Long – lived heavy neutrino searches at the colliders

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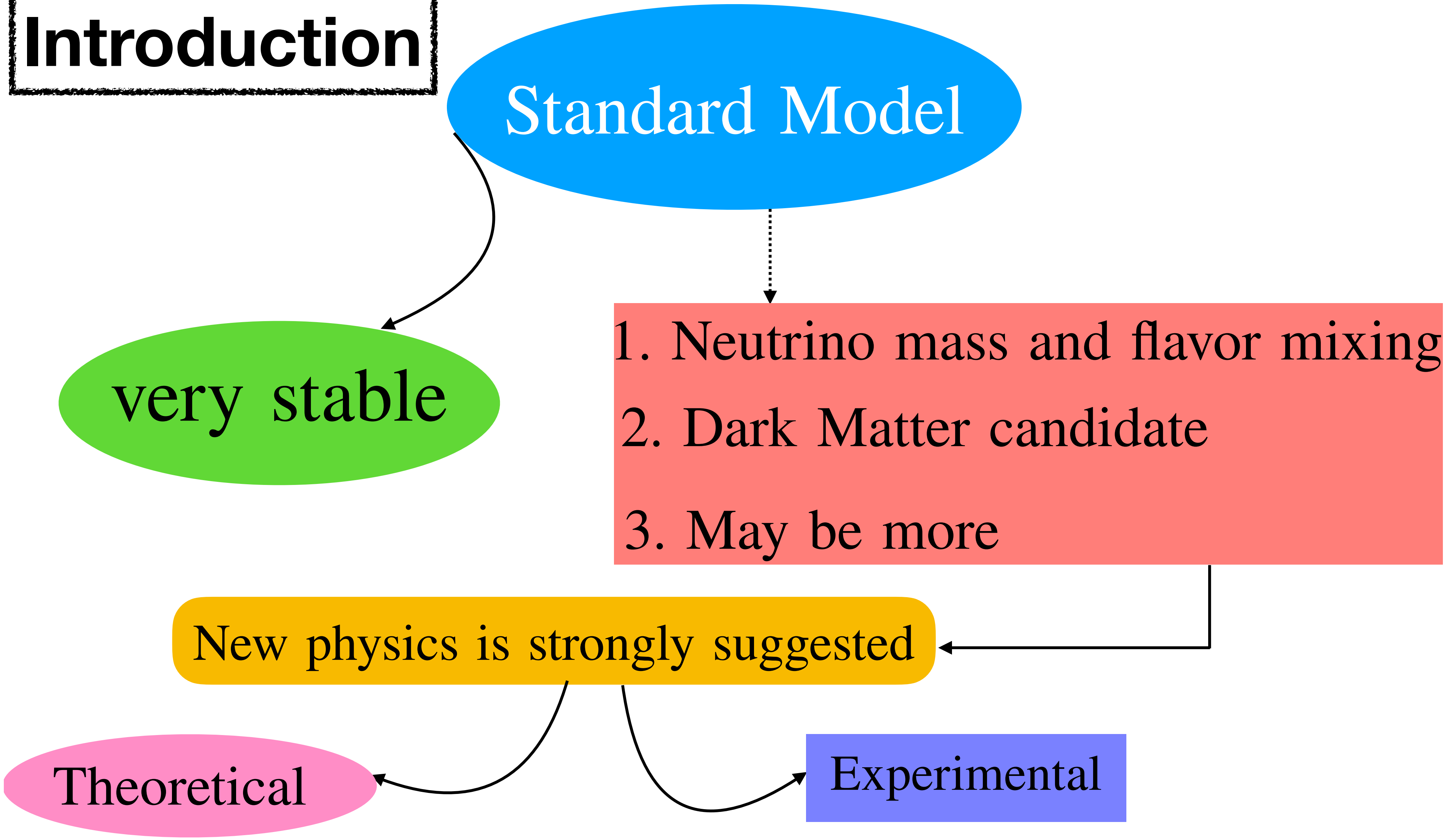
Introduction



We definitely need new physics to provide missing pieces

Particle content of the model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$			$U(1)_X$
q_L^i	**3**	**2**	$+1/6$	x_q	=	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	**3**	**1**	$+2/3$	x_u	=	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	**3**	**1**	$-1/3$	x_d	=	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	x_ℓ	=	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	**1**	**1**	-1	x_e	=	$-x_H - x_\Phi$
H	**1**	**2**	$+1/2$	x_H'	=	$\frac{1}{2}x_H$
N_R^i	**1**	**1**	0	x_ν	=	$-x_\Phi$
Φ	**1**	**1**	0	x_Φ'	=	$2x_\Phi$

$$m_{Z'} = 2\, g_X v_\Phi$$

x_H, x_Φ will appear the coupling with Z'

3 generations of SM singlet right handed neutrinos (anomaly free)

Charges after Imposing the anomaly cancellations

Charges before the anomaly cancellations

Neutrino sector

$U(1)_X$ **breaking**

EWSB

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{i=k}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

