Neutrinos at colliders and LNV

Martin Hirsch

Instituto de Física Corpuscular - CSIC
Universidad Valencia, Spain

http://www.astroparticles.es/

Experimental talks

J.P. Chou

New detectors at the lifetime frontier of the LHC and beyond

L. Shchutska

LHC searches for heavy neutral leptons and displaced signatures

Outline

$\mathcal{I}$. Introduction

$\mathcal{II}$. Seesaw @ LHC

$\mathcal{III}$. Beyond minimal seesaw(s)

$\mathcal{IV}$. Leptogenesis and LHC

$\mathcal{I}.$

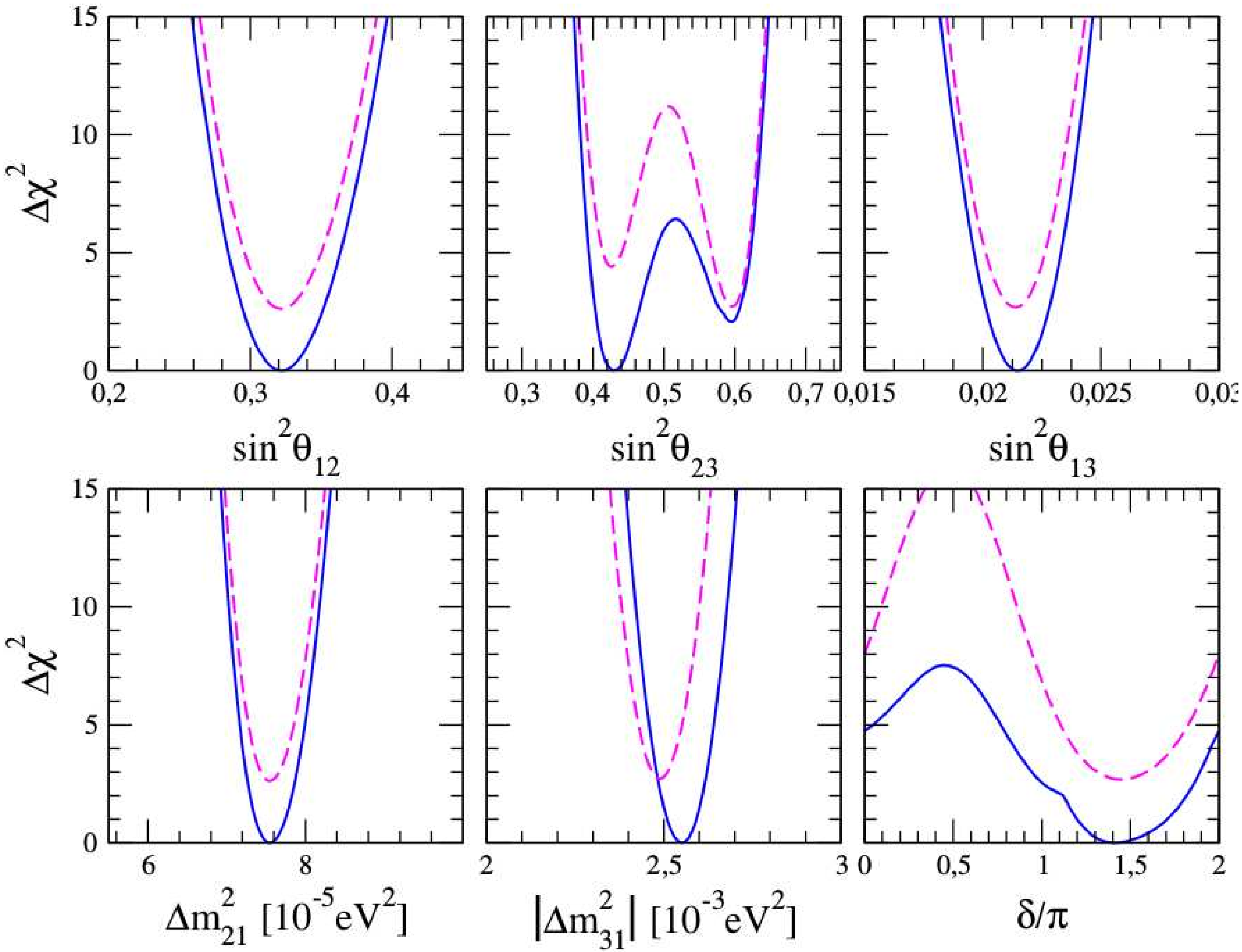
Introduction

or

Why is m_ν so small?

Global fit: Oscillation data

https://globalfit.astroparticles.es/
P. de Salas et al.,
PLB782 (2018) 633



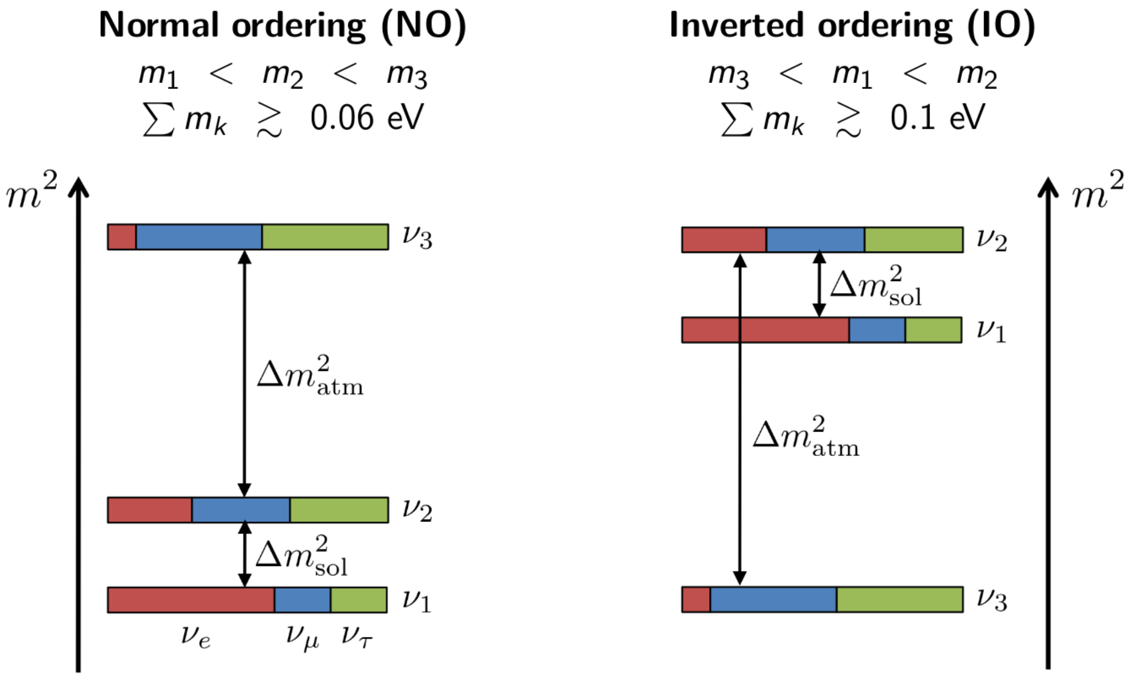
θ_{12} $\equiv$ solar angle
θ_{23} $\equiv$ atmospheric
θ_{13} $\equiv$ reactor

full: NH
dashed: IH

Δm^2_{12} $\equiv$ solar scale
Δm^2_{23} $\equiv$ atm. scale
δ $\equiv$ Dirac phase

Experiments: Super-K (atm), Super-K (solar), SNO, Gallex, Borexino, KamLAND, MINOS, NOνA, T2K, IceCube-DeepCore, RENO, Double-Chooz, DayaBay, ...

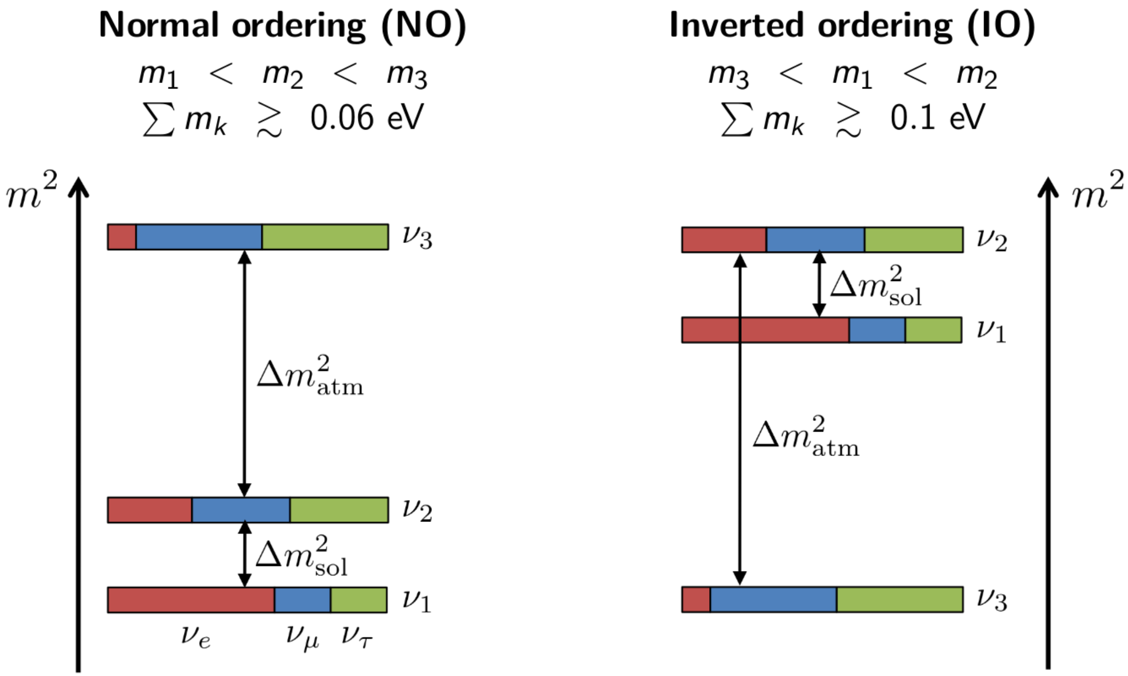
Neutrino oscillations



20 years after
Super-K, 1998

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

Neutrino oscillations



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BUT, still unknown:

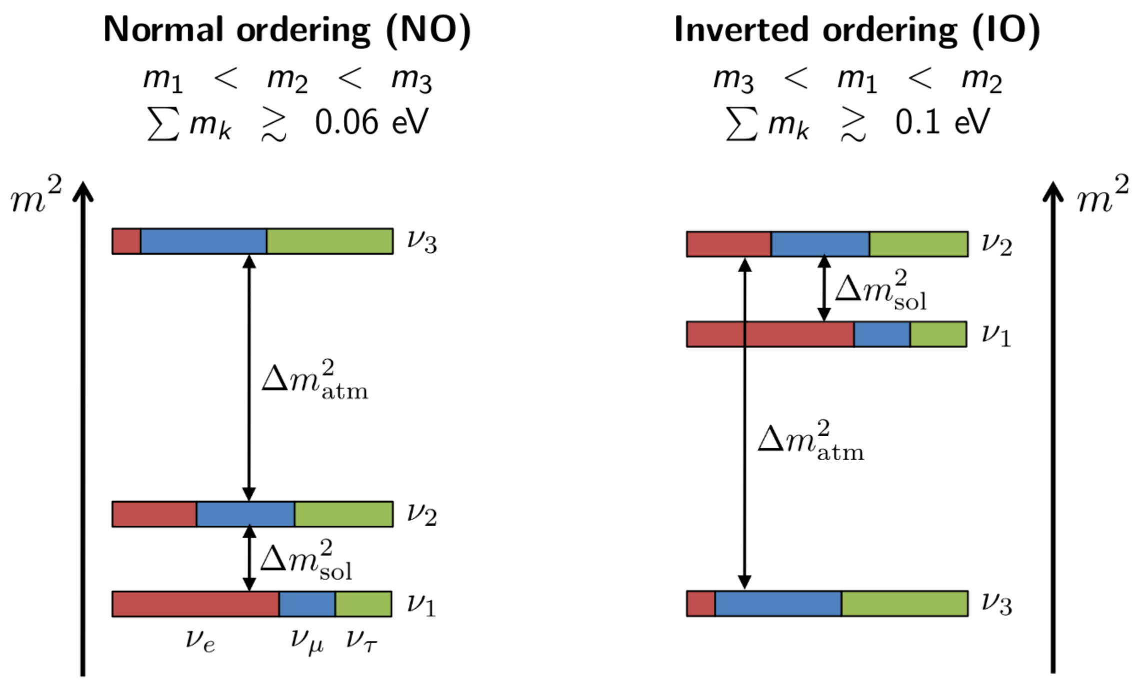
Absolute mass scale?

Which hierarchy?

CP phase?

Majorana OR Dirac?

