Rare decays in the NSMEFT

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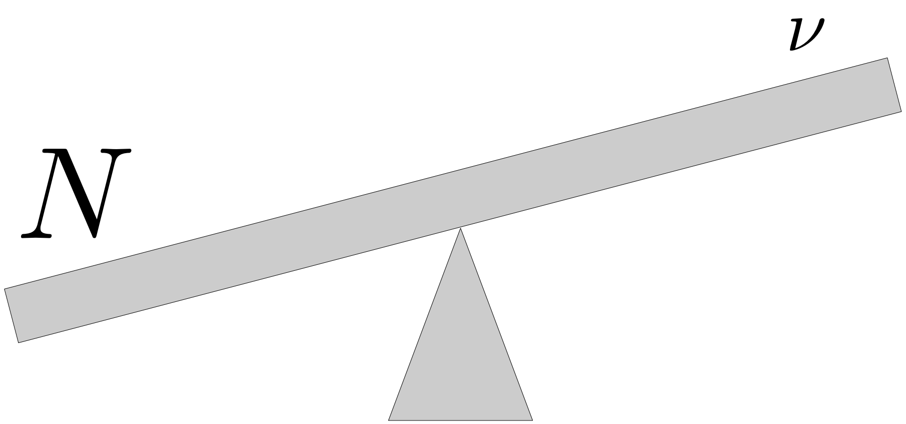
1905.11375, 1909.04665, 2006.14596 and *2007.00673*

In collaboration with S. Banerjee, A. Biekotter,
J. Butterworth, C. Englert, M. Spannowsky and A. Titov

ECFA HTE meeting on Z pole physics; September 23, 2022

See-saw type I is one of the most appealing explanations for neutrino masses

$$m_\nu \sim \frac{y^2 v^2}{m_N}$$



Variants (more realistic?) incarnations of this setup involve: (i) N at electroweak scale and/or (ii) further heavier particles

If both (i) and (ii), then NSMEFT: $L = L_{\mathrm{SM}+N} + \sum \frac{\mathcal{O}}{\Lambda} + \cdots$

Other aspects: Weinberg operator, Dirac limit, ...

See-saw type I is one of the most appealing explanations for neutrino masses

In favor of **Majorana**: "natural" scale, GUTs, charge quantisation via anomaly cancellations...

In favor of **Dirac**: same as rest of SM?, swampland program [1706.05392], most likely if residual Z_n symmetry of LN [1711.06181], ...

Varian… : (i) N at elec…

If both… $+ \cdots$

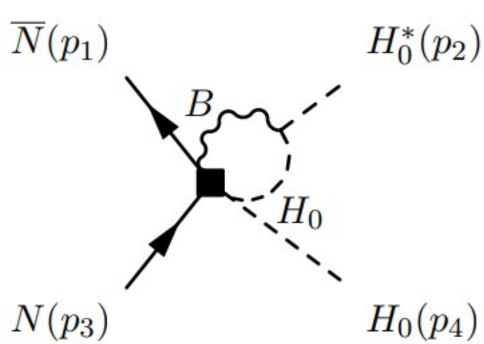
Other aspects: Weinberg operator, **Dirac limit**, ...

SF	$(\overline{L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{LNH}$ (+h.c.)		
	$(\overline{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HN}$	$(\overline{N}\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{HNe}$ (+h.c.)
	$(\overline{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$	$\mathcal{O}_{NB}$ (+h.c.)	$(\overline{L}\sigma_{\mu\nu}N)\sigma_I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{NW}$ (+h.c.)
RRRR	$(\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{NN}$		
	$(\overline{e}\gamma_\mu e)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{eN}$	$(\overline{u}\gamma_\mu u)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN}$
	$(\overline{d}\gamma_\mu d)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{dN}$	$(\overline{d}\gamma_\mu u)(\overline{N}\gamma^\mu e)$	$\mathcal{O}_{duNe}$ (+h.c.)
LLRR	$(\overline{L}\gamma_\mu L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{LN}$	$(\overline{Q}\gamma_\mu Q)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{QN}$
LRRL	$(\overline{L}N)\epsilon(\overline{L}e)$	$\mathcal{O}_{LNLe}$ (+h.c.)	$(\overline{L}N)\epsilon(\overline{Q}d)$	$\mathcal{O}_{LNQd}$ (+h.c.)
	$(\overline{L}d)\epsilon(\overline{Q}N)$	$\mathcal{O}_{LdQN}$ (+h.c.)	$(\overline{Q}u)(\overline{N}L)$	$\mathcal{O}_{QuNL}$ (+h.c.)

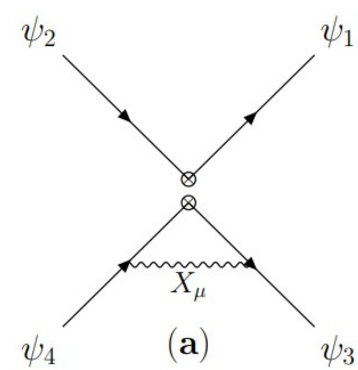
[1612.04527]

The theory has been fully renormalised at one loop in 2006.14596 and 2010.12109

MC, Titov '20



Datta et al '20



SF			$(\overline{L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{LNH}$ (+h.c.)
	$(\overline{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HN}$	$(\overline{N}\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{HNe}$ (+h.c.)
	$(\overline{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$	$\mathcal{O}_{NB}$ (+h.c.)	$(\overline{L}\sigma_{\mu\nu}N)\sigma_I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{NW}$ (+h.c.)
RRRR				h.c.)
LLR				
LRRL				h.c.)
				h.c.)

