$0\nu\beta\beta$ decay:

Beyond the mass mechanism

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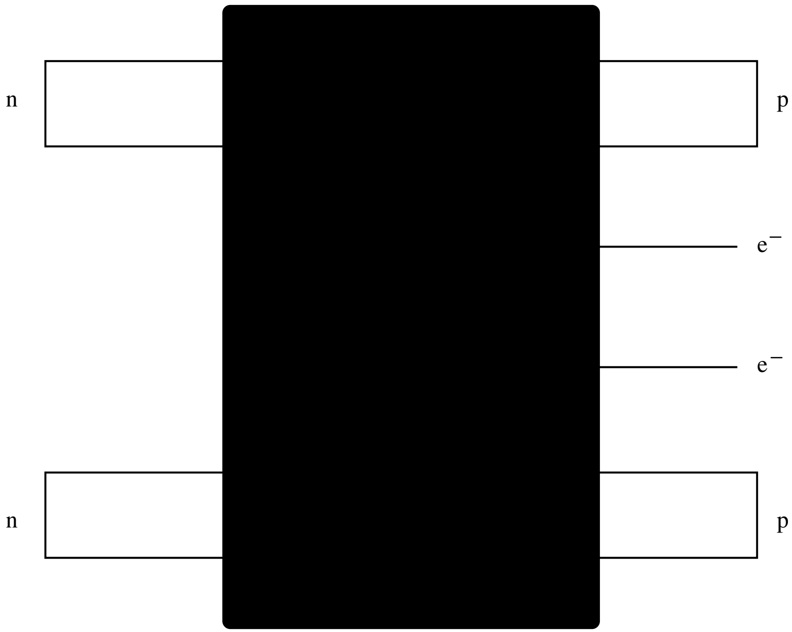
Contents

$\mathcal{I}.$

Introduction

Black box!

Experimentalist observes:



Neutrinoless double beta decay is:

$nn \to pp + e^- e^-$

(no missing energy)

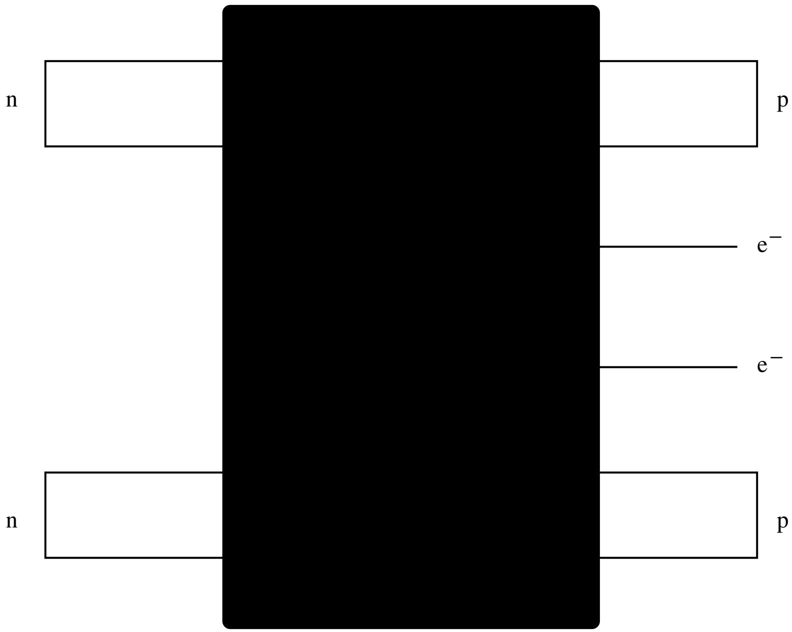
Lepton number is violated:

$\Delta L = 2$!

What is the scale Λ_{LNV}?

Black box!

Experimentalist observes:



Express half-live as:

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = G_{0\nu}|\epsilon_i|^2|M_i^{0\nu\beta\beta}|^2$$

$G_{0\nu}$ - phase space

$M_i^{0\nu\beta\beta}$ - nuclear matrix element

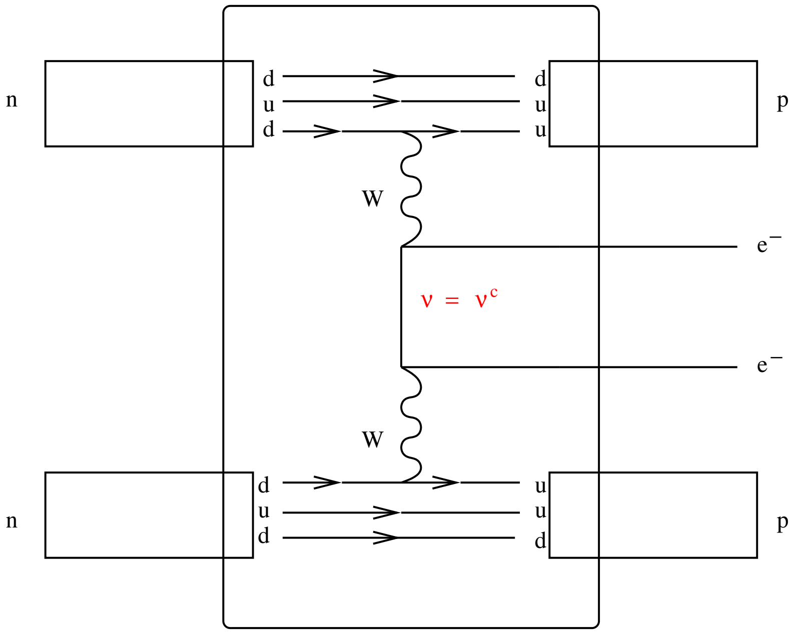
ϵ_i - particle physics

Many, many possible contributions:

RPV SUSY
Leptoquarks
Left-right symmetry
... etc ... etc ...

Mass mechanism

Experimentalist observes:



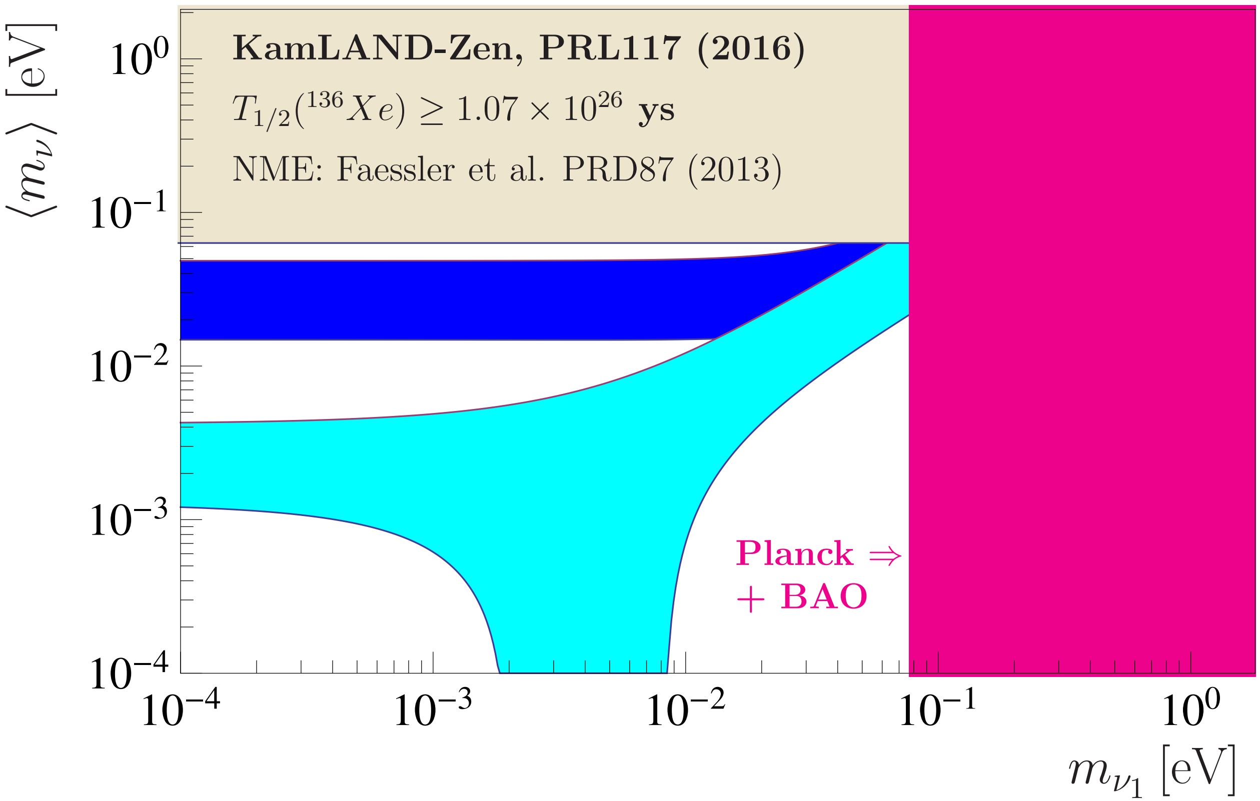
Neutrino propagator:

$$\int \frac{d^4p}{(2\pi)^4} \frac{m_\nu + \not{p}}{p^2 - m_\nu^2}$$

"Mass mechanism" because weak interaction is left-handed:

$$P_L(m_\nu + \not{p}\ )P_L = m_\nu P_L$$

$\langle m_\nu \rangle$ versus m_{ν_1} - status 2017



Global fit to oscillation data:

Forero, Tortola & Valle; PRD90 (2014) 093006

all ranges at 1 σ c.l.

⇒ Planck - limits from cosmological data

⇒ Uncertainty in $\langle m_\nu \rangle \lesssim (60/140)$ meV (largest/smallest) NME in Faessler et al. PRD87 (2013)

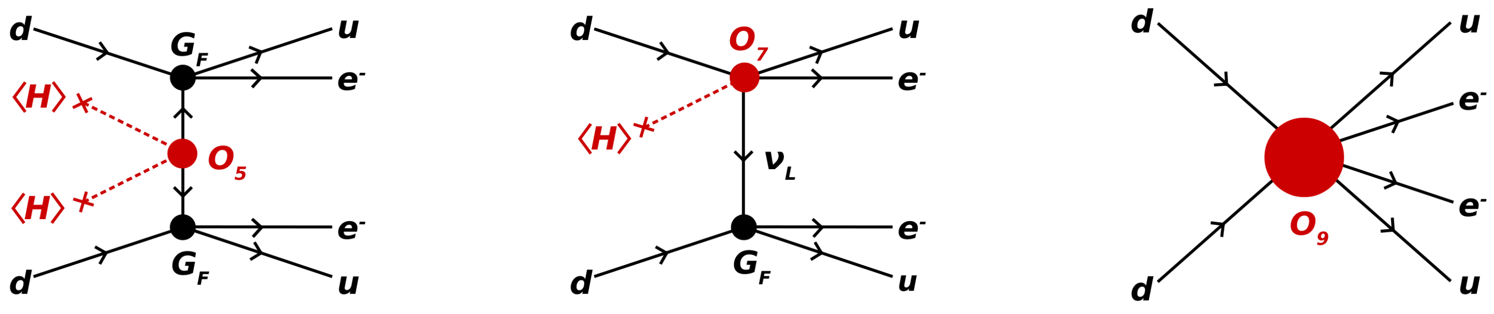
$\mathcal{II}.$

EFT & QCD running

$0\nu\beta\beta$ *decay: Decomposition*

Päs et al, PLB453 (1999)

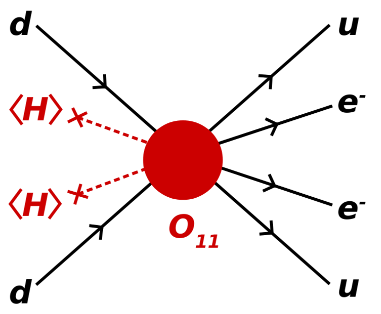
Amplitude for $(Z, A) \rightarrow (Z \pm 2, A) + e^{\mp}e^{\mp}$ can be divided into: & PLB498 (2001)



(a) (b) (c)

Mass mechanism — "long-range" — "short-range"

Higher order:

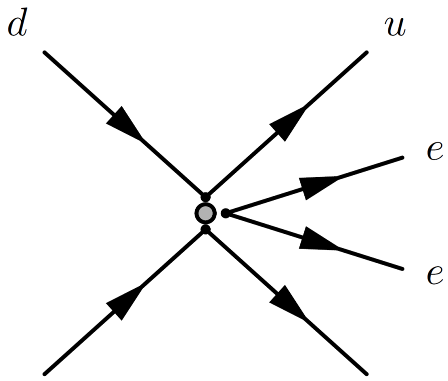


(d)

$+ \cdots$

QCD corrections

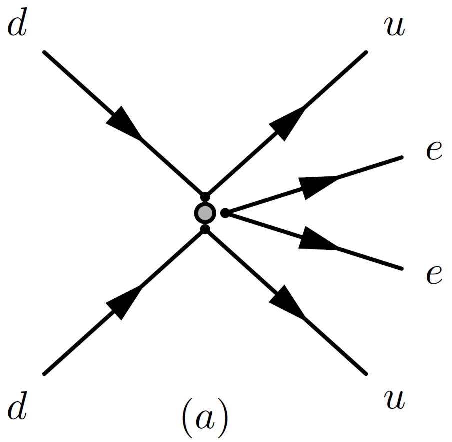
Consider any short-range operator. At tree-level:



(a)

QCD corrections

Consider any short-range operator. At tree-level:

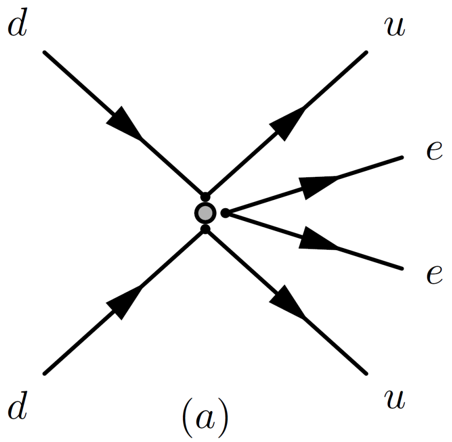


Heavy particles
integrated out
at scale Λ:

$\Lambda \simeq g_{eff}^{4/5}$ (2-7) TeV

QCD corrections

Consider any short-range operator. At tree-level:



Heavy particles integrated out at scale Λ:

$\Lambda \simeq g_{eff}^{4/5}$ (2-7) TeV

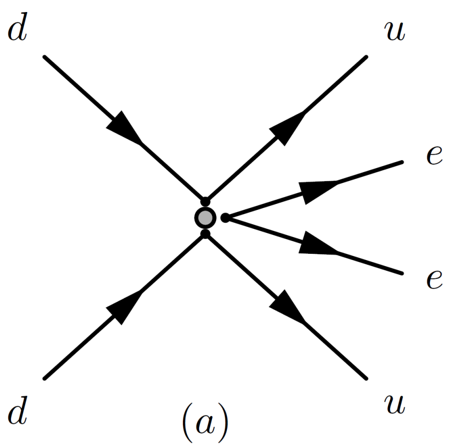
$\Rightarrow$ Double beta decay is a low-energy process. Energy scale:

$p_F \simeq$ 100 MeV

$\Rightarrow$ Need to run operator from $\Lambda \simeq$ TeV to $\mu \simeq 10^{-4}$ TeV

