Neutrinos - Theory

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Outline

$\mathcal{I}$. Introduction

$\mathcal{II}$. Trees and Loops

$\mathcal{III}$. $0\nu\beta\beta$, LNV and m_ν

$\mathcal{IV}$. LNV and LHC

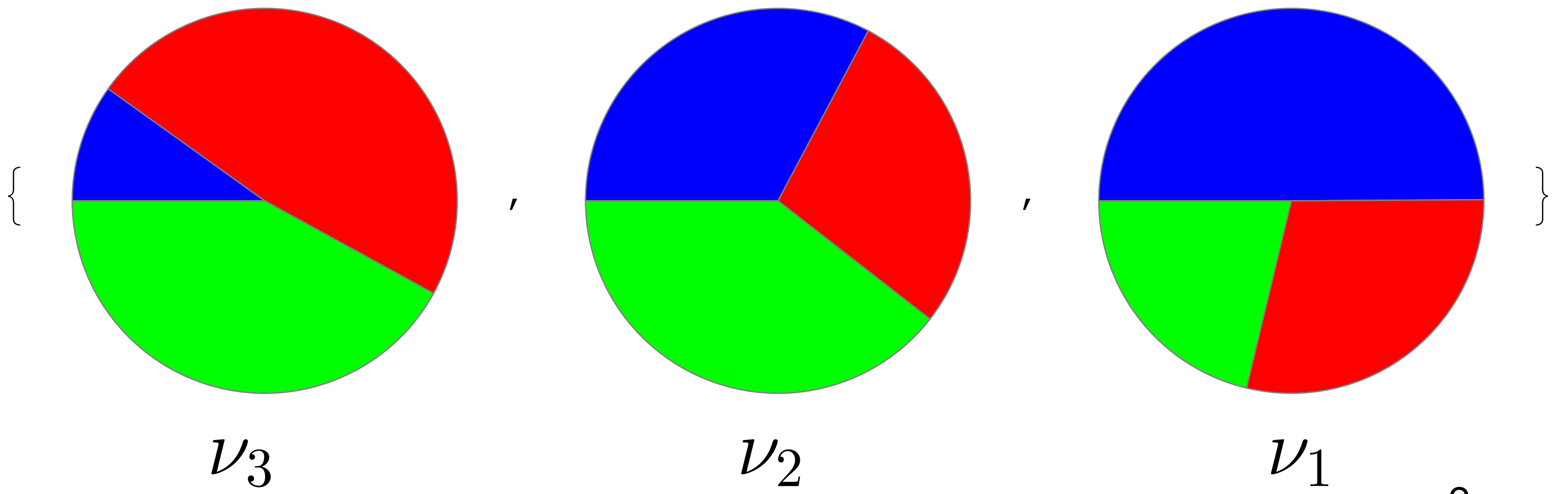
$\mathcal{V}$. Summary

$\mathcal{I}$.

Introduction

What we know

Experimental
overview Talk:
K Scholberg



ν_e

ν_μ

ν_τ

See global fits by
Bari group:
Capozzi et al., 2014
Valencia group:
Forero et al., 2014

$$\Delta m^2_{\rm Atm} = (2.2 - 2.7) \times 10^{-3} \text{ eV}^2$$

$$\Delta m^2_{\odot} = (7.1 - 8.2) \times 10^{-5} \text{ eV}^2$$

GERDA, EXO
KamLAND-Zen

$$\langle m_\nu \rangle \lesssim (0.2 - 0.4) \text{ eV}$$

Limit still from: Mainz & Troitsk

$$m_\beta \lesssim 2.2 \text{ eV}$$

Planck & BAO

$$\sum_i m_{\nu_i} \lesssim (0.23 - 0.68) \text{ eV}$$

Open questions

Open questions

$\Rightarrow$ Are neutrinos Majorana particles?

Dirac $\mathcal{M}_\nu$

If Lepton Number is Conserved:

$$\mathcal{L} = \mathcal{L}^{SM} + Y_{ij}^{\nu} \bar{L}_i H \nu_{R,j}$$

Experimental data requires: $|Y_\nu| \simeq 10^{-12}$

Fit to all oscillation data possible and simple, but ...

$\Rightarrow$ Any "predictions" of this scenario???

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Fit to all oscillation data possible and simple, but ...

$\Rightarrow$ Any "predictions" of this scenario???

(i) No double beta decay

(ii) No charged lepton flavour violation

(iii) No Accelerator tests

$\Rightarrow$ Experimentalists only measuring a "bunch of Yukawas"

$\Rightarrow$ To exclude this scenario: MUST observe a $\Delta L = 2$ process

Open questions

$\Rightarrow$ Are neutrinos Majorana particles?

A: Observe LNV!

Open questions

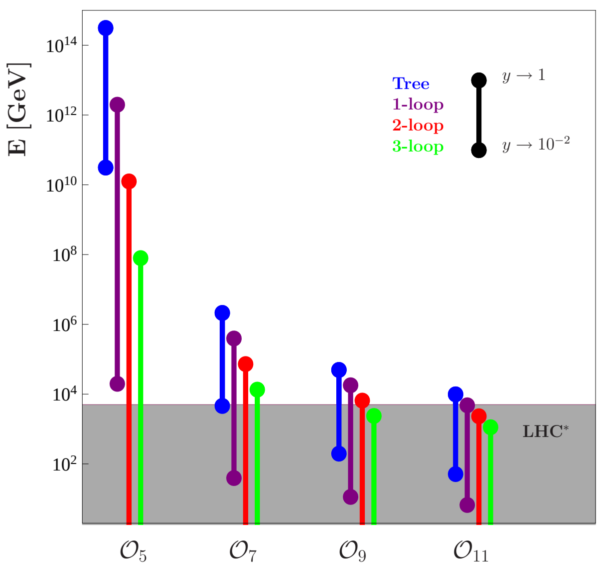
⇒ Are neutrinos Majorana particles?

A: Observe LNV!

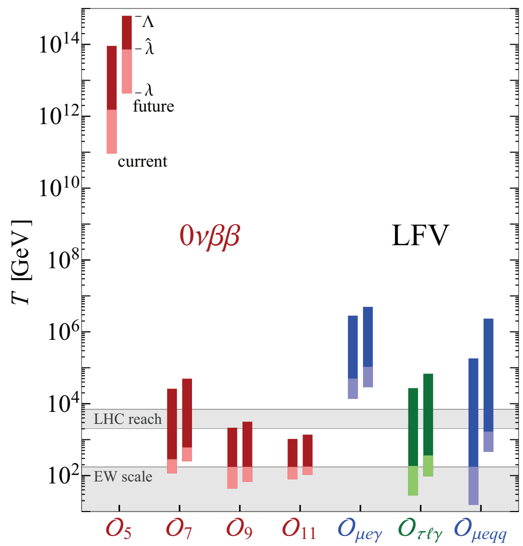
⇒ What is the energy scale of LNV?

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

m_ν:



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



Open questions

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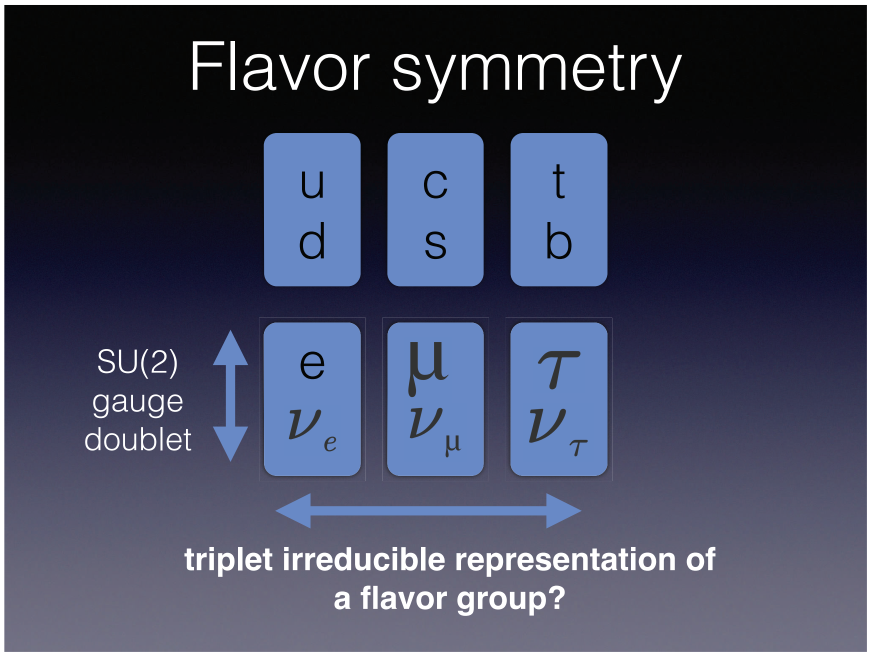

See talks by:
S. Morisi
A. Merle

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

Open questions

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⇒ Can we understand flavour structure?

⇒ Are neutrinos related to DM?

→ (keV sterile) Neutrinos could be DM — Talk by: T. Asaka

→ 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

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

⇒ Can we predict CPV?

Talks by: H. Minakata
M.-C. Chen
A. Titov
M. Tanimoto

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⇒ Are neutrinos linked to the BAU?

Talks by: J. Harz
B. Dev

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⇒ Are there more than 3 light neutrinos?

Talks by: J. Kopp
G. Collin

Open questions

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⇒ Are there more than 3 light neutrinos?

⇒ Normal hierarchy or Inverted Hierarchy?

⇒ Others ...

$\mathcal{II}$.

Majorana neutrinos:

A tale of

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:

Minkowski, 1977

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

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:

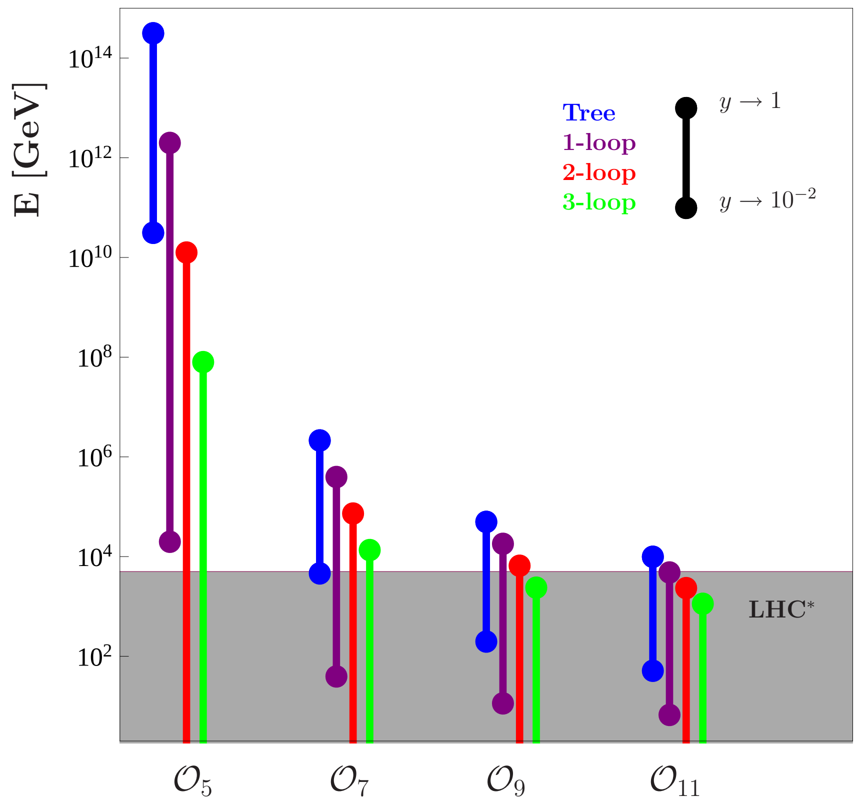
⇒ High scale: Large Λ
"classical" seesaw

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

⇒ Higher order: $d = 7, 9, 11$

⇒ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

$\cdots$ or combination thereof



Effective operators $d \geq 5$

$d = 5$: Weinberg, 1979

$$\mathcal{O}_W \propto (LH)(LH)$$ One d=5

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$d = 5$: Weinberg, 1979

$$\mathcal{O}_W \propto (LH)(LH)$$

One d=5

$d = 7$: Babu & Leung, 2001

de Gouvea & Jenkins, 2007

4 (+1) $d = 7$

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

$$\mathcal{O} \propto (LH)(LH)(H_uH_d)$$

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

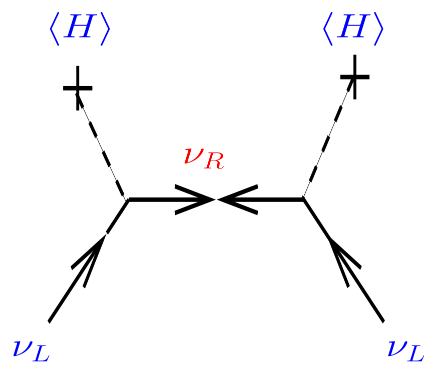
$$\mathcal{O}_5 \propto LLQd^cHHH^\dagger$$
$$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^cHH^\dagger H$$
$$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$$
$$\ldots\ldots$$

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

$d = 5$ tree-level: Seesaw

Seesaw type-I, right-handed neutrinos:

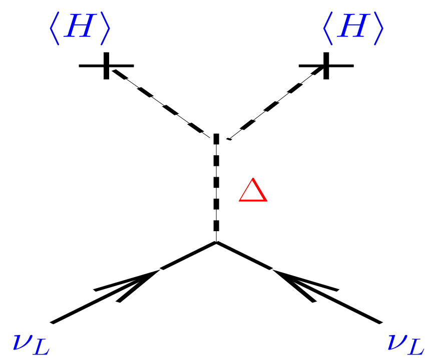
$$m_{1/2} \simeq (-\frac{Y_\nu^2 v^2}{M_M}, M_M)$$



For $M_M \sim 10^{15}$ GeV $\Rightarrow Y_\nu \sim 1$

Seesaw type-II, scalar triplet:

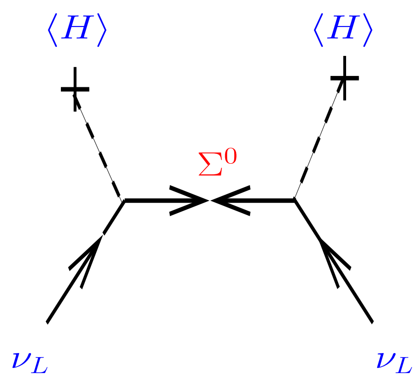
$$m_\nu \simeq Y_T \langle \Delta_L^0 \rangle \simeq Y_T v^2 \frac{\mu_\Delta}{m_\Delta^2}$$



For $m_\Delta \simeq \mu_\Delta \sim 10^{15}$ GeV $\Rightarrow Y_T \sim 1$

Type-III: Replace ν_R by $\mathbf{\Sigma} = (\Sigma^+, \Sigma^0, \Sigma^-)$:

$$m_{1/2} \simeq (-\frac{Y_\Sigma^2 v^2}{M_\Sigma}, M_\Sigma)$$



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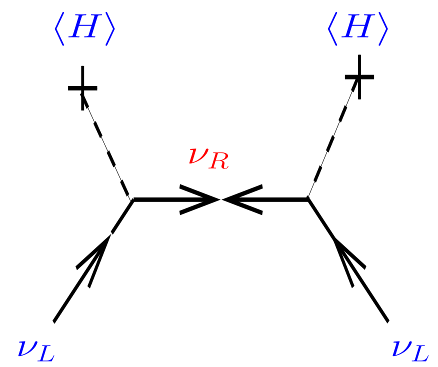
Seesaw: Near EW scale