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The th .14596
and 20

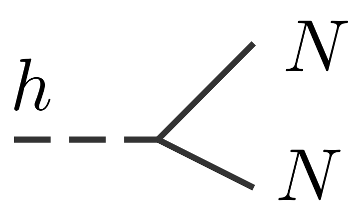
Two remarks

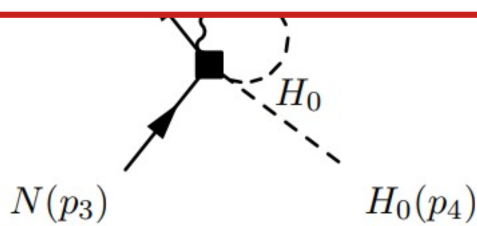
1. We most often use:

$$\mathcal{O}^i_{NA} = \quad c_W \mathcal{O}^i_{NB} + s_W \mathcal{O}^i_{NW}$$
$$\mathcal{O}^i_{NZ} = -s_W \mathcal{O}^i_{NB} + c_W \mathcal{O}^i_{NW}$$

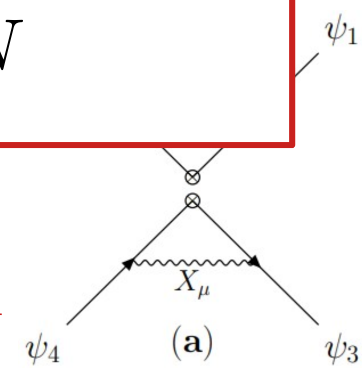
2. Some other (LNV) operators ignored:

$$\mathcal{O}^{ij}_{LH} = \overline{L^c_i}\tilde{H}^*\tilde{H}^\dagger L_j$$
$$\mathcal{O}_{NNH} = \overline{N^c}NH^\dagger H\,.$$





MC, Titov '20



Datta et al '20

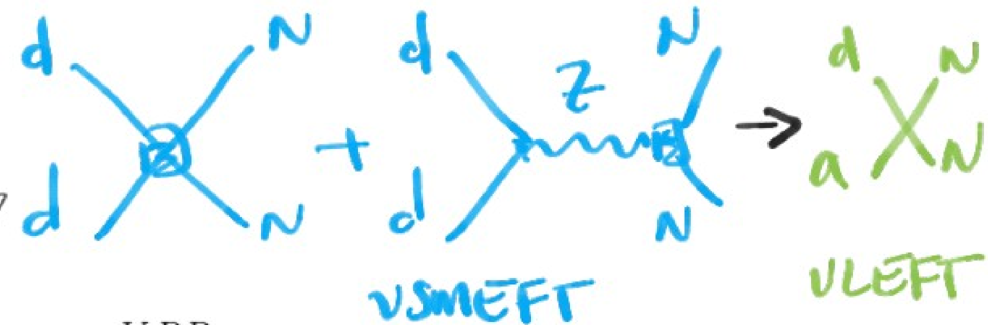
Basis for the NLEFT

MC, Titov '20

Dipole	$\mathcal{O}_{N\gamma} = \overline{\nu_L}\sigma^{\mu\nu} N A_{\mu\nu}$	
RRRR	$\mathcal{O}^{V,RR}_{NN} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	
	$\mathcal{O}^{V,RR}_{eN} = (\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}^{V,RR}_{uN} = (\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}^{V,RR}_{dN} = (\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}^{V,RR}_{udeN} = (\overline{u_R}\gamma_\mu d_R)(\overline{e_R}\gamma^\mu N)$
LLRR	$\mathcal{O}^{V,LR}_{\nu N} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}^{V,LR}_{eN} = (\overline{e_L}\gamma_\mu e_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}^{V,LR}_{uN} = (\overline{u_L}\gamma_\mu u_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}^{V,LR}_{dN} = (\overline{d_L}\gamma_\mu d_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}^{V,LR}_{udeN} = (\overline{u_L}\gamma_\mu d_L)(\overline{e_R}\gamma^\mu N)$	
LRLR	$\mathcal{O}^{S,RR}_{NN} = (\overline{\nu_L} N)(\overline{\nu_L} N)$	
	$\mathcal{O}^{S,RR}_{eN} = (\overline{e_L} e_R)(\overline{\nu_L} N)$	$\mathcal{O}^{T,RR}_{eN} = (\overline{e_L}\sigma_{\mu\nu} e_R)(\overline{\nu_L}\sigma^{\mu\nu} N)$
	$\mathcal{O}^{S,RR}_{uN} = (\overline{u_L} u_R)(\overline{\nu_L} N)$	$\mathcal{O}^{T,RR}_{uN} = (\overline{u_L}\sigma_{\mu\nu} u_R)(\overline{\nu_L}\sigma^{\mu\nu} N)$
	$\mathcal{O}^{S,RR}_{dN} = (\overline{d_L} d_R)(\overline{\nu_L} N)$	$\mathcal{O}^{T,RR}_{dN} = (\overline{d_L}\sigma_{\mu\nu} d_R)(\overline{\nu_L}\sigma^{\mu\nu} N)$
	$\mathcal{O}^{S,RR}_{udeN} = (\overline{u_L} d_R)(\overline{e_L} N)$	$\mathcal{O}^{T,RR}_{udeN} = (\overline{u_L}\sigma_{\mu\nu} d_R)(\overline{e_L}\sigma^{\mu\nu} N)$
RLLR	$\mathcal{O}^{S,LR}_{eN} = (\overline{e_R} e_L)(\overline{\nu_L} N)$	$\mathcal{O}^{S,LR}_{uN} = (\overline{u_R} u_L)(\overline{\nu_L} N)$
	$\mathcal{O}^{S,LR}_{dN} = (\overline{d_R} d_L)(\overline{\nu_L} N)$	$\mathcal{O}^{S,LR}_{udeN} = (\overline{u_R} d_L)(\overline{e_L} N)$