Neutrino oscillations



20 years after
Super-K, 1998

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

BUT, still unknown:

Absolute mass scale?	Upper limit only, ~ 2 eV (^{3}H), $\sim (0.1 - 0.2)$ eV ($0\nu\beta\beta$)
Which hierarchy?	$\sim 2\,\sigma$ preference for NH
CP phase?	Indication for $\delta \sim (3/2)\pi$
Majorana OR Dirac?	Unknown

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

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:

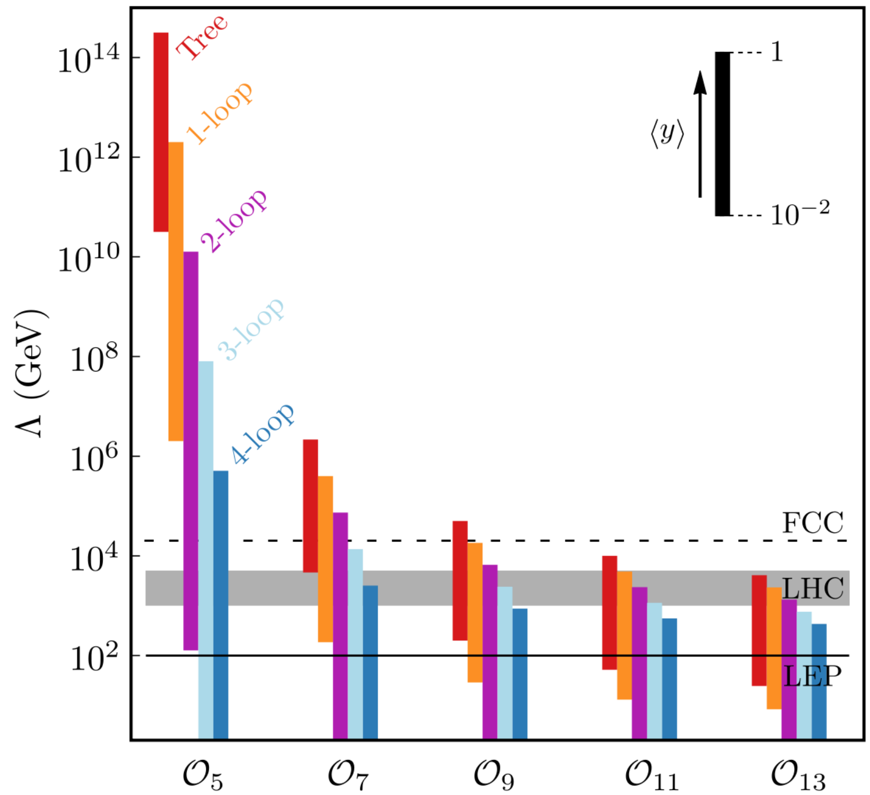
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

$\Rightarrow$ 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")

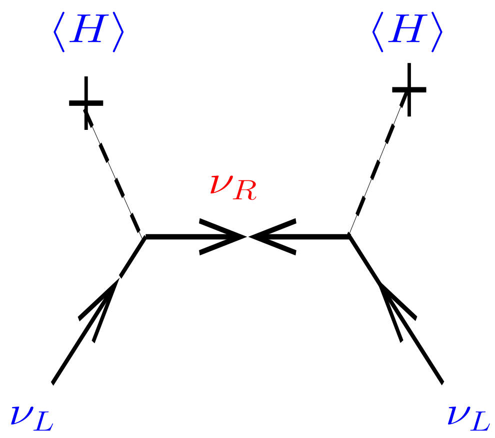
$\cdots$ or combination thereof



$\mathcal{II}.$

Seesaw @ LHC

HNL decay seesaw-I



$$m_\nu \simeq \frac{(m_D)^2}{M_M} = \frac{(Y_\nu v)^2}{M_M}$$

$$U_{\alpha i} \propto \frac{(Y_{\nu_{\alpha i}} v)}{M_{M_i}} \propto \sqrt{\frac{m_{\nu_\alpha}}{M_{M_I}}}$$

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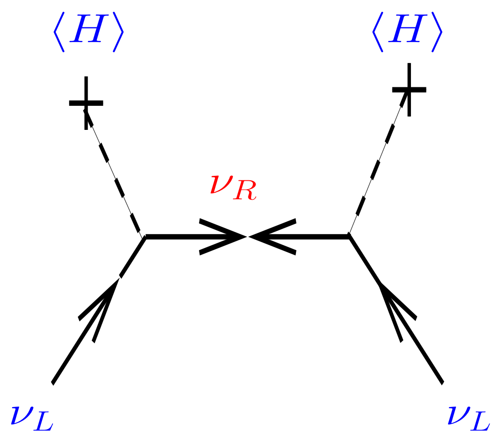

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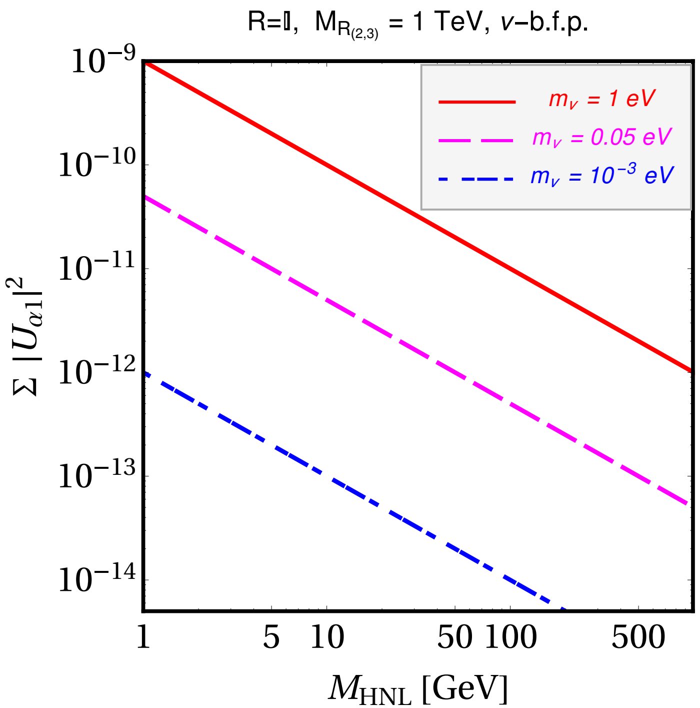
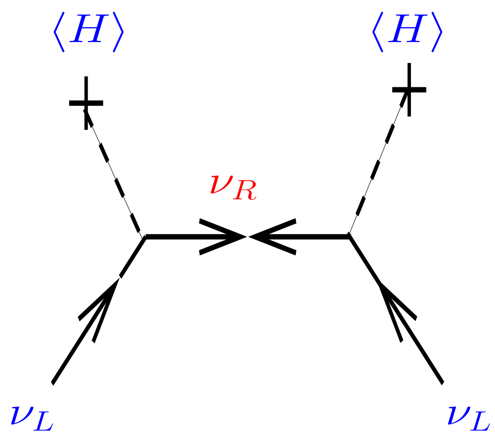


Decay length seesaw-I



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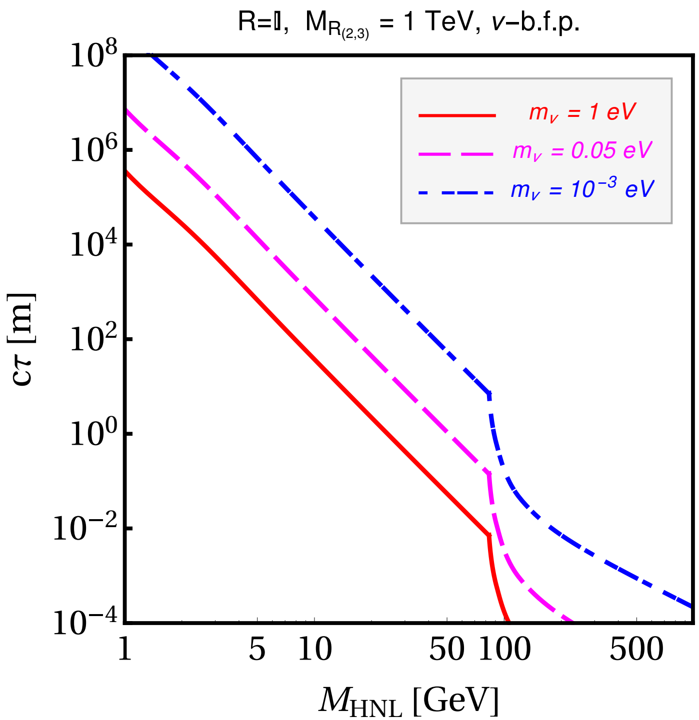


Neutrino width from:
Atre et al.
JHEP 0905 (2009) 030
and
Bondarenko et al.
1805.08567

Inverse seesaw

Inverse seesaw, basis (ν_L, ν_R^c, S_R^c):

Mohapatra & Valle, 1986

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

"Inverse" seesaw, because:

$$\hat{m}_\nu = V_L m_\nu V_L^T = V_L m_D^T.(M_R^T)^{-1}.\mu.(M_R)^{-1}.m_D V_L^T$$

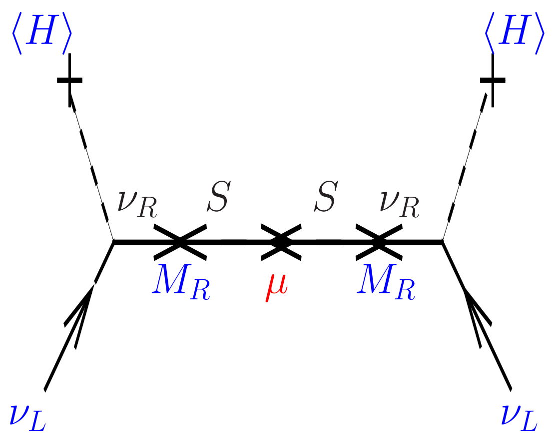
$$M_\pm = \left(\hat{M}_R + \left\{m_D.m_D^T, \hat{M}_R^{-1}\right\}\right) \pm \frac{1}{2}\mu_V$$

$\Rightarrow$ - 3 light eigenvalues: $\hat{m}_\nu$

$\Rightarrow$ - (3+3) heavy (nearly diagonal) eigenvalues : $\hat{M}_\pm = \hat{M}_R \pm \frac{1}{2}\mu_V$ Quasi-Dirac!

Smallness of m_ν due to nearly conserved L!

Decay length ISS



$$m_\nu \simeq \left(\frac{m_D}{M_R}\right)^2 \mu$$

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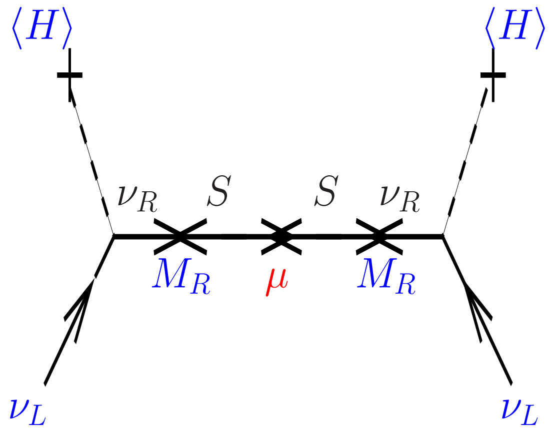

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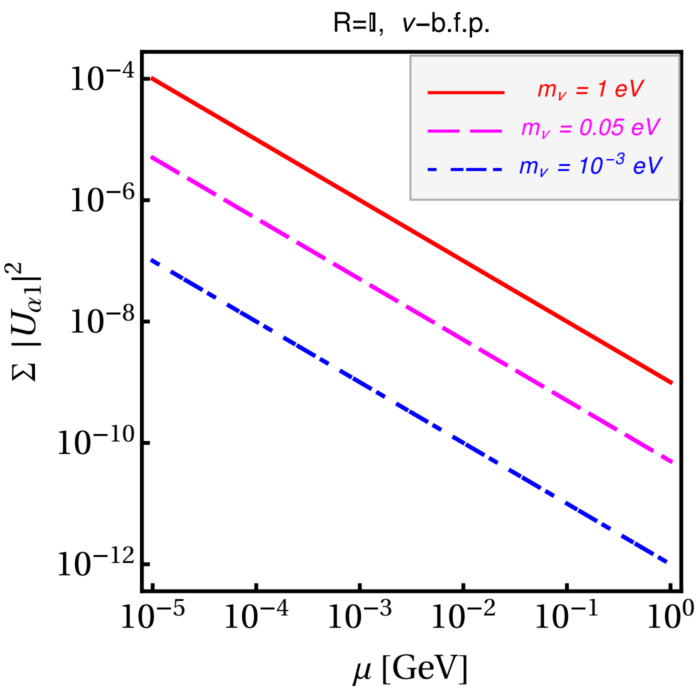
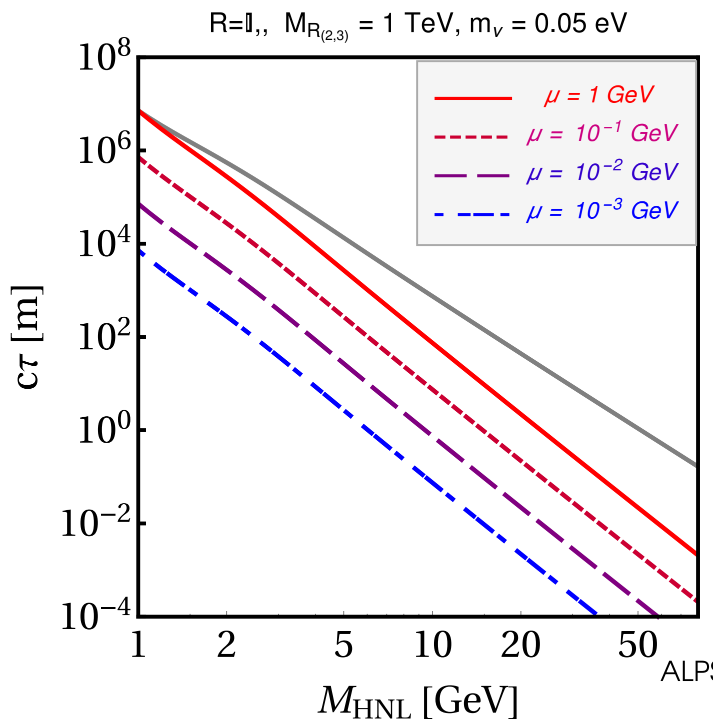
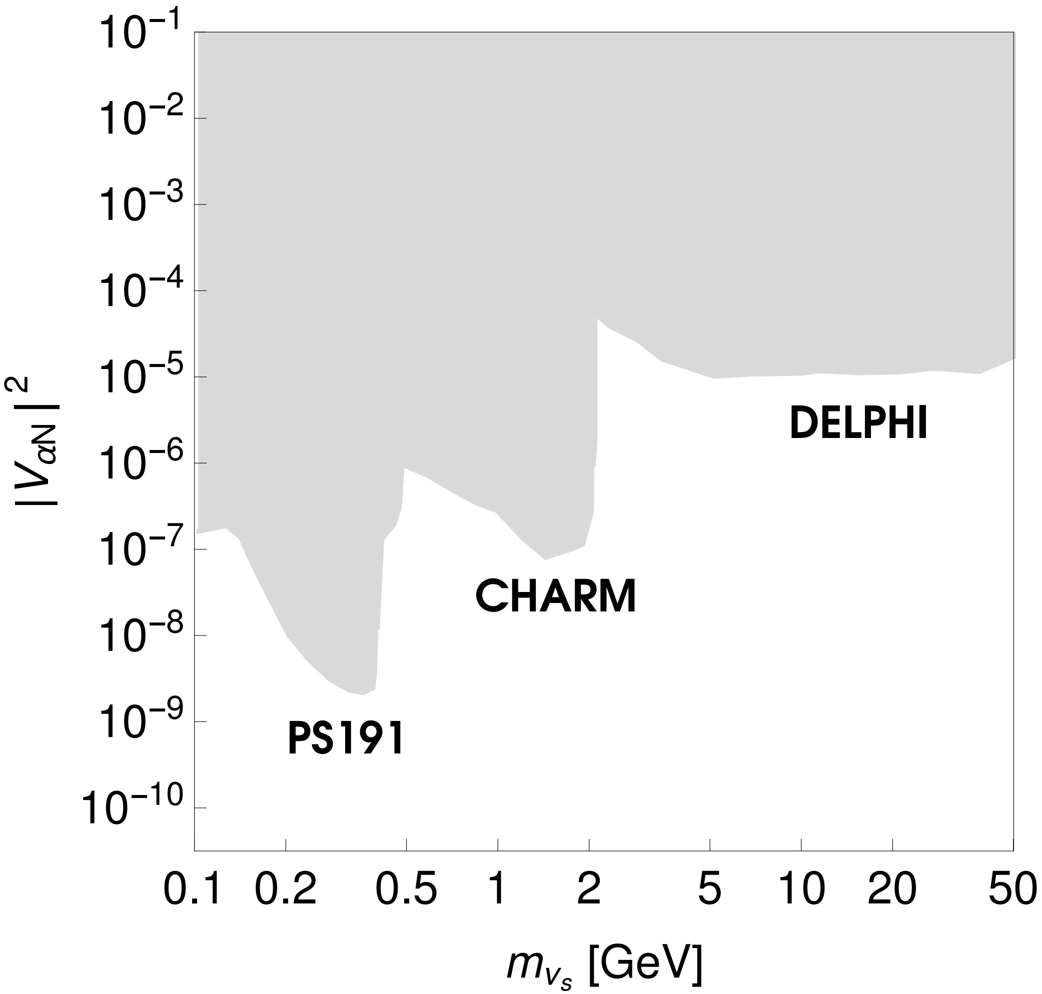