QCD corrections

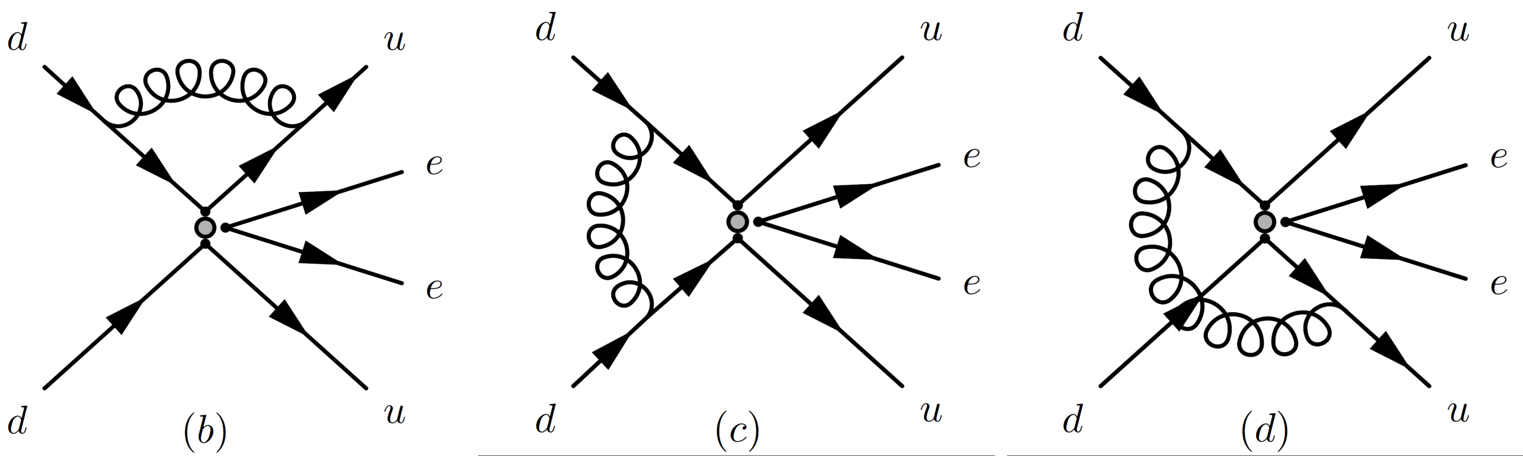
At tree-level:



Add gluon exchange diagrams

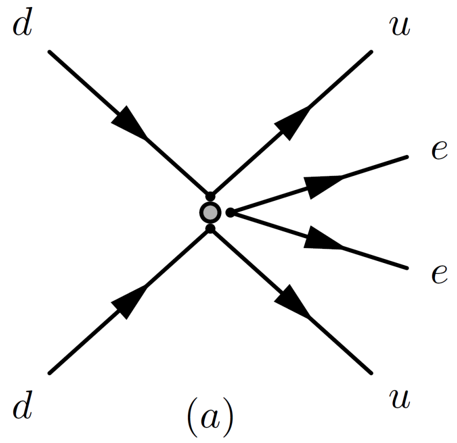
Naive estimate is:

$\alpha_S/(4\pi) \times \ln(\Lambda/\mu) \simeq$ (20-30) %

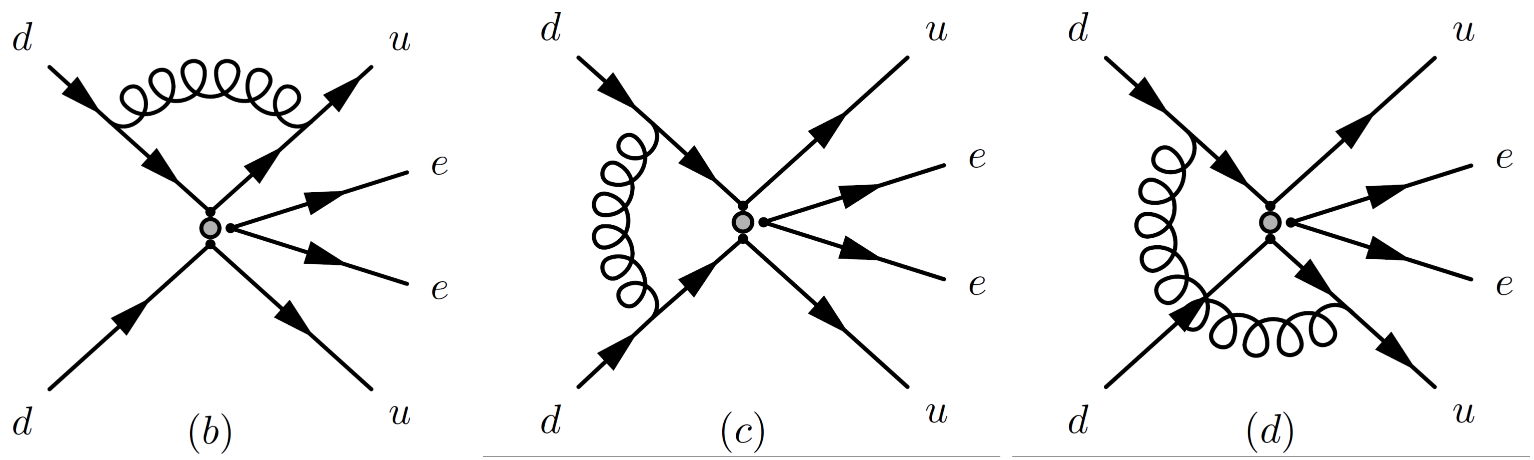


QCD corrections

At tree-level:



BUT ...
Colour index connects
different nucleon currents:
"Operator mixing"



QCD corrected limits

González, Hirsch
Kovalenko, PRD93 (2016)

^{A}X	$\lvert C_1^{XX}(M_W)\rvert$	$\lvert C_1^{XX}(\Lambda_{LNV})\rvert$	$\lvert C_1^{XX(0)}\rvert$	$\lvert C_1^{LR,RL}(M_W)\rvert$	$\lvert C_1^{LR,RL}(\Lambda_{LNV})\rvert$	$\lvert C_1^{LR,RL(0)}\rvert$
^{76}Ge	5.0×10^{-10}	3.8×10^{-10}	2.6×10^{-7}	8.6×10^{-8}	6.2×10^{-8}	2.6×10^{-7}
^{136}Xe	3.4×10^{-10}	2.6×10^{-10}	1.8×10^{-7}	6.0×10^{-8}	4.3×10^{-8}	1.8×10^{-7}
^{A}X	$\lvert C_2^{XX}(M_W)\rvert$	$\lvert C_2^{XX}(\Lambda_{LNV})\rvert$	$\lvert C_2^{XX(0)}\rvert$	–		
^{76}Ge	3.5×10^{-9}	5.2×10^{-9}	1.4×10^{-9}	–		
^{136}Xe	2.4×10^{-9}	3.5×10^{-9}	9.4×10^{-10}	–		
^{A}X	$\lvert C_3^{XX}(M_W)\rvert$	$\lvert C_3^{XX}(\Lambda_{LNV})\rvert$	$\lvert C_3^{XX(0)}\rvert$	$\lvert C_3^{LR,RL}(M_W)\rvert$	$\lvert C_3^{LR,RL}(\Lambda_{LNV})\rvert$	$\lvert C_3^{LR,RL(0)}\rvert$
^{76}Ge	1.5×10^{-8}	1.6×10^{-8}	1.1×10^{-8}	2.0×10^{-8}	2.1×10^{-8}	1.8×10^{-8}
^{136}Xe	9.7×10^{-9}	1.1×10^{-8}	7.4×10^{-9}	1.4×10^{-8}	1.4×10^{-8}	1.2×10^{-8}
^{A}X	$\lvert C_4^{XX}(M_W)\rvert$	$\lvert C_4^{XX}(\Lambda_{LNV})\rvert$	$\lvert C_4^{XX(0)}\rvert$	$\lvert C_4^{LR,RL}(M_W)\rvert$	$\lvert C_4^{LR,RL}(\Lambda_{LNV})\rvert$	$\lvert C_4^{LR,RL(0)}\rvert$
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$C_1 \propto (S \pm P)$

$C_3 \propto (V \pm A)$

Some coefficients change by huge factors due to operator mixing!