Tree level matching of vSMEFT onto vLEFT

2001.07732



$$\frac{\alpha_{N\gamma}}{v} = \frac{v}{\sqrt{2}\Lambda^2}\left(\alpha_{NB}c_W + \alpha_{NW}s_W\right), \quad \text{(C.1)} \qquad \frac{\alpha^{V,RR}_{NN}}{v^2} = \frac{\alpha_{NN}}{\Lambda^2}, \quad \text{(C.2)}$$

$$\frac{\alpha^{V,RR}_{eN}}{v^2} = \frac{\alpha_{eN}}{\Lambda^2} - \frac{g_Z^2 Z_{e_R} Z_N}{m_Z^2}, \quad \text{(C.3)} \qquad \frac{\alpha^{V,RR}_{uN}}{v^2} = \frac{\alpha_{uN}}{\Lambda^2} - \frac{g_Z^2 Z_{u_R} Z_N}{m_Z^2}, \quad \text{(C.4)}$$

$$\frac{\alpha^{V,RR}_{dN}}{v^2} = \frac{\alpha_{dN}}{\Lambda^2} - \frac{g_Z^2 Z_{d_R} Z_N}{m_Z^2}, \quad \text{(C.5)} \qquad \frac{\alpha^{V,RR}_{duNe}}{v^2} = \frac{\alpha_{duNe}}{\Lambda^2}, \quad \text{(C.6)}$$

$$\frac{\alpha^{V,LR}_{\nu N}}{v^2} = \frac{\alpha_{LN}}{\Lambda^2} - \frac{g_Z^2 Z_{\nu_L} Z_N}{m_Z^2}, \quad \text{(C.7)} \qquad \frac{\alpha^{V,LR}_{eN}}{v^2} = \frac{\alpha_{LN}}{\Lambda^2} - \frac{g_Z^2 Z_{e_L} Z_N}{m_Z^2}, \quad \text{(C.8)}$$

$$\frac{\alpha^{V,LR}_{uN}}{v^2} = \frac{\alpha_{QN}}{\Lambda^2} - \frac{g_Z^2 Z_{u_L} Z_N}{m_Z^2}, \quad \text{(C.9)} \qquad \frac{\alpha^{V,LR}_{dN}}{v^2} = \frac{\alpha_{QN}}{\Lambda^2} - \frac{g_Z^2 Z_{d_L} Z_N}{m_Z^2}, \quad \text{(C.10)}$$

Decay modes for N

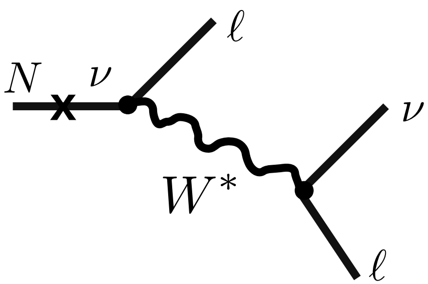
Under some mild assumptions (LNV, flavour, power counting...), we get that for m_N of about 1-100 GeV:

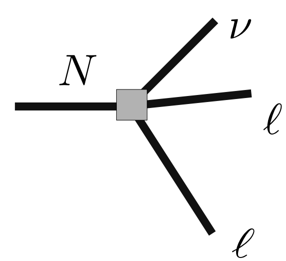
$$\Gamma_{\rm mix} < \Gamma_{\rm tree} < \Gamma_{\rm loop}$$

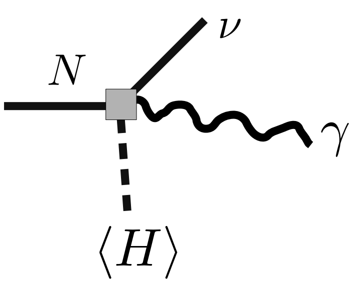
For cuttoff of 10 TeV

For too small m_N, N stable at colliders (equivalent to Dirac limit)

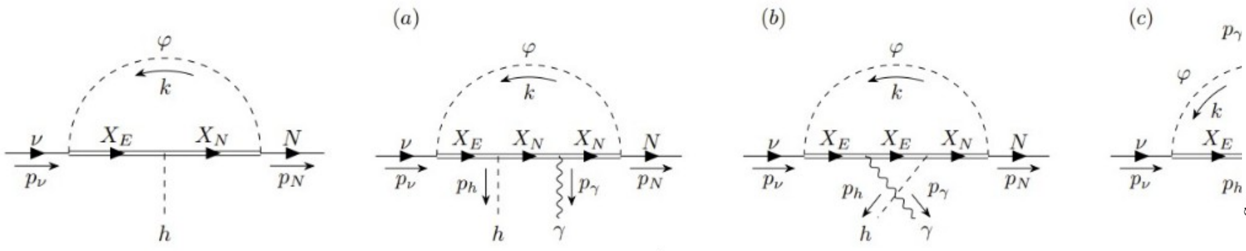
$$\frac{\Gamma_{\rm mix}}{\rm GeV} \approx 10^{-21}\left(\frac{m_N}{\rm GeV}\right)^4 , \quad \frac{\Gamma_{\rm tree}}{\rm GeV} \approx 10^{-20}\left(\frac{m_N}{\rm GeV}\right)^5 , \quad \frac{\Gamma_{\rm loop}}{\rm GeV} \approx 10^{-15}\left(\frac{m_N}{\rm GeV}\right)^3$$

