Neutrinos - Theory

Majorana neutrino masses: A story of trees and loops

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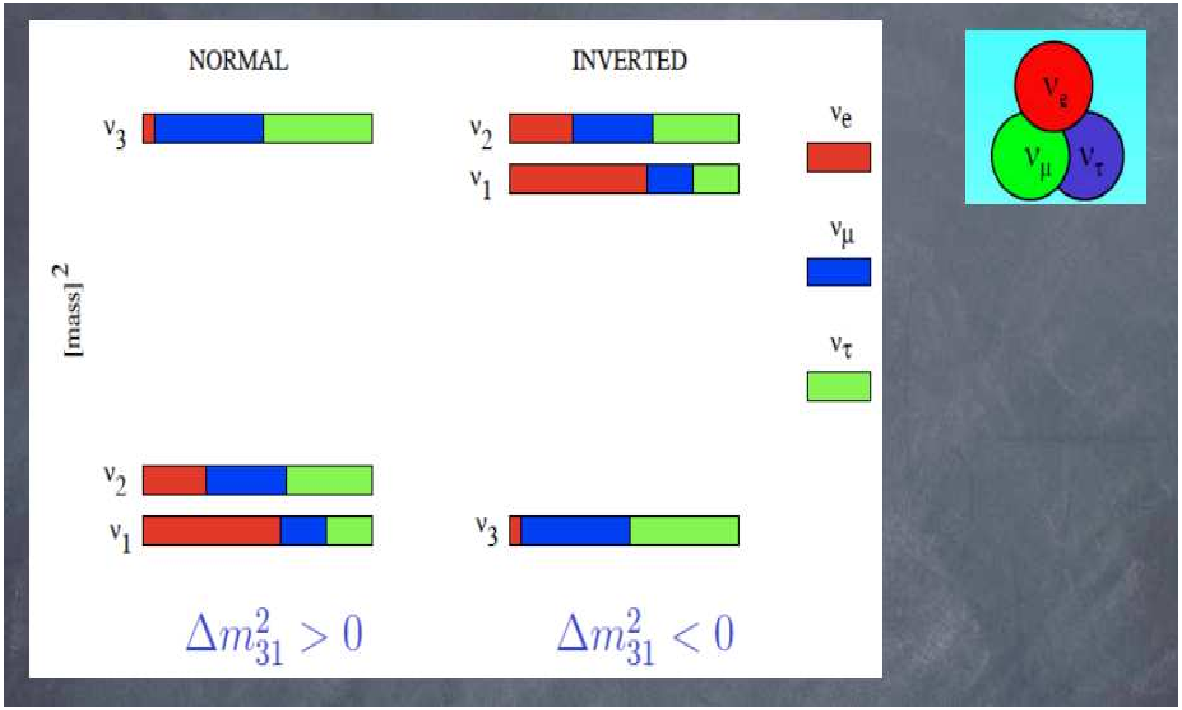
Contents

$\mathcal{I}.$

Introduction

What do we know?



2 Δm^2 and all 3 θ_{ij} measured with high precision, but ...

Upper limits on neutrino mass scale:

$\langle m_\nu \rangle \lesssim (0.2 - 0.4)$ eV — LNV! — GERDA, EXO KamLAND-Zen

$m_\beta \lesssim 2.2$ eV — Limit still from: Mainz & Troitsk

$\sum_i m_{\nu_i} \lesssim (0.23 - 0.68)$ eV — Planck & BAO

Open questions

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$\Rightarrow$ Are neutrinos Majorana particles?

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A: Observe LNV!

Open questions

⇒ Are neutrinos Majorana particles?

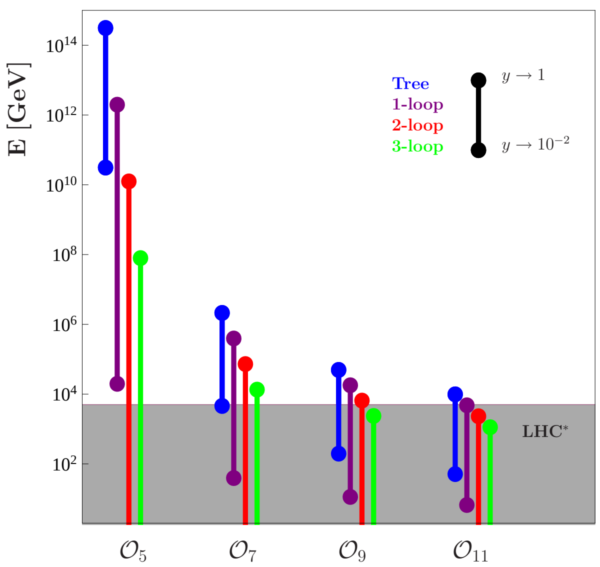
A: Observe LNV!

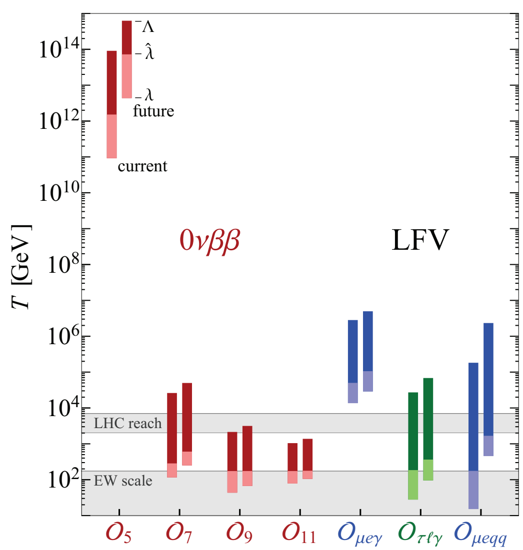
⇒ What is the origin and energy scale of LNV?

Direct test: LHC? Or indirect: LFV? $0\nu\beta\beta$ decay?

m_ν:

$0\nu\beta\beta$, LFV:





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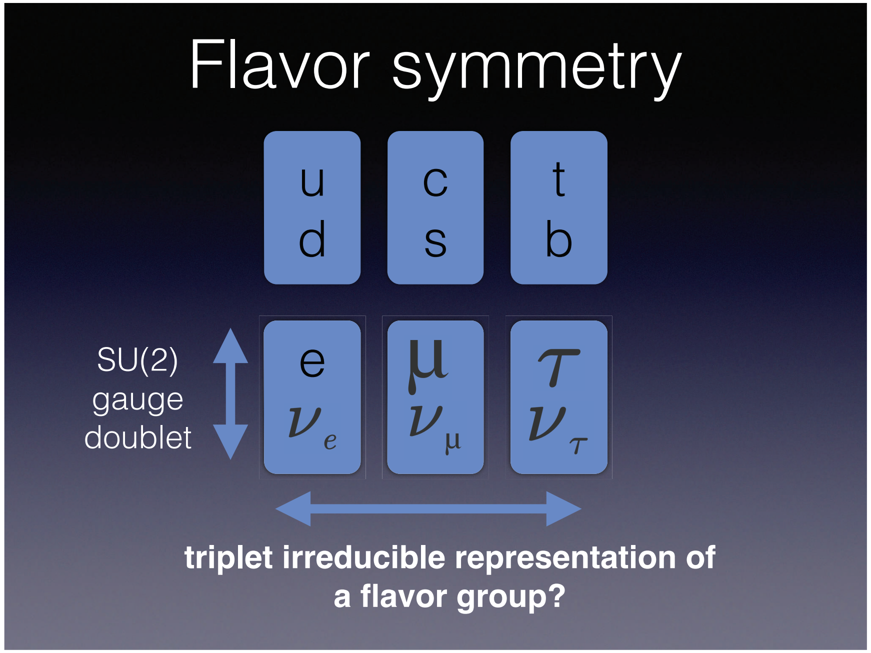
⇒ Can we understand flavour structure?



Discrete symmetries:

$S_3, A_4, \cdots$

$$\sin^2(\theta_{\rm Atm}) \simeq 1/2$$
$$\sin^2(\theta_\odot) \simeq 1/3$$
$$\sin^2(\theta_{\rm R}) \simeq \text{“}\epsilon\text{“}$$

Open questions

⇒ Are neutrinos Majorana particles?

A: Observe LNV!

⇒ What is the origin and energy scale of LNV?
Direct test: LHC? Or indirect: LFV? $0\nu\beta\beta$ decay?

⇒ Can we understand flavour structure?

⇒ Are neutrinos related to DM?

→ (keV sterile) Neutrinos could be DM

→ Particles generating m_ν could be DM
Example: "scotogenic" neutrino model — Ma, 2006
Explain flavour as well? "Discrete DM" — Morisi et al, 2010

Open questions

⇒ Are neutrinos Majorana particles?

A: Observe LNV!

⇒ What is the origin and energy scale of LNV?
Direct test: LHC? Or indirect: LFV? $0\nu\beta\beta$ decay?

⇒ Can we understand flavour structure?

⇒ Are neutrinos related to DM?

⇒ Are neutrinos linked to the BAU?

⇒ Is there CPV in the lepton sector? Majorana phases?

⇒ Can we predict CPV?

⇒ Are there more than 3 light neutrinos?

⇒ Normal hierarchy or Inverted Hierarchy?

⇒ Many others ...

Open questions

$\Rightarrow$ Are neutrinos Majorana particles?

A: Observe LNV!

$\Rightarrow$ What is the origin and energy scale of LNV? $\Leftarrow$ This talk!

Direct test: LHC? Or indirect: LFV? $0\nu\beta\beta$ decay?

$\Rightarrow$ Can we understand flavour structure?

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$\Rightarrow$ Are there more than 3 light neutrinos?

$\Rightarrow$ Normal hierarchy or Inverted Hierarchy?

$\Rightarrow$ Many others ...

$\mathcal{II}.$

Trees and Loops

Theoretical expectation?

Majorana Neutrino mass

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

Weinberg, 1979

Smallness of neutrino mass can be "explained" by:

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

Minkowski, 1977

Yanagida, 1979
Gell-Mann, Ramond, Slansky, 1979
Mohapatra, Senjanovic, 1980
Schechter, Valle, 1980
. . . , . . . , . . .
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:

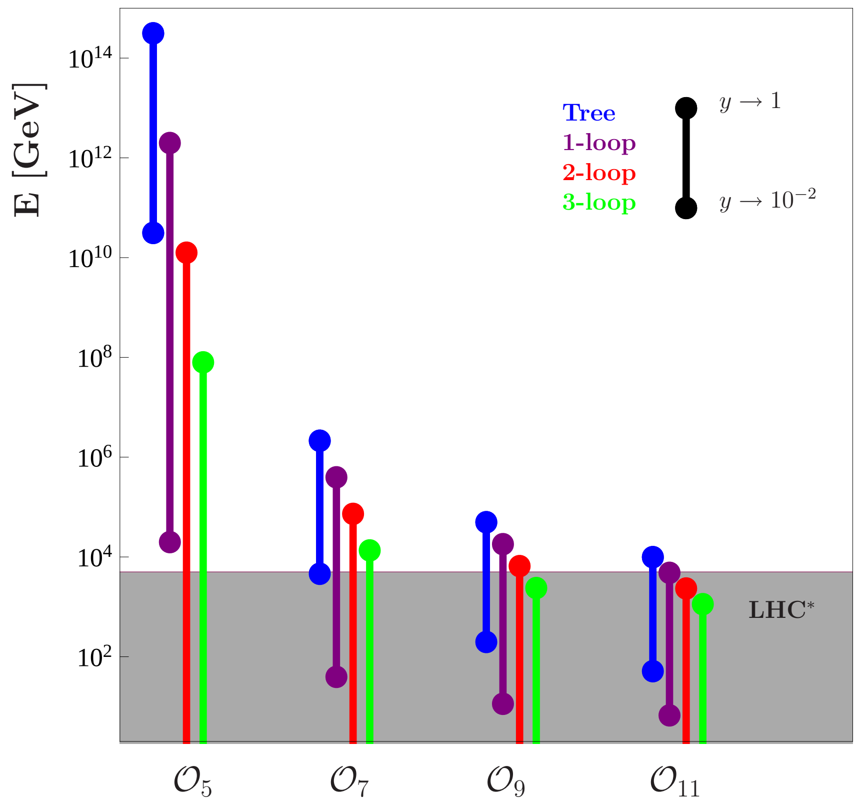
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

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

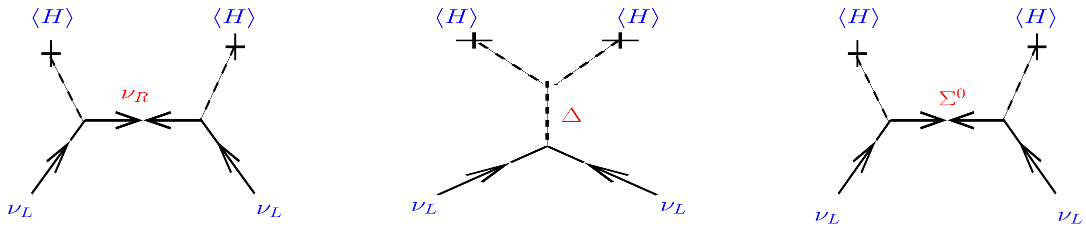
$\Rightarrow$ Higher order: $d = 7, 9, 11$