Forecast searches



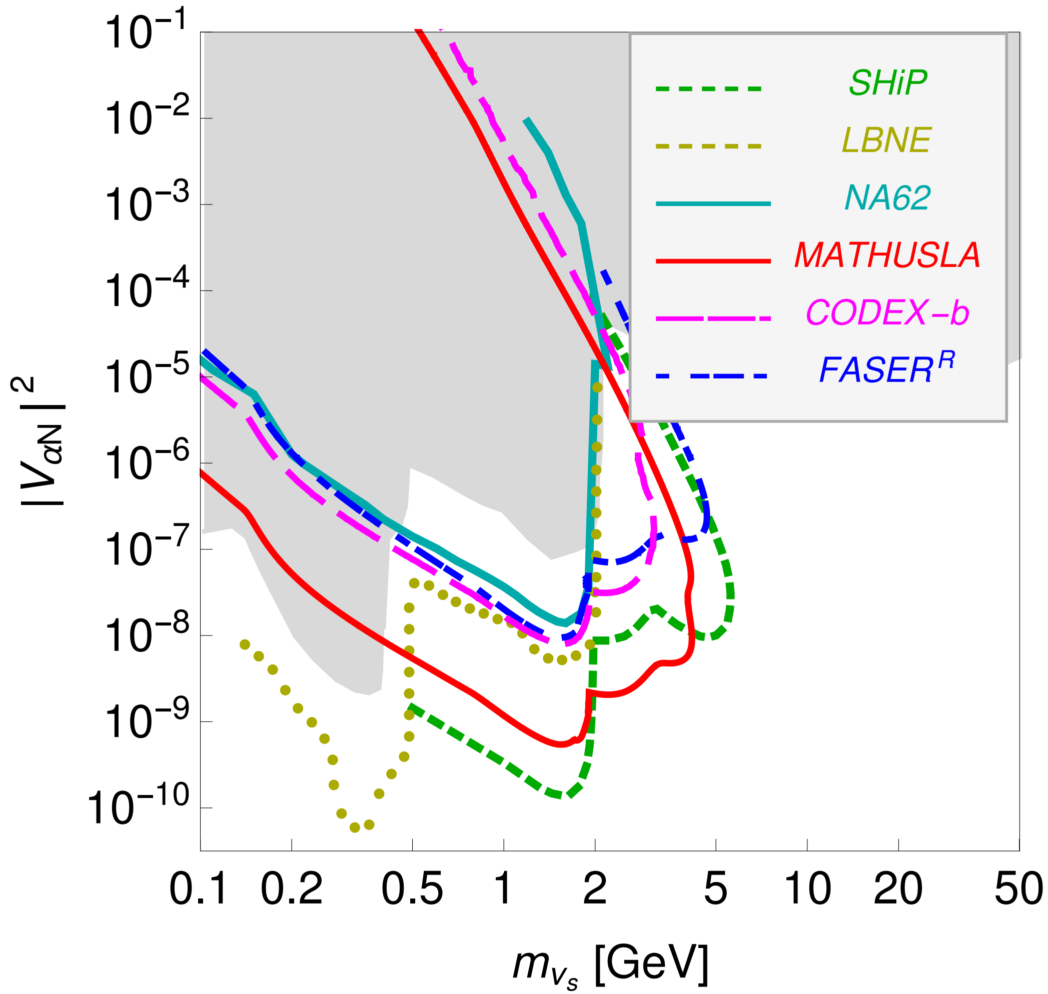
Existing limits as reviewed in:

Atre et al,
JHEP 0905 (2009) 030

and

D. Curtin et al.,
1806.07396

Forecast searches



Plot from:
Helo et al.; 1803.02212

SHiP; 1504.04855, 1810.03636

LBNE; 1307.7335

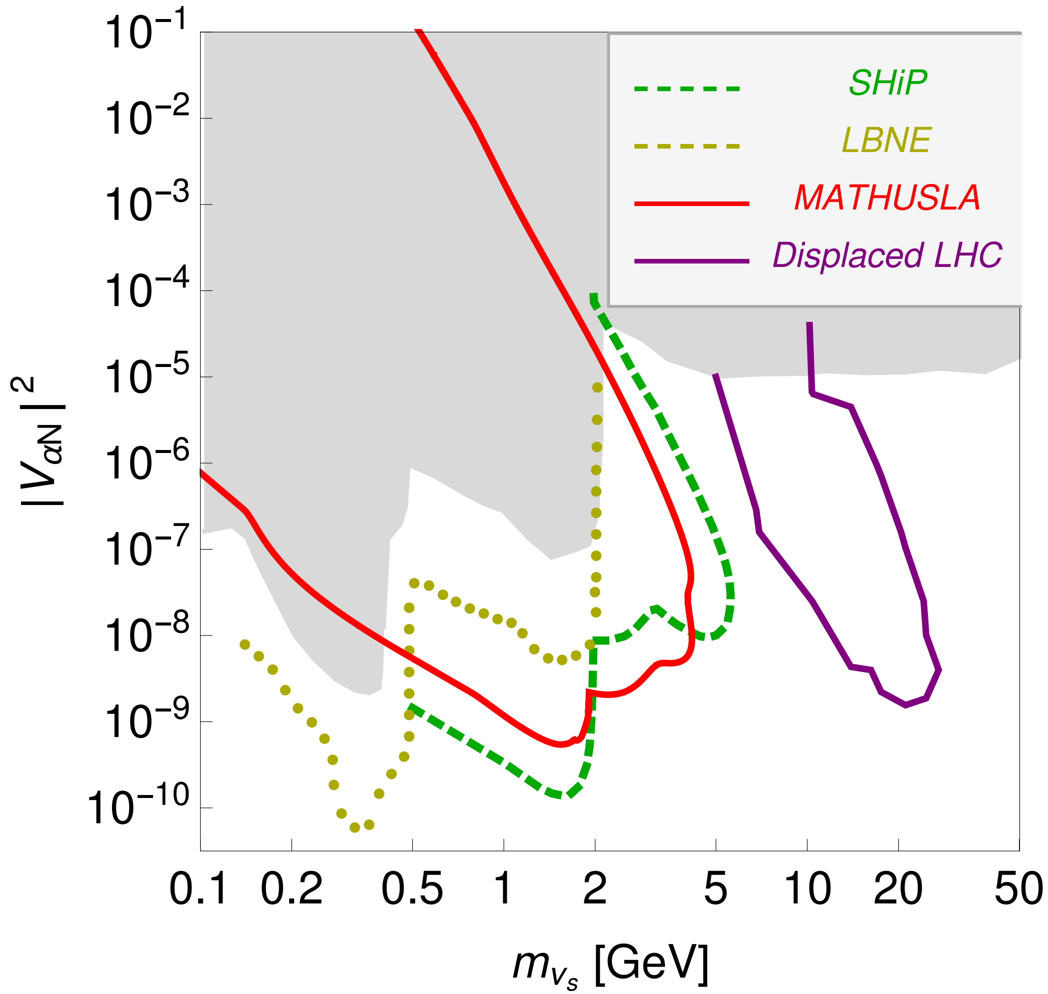
NA62; 1801.04207

MATHUSLA; 1806.07396

CODEXb; 1708.09395

FASER; 1708.09389

Forecast searches

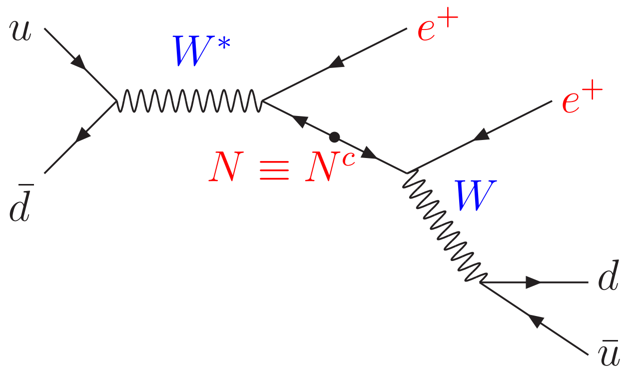


LHC displaced vertex search forecast for $\mathcal{L} = 3$/ab:

Cottin et al.; arXiv:1806.05191

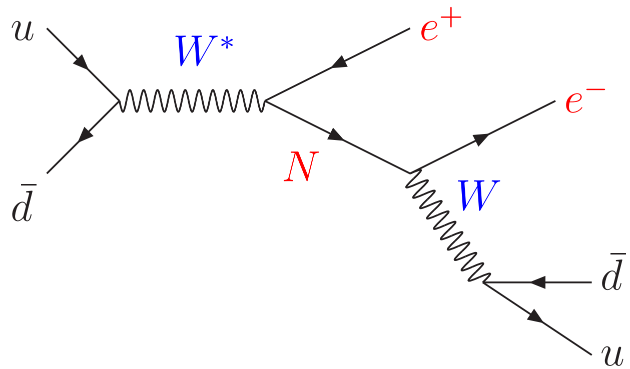
LNV @ LHC

$pp \to l^+ l^+ + jj$ $\qquad$ $pp \to l^+ l^- + jj$



Majorana neutrino

$R_{ll} \equiv 1$



Dirac neutrino

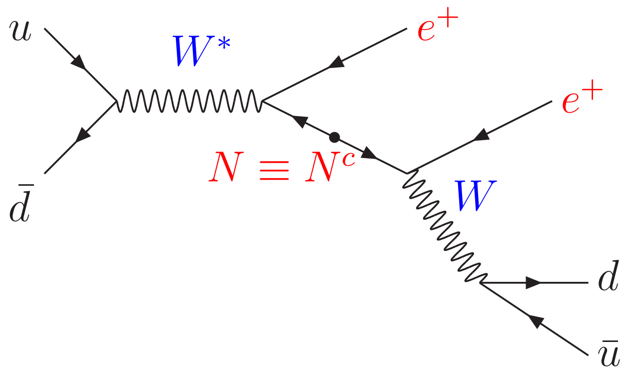
$R_{ll} \equiv 0$

where:

$$R_{ll} = \frac{\#(l^+ l^+ jj) + \#(l^- l^- jj)}{\#(l^+ l^- jj)}$$

LNV @ LHC

$pp \to l^+ l^+ + jj$



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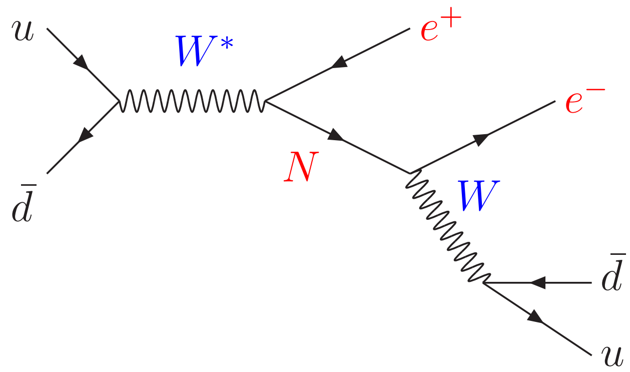
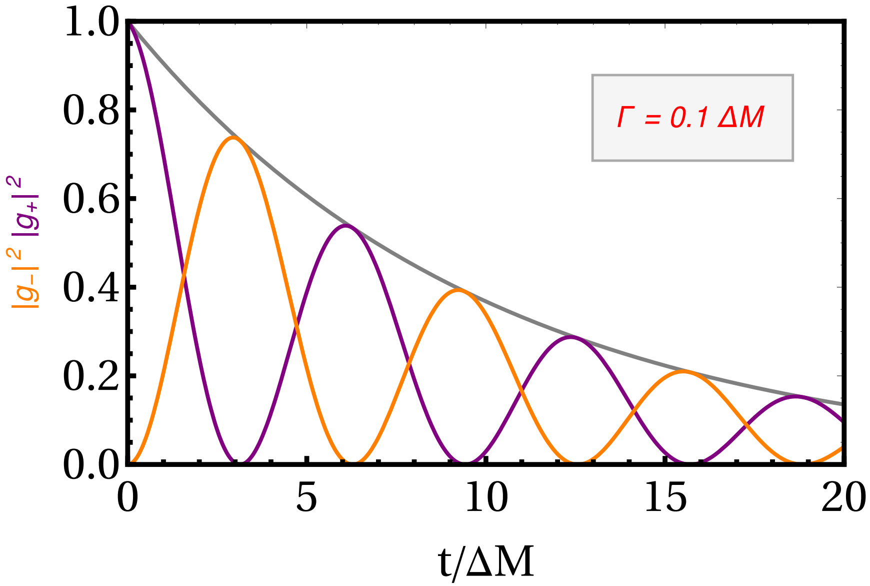


Dirac neutrino

$R_{ll} \equiv 0$

Can one have $R_{ll} = 1/2, 1/4 \ldots 1/13$?