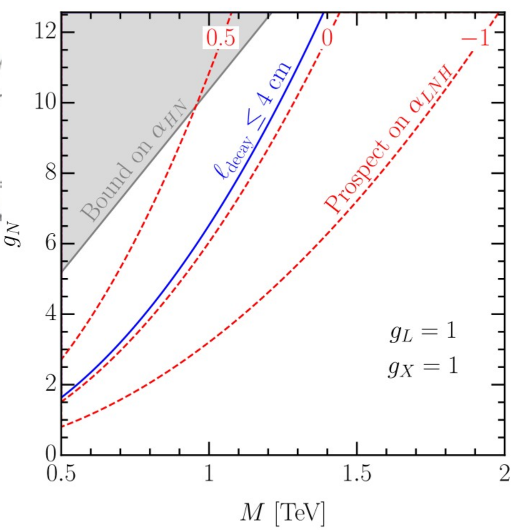


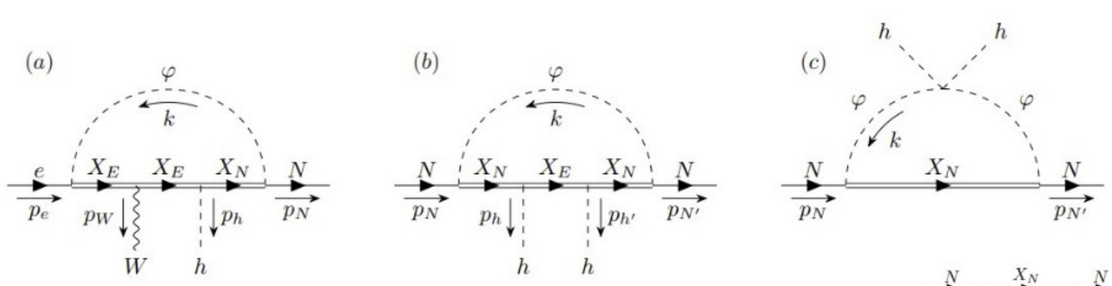


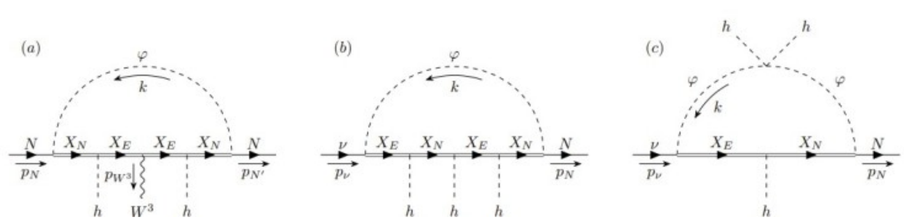


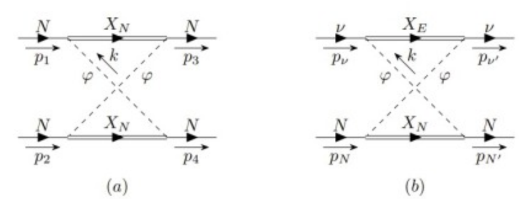
Reasonable UV completions of the NSMEFT can be built for very different IR scenarios, e.g. without four-fermions and with mostly N $\to$ $\nu\gamma$