Seesaw type-I, right-handed neutrinos:

$$m_{1/2} \simeq \left(-\frac{Y_\nu^2 v^2}{M_M}, M_M\right)$$

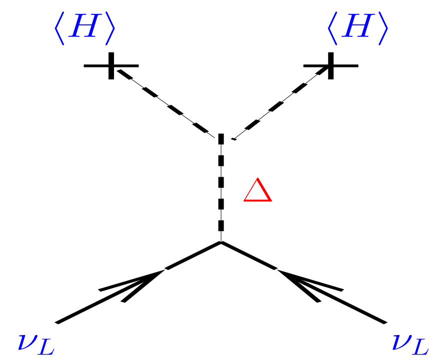
For $M_M \sim 100$ GeV $\Rightarrow Y_\nu \sim 10^{-7}$



Seesaw type-II, scalar triplet:

$$m_\nu \simeq Y_T \langle \Delta_L^0 \rangle \simeq Y_T v^2 \frac{\mu_\Delta}{m_\Delta^2}$$

For $m_\Delta \simeq 100$ GeV and $\mu_\Delta \sim 1$ eV $\Rightarrow Y_T \sim 1$



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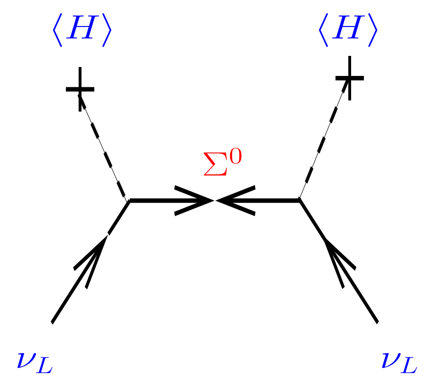


Linear & inverse seesaw

Inverse seesaw, basis (ν, ν^c, S):

Mohapatra & Valle, 1986

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

After EWSB the effective light neutrino mass matrix is given by

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

Linear seesaw:

Akhmedov et al., 1995

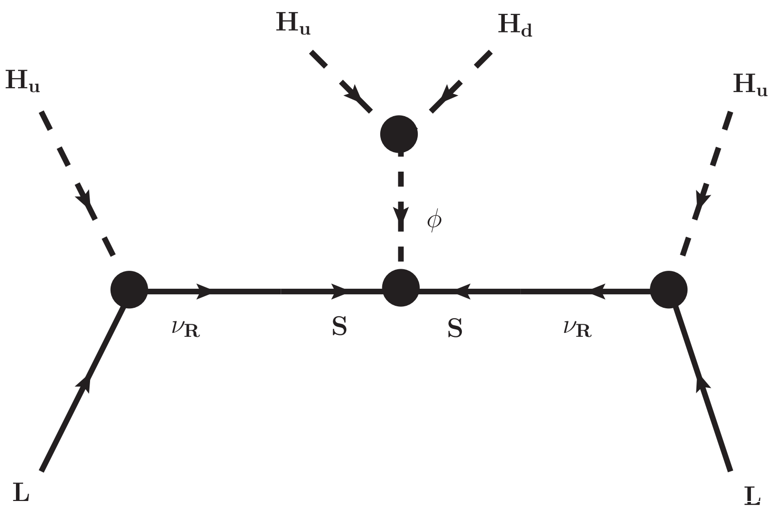
$$M_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M \\ M_L^T & M^T & 0 \end{pmatrix}.$$

Light neutrino mass:

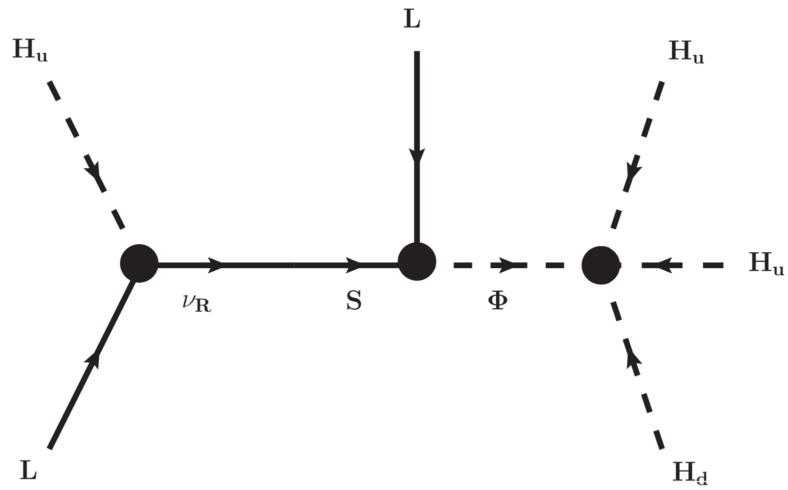
$$M_\nu = m_D (M_L M^{-1})^T + (M_L M^{-1}) {m_D}^T$$

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

"Open" $d = 7$ operator. Two examples: Bonnet et al., 2009



Inverse seesaw



Linear seesaw

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

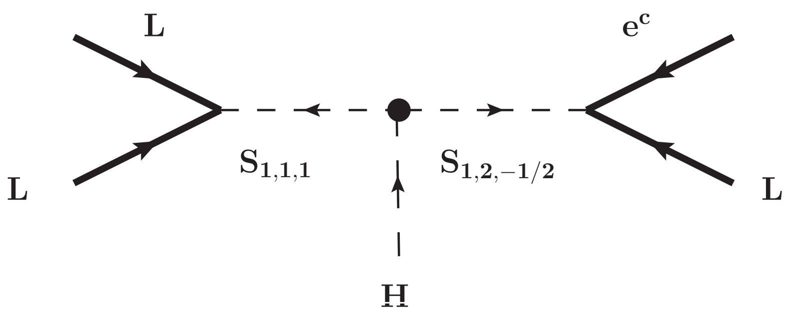
Requires at least 2 Higgses, example: H_u, H_d

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

$\mathcal{O}_2 \propto LLLe^cH$

One more example, open $d = 7$:

Babu & Leung, 2001



Only few possible decompositions

Cai et al., 2014

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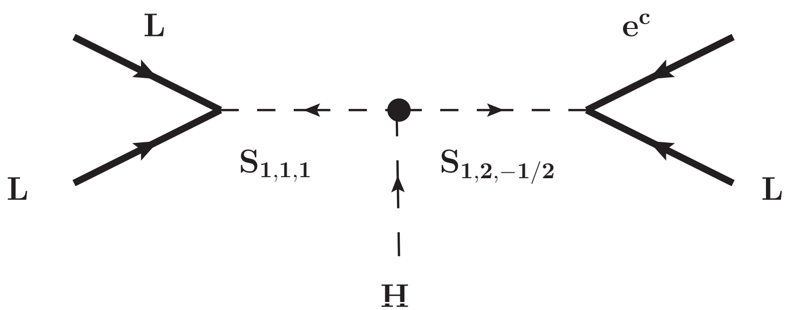
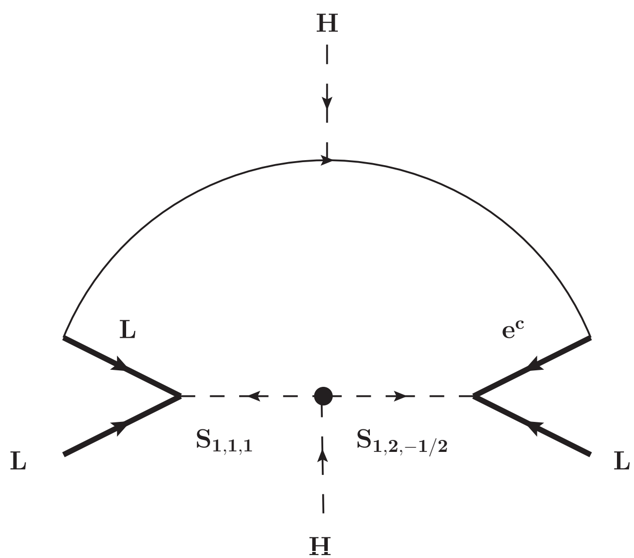


Only few possible decompositions

Cai et al., 2014

Close using SM Yukawa interaction:

Zee, 1980



proto-type 1-loop neutrino mass model

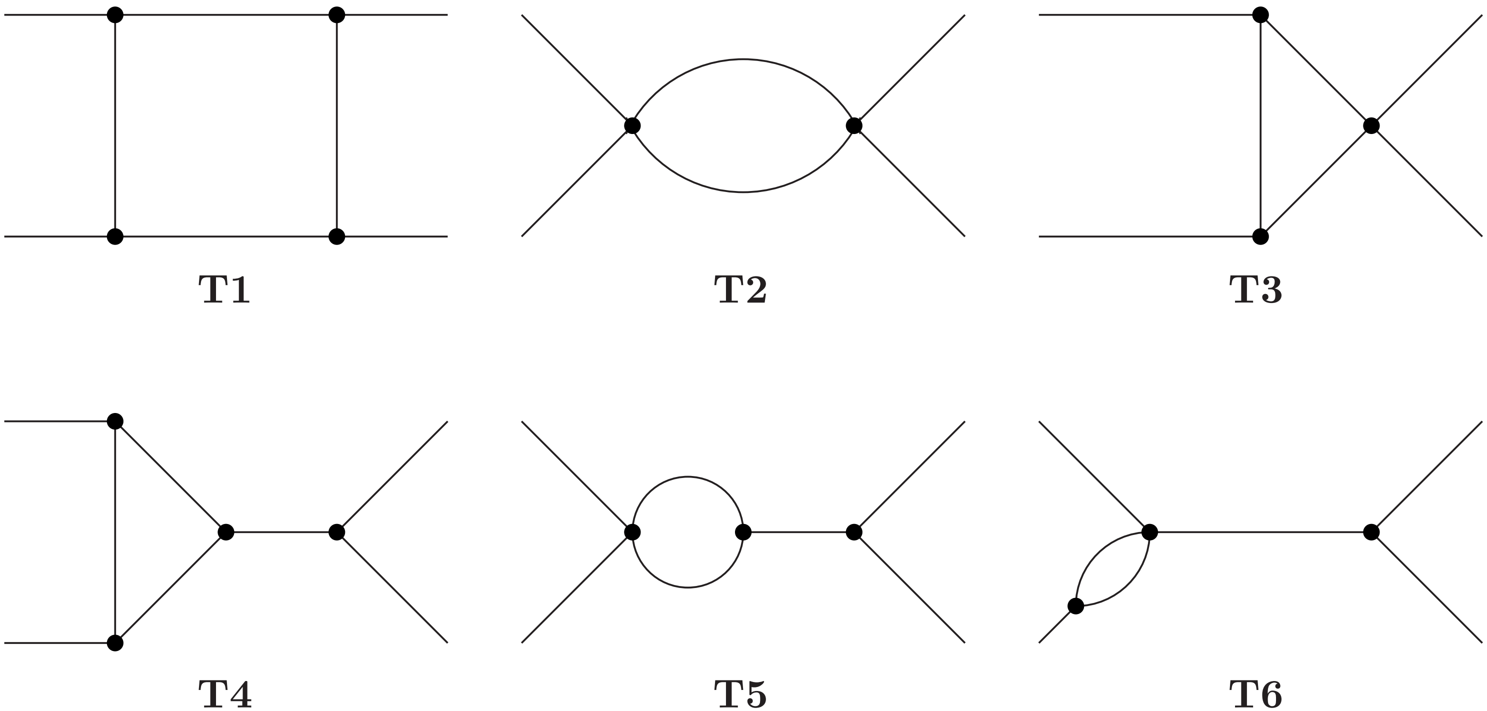
"Zee-model"

$m_\nu \Rightarrow$ d=5 1-loop

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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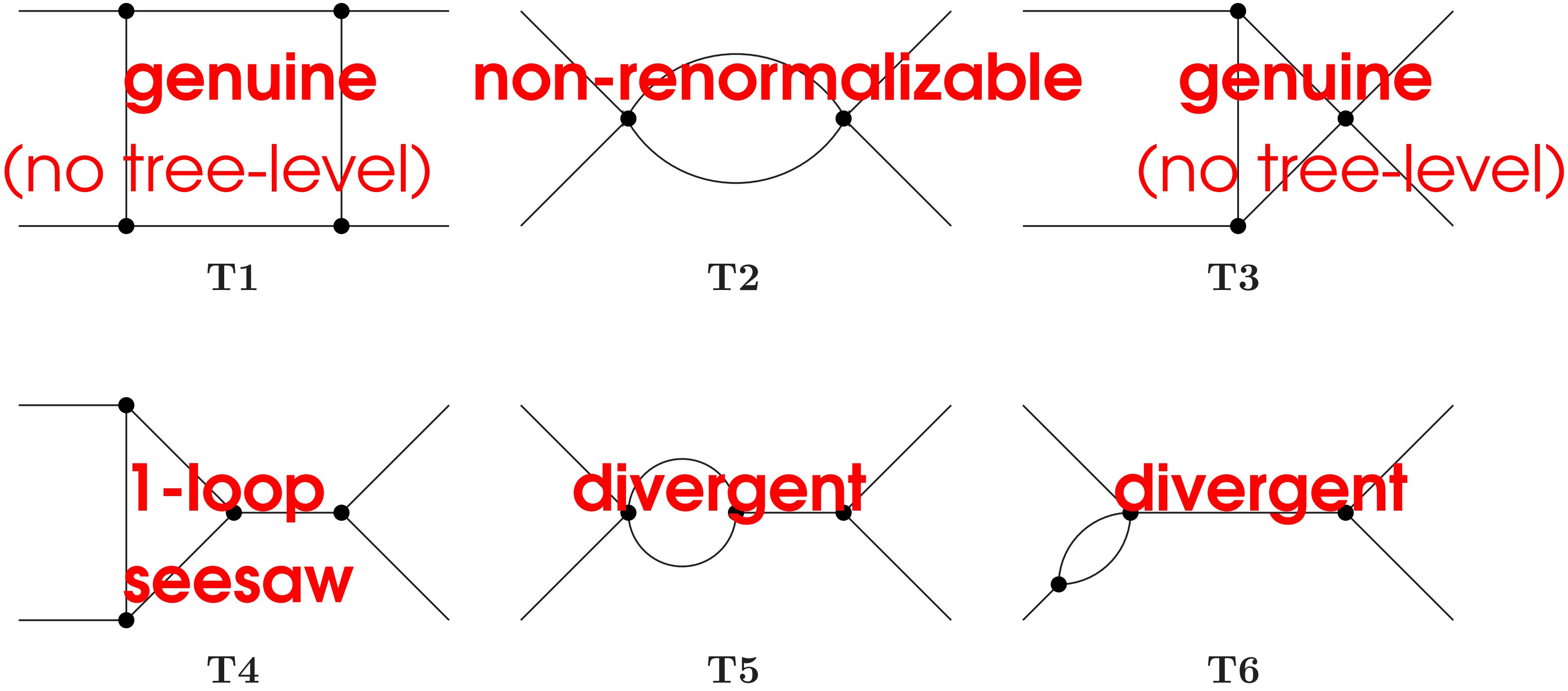

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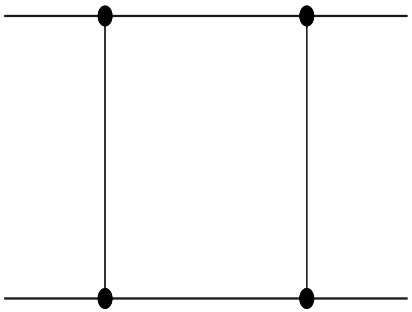
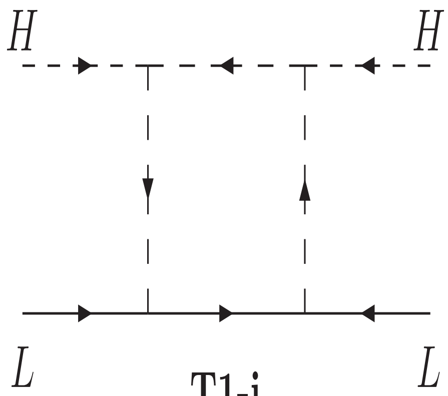
Topology-1