Dirac mass term

$$m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v_h$$

Majorana mass term

$$m_{N^i} = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$

Seesaw mechanism to generate the light neutrino mass

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$$

$$m_\nu \simeq -M_D M_N^{-1} M_D^T$$

Properties of the model and phenomenology

New particles

Z' boson

Heavy Majorana Neutrino

$U(1)_X$ Higgs boson

Phenomenology

Z' boson production and decay

Z' boson mediated processes

Heavy neutrino production

$U(1)_X$Higgs phenoemenology : Vacuum Stability

collider

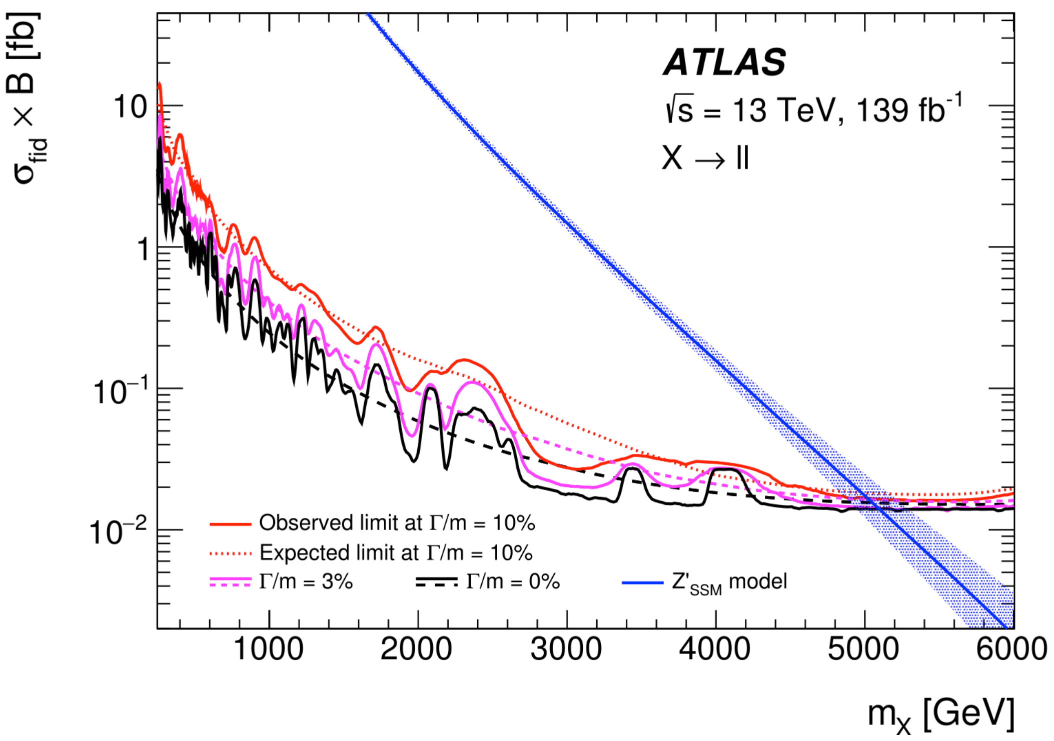
Dark Matter

Leptogenesis and many more

We focus on the Z' boson and heavy neutrino phenomenology

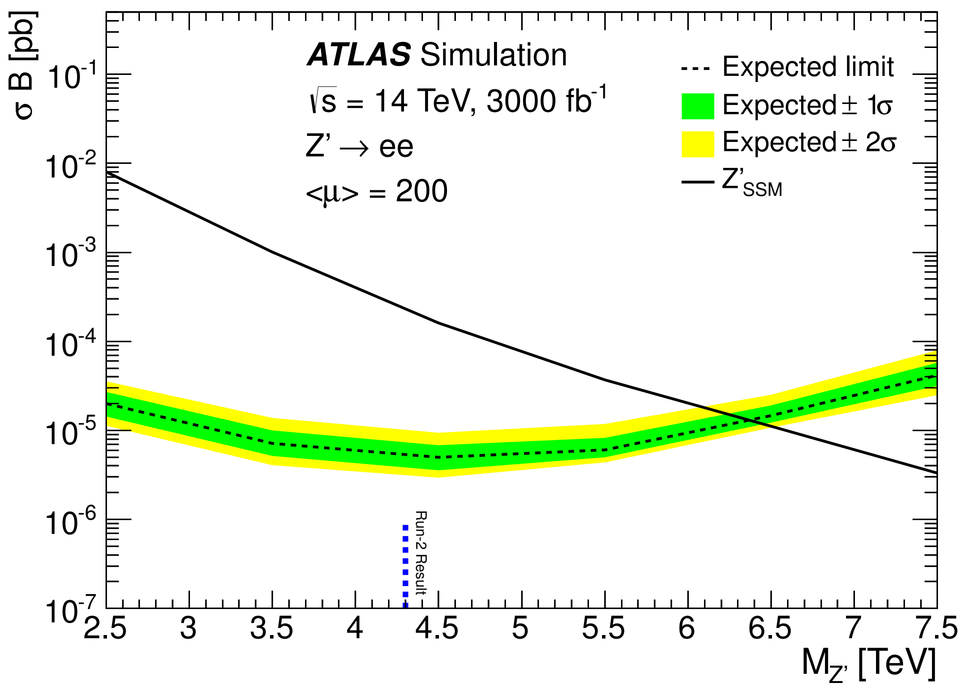
Bounds on the $U(1)_X$ gauge coupling

ATLAS: 1903.06248 (139/fb)