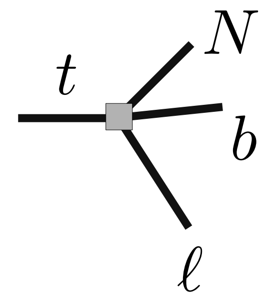




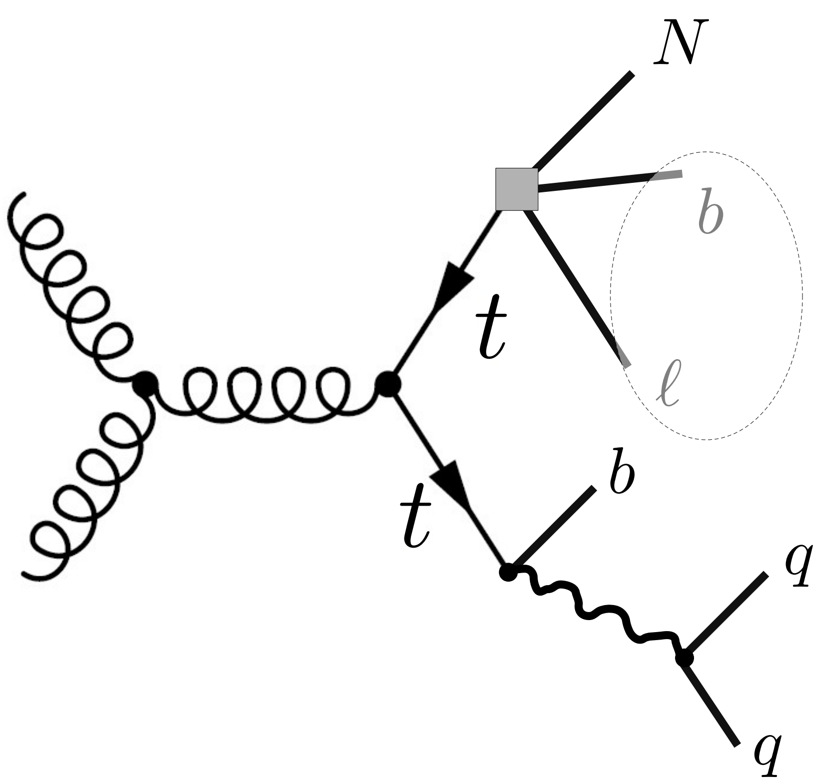


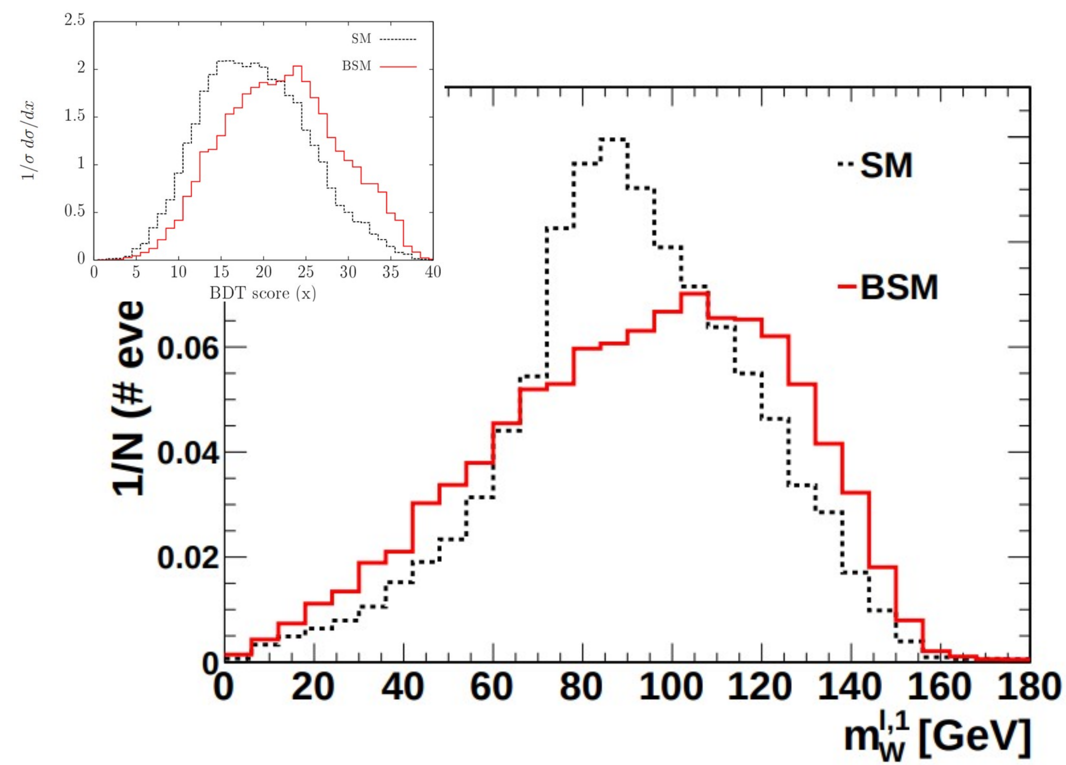
[2001.07732]

Rare top decays

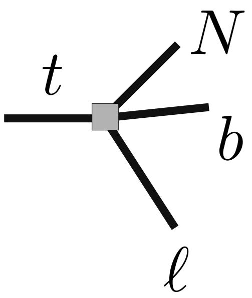


Signal very similar to background. Use neural network based on *m(l,b)*, momenta and angular separation





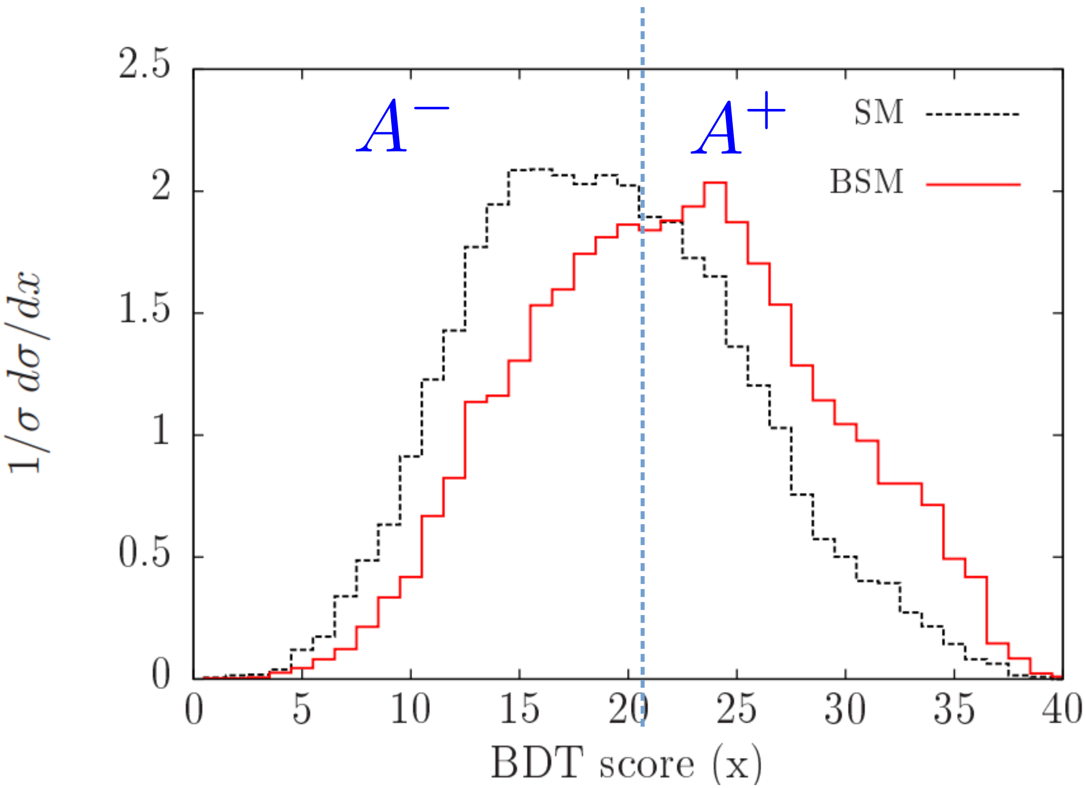
Rare top decays



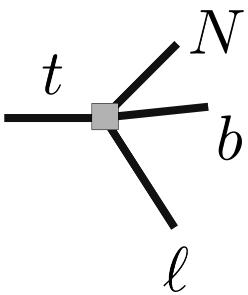
Signal very similar to background. Use neural network based on *m(l,b)*, momenta and angular separation