T1

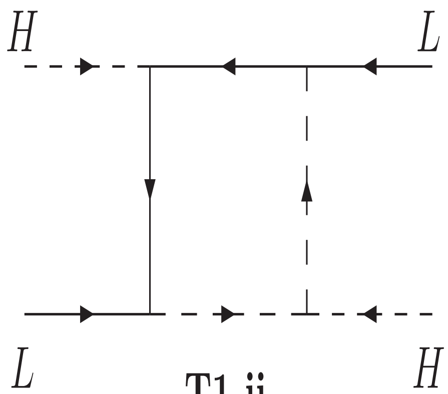


T1-i

Dark doublet model

Ma, 2006

Kubo, Ma & Suematsu, 2006



T1-ii

Zee, 1980

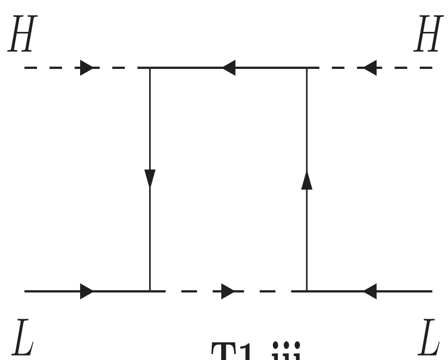
Zee model

Cheng & Li, 1980

Hall & Suzuki, 1984

R-parity violating SUSY

trilinear loop



T1-iii

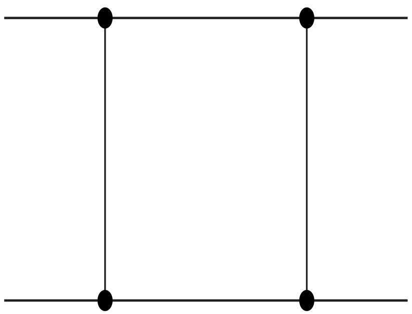
Ma, 1998

Hall & Suzuki, 1984

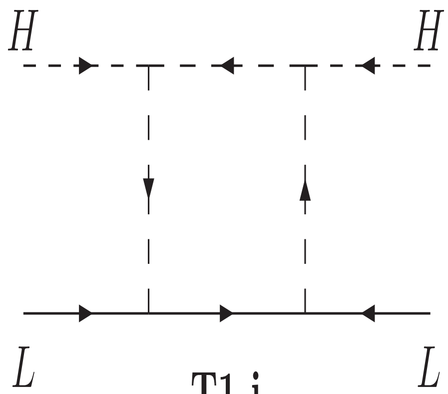
R-parity violating SUSY

bilinear-trilinear loop

Topology-1



T1



T1-i

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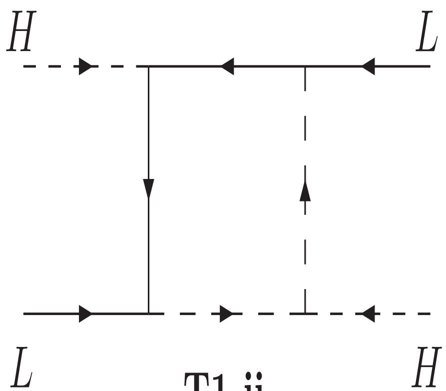

T1-ii

Zee, 1980

Zee model

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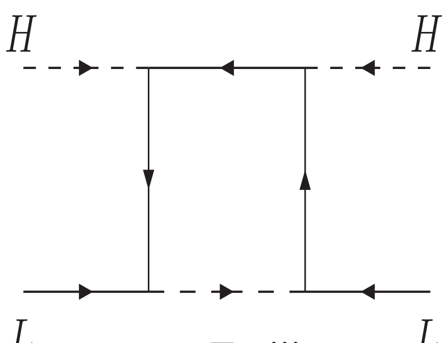
R-parity violating SUSY

trilinear loop

many, many more references ...



T1-iii

Ma, 1998

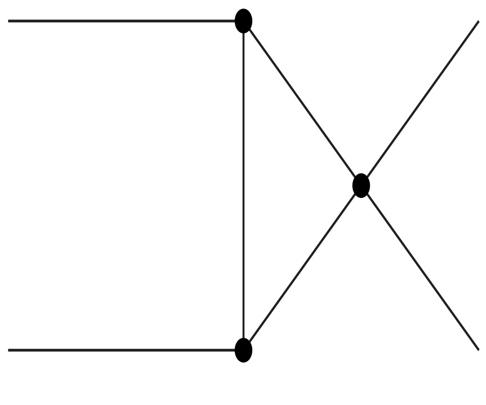
Hall & Suzuki, 1984

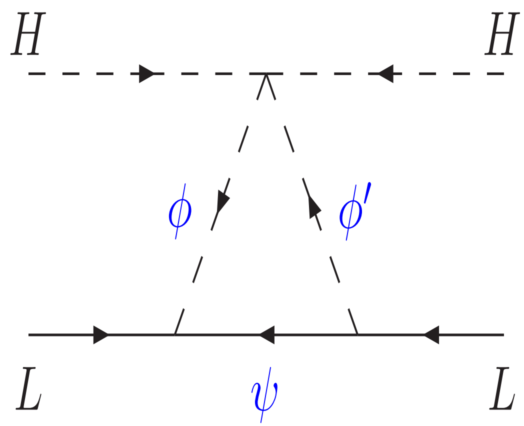
R-parity violating SUSY

bilinear-trilinear loop

Apologies for not citing YOUR model here!

Topology-3



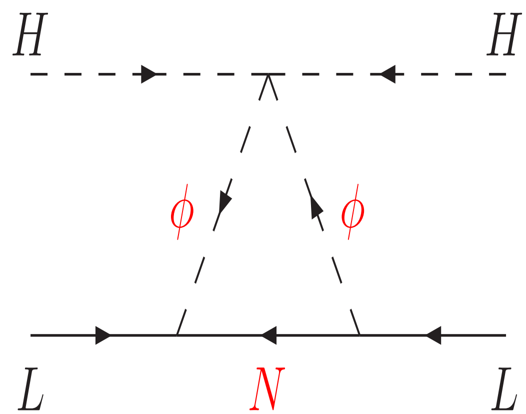


Ma, 1998
Ma, 2006

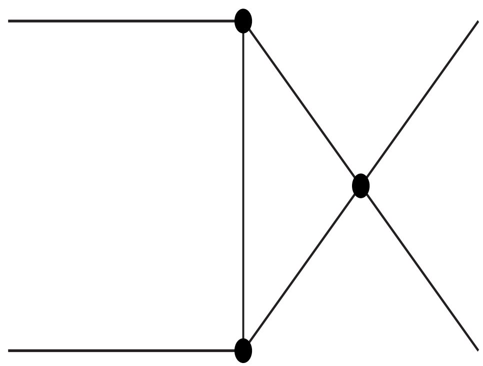
Systematically:

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

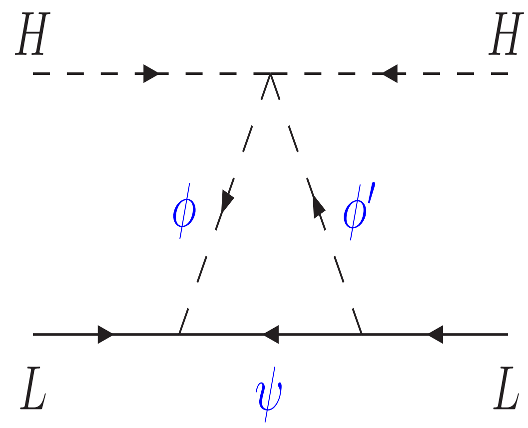
$\Leftarrow$ If $\alpha = -1$ and ψ has a Majorana mass ($\psi = N$) 1-loop correction to type-I, unless Z_2 symmetry forbids v_ϕ Dark Matter!



Topology-3



T3



Ma, 1998
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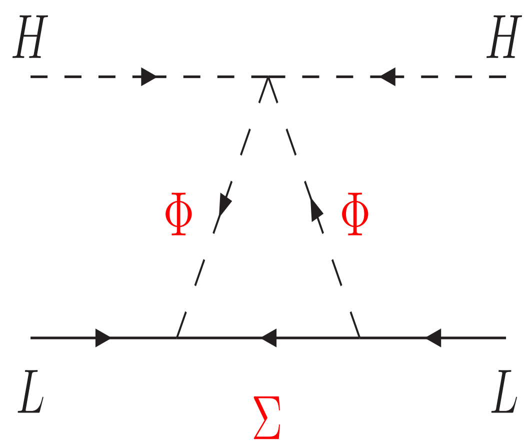
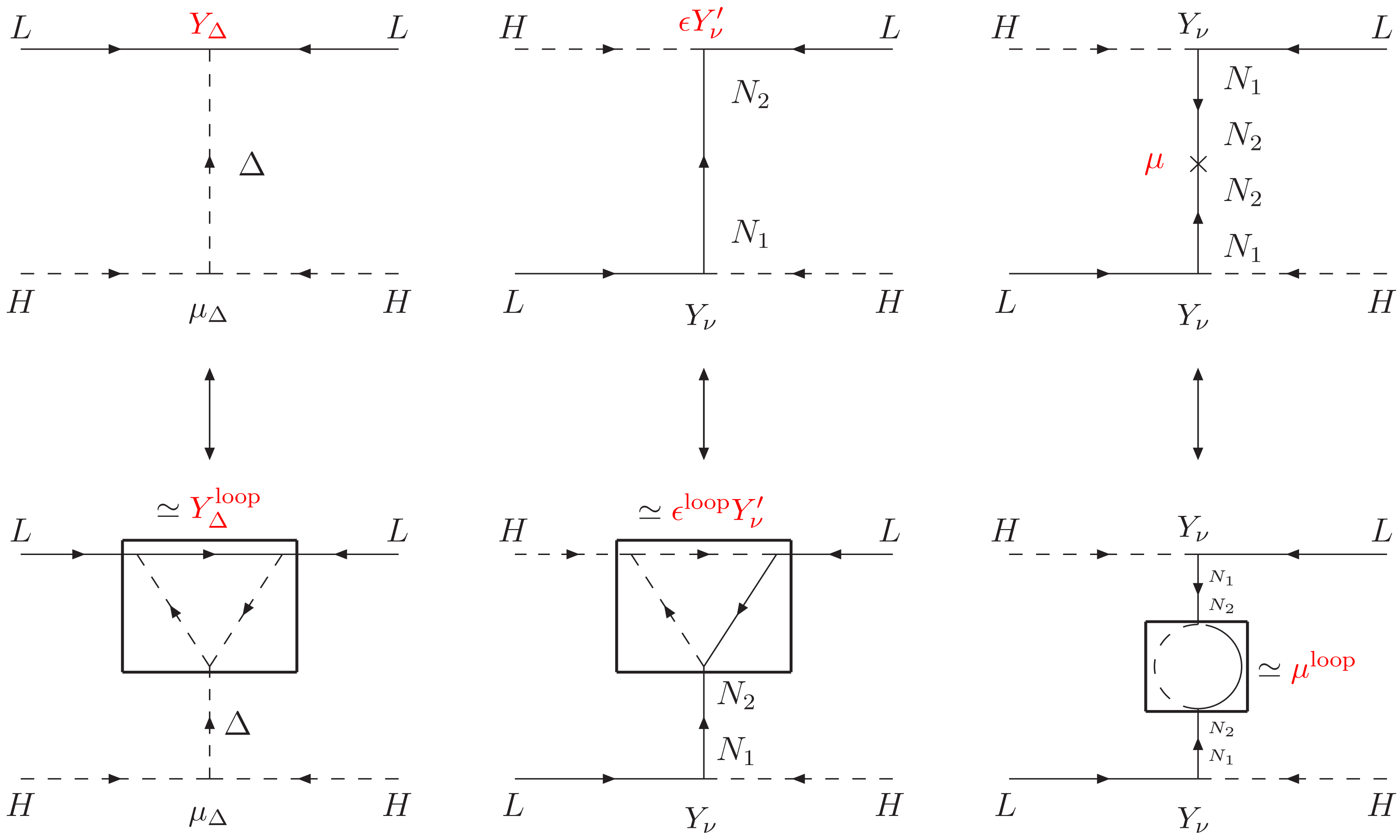
$\Leftarrow$ If $\alpha = -1$ and ψ has a Majorana mass ($\psi = \Sigma$) 1-loop correction to type-III, unless Z_2 symmetry forbids v_ϕ Dark Matter!



T-4: Loop generated vertices

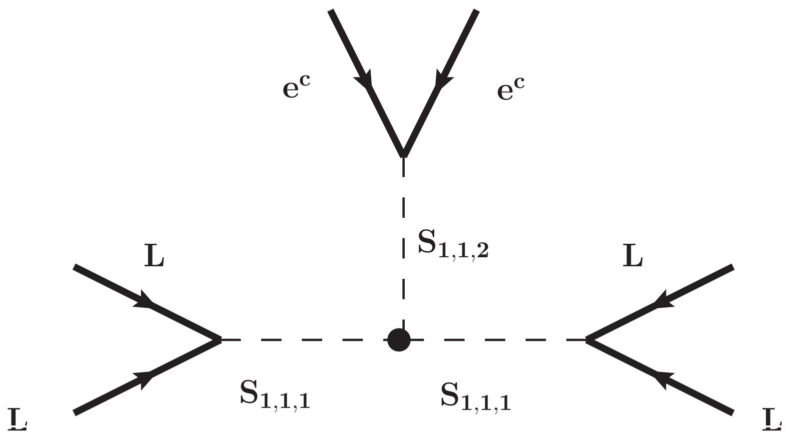
Bonnet et al., 2012



T4-2-i **T4-3-i** **self-energy**

$\mathcal{O}_9 \propto LLLe^cLe^c$

One example for $d = 9$: Babu & Leung, 2001



$$S_{1,1,2} \to k^{++}$$
$$S_{1,1,1} \to h^{+}$$

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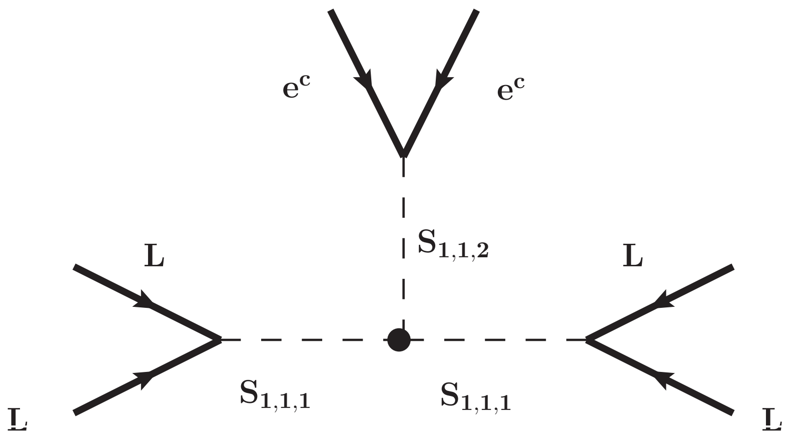
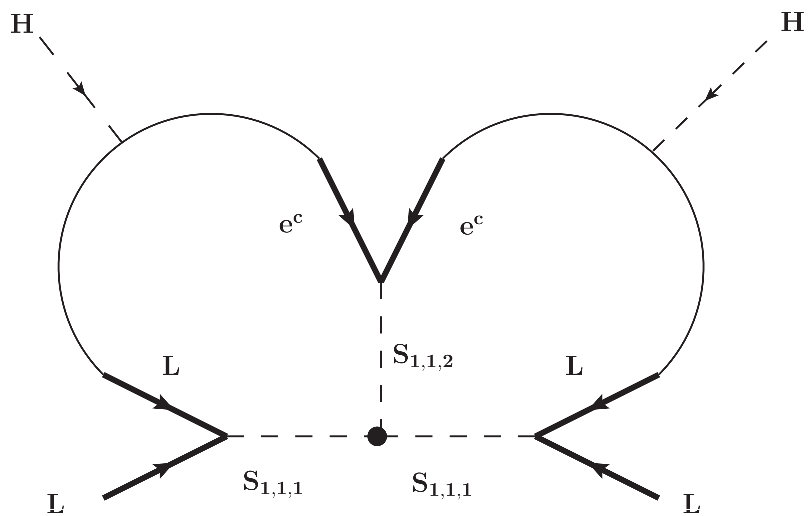


