Particle Theory of $0\nu\beta\beta$ decay

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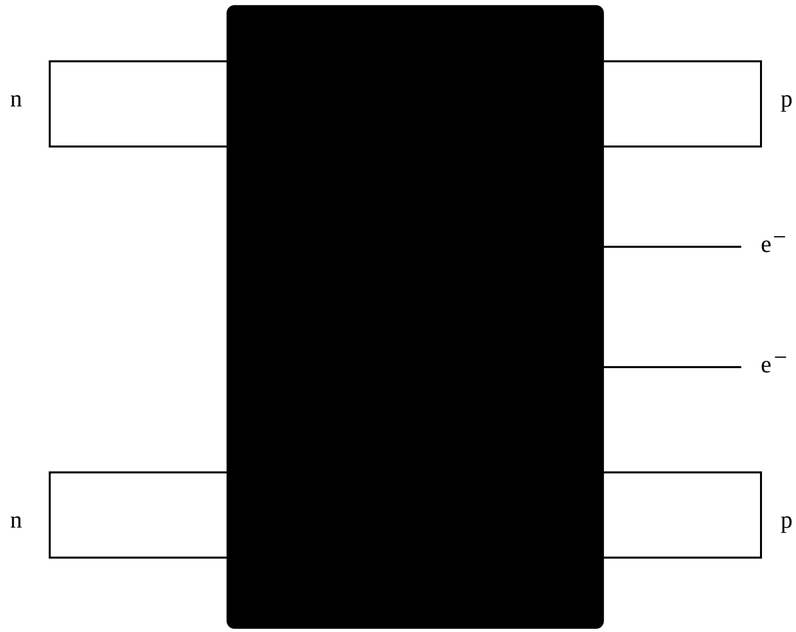
Introduction

Black box!

Experimentalist observes:



Neutrinoless double beta decay is:

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

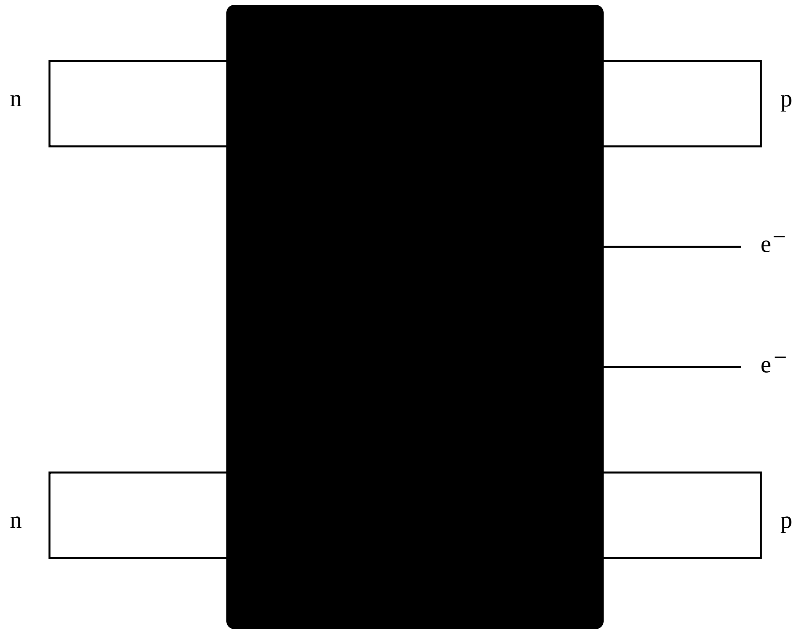
(no missing energy)

Lepton number is violated:

$\Delta L = 2$!

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

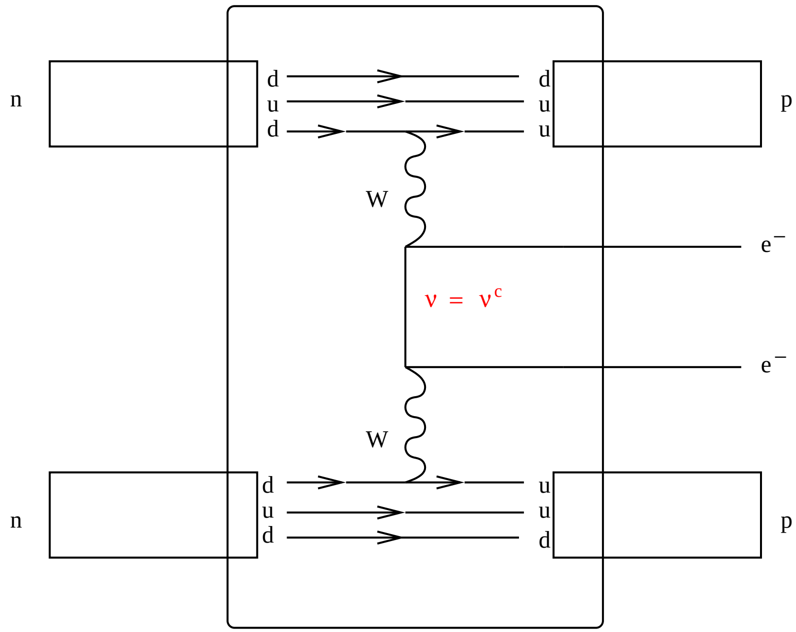
ϵ_i - particle physics

Many, many possible contributions:

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

Mass mechanism

Experimentalist observes:



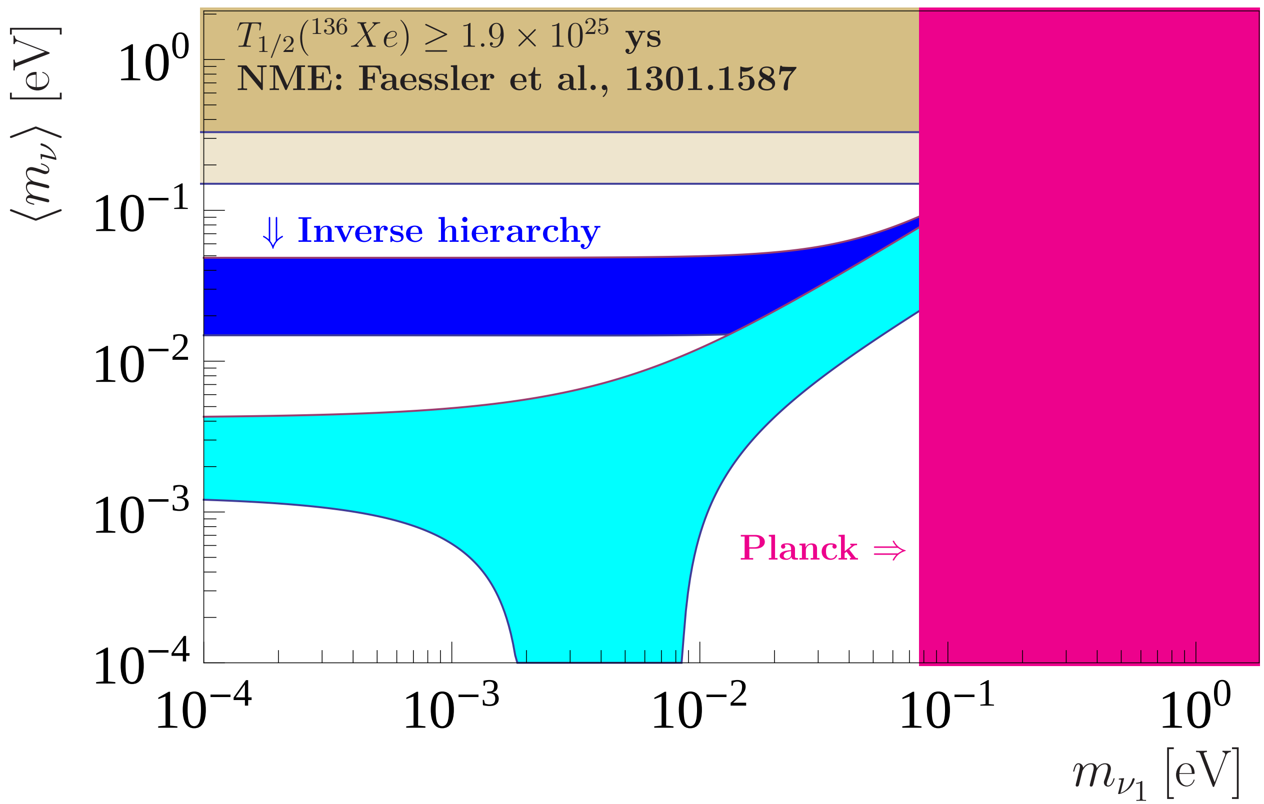
Neutrino propagator:

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

"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 2015



Global fit data from:

Forero, Tortola & Valle; arXiv:1405.7540

all ranges at 1 σ c.l.

⇒ Planck - limits from cosmological data

⇒ $T_{1/2}(^{136}Xe)$ - limit from KamLAND-Zen

$\mathcal{III}.$

$0\nu\beta\beta$ decay,

LNV operators and m_ν

Theoretical expectation?

Majorana Neutrino mass

$$m_\nu \simeq \frac{(Yv)^2}{\Lambda}.$$

Weinberg, 1979

Smallness of neutrino mass
can be "explained" by:

Minkowski, 1977

$\Rightarrow$ High scale: Large Λ
"classical" seesaw

Yanagida, 1979
Gell-Mann, Ramond, Slansky, 1979
Mohapatra, Senjanovic, 1980
Schechter, Valle, 1980
$\ldots, \ldots, \ldots$
Foot et al., 1988

Theoretical expectation?

Majorana Neutrino mass generated from an n-loop dimension d diagram:

$$m_\nu \simeq \frac{(Yv)^2}{\Lambda} \cdot \epsilon \cdot \left(\frac{Y^2}{16\pi^2}\right)^n \cdot \left(\frac{Yv}{\Lambda}\right)^{d-5}$$

Smallness of neutrino mass can be "explained" by:

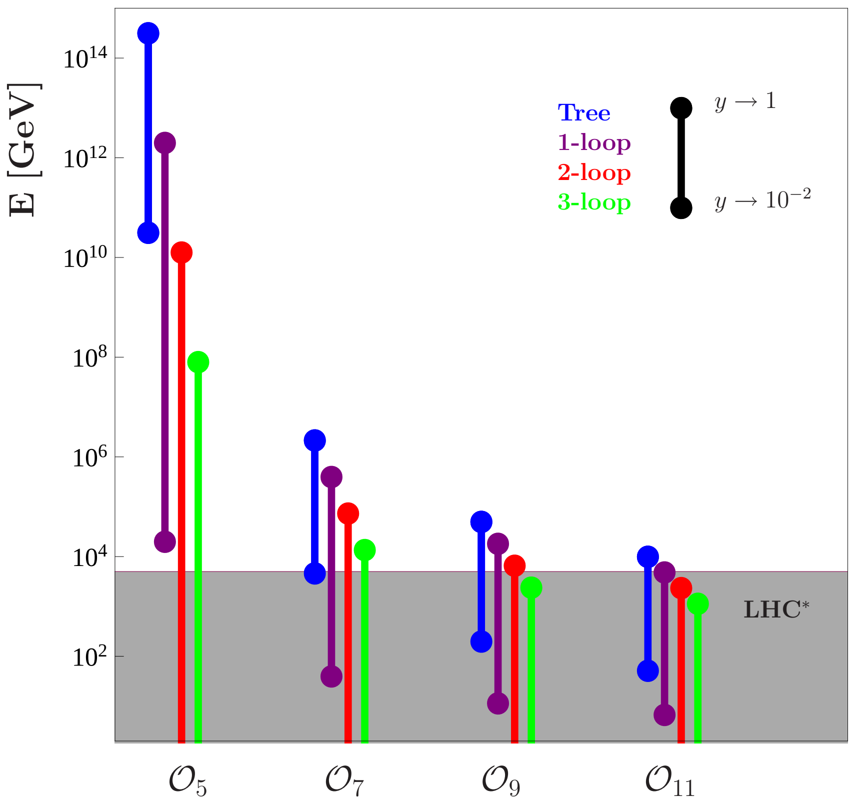
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

$\Rightarrow$ Loop factor: $n \geq 1$
+ "smallish" $Y \sim \mathcal{O}(10^{-3} - 10^{-1})$

$\Rightarrow$ Higher order: $d = 7, 9, 11$

$\Rightarrow$ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

$\cdots$ or combination thereof



$\Delta L = 2$ operators

$d = 5$: Weinberg, 1979

$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$ One d=5

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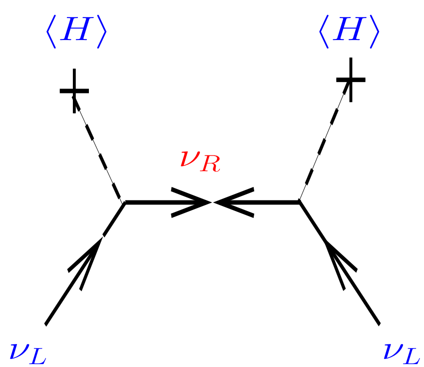
One d=5

Example realization, seesaw type-I:



$$\Lambda \simeq M_{\nu_{R_k}}$$

$$c_{ij} \propto Y^{\nu}_{ik} Y^{\nu}_{jk}$$

$\Delta L = 2$ operators

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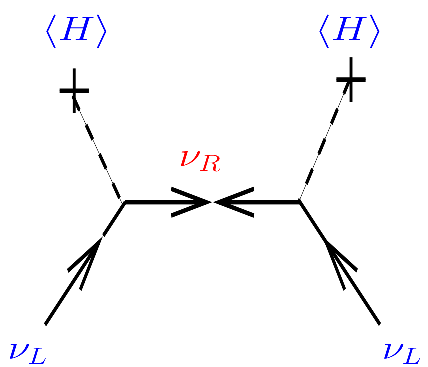

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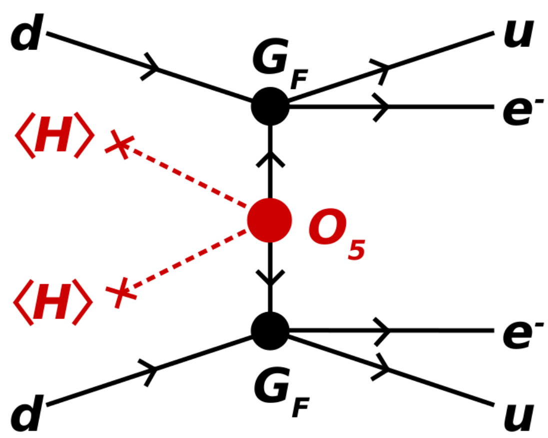
$0\nu\beta\beta$ decay:



(a)

Mass mechanism!