$$\mathcal{A} = \frac{A^+ - A^-}{A^+ + A^-}$$

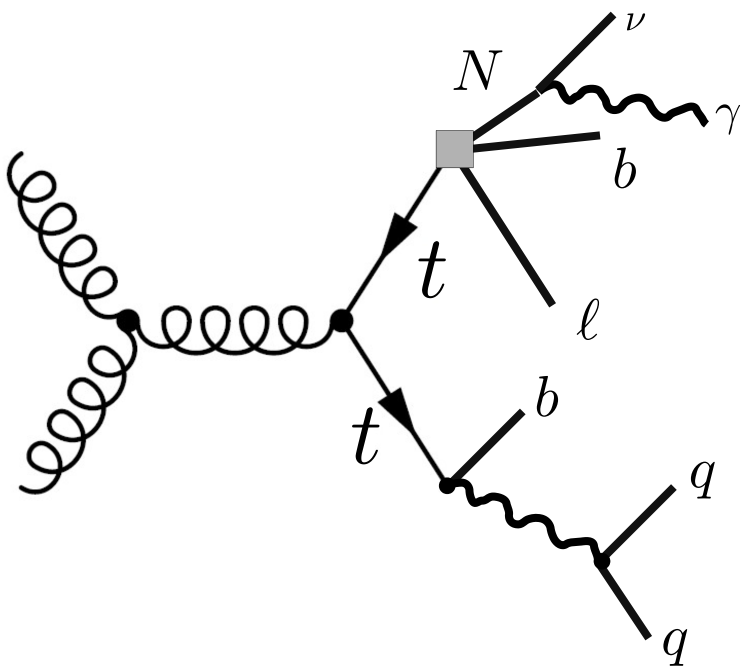
$\Lambda \sim 2\,\text{TeV}$

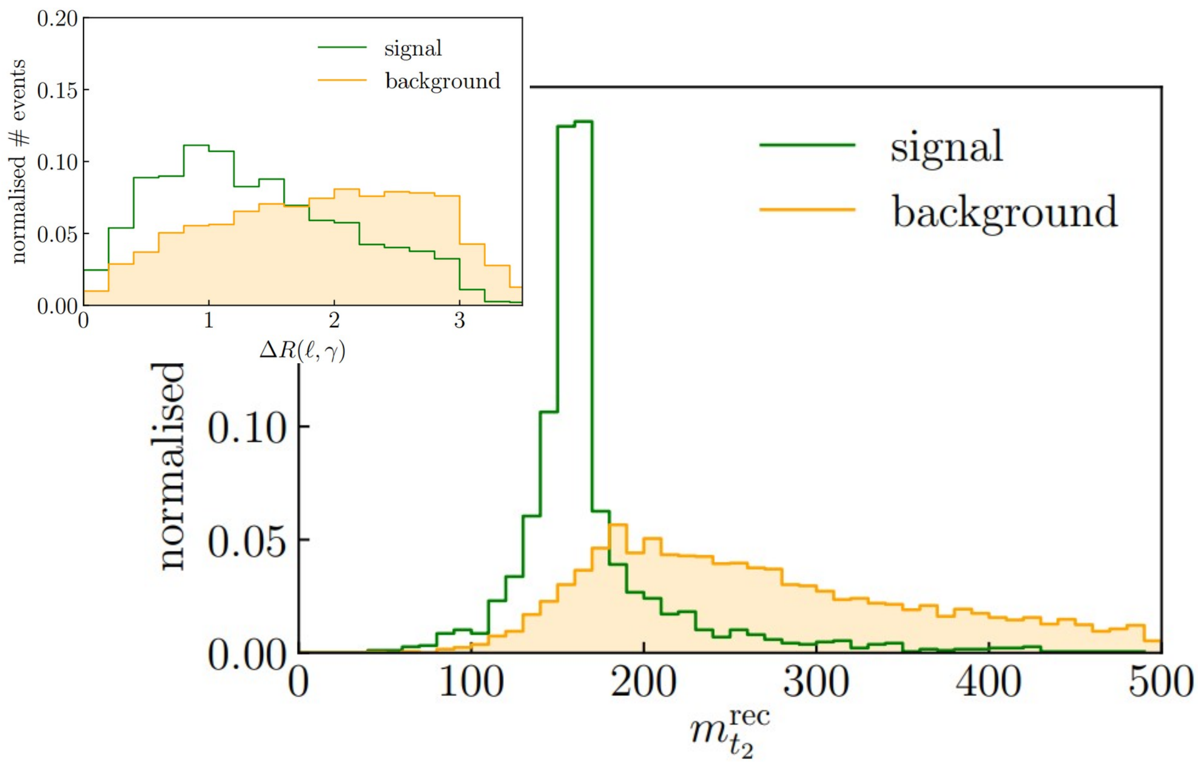


Rare top decays

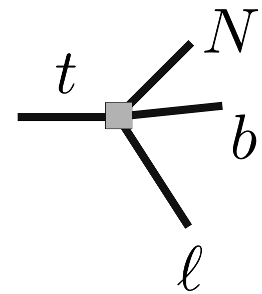


In this case, N is assumed to decay into a neutrino (which can be reconstructed fully in the collinear aprox.) and a photon