Close using SM Yukawa interaction:

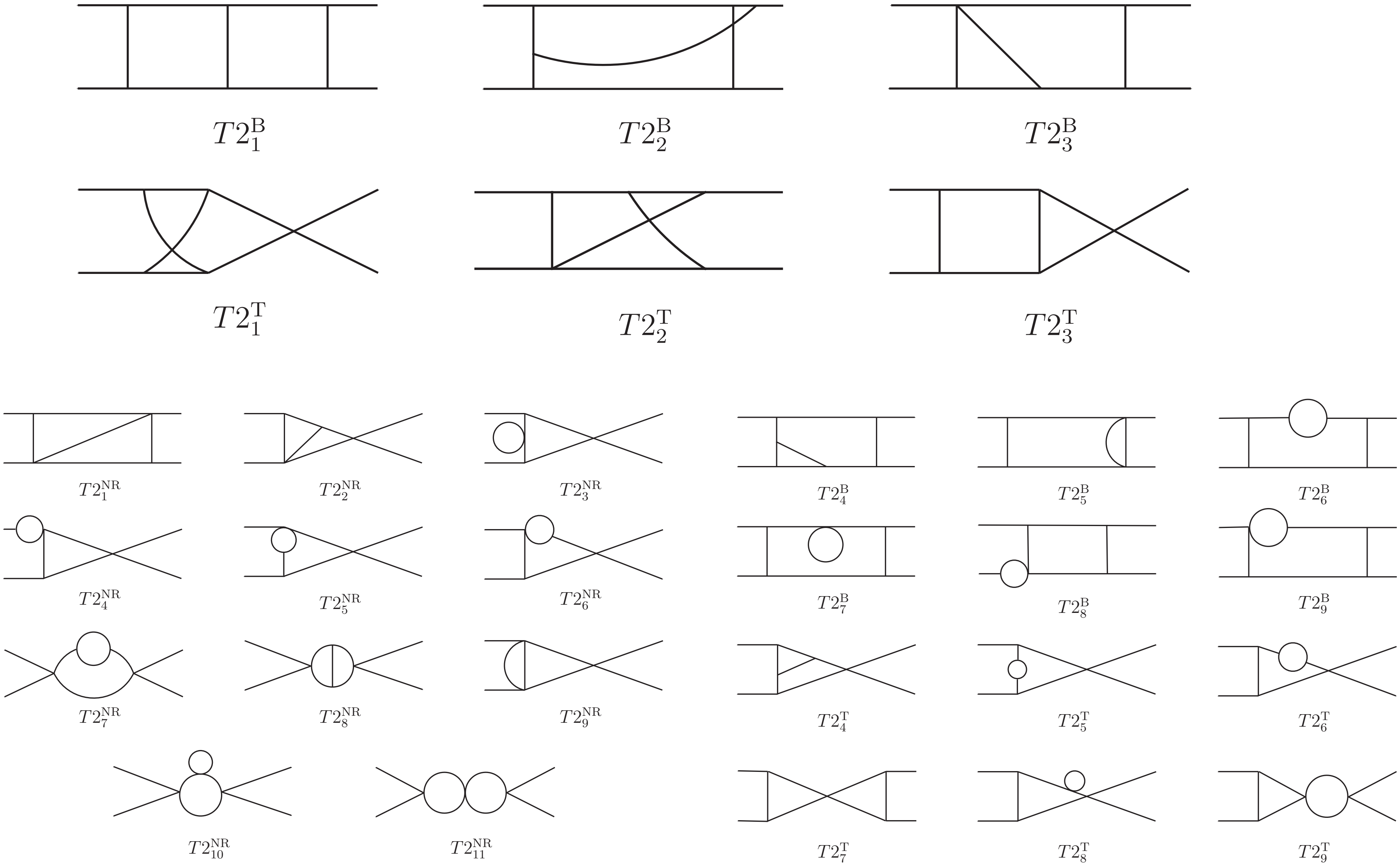
"Cheng-Li-Babu-Zee" - model

Babu, 1988
Zee, 1986
Cheng & Li, 1980



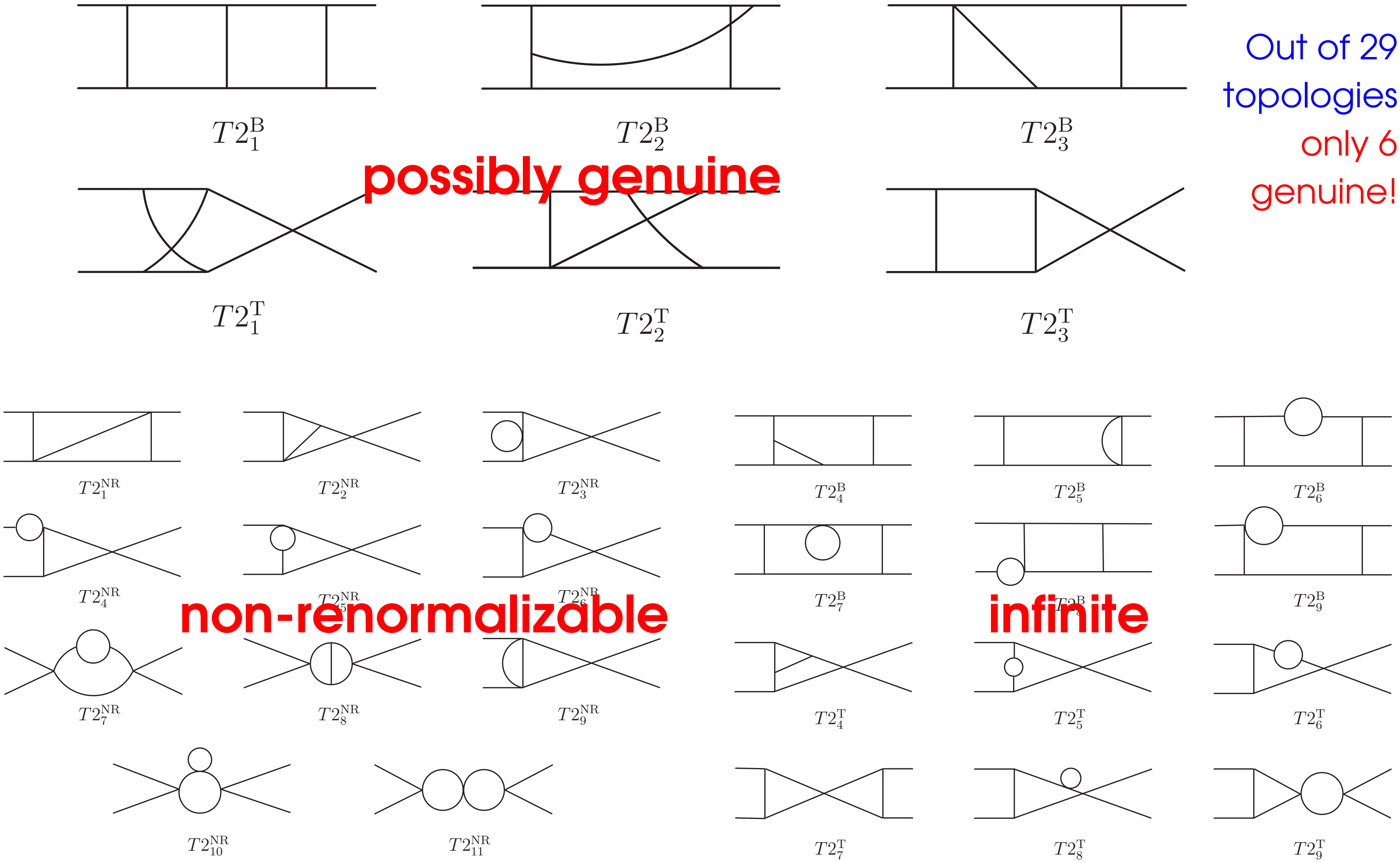
m_ν @ 2-loop and $d = 5$

Aristizabal et al, 2015



m_ν @ 2-loop and $d = 5$

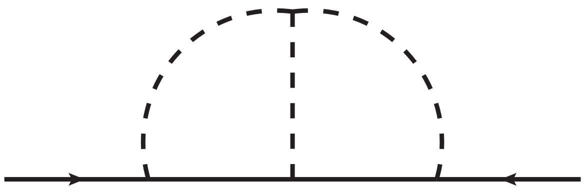
Aristizabal et al, 2015



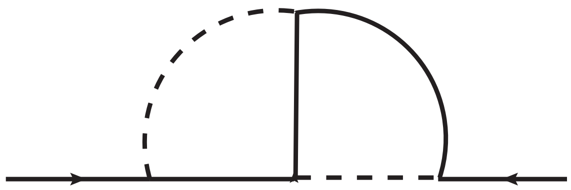
Out of 29 topologies only 6 genuine!

m_ν @ 2-loop and $d = 5$

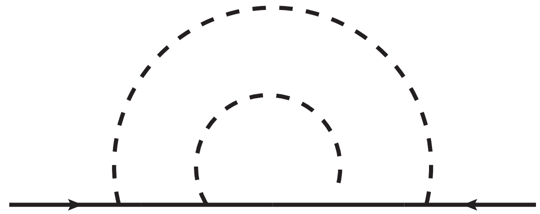
Only three types of genuine diagrams:



CLBZ



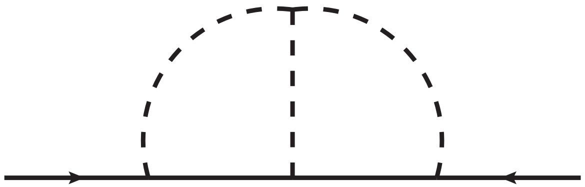
PTBM



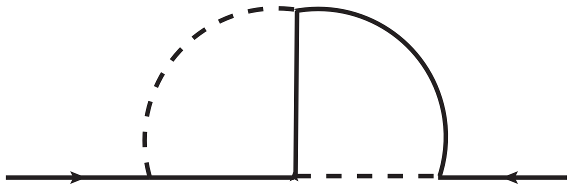
Rainbow

m_ν @ 2-loop and $d = 5$

Only three types of genuine diagrams:

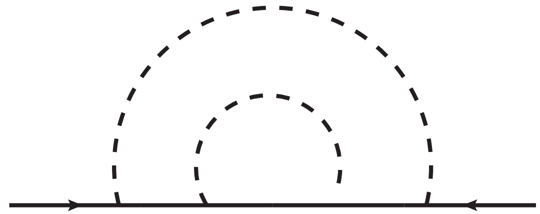


CLBZ



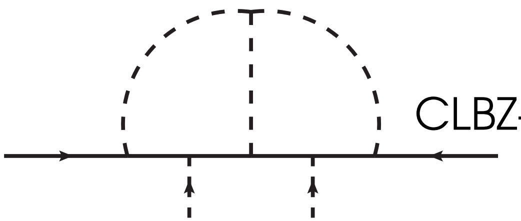
PTBM

6 diagrams

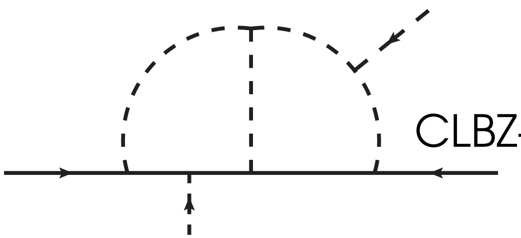


Rainbow

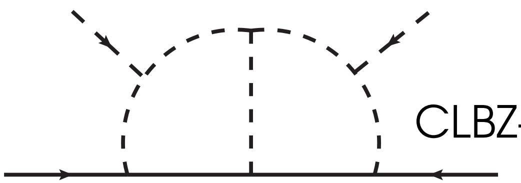
4 diagrams



CLBZ-1



CLBZ-2



CLBZ-3

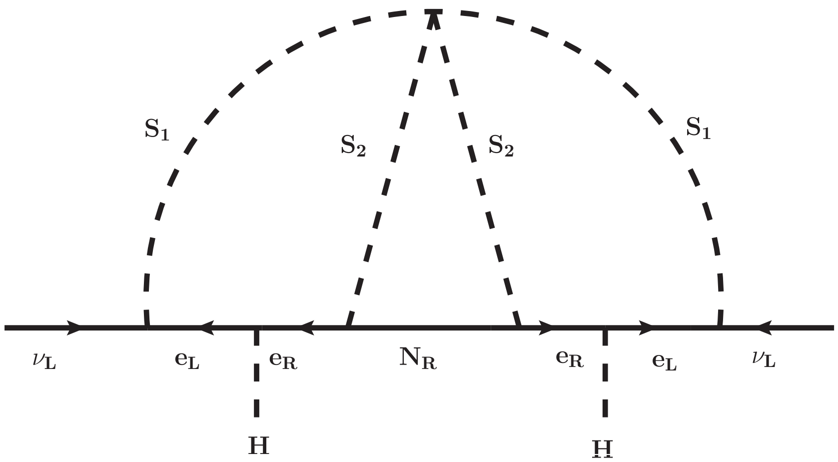
in total 10 diagrams

Complete lists
"Recipes"
(integrals, QNs, etc. etc.) in:

Aristizabal et al., 2015

m_ν @ 3-loop?