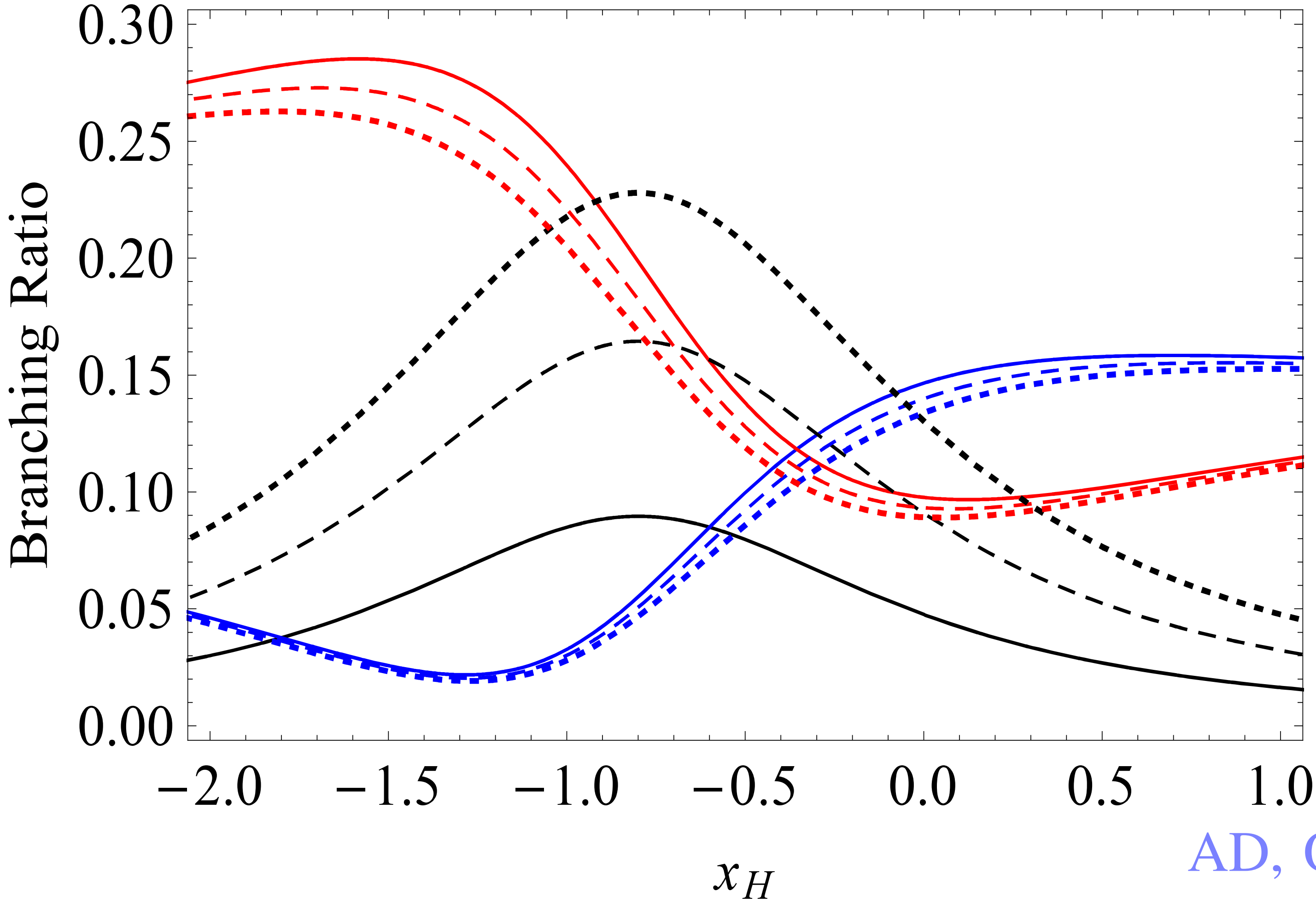


CMS (36/fb) and ATLAS (139/fb) searches at the LHC Run-1 and Run-2 respectively

ATLAS-TDR-027 (prospective)



The branching ratios of Z' boson as a function of x_H with a fixed $M_{Z'} = 3.0$ TeV



