$0\nu\beta\beta$ decay:

Beyond the mass mechanism

(v.19.5)

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http://www.astroparticles.es/

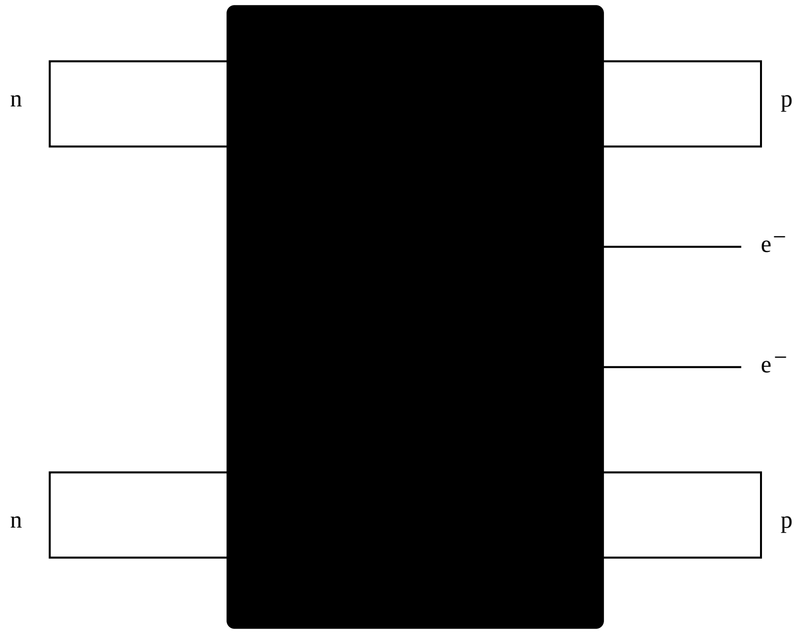
Contents

$\mathcal{I}.$

Introduction

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

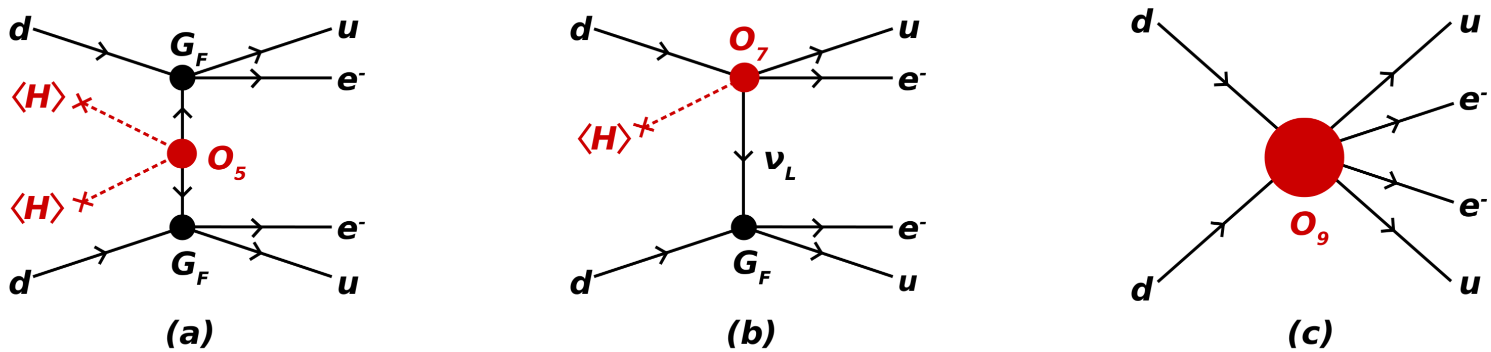
ϵ_i - particle physics

Many, many possible contributions!

Note: Factorization requires no new physics with $\Lambda \simeq p_F$

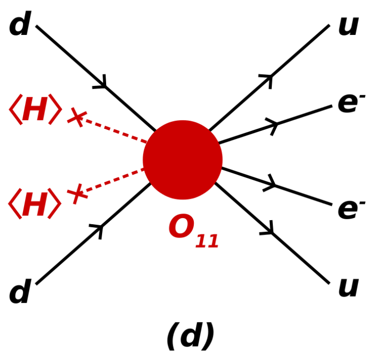
$0\nu\beta\beta$ decay: Decomposition

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



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

Higher order:



$+ \cdots$

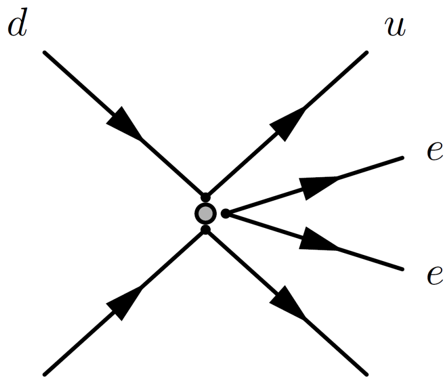
$\mathcal{II}$.

Run and freeze

PRD97 (2018) 115005
and PRD93 (2016) 013017

QCD corrections

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



(a)

QCD corrections

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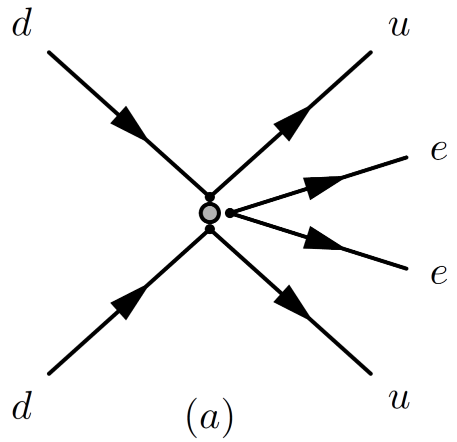

Heavy particles integrated out at scale Λ:

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

QCD corrections

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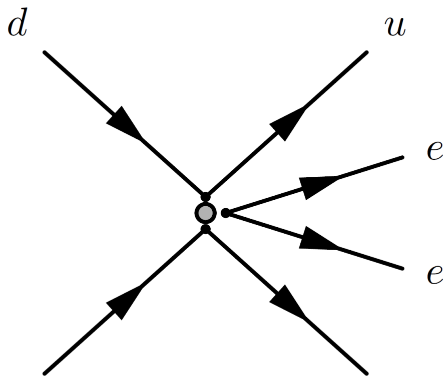


(a)

Heavy particles
integrated out
at scale Λ:

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

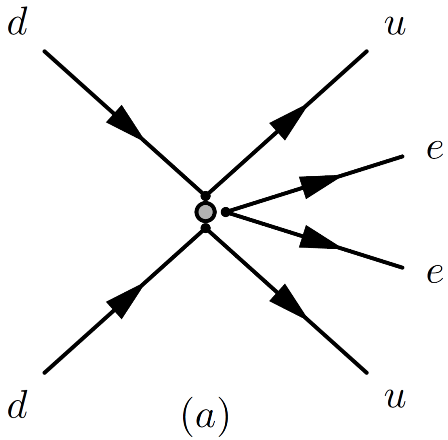
$\Rightarrow$ Double beta decay is a low-energy process. Energy scale:

$p_F \simeq$ 100 MeV

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

QCD corrections

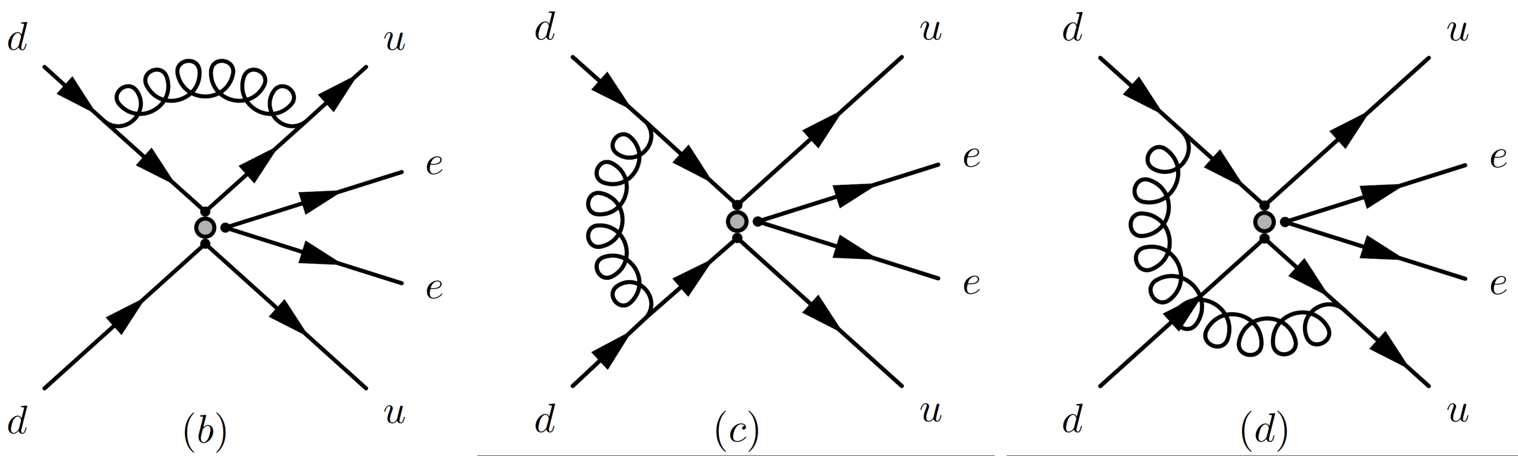
At tree-level:



Add gluon exchange diagrams

Naive estimate is:

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



QCD corrections

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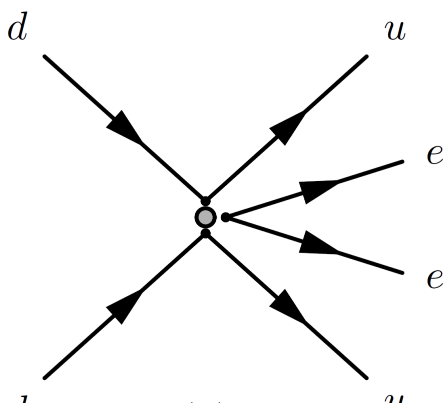