$\Delta L = 2$ operators

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One d=5

$d = 7$: Babu & Leung, 2001

de Gouvea & Jenkins, 2007

$$\mathcal{O}_2 \propto LLLe^c H$$

4 (+1) $d = 7$

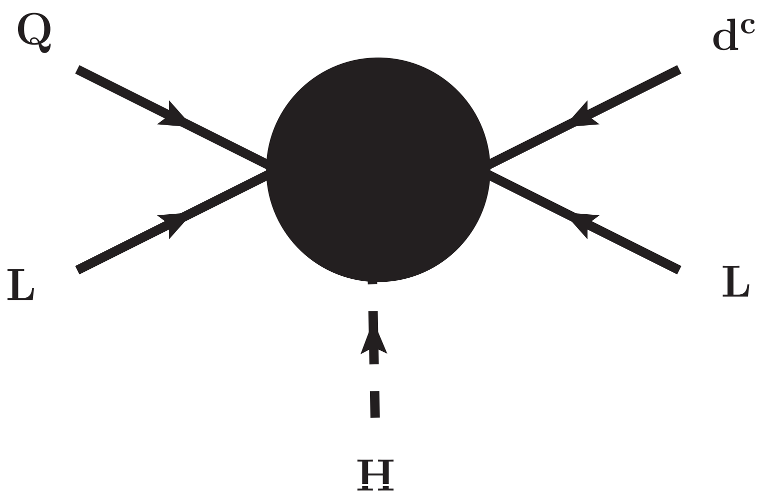
$$\mathcal{O}_3 \propto LLQd^c H \qquad \mathcal{O} \propto (LH)(LH)(H_u H_d)$$

$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^c H$$

$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^c d^c H$$

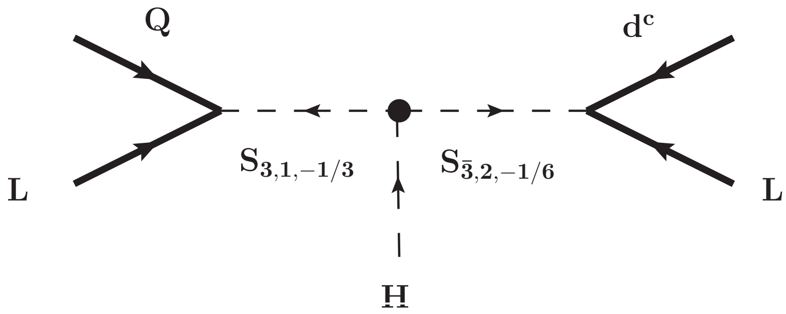
Example $d = 7$: $LLQd^cH$

Graphically:



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

Again, more than one realization.
Example:



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

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

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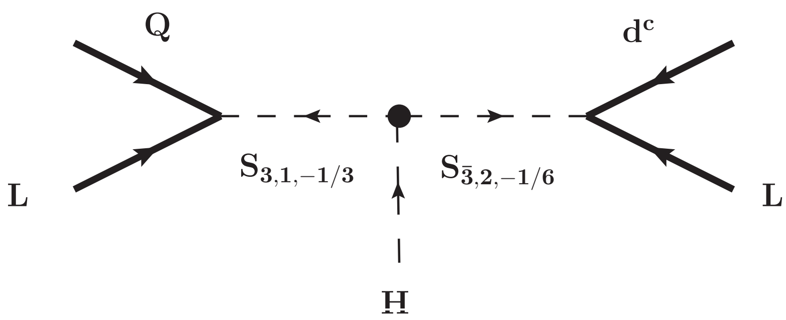

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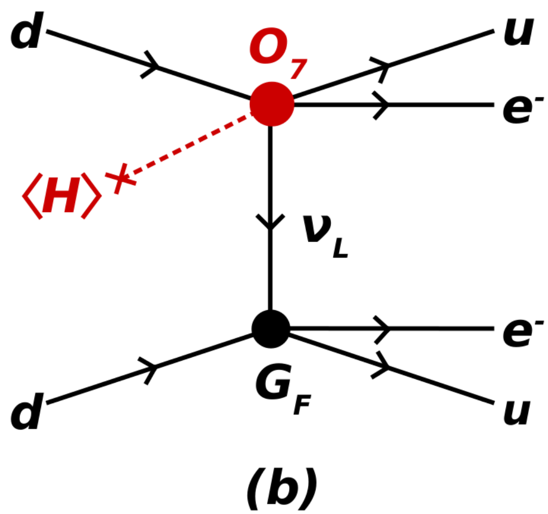

Long range contribution!

$$\mathcal{A} \propto \frac{\mu \times \langle H^0 \rangle}{m^2_{3,1,1/3} m^2_{3,2,1/6}}$$

$$\propto \frac{v}{\Lambda^3}$$

No helicity suppression!

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

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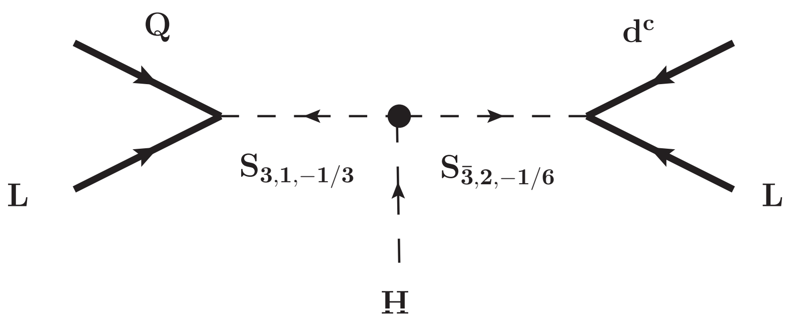

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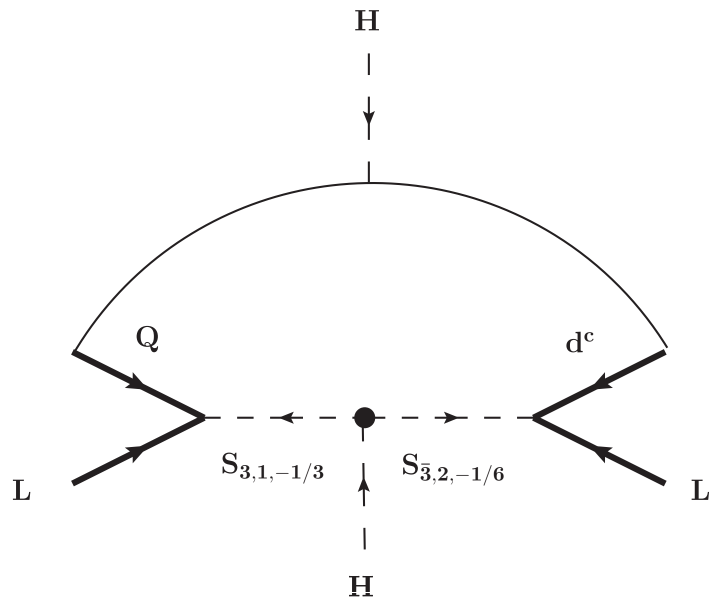
1-loop neutrino mass:



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

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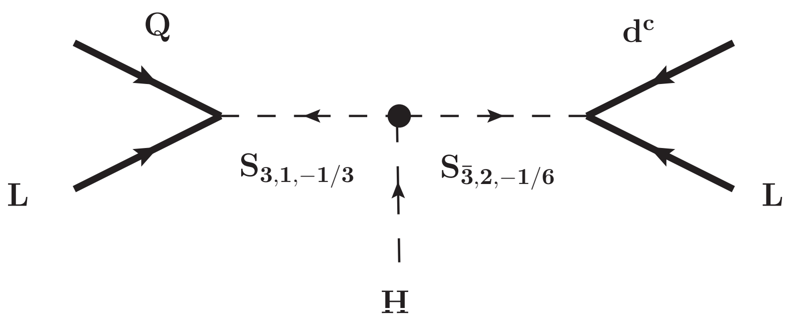
Example:



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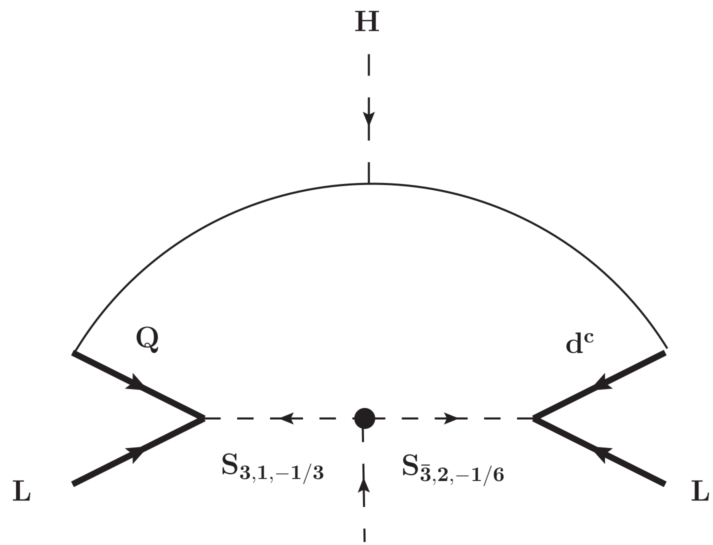
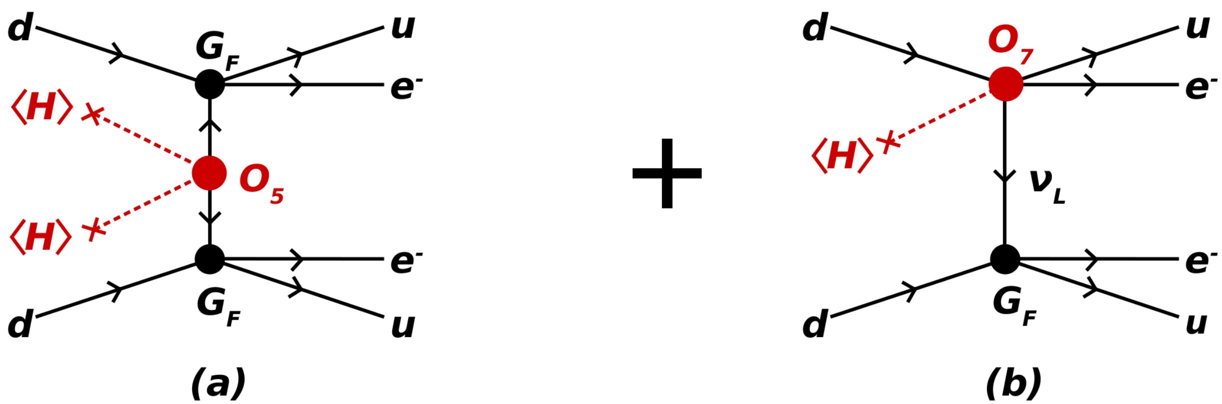


$0\nu\beta\beta$ decay has both contributions:



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$$\mathcal{O} \propto (LH)(LH)(H_u H_d)$$

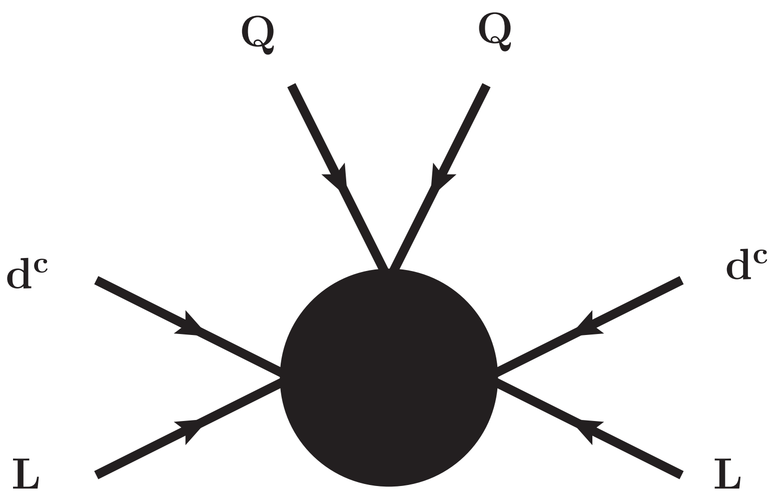
$d = 9$: many $d = 9$ and $d = 11$ ops

$$\mathcal{O}_5 \propto LLQd^c HHH^\dagger$$
$$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^c HH^\dagger H$$
$$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$$
$$\ldots\ldots$$

$$\mathcal{O}_9 \propto LLLe^c Le^c$$
$$\mathcal{O}_{10} \propto LLLe^c Qd^c$$
$$\mathcal{O}_{11} \propto LLQd^c Qd^c$$
$$\ldots\ldots$$

Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:



Many, many realizations ...