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

$\cdots$ or combination thereof



Diagramatic method

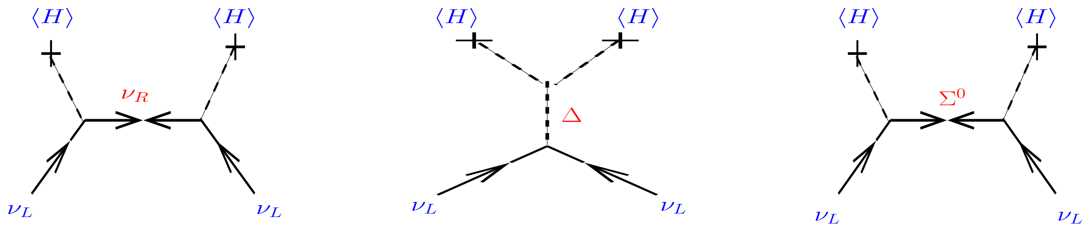


Ma 1998

Tree-level

3 diagrams

Diagramatic method



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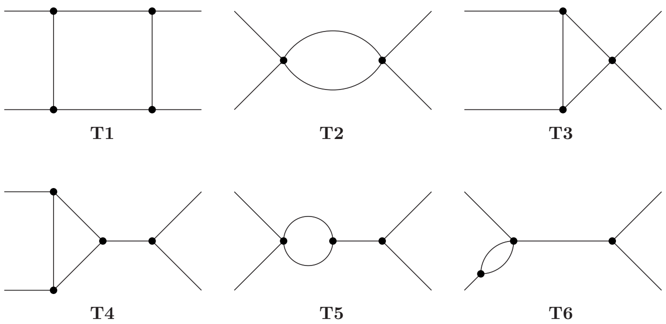


Bonnet et al., 2012

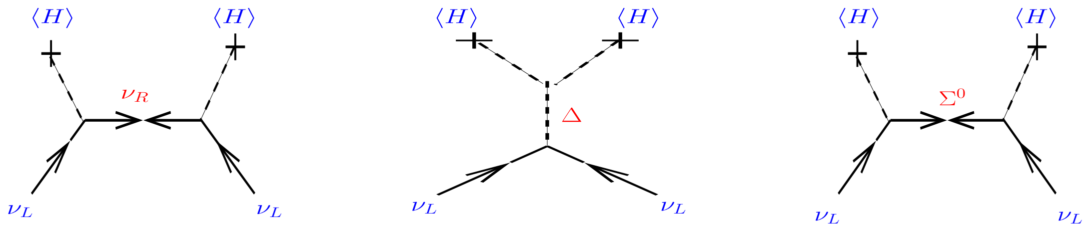
1-loop level:

6 topologies

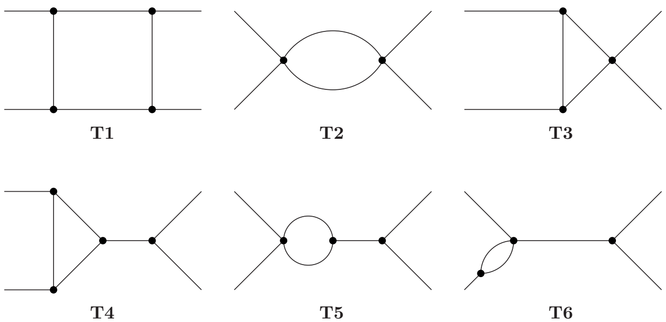
12 diagrams

4 genuine diagrams

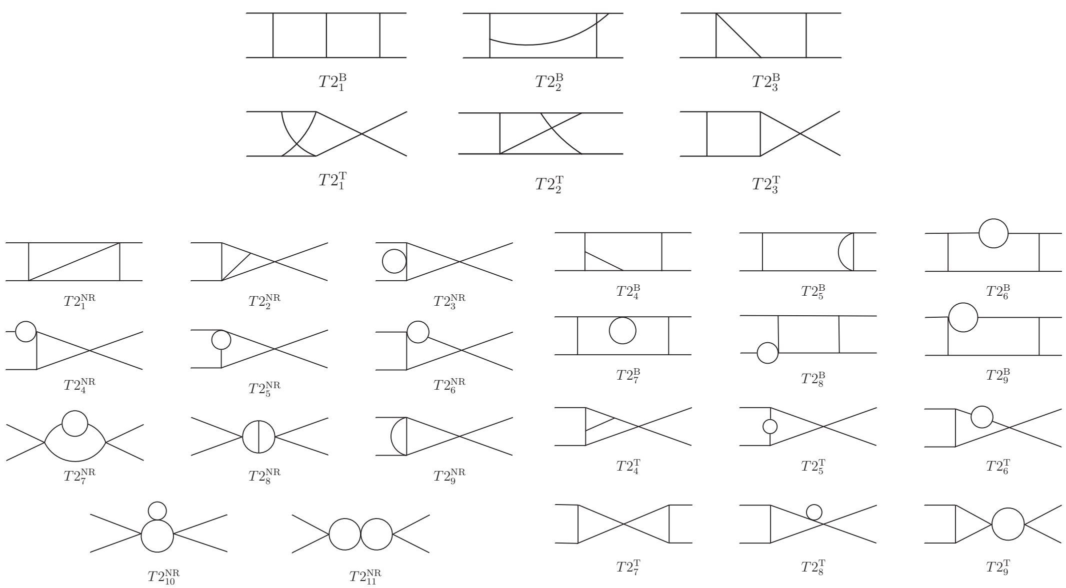
Diagramatic method



Ma 1998
Tree-level
3 diagrams



Bonnet et al., 2012
1-loop level:
6 topologies
12 diagrams
4 genuine diagrams



Aristizabal et al, 2015
2-loop level:
29 topologies
6 genuine topologies
many, many
diagrams!

$\Delta L = 2$ operators

$d = 5$: Weinberg, 1979

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

One d=5

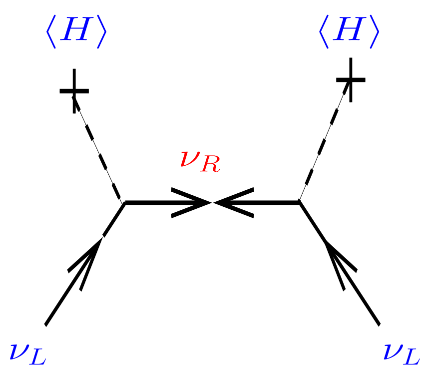
$\Delta L = 2$ operators

$d = 5$: Weinberg, 1979

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

One d=5

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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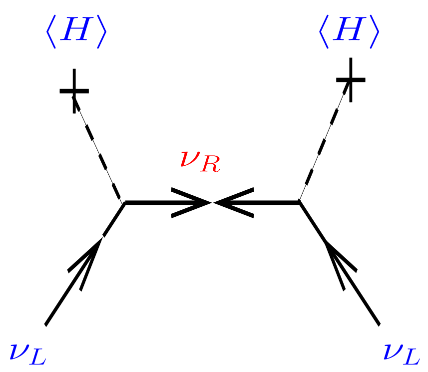

$\Lambda \simeq M_{\nu_{R_k}}$

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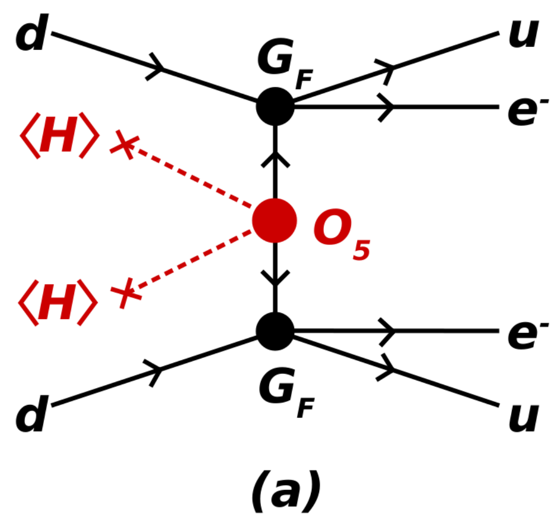
$0\nu\beta\beta$ decay:

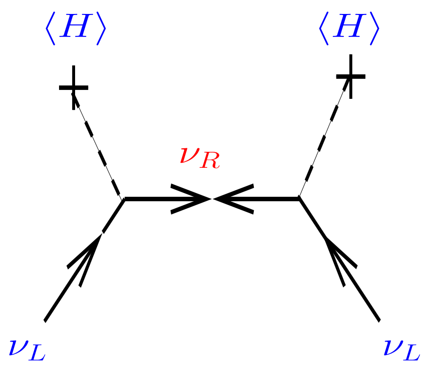


Mass mechanism!

Seesaw: Near EW scale??

Type-I:

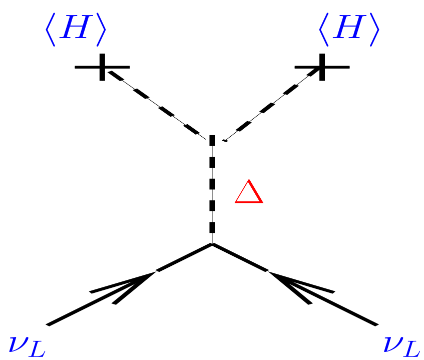
$M_M \sim 100$ GeV $\Rightarrow h_\nu \sim 10^{-7}$



Type-II;

$m_\triangle \simeq 100$ GeV and $\mu_\triangle \sim 1$ eV

$\Rightarrow Y_T \sim 1$



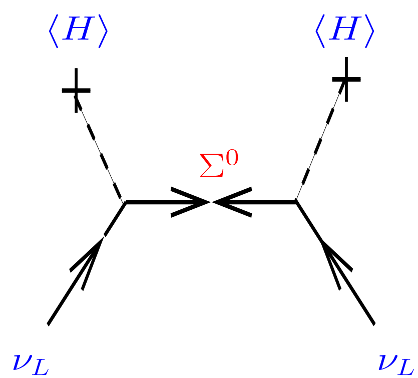
Tree-level

$d = 5$: Only

3 realizations

Type-III:

$M_\Sigma \sim 100$ GeV $\Rightarrow Y_\Sigma \sim 10^{-7}$



$\Delta L = 2$ *operators*

$d = 5$: Weinberg, 1979

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

One d=5

$d = 7$: Babu & Leung, 2001

de Gouvea & Jenkins, 2007

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

$$\mathcal{O}_3 \propto LLQd^c H$$

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

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

4 (+1) $d = 7$

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

Nearly conserved L?

Mohapatra & Valle, 1986

Inverse seesaw, basis (ν, ν^c, S):

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix},$$

After EWSB the effective light neutrino mass matrix is given by

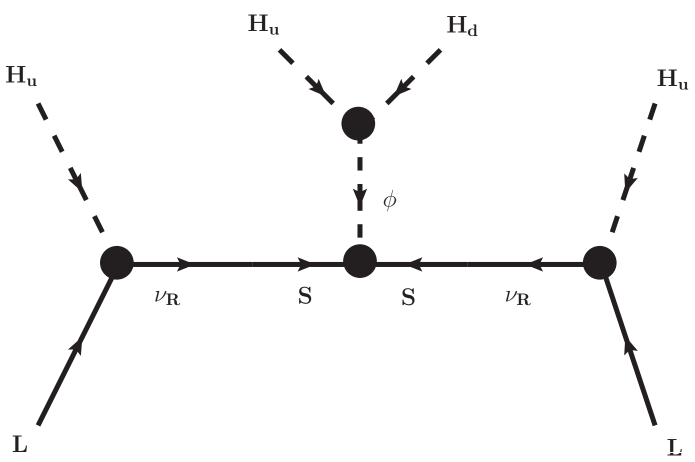
$$M_\nu = m_D {M^T}^{-1} \mu M^{-1} m_D^T.$$

“Inverse” seesaw, because:

$$M_\nu \Rightarrow 0 \qquad \text{IF} \qquad \mu \Rightarrow 0$$

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

"Open" $d = 7$ operator. Just one example: Bonnet et al., 2009



Inverse seesaw

However: $(HH^\dagger)$ is a singlet under any symmetry.
Thus:

Requires at least 2 Higgses, example: H_u, H_d

$\Rightarrow$ Suppression by: $\mu_\phi \langle H_u \rangle \langle H_d \rangle / m_\phi^2$
$\Rightarrow$ "Enough" if $m_\phi \simeq 10^{14}$ GeV

$\Delta L = 2$ 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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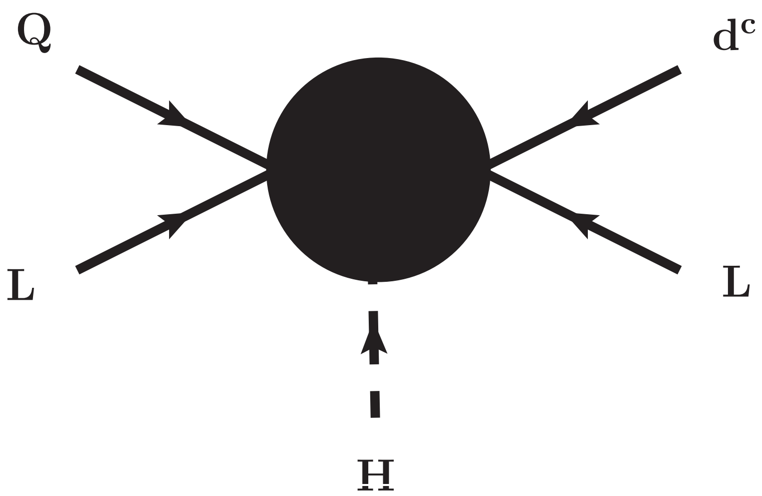
$$\mathcal{O} \propto (LH)(LH)(H_u H_d)$$