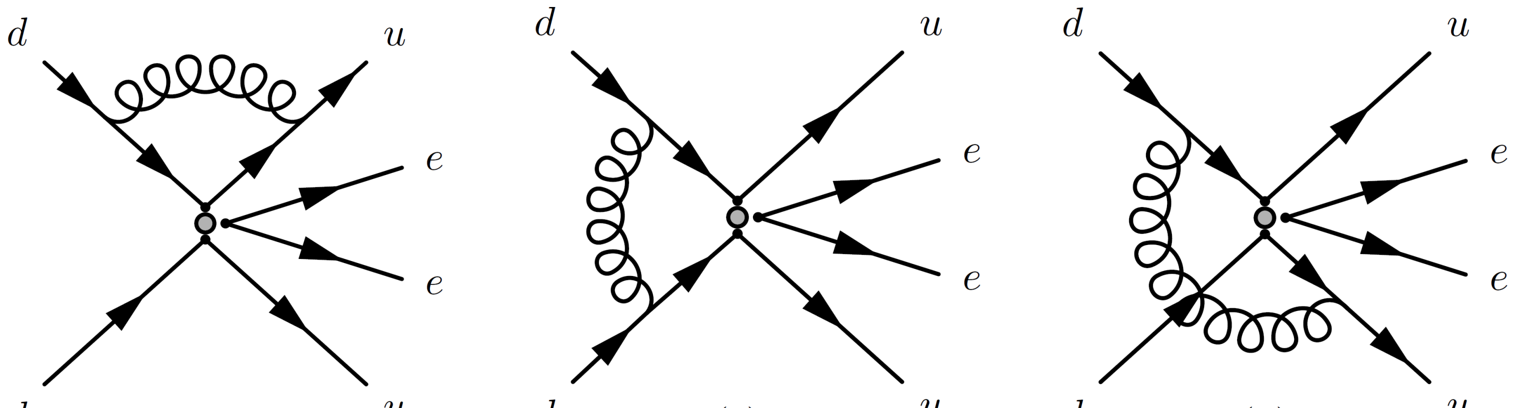
(a)

BUT ...

Colour index connects different nucleon currents:

"Operator mixing"

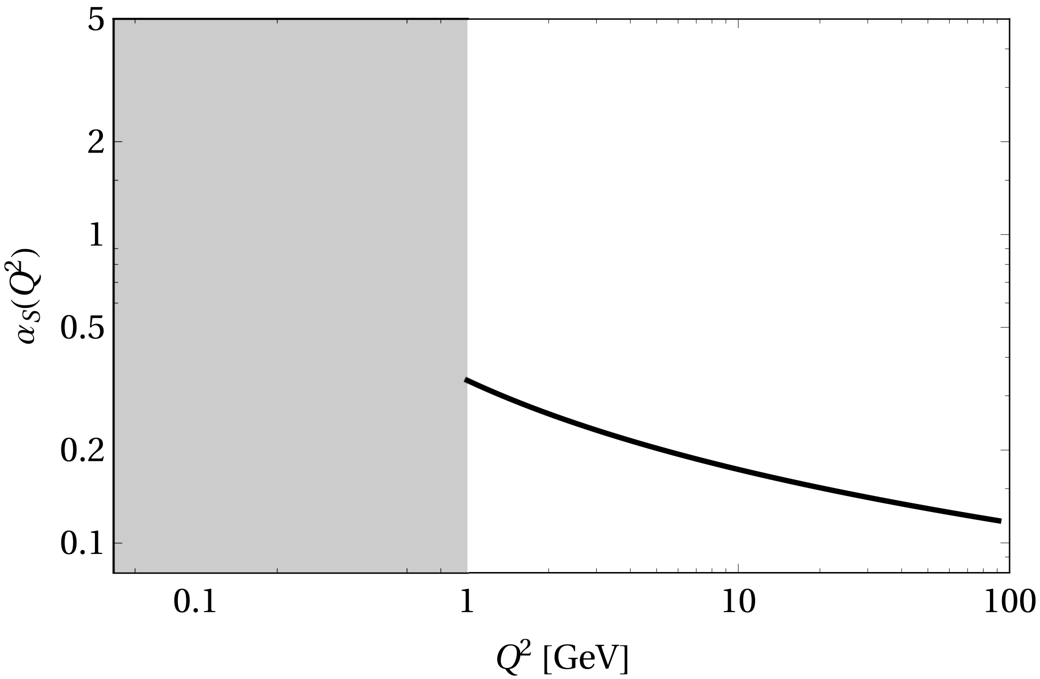
$\Rightarrow$ Limits change considerably



(b) (c) (d)

Running of α_S

Consider the running of α_S, usually stop running at ~ 1 GeV:



At 1-loop level:

$$\alpha_S(Q^2) \simeq \frac{\alpha_S(m_Z)}{1 - \beta\frac{\alpha_S(m_Z)}{2\pi}\log(m_Z/Q)}$$

Experimental input: $\alpha_S(m_Z) \simeq 0.118$

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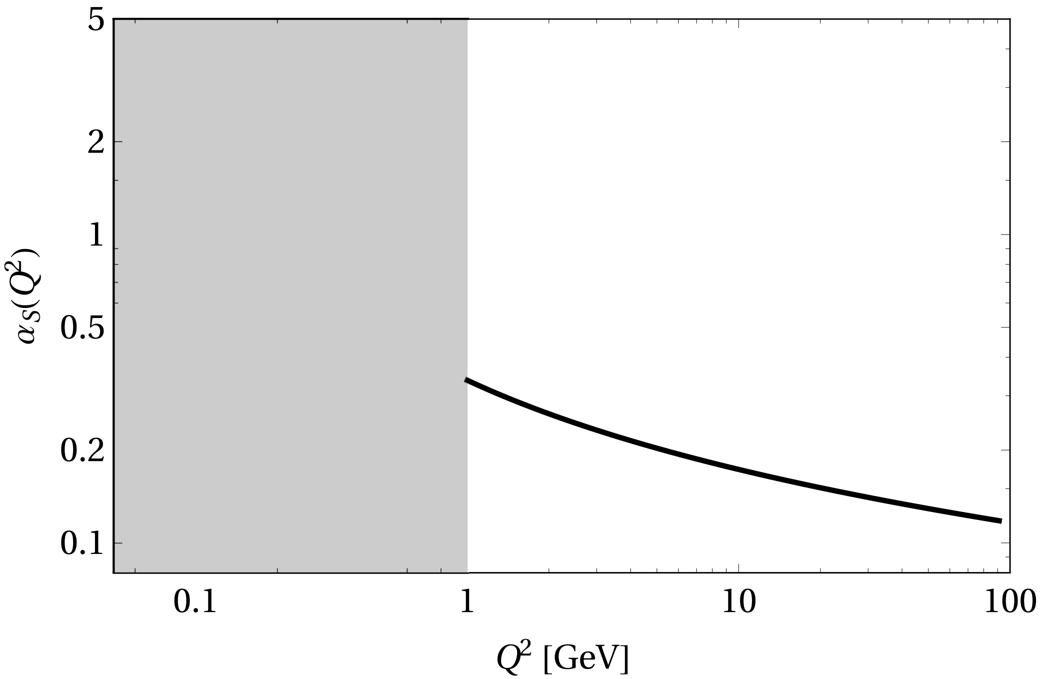

$0\nu\beta\beta \Rightarrow 0\nu\beta\beta(Q^2)$
with:
$Q \simeq (0.1 - 0.2)$ GeV

What happens below 1 GeV?

At 1-loop level:

$$\alpha_S(Q^2) \simeq \frac{\alpha_S(m_Z)}{1 - \beta\frac{\alpha_S(m_Z)}{2\pi}\log(m_Z/Q)}$$

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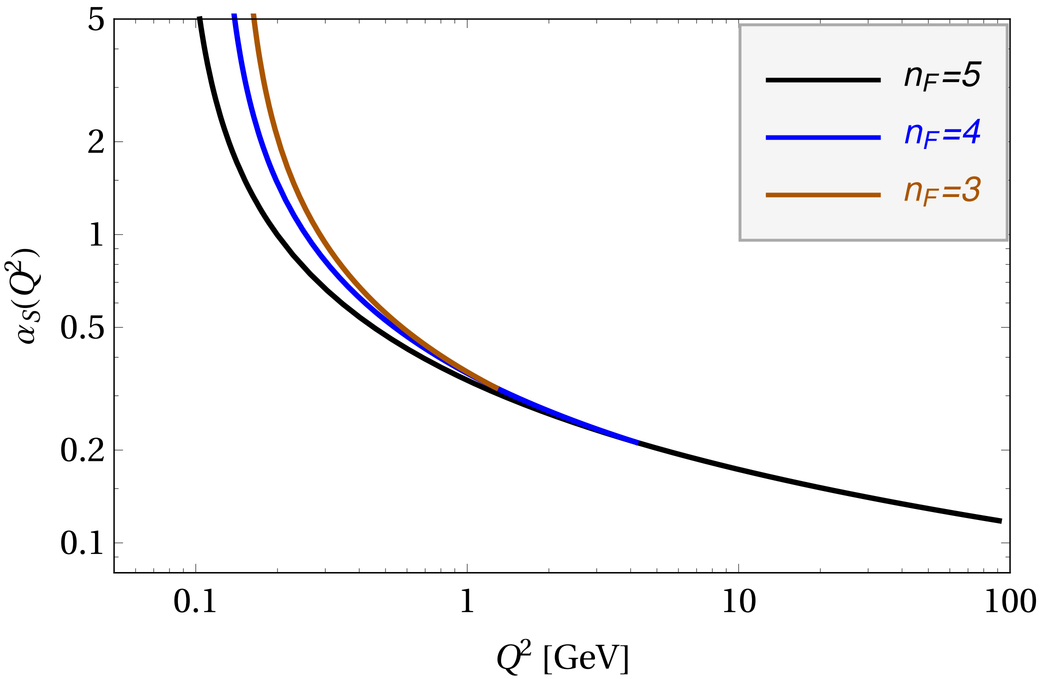

