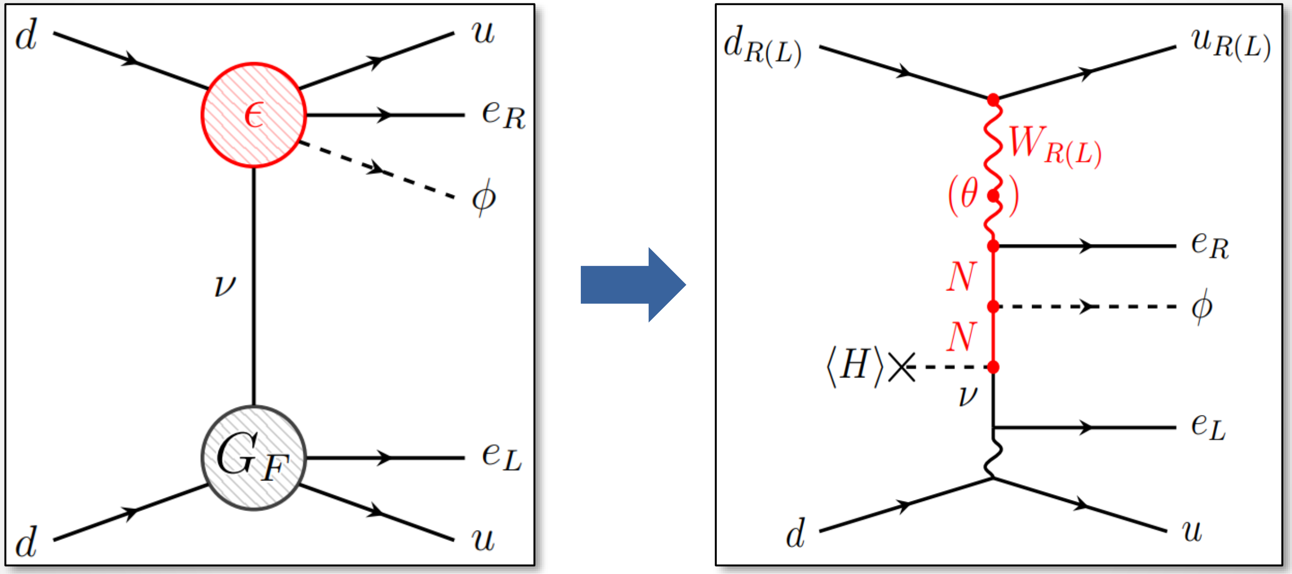




UV Model: LR Symmetry

University College London

- UV Diagram



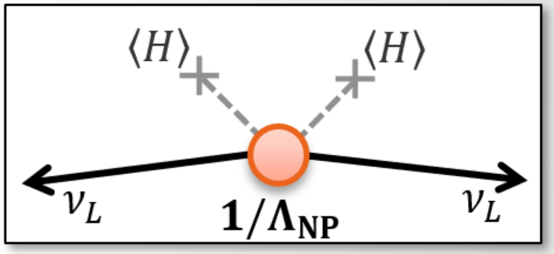
- Sensitivity from ϵ_{RL}^{ϕ}

$$\frac{T_{1/2}^{\mathrm{Xe}}}{10^{25}\ \mathrm{y}} \approx \left(\frac{1.4 \times 10^{-4}}{g_R^2 \kappa y_N y_\nu}\right)^2 \left(\frac{m_{W_R}}{25\ \mathrm{TeV}}\right)^4 \left(\frac{m_N}{100\ \mathrm{MeV}}\right)^4$$

Conclusion

University College London

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
  - Determination of absolute mass scale
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Standard interpretation: New Physics near GUT scale breaking lepton number
  - Important to look for alternative scenarios
    - Missing energy → lepton number conserved?
    - Neutrino mass may be associated with exotic light particles



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

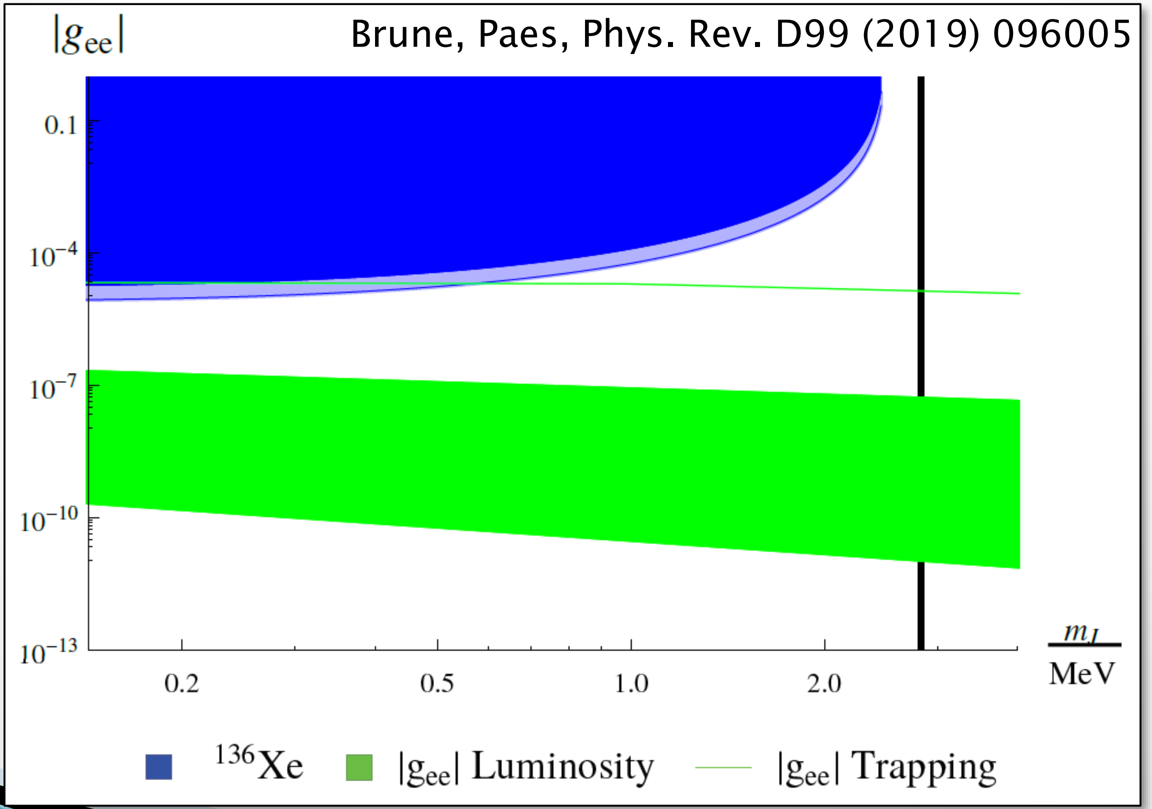
- **Importance of probing LNV around the TeV scale**
  - Can we rule out mechanisms of neutrino mass generation?
  - Impact on baryon asymmetry of the Universe
    (FFD, Harz, Hirsch, Phys. Rev. Lett. 112 (2014) 221601;
    FFD, Harz, Hirsch, Huang, Päs, Phys. Rev. D 92 (2015) 036005)