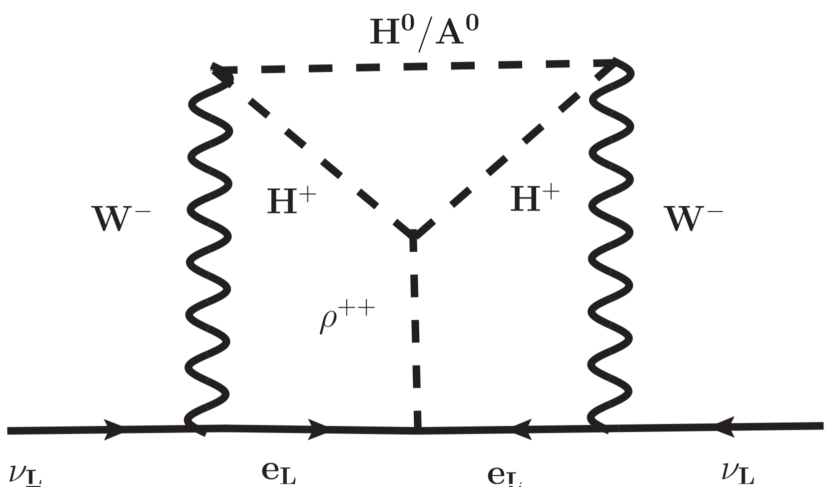
No systematic analysis, but several example models exist:



Krauss, Nasri & Trodden, 2002

Similar diagrams by:

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



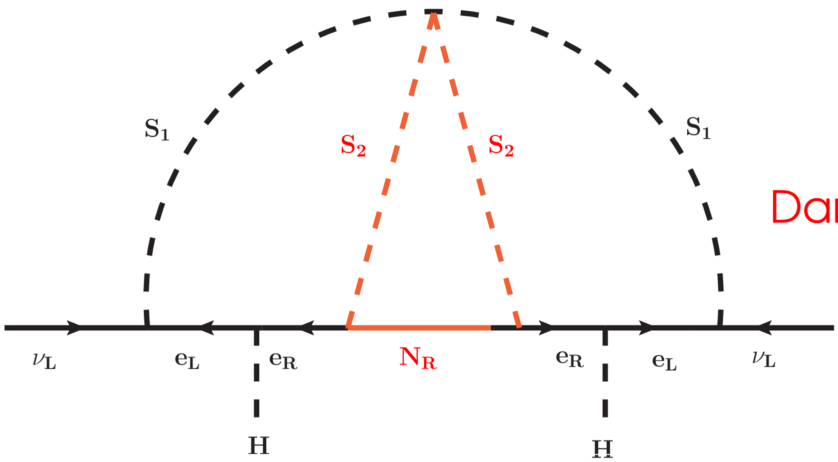
Gustafsson et al, 2012

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:



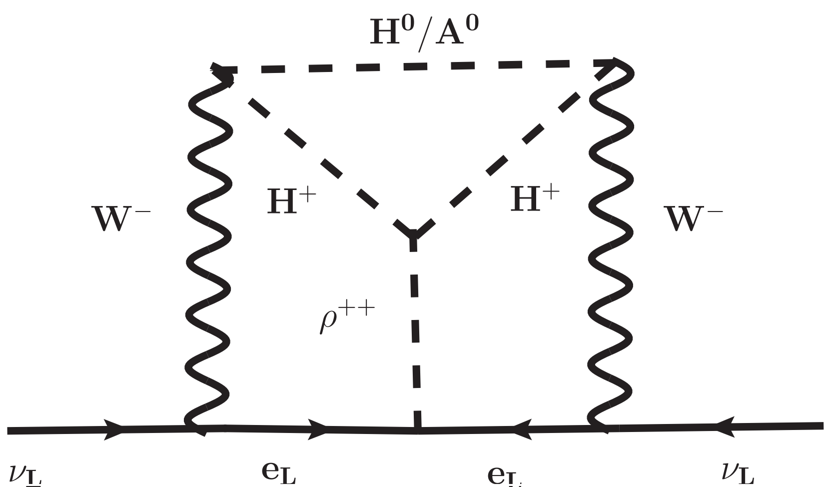
Dark Matter!

Krauss, Nasri & Trodden, 2002

Similar diagrams by:

Aoki et al, 2008 & 2011

Culjac et al., 2015



Gustafsson et al, 2012

Similar (but scalar) diagram in:

Kajiyama et al., 2013

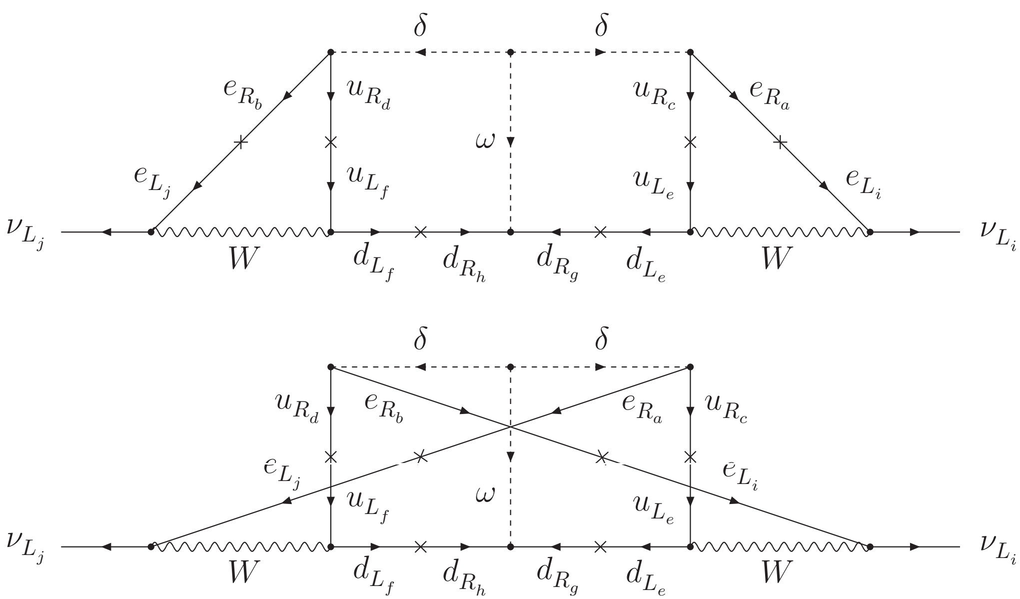
(T_7 flavour model)

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

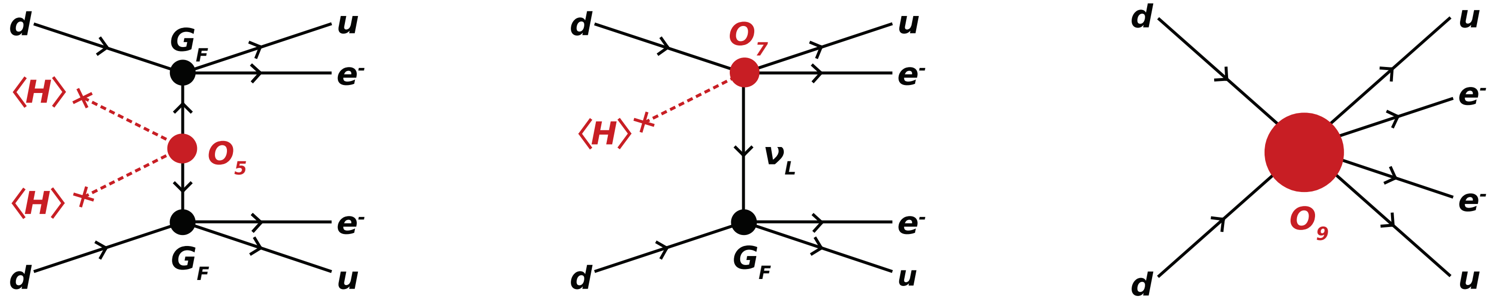
A few more examples in: Helo et al., 2015

$\mathcal{III}.$

$0\nu\beta\beta$ decay, LNV and m_ν

$0\nu\beta\beta$ *decay*

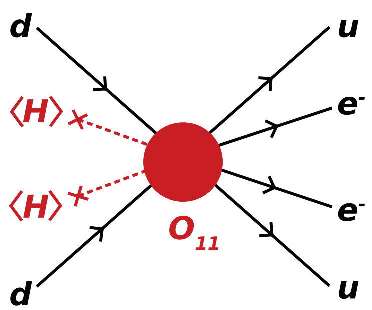
Amplitude for $(Z, A) \to (Z \pm 2, A) + e^{\mp}e^{\mp}$ can be divided into:



(a) (b) (c)

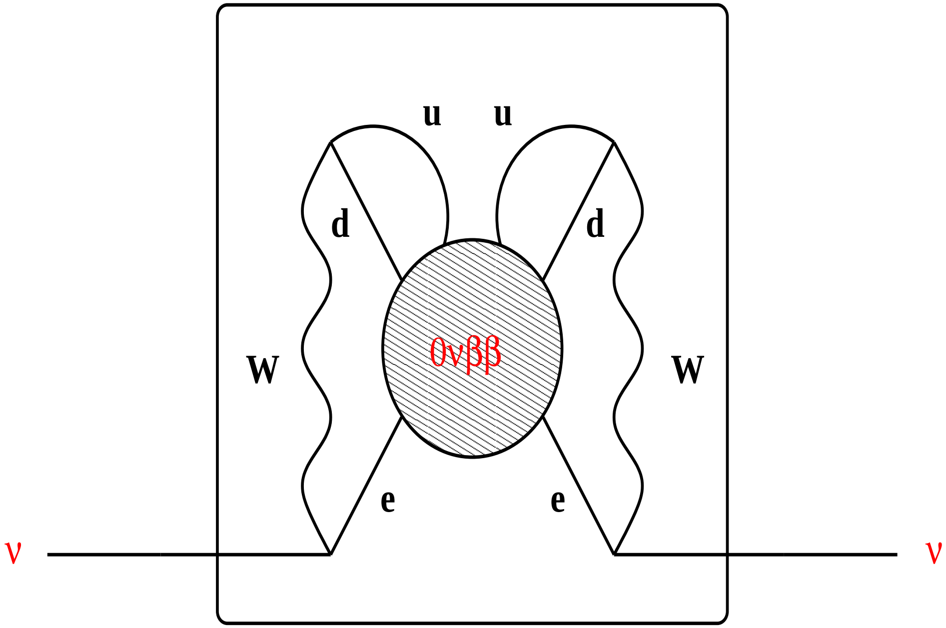
Mass mechanism "long-range" "short-range"

Higher order:



(d)

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

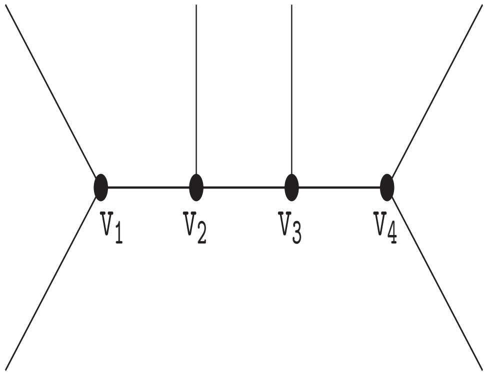
$\Rightarrow$ Tree-level, 1-loop, $\cdots$ 4-loop possible ...

Can we determine if mass mechanism is dominant?

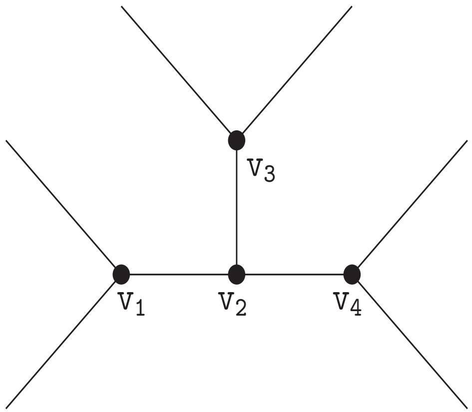
Could we determine which model dominant?

Tree-level topologies

Topology-I:

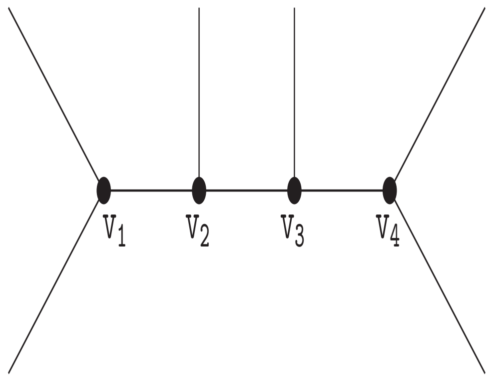


Topology-II:

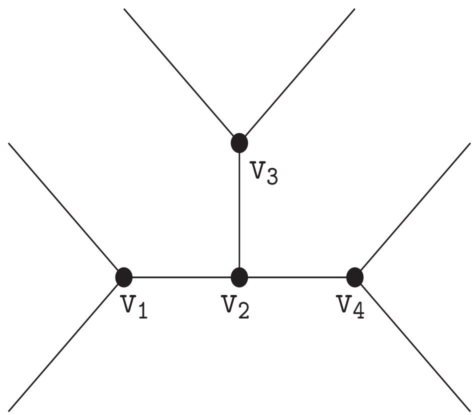


Tree-level topologies

Topology-I:

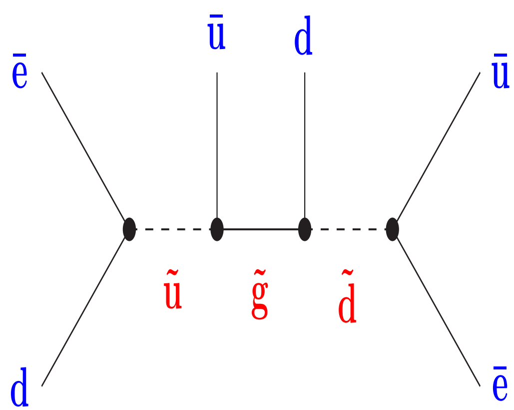


Topology-II:

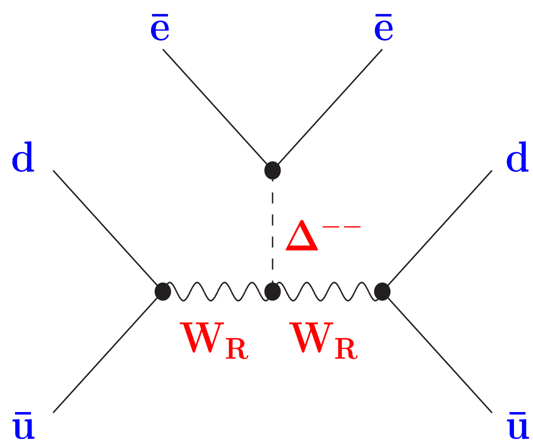


Examples:

RPV squark exchange:



LR symmetric model:



T-I: Decomposition

Bonnet et al., 2013

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$: S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(-1, \mathbf{1}\oplus\mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$

18 decompositions in total

× SFS, VFS and VFV

× # of different chirality insertions P_L and P_R

T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$: S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+\mathbf{1}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(-\mathbf{1}, \mathbf{1} \oplus \mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a} \oplus \overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_{\rm a} \oplus \overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$

$\Leftarrow$ Mass mechanism

T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	RPV SUSY:
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(\mathbf{+1}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{-1}, \mathbf{1} \oplus \mathbf{8})$	$\Leftarrow \tilde{e} - \chi - \tilde{e}$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(\mathbf{+1}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{+1/3}, \bar{\mathbf{3}})$	$\Leftarrow \tilde{e} - \chi - \tilde{d}$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(\mathbf{+1}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{+2/3}, \mathbf{3})$	$\Leftarrow \tilde{e} - \chi - \tilde{u}$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(\mathbf{-2/3}, \bar{\mathbf{3}})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{+1/3}, \bar{\mathbf{3}})$	$\Leftarrow \tilde{u} - \chi/\tilde{g} - \tilde{d}$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \bar{\mathbf{3}})$	$(-1/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+1/3, \bar{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(\mathbf{-2/3}, \bar{\mathbf{3}})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{+2/3}, \mathbf{3})$	$\Leftarrow \tilde{u} - \chi/\tilde{g} - \tilde{u}$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(\mathbf{-1/3}, \mathbf{3})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{+1/3}, \bar{\mathbf{3}})$	$\Leftarrow \tilde{d} - \chi/\tilde{g} - \tilde{d}$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \bar{\mathbf{3}}_a \oplus \mathbf{6}_s)$	

T-I: Decomposition

		Mediator ($Q_{\rm em}, SU(3)_c$)			
#	Decomposition	S or V_ρ	ψ	S' or V'_ρ	
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{0}, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{-1}, \mathbf{1}\oplus\mathbf{8})$	Leptoquarks
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	⇐ Long-range LQ
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$	⇐ Long-range LQ
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$	
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	

T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$: S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{-1}, \mathbf{1} \oplus \mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a} \oplus \overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(\mathbf{-2/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(\mathbf{+2/3}, \mathbf{3}_{\rm a} \oplus \overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$	$(\mathbf{-2/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(\mathbf{-2/3}, \overline{\mathbf{3}}_{\rm a} \oplus \mathbf{6}_{\rm s})$

Di-quarks

T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$: S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{0}, \mathbf{1}\oplus\mathbf{8})$	$(-\mathbf{1}, \mathbf{1}\oplus\mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$

Coloured fermions/
vector-like quarks

T-II: Decomposition

Bonnet et al., 2013

For completeness:

#	Decomposition	Mediator $(Q_{em}, SU(3)_c)$ S or V_ρ	S' or V'_ρ	S'' or V''_ρ	
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(-2, \mathbf{1})$	⇐ LR Δ^{--} (Rizzo, 1982)
2	$(\bar{u}d)(\bar{u}\bar{e})(\bar{e}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(-1/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}})$	⇐ (New) LQ
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(-2, \mathbf{1})$	⇐ (New) DQ
4	$(\bar{u}\bar{u})(\bar{e}d)(\bar{e}d)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	⇐ (New) LQ+DQ
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(-1/3, \mathbf{3})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	⇐ P.-H. Gu, 2011 & Kohda et al., 2012

⇒ Note: All decomps contain at least one of the following:

S_{+1} - singly charged scalar (vector)

$S^{LQ}_{2/3}$, $S^{LQ}_{1/3}$ - leptoquarks

LHC!