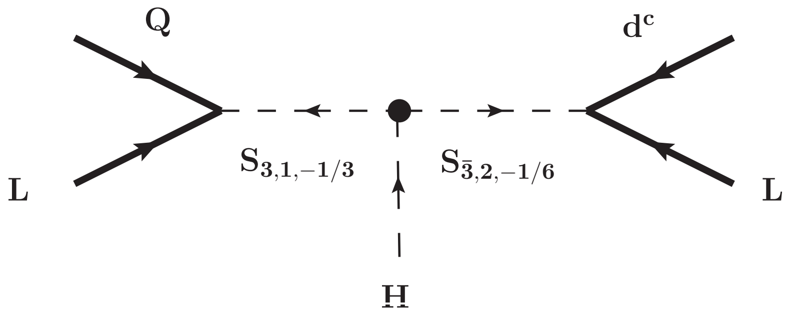
Example $d = 7$: $LLQd^cH$

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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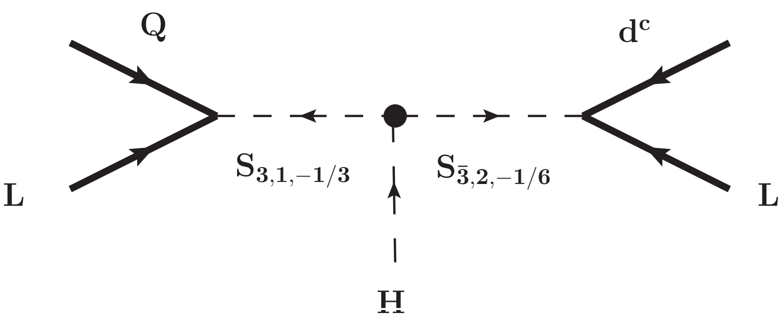

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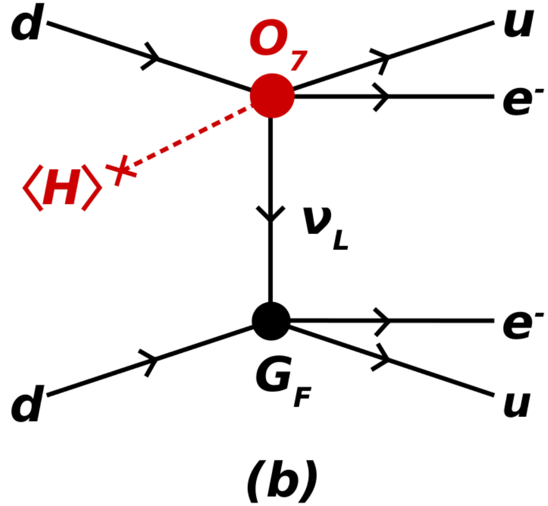
$0\nu\beta\beta$ decay:



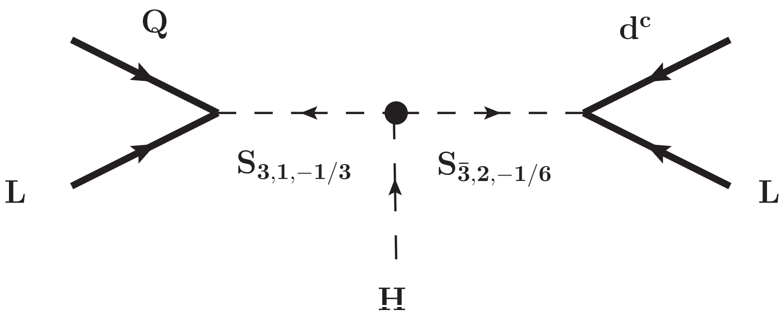
Long range contribution!

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

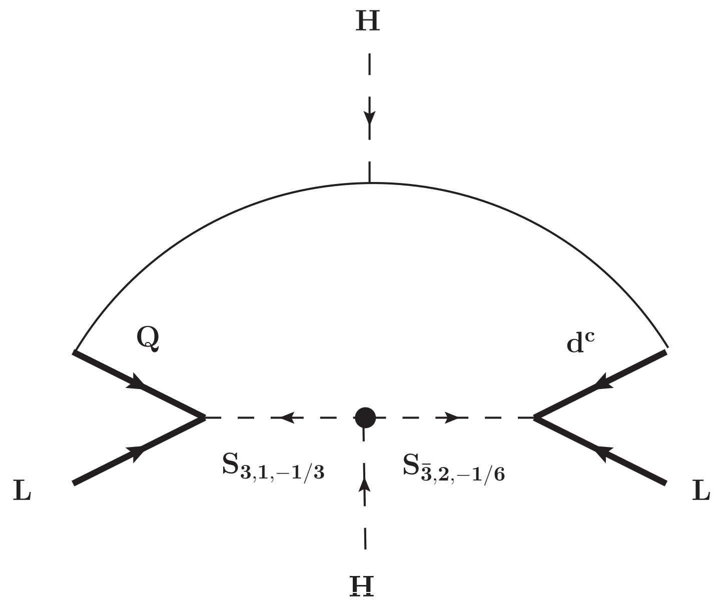
No helicity suppression!

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

Again, more than one realization.
Example:



1-loop neutrino mass:



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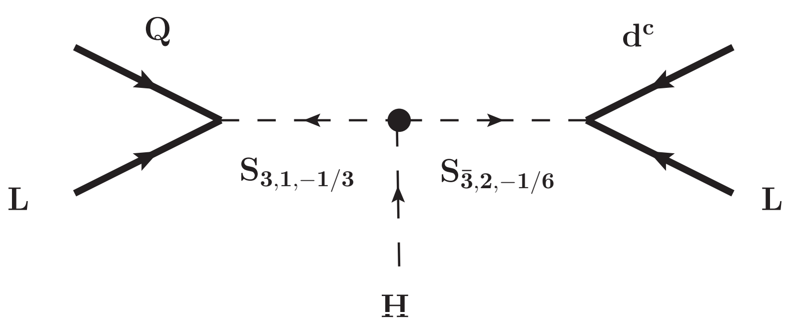

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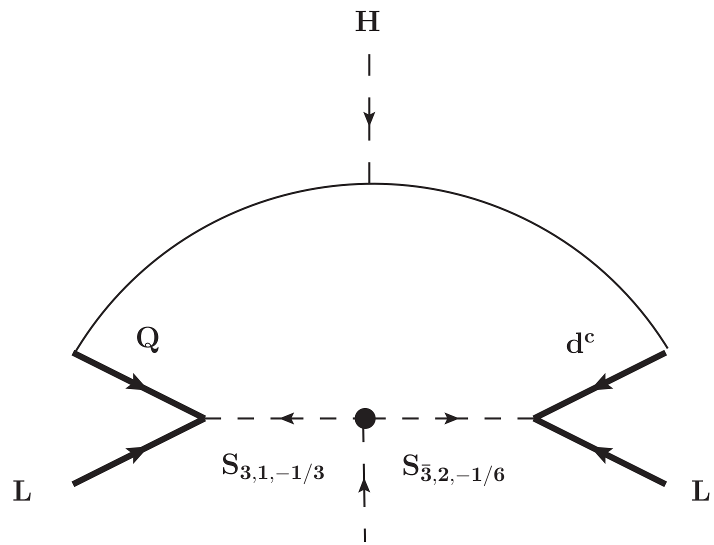
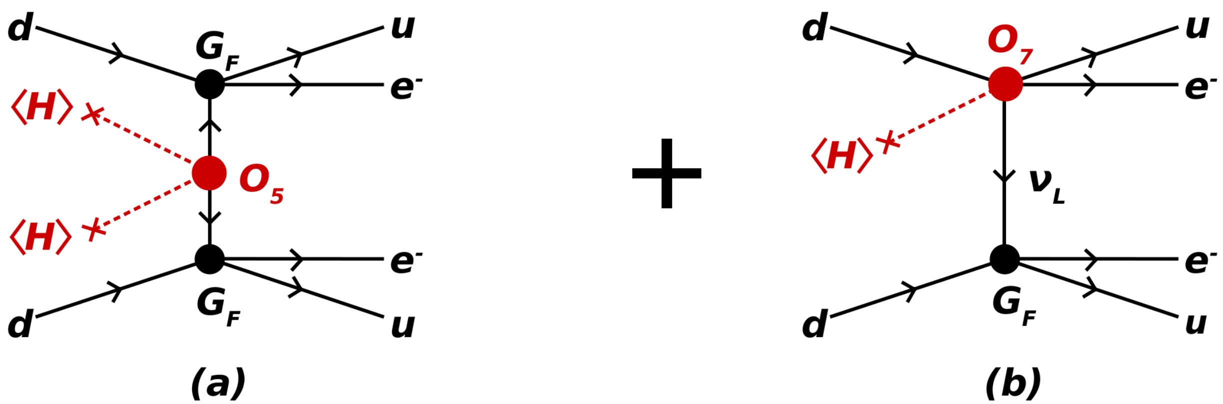


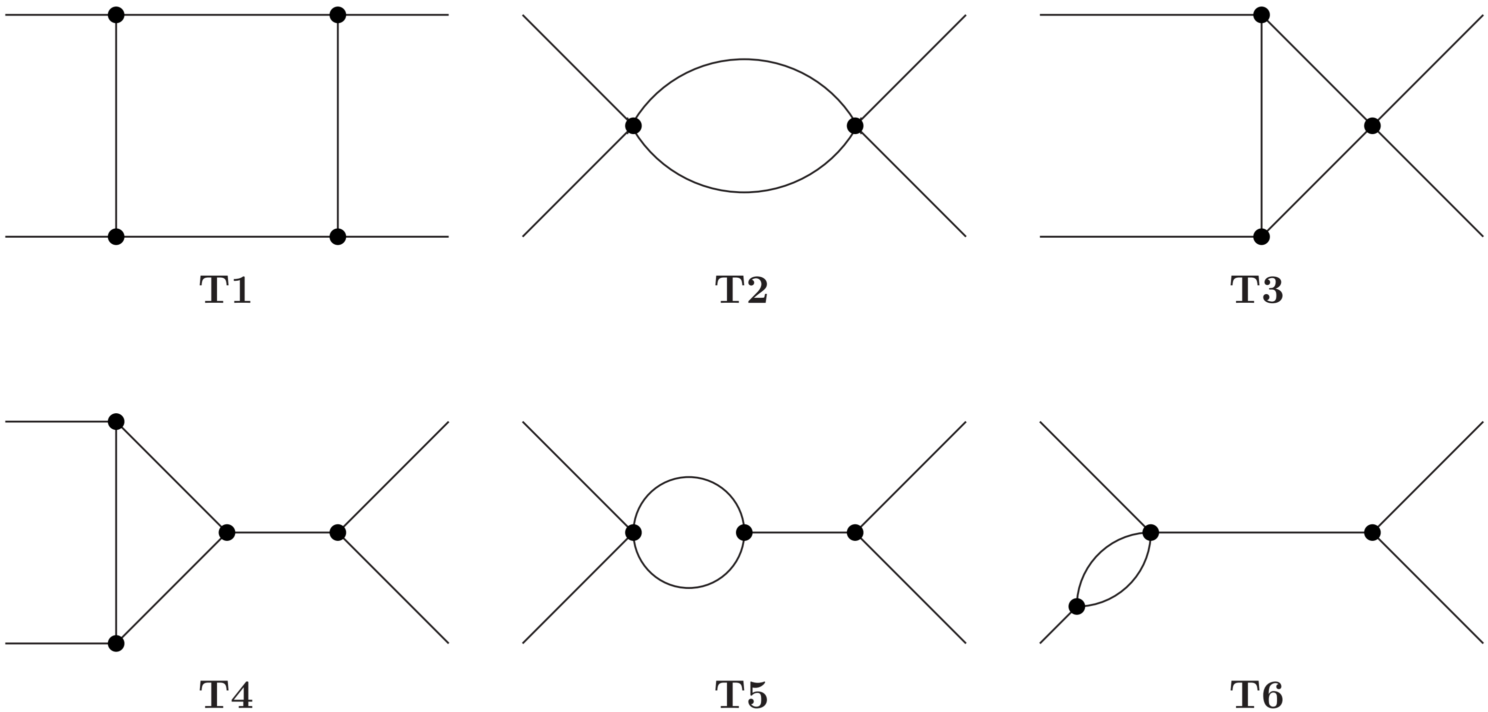
$0\nu\beta\beta$ decay has both contributions:



m_ν @ *1-loop and* $d = 5$

Bonnet et al., 2012

With 4-external legs and no self-energy diagrams, there is a total of 6 topologies:



All $d = 5$ 1-loop neutrino mass models covered!