At 1-loop level:

$$\alpha_S(Q^2) \simeq \frac{\alpha_S(m_Z)}{1 - \beta \frac{\alpha_S(m_Z)}{2\pi} \log(m_Z/Q)}$$

"Integrate out" quark flavours at their mass: β changes

Running of α_S

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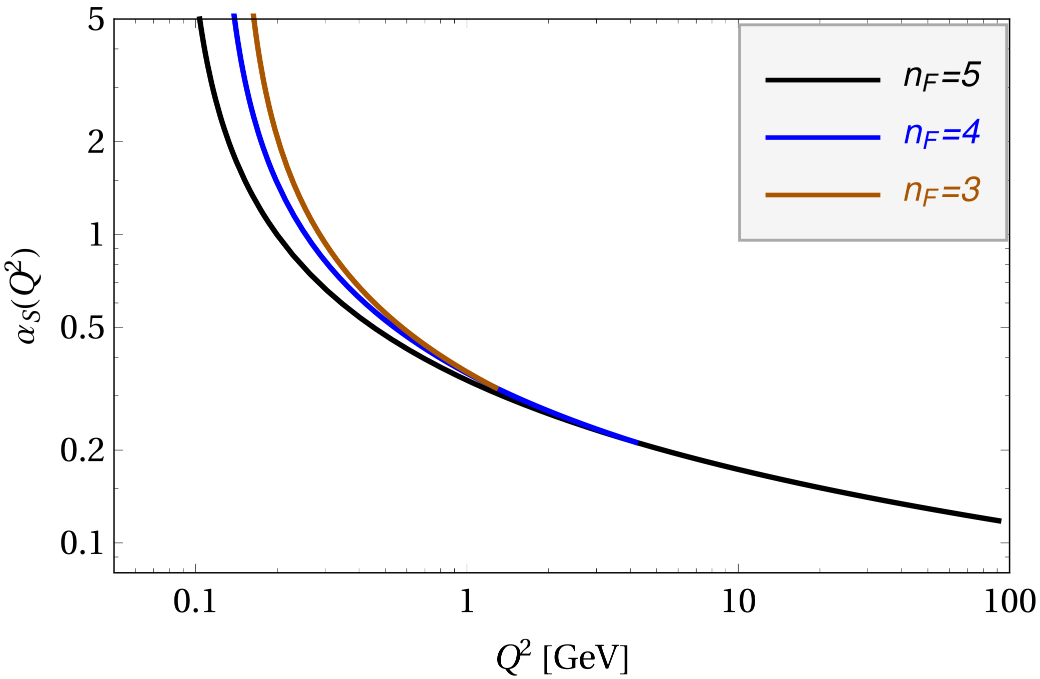


Perturbative $\alpha_S(Q^2)$ diverges for $Q^2 \to 0$

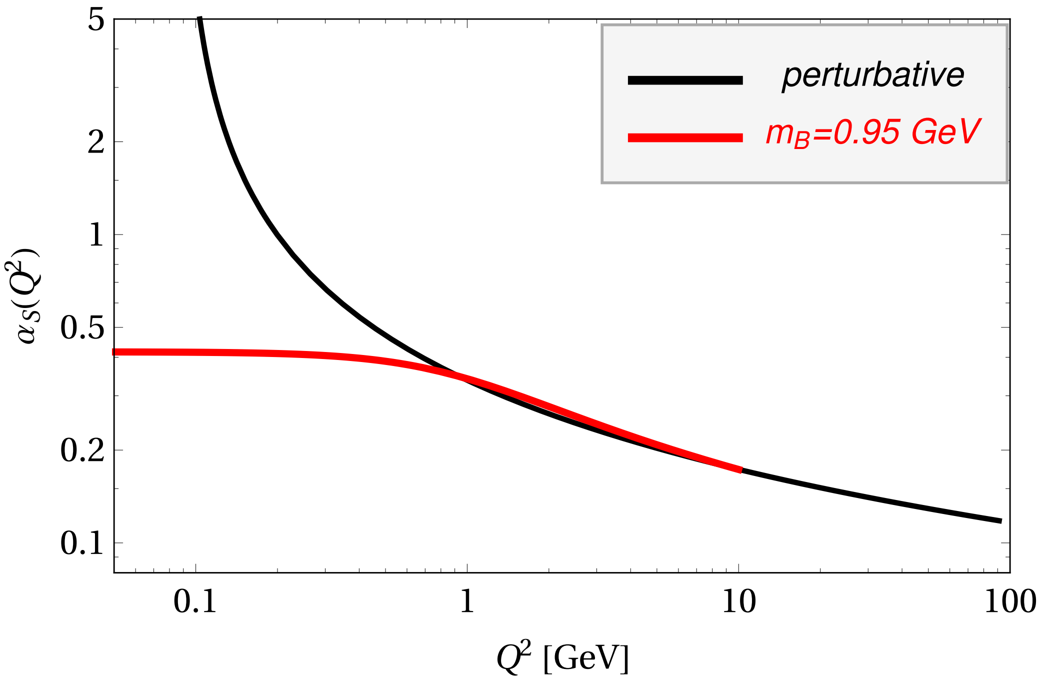
At 1-loop level:

$$\alpha_S(Q^2) \simeq \frac{\alpha_S(m_Z)}{1 - \beta \frac{\alpha_S(m_Z)}{2\pi} \log(m_Z/Q)}$$

"Integrate out" quark flavours at their mass: β changes

Freezing of α_S

Consider the running of α_S:



"Background Field Method"

Parameter m_B needs to be fixed

($\alpha_s(\lambda)$ is fixed by normalization to perturbative value)

Freezing:

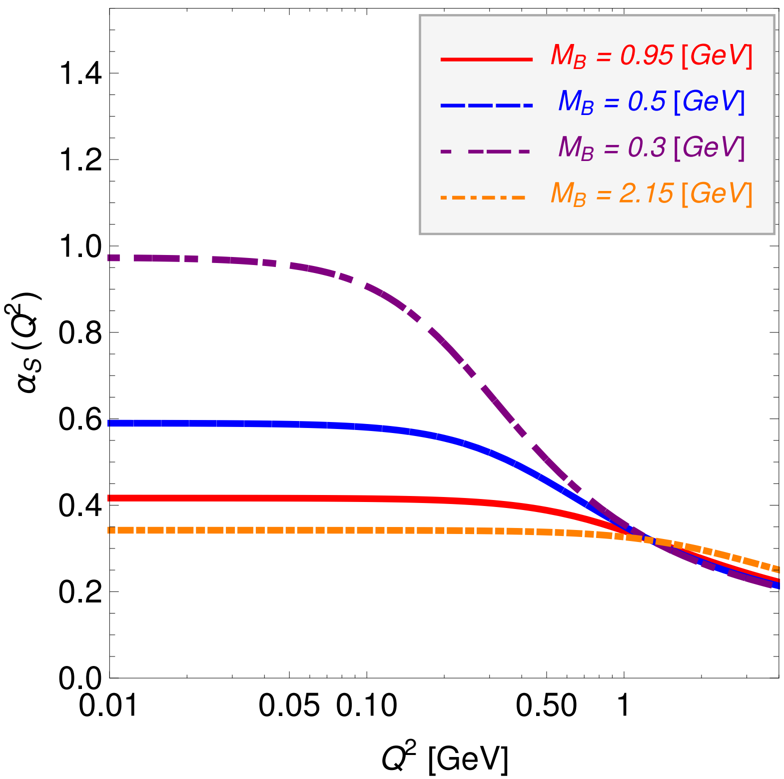
$$\tilde{\alpha}_s(\mu^2) = \frac{\alpha_s(\lambda)}{1 + \beta_0 \frac{\alpha_s(\lambda)}{4\pi} \log \frac{\mu^2 + m_B^2}{\lambda^2}}$$

L. F. Abbott, NPB195 (1981)

see also the review: Deur et al., 1604.08082

Freezing of α_S

Consider different choices of m_B:



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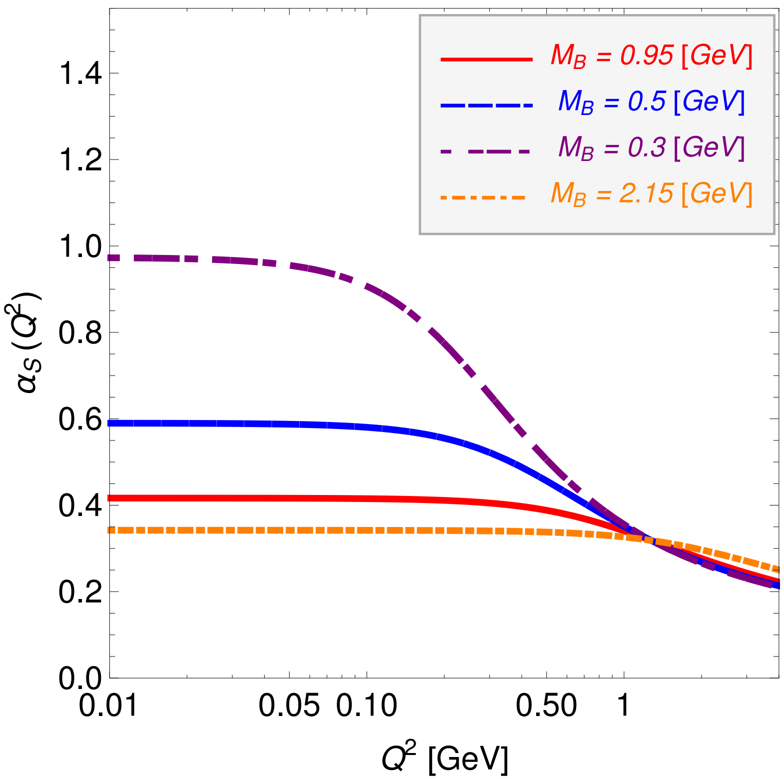

Low-energy value of α_S very sensitive to choice of m_B

Freezing:

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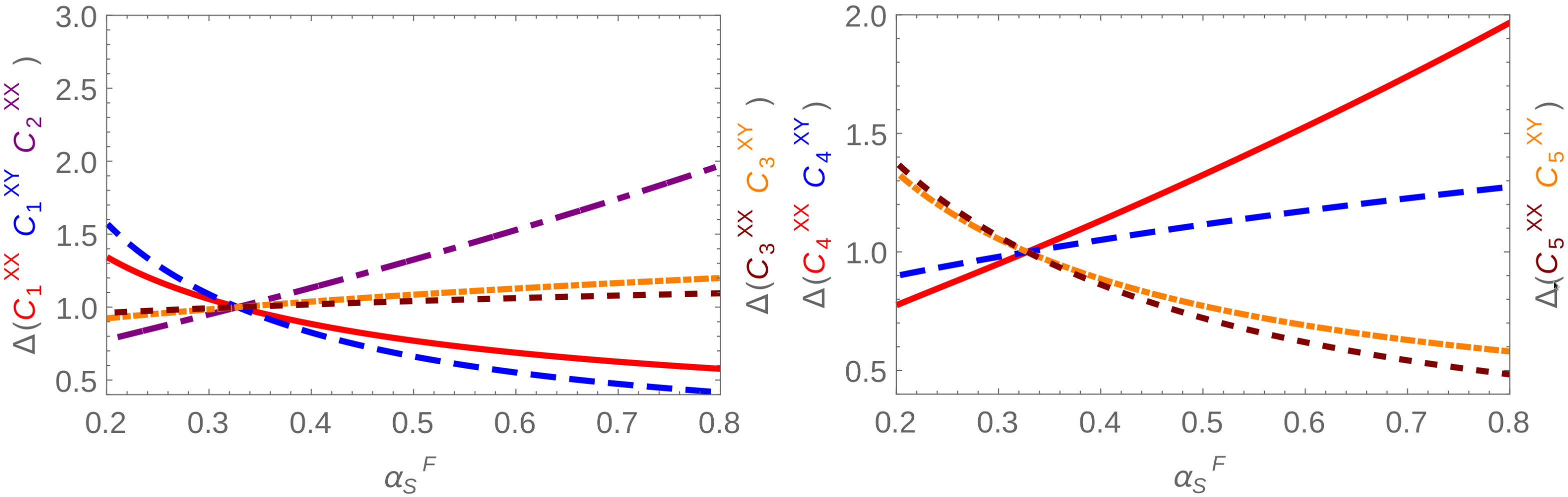
Limits on SR coefficients

Change in short-range coefficients as function of α_S^F,
normalized to the value at $\alpha_S = 0.32$ without freezing:



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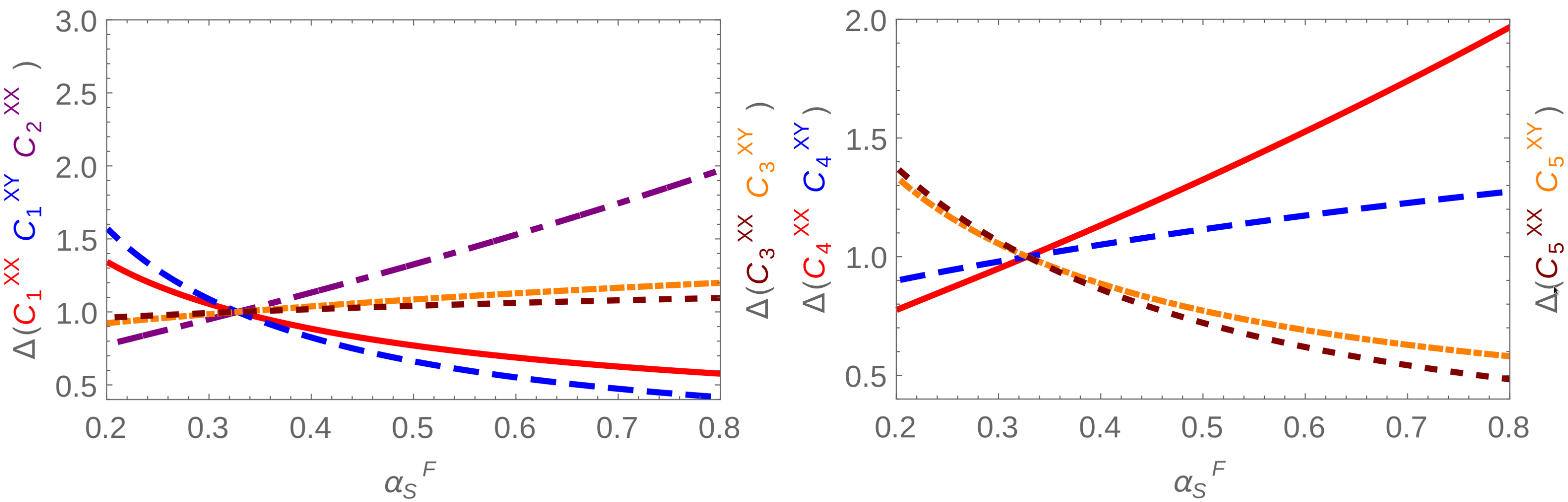


$\Rightarrow$ For $\alpha_S^F \lesssim 0.8$ changes are ~ 2

$\Rightarrow$ For $\alpha_S^F \gtrsim 0.8$ large uncertainty in nearly all coefficients

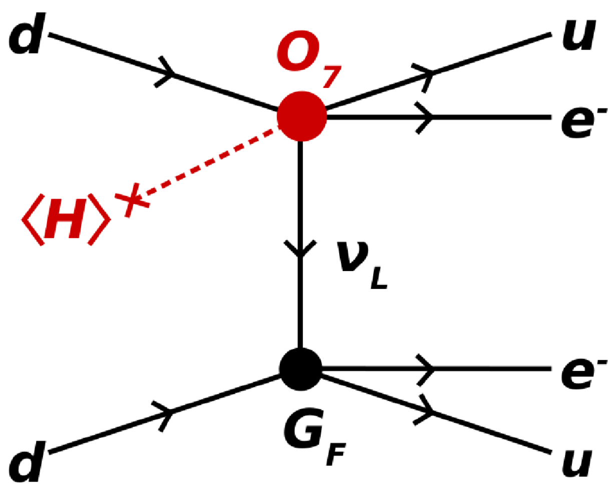
$\mathcal{III}.$

Long-range $0\nu\beta\beta$ reconsidered

JHEP06 (2016) 006

Effective operators for LR

Consider once more:



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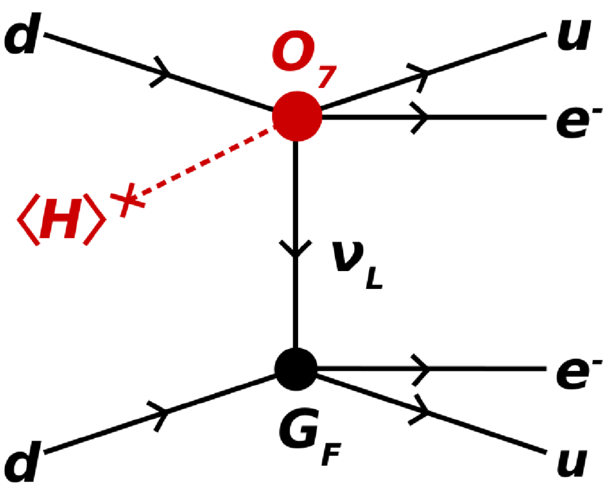

At low energies,
Higgs replaced by vev

Charged current is $d=6$:

$\mathcal{L}^{\rm LNV} \propto \sum_{\alpha\beta} \epsilon_\alpha^\beta j_\beta J_\alpha$

with:

$j_\beta = \bar{e}\mathcal{O}_\beta \nu$
$J_\alpha = \bar{u}\mathcal{O}_\alpha d$

Only $\mathcal{O}_\beta$ with $\mathcal{O}_\beta = \mathcal{O}'_\beta P_R$ interesting

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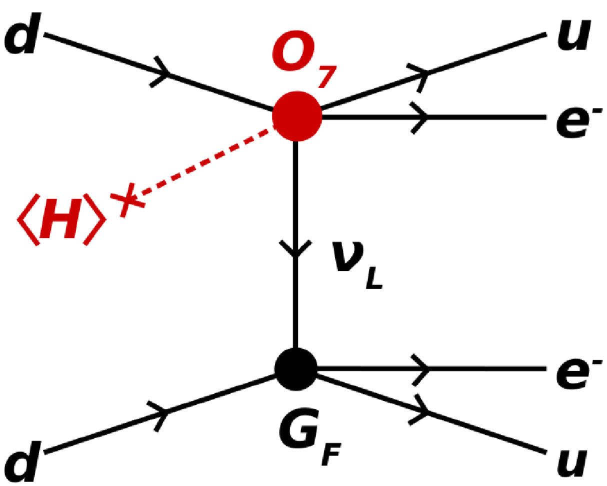

$\Delta L = 2\ d-7$ operators in the SM:

$\mathcal{O}_2 \propto LLLe^cH$
$\mathcal{O}_3 \propto LLQd^cH$
$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$
$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$

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Babu & Leung, 2001

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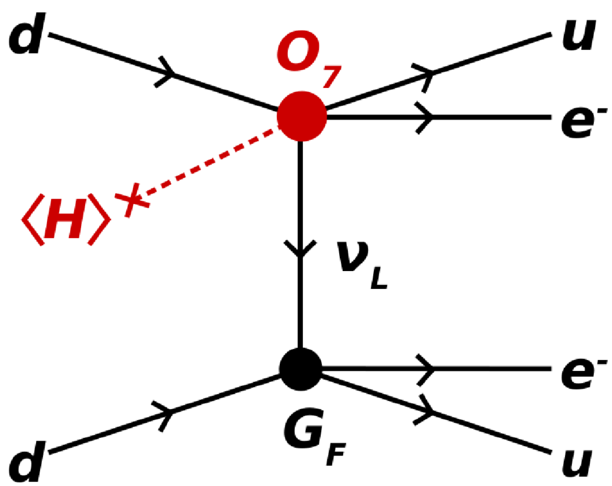

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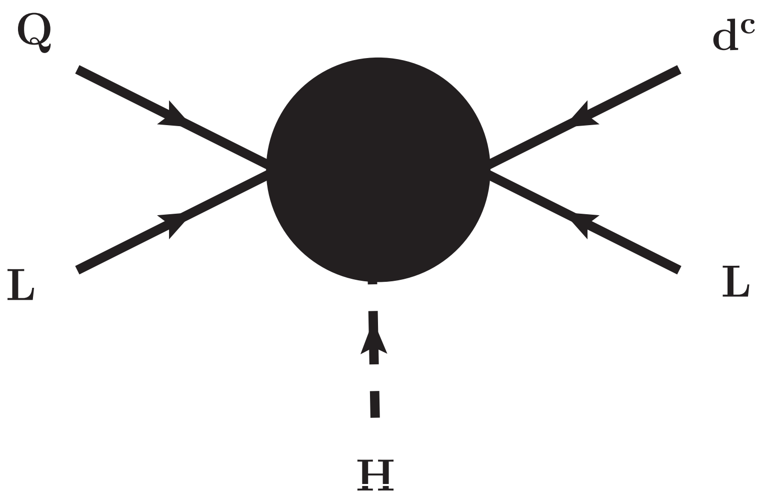
$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$
$\mathcal{O}_7 \propto L\bar{e}^cQ\bar{Q}HHH$ $d = 9$, but see below ...