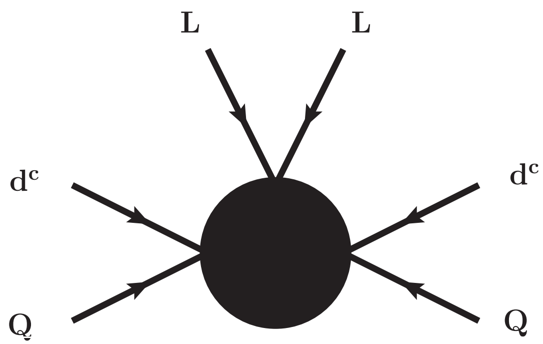
$S^{DQ}_{2/3}$, $S^{DQ}_{4/3}$ - “diquarks”

$0\nu\beta\beta$ and m_ν

Only one example. BL# 11:

$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

Graphically:

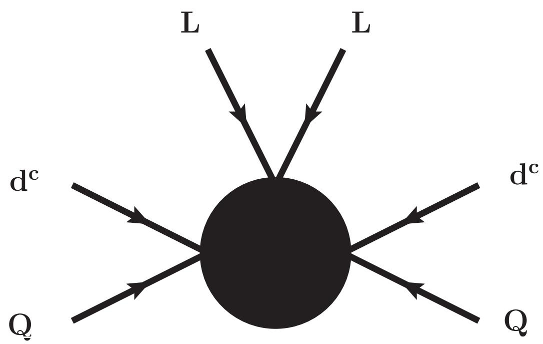


$0\nu\beta\beta$ and m_ν

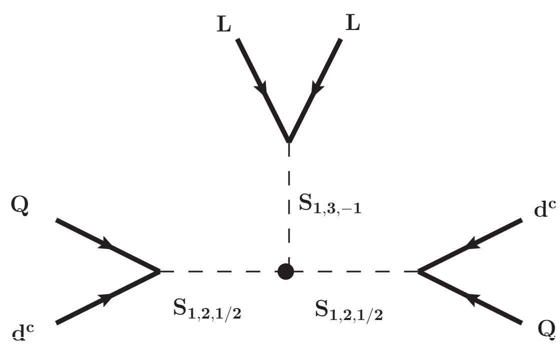
Only one example. BL# 11:

$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

Graphically:



Open as T-II-1:

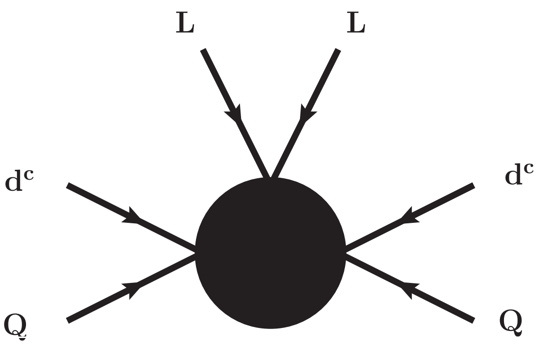


$0\nu\beta\beta$ and m_ν

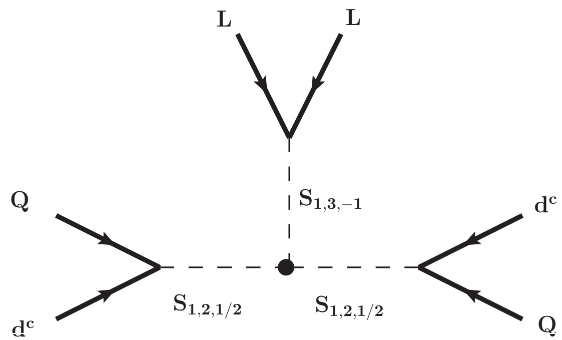
Only one example. BL# 11:

$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

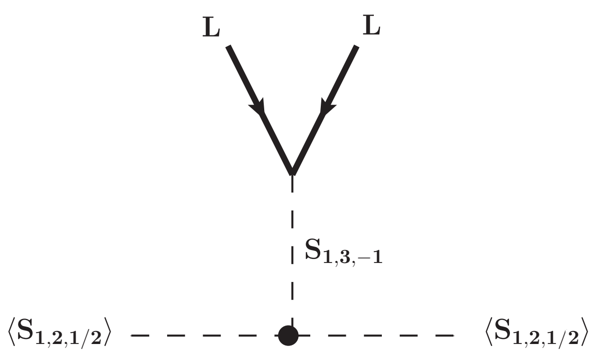
Graphically:



Open as T-II-1:



⇒ Unless fine-tuned:
$0\nu\beta\beta$ decay
dominated by m_ν



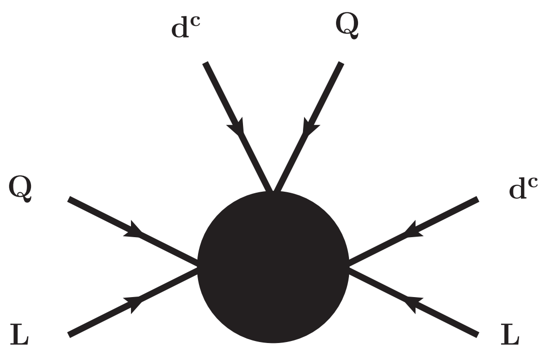
Seesaw type-II

$0\nu\beta\beta$ and m_ν

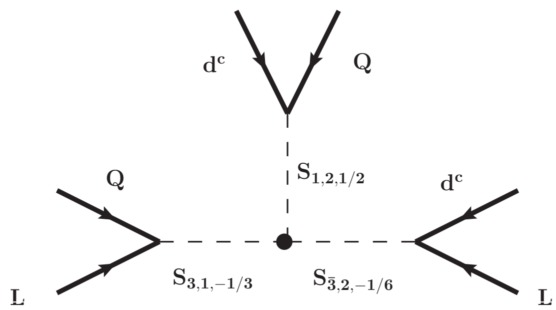
Only one example. BL# 11:

$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

Graphically:



Open as T-II-2:

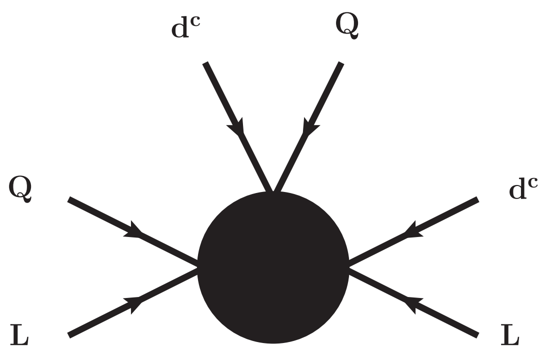


$0\nu\beta\beta$ and m_ν

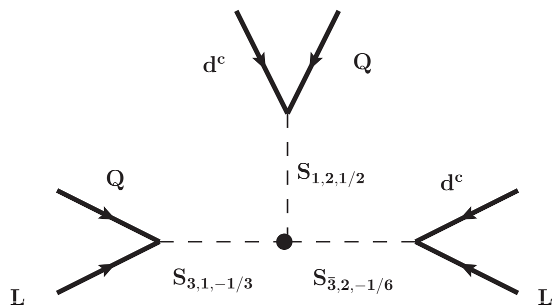
Only one example. BL# 11:

$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

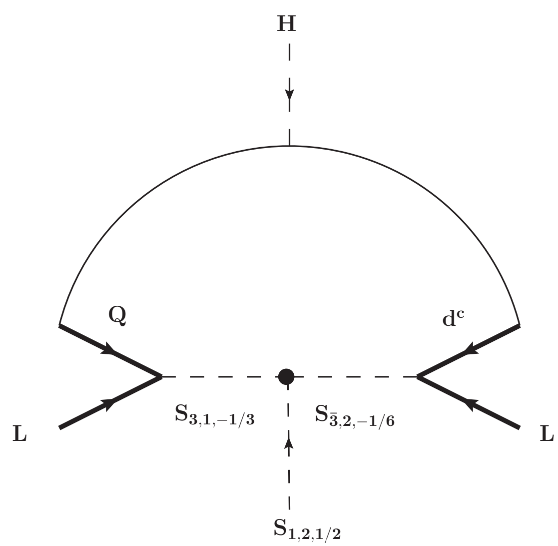
Graphically:



Open as T-II-2:



$\Rightarrow$ Unless fine-tuned:
$0\nu\beta\beta$ decay
dominated by m_ν



One loop: T1-ii

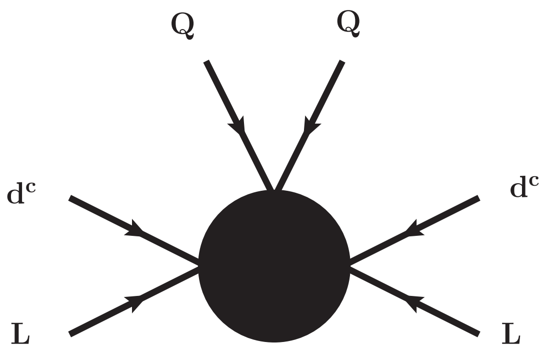
"Coloured Zee-model"

$0\nu\beta\beta$ and m_ν

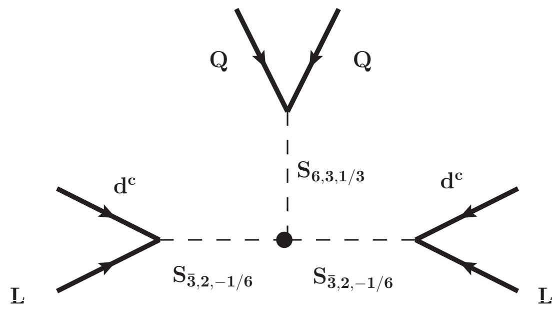
Only one example. BL# 11:

$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

Graphically:



Open as T-II-4:

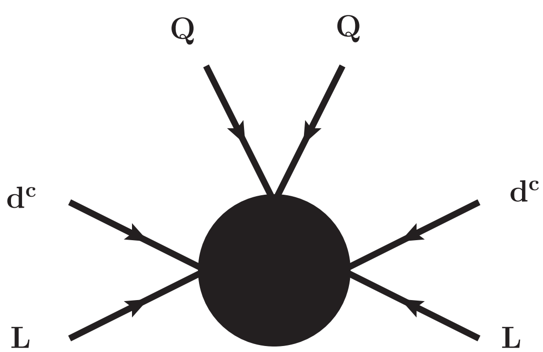


$0\nu\beta\beta$ and m_ν

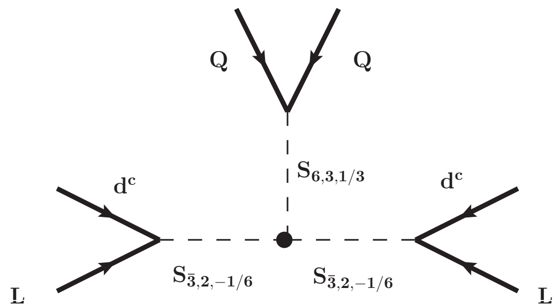
Only one example. BL# 11:

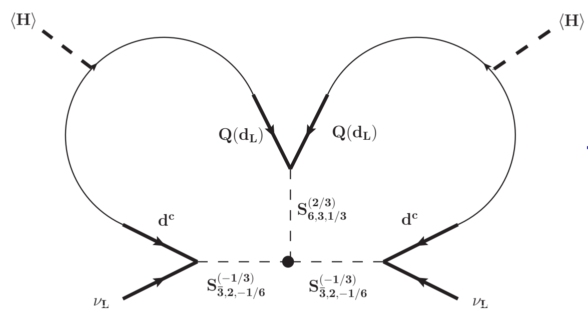
$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

Graphically:



Open as T-II-4:





Two loop: CLBZ-1

$\Rightarrow$ Short-range $0\nu\beta\beta$ decay and m_ν comparable!

T-II: Loops versus Decomps

Helo et al., 2015

Tree-level — SR $\ll \langle m_\nu \rangle$

T-II #	Op.	BL #	S	S'	S''	Diagram	Add. Int.
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	11, 12, 14	$(1,2)_{+1/2}$	$(1,2)_{+1/2}$	$(1,3)_{-1}$	type II	$S_{13-1}HH$
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	11, 12, 14	$(8,2)_{+1/2}$	$(8,2)_{+1/2}$	$(1,3)_{-1}$	type II	$S_{13-1}HH$
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	11	$(6,3)_{+1/3}$	$(\bar{6},1)_{+2/3}$	$(1,3)_{-1}$	type II	$S_{13-1}HH$
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	12	$(6,1)_{+4/3}$	$(\bar{6},3)_{-1/3}$	$(1,3)_{-1}$	type II	$S_{13-1}HH$

1-loop $d=5$ — SR $\ll \langle m_\nu \rangle$

T-II #	Op.	BL #	S	S'	S''	Diagram	Add. Int.
2	$(\bar{u}d)(\bar{u}\bar{e})(d\bar{e})$	11, 14	$(1,2)_{+1/2}$	$(3,1)_{-1/3}$	$(\bar{3},2)_{-1/6}$	Tν-1-ii	$S^\dagger_{32-\frac{1}{6}}S^\dagger_{31-\frac{1}{3}}H^\dagger$
2	$(\bar{u}d)(\bar{u}\bar{e})(d\bar{e})$	11, 14	$(1,2)_{+1/2}$	$(3,3)_{-1/3}$	$(\bar{3},2)_{-1/6}$	Tν-1-ii	$S^\dagger_{32-\frac{1}{6}}S^\dagger_{33-\frac{1}{3}}H^\dagger$
2	$(\bar{u}d)(\bar{u}\bar{e})(d\bar{e})$	11, 14	$(8,2)_{+1/2}$	$(3,1)_{-1/3}$	$(\bar{3},2)_{-1/6}$	Tν-1-ii	$S^\dagger_{32-\frac{1}{6}}S^\dagger_{31-\frac{1}{3}}H^\dagger$
2	$(\bar{u}d)(\bar{u}\bar{e})(d\bar{e})$	11, 14	$(8,2)_{+1/2}$	$(3,3)_{-1/3}$	$(\bar{3},2)_{-1/6}$	Tν-1-ii	$S^\dagger_{32-\frac{1}{6}}S^\dagger_{33-\frac{1}{3}}H^\dagger$

2-loop $d=5$ — SR $\sim \langle m_\nu \rangle$

T-II #	Op.	BL #	S	S'	S''	Diagram
4	$(\bar{u}\bar{u})(d\bar{e})(d\bar{e})$	11	$(6,3)_{+1/3}$	$(\bar{3},2)_{-1/6}$	$(\bar{3},2)_{-1/6}$	CLBZ-1
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	11	$(3,1)_{-1/3}$	$(3,1)_{-1/3}$	$(\bar{6},1)_{+2/3}$	CLBZ-1
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	11	$(3,3)_{-1/3}$	$(3,3)_{-1/3}$	$(\bar{6},1)_{+2/3}$	CLBZ-1