Example $d = 9$: $LLQd^cQd^c$

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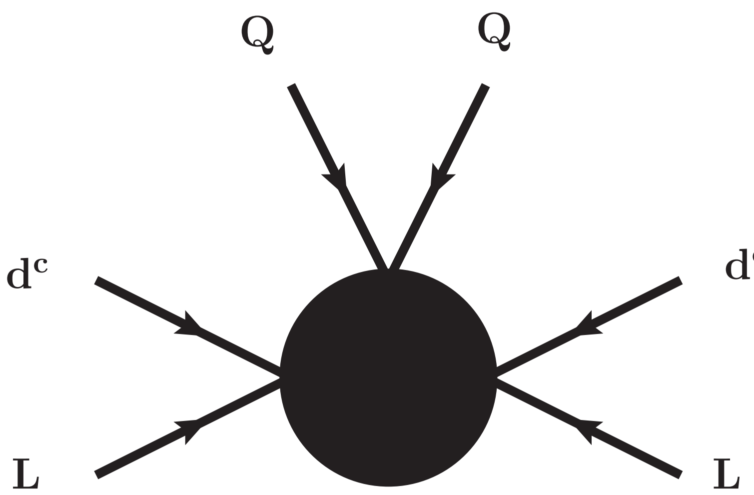
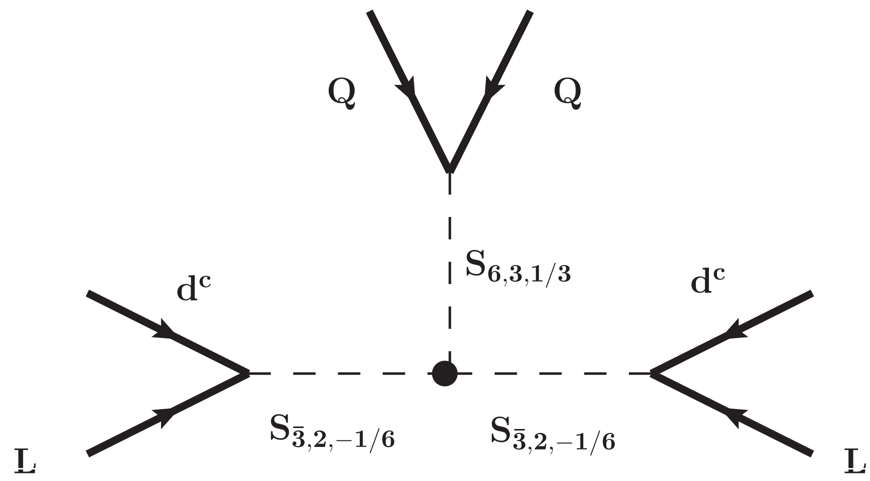


Many, many realizations ...
One example:



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

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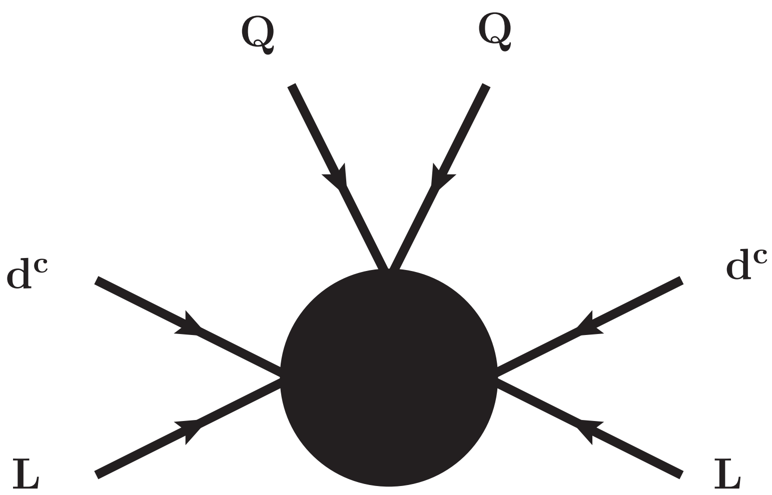

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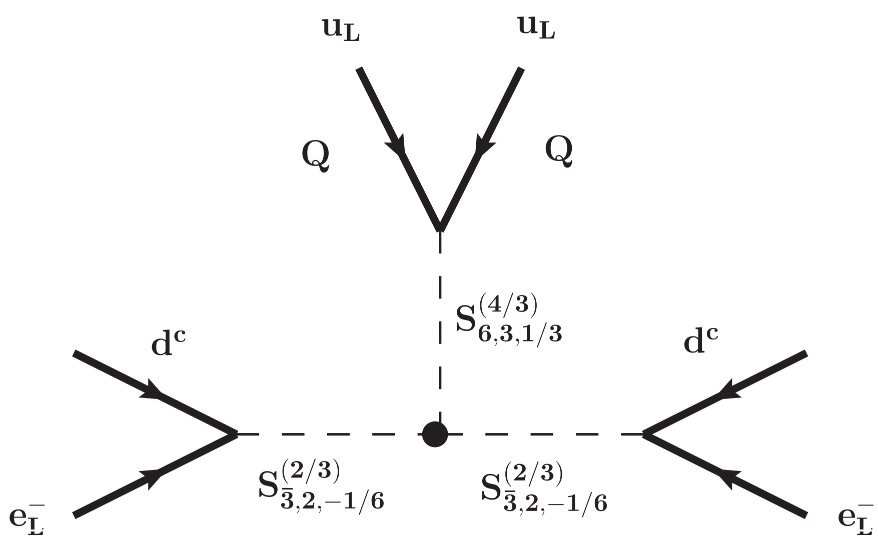


$S_{6,3,1/3}$ - triplet diquark

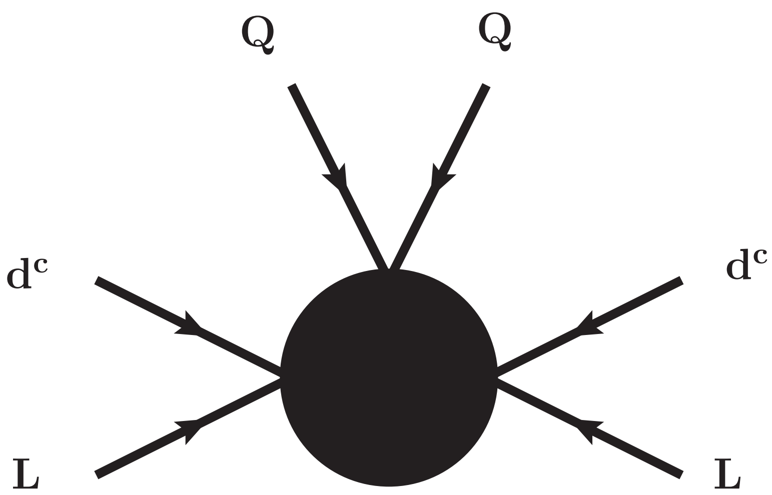
$S_{3,2,1/6}$ - doublet leptoquark

$0\nu\beta\beta$ decay without neutrino!

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

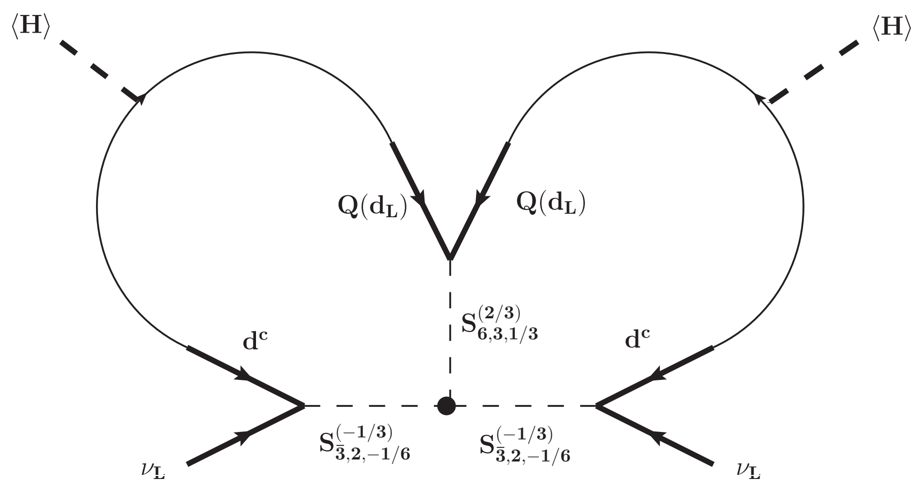
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:



Many, many realizations ...

One example:



$S_{6,3,1/3}$ - triplet diquark

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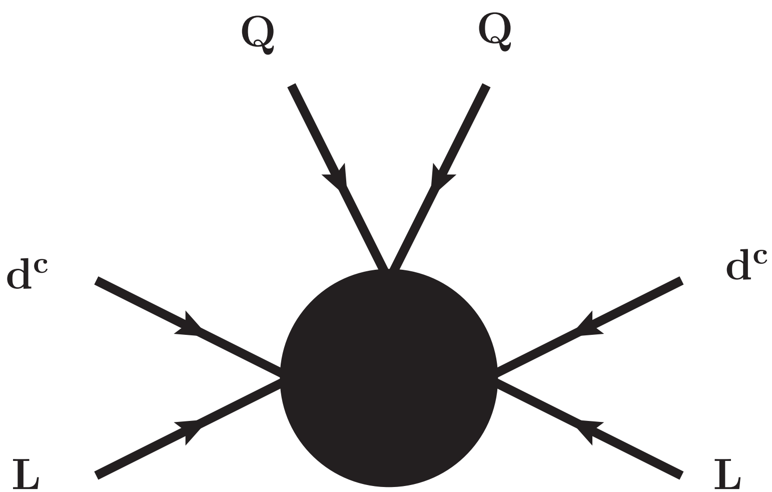
2-loop neutrino mass!

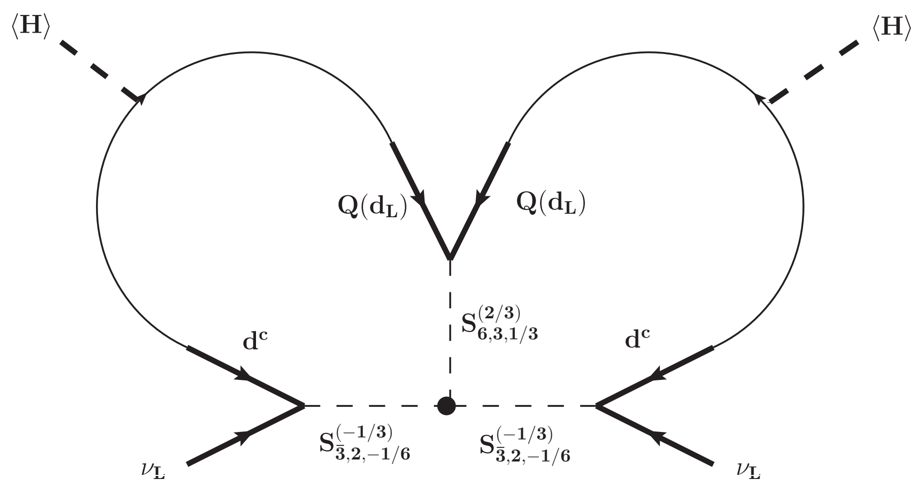
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:

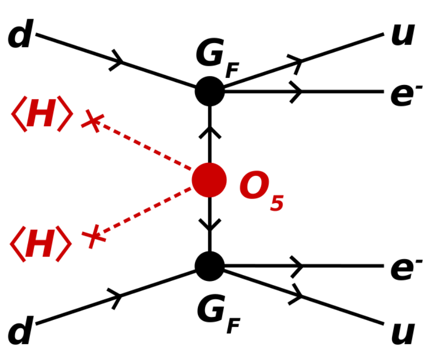


Many, many realizations ...

One example:

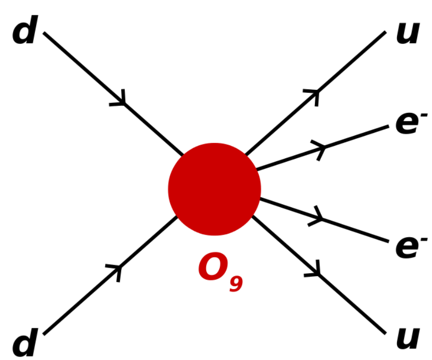


Again, $0\nu\beta\beta$ decay has two contributions:



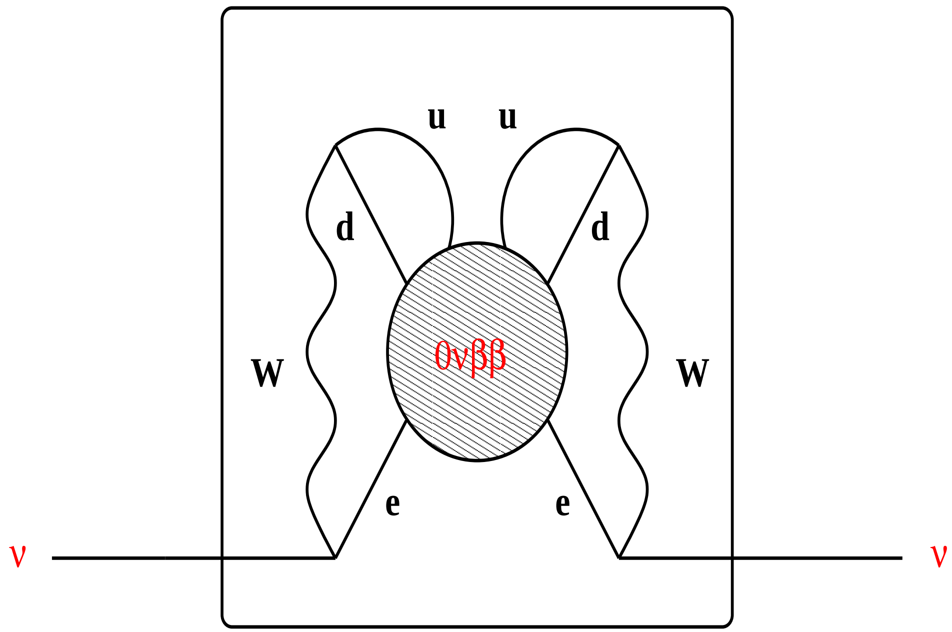
(a)

$+$



(c)

Black Box Theorem



Schechter & Valle, PRD 1982

Takasugi, PLB 1984

If $0\nu\beta\beta$
is observed
the neutrino is a
Majorana particle!