Two simple examples

(a) Pure (scalar+pseudo-scalar) exchange, C_1^{LL}:

Including running:

$\Lambda \gtrsim (g_{eff}/g_L)^{4/5} 4.0$ TeV

Without running:

$\Lambda \gtrsim (g_{eff}/g_L)^{4/5} 1.1$ TeV

(b) Right-handed vector boson exchange, C_3^{RR}:

Including running:

$\Lambda \gtrsim (g_{eff}/g_L)^{4/5} 1.9$ TeV

Without running:

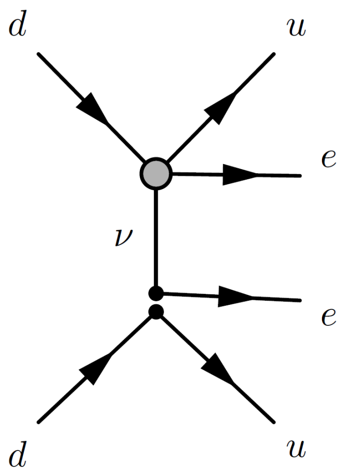
$\Lambda \gtrsim (g_{eff}/g_L)^{4/5} 2.1$ TeV

Conversion coefficient to scale using:

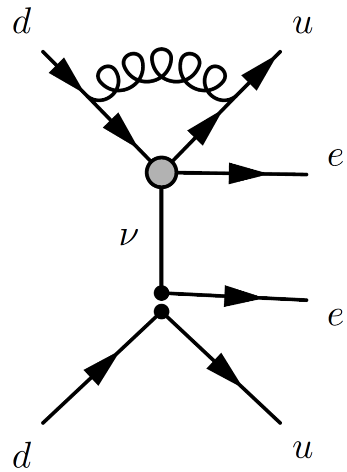
$$\Lambda = \left(\frac{1}{8}\frac{2m_P}{C_i G_F^2}\right)^{1/5} g_{eff}^{4/5}$$

QCD corrections: LR

At tree-level:

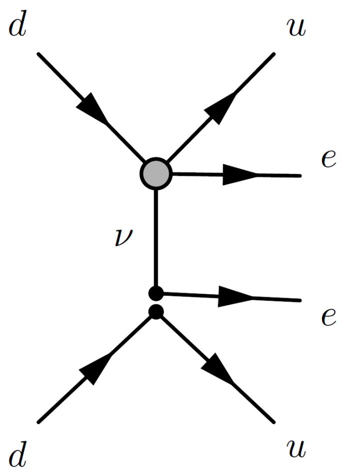


QCD corrected:

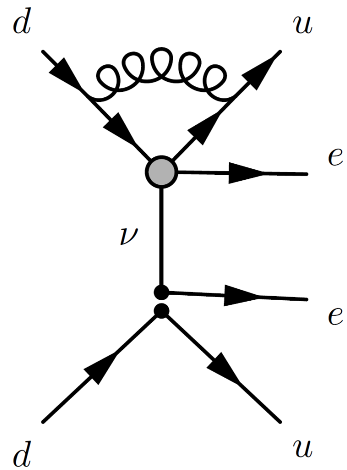


QCD corrections: LR

At tree-level:



QCD corrected:



Arbeláez, González
Hirsch, Kovalenko
PRD94 (2016)

	Without QCD		With QCD	
	^{76}Ge	^{136}Xe	^{76}Ge	^{136}Xe
C_1^L	5.3×10^{-9}	3.7×10^{-9}	3.3×10^{-9}	2.3×10^{-9}
C_1^R	5.3×10^{-9}	3.7×10^{-9}	3.3×10^{-9}	2.3×10^{-9}
C_2^L	3.1×10^{-10}	2.2×10^{-10}	5.0×10^{-10}	3.5×10^{-10}
C_2^R	8.2×10^{-10}	5.7×10^{-10}	1.4×10^{-9}	9.2×10^{-10}
C_3^L	2.2×10^{-9}	1.5×10^{-9}	2.7×10^{-9}	1.9×10^{-9}
C_3^R	3.4×10^{-7}	2.4×10^{-7}	4.3×10^{-7}	3.0×10^{-7}

Due to "long-range"
of interaction
no gluon exchange
between quarks from
different nucleons
NO operator mixing

Corrections order of:
$\alpha_S/(4\pi) \times \ln(\Lambda/\mu)$
$\simeq$(20-30) %

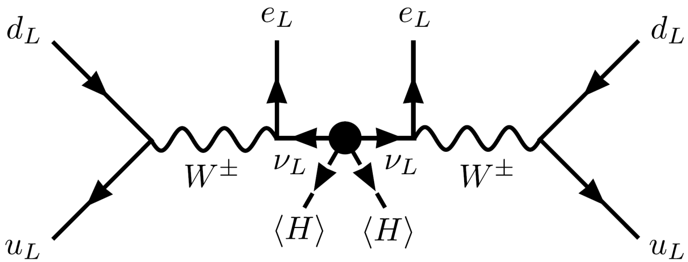
$\mathcal{III}.$

Vector contributions to $0\nu\beta\beta$ decay

R. Fonseca & M. Hirsch, PRD95 (2017)

Mass mechanism again

In $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant language:

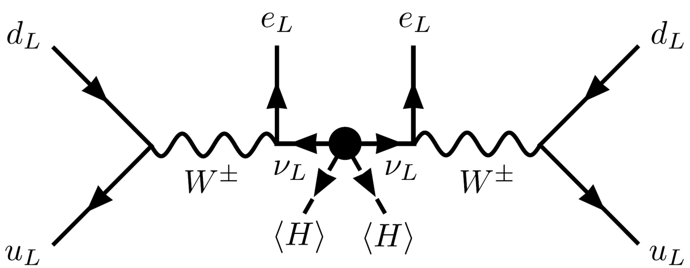


$$\mathcal{O}^{MM} \propto (\overline{Q}Q)(\overline{L})(H^* H^*)(\overline{L})(\overline{Q}Q)$$

$\Rightarrow$ The MM is a $d = 11$ operator!

$\Delta L = 2$ operators

In $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant language:



$$\mathcal{O}^{MM} \propto (\overline{Q}Q)(\overline{L})(H^* H^*)(\overline{L})(\overline{Q}Q)$$

$\Rightarrow$ The MM is a $d = 11$ operator!

List of $\Delta L = 2$ operators: Babu & Leung, 2001

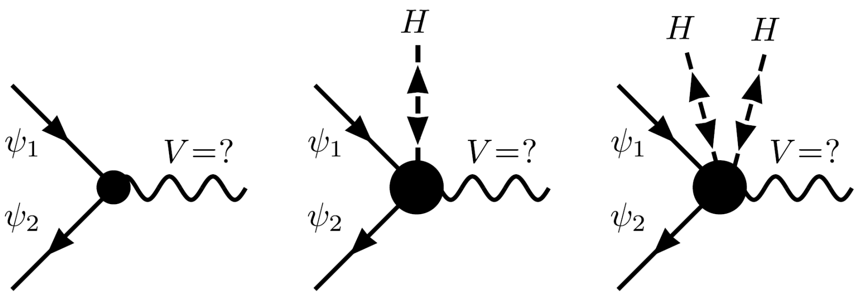
$\mathcal{O}^{\text{d=9}} = \overline{QQLLd^c d^c}, QQu^c u^c \overline{LL}, \cdots$ 6 operators

$\mathcal{O}^{\text{d=11}} = u^c u^c \overline{d^c d^c} e^c e^c H H^*, u^c u^c \overline{d^c d^c LL} HH, \cdots$ 13 operators

Constructing vectors

Finding all possible gauge vector contributions, involves three steps:

Step 1:

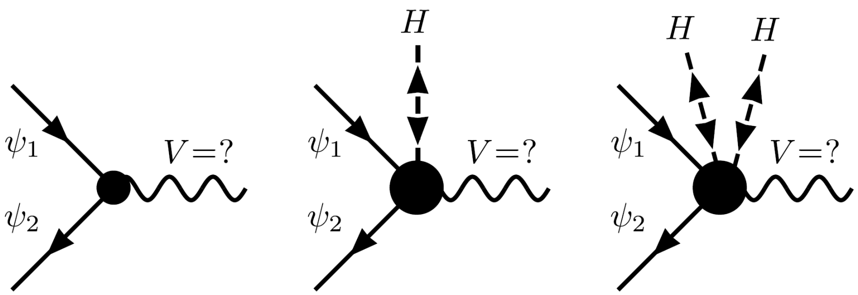


Find all V^μ from attaching
$\psi_{1,2} = \bar{L}, e^c, \bar{Q}, Q, u^c, \bar{d}^c, H$

Constructing vectors

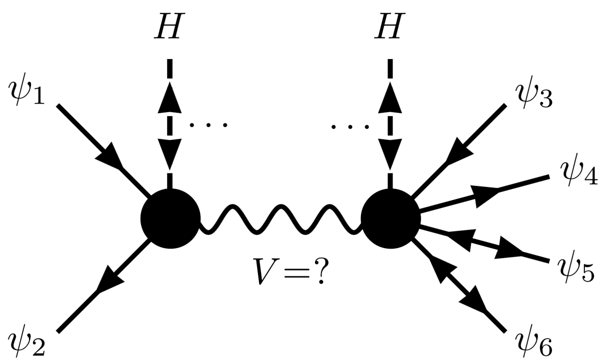
Finding all possible gauge vector contributions, involves three steps:

Step 1:



Find all V^μ from attaching $\psi_{1,2} = \bar{L}, e^c, \bar{Q}, Q, u^c, \bar{d}^c, H$

Step 2:

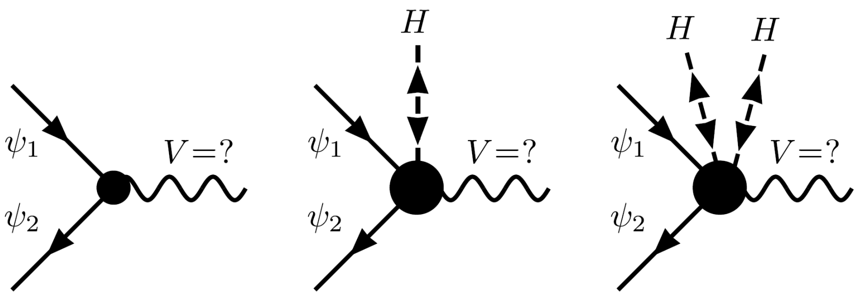


Eliminate all V^μ that can not complete $\Delta L = 2$ operator

Constructing vectors

Finding all possible gauge vector contributions, involves three steps:

Step 1:



Find all V^μ from attaching $\psi_{1,2} = \bar{L}, e^c, \bar{Q}, Q, u^c, \bar{d}^c, H$

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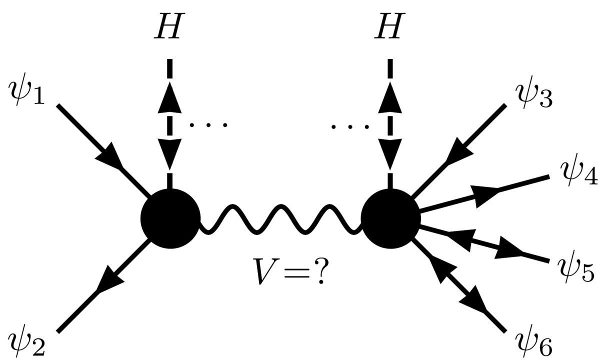

Eliminate all V^μ that can not complete $\Delta L = 2$ operator

Step 3:

Find all gauge groups, where V^μ is in the adjoint

Vectors and gauge groups

Vector representation(s)	Minimal group(s) (without $U(1)$'s)
$(\mathbf{1},\mathbf{1},\boxed{y=1},2)$	$\boxed{SU(3)_C\times SU(2)_L\times SU(2)}$
$\boxed{\left(\mathbf{1},\mathbf{2},y=\frac{1}{2},\frac{3}{2}\right)}$	$\boxed{SU(3)_C\times SU(3)}$, $SU(3)_C\times Sp(4)$
$\boxed{(\mathbf{1},\mathbf{3},0)}$	$\boxed{SU(3)_C\times SU(2)_L}$
$(\mathbf{1},\mathbf{3},y=1,2)$	$SU(3)_C\times Sp(4)$
$\left(\mathbf{1},\mathbf{4},y=\frac{1}{2}\right)$	$SU(3)_C\times SU(5)$, $SU(3)_C\times Sp(6)$, $SU(3)_C\times G_2$
$(\mathbf{1},\mathbf{5},1)$	$SU(3)_C\times SO(7)$, $SU(3)_C\times Sp(6)$
$(\mathbf{3},\mathbf{1},y=-\frac{4}{3},-\frac{1}{3},\boxed{\frac{2}{3}})$	$\boxed{SU(4)\times SU(2)_L}$
$\left(\mathbf{3},\mathbf{2},y=-\frac{11}{6},-\frac{5}{6},\frac{1}{6},\frac{7}{6}\right)$	$SU(5)$, $Sp(8)$, F_4
$\left(\mathbf{3},\mathbf{3},y=-\frac{4}{3},-\frac{1}{3},\frac{2}{3}\right)$	$SU(6)$, $SO(9)$
$\left(\mathbf{3},\mathbf{4},y=-\frac{11}{6},\frac{1}{6},\frac{7}{6}\right)$	$SU(7)$, $Sp(10)$, E_6
$\left(\mathbf{3},\mathbf{5},y=-\frac{1}{3}\right)$	$SU(8)$, $SO(11)$
$\left(\mathbf{6},\mathbf{1},y=-\frac{2}{3},\frac{1}{3},\frac{4}{3}\right)$	$Sp(6)\times SU(2)_L$
$\left(\mathbf{6},\mathbf{2},y=-\frac{7}{6},-\frac{1}{6},\frac{5}{6},\frac{11}{6}\right)$	$SU(8)$, $Sp(14)$, F_4
$\left(\mathbf{6},\mathbf{3},y=-\frac{2}{3},\frac{1}{3},\frac{4}{3}\right)$	$SU(9)$, $SO(15)$, $Sp(12)$
$\left(\mathbf{6},\mathbf{4},y=-\frac{7}{6},-\frac{1}{6},\frac{5}{6},\frac{11}{6}\right)$	$Sp(16)$ [*]
$(\mathbf{8},\mathbf{1},y=1,2)$	$SU(6)\times SU(2)_L$, $SO(10)\times SU(2)_L$
$\left(\mathbf{8},\mathbf{2},y=\frac{1}{2},\frac{3}{2}\right)$	$SU(9)$, $SO(12)$, E_6
$(\mathbf{8},\mathbf{3},0)$	$SU(6)$, $SO(11)$
$(\mathbf{8},\mathbf{3},y=1,2)$	$SO(14)$ [*]
$\left(\mathbf{8},\mathbf{4},\frac{1}{2}\right)$	$SO(16)$ [*]
$(\mathbf{8},\mathbf{5},1)$	$SO(18)$ [*]

Vectors and gauge groups

Vector representation(s)	Minimal group(s) (without $U(1)$'s)	
$(\mathbf{1},\mathbf{1},y=1,2)$	$SU(3)_C\times SU(2)_L\times SU(2)$	⇐ Left-right symmetric model
$\left(\mathbf{1},\mathbf{2},y=\frac{1}{2},\frac{3}{2}\right)$	$SU(3)_C\times SU(3)$, $SU(3)_C\times Sp(4)$	⇐ "331-models" SVS*, PPF*
$(\mathbf{1},\mathbf{3},0)$	$SU(3)_C\times SU(2)_L$	⇐ standard model (MM)
$(\mathbf{1},\mathbf{3},y=1,2)$	$SU(3)_C\times Sp(4)$	
$\left(\mathbf{1},\mathbf{4},y=\frac{1}{2}\right)$	$SU(3)_C\times SU(5)$, $SU(3)_C\times Sp(6)$, $SU(3)_C\times G_2$	
$(\mathbf{1},\mathbf{5},1)$	$SU(3)_C\times SO(7)$, $SU(3)_C\times Sp(6)$	
$(\mathbf{3},\mathbf{1},y=-\frac{4}{3},-\frac{1}{3},\frac{2}{3})$	$SU(4)\times SU(2)_L$	⇐ Pati-Salam
$\left(\mathbf{3},\mathbf{2},y=-\frac{11}{6},-\frac{5}{6},\frac{1}{6},\frac{7}{6}\right)$	$SU(5)$, $Sp(8)$, F_4	
$\left(\mathbf{3},\mathbf{3},y=-\frac{4}{3},-\frac{1}{3},\frac{2}{3}\right)$	$SU(6)$, $SO(9)$	
$\left(\mathbf{3},\mathbf{4},y=-\frac{11}{6},\frac{1}{6},\frac{7}{6}\right)$	$SU(7)$, $Sp(10)$, E_6	
$\left(\mathbf{3},\mathbf{5},y=-\frac{1}{3}\right)$	$SU(8)$, $SO(11)$	
$\left(\mathbf{6},\mathbf{1},y=-\frac{2}{3},\frac{1}{3},\frac{4}{3}\right)$	$Sp(6)\times SU(2)_L$	
$\left(\mathbf{6},\mathbf{2},y=-\frac{7}{6},-\frac{1}{6},\frac{5}{6},\frac{11}{6}\right)$	$SU(8)$, $Sp(14)$, F_4	
$\left(\mathbf{6},\mathbf{3},y=-\frac{2}{3},\frac{1}{3},\frac{4}{3}\right)$	$SU(9)$, $SO(15)$, $Sp(12)$	
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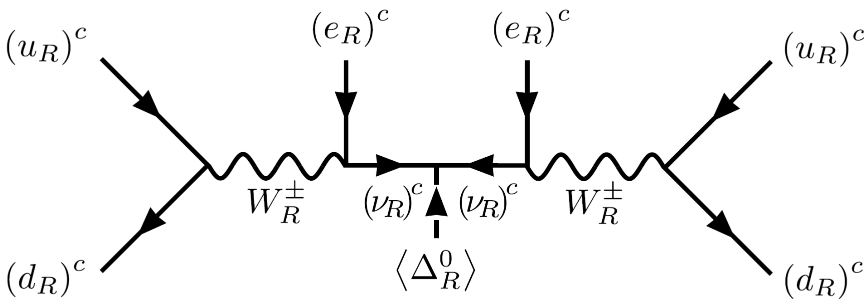
$(\mathbf{8},\mathbf{5},1)$	$SO(18)$ [*]	