Quasi-Dirac ν oscillations



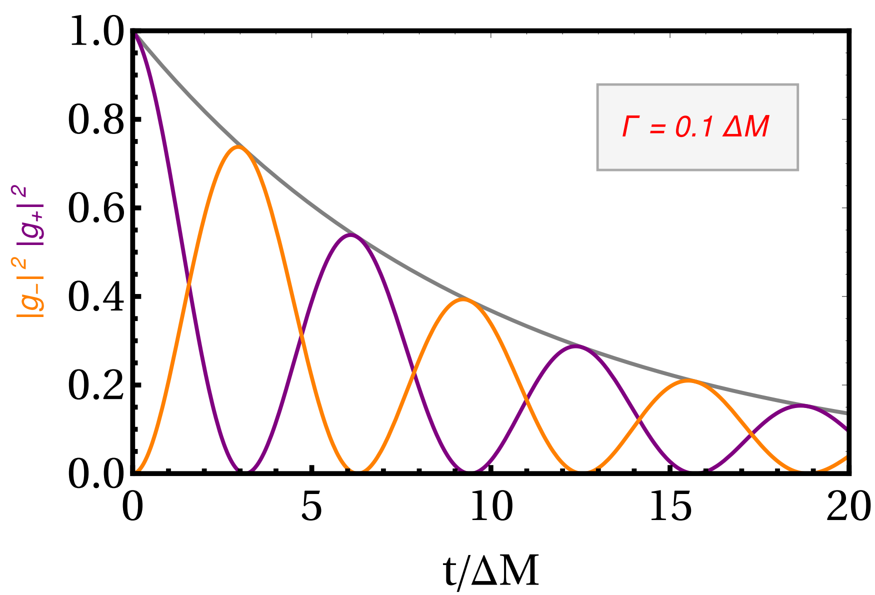
Quasi-Dirac neutrino as function of t:

$$N_\ell(t) = g_+(t)N_\ell + g_-(t)N_{\bar{\ell}}$$

Physics interpretation:

If $\Gamma \simeq \Delta M$
states can interfere!

Quasi-Dirac ν oscillations



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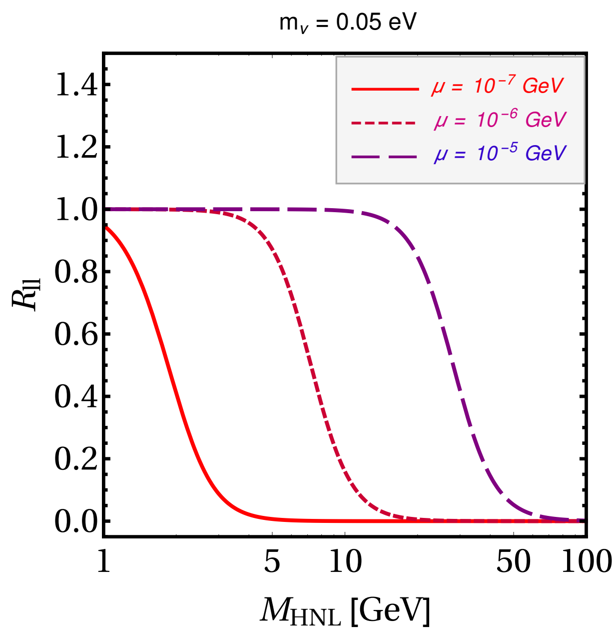

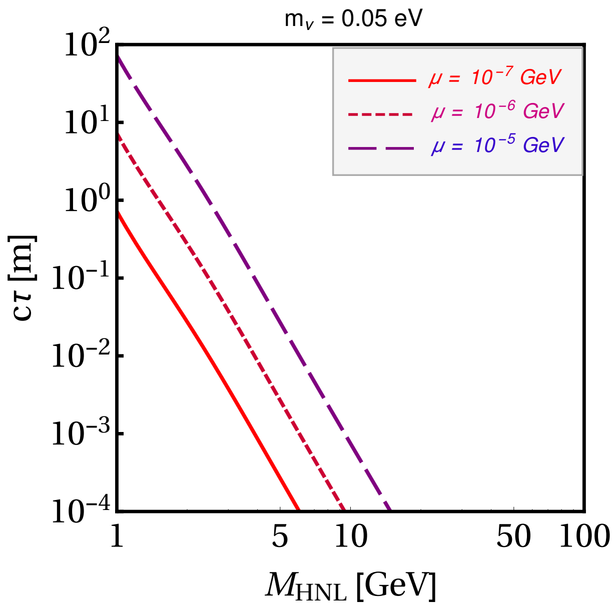

Anamiati et al. 1607.05641

If decay length short, integrate over time:

$$R_{ll} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

$\mathcal{III}.$

Beyond minimal seesaw(s)

Theoretical expectation?

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

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⇒ High scale: Large Λ
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⇒ Higher order: $d = 7, 9, 11$

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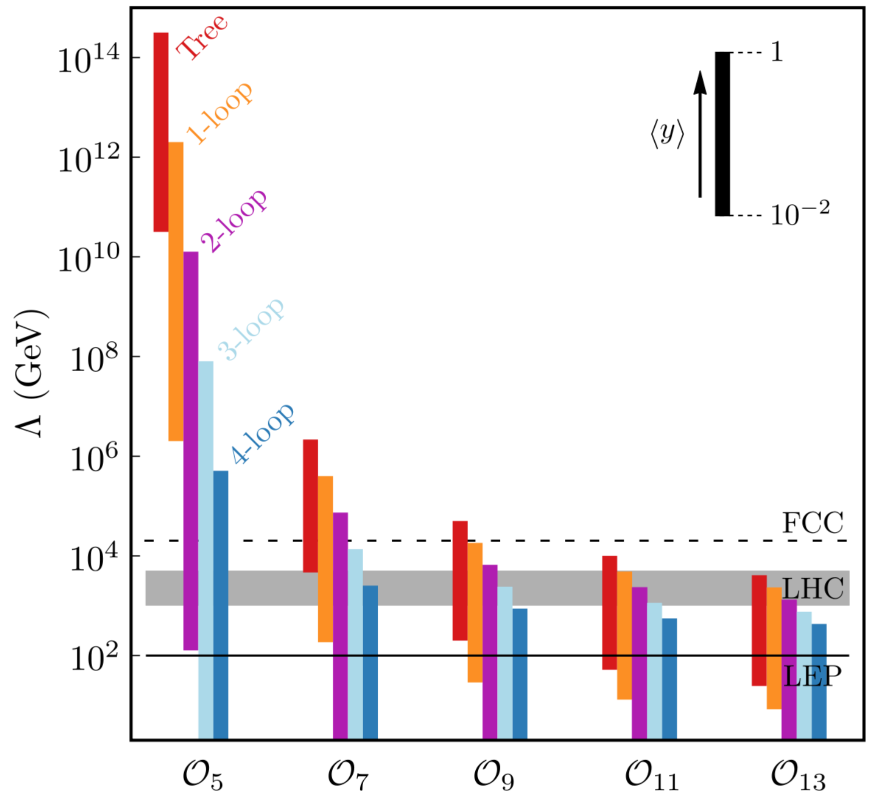

$\Delta L = 2$ operators

$d = 5$: Weinberg, 1979

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

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One d=5

$d = 7$: Babu & Leung, 2001

de Gouvea & Jenkins, 2007

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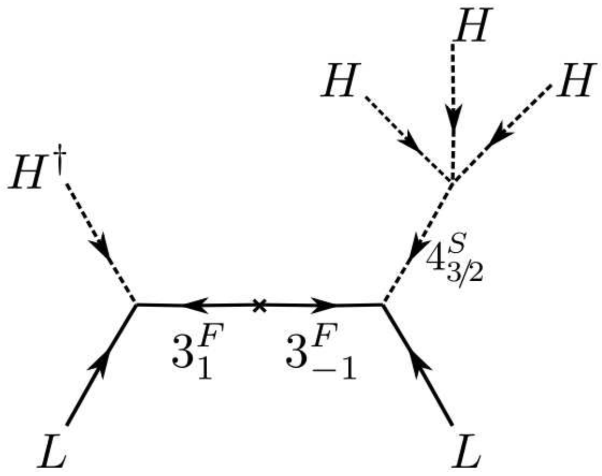
4 (+1) $d = 7$

$$\mathcal{O} \propto (LH)(LH)(H^\dagger H)$$

High-d neutrino masses



d=7:
Babu, Nandi
& Tavartkiladze, 2009 (BNT)

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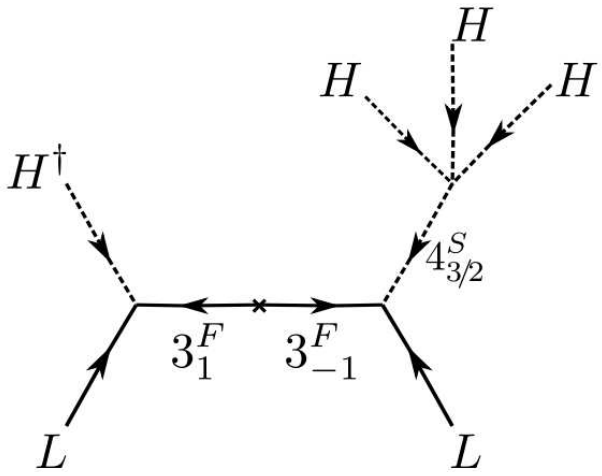

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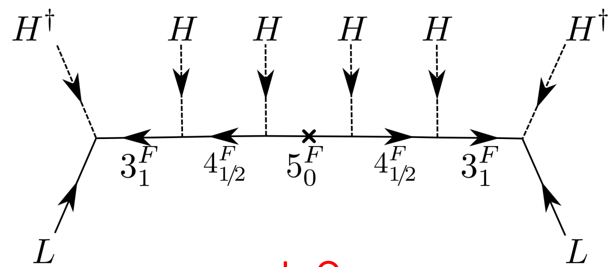
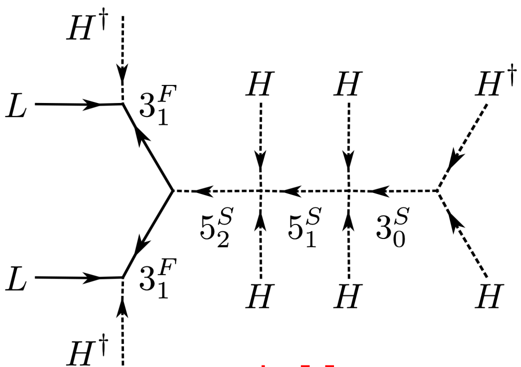
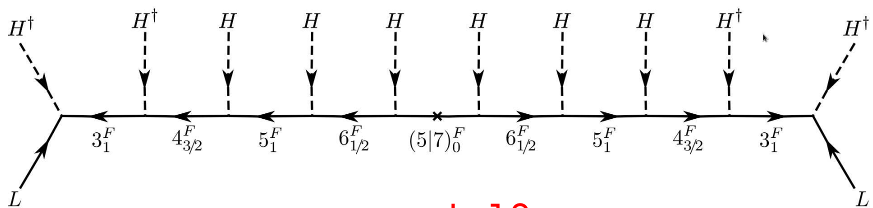
Anamiati et al. 2018



d=9



d=11



d=13

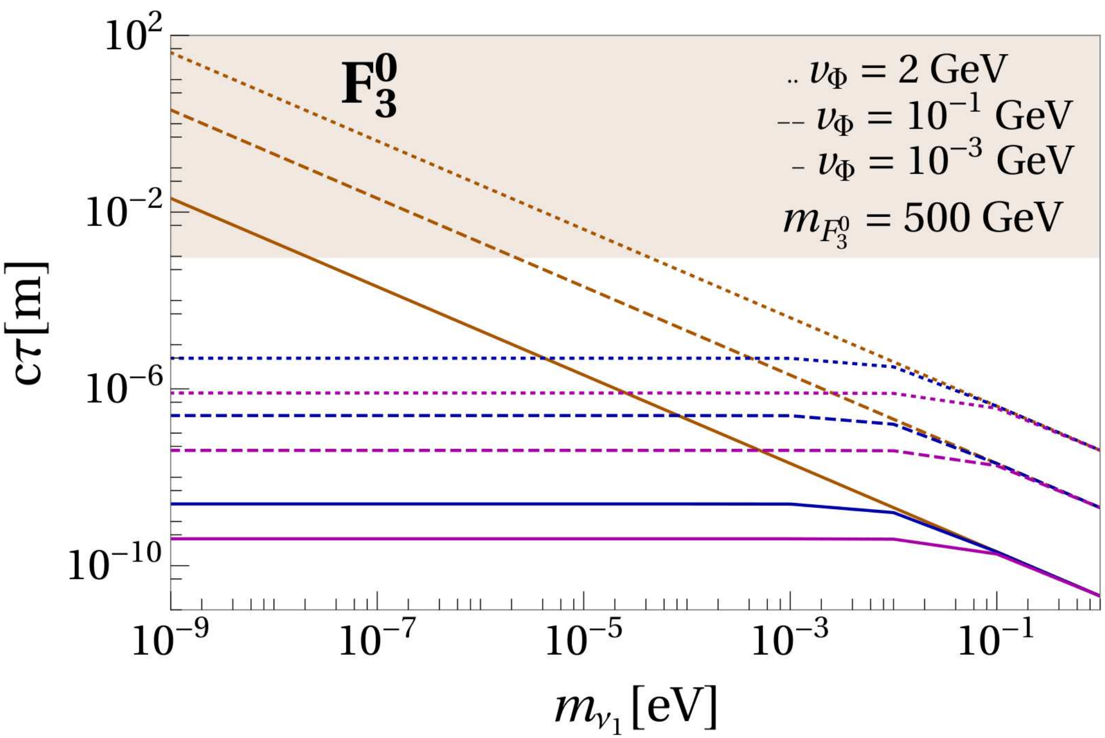
BNT model

Neutrino mass matrix is as in "linear seesaw":

$$m_\nu = (Y_3^T M_3^{-1} Y_{\bar{3}} + Y_{\bar{3}}^T M_3^{-1} Y_3) v v_\Phi$$

Vev v_Φ of quadruplet seesaw suppressed:

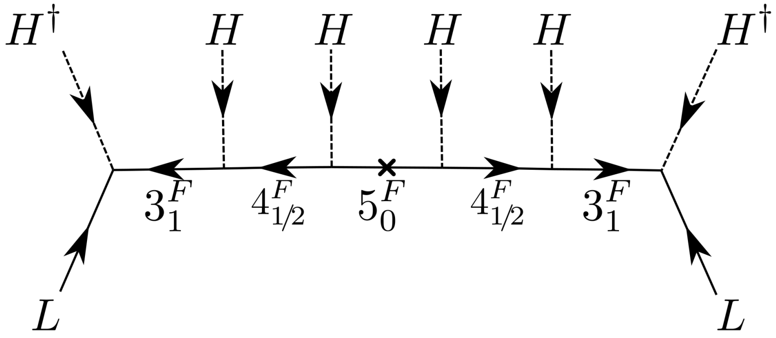
$$v_\Phi \sim \lambda_5 \frac{v^3}{m_{4S}^2}$$



Arbelaéz et al., 2019

Decay length for different v_Φ as function of m_{ν_1}

Decay length in d=9 model



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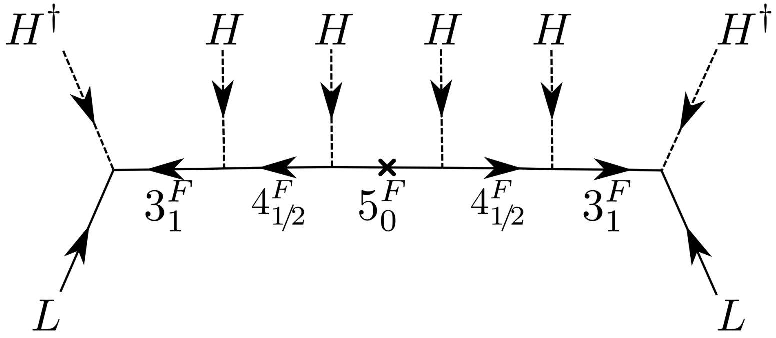
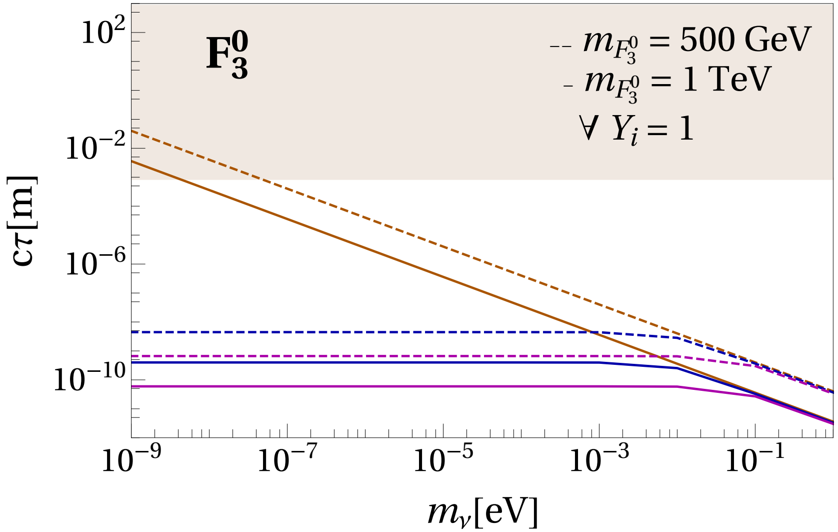
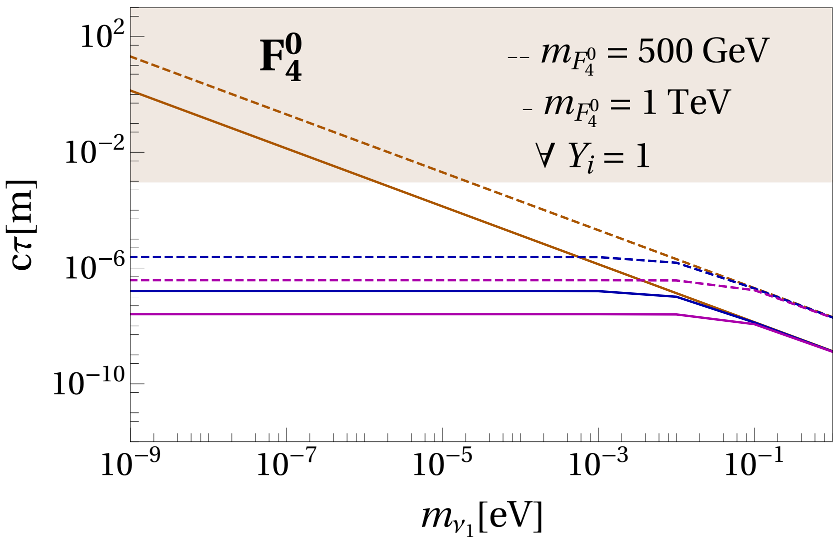
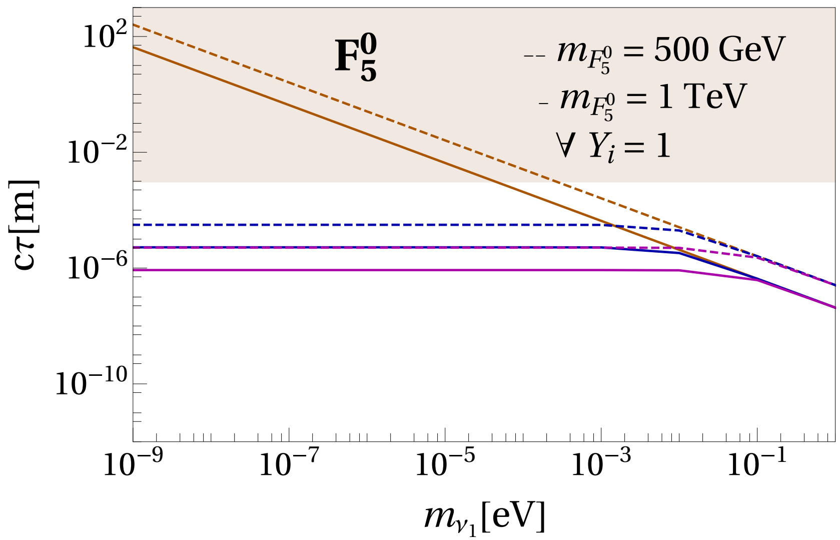


Arbeláez et al., 2019



Decay length depends on which fermion is lightest





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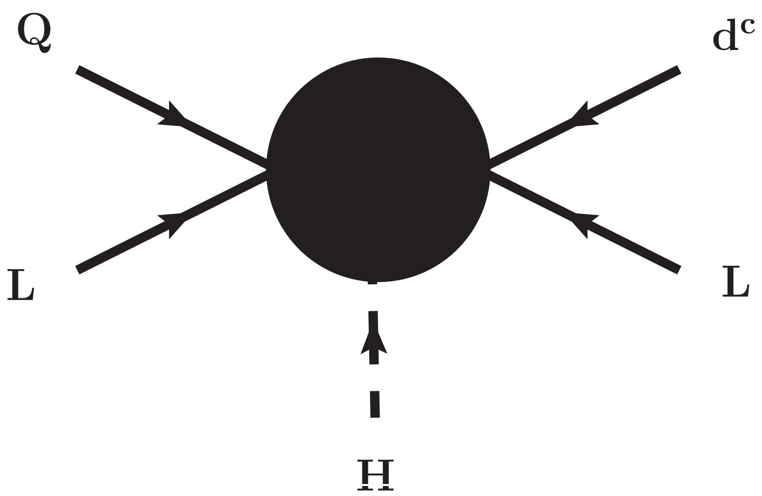
Example $d = 7$: $LLQd^cH$

Graphically:



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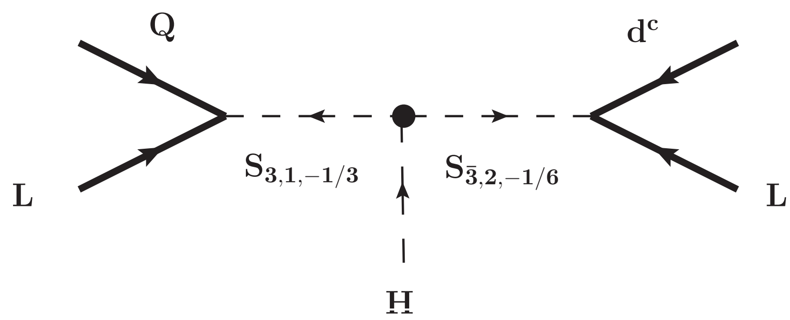
More than one realization.
Example:



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

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

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

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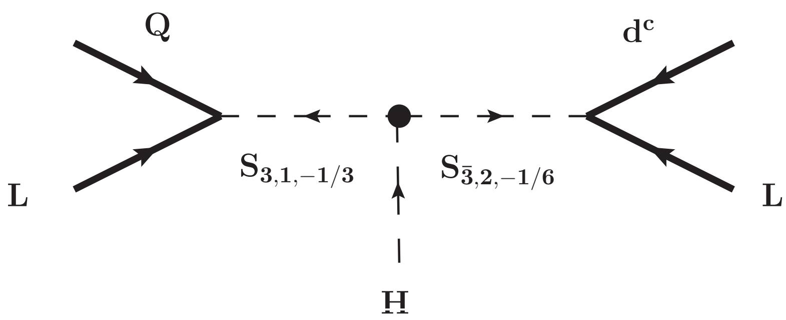

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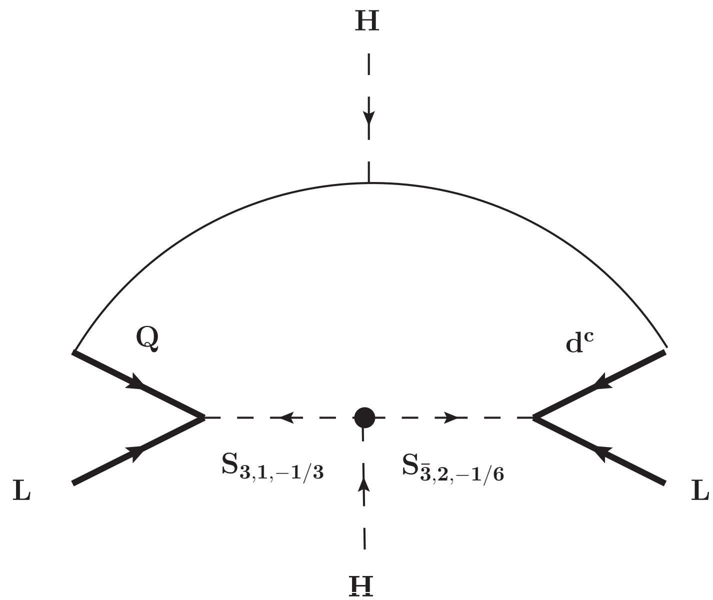
1-loop neutrino mass:



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$$\mathcal{O} \propto (LH)(LH)(H^\dagger H)$$

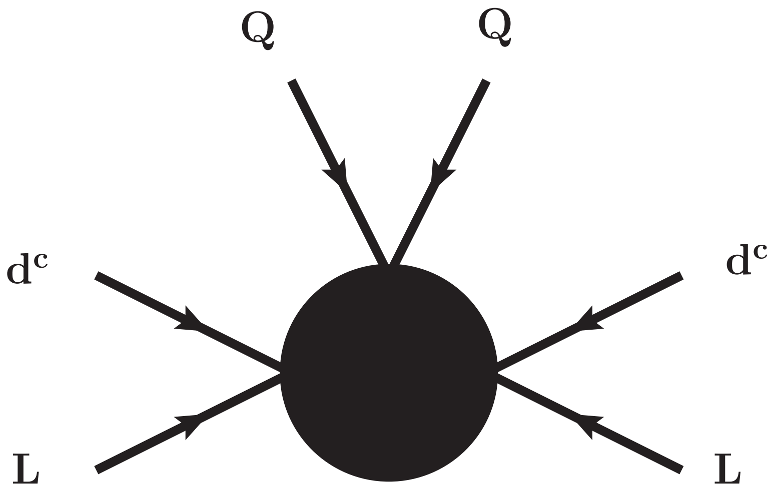
$d=9$: many $d=9$ and $d=11$ ops

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

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

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

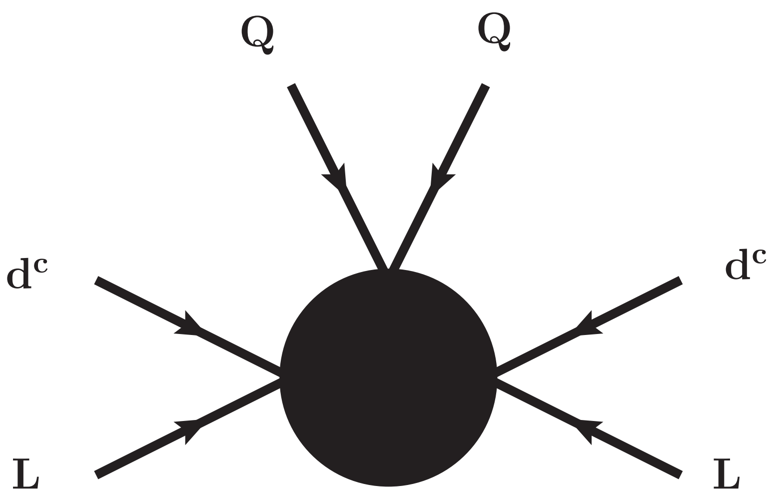
True $d = 9$ operator:



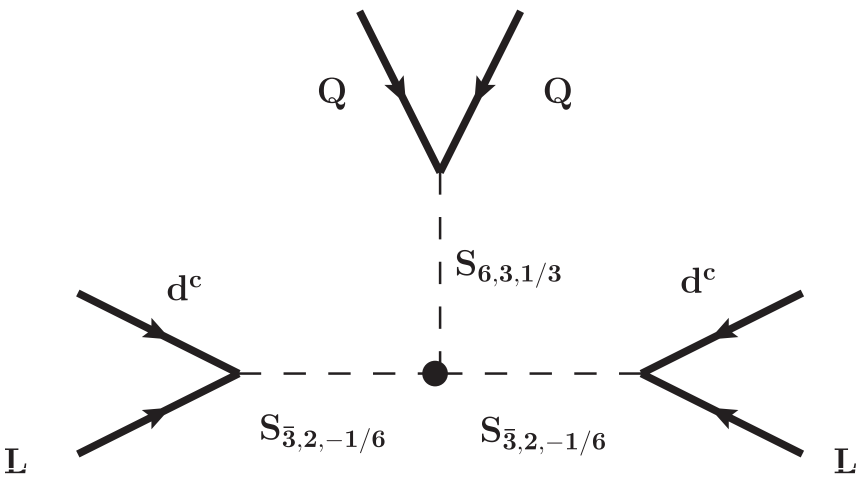
Many, many realizations ...