$\Rightarrow$ 4-loop "butterfly" diagram: $m_\nu \sim 10^{-24}$ eV — Duerr et al 2011

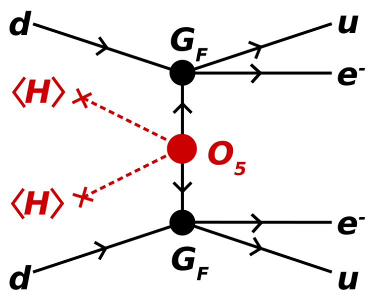
$\Rightarrow$ Tree-level, 1-loop, $\cdots$ 4-loop possible

$\Rightarrow$ Rule of thumb: — Helo et al., 2015

- $\longrightarrow$ Models with tree-level, 1-loop m_ν - mass mechanism dominates
- $\longrightarrow$ Models with 2-loop, 3-loop m_ν - mass mechanism $\sim$ SR
- $\longrightarrow$ Models with 4-loop m_ν - SR dominates

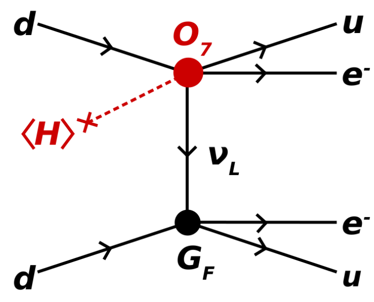
Distinguish mechanisms?

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



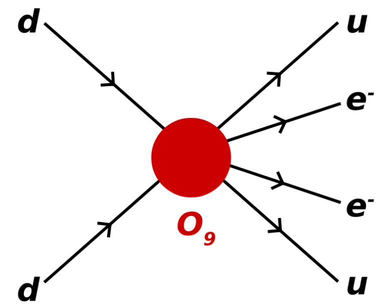
(a)

Mass mechanism



(b)

"long-range"



(c)

"short-range"

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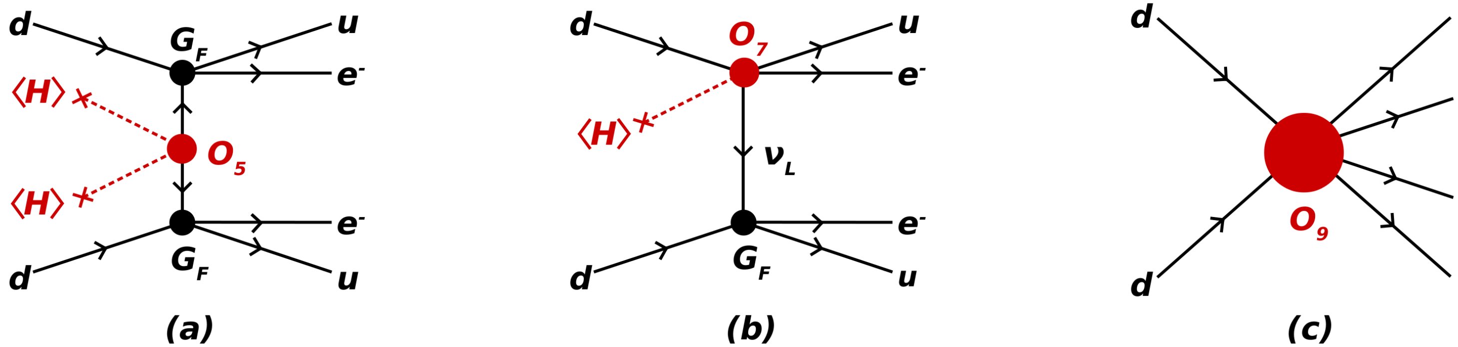
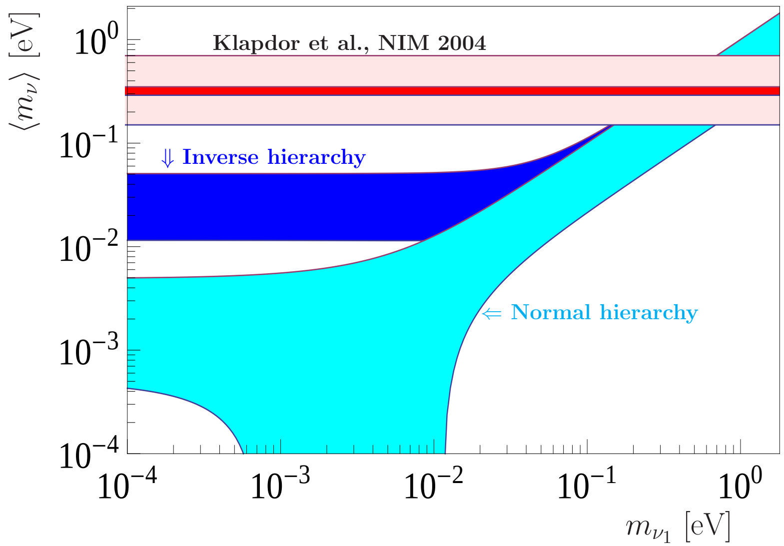


Mass mechanism — "long-range" — "short-range"

Compare with other experiments:
Cosmology
KATRIN?



Red line:

Claim for $T_{1/2}^{0\nu\beta\beta}(^{76}Ge) = (1.19^{+0.37}_{-0.23}) \times 10^{25}$ ys

Distinguish mechanisms?

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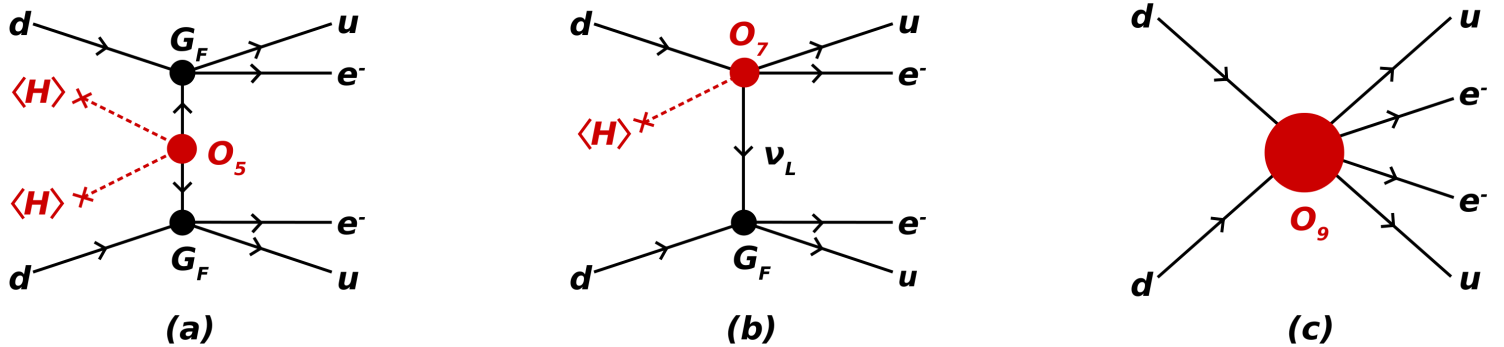

Mass mechanism | "long-range" | "short-range"

Compare with other experiments:
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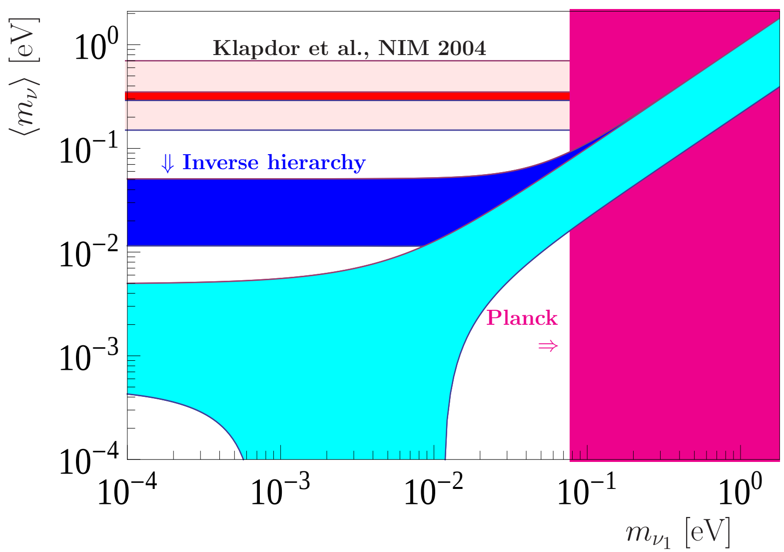

Planck + BAO:

NO overlap with allowed region of $\langle m_\nu \rangle$!

Distinguish mechanisms?

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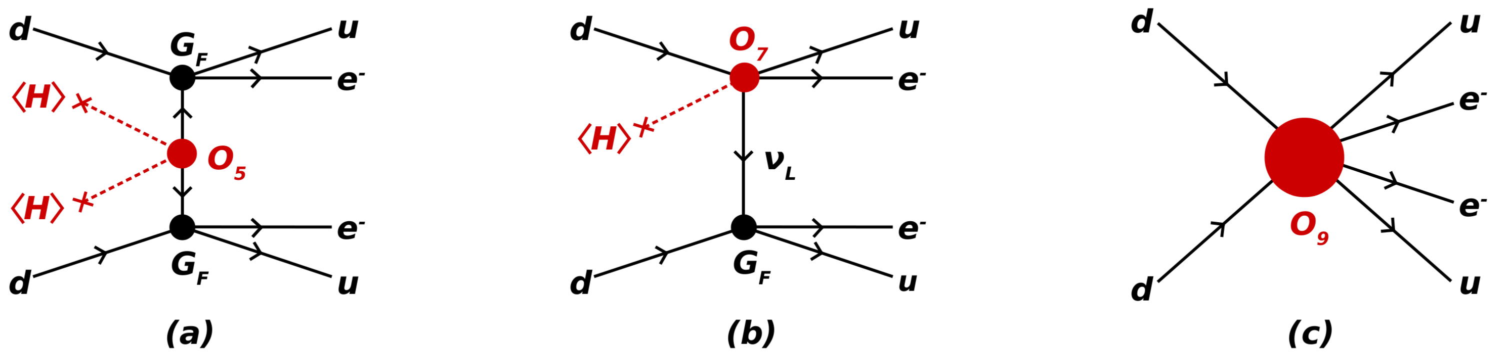

Mass mechanism | "long-range" | "short-range"

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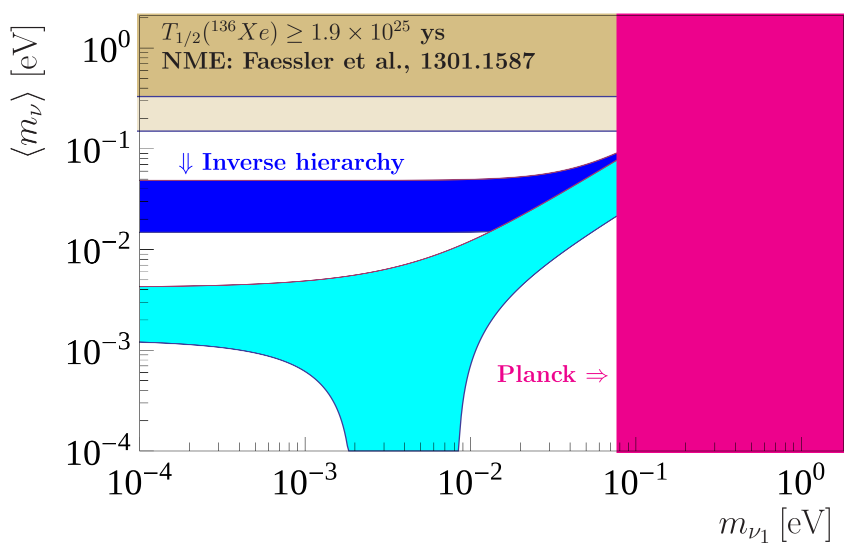

Claim now ruled out by:
GERDA
EXO-200
KamLAND-Zen

Distinguish mechanisms?

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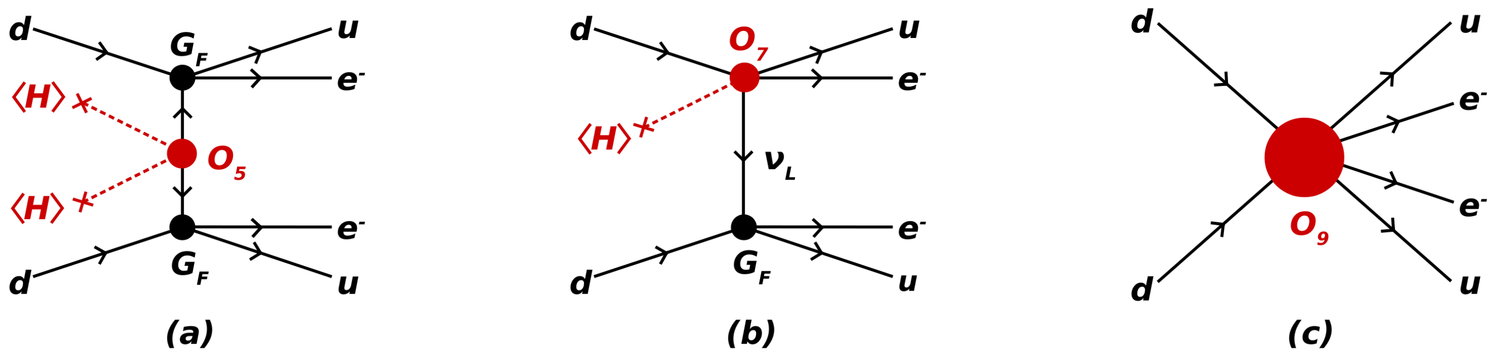
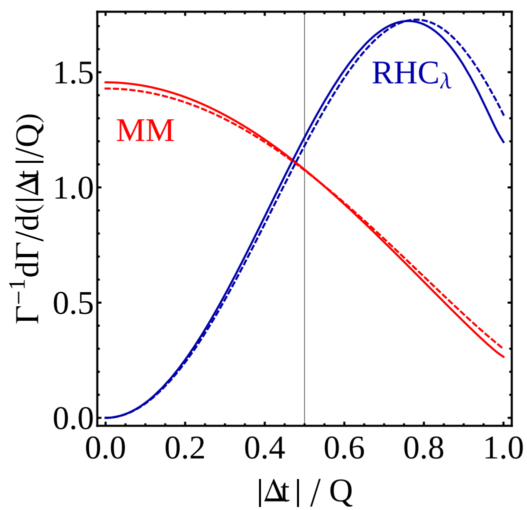


Mass mechanism | "long-range" | "short-range"

Angular correlations
$0\nu\beta^+/EC$ decays
LHC?