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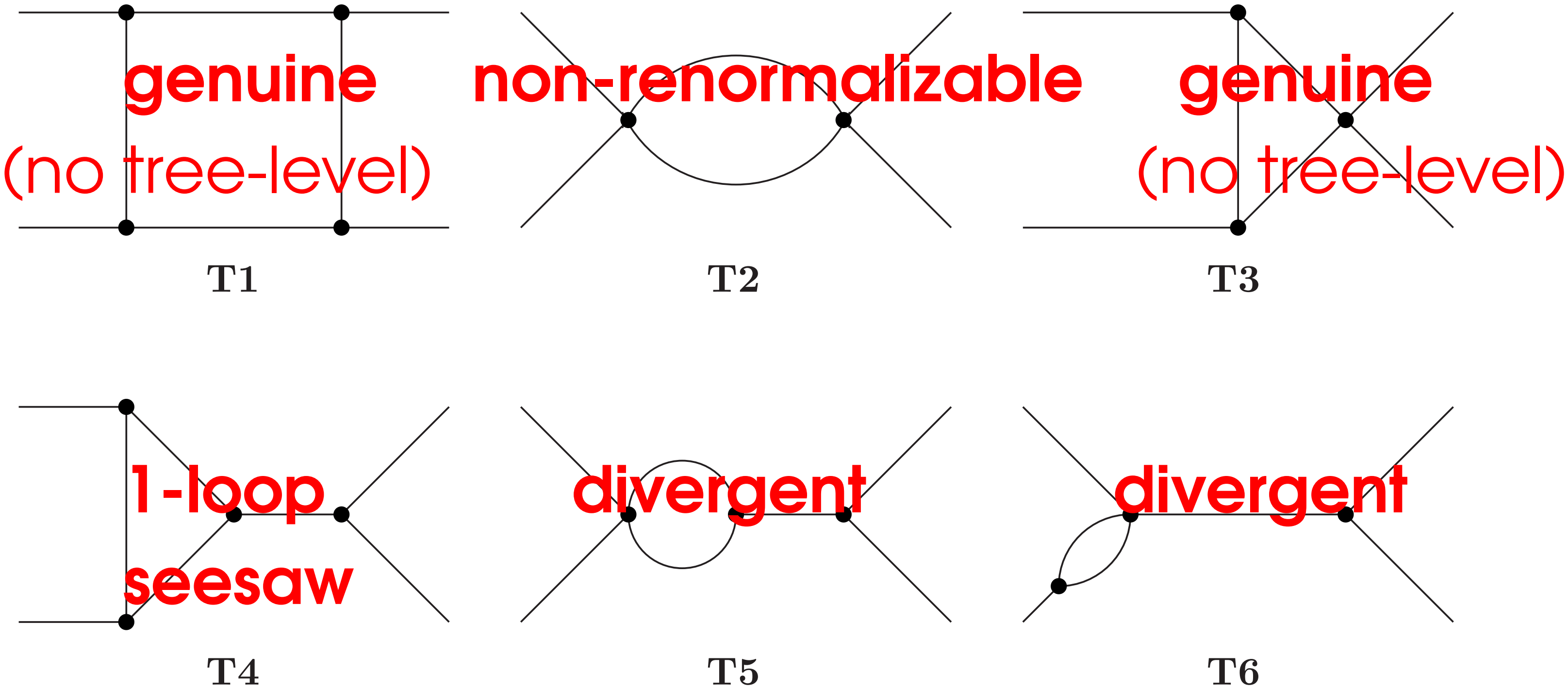
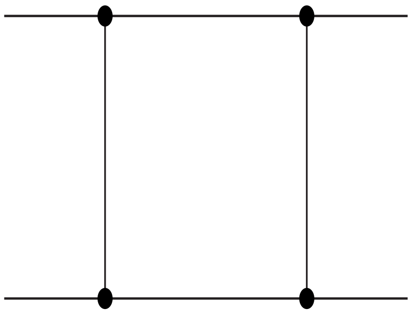
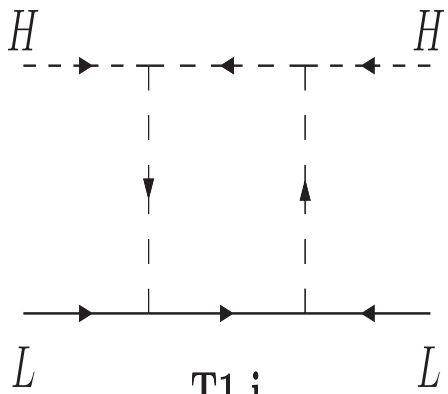


All $d = 5$ 1-loop neutrino mass models covered!

Topology-1



T1

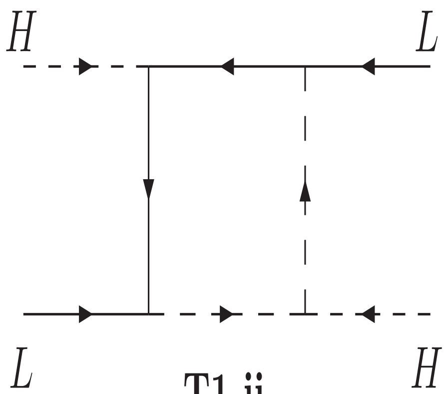


T1-i

Dark doublet model

Ma, 2006

Kubo, Ma & Suematsu, 2006



T1-ii

Zee, 1980

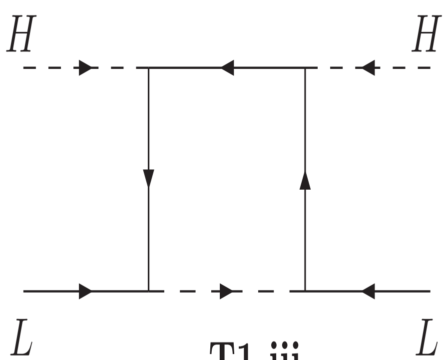
Zee model

Cheng & Li, 1980

Hall & Suzuki, 1984

R-parity violating SUSY

trilinear loop



T1-iii

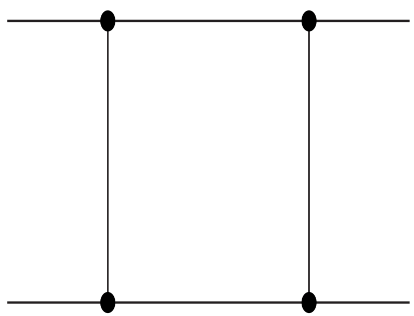
Ma, 1998

Hall & Suzuki, 1984

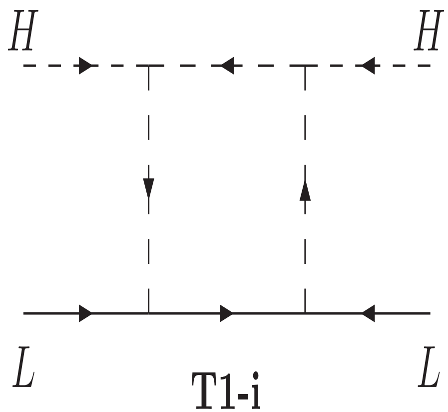
R-parity violating SUSY

bilinear-trilinear loop

Topology-1



T1

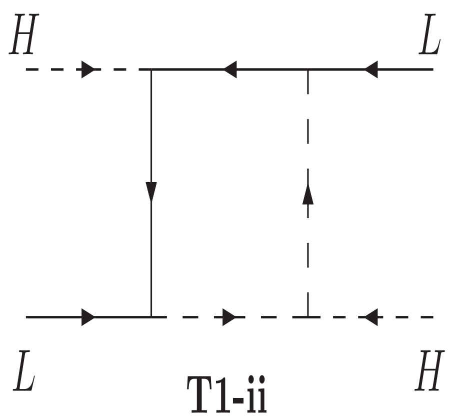


T1-i

Dark doublet model

Ma, 2006

Kubo, Ma & Suematsu, 2006



T1-ii

Zee, 1980

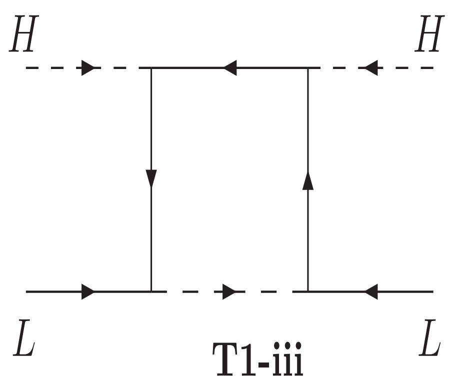
Zee model

Cheng & Li, 1980

Hall & Suzuki, 1984

R-parity violating SUSY

trilinear loop



T1-iii

Ma, 1998

Hall & Suzuki, 1984

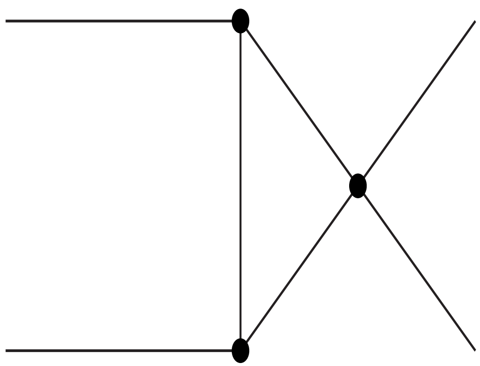
R-parity violating SUSY

bilinear-trilinear loop

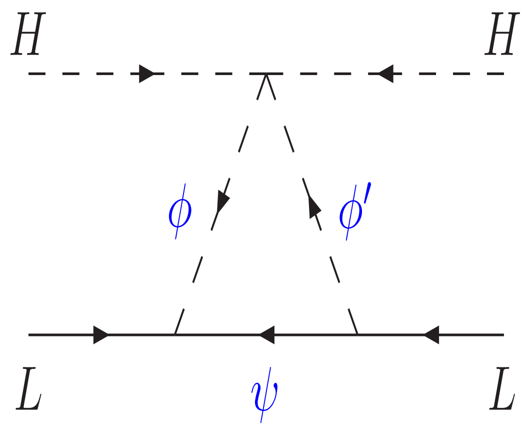
many, many more references ...

Apologies for not citing YOUR model here!

Topology-3



T3

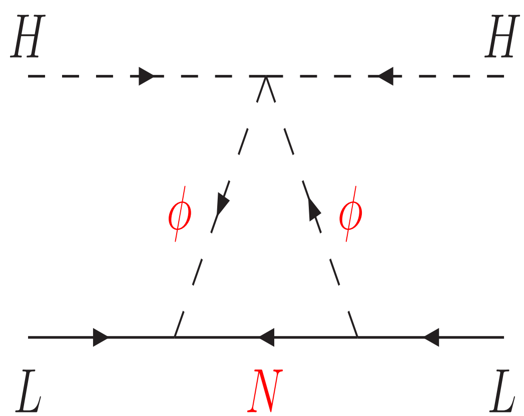


Ma, 1998
Ma, 2006

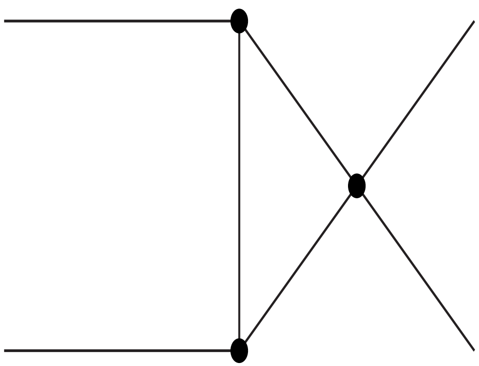
Systematically:

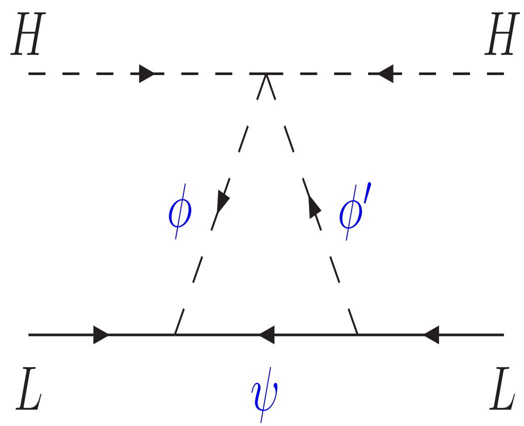
ϕ'	ϕ	ψ
1^S_α	$3^S_{2+\alpha}$	$2^F_{1+\alpha}$
2^S_α	$2^S_{2+\alpha}$	$1^F_{1+\alpha}$
2^S_α	$2^S_{2+\alpha}$	$3^F_{1+\alpha}$
3^S_α	$1^S_{2+\alpha}$	$2^F_{1+\alpha}$
3^S_α	$3^S_{2+\alpha}$	$2^F_{1+\alpha}$

$\Leftarrow$ If $\alpha = -1$ and ψ has a Majorana mass ($\psi = N$) 1-loop correction to type-I, unless Z_2 symmetry forbids v_ϕ Dark Matter!