Backup Slides

Astrophysical Effects

University College London

- If massive, Majoron can be Dark Matter
  - Singlet Majoron Model
    (Berezinsky, Valle, Phys. Lett. B318 (1993) 360; Garcia-Cely, Heeck, JHEP 05 (2017) 102)
- Strong constraints from Supernovae



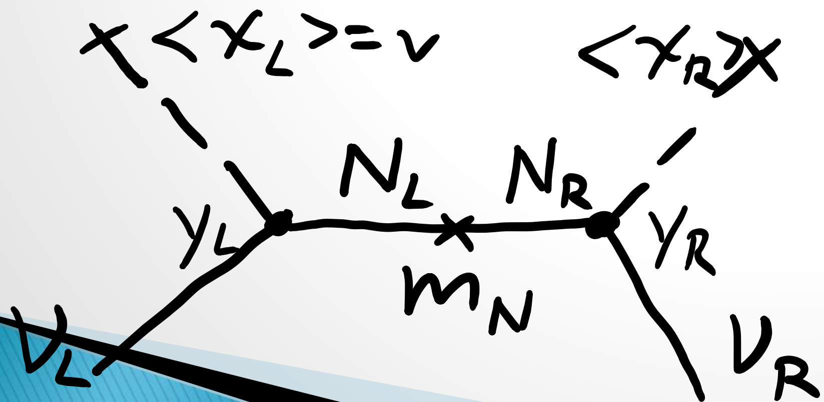
UV Model: LR Symmetry

- Extended Gauge Symmetry

$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Minimal LR model: $X = B - L$
- We consider $X \neq B - L$ broken but $B - L$ conserved
- Dirac neutrinos (and charged SM fermions) via Dirac seesaw via heavy, vector-like fermions
(Bolton, FFD, Hati, arXiv:1902.05802)

Field	$SU(2)_L$	$SU(2)_R$	$B-L$	ζ	X	$SU(3)_C$
q_L	2	1	1/3	0	1/3	3
q_R	1	2	1/3	0	1/3	3
ℓ_L	2	1	-1	0	-1	1
ℓ_R	1	2	-1	0	-1	1
$U_{L,R}$	1	1	1/3	+1	4/3	3
$D_{L,R}$	1	1	1/3	-1	-2/3	3
$E_{L,R}$	1	1	-1	-1	-2	1
$N_{L,R}$	1	1	-1	+1	0	1
χ_L	2	1	0	+1	1	1
χ_R	1	2	0	+1	1	1
ϕ	1	1	2	-2	0	1



UV Model: Leptoquarks

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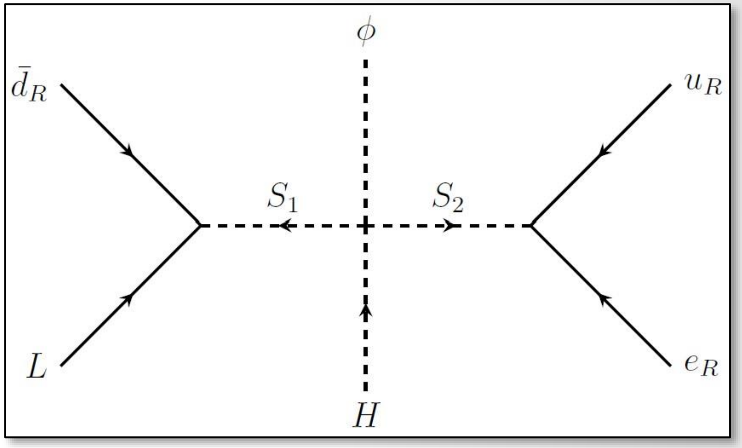
- Add heavy scalar leptoquarks $S_1(3,2,1/6)$, $S_2(3^*,1,1/3)$
  - Effective operator at tree level
  - Lepton number conserved if $L(S_1) = L(S_2) = -1$, $L(\phi) = -2$



  - LNV and Majorana neutrino mass at two-loop if $\langle\phi\rangle \neq 0$