SuperNEMO
Arnold et al., 2010



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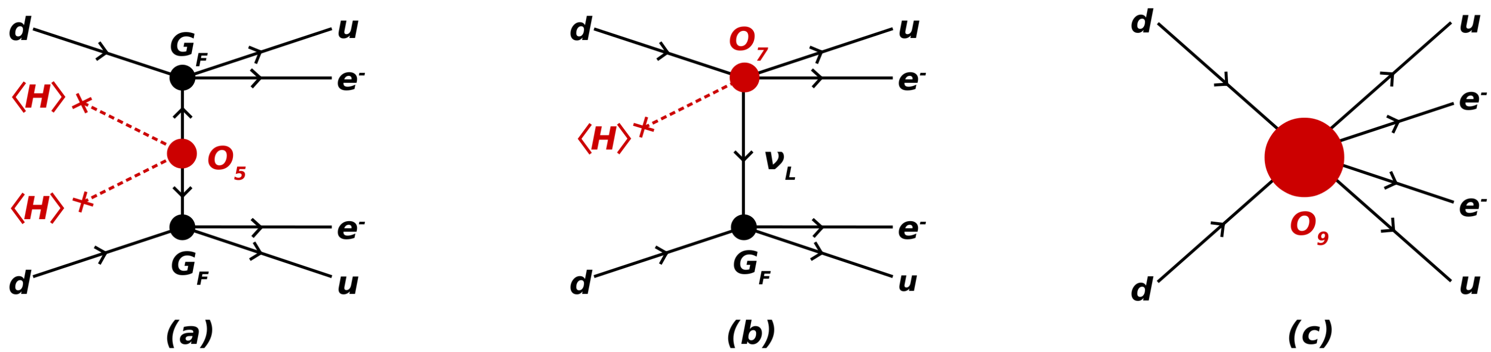
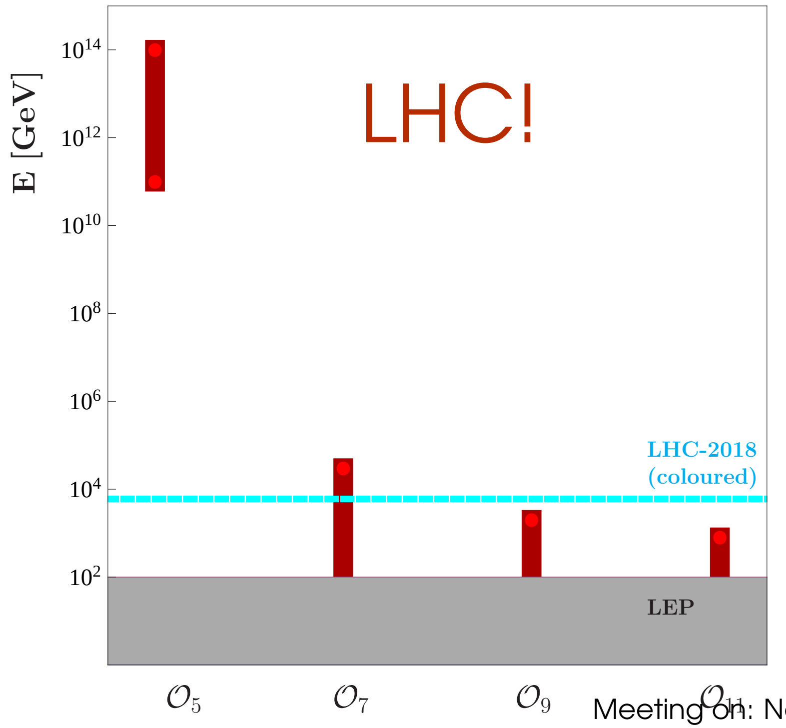




Estimate $0\nu\beta\beta$ sensitivity for different operators:

LHC tests $\mathcal{O}_9$ and $\mathcal{O}_{11}$

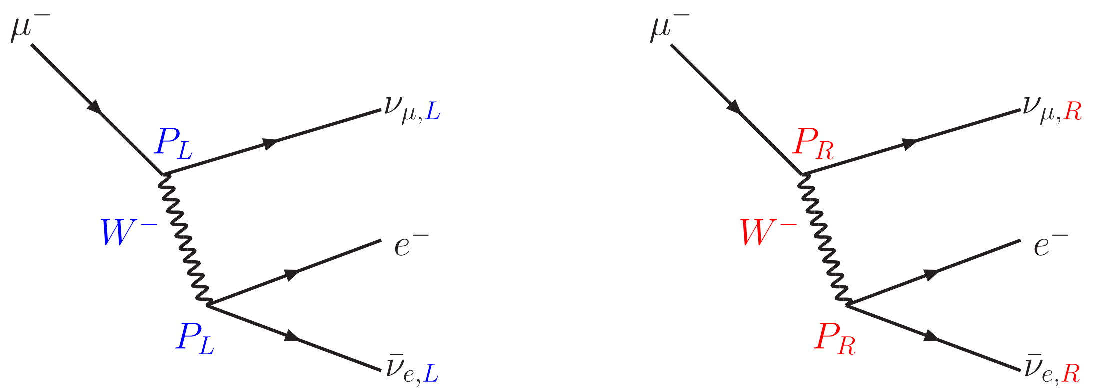
and partially $\mathcal{O}_7$

$\mathcal{III}.$

$0\nu\beta\beta$ decay, LNV and LHC

Left-right symmetry

Motivation:



$\sim 1/m^2_{W_L} \to G_F$ $\qquad$ $\sim 1/m^2_{W_R}$

Extend standard model gauge group to:

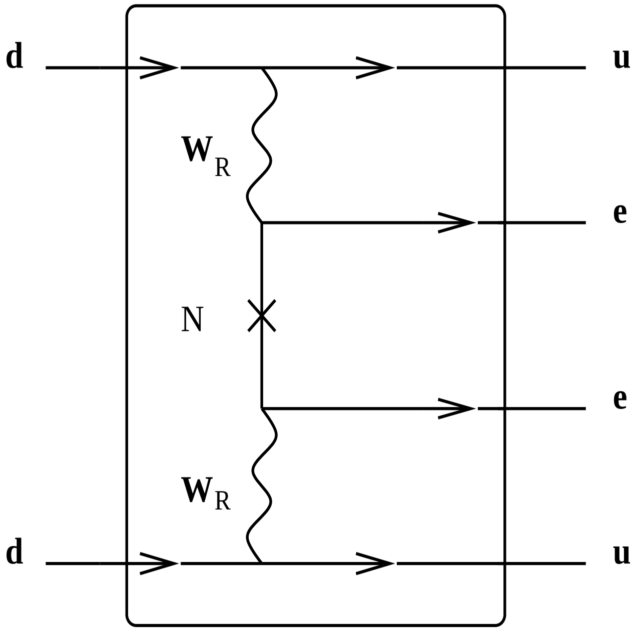
$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

If $m_{W_R} \gg m_{W_L}$ - interactions mostly left-handed

$\Rightarrow$ LR symmetry implies: $L \leftrightarrow L^c$ - ν_R is part of theory!
$\Rightarrow$ Seesaw mechanism included in theory

W_R and $0\nu\beta\beta$ decay

The experimentalist sees:



$\sim 1/m^2_{W_R}$

$\sim 1/m_N$

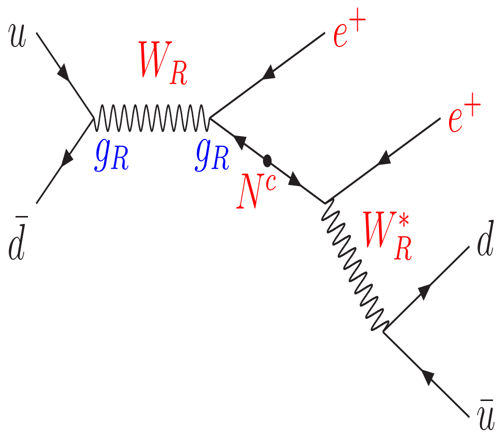
$\sim 1/m^2_{W_R}$

If $m_N \rightarrow \infty$
limit on
$m_{W_R} \rightarrow 0$

With $T^{0\nu\beta\beta}_{1/2}(^{136}Xe) \geq 1.6 \times 10^{25}$ ys:

$$m_{W_R} \gtrsim 1.3 \left(\frac{\langle m_N \rangle}{[1\text{TeV}]} \right)^{-1/4} \text{ TeV}$$

Example: W_R @ LHC

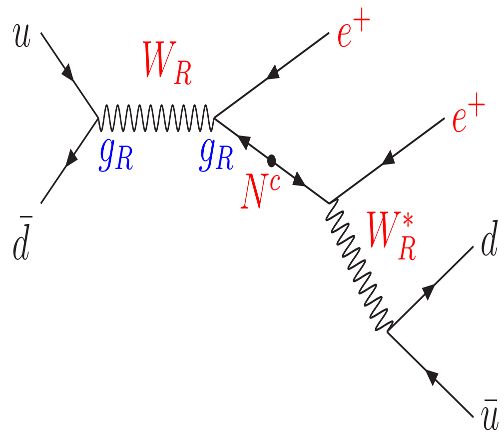


Keung & Senjanovic, 1983

Signal:

Same-sign and opposite-sign di-lepton + jets, **no** $\not{E}_T$

Example: W_R @ LHC



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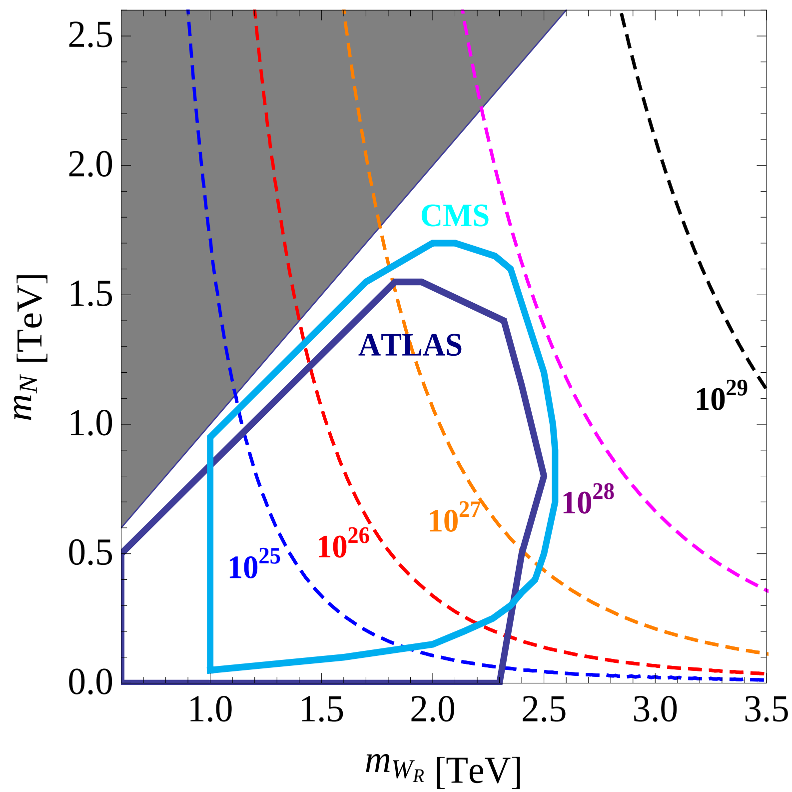


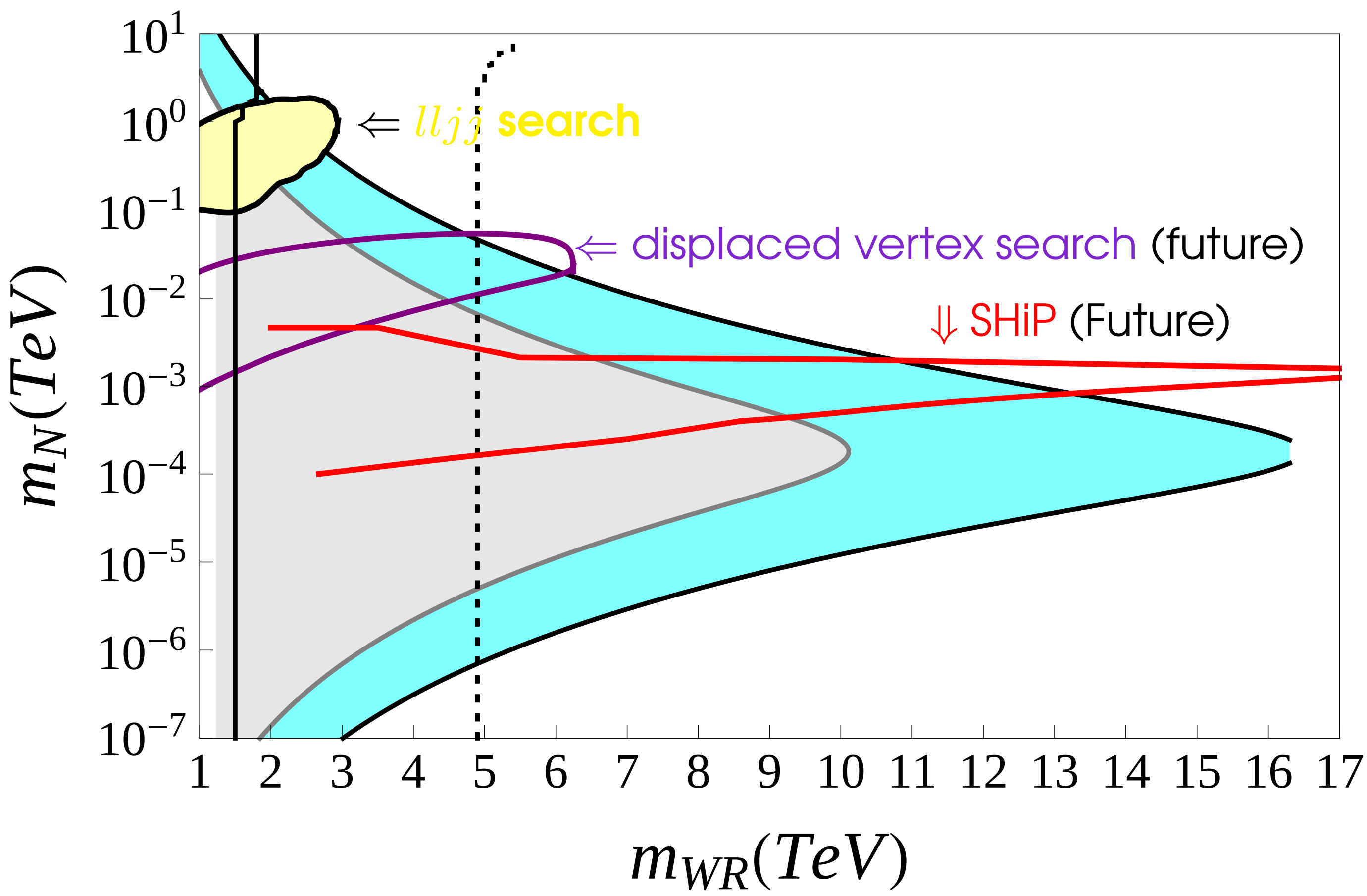
CMS (and ATLAS) with $\sqrt{s} = 8$ TeV:

Non-observation gives stringent limits on short-range W_R diagrams for $0\nu\beta\beta$ decay.