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

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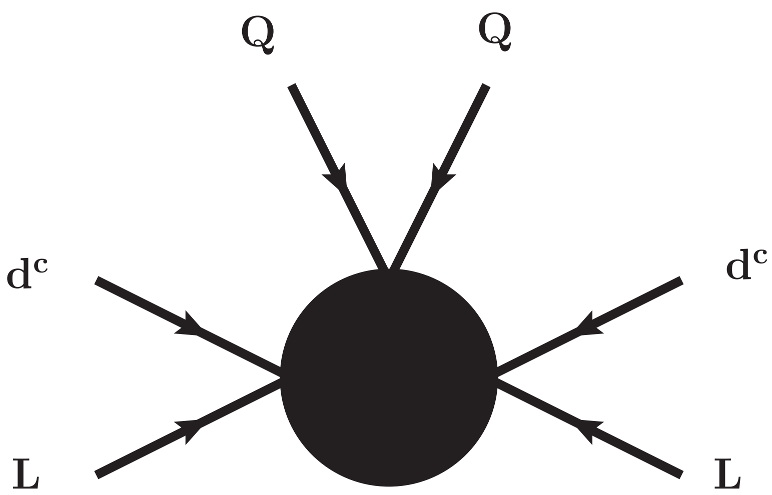

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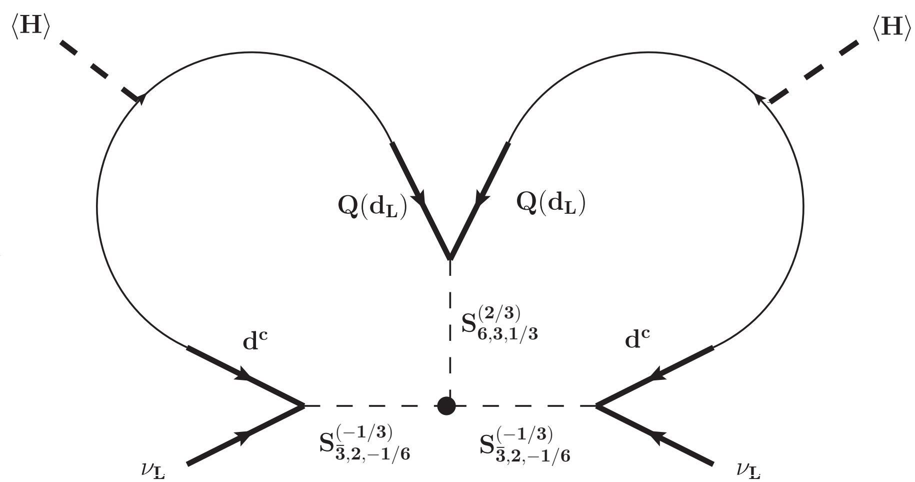


$S_{6,3,1/3}$ - triplet diquark

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

2-loop neutrino mass!

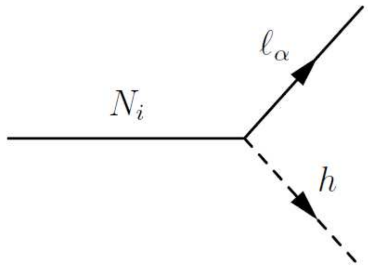
$\mathcal{IV}.$

Leptogenesis and LHC

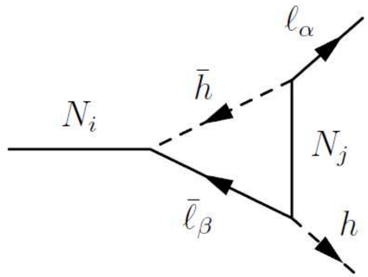
Leptogenesis

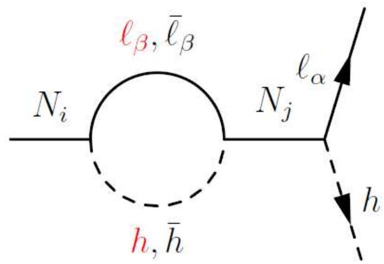
Sakharov's conditions:

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



(e) Tree

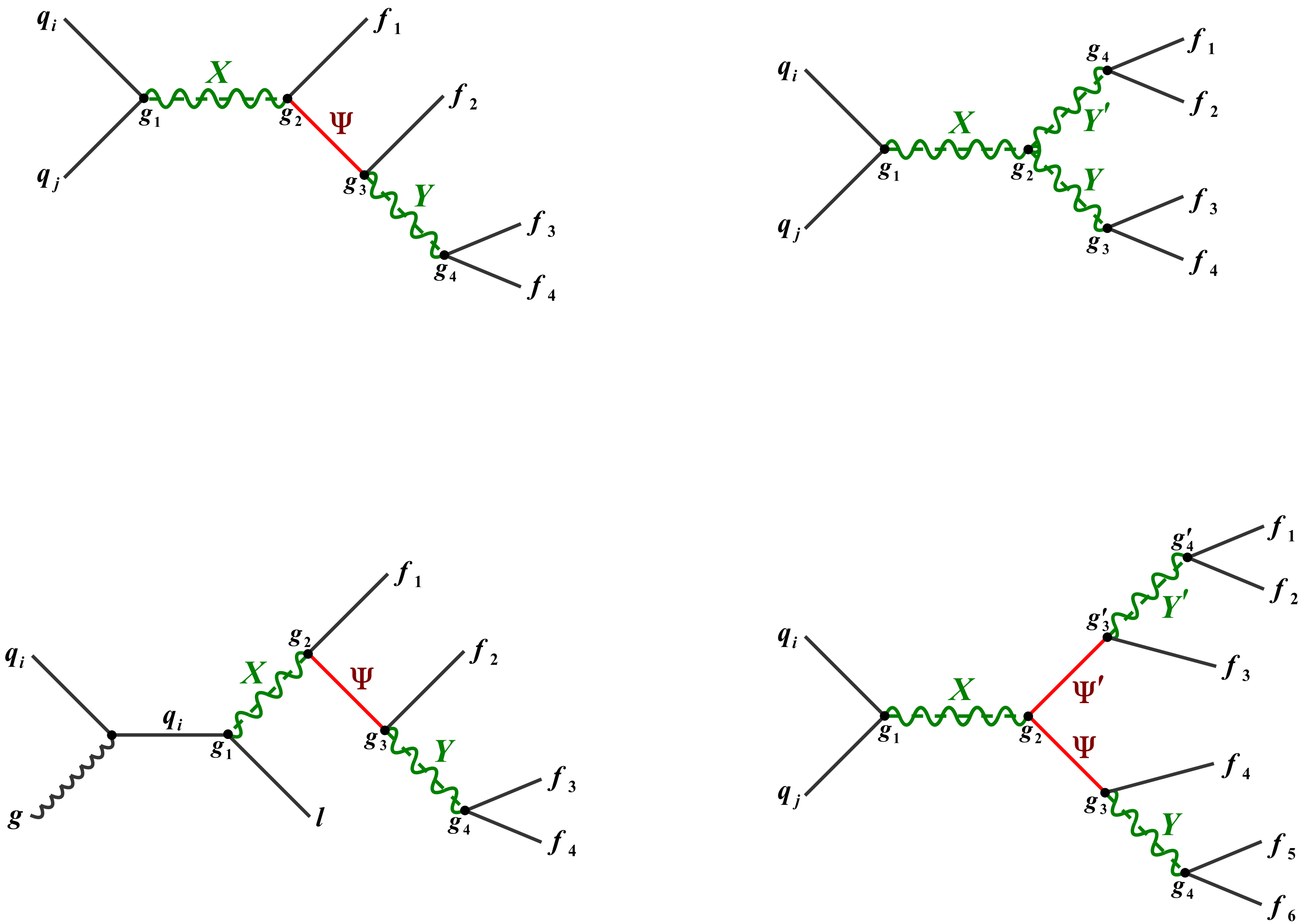




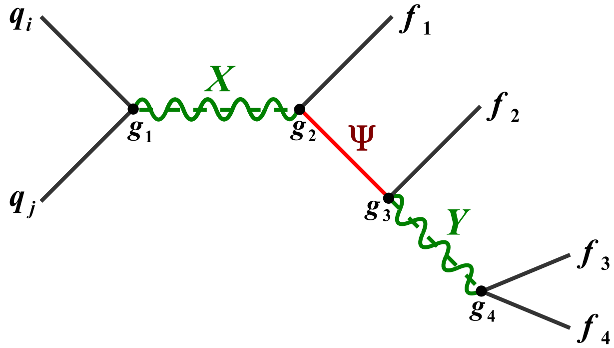
In Leptogenesis:

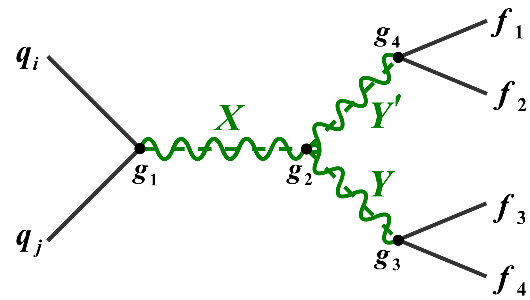
(i) Convert L to B through SM sphalerons
(ii) CP violation through interference tree $\leftrightarrow$ 1-loop
(iii) L out of equilibrium via right-handed neutrino decay

LNV @ LHC



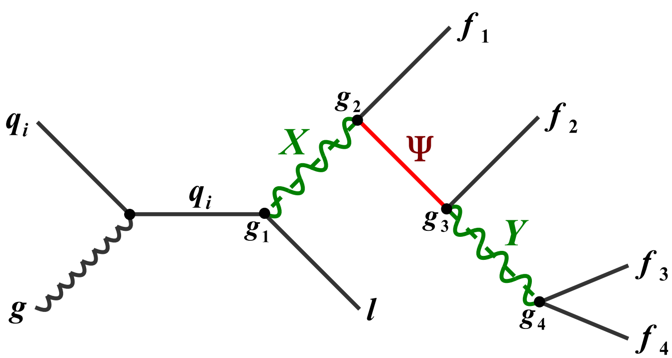
LNV @ LHC

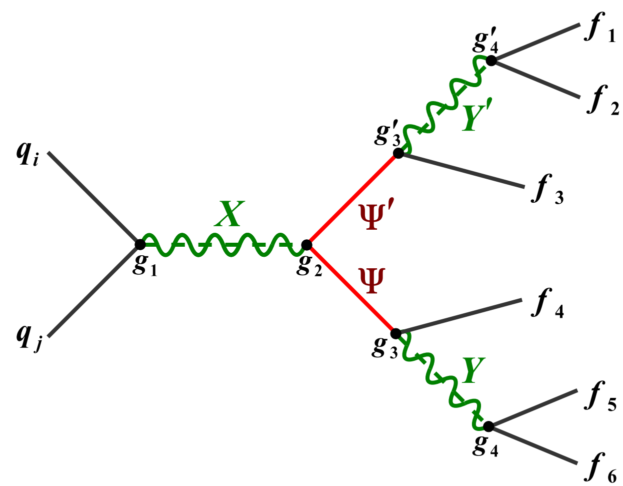




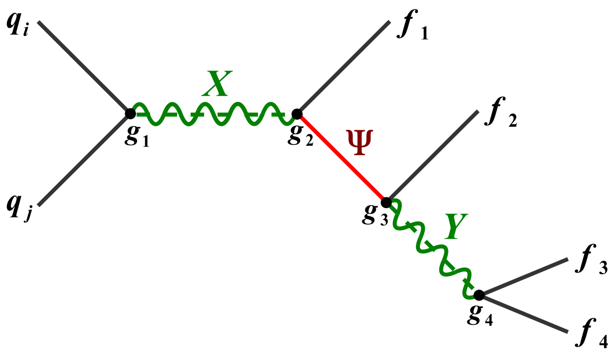
Example:

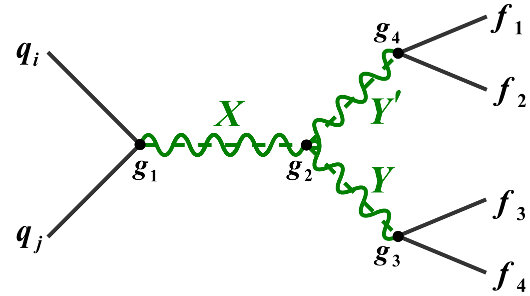
$$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$$