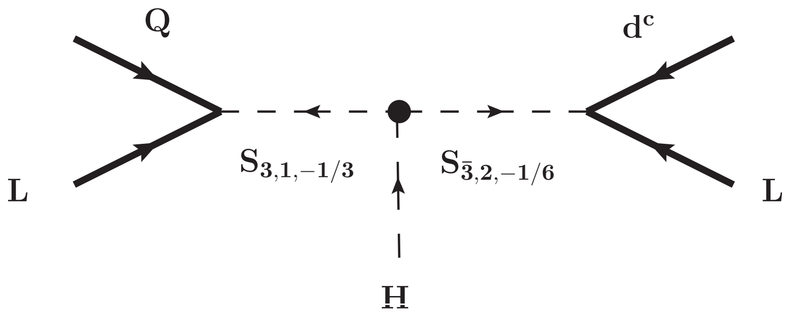
Example $d = 7$: $LLQd^cH$

Graphically:



Example $d = 7$: $LLQd^cH$

More than one realization.
Example, $(\mathcal{O}_3, \#2)$:



$S_{3,1,-1/3}$ - singlet leptoquark
$S_{3,2,1/6}$ - doublet leptoquark

$\Delta L = 2$, so ...

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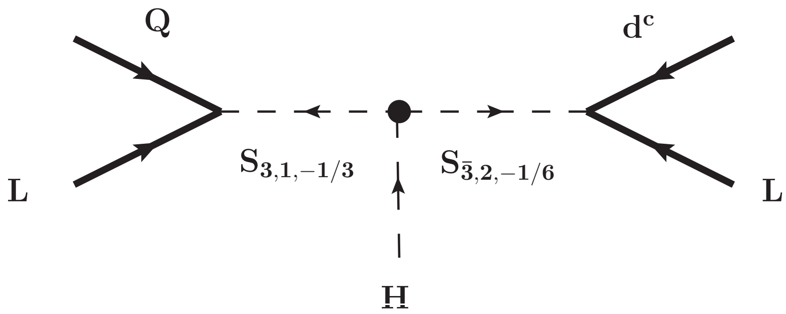

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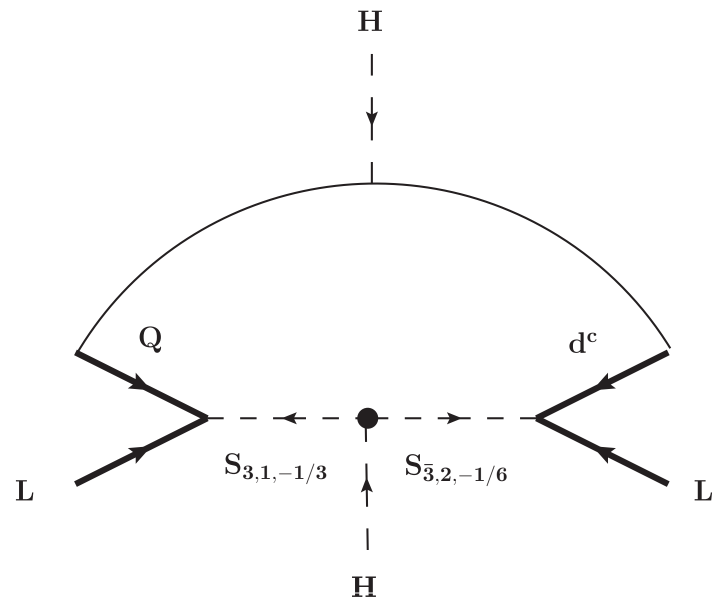
1-loop neutrino mass:



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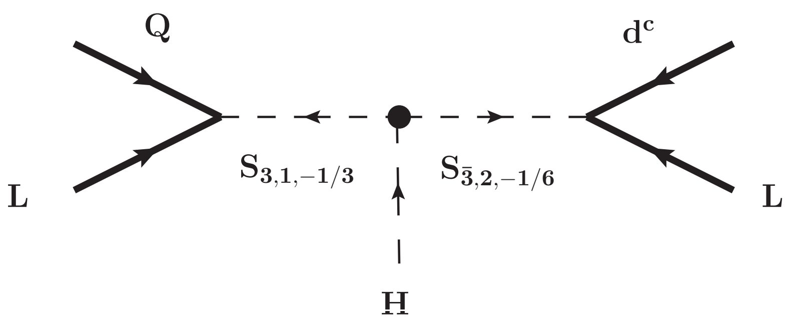

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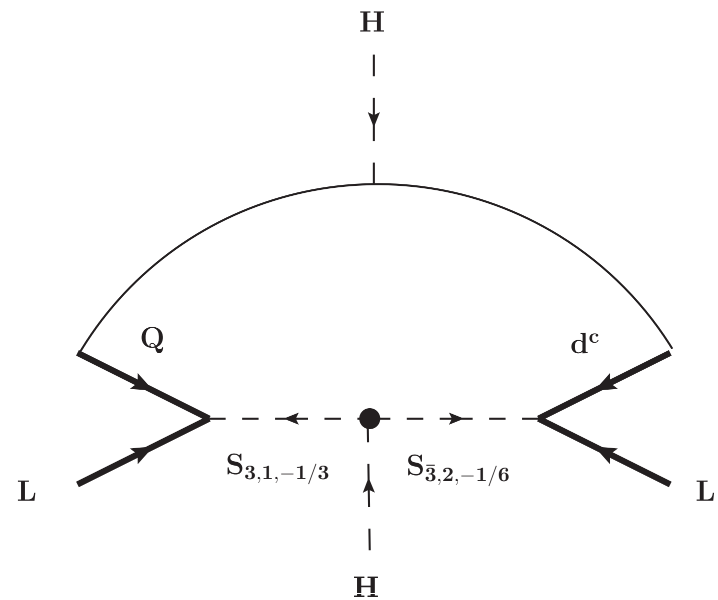
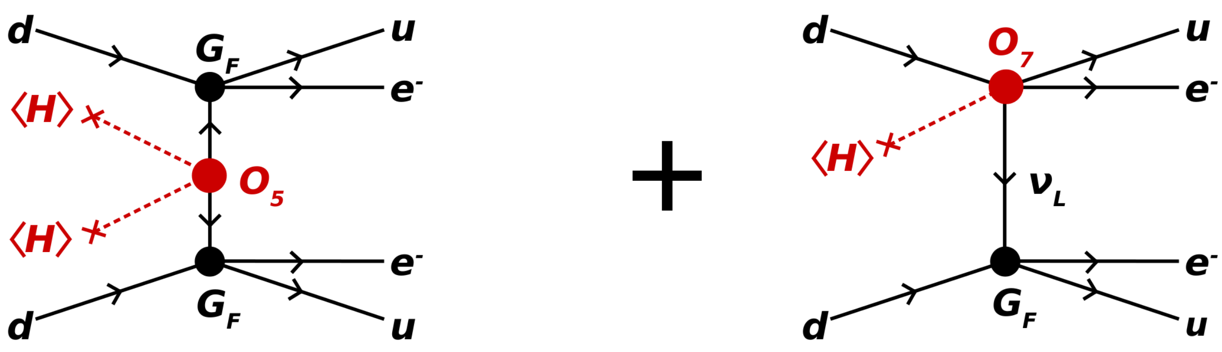


$0\nu\beta\beta$ decay has both contributions:



(a) (b)

Example $d = 7$: $LLQd^cH$

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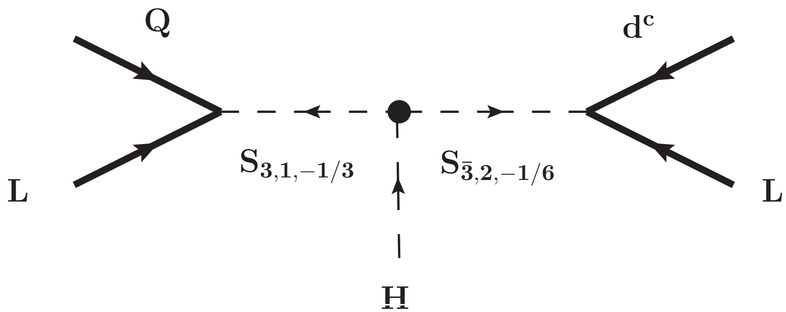