Solid : $M_{N_1} = \frac{M_{Z'}}{4}, M_{N_{2,3}} > \frac{M_{Z'}}{2}$

Dashed : $M_{N_{1,2}} = \frac{M_{Z'}}{4}, M_{N_3} > \frac{M_{Z'}}{2}$

Dotted : $M_{N_{1,2,3}} = \frac{M_{Z'}}{4}$

AD, Okada, Raut, 1710.03377

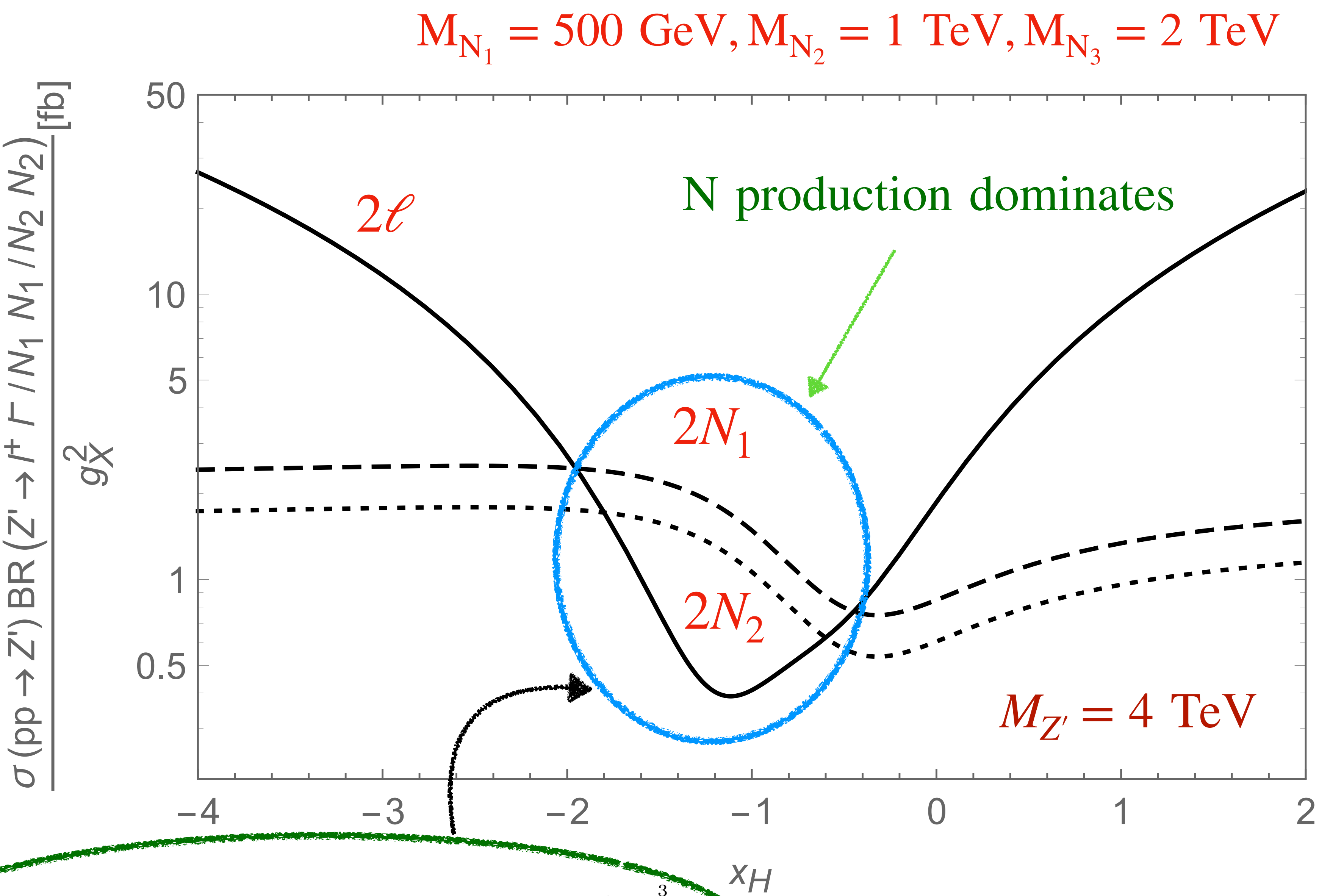
Top → bottom : Solid (Red, Black, Blue)

Up and down quarks

Heavy neutrinos

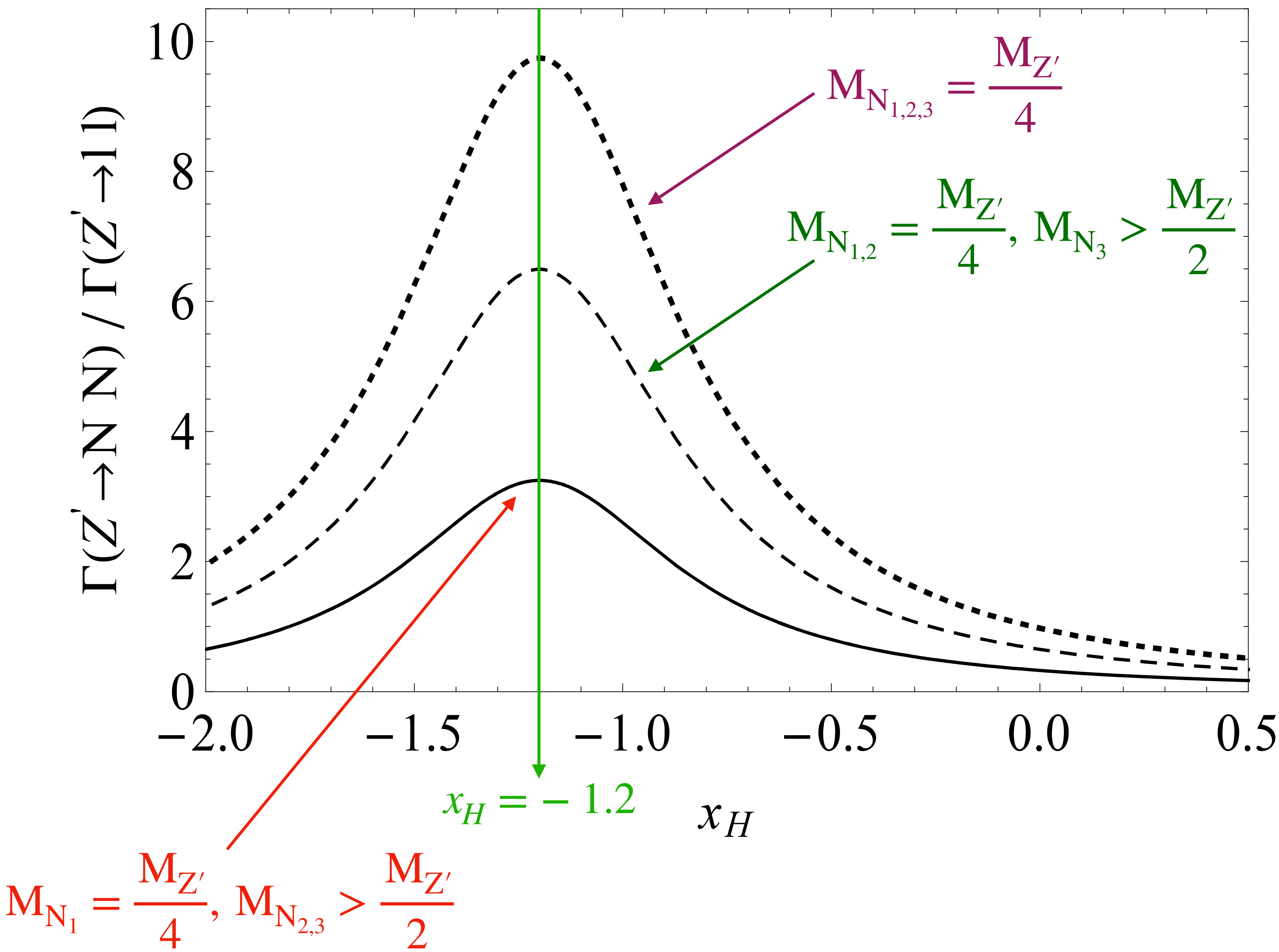
Charged leptons

Pair Production of the RHNs as function of x_H



$$\frac{\Gamma(Z' \to NN)}{\Gamma(Z' \to \ell^+\ell^-)} = \frac{4}{8 + 12x_H + 5x_H^2}\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{\frac{3}{2}}$$