Topology-3





Ma, 1998
Ma, 2006

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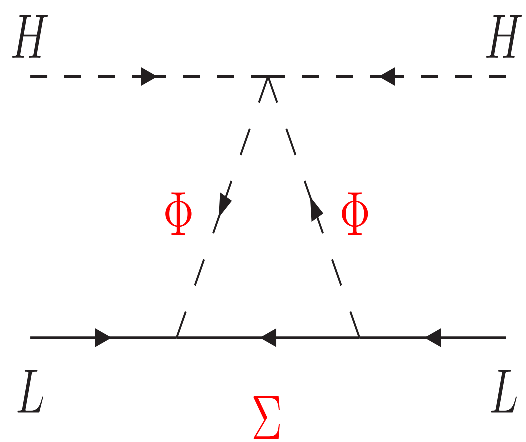
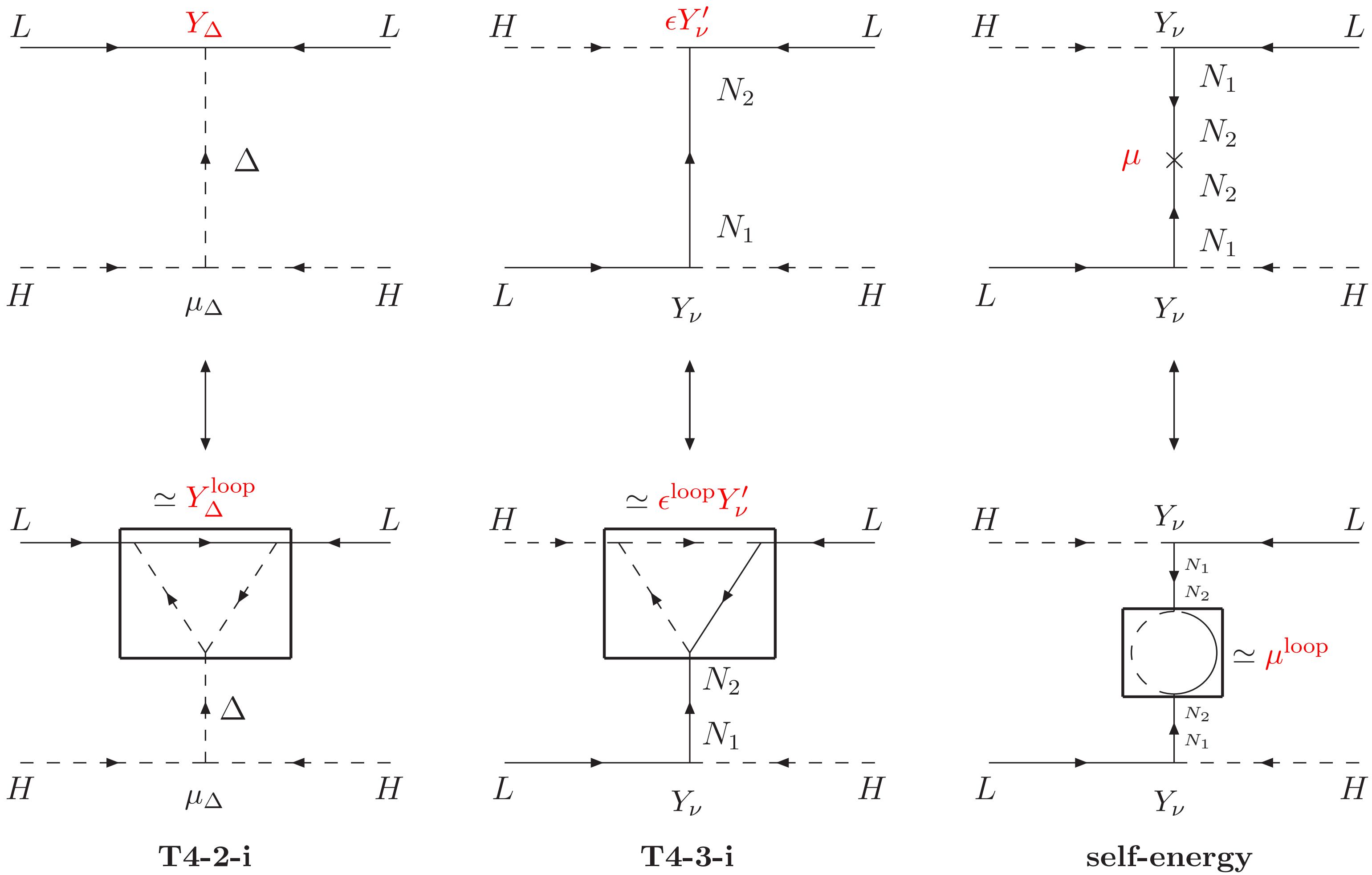
1^S_α	$3^S_{2+\alpha}$	$2^F_{1+\alpha}$
2^S_α	$2^S_{2+\alpha}$	$1^F_{1+\alpha}$
2^S_α	$2^S_{2+\alpha}$	$3^F_{1+\alpha}$
3^S_α	$1^S_{2+\alpha}$	$2^F_{1+\alpha}$
3^S_α	$3^S_{2+\alpha}$	$2^F_{1+\alpha}$

$\Leftarrow$ If $\alpha = -1$ and ψ has a Majorana mass ($\psi = \Sigma$) 1-loop correction to type-III, unless Z_2 symmetry forbids v_ϕ Dark Matter!



T-4: Loop generated vertices

Bonnet et al., 2012



⇒ If tree coupling vanishes (Majorana fermion plus Z_2):

$$Y^{\text{loop}} \propto y^3/(16\pi^2)$$

$\Delta L = 2$ operators

$d = 5$: Weinberg, 1979

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

One d=5

$d = 7$: Babu & Leung, 2001

de Gouvea & Jenkins, 2007

4 (+1) $d = 7$

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

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

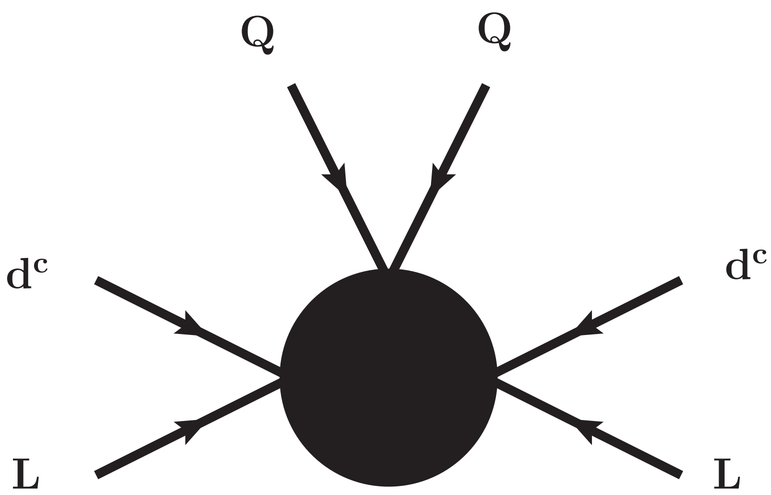
$d = 9$: many $d = 9$ and $d = 11$ ops

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

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

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

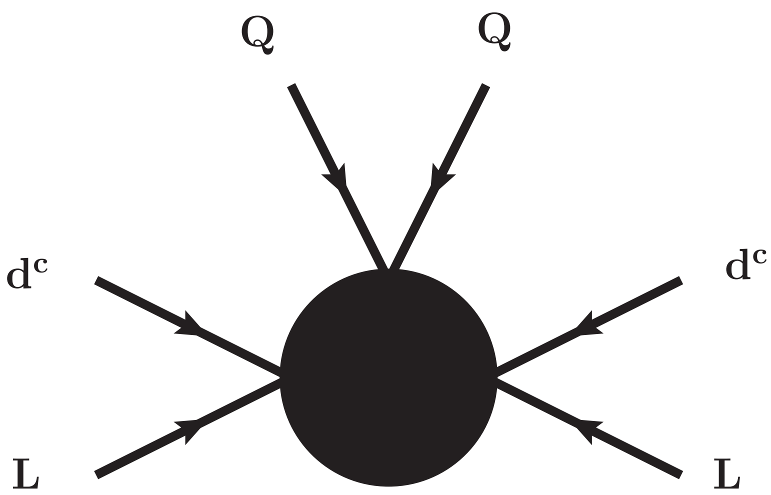
True $d = 9$ operator:



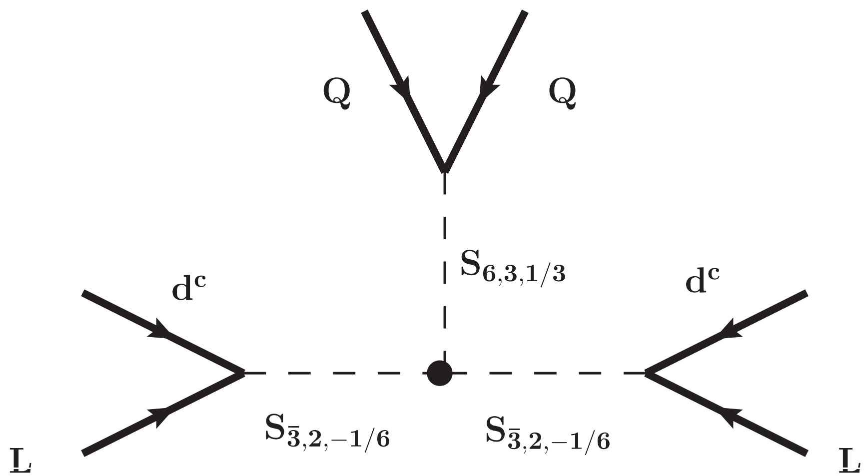
Many, many realizations ...

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

True $d = 9$ operator:



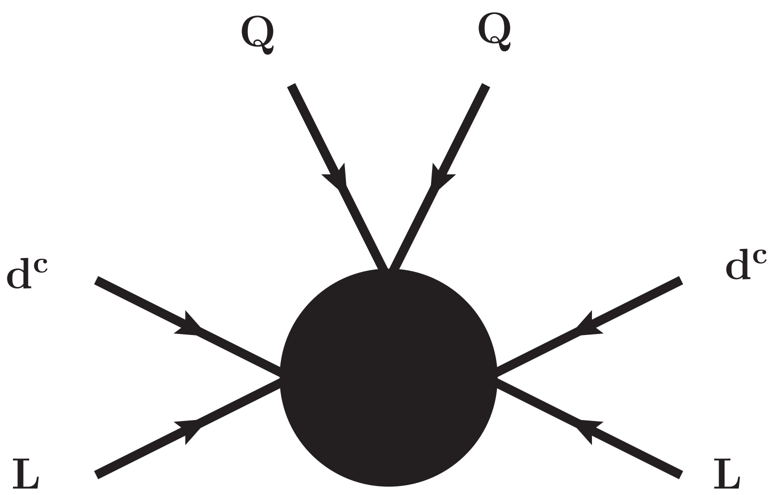
Many, many realizations ...
One example:



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

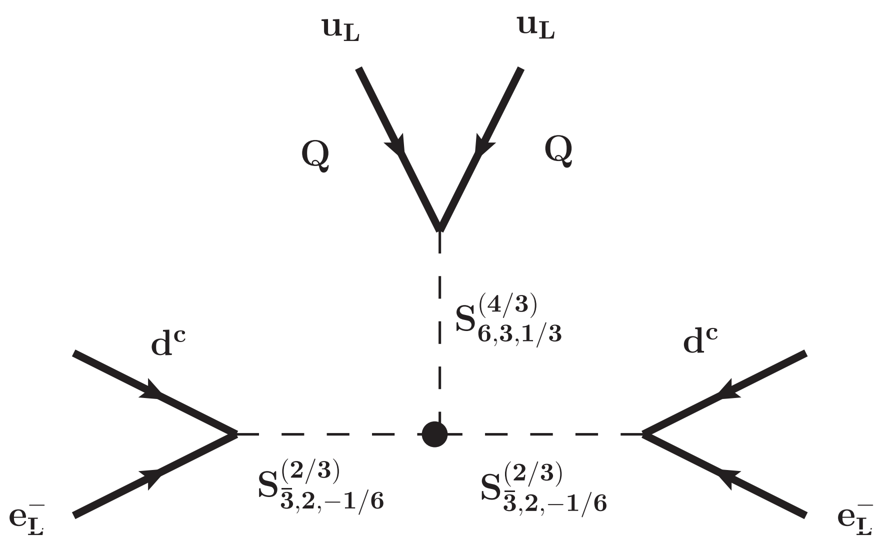
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:



Many, many realizations ...

One example:



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

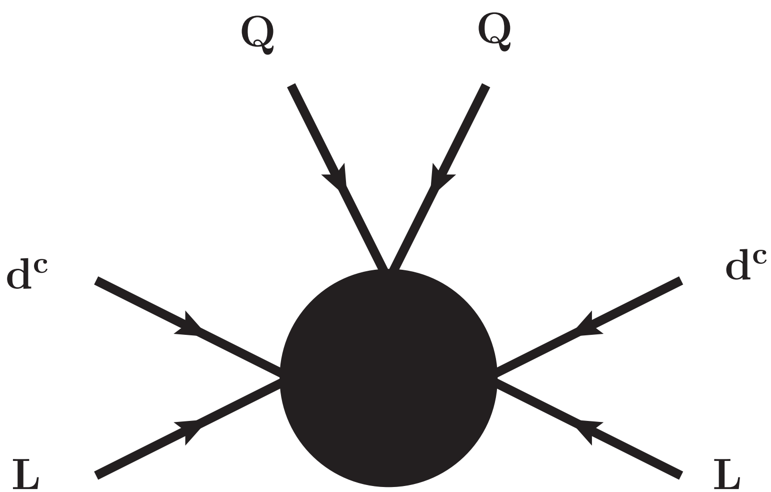
$S_{3,2,1/6}$ - doublet leptoquark

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

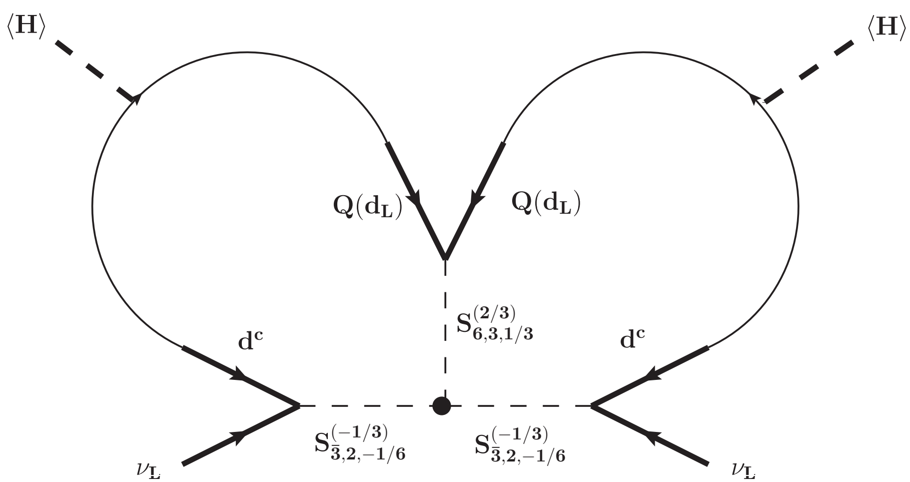
$\Delta L = 2$, so ...