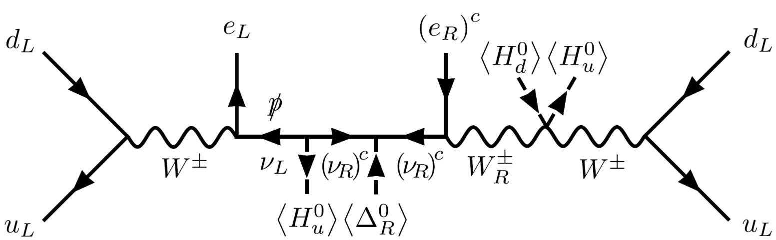
SVS* = Singer, Schechter & Valle, 1980

PPF* = Pisano & Pleitez , 1992; Frampton, 1992

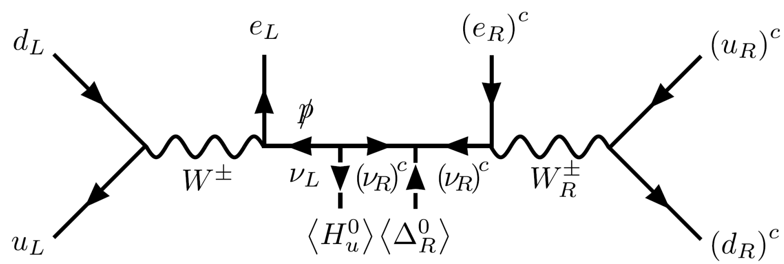
Left-right symmetric group

Short-range diagram:



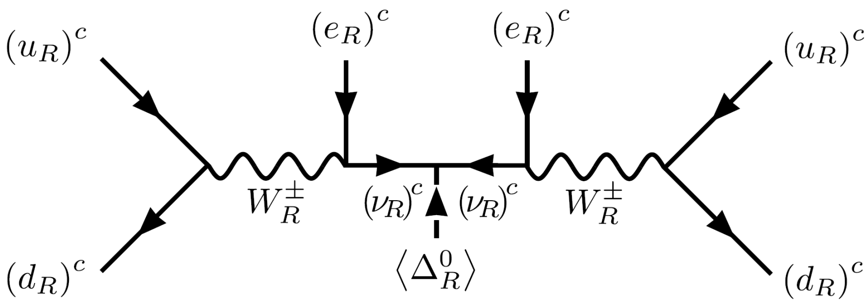


Long-range



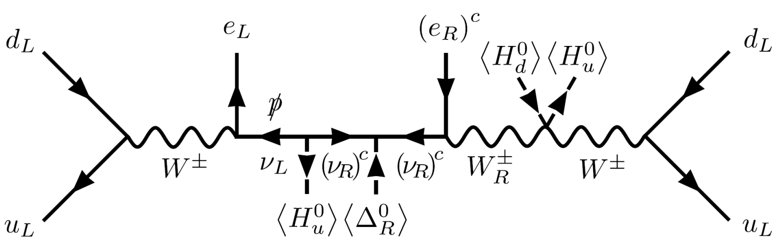
Long-range

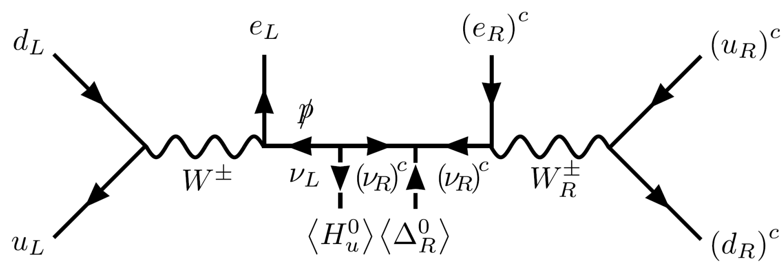
Left-right symmetric group



Short-range diagram:

$M_{W_R} \gtrsim 1.9\ (g_R/g_L)(\frac{1\ \mathrm{TeV}}{\langle m_N \rangle})^{1/2}$ TeV





Long-range

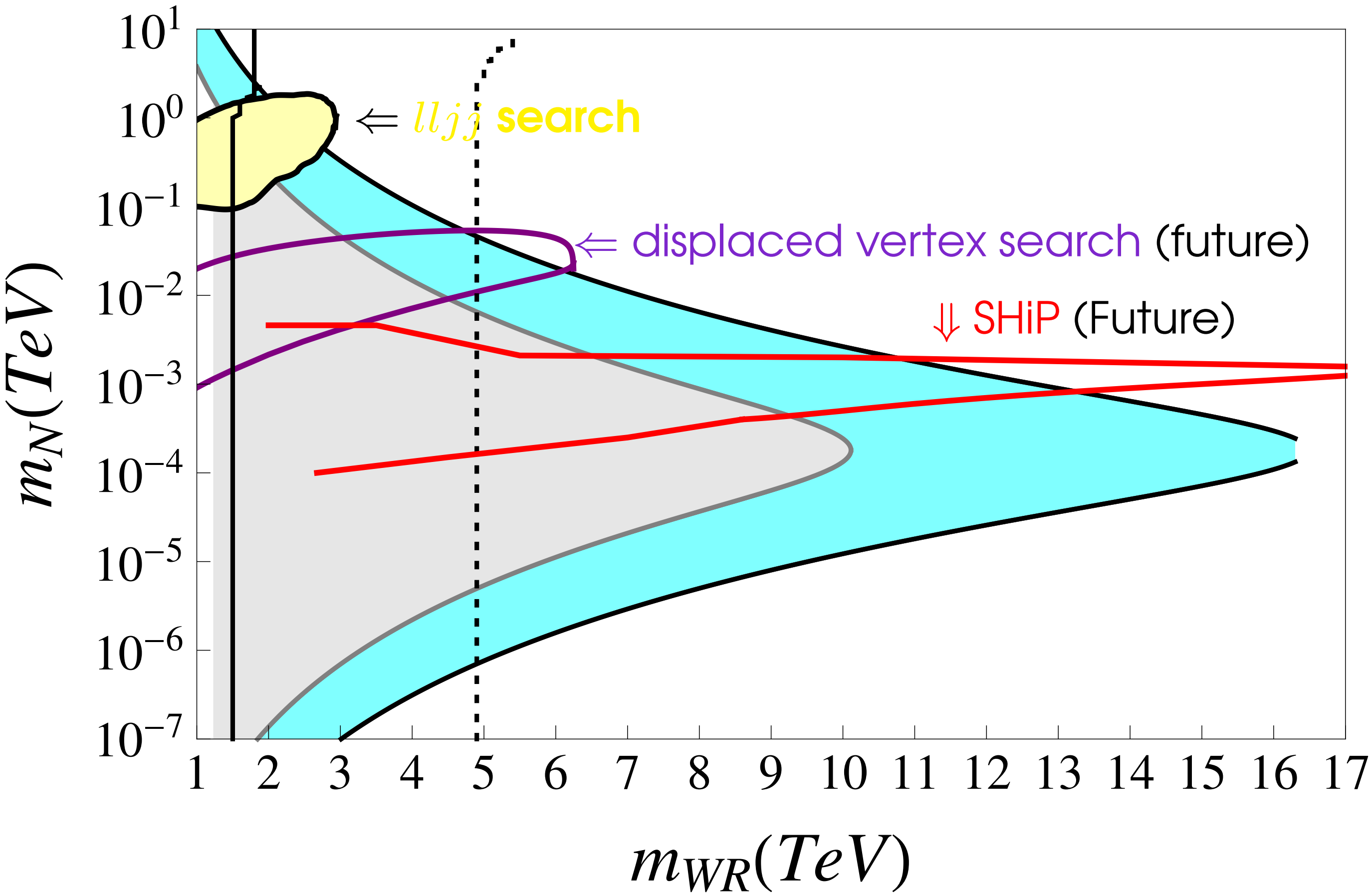
$$\langle \eta \rangle = \sum U_{ej} V_{ej} \tan \zeta \lesssim 1.1 \times 10^{-9}$$