2-loop $d=7$ — SR $\simeq \langle m_\nu \rangle$

T-II #	Op.	BL #	S	S'	S''	Diagram	Add. Int.
2	$(\bar{u}d)(\bar{u}\bar{e})(d\bar{e})$	19, 20	$(1,2)_{+1/2}$	$(3,1)_{-1/3}$	$(\bar{3},2)_{-1/6}$	(d)	$S^\dagger_{32-\frac{1}{6}}S^\dagger_{31-\frac{1}{3}}H^\dagger$
2	$(\bar{u}d)(\bar{u}\bar{e})(d\bar{e})$	19, 20	$(8,2)_{+1/2}$	$(3,1)_{-1/3}$	$(\bar{3},2)_{-1/6}$	(d)	$S^\dagger_{32-\frac{1}{6}}S^\dagger_{31-\frac{1}{3}}H^\dagger$

3-loop $d=5$ — $\langle m_\nu \rangle \ll SR$

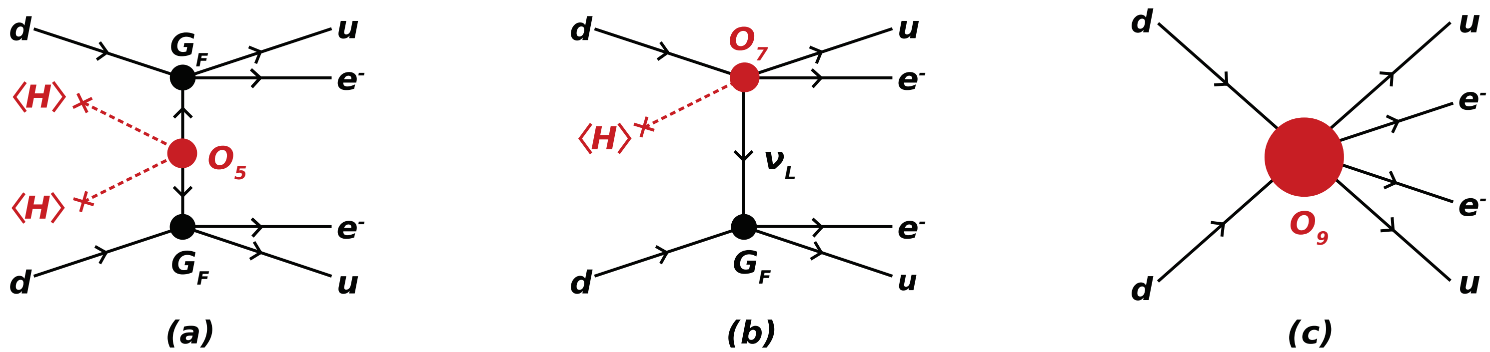
T-II #	Op.	BL #	S	S'	S''
4	$(\bar{u}\bar{u})(d\bar{e})(d\bar{e})$	20	$(6,1)_{+4/3}$	$(\bar{3},2)_{-7/6}$	$(\bar{3},2)_{-1/6}$
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	19	$(3,1)_{-1/3}$	$(3,1)_{-1/3}$	$(\bar{6},1)_{+2/3}$

4-loop $d=9$ — $\langle m_\nu \rangle \ll SR$

T-II #	Op.	BL #	S	S'	S''
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	-	$(6,1)_{+4/3}$	$(\bar{6},1)_{+2/3}$	$(1,1)_{-2}$
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	-	$(3,1)_{-1/3}$	$(3,1)_{-1/3}$	$(\bar{6},1)_{+2/3}$

Distinguish mechanisms?

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



Mass mechanism

"long-range"

"short-range"

Compare with other experiments:

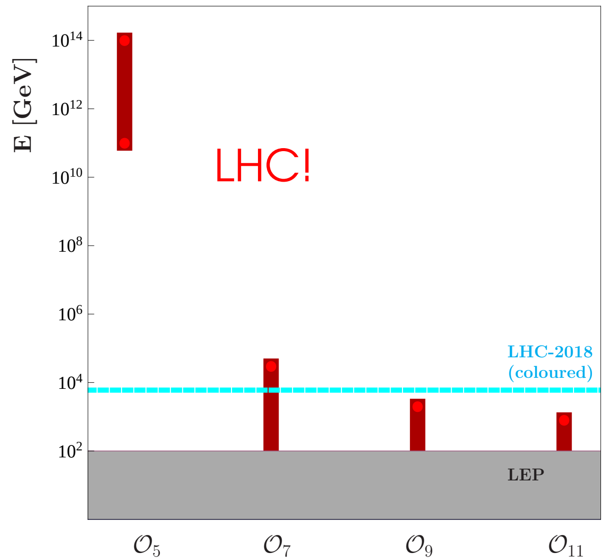
Cosmology

KATRIN?

Angular correlations

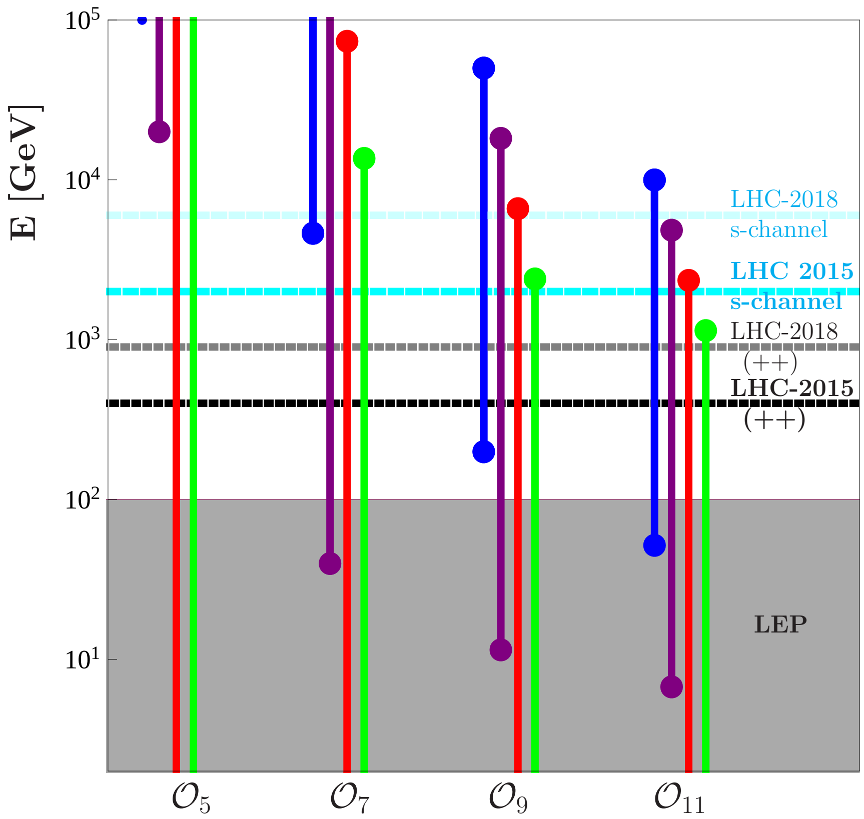
$0\nu\beta^+/EC$ decays

LHC?

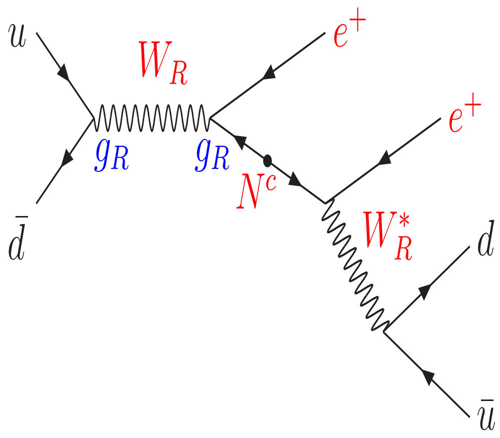


$\mathcal{IV}.$

LNV @ LHC



Example: W_R @ LHC

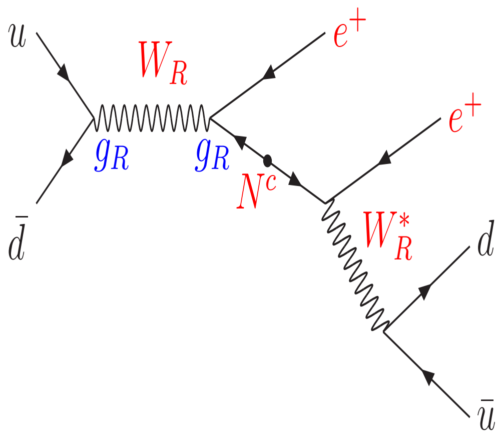


Keung & Senjanovic, 1983

Signal:

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

Example: W_R @ LHC

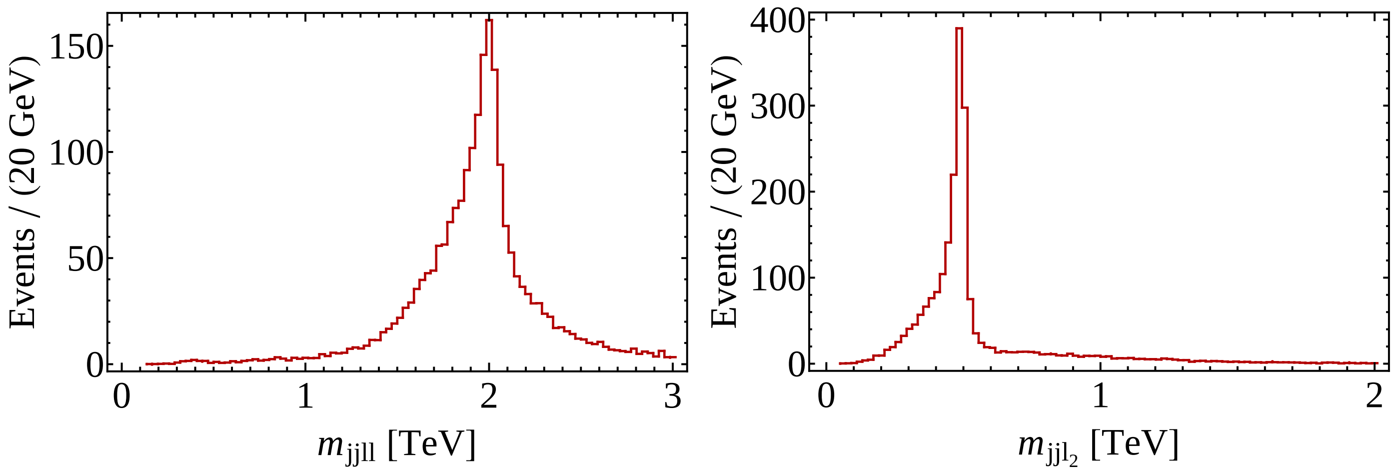


Keung & Senjanovic, 1983

Signal:

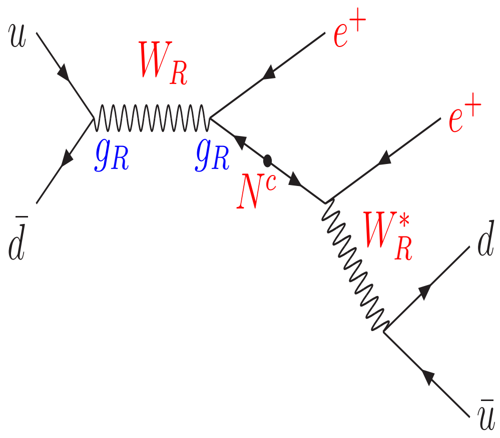
Same-sign and opposite-sign di-lepton + jets, **no** $\not{E}_T$

Plot from: S.P. Das et al., PRD **86**



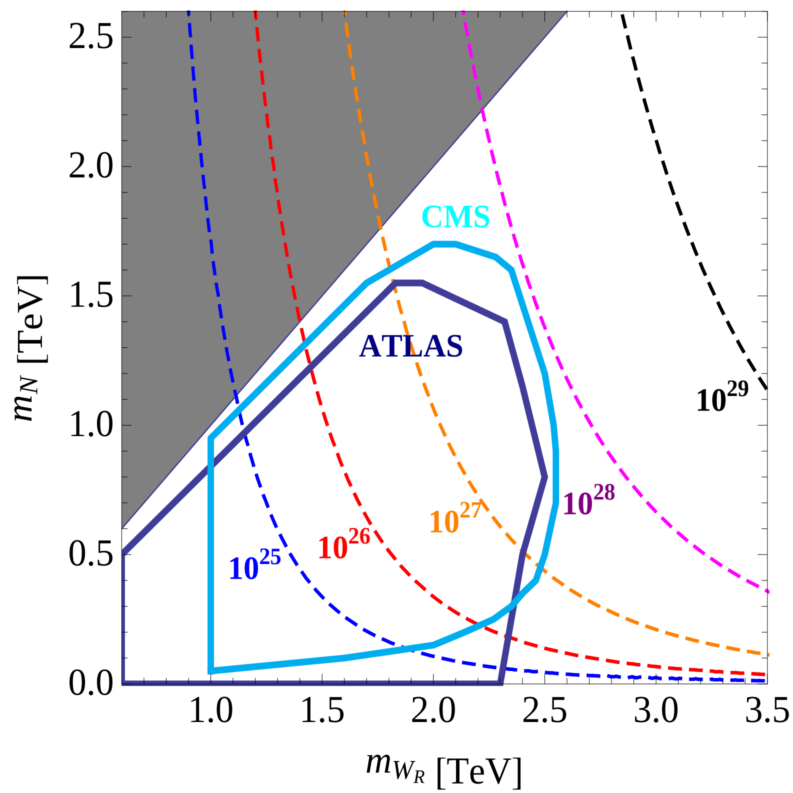
⇒ Assumes $\mathcal{L} = 30$ fb^{-1} at $\sqrt{s} = 14$ TeV

Example: W_R @ LHC



Signal:

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

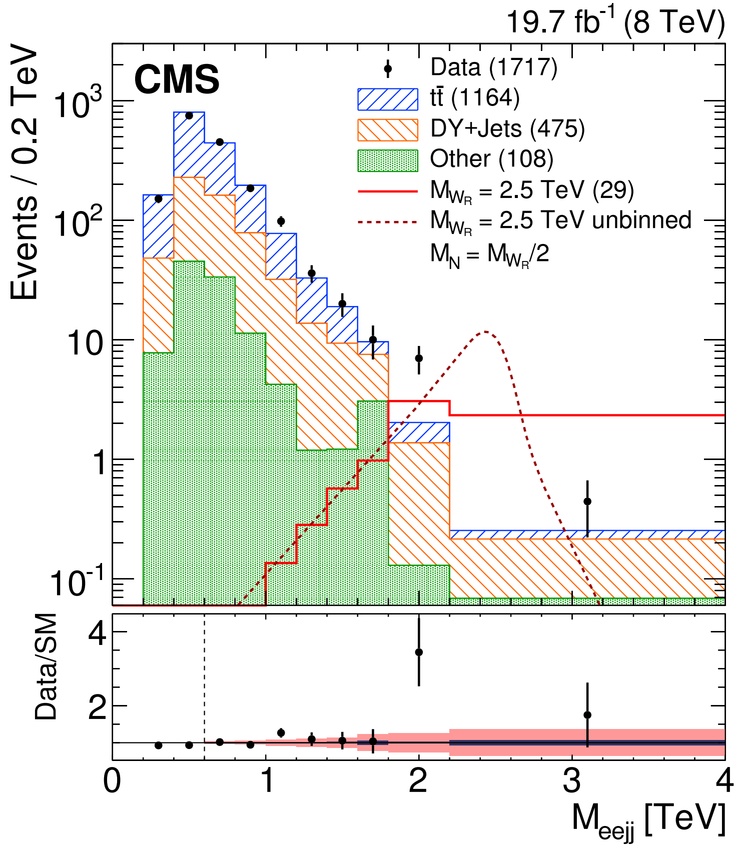


CMS (and ATLAS) with $\sqrt{s} = 8$ TeV:

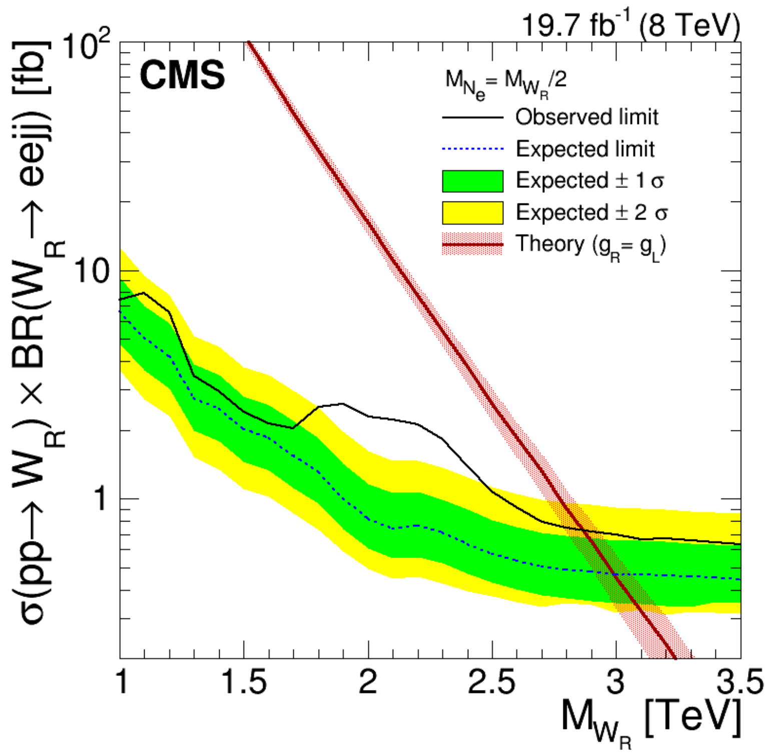
Already from run-I: stringent limits in the plane $m_{W_R} - m_N$

Assumes: $g_R = g_L$!