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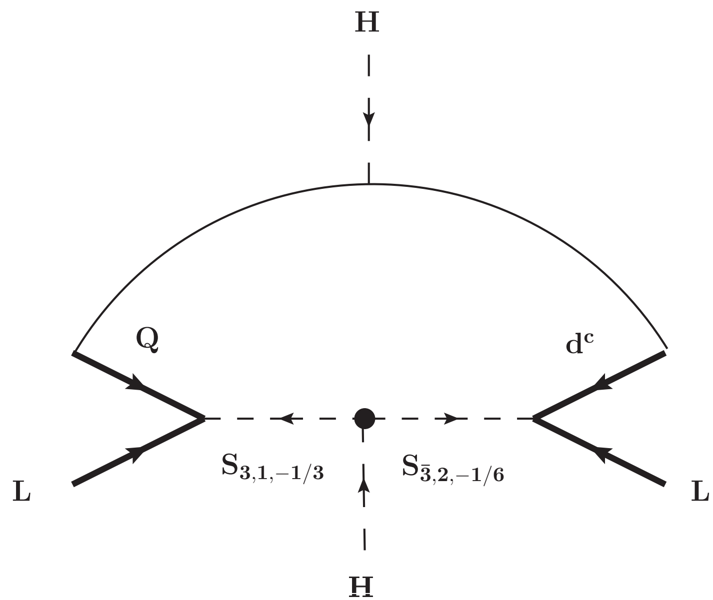

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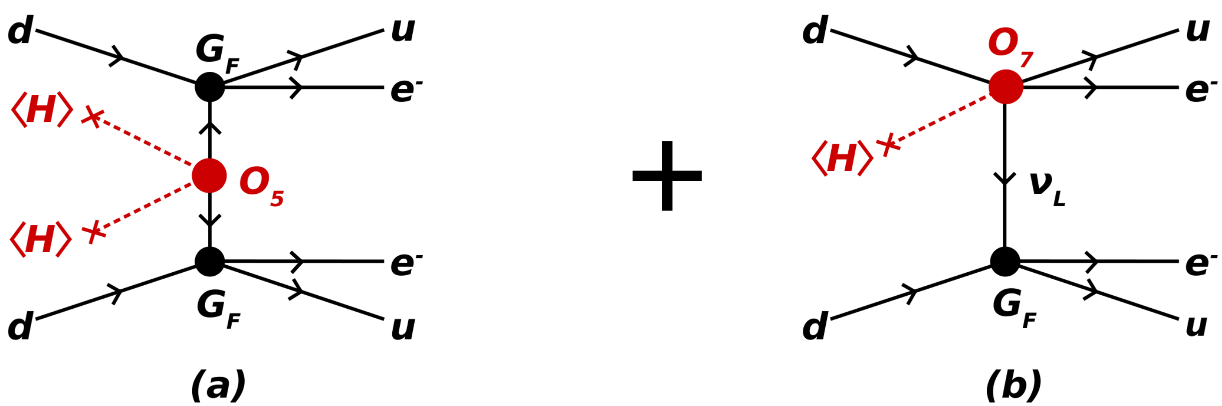
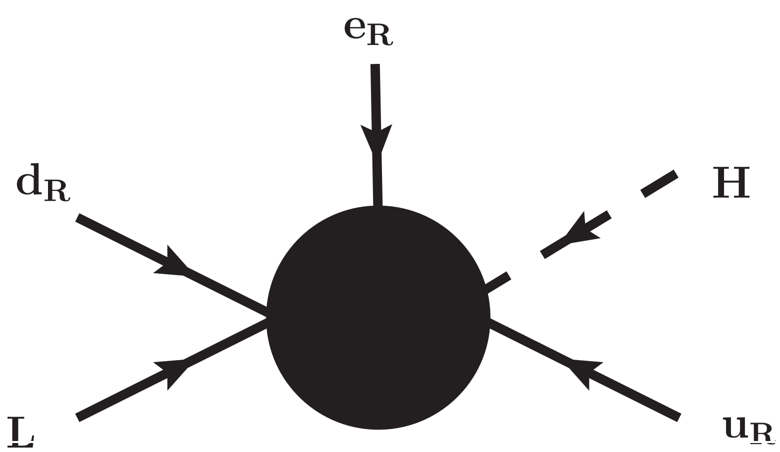


True for all
$d = 7$
$\Delta L = 2$
operators!

Example $d = 7$: $L\bar{e}^c\bar{u}^c d^c H$

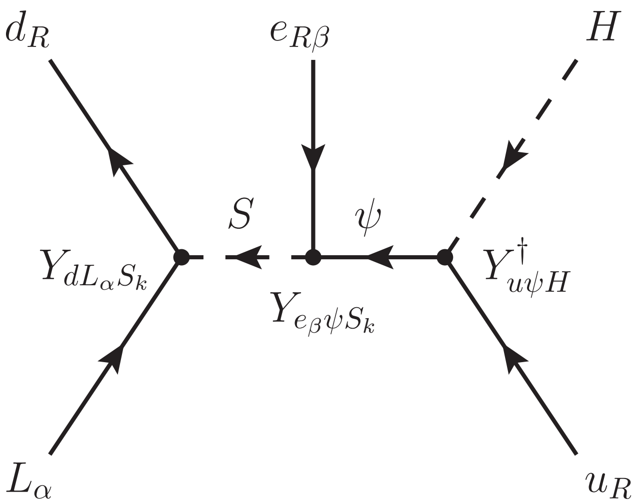
Graphically:



Example $d = 7$: $L\bar{e}^c\bar{u}^c d^c H$

More than one realization.

Example, $(\mathcal{O}_8, \#15)$:



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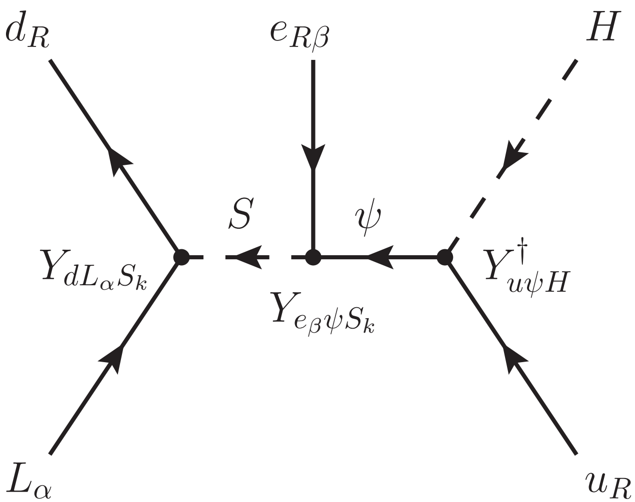
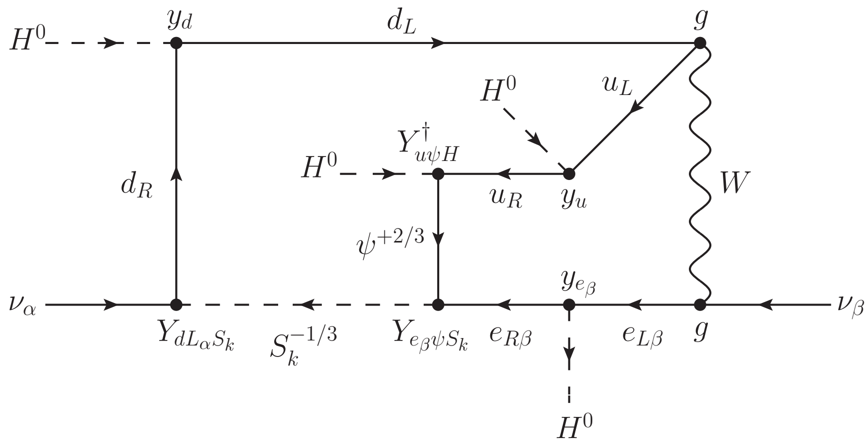


Neutrino mass:



Long-range enhanced by $\not{p}$

Neutrino mass is 2-loop $d = 7$ suppressed!

Long-range wins over mass mechanism!

Summary table

Helo, Hirsch & Ota
JHEP06 (2016) 006

Eff. op.	Decom.	$(m_\nu)_{\alpha\beta}$	Λ_7 [GeV] suggested by $m_\nu = 0.05$ eV	$\mathcal{A}^{\rm MM}/\mathcal{A}^{\rm LR}$
$LL\overline{d_R}QH$	#1,3,4,5,6,9	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,7,8	$\frac{y_b}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{11}$	$\frac{y_b}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{17}$
	[#1, 3, 5, 8	$\frac{y_b g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$ $(\alpha \neq \beta)$	$\sim 10^{8}$	$\frac{y_b g^2}{(16\pi^2)^2}\frac{\Lambda^2}{p_F v} \sim 10^{9}$]
$LL\overline{Q}u_R H$	#1,3,4,5,6,8,9	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,7,8	$\frac{y_t}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{12}$	$\frac{y_t}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{21}$
	[#1, 3, 5, 8	$\frac{y_t g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$ $(\alpha \neq \beta)$	$\sim 10^{10}$	$\frac{y_t g^2}{(16\pi^2)^2}\frac{\Lambda^2}{p_F v} \sim 10^{14}$]
$Le_R\overline{d_R}u_R H$	#5,8,14	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,12	$\frac{y_t}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{12}$	$\frac{y_t}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{21}$
	#3,11	$\frac{y_b}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{11}$	$\frac{y_b}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{17}$
	#1,4,6,7,9, 10,13,15	$y_{\ell_\beta}\frac{y_b y_t g^2}{(16\pi^2)^2}\frac{v^4}{\Lambda^3}$	$\sim 10^{3}$ $(\beta = \tau)$	$y_e\frac{y_b y_t g^2}{(16\pi^2)^2}\frac{v}{p_F} \sim 10^{-9}$

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	[#1, 3, 5, 8	$\frac{y_t g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$ $(\alpha \neq \beta)$	$\sim 10^{10}$	$\frac{y_t g^2}{(16\pi^2)^2}\frac{\Lambda^2}{p_F v} \sim 10^{14}$]
$Le_R\overline{d_R}u_R H$	#5,8,14	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,12	$\frac{y_t}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{12}$	$\frac{y_t}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{21}$
	#3,11	$\frac{y_b}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{11}$	$\frac{y_b}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{17}$
	#1,4,6,7,9, 10,13,15	$y_{\ell_\beta}\frac{y_b y_t g^2}{(16\pi^2)^2}\frac{v^4}{\Lambda^3}$	$\sim 10^{3}$ $(\beta = \tau)$	$y_e\frac{y_b y_t g^2}{(16\pi^2)^2}\frac{v}{p_F} \sim 10^{-9}$

$\Rightarrow$ Assumes SM couplings 3rd generation and unknown couplings $\mathcal{O}(1)$!