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

True $d = 9$ operator:



Many, many realizations ...
One example:

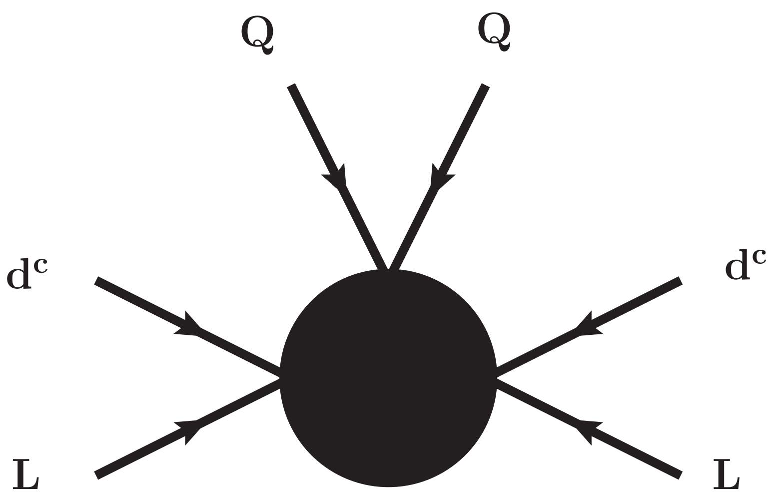


$S_{6,3,1/3}$ - triplet diquark
$S_{3,2,1/6}$ - doublet leptoquark

2-loop neutrino mass!

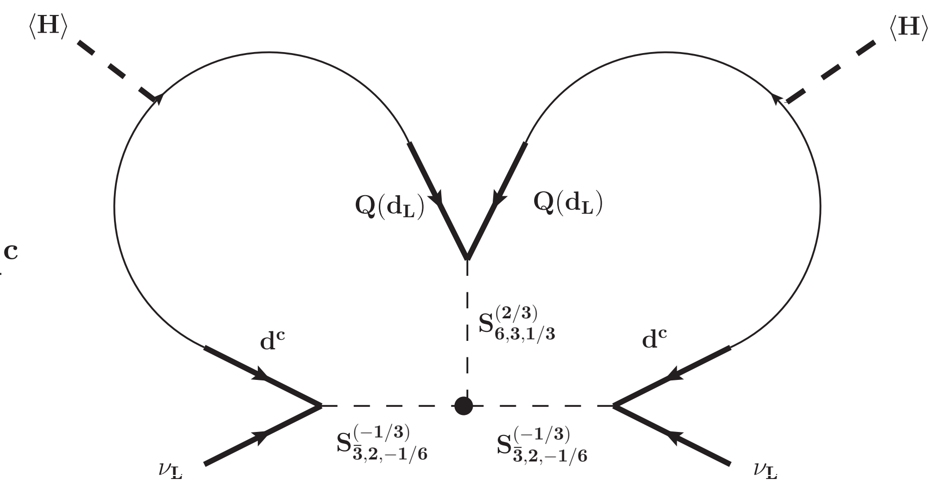
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:

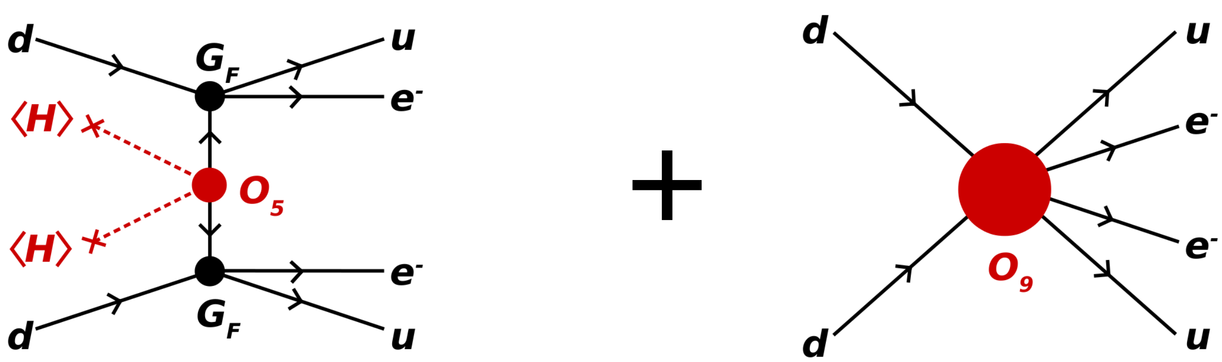


Many, many realizations ...

One example:



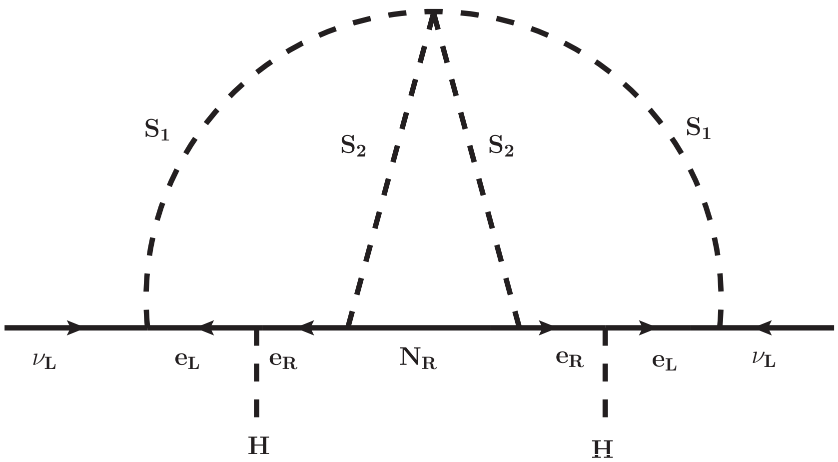
Again, $0\nu\beta\beta$ decay has two contributions:



(a) (c)

m_ν @ 3-loop?

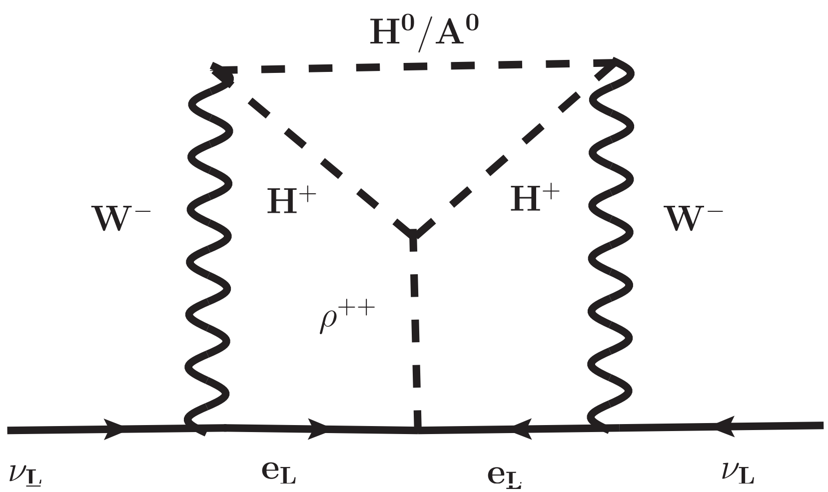
No systematic analysis, but several example models exist:



Krauss, Nasri & Trodden, 2002

Similar diagrams by:

Aoki et al, 2008 & 2011
Culjac et al., 2015



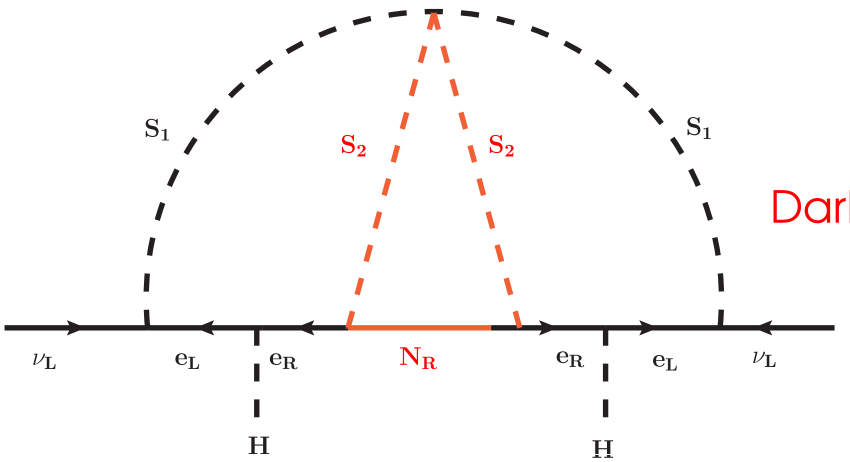
Gustafsson et al, 2012

Similar (but scalar) diagram in:

Kajiyama et al., 2013
(T_7 flavour model)

m_ν @ 3-loop?

No systematic analysis, but several example models exist:



Dark Matter!

Krauss, Nasri & Trodden, 2002

Similar diagrams by:

Aoki et al, 2008 & 2011

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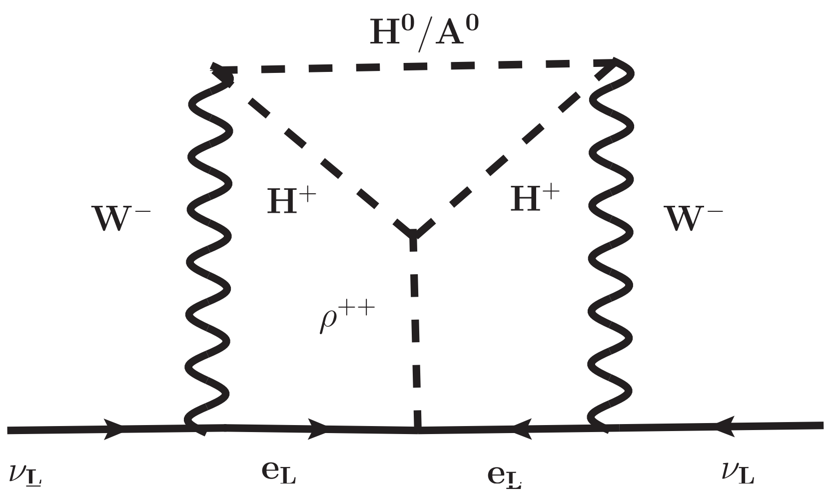


Gustafsson et al, 2012

Similar (but scalar) diagram in:

Kajiyama et al., 2013

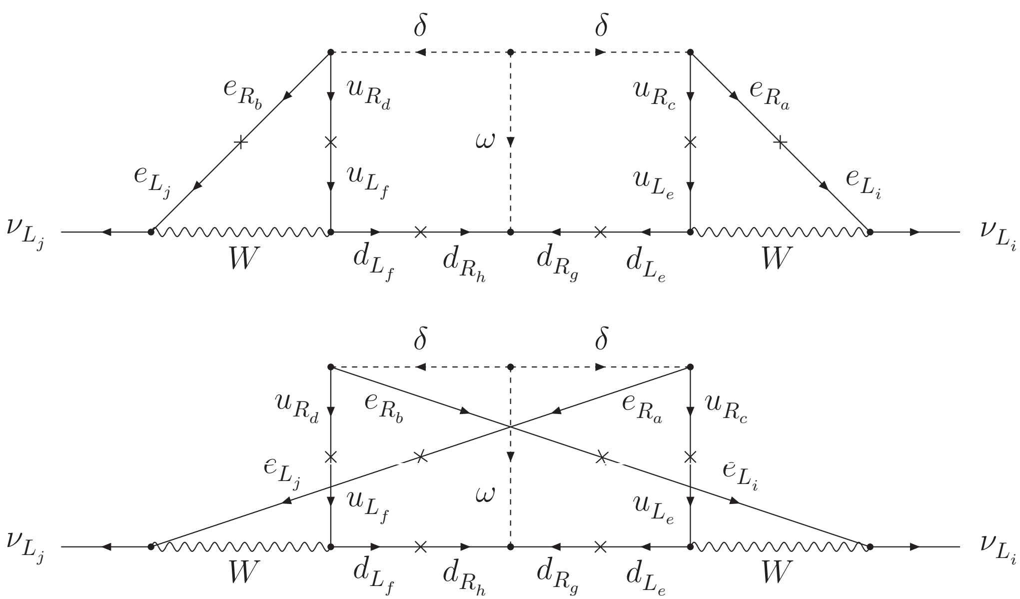
(T_7 flavour model)

m_ν @ 4-loop?