CMS excess: arXiv:1407.3683



Local significance 2.8 σ



Note:

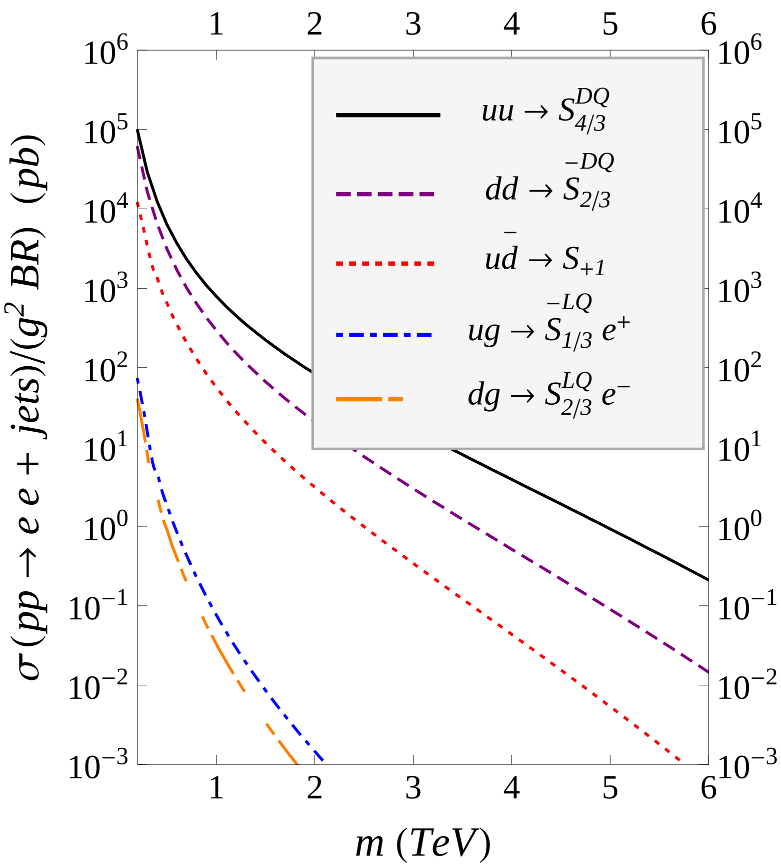
⇒ excess only in ee final state

⇒ only 1 out of 14 events is like-sign

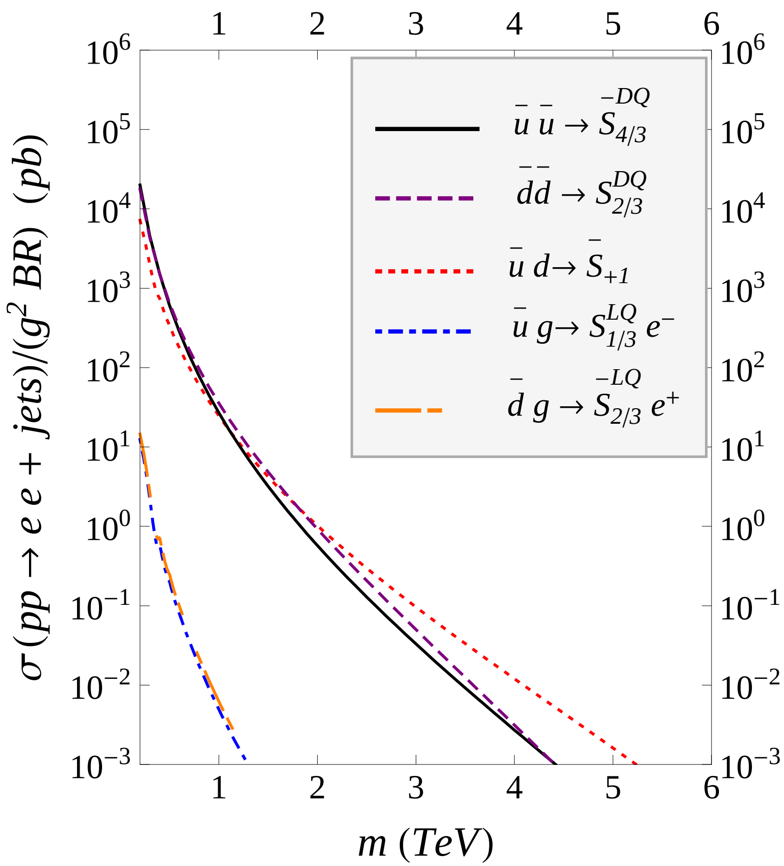
⇒ no excess is seen in $m_{e_2 jj}$

Cross sections for $\sqrt{s} = 14$ TeV

"Dominant" sign producion:



"wrong" sign production:

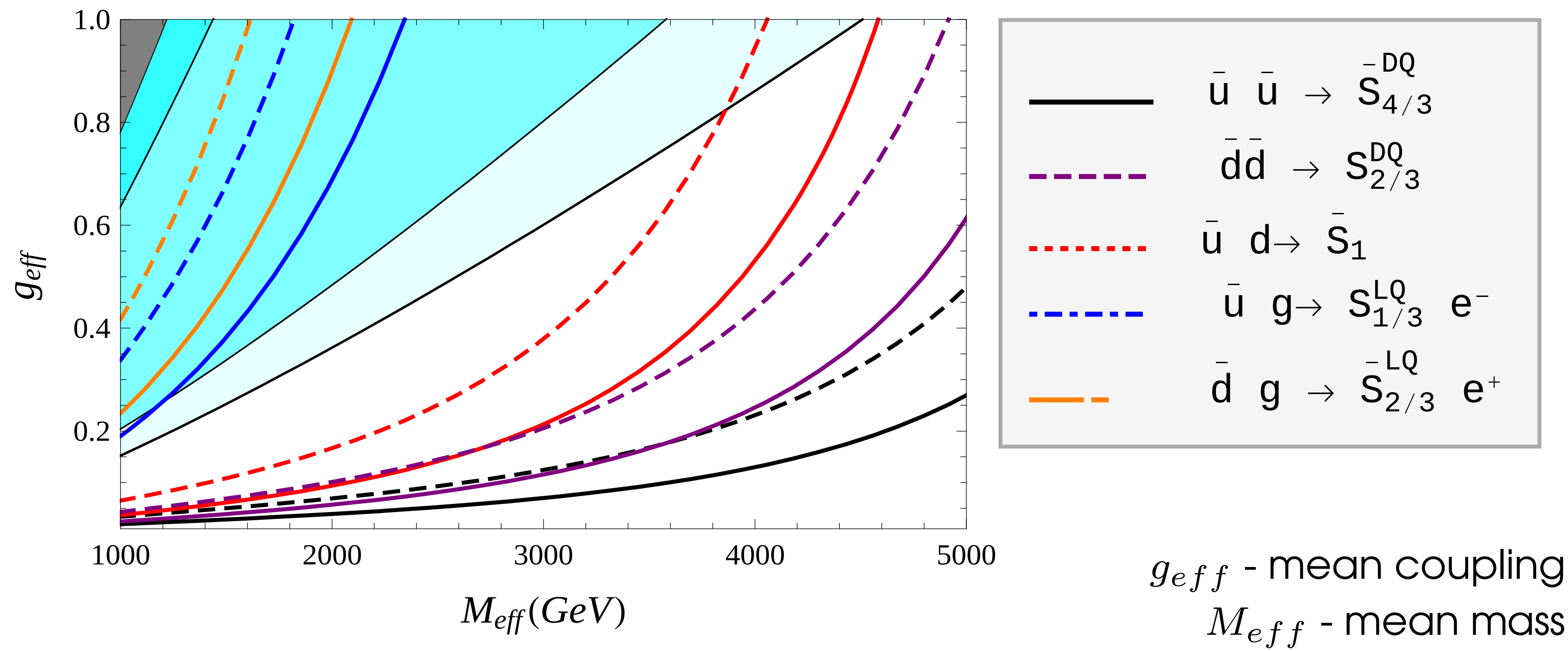


⇒ All $0\nu\beta\beta$ decay SR contributions can be tested

⇒ Number of e^-e^--like and e^+e^+-like events differ, depending on scalar!

Compare $0\nu\beta\beta$ and LHC

Helo et al, 2013



g_{eff} - mean coupling
M_{eff} - mean mass

$\Rightarrow$ cyan background: $0\nu\beta\beta$ decay $10^{25} - 10^{27}$ ys

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

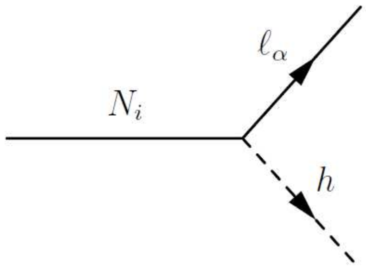
$\Rightarrow$ $m_F = 1000$ GeV (realistic (?) case)

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

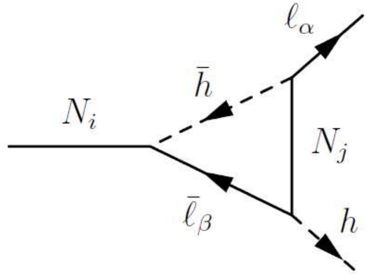
Leptogenesis

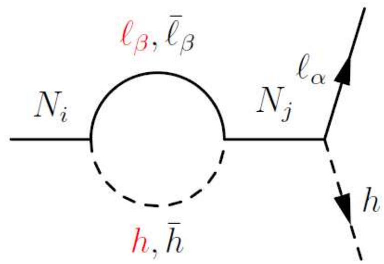
Sakharov's conditions:

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



(e) Tree

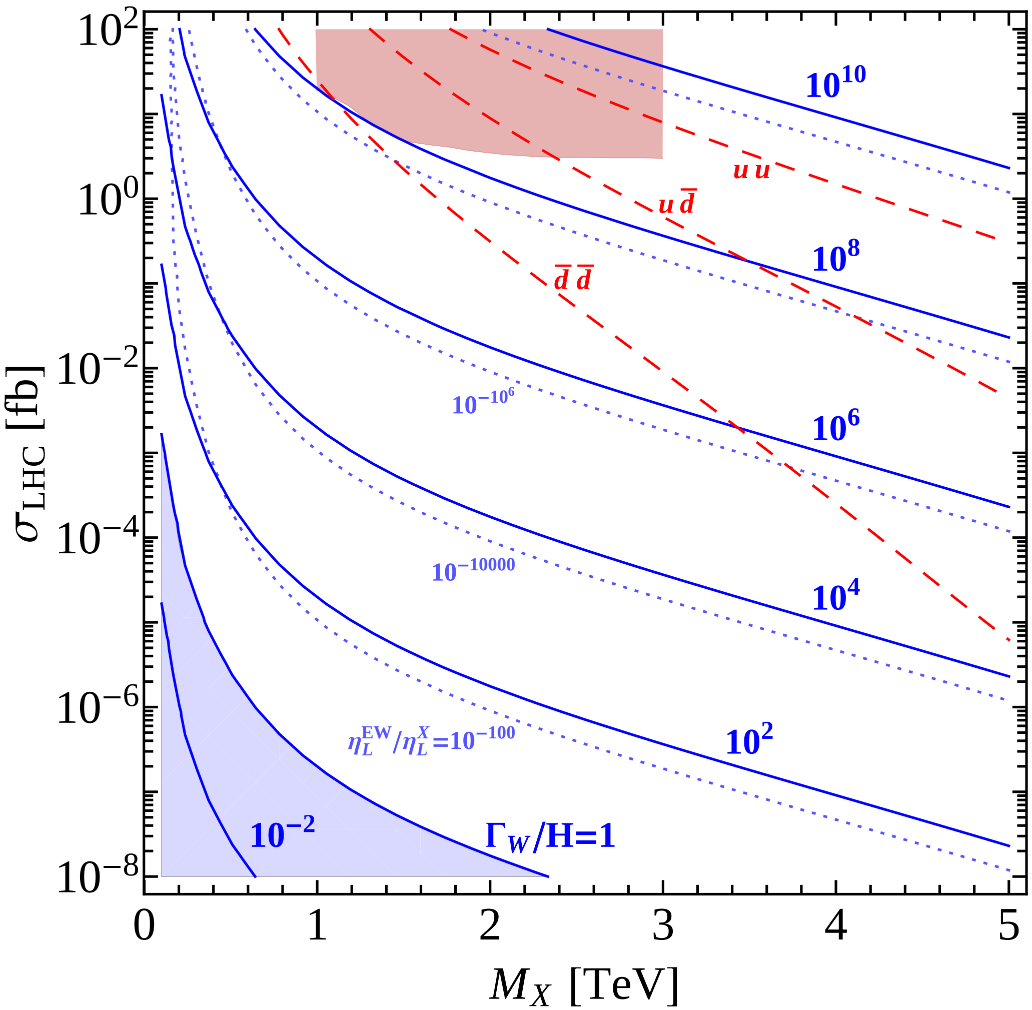




In Leptogenesis:

(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 et al., 2014

See talk by: J Harz

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?

Conclusions

⇒ Are neutrinos Majorana particles?

A: Observe LNV!

⇒ What is the energy scale of LNV?
Direct test: LHC? Or indirect: LFV?

⇒ Can we understand flavour structure?

⇒ Are neutrinos related to DM?

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

⇒ Can we predict CPV?

⇒ Are neutrinos linked to the BAU?

⇒ Are there more than 3 light neutrinos?

⇒ Normal hierarchy or Inverted Hierarchy?

⇒ Others ...