The ratio of the partial decay widths of Z' boson into RHNs and dilepton final states as a function of x_H



Right handed neutrino pair production

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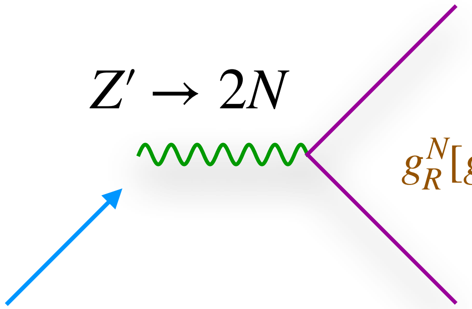
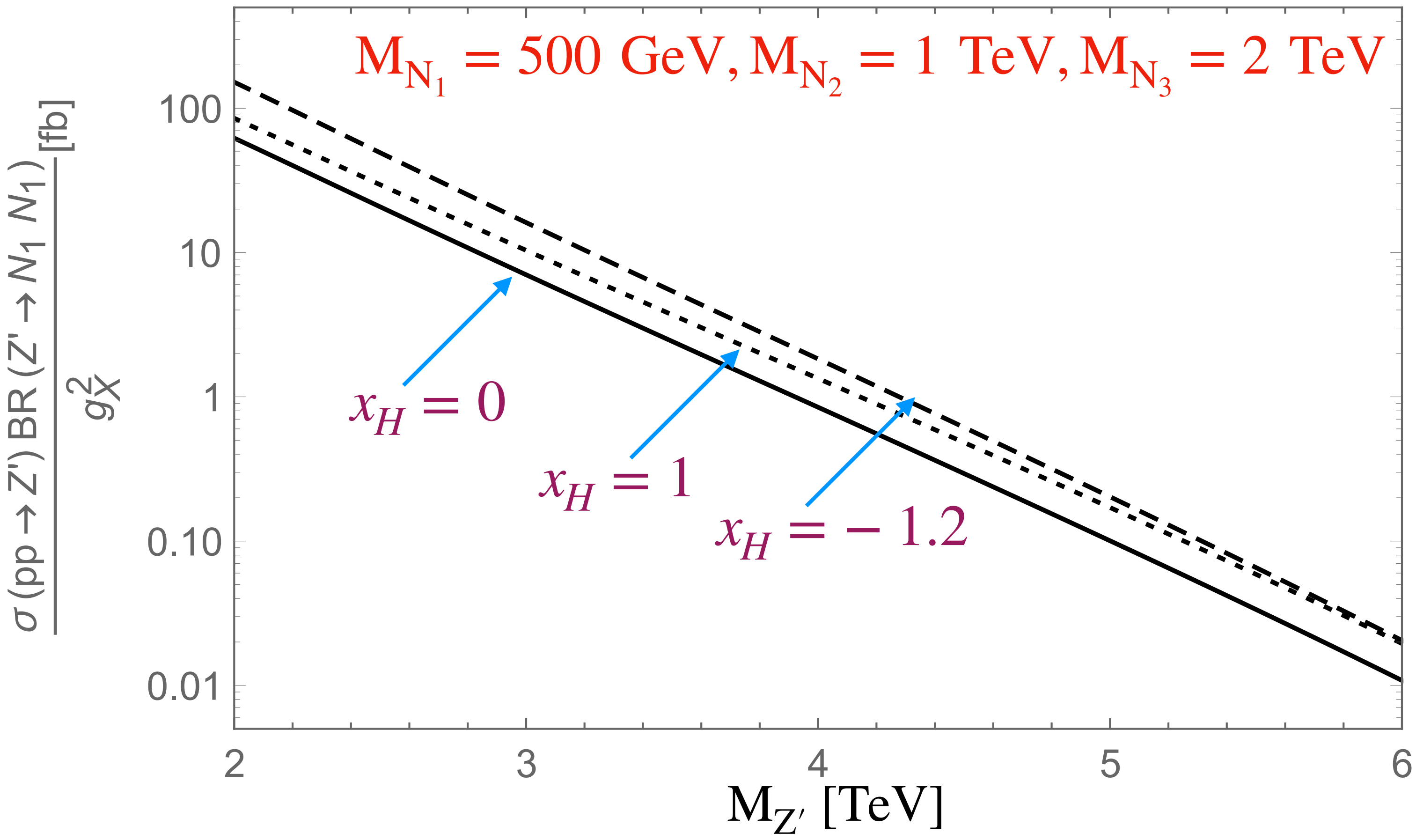
$M_{Z'} > 2M_N$ (at least)