From $d = 9$ operator: Only example!

$$\mathcal{O}_- = \frac{1}{\Lambda^5_{\rm LNV}} e^c e^c u^c u^c \bar{d}^c \bar{d}^c$$

$0\nu\beta\beta$ decay variant TII-5: Bonnet et al., 2013



Gu, 2011

$m_\nu \simeq 10^{-8}$ eV

... because $d = 9$ 4-loop

Needs (Quasi)-Dirac ν's

to explain oscillation data

A few more examples in:

Helo et al., 2015

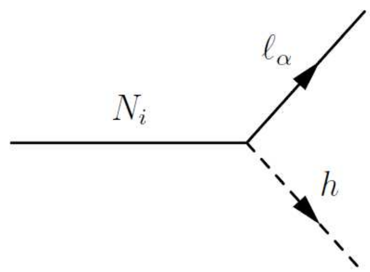
$\mathcal{III}.$

Leptogenesis and LHC

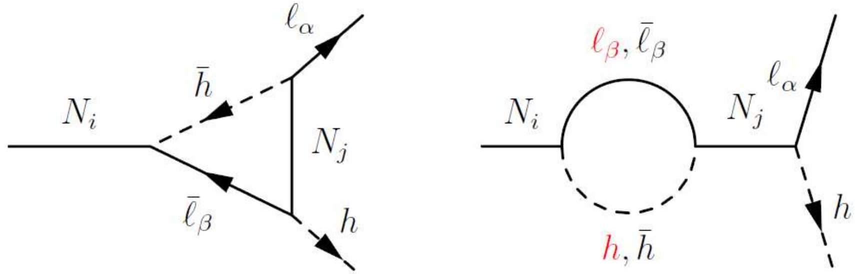
Leptogenesis

Sakharov's conditions:

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



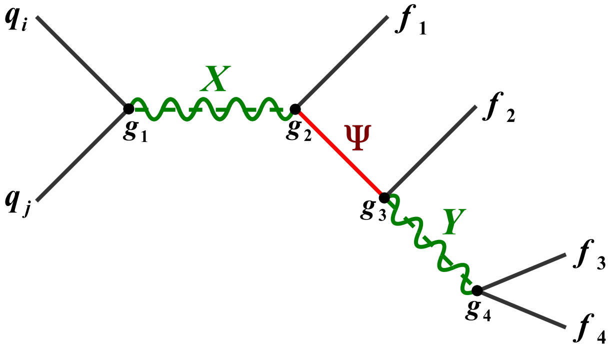
(e) Tree



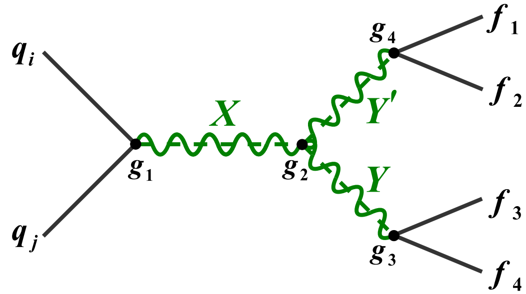
In Leptogenesis:

(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

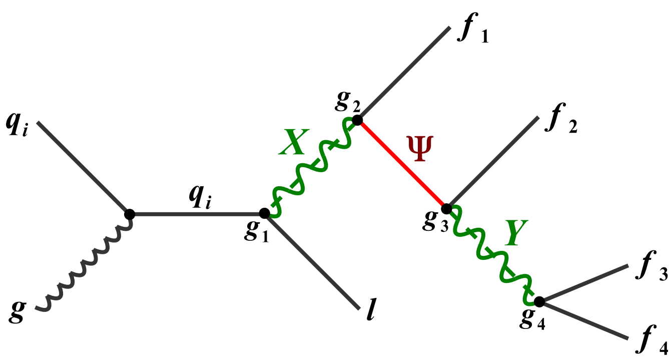
LNV @ LHC



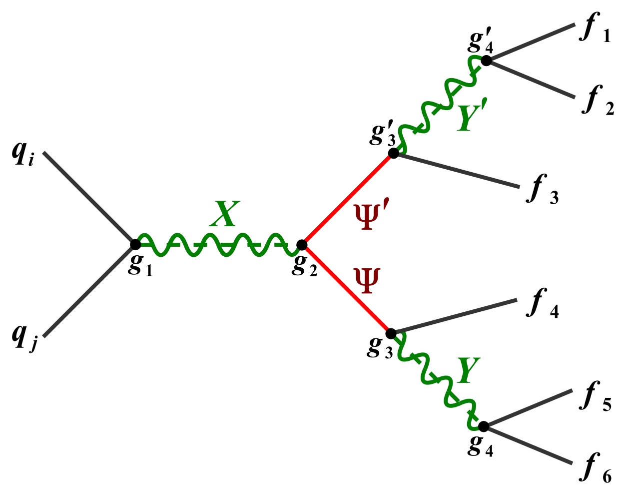
q_i
q_j
X
g_1
g_2
Ψ
g_3
Y
g_4
f_1
f_2
f_3
f_4



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

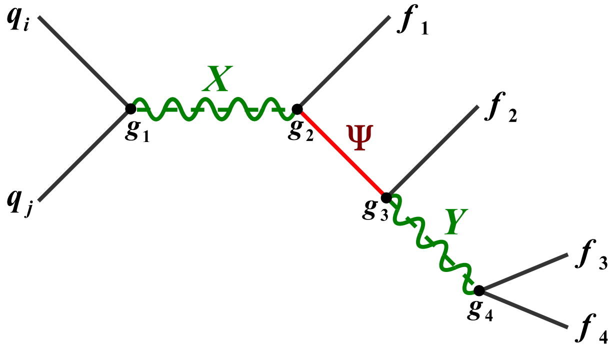


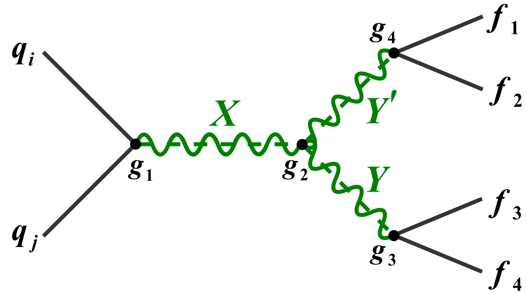
q_i
g
q_i
g_1
l
X
g_2
Ψ
g_3
Y
g_4
f_1
f_2
f_3
f_4



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

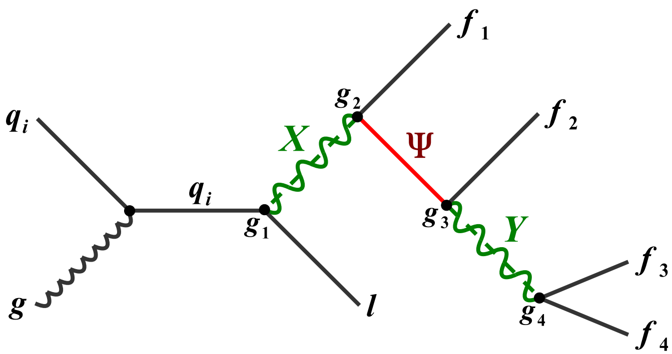
LNV @ LHC

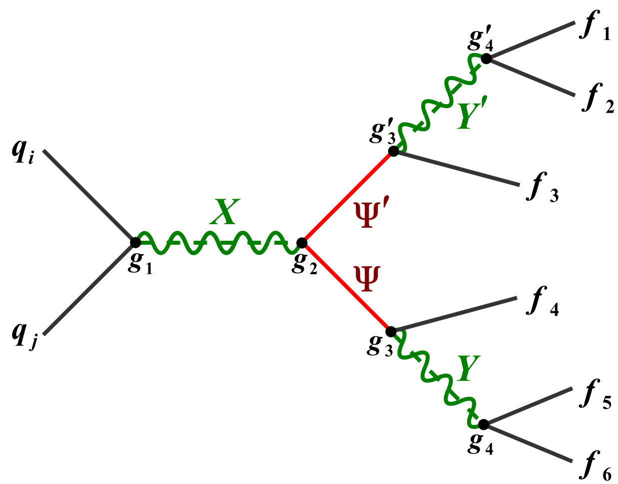




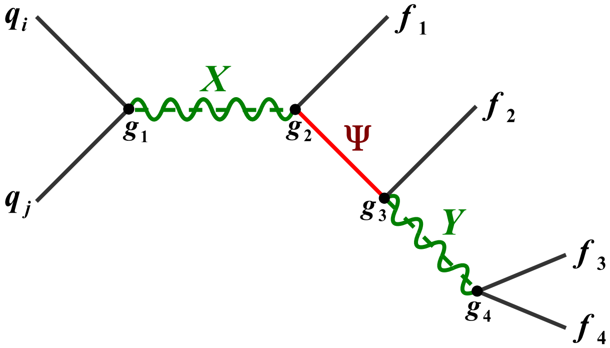
Example:

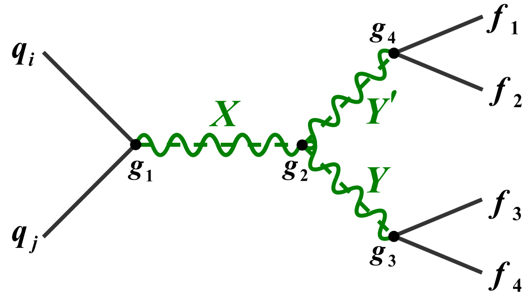
$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$





LNV @ LHC



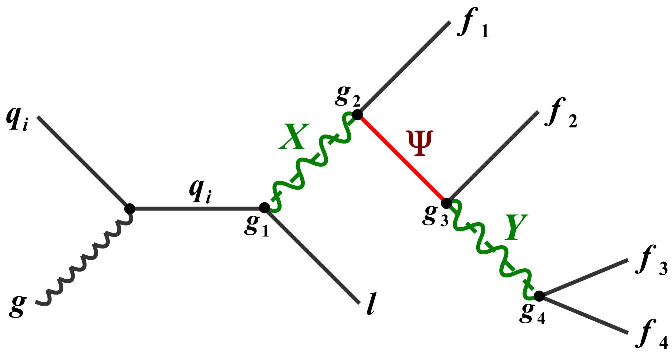


Example:

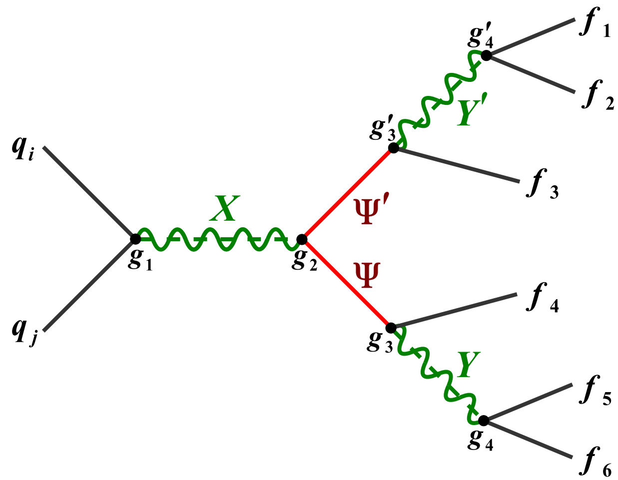
$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$

Example:

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



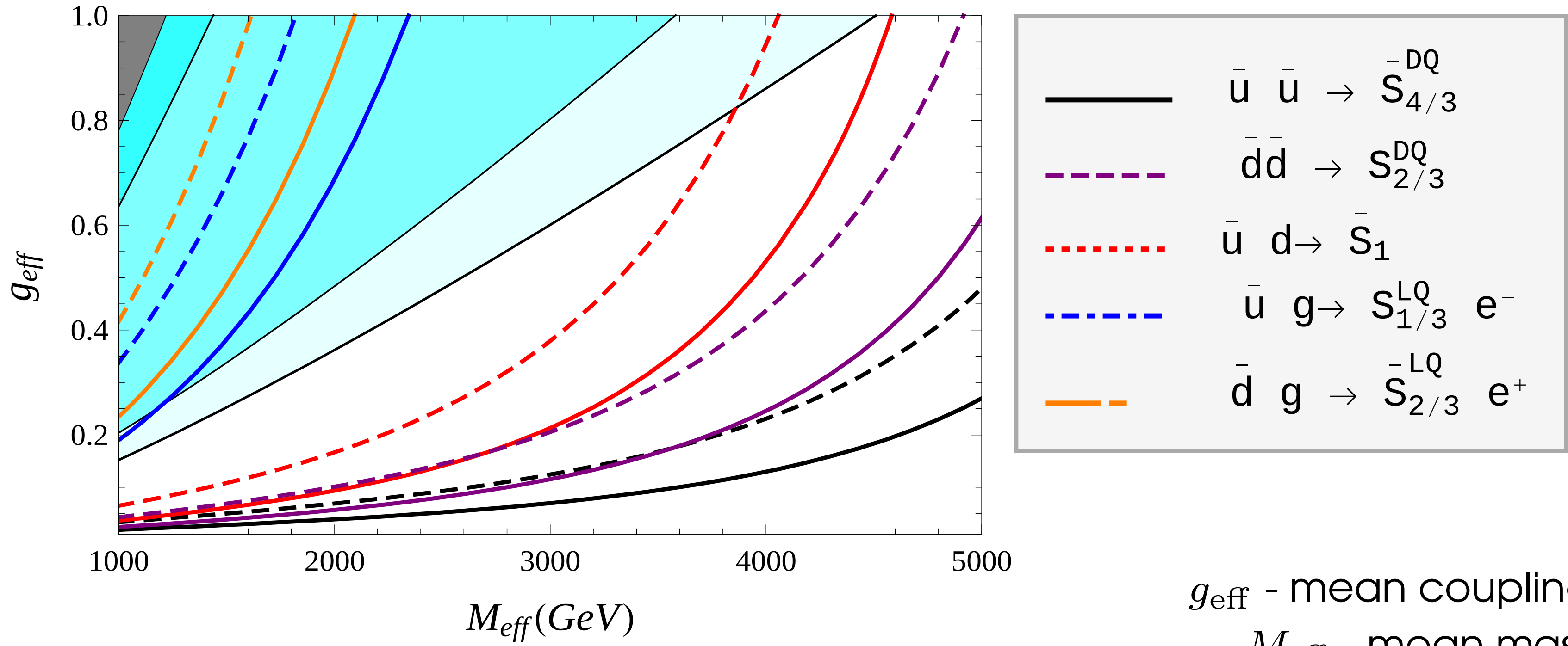
$ug \to S_{3,1,1/3} + l^+ \to l^+ l^+ jjj$