LNV @ LHC



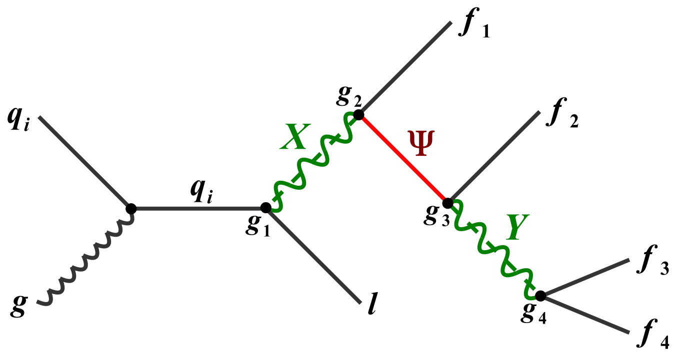


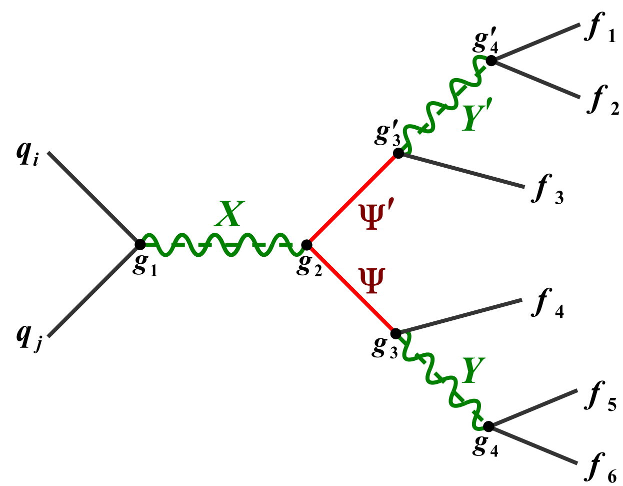
Example:

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

Example:

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



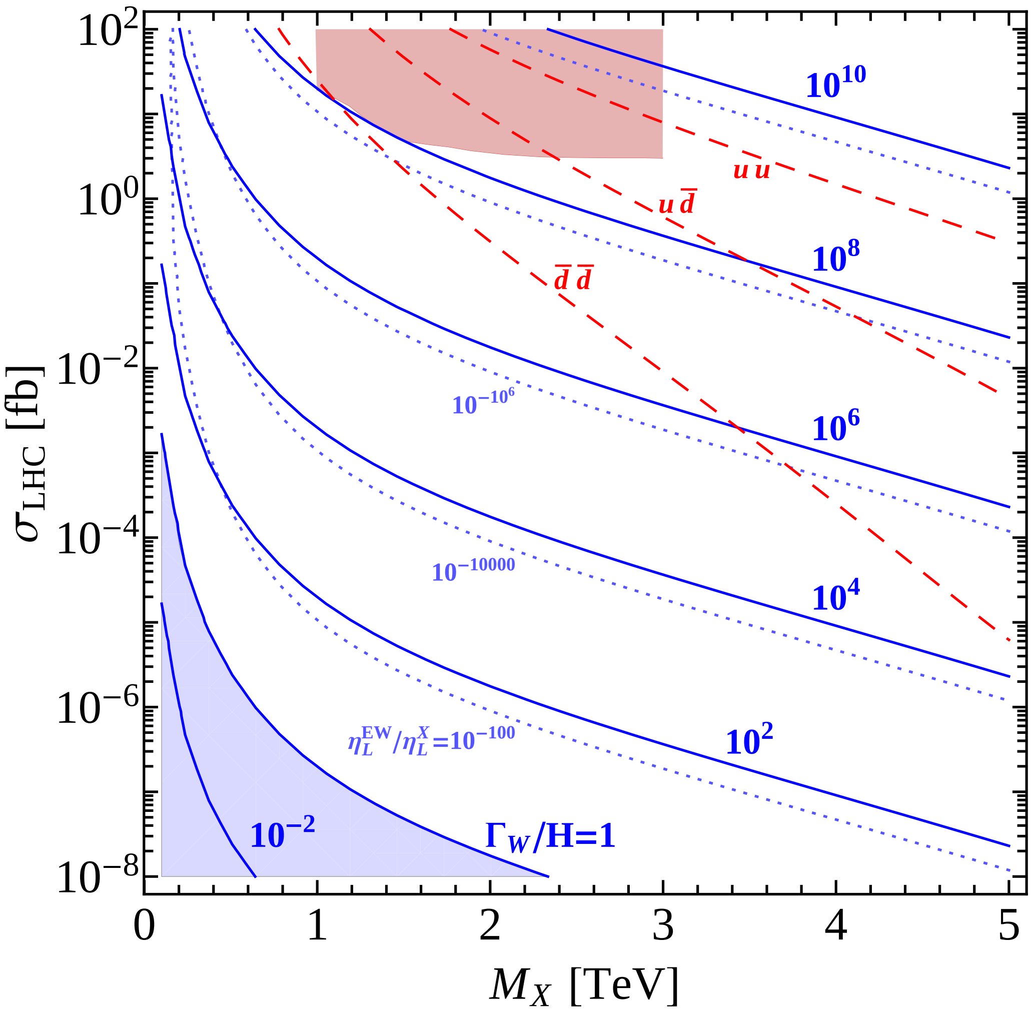


$ug \to S_{3,1,1/3} + l^+ \to l^+ l^+ jjj$

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

Leptogenesis and LHC

Deppisch, Hartz & Hirsch (2014)



blue lines

washout factor Γ_W

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

Observation of

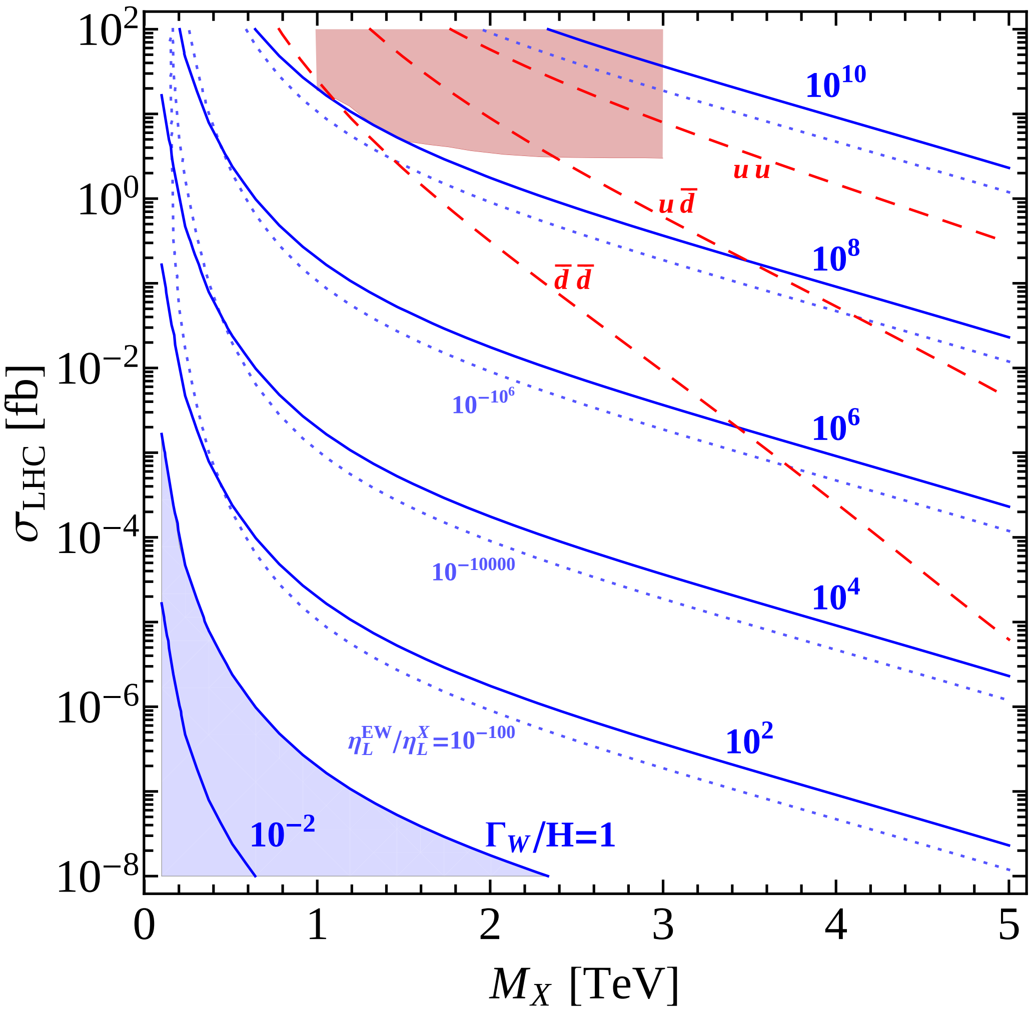
LNV @ LHC implies:

(High-scale) Leptogenesis

is ruled out!

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

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?

(iii) Frandsen et al., 1801.09314:

Additional global $U(1)_X$ "Asymmetric DM"

Conclusions

LNV & LHC:

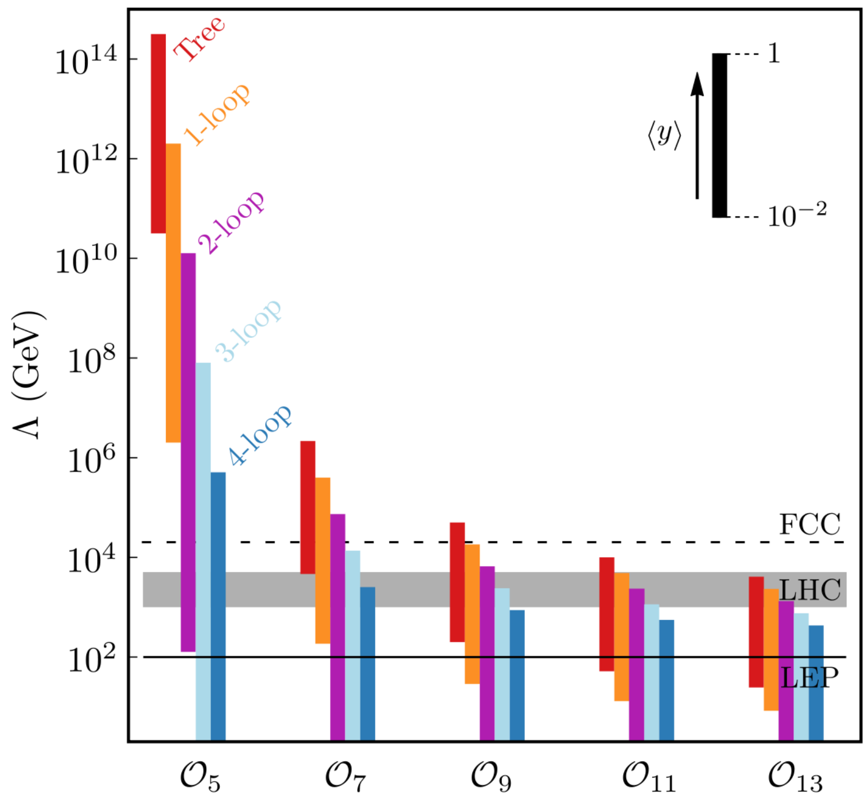
⇒ Majorana neutrino mass and LNV always related

⇒ What is the scale of LNV?

⇒ Smallness of m_ν implies small decay width of HNL

⇒ Quasi-Dirac neutrinos can have LNV oscillations

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

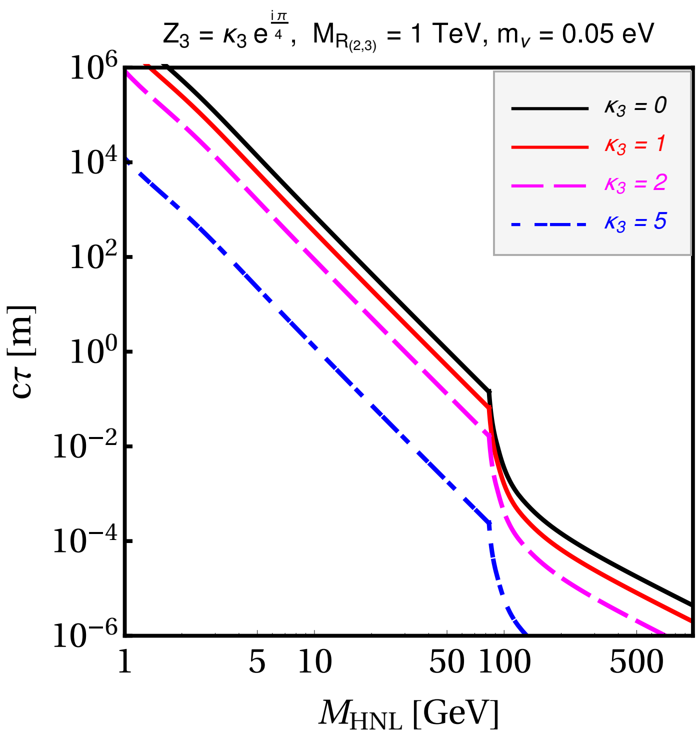


Backup

Decay length and R-matrix

Casa & Ibarra, 2001:

$$m_D = i\sqrt{\hat{M}_R}\mathcal{R}\sqrt{m_{\nu_i}}U_\nu^\dagger$$



Parametrize $\mathcal{R}$ as product of 3 complex rotations $\sin(Z_i)$

Example: $Z_3 = \kappa_3 e^{i\beta_3}$

Note:

For $\kappa_i \gtrsim 1$

Loop contributions to m_ν larger than tree-level seesaw

Quasi-Dirac ν oscillations

Write the state from $W^+_{L/R} \to \bar{\ell} N_\ell$ and its conjugate state from $W^-_{L/R} \to \ell N_{\bar{\ell}}$ in terms of the mass eigenstates as:

$$\begin{aligned} N_\ell &= \frac{1}{\sqrt{2}}(N_+ - iN_-)\,, \\ N_{\bar{\ell}} &= \frac{1}{\sqrt{2}}(N_+ + iN_-)\,. \end{aligned}$$

Let them evolve. After time t:

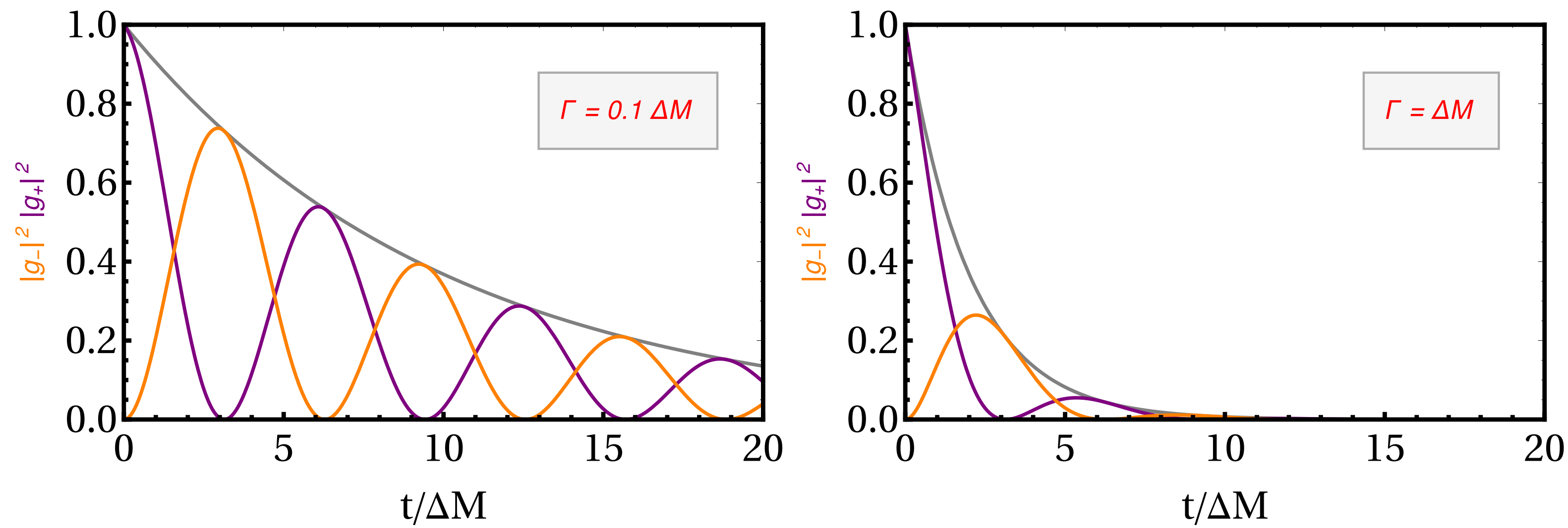
$$\begin{aligned} N_\ell(t) &= g_+(t) N_\ell + g_-(t) N_{\bar{\ell}}\,, \\ N_{\bar{\ell}}(t) &= g_-(t) N_\ell + g_+(t) N_{\bar{\ell}}\,, \end{aligned}$$

where the oscillating amplitudes read :

$$\begin{aligned} g_+(t) &= e^{-iMt} e^{-\frac{\Gamma}{2}t} \cos\left(\frac{\Delta M}{2} t\right)\,, \\ g_-(t) &= i\, e^{-iMt} e^{-\frac{\Gamma}{2}t} \sin\left(\frac{\Delta M}{2} t\right)\,. \end{aligned}$$

Quasi-Dirac ν oscillations

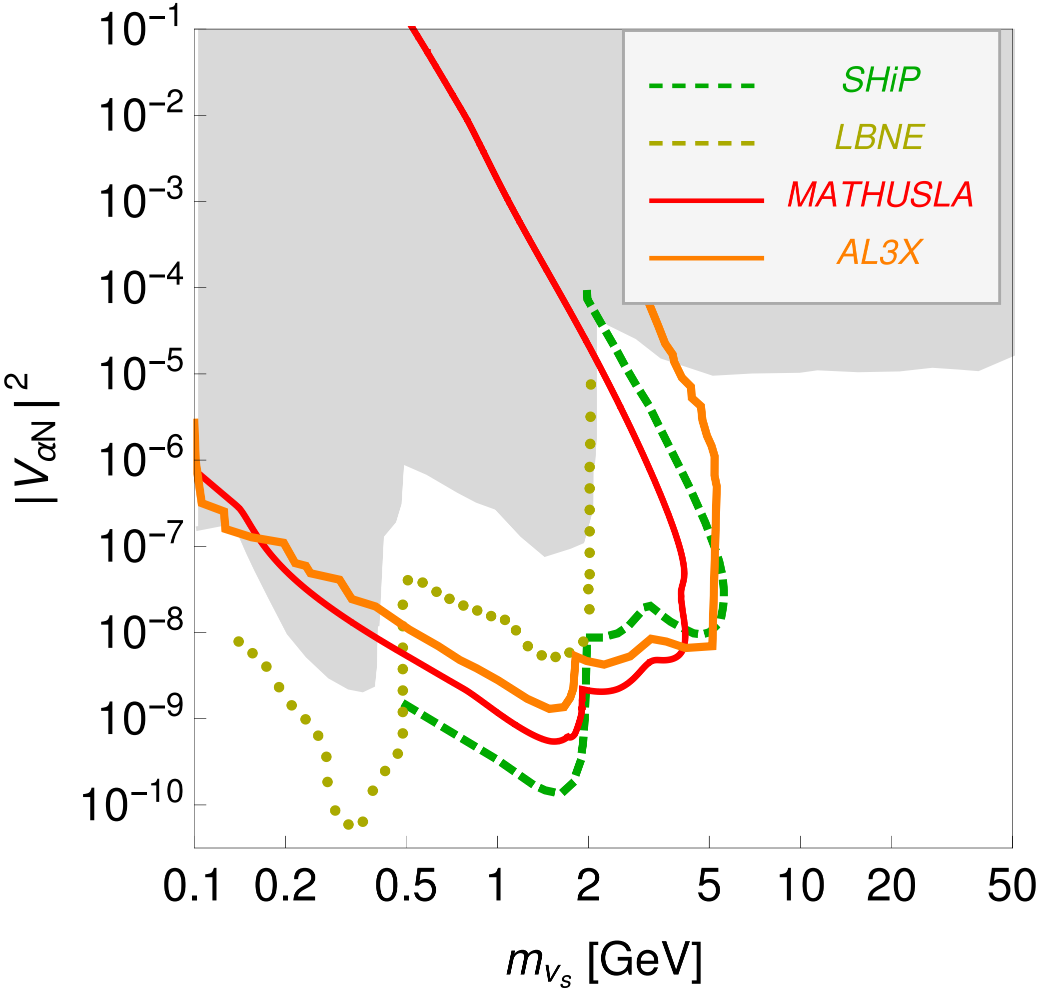
Oscillation and decay amplitudes as function of time:



If $\Gamma \gtrsim 10^{-13}$ GeV (or so), decay length short. Integrate over time:

$$R_{ll} = \frac{\int_0^\infty |g_-|^2 \, dt}{\int_0^\infty |g_+|^2 \, dt} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2} \,.$$

Forecast searches



Plot from:
Dercks et al.; 1811.01995

SHiP; 1504.04855, 1810.03636

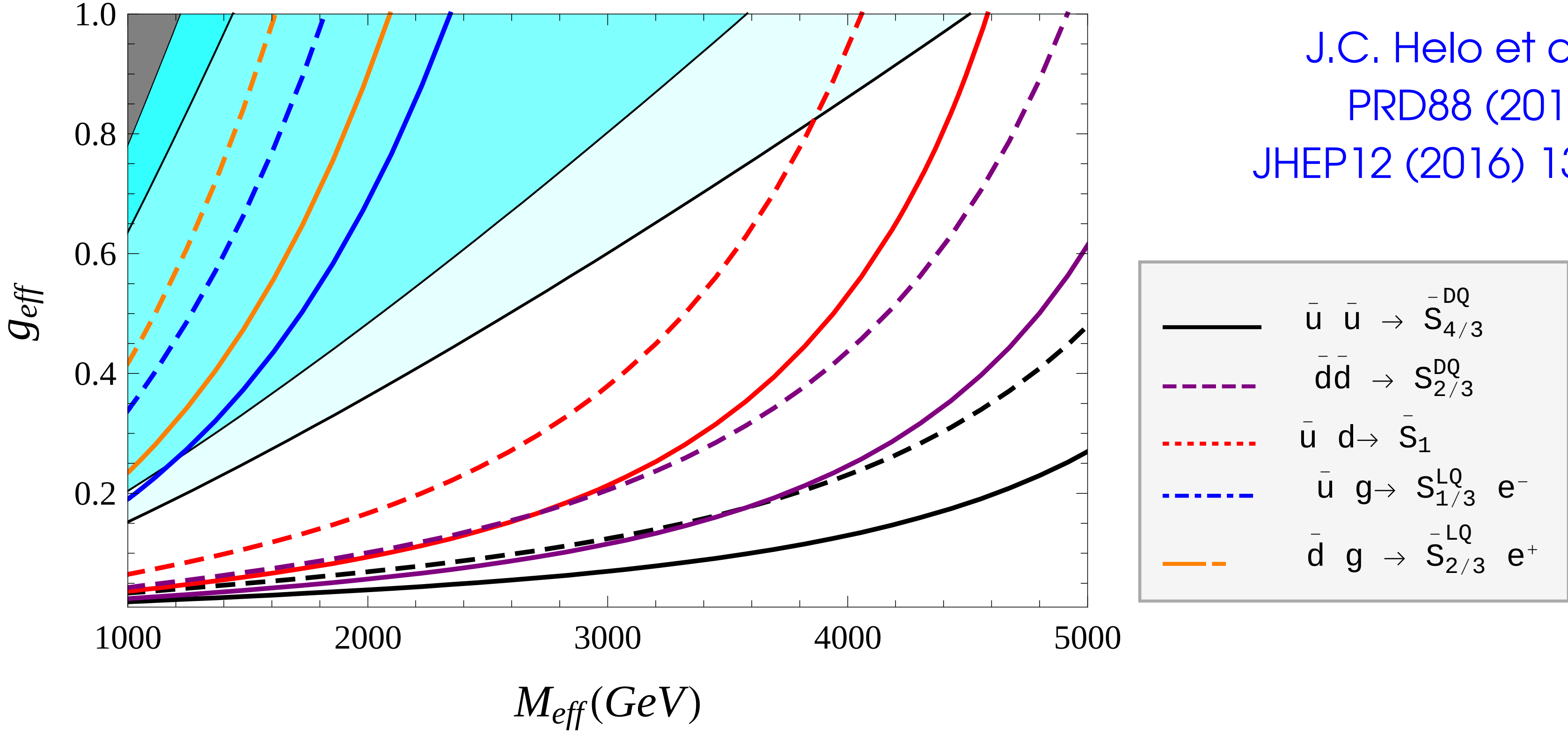
LBNE; 1307.7335

MATHUSLA; 1806.07396

AL3X; 1810.03636

LNV models and LHC

J.C. Helo et al,
PRD88 (2013)
JHEP12 (2016) 130

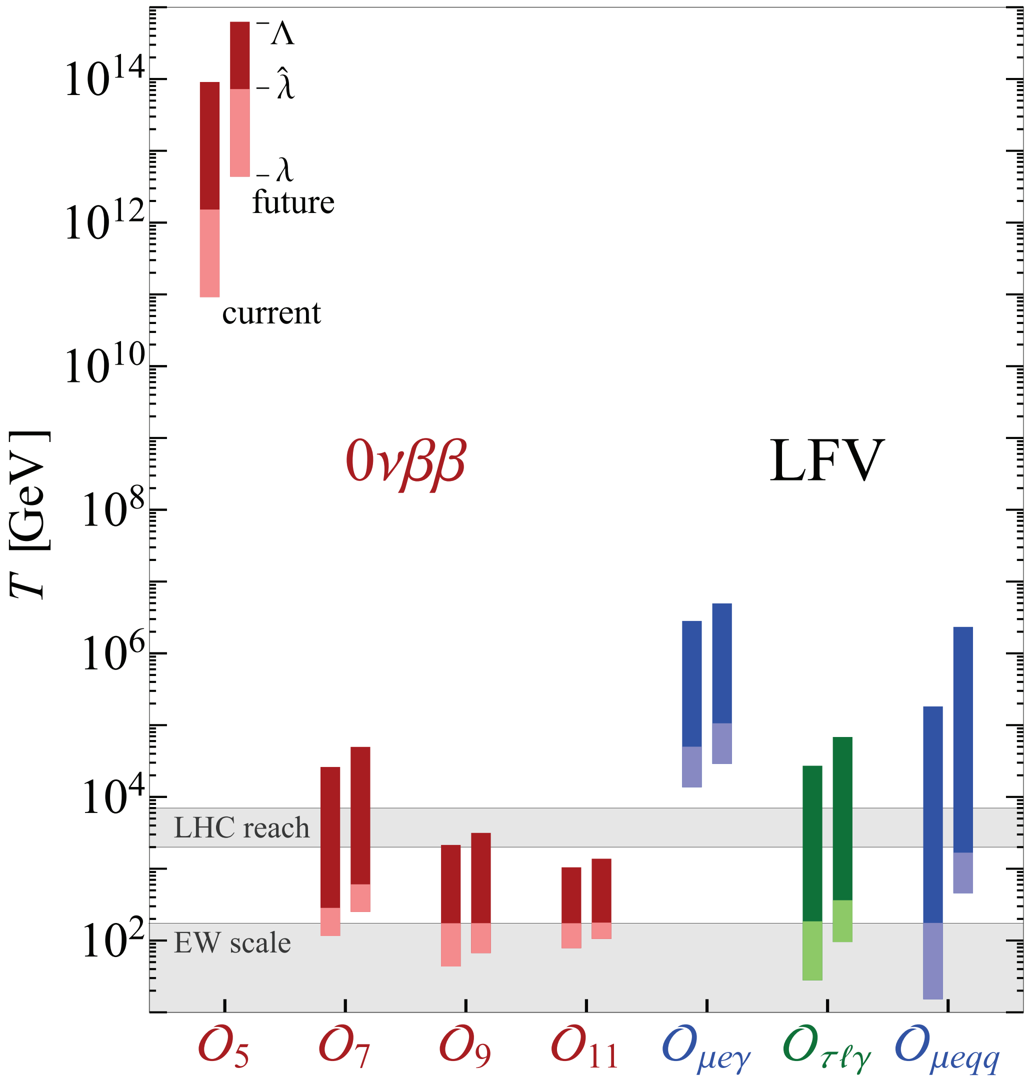


$g_{\rm eff}$ - mean coupling

$M_{\rm eff}$ - mean mass

Dashed (full) lines $Br(S \to eejj) = 0.01\ (0.1)$

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