$g_R^N[g_x, x_H] = \left(0\ x_H + (-1)\right) g_x$

$$\Gamma[Z' \to 2N_i] = \frac{M_{Z'}}{24\pi} g_R^N[g_x, x_H]^2 (1 - 4\frac{M_{N_i}^2}{M_{Z'}^2})^{\frac{3}{2}}$$

$$M_N = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$



Generalizing the mixing parameter

$$\mathcal{R}^{\mathrm{NH/IH}} = U^*_{\mathrm{PMNS}}\sqrt{D^{\mathrm{NH/IH}}}\,O\,\sqrt{m_N^{-1}}$$

general orthogonal matrix

$$O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos x & \sin x \\ 0 & -\sin x & \cos x \end{pmatrix} \begin{pmatrix} \cos y & 0 & \sin y \\ 0 & 1 & 0 \\ -\sin y & 0 & \cos y \end{pmatrix} \begin{pmatrix} \cos z & \sin z & 0 \\ -\sin z & \cos z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Normal hierarchy

$$D^{\mathrm{NH}} = \mathrm{diag}\left(m_{\mathrm{lightest}}, m_2^{\mathrm{NH}}, m_3^{\mathrm{NH}}\right)$$

$$m_2^{\mathrm{NH}} = \sqrt{\Delta m_{12}^2 + m_{\mathrm{lightest}}^2}$$

$$m_3^{\mathrm{NH}} = \sqrt{\Delta m_{23}^2 + (m_2^{\mathrm{NH}})^2}$$

Inverted hierarchy

$$D^{\mathrm{IH}} = \mathrm{diag}\left(m_1^{\mathrm{IH}}, m_2^{\mathrm{IH}}, m_{\mathrm{lightest}}\right)$$

$$m_2^{\mathrm{IH}} = \sqrt{\Delta m_{23}^2 + m_{\mathrm{lightest}}^2}$$

$$m_1^{\mathrm{IH}} = \sqrt{(m_2^{\mathrm{IH}})^2 - \Delta m_{12}^2}.$$

$$m_N = \mathrm{diag}\left(m_{N_1}, m_{N_2}, m_{N_3}\right)$$

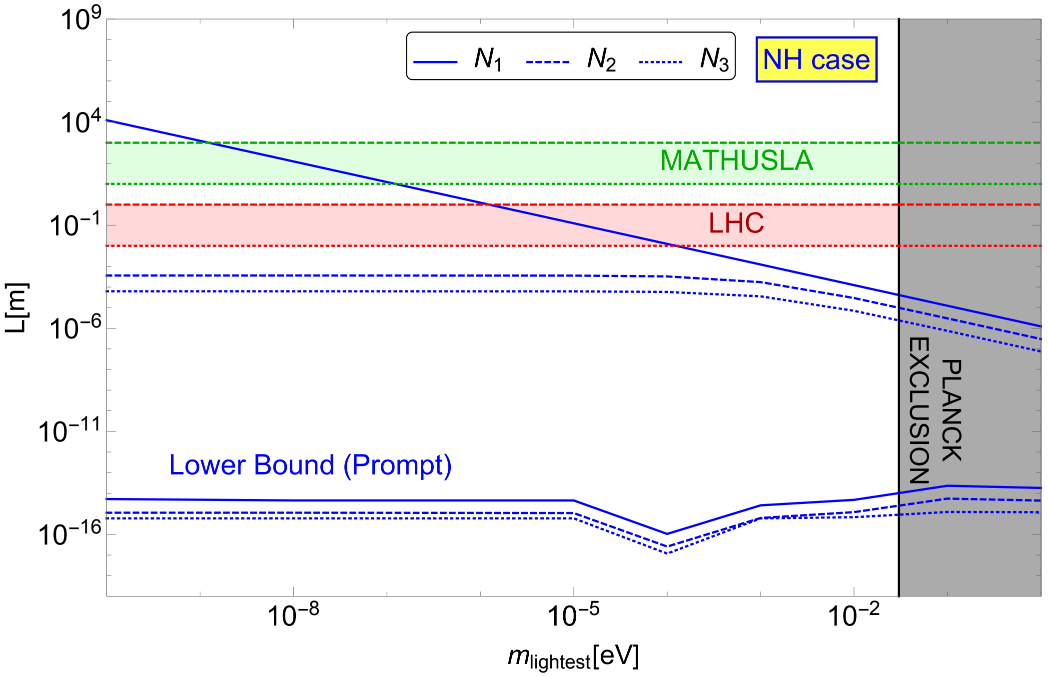
Decay length of RHNs neutrinos as a function of lightest active neutrino mass

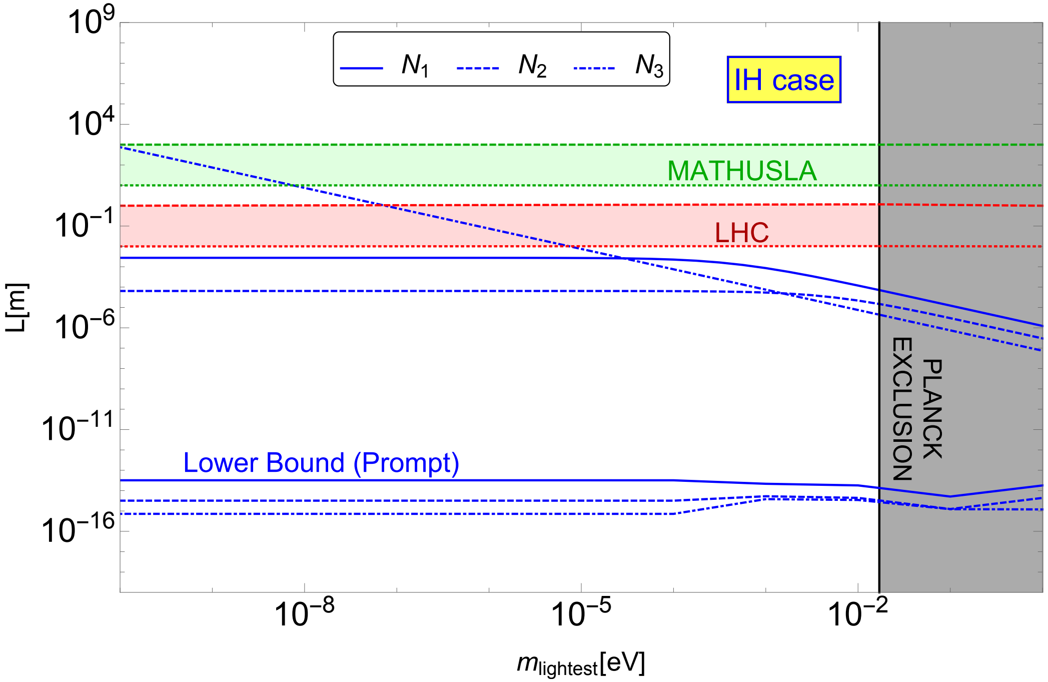
$$L_i^{\rm NH/IH} = \frac{1.97 \times 10^{-13}}{\Gamma_{N_i}^{\rm NH/IH}[\rm GeV]} \ [\rm mm].$$