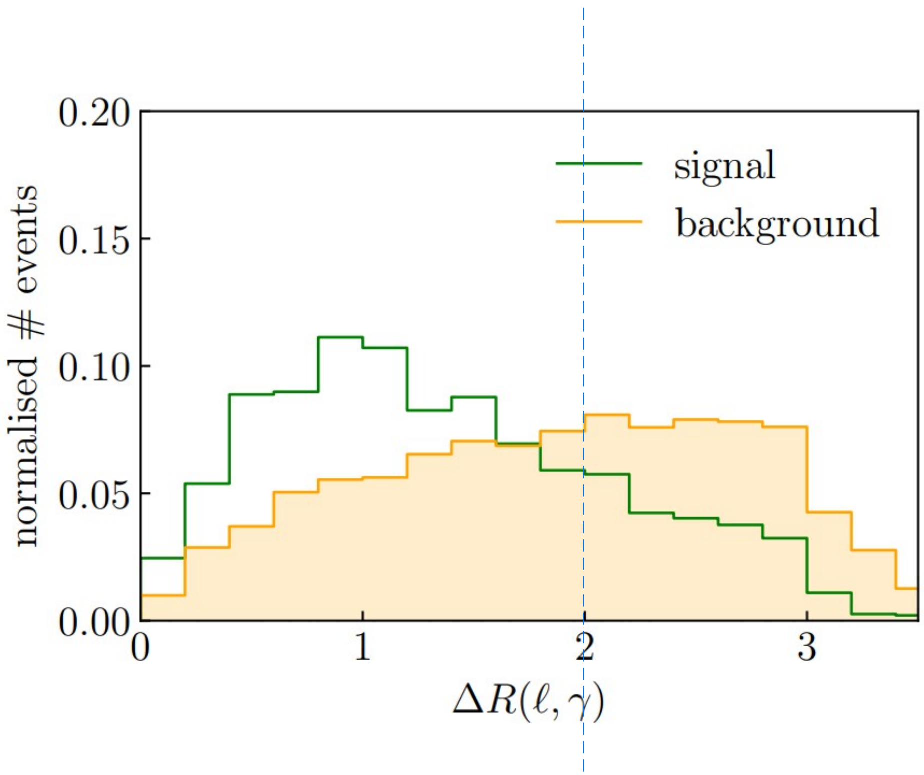


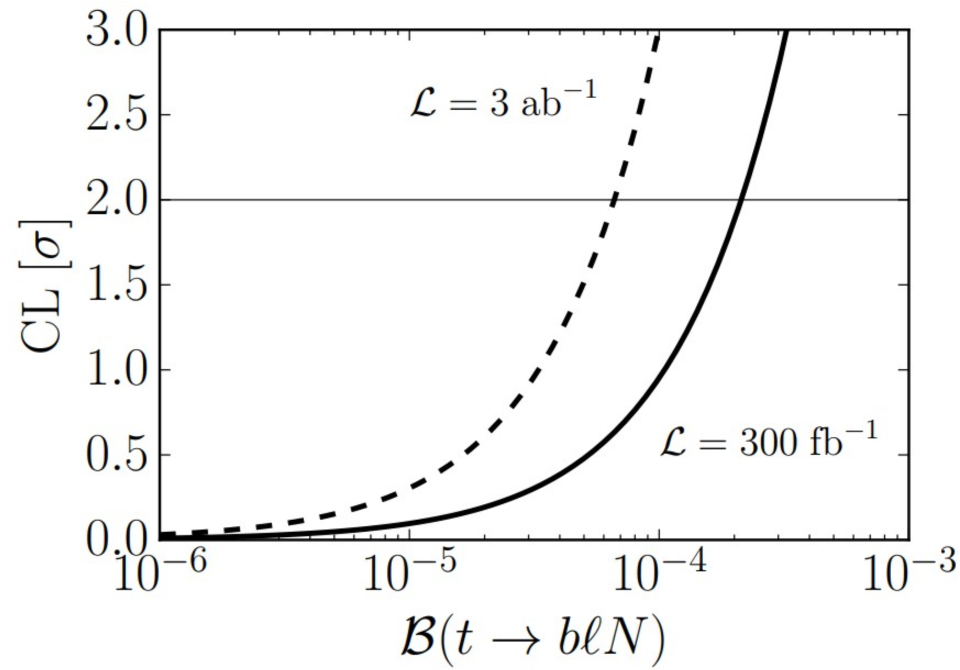


Rare top decays

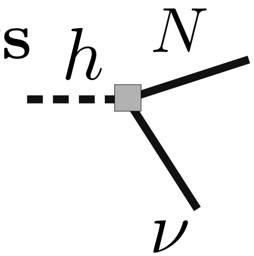


$$A = \frac{N_+ - N_-}{N_+ + N_-} = \frac{N(\Delta R(\ell,\gamma) > 2) - N(\Delta R(\ell,\gamma) < 2)}{N(\Delta R(\ell,\gamma) > 2) + N(\Delta R(\ell,\gamma) > 2)}$$