Assumes: $g_R = g_L$!

Dijet and $0\nu\beta\beta$ decay

Absence of $pp \to W_R \to jj$ gives limit on $0\nu\beta\beta$:



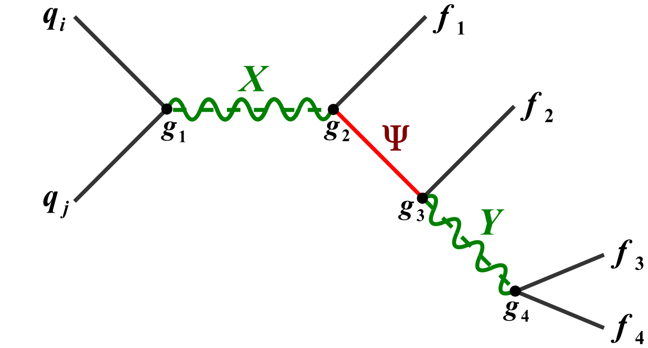
Helo & Hirsch
1509.00423

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

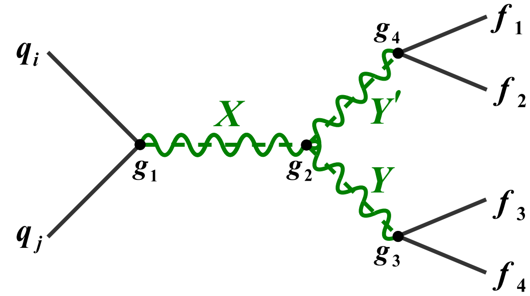
cyan:
$T^{0\nu\beta\beta}_{1/2} \gtrsim 10^{27}$ ys

$\Rightarrow$ **full (dashed) current limits (future sensitivity) for dijet data**

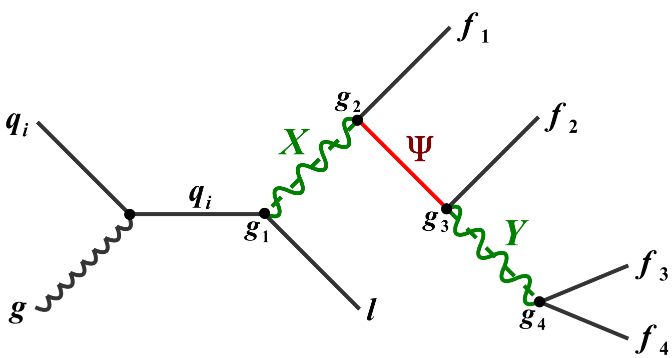
LNV @ LHC



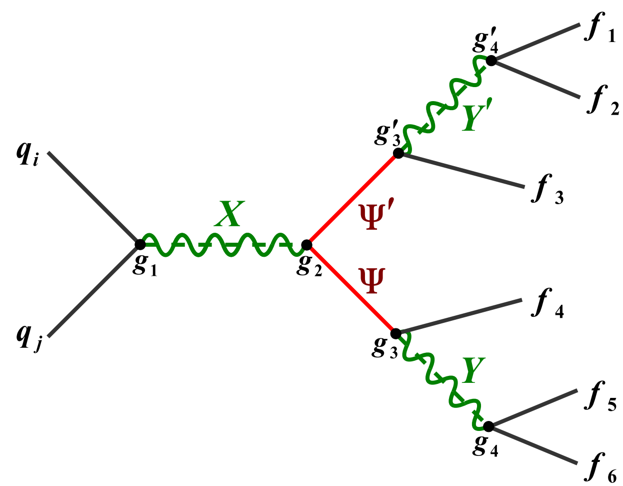
q_i
q_j
X
Ψ
Y
g_1
g_2
g_3
g_4
f_1
f_2
f_3
f_4



q_i
q_j
X
Y'
Y
g_1
g_2
g_3
g_4
f_1
f_2
f_3
f_4

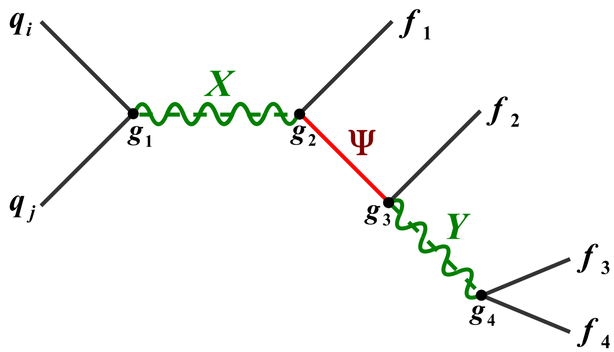


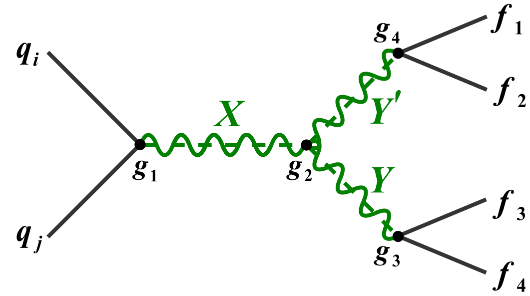
q_i
g
q_i
l
X
Ψ
Y
g_1
g_2
g_3
g_4
f_1
f_2
f_3
f_4



q_i
q_j
X
Ψ'
Ψ
Y'
Y
g_1
g_2
g'_3
g'_4
g_3
g_4
f_1
f_2
f_3
f_4
f_5
f_6

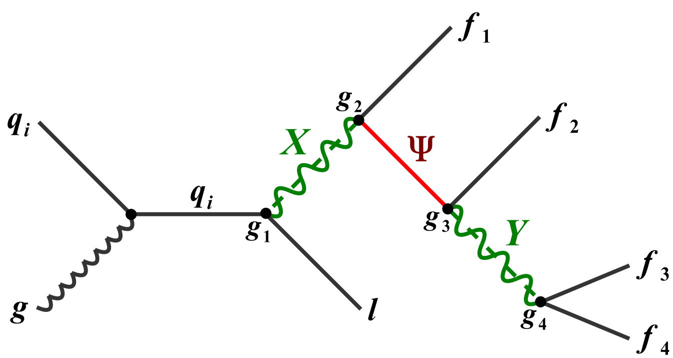
LNV @ LHC

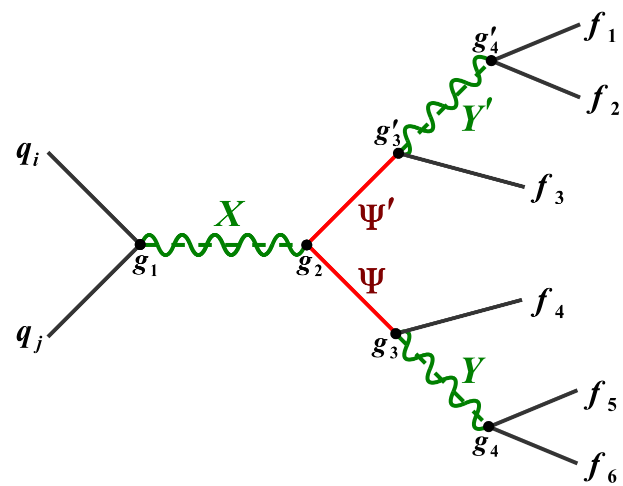




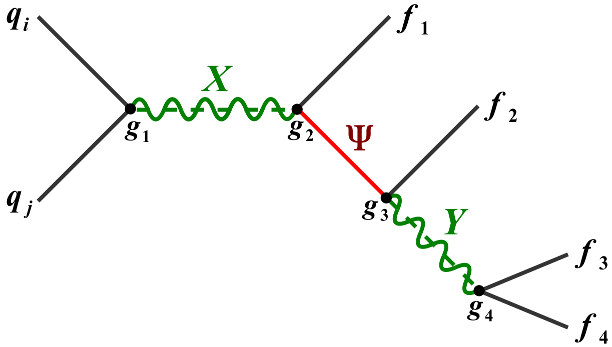
Example:

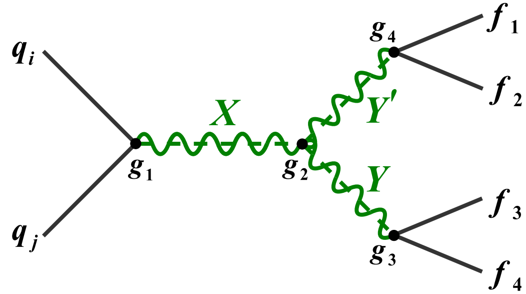
$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$





LNV @ LHC



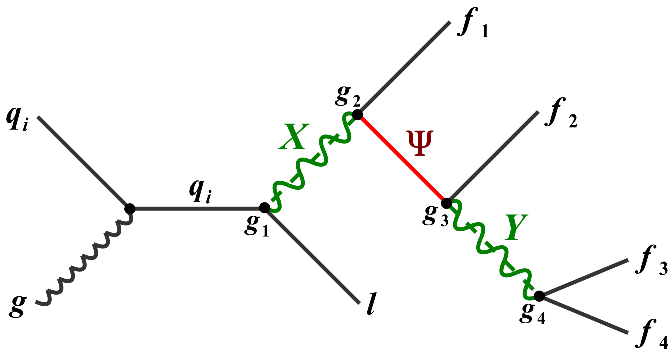


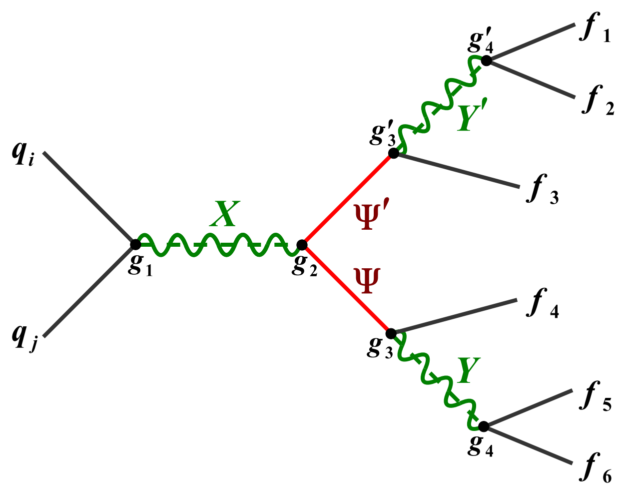
Example:

$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$

Example:

$uu \to S_{6,3,1/3} \to 2S_{3,2,1/6} \to l^+ l^+ jj$



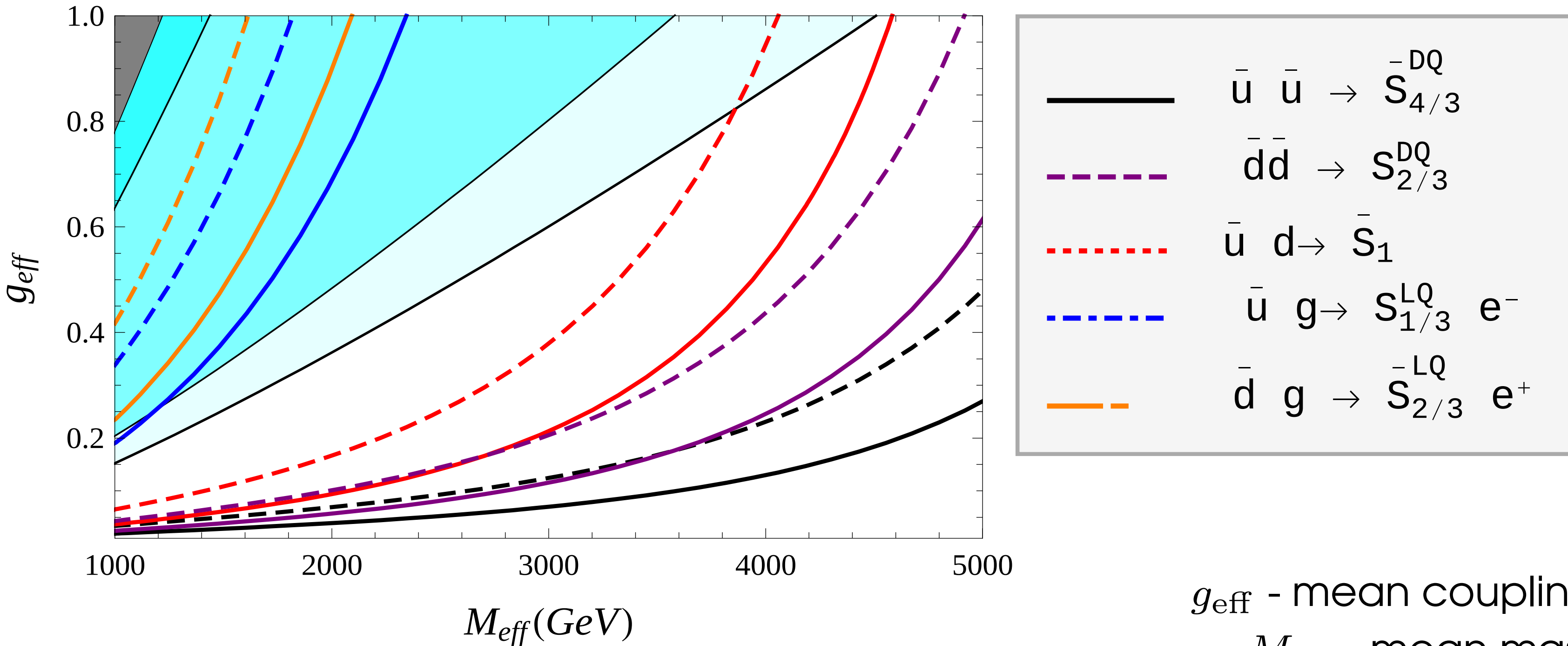


$ug \to S_{3,1,1/3} + l^+ \to l^+ l^+ jjj$

$q\bar{q} \to g \to \psi_{6,2,1/6} + \bar{\psi}_{6,2,1/6} \to l^+ l^+ jjjj$

$0\nu\beta\beta$ *and LHC* ($\sqrt{s} = 14$ *TeV*)