Long-range

$$\langle \lambda \rangle = \sum U_{ej} V_{ej} (\frac{m_{W_L}}{m_{W_R}})^2 \lesssim 2.1 \times 10^{-7}$$

LR: LHC & $0\nu\beta\beta$ decay

Absence of $pp \to W_R \to jj$ gives limit on LR model space:



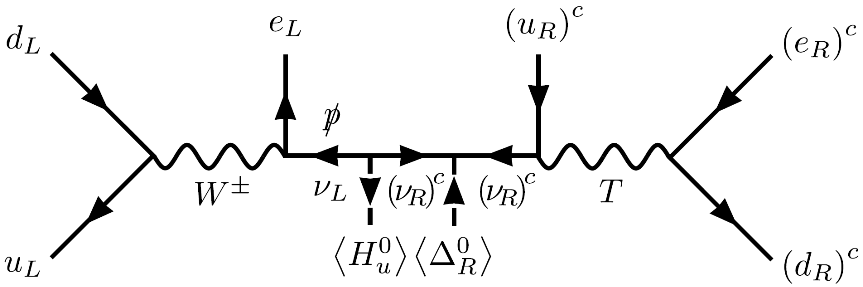
Helo & Hirsch
PRD92 (2015)

gray:
$T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{25}$ **ys**

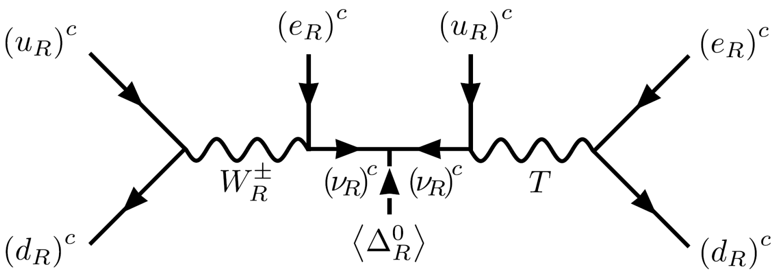
cyan:
$T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{27}$ ys

$\Rightarrow$ **full (dashed) 8 TeV data limit**
(future sensitivity) for dijet data

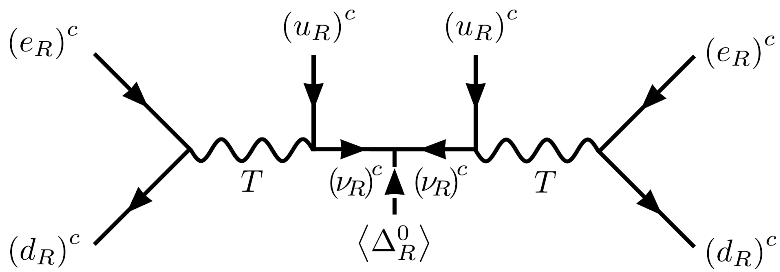
Pati-Salam group



Long-range diagram

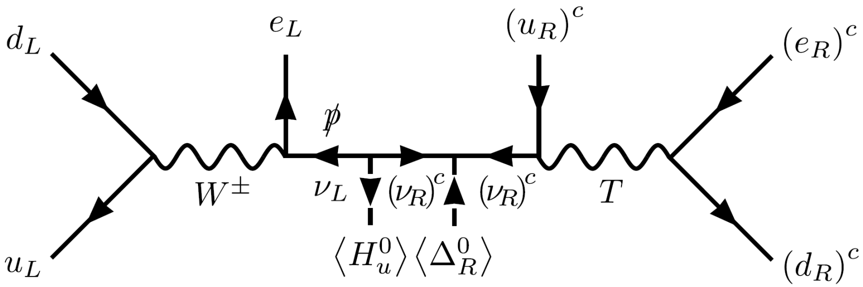


Short-range

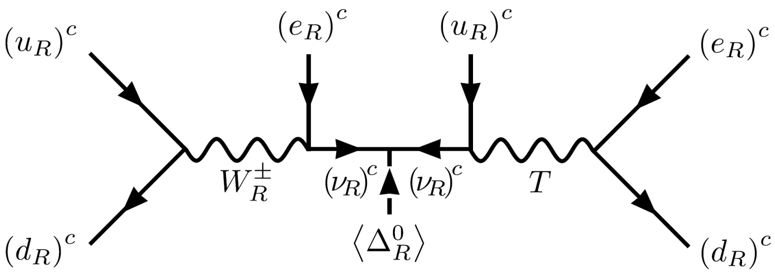


Short-range

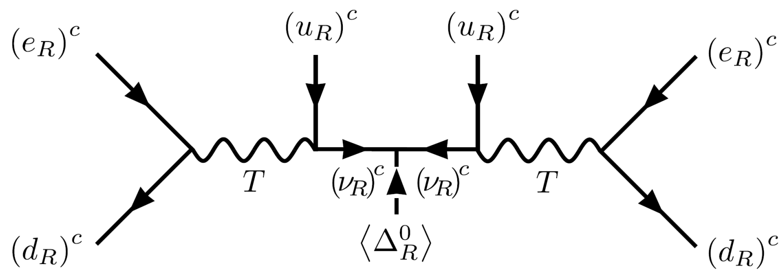
Pati-Salam group



Long-range diagram



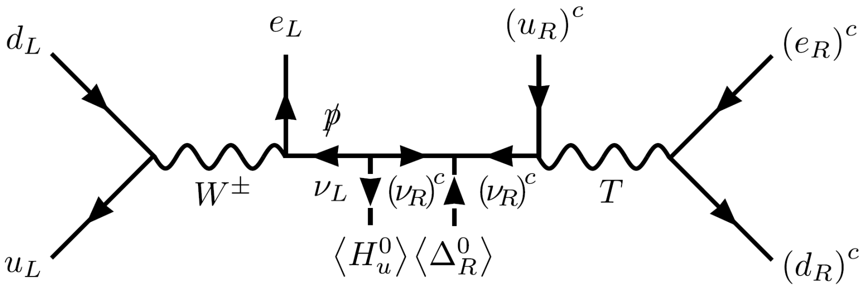
Short-range



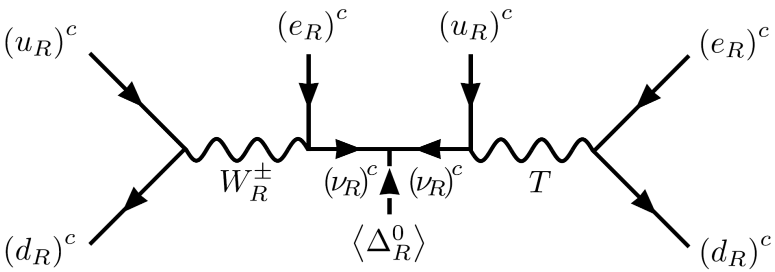
Short-range

$\Rightarrow$ Limits on $T = V^\mu_{3,1,2/3}$ similar to W_R limits ($\mathcal{O}(2\ \mathrm{TeV})$)