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

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

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



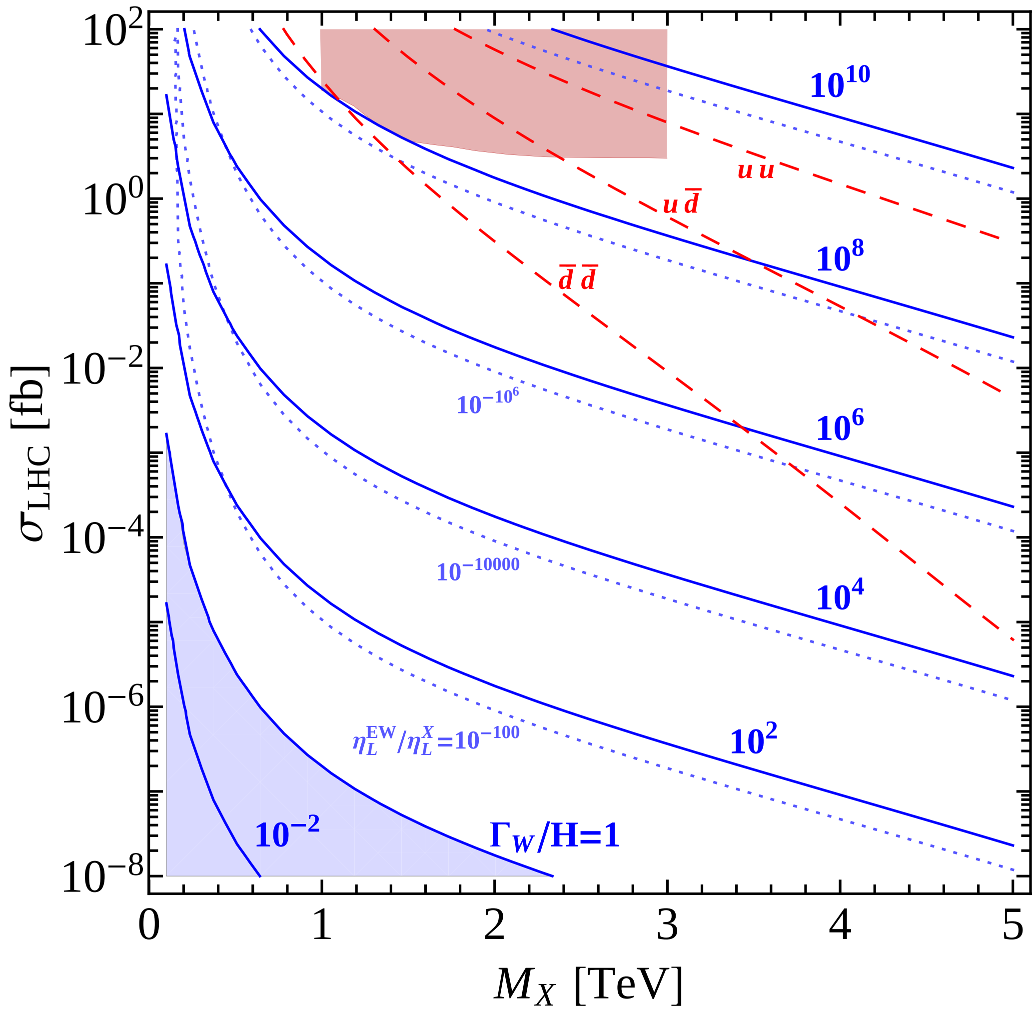
$g_{\rm eff}$ - mean coupling
$M_{\rm eff}$ - mean mass

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

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

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

Leptogenesis and LHC



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

Deppisch, Hartz & Hirsch (2014)

blue lines washout factor Γ_W

- Suppression of L $\propto 10^{-\Gamma_W}$

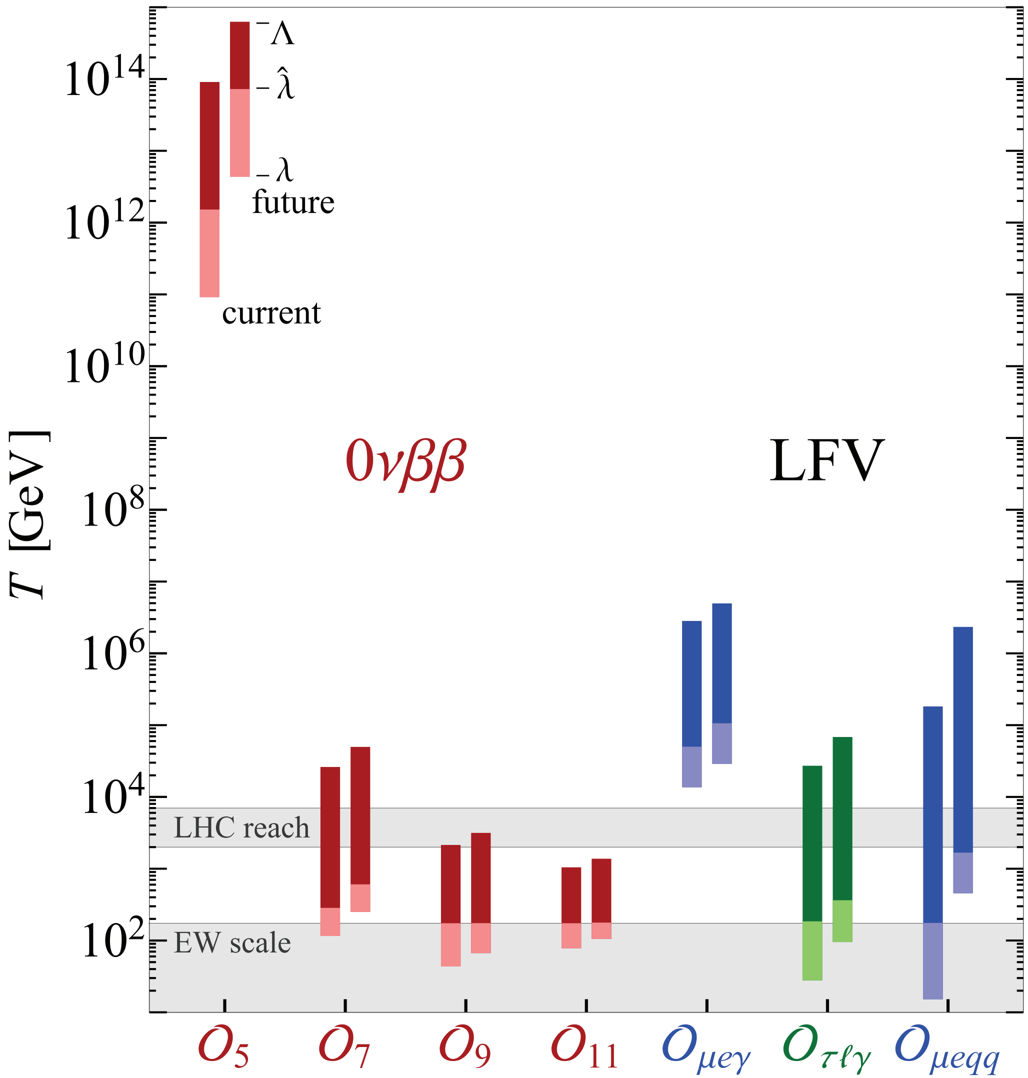
Observation of LNV @ LHC implies: (High-scale) Leptogenesis is ruled out!

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

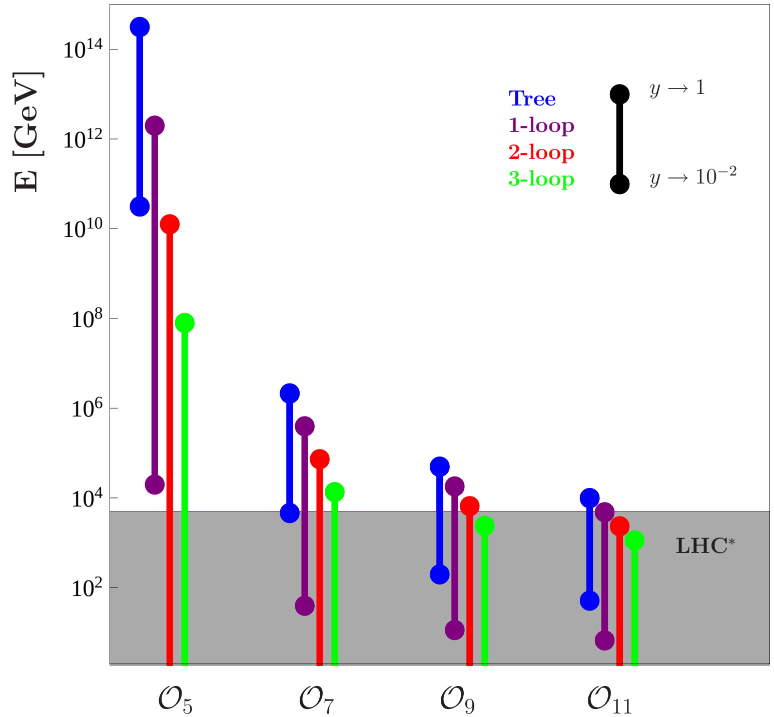
Conclusions

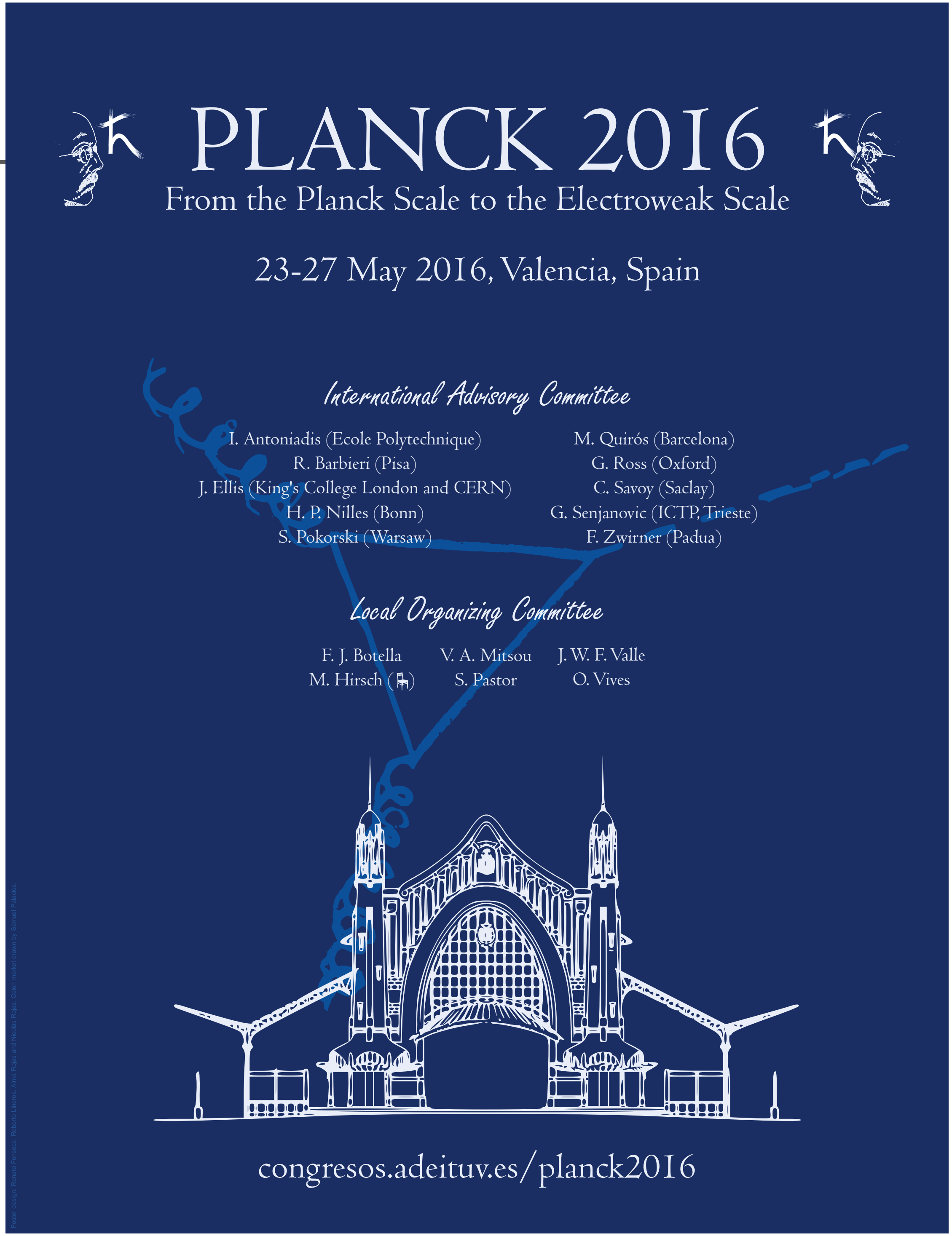
LNV & $0\nu\beta\beta$ decay:

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

⇒ What is the scale of LNV?

⇒ Observation of LNV at LHC implies high-scale leptogenesis ruled out

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