J.C. Helo et al, PRD88 (2013)



$g_{\rm eff}$ - mean coupling

$M_{\rm eff}$ - mean mass

$\Rightarrow$ Assumed upper limit on $\sigma(pp \rightarrow X)$: 10^{-2} fb

$\Rightarrow$ $m_F = 1000$ GeV (realistic (?) case)

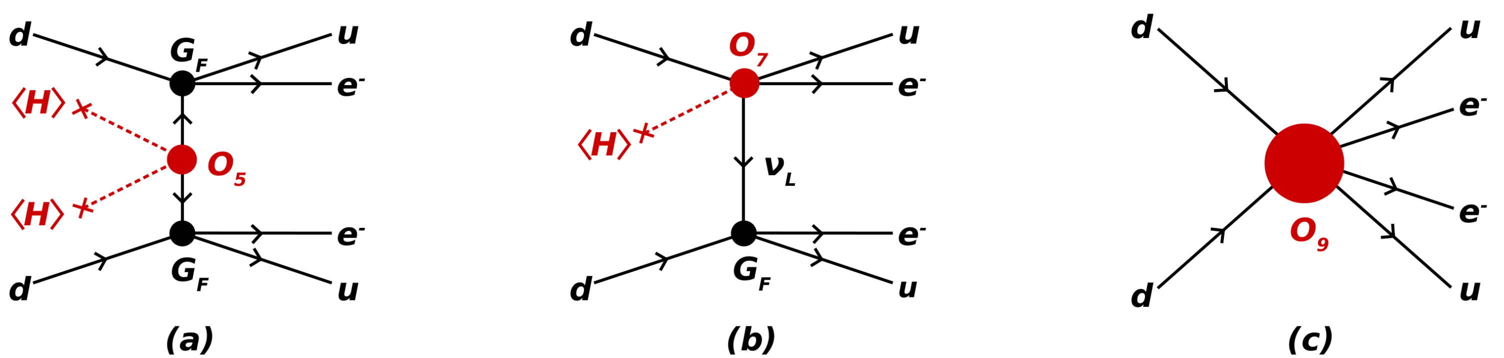
$\Rightarrow$ Full lines: Br$= 10^{-1}$, dashed lines Br$= 10^{-2}$

Conclusions

LNV & $0\nu\beta\beta$ decay:

$\Rightarrow$ Majorana neutrino mass and
$0\nu\beta\beta$ decay always related

$\Rightarrow$ What is the scale of LNV?



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

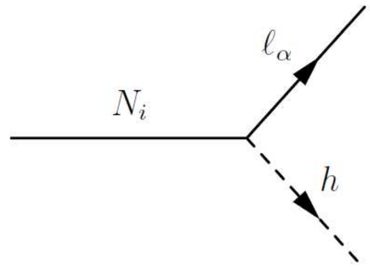
Backup slides

Leptogenesis, $0\nu\beta\beta$ and LHC

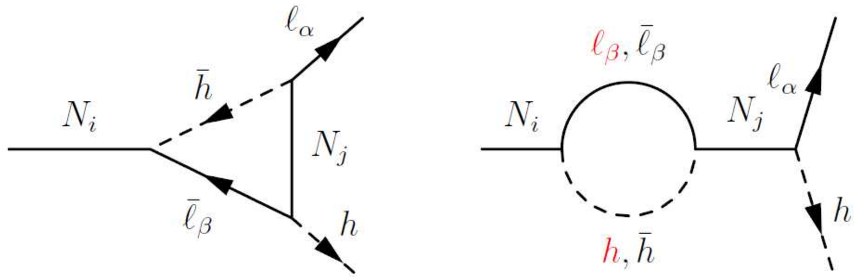
Leptogenesis

Sakharov's conditions:

(i) Baryon number violation
(ii) C and CP violation
(iii) departure from thermal equilibrium



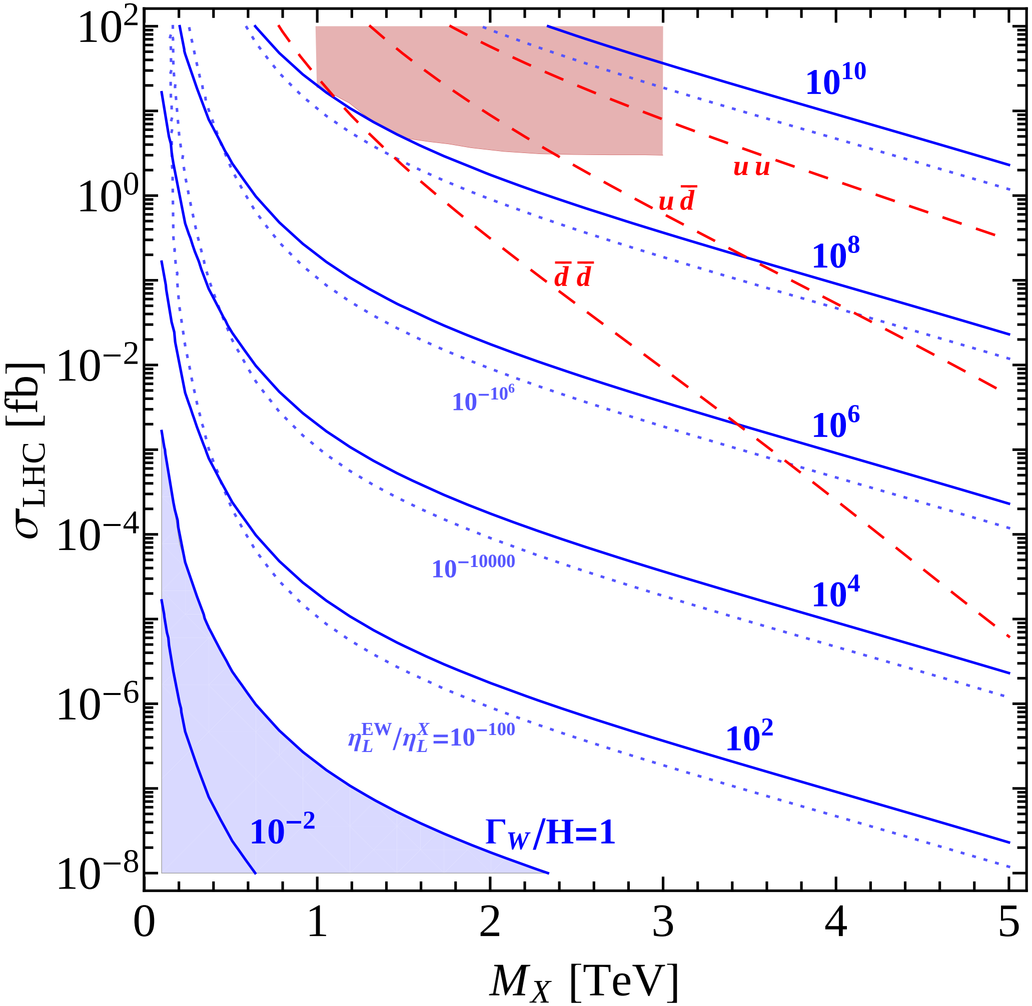
(e) Tree



In Leptogenesis:

(i) Convert L to B through SM sphalerons
(ii) CP violation through interference tree $\leftrightarrow$ 1-loop
(iii) L out of equilibrium via right-handed neutrino decay

Leptogenesis and LHC



$\sigma_{\rm LHC} = \sigma_{pp->l^\pm l^\pm+jj}$

Deppisch, Hartz & Hirsch
arXiv:1312.4447
PRL 112 (2014)

blue lines
washout factor Γ_W
- Suppression of L $\propto 10^{-\Gamma_W}$

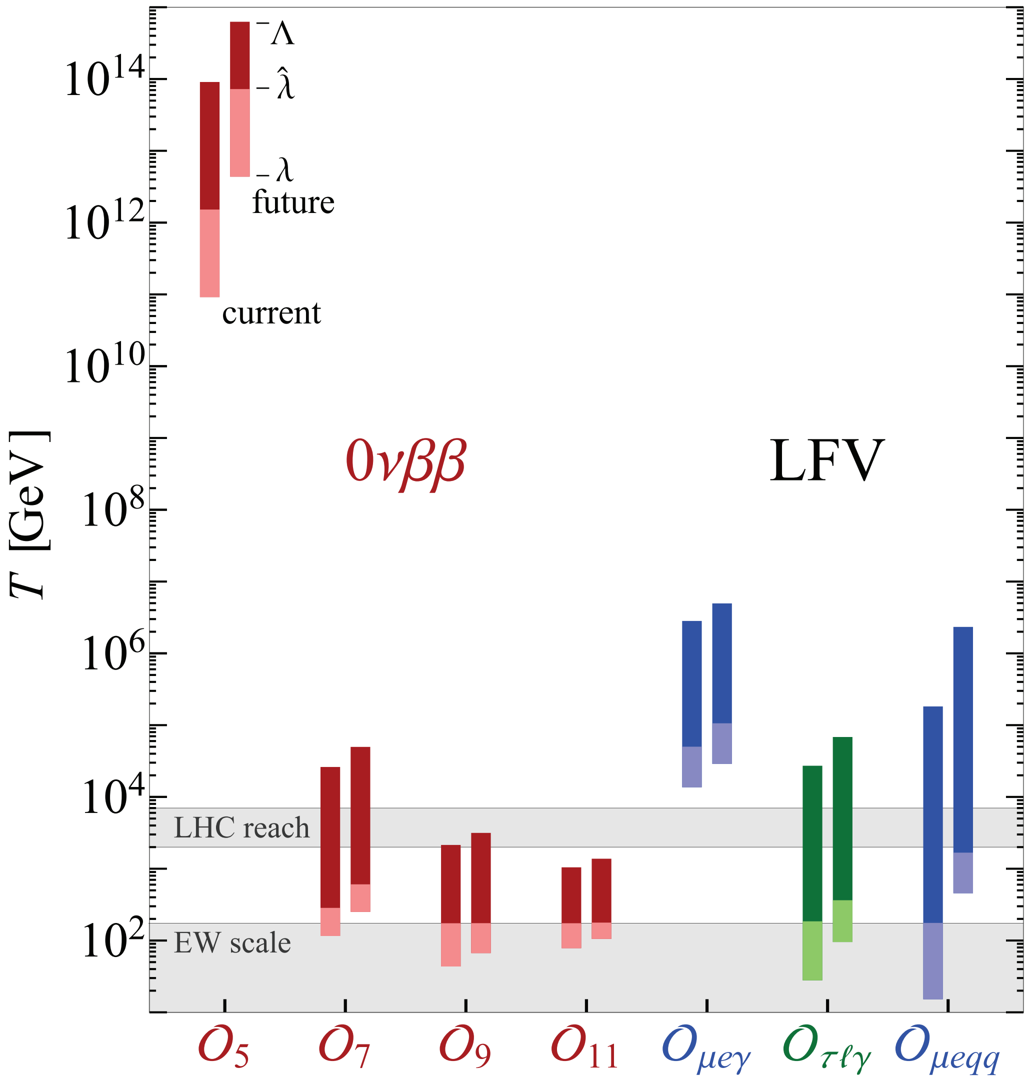
Observation of
LNV @ LHC implies:
(High-scale) Leptogenesis
is ruled out!

Loopholes???

(i) Resonant LG
with $m_N \ll m_X$?

(ii) Hide LG in τ's?

LG and $0\nu\beta\beta$ decay



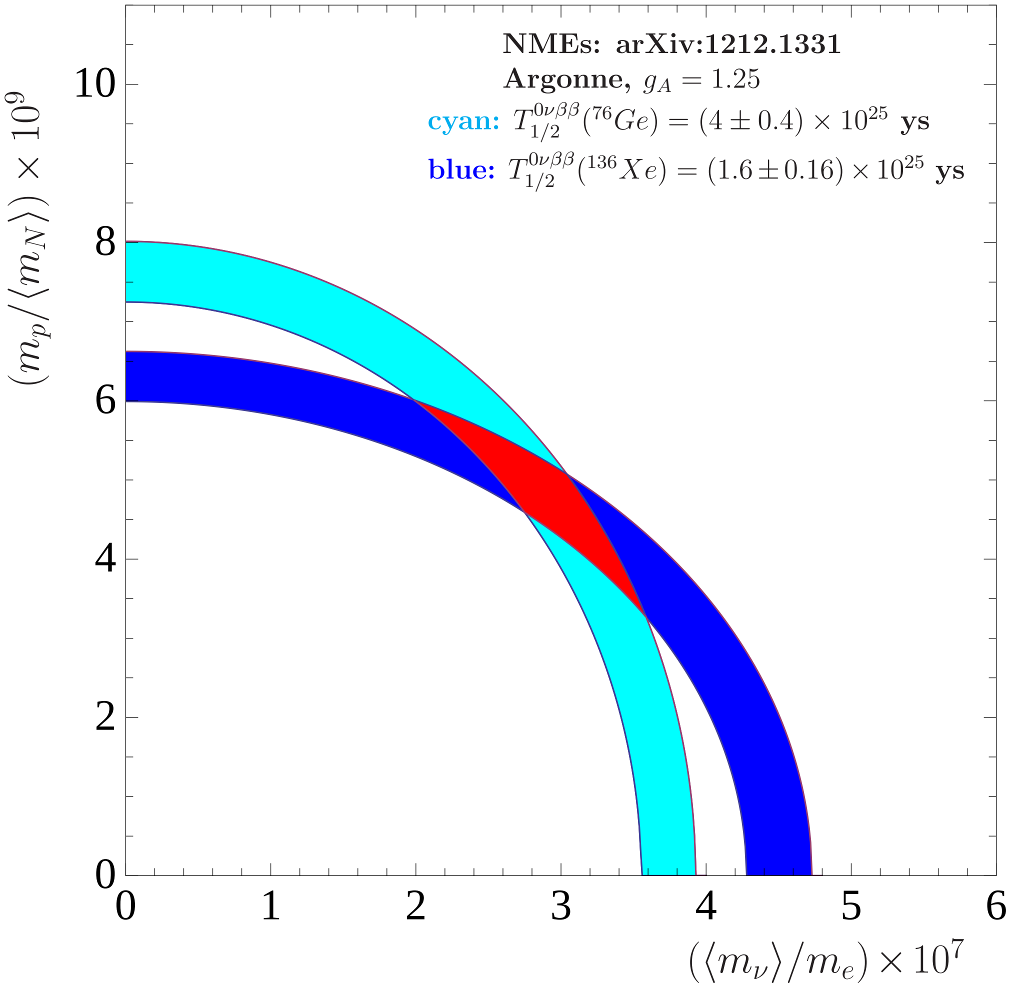
Deppisch et al., 2015

If $0\nu\beta\beta$ is found and demonstrated to be not due to $\langle m_\nu \rangle$

LG ruled out above scale λ

Comments on using different isotopes

More than one isotope?