1906.04132

Fitting
Neutrino oscillation data

$$\Gamma_{N_i}^{\rm NH/IH} = \sum_{\alpha=e,\mu,\tau} \left[\Gamma(N_i \to \ell_\alpha W)^{\rm NH/IH} + \Gamma(N_i \to \nu_\alpha Z)^{\rm NH/IH} + \Gamma(N_i \to \nu_\alpha h)^{\rm NH/IH}\right]$$



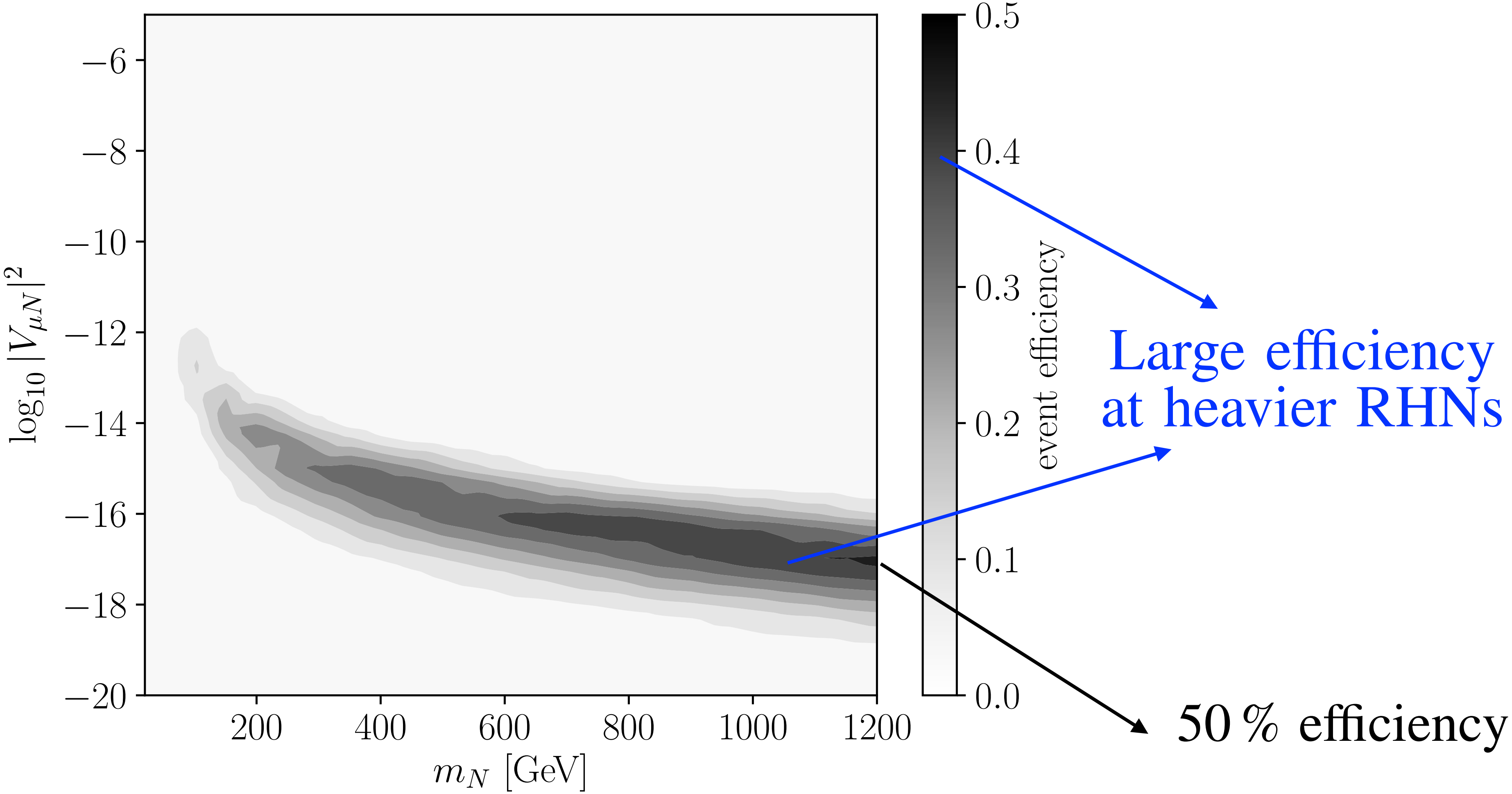


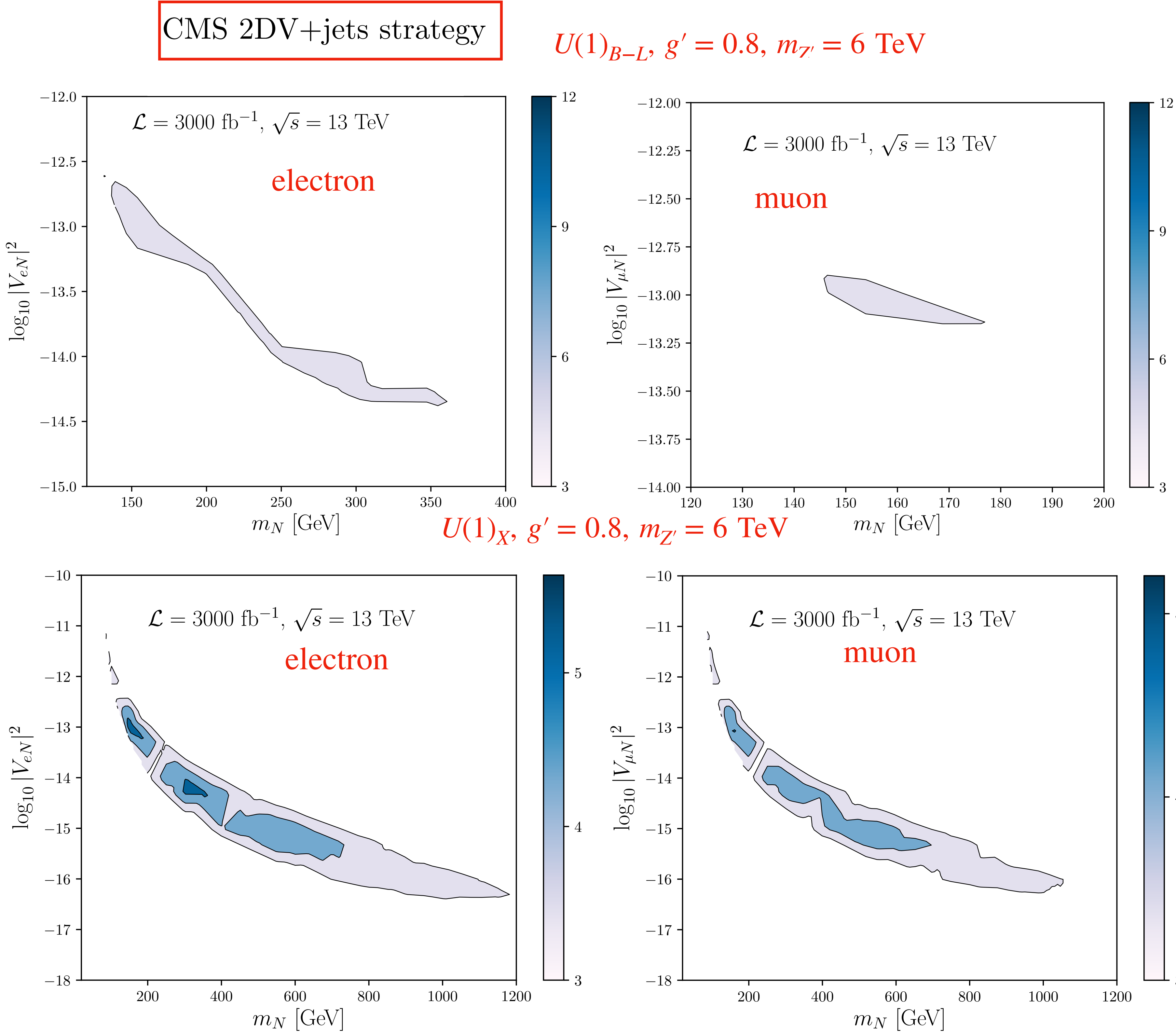
$M_{N_1} = 500$ GeV $\quad M_{N_2} = 1$ TeV $\quad M_{N_3} = 2$ TeV

CMS – 2DV

1908.09838

Trigger	$H_T > 1000$ GeV
Jet selection	At least 4 jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$
DV region	2 DVs within 0.1 mm $< r_{DV} <$ 20 mm and $d_{VV} > 0.4$ mm
DV selection	Made from tracks with $\|d_0\| \geq 0.1$ mm, $p_T > 20$ GeV and $\|\eta\| < 2.5$.
	$\sum p_T \geq 350$ GeV, correcting for b quarks.





CMS 2DV+jets strategy
$U(1)_{B-L}$, $g' = 0.8$, $m_{Z'} = 6$ TeV
$\mathcal{L} = 3000$ fb^{-1}, $\sqrt{s} = 13$ TeV
electron
$\log_{10}|V_{eN}|^2$
m_N [GeV]
$\mathcal{L} = 3000$ fb^{-1}, $\sqrt{s} = 13$ TeV
muon
$\log_{10}|V_{\mu N}|^2$
m_N [GeV]
$U(1)_X$, $g' = 0.8$, $m_{Z'} = 6$ TeV
$\mathcal{L} = 3000$ fb^{-1}, $\sqrt{s} = 13$ TeV
electron
$\log_{10}|V_{eN}|^2$
m_N [GeV]
$\mathcal{L} = 3000$ fb^{-1}, $\sqrt{s} = 13$ TeV
muon
$\log_{10}|V_{\mu N}|^2$
m_N [GeV]

Conclusions

We study a general scenario where the SM is extended by a general U(1) group which has three generations of the right handed neutrinos (RHNs) for the anomaly cancellations and they participate in the seesaw mechanism after the U(1) symmetry is broken.

These RHNs can be produced at the LHC from the heavy Z-prime resonance in pair directly. Such RHNs can be long lived. Considering the long livedness we have showed the dependence of the decay length as a function of the lightest neutrino mass eigenvalue.

We have also compared our analyses validating with the current CMS displaced vertex (DV) searches using two DVs. We have found that heavier RHN mass can probe a very small mixing through the DV signatures.

Thank you very much