Summary table

Helo, Hirsch & Ota
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Eff. op.	Decom.	$(m_\nu)_{\alpha\beta}$	Λ_7 [GeV] suggested by $m_\nu = 0.05$ eV	$\mathcal{A}^{\rm MM}/\mathcal{A}^{\rm LR}$
$LL\overline{d_R}QH$	#1,3,4,5,6,9	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,7,8	$\frac{y_b}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{11}$	$\frac{y_b}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{17}$
	[#1, 3, 5, 8	$\frac{y_b g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$ $(\alpha \neq \beta)$	$\sim 10^{8}$	$\frac{y_b g^2}{(16\pi^2)^2}\frac{\Lambda^2}{p_F v} \sim 10^{9}$]
$LL\overline{Q}u_R H$	#1,3,4,5,6,8,9	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,7,8	$\frac{y_t}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{12}$	$\frac{y_t}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{21}$
	[#1, 3, 5, 8	$\frac{y_t g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$ $(\alpha \neq \beta)$	$\sim 10^{10}$	$\frac{y_t g^2}{(16\pi^2)^2}\frac{\Lambda^2}{p_F v} \sim 10^{14}$]
$Le_R\overline{d_R}u_R H$	#5,8,14	$\frac{v^2}{\Lambda}$	$\sim 10^{15}$	$\frac{\Lambda^2}{p_F v} \sim 10^{28}$
	#2,12	$\frac{y_t}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{12}$	$\frac{y_t}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{21}$
	#3,11	$\frac{y_b}{16\pi^2}\frac{v^2}{\Lambda}$	$\sim 10^{11}$	$\frac{y_b}{16\pi^2}\frac{\Lambda^2}{p_F v} \sim 10^{17}$
	#1,4,6,7,9, 10,13,15	$y_{\ell_\beta}\frac{y_b y_t g^2}{(16\pi^2)^2}\frac{v^4}{\Lambda^3}$	$\sim 10^{3}$ $(\beta = \tau)$	$y_e\frac{y_b y_t g^2}{(16\pi^2)^2}\frac{v}{p_F} \sim 10^{-9}$

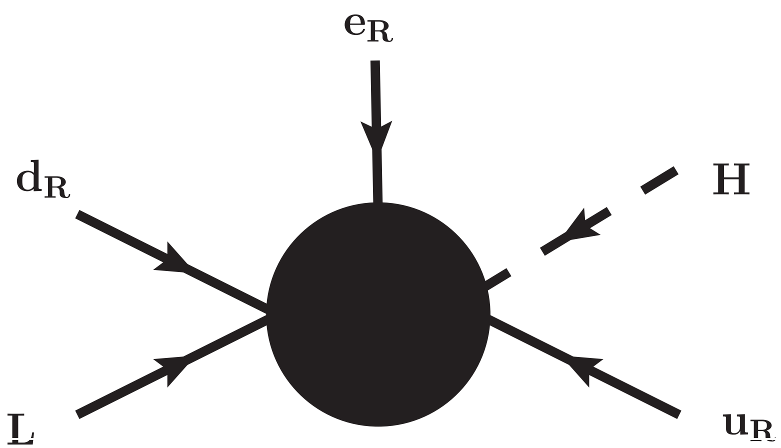
$\Rightarrow$ Assumes SM couplings 3rd generation and unknown couplings $\mathcal{O}(1)$!

Extreme example:

Tree-level: $\Lambda \sim 10^{15}$ GeV $(Y = 1)$ $\Rightarrow$ $\Lambda \sim 10^{3}$ GeV $(Y \sim 10^{-6} \sim Y_e)$

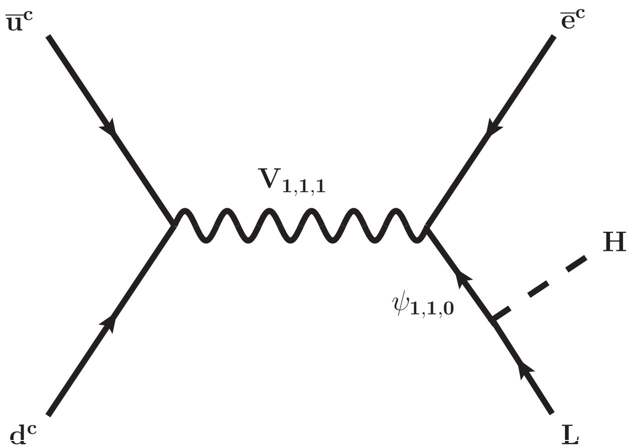
$d = 7$ versus $d = 9$ operator

Another look at:



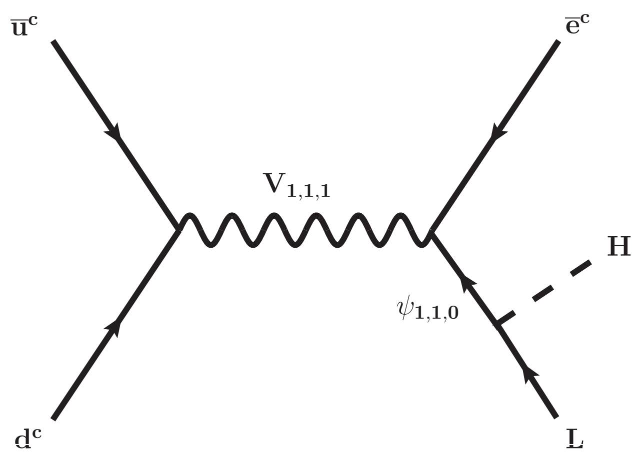
$d = 7$ versus $d = 9$ operator

Another example, $(\mathcal{O}_8, \#14)$:

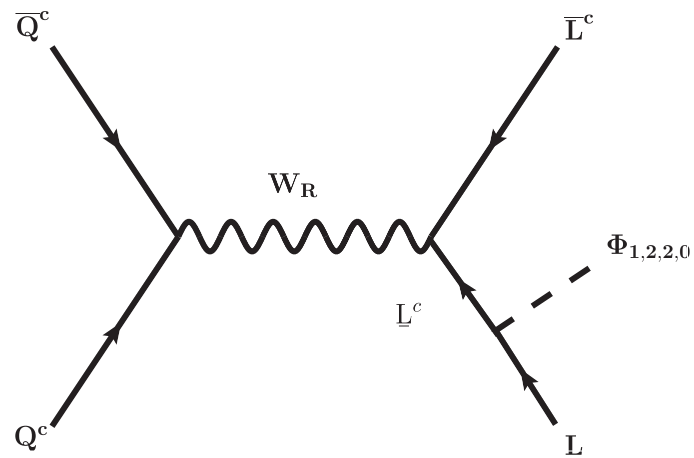


$d = 7$ versus $d = 9$ operator

Another example, $(\mathcal{O}_8, \#14)$:



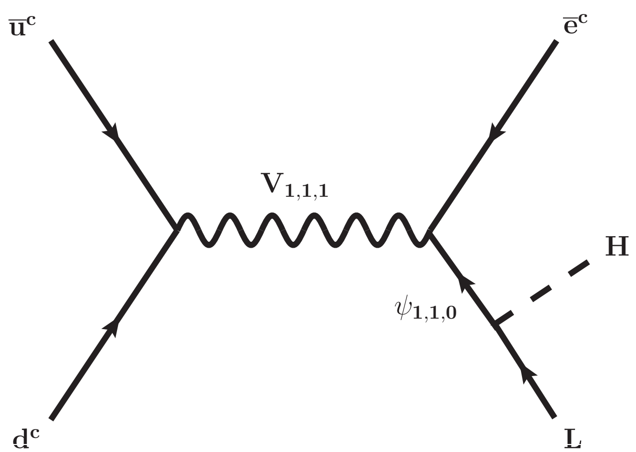
In left-right symmetric extension of SM:

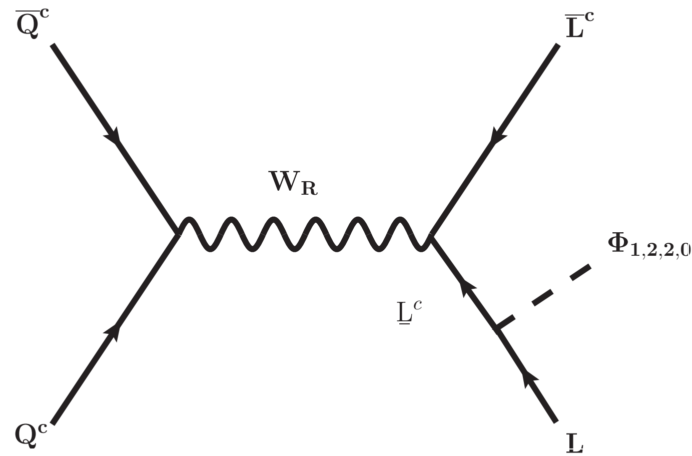


$d = 7$ versus $d = 9$ operator

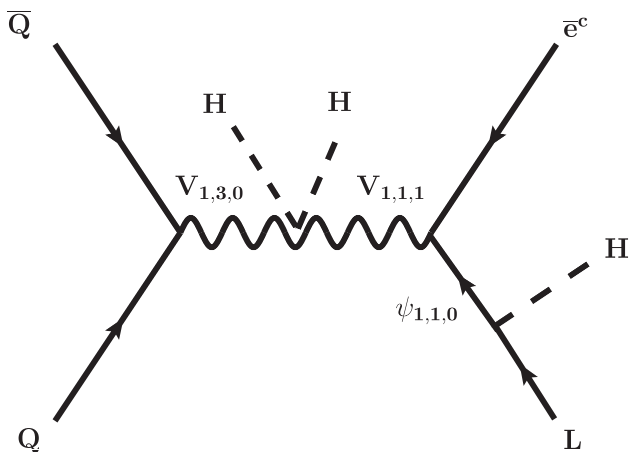
Another example, $(\mathcal{O}_8, \#14)$:

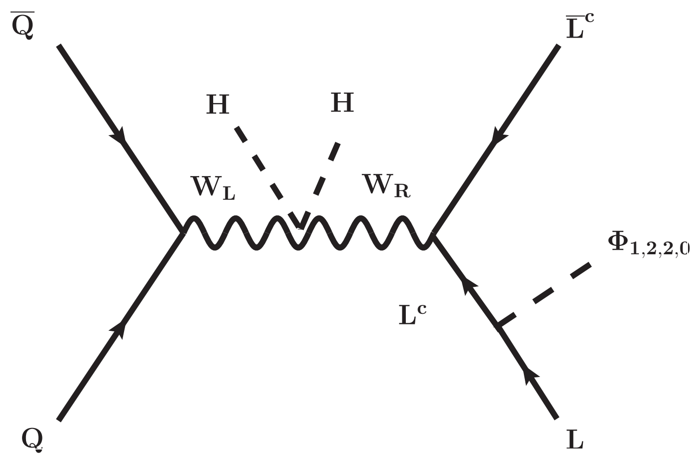
In left-right symmetric extension of SM:





Compare to $d = 9$ $\mathcal{O}_7$ decomposition:

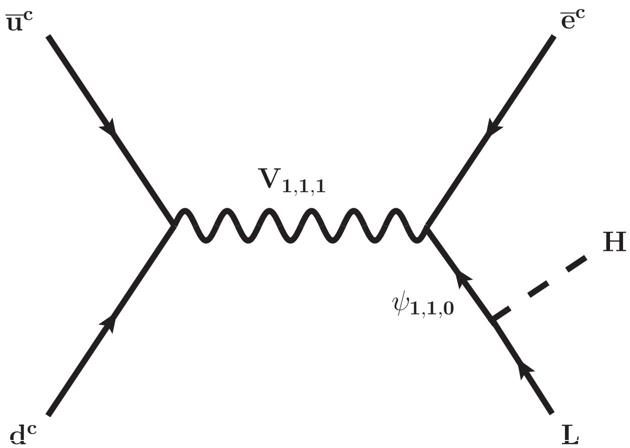


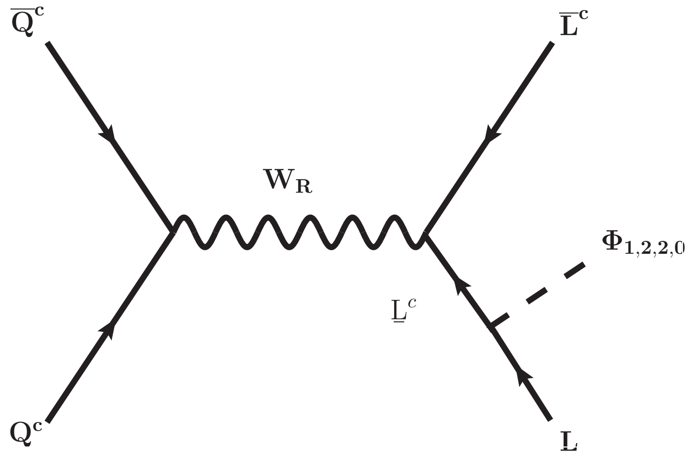


$d = 7$ versus $d = 9$ operator

Another example, $(\mathcal{O}_8, \#14)$:

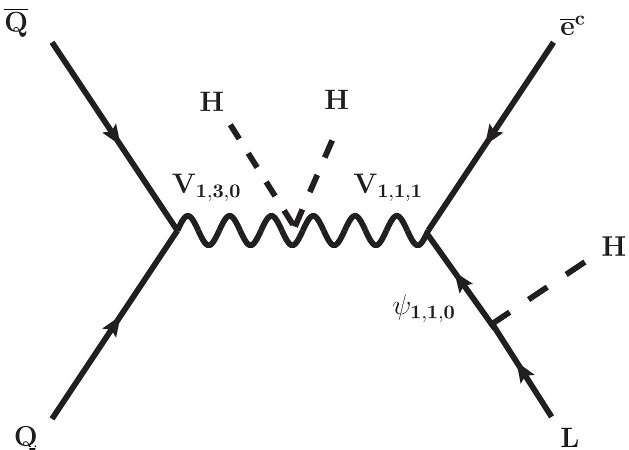
In left-right symmetric extension of SM:

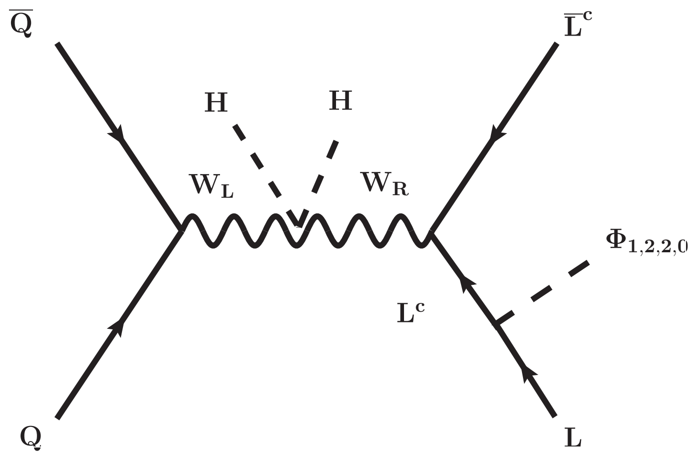




$\sim \langle \lambda \rangle$

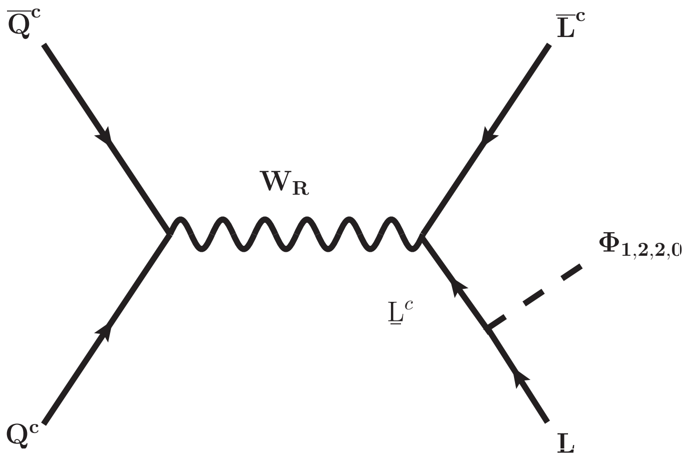
Compare to $d = 9$ $\mathcal{O}_7$ decomposition:



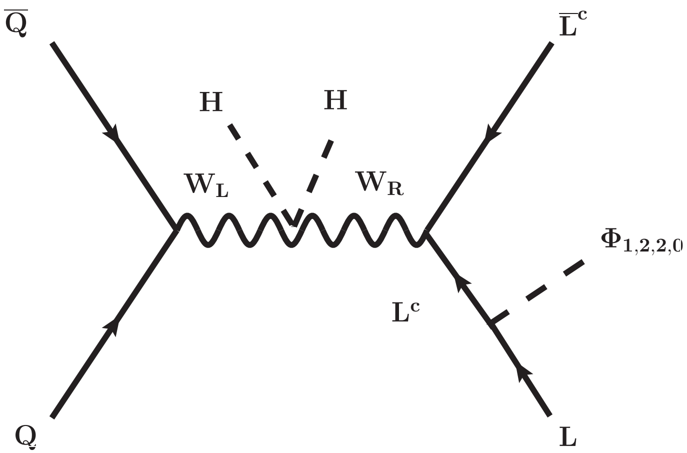


$\sim \langle \eta \rangle$

$d = 7$ *versus* $d = 9$ *operator*



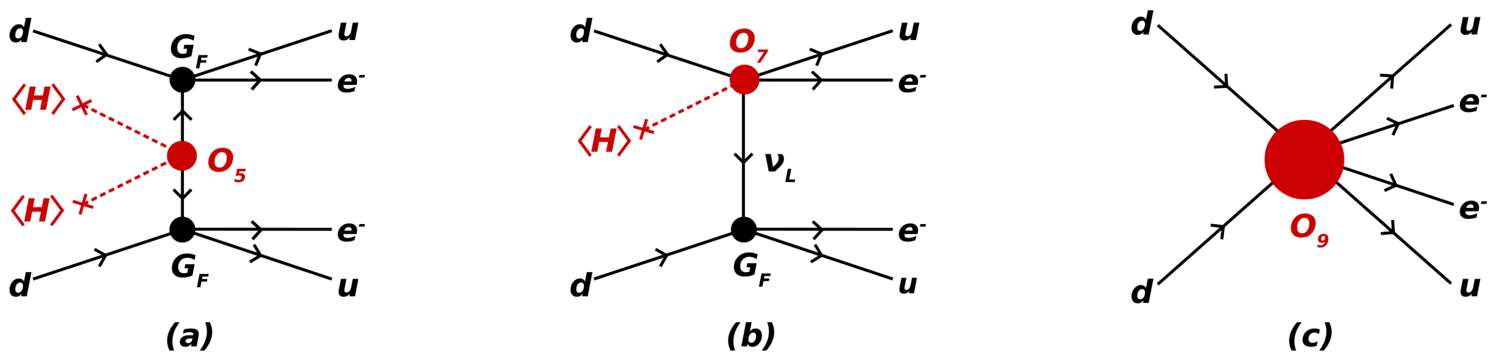
$$\sim \langle \lambda \rangle \propto \frac{g_R^2}{m_{W_R}^2} \times \frac{Y v_{SM}}{m_N} \longrightarrow \frac{v_{SM}}{\Lambda^3}$$



$$\sim \langle \eta \rangle \propto \frac{g_L^2 g_R^2 v_{SM}^2}{m_{W_R}^2 m_{W_L}^2} \times \frac{Y v_{SM}}{m_N} \longrightarrow \frac{v_{SM}}{\Lambda^3}$$

Conclusions ???

⇒ What is the scale of LNV?



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