Simple idea:

$$T_{1/2} = G\Big\{(\epsilon_1 \mathcal{M}_1)^2 + (\epsilon_2 \mathcal{M}_2)^2\Big\}$$

Only one example:

$\epsilon_1 = (\langle m_\nu\rangle/m_e)$

$\epsilon_2 = (m_p/\langle m_N\rangle)$

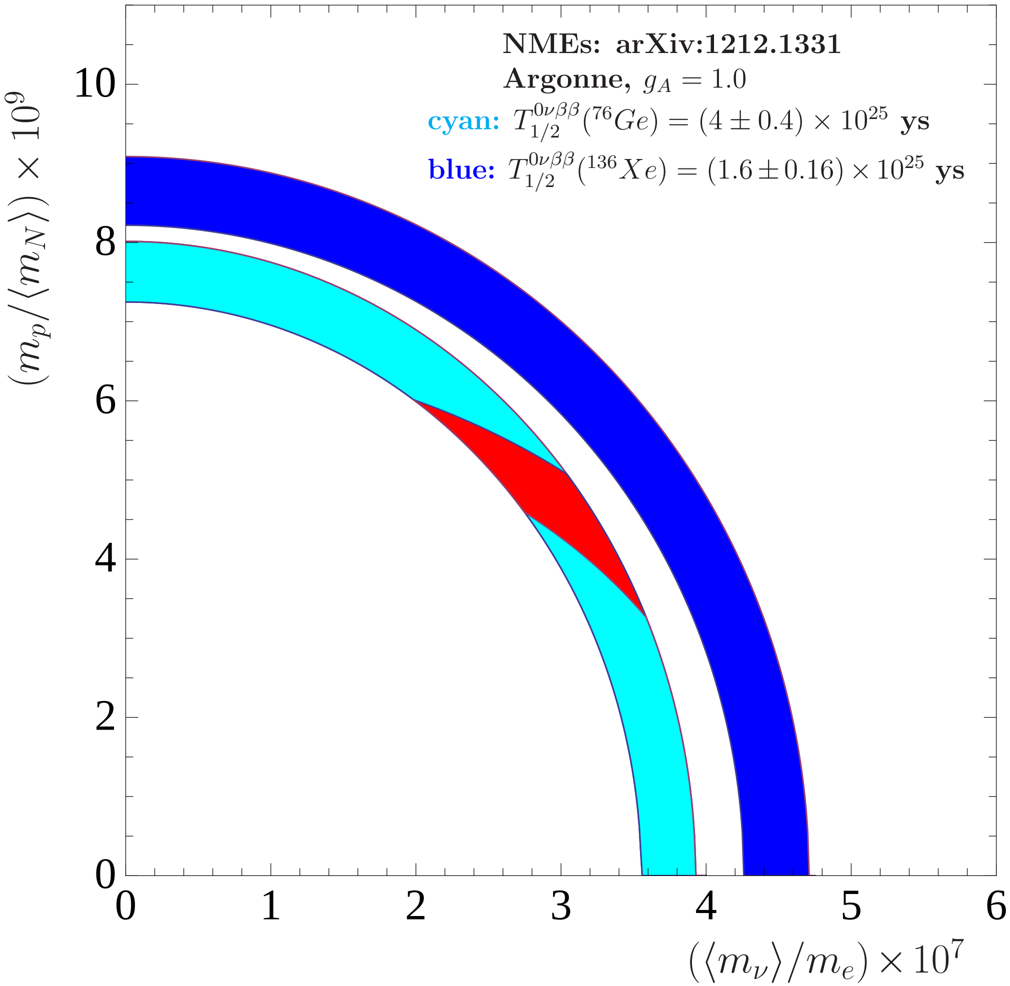
$\mathcal{M}_i$ - matrix elements

Use two (or more) isotopes solve for two unknowns ...

Consistency region shown in red

Note:
Plot is not based on experimental data! For illustration only.

More than one isotope?



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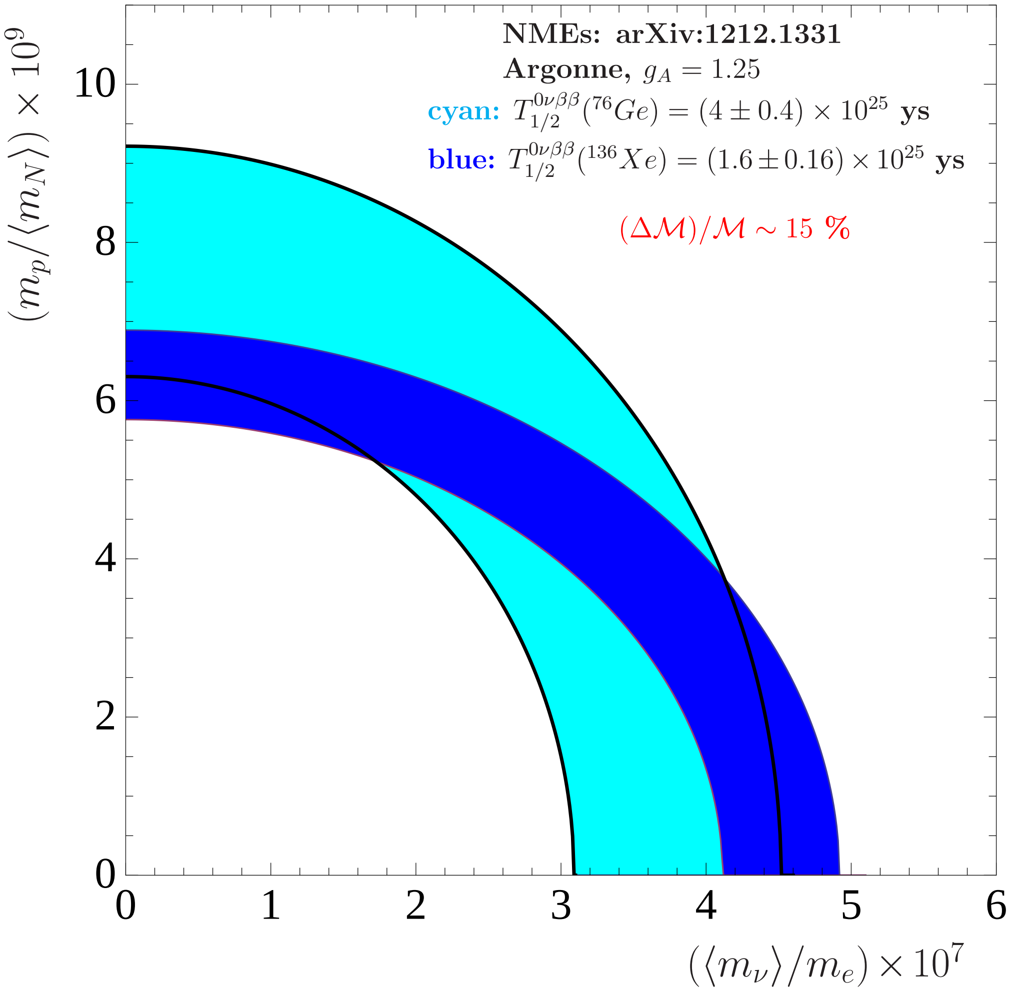
$\mathcal{M}_i$ - matrix elements

Use two (or more) isotopes solve for two unknowns ...

No overlap for exactly same numbers, except: $\mathcal{M}_i$!

Note:
Plot is not based on experimental data! For illustration only.

More than one isotope?



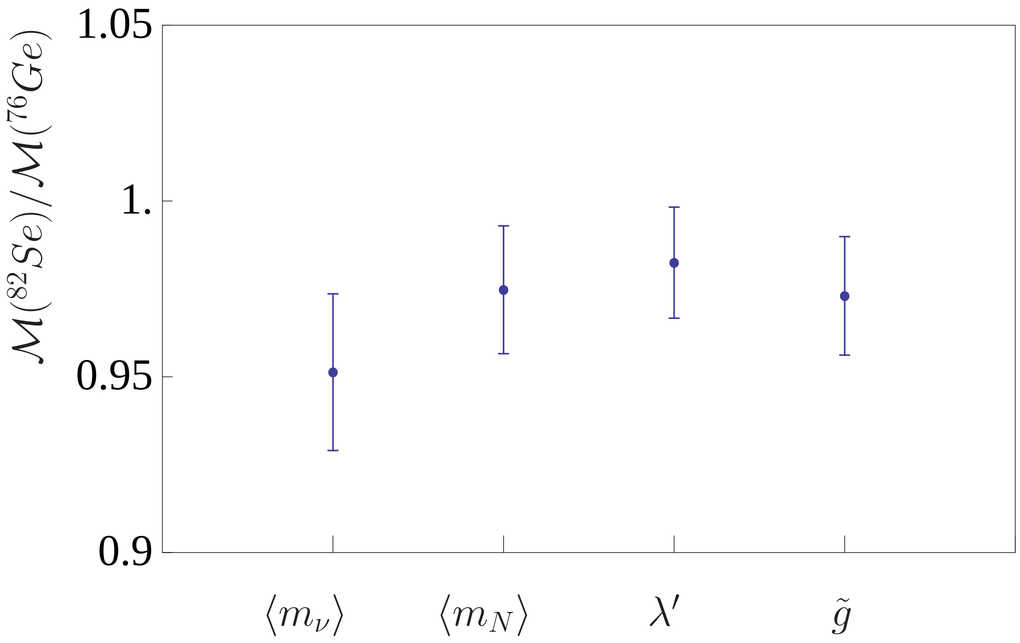
Same numbers except:

Arbitrary error for:
$(\Delta\mathcal{M})/\mathcal{M} \sim 20$ % for ^{76}Ge

Different mechanisms in different nuclei lead to (5-25) % differences, much smaller than typical error $(\Delta\mathcal{M})$

Conclusion:
Better $\mathcal{M}$ needed!

Ratios of matrix elements



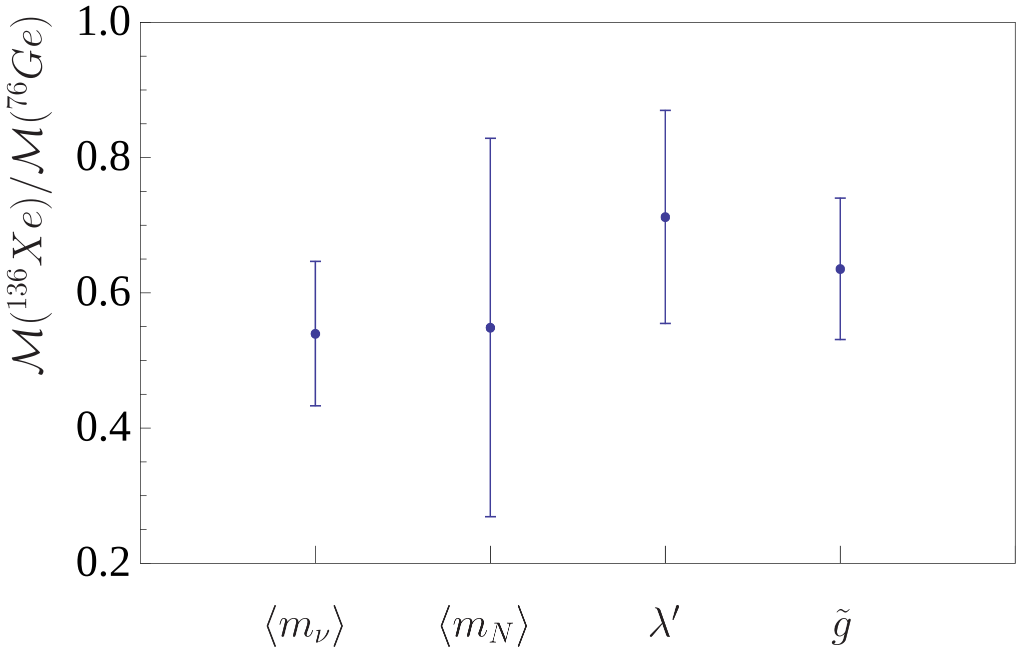
To distinguish:
Need different mechanisms
to have different NME ratios.

"Error bar" due to variation
of NMEs in Table 1 of 1212.1331

Plot shows ratio of matrix elements for different "mechanisms", see 1212.1331:

$\langle m_\nu \rangle$ - Mass mechanism
$\langle m_N \rangle$ - heavy neutrino exchange
λ' - "trilinear RPV"
$\tilde{g}$ - gluino RPV

Ratios of matrix elements



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