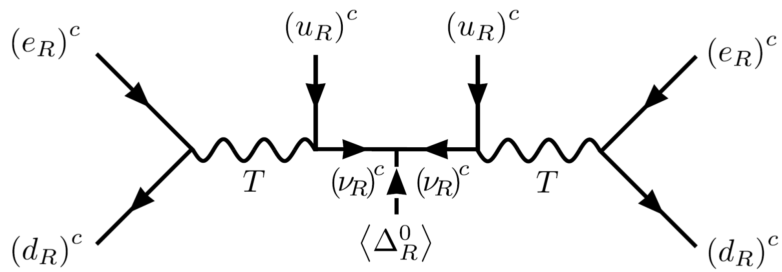
Pati-Salam group



Long-range diagram



Short-range



Short-range

$\Rightarrow$ Limits on $T = V^{\mu}_{3,1,2/3}$ similar to W_R limits ($\mathcal{O}(2\ \mathrm{TeV})$)

$\Rightarrow$ Limits on Pati-Salam scale from flavour violating decays:

A. Kuznetsov et al, Int.J.Mod.Phys. A27, 2012

Naive constraint: $K_L^0 \to \mu^\pm e^\mp \to \Lambda_{PS} \gtrsim 1700$ TeV

"Unavoidable" constraint, combining:

$(\tau^- \to \mu^- K_S^0, \tau^- \to \mu^- \pi^0\ B^0 \to \mu^\pm e^\mp, B_s^0 0 \to \mu^\pm e^\mp) \to \Lambda_{PS} \gtrsim 38$ TeV

$SU(3)_L$ group

Enlarge $SU(2)_L$ to $SU(3)_L$. Fundamental is a triplet.
In PPF model ($\beta = -\sqrt{3}$) leptons, for example, are:

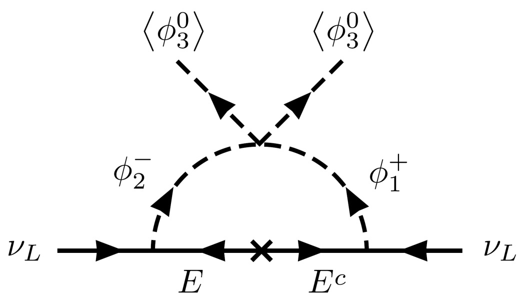
Pisano & Pleitez, 1992
Frampton, 1992

$$\psi_L = \Big((\nu_L, e_L), e^c_R\Big)$$

Adjoint is an octet:

$$\mathbf{8} \quad = \begin{pmatrix} Z^0 & W^+ & V^- \\ W^- & Z'^0 & U^{--} \\ V^+ & U^{++} & Z''^0 \end{pmatrix}$$

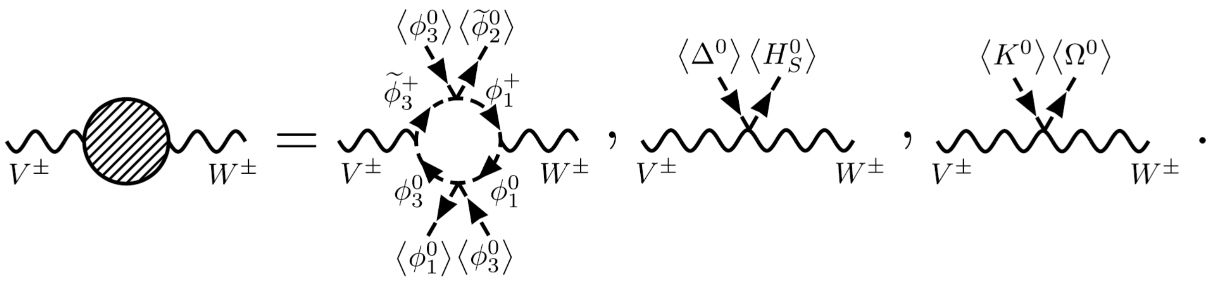
Modify PPF model (PPF-E) to generate meutrino mass:



For LNV in 331, see:
Fonseca & Hirsch,
PRD94 (2017)

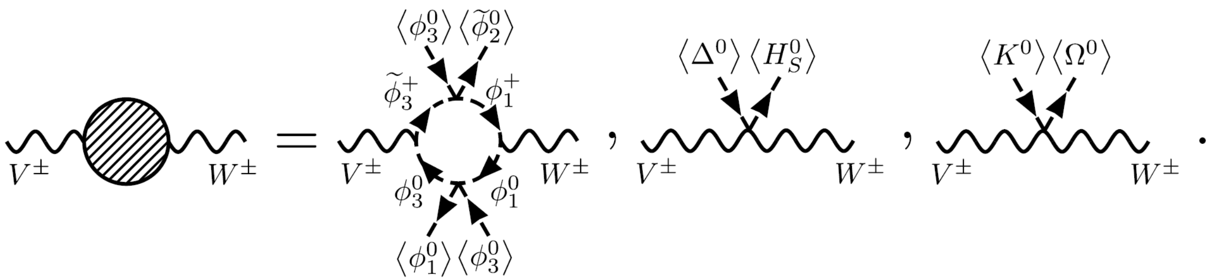
Gauge boson mixing

$V^\pm$ and $W^\pm$ can mix. Three examples:

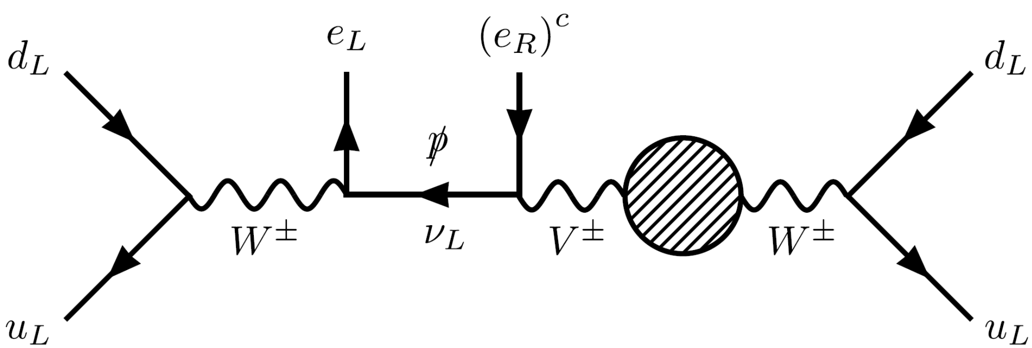


Gauge boson mixing

$V^{\pm}$ and $W^{\pm}$ can mix. Three examples:



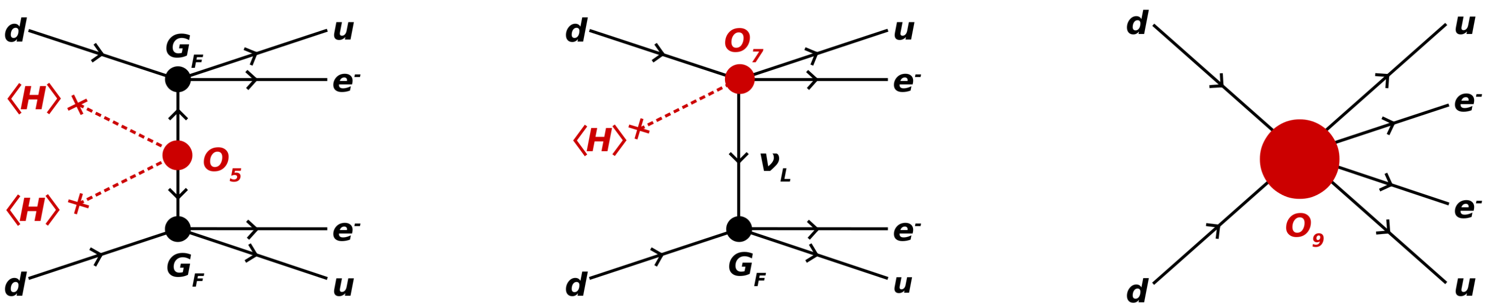
$0\nu\beta\beta$ decay long-range diagram:



$\Rightarrow$ Limit on mixing angle from C_3^L: $\zeta \lesssim 1.9 \times 10^{-9}$

Conclusions ???

$\Rightarrow$ What is the scale of LNV?



(a) (b) (c)

Mass mechanism	“long-range”	“short-range”
near GUT scale ?	$(10^3 - 10^6)$ GeV?	“few” TeV?