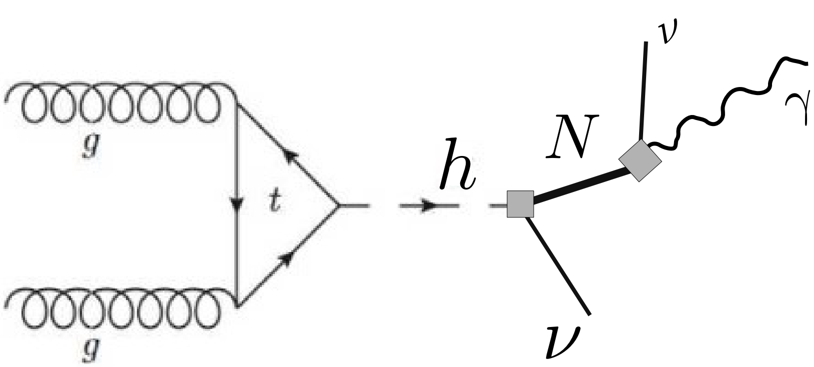
Rare Higgs decays

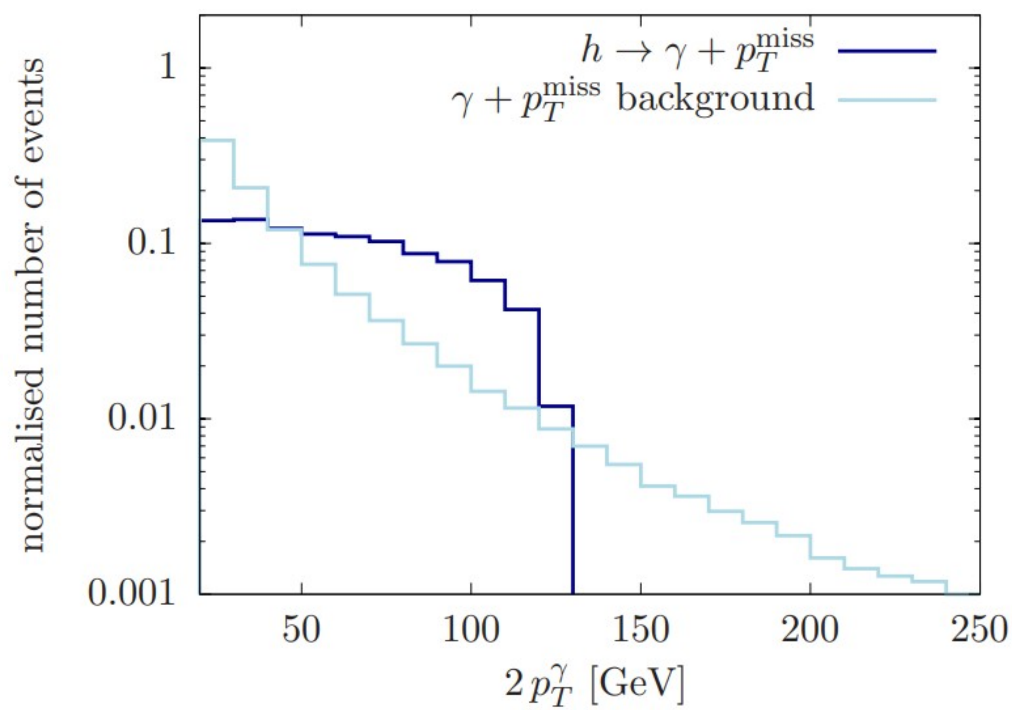


$\mathcal{O}^i_{LNH} = \overline{L_i} N \tilde{H} H^\dagger H$

As for the top interactions, this channel is very poorly constrained (mostly by monophoton searches [1810.00196])

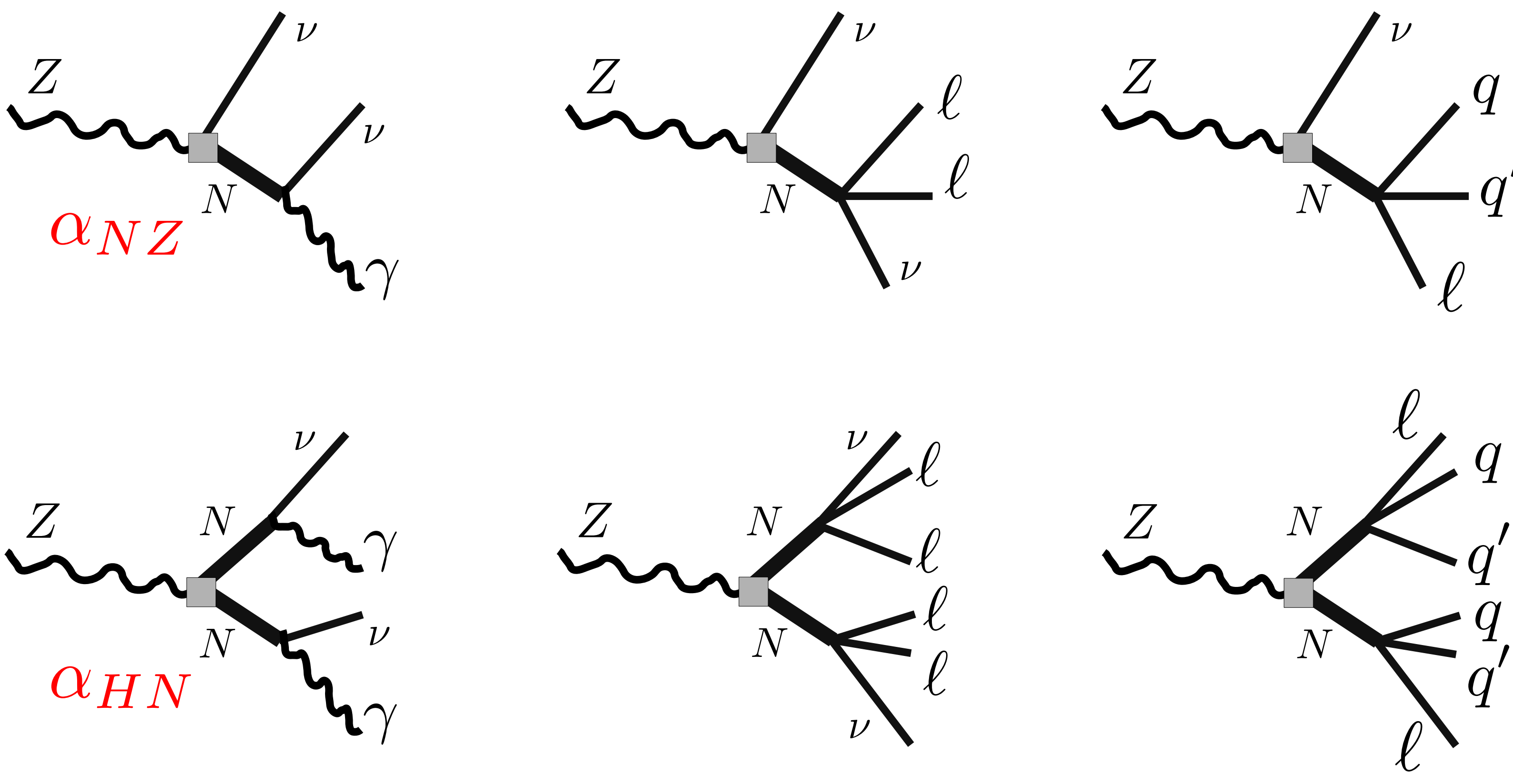
Sensitivity to BR of about 10^{-3} at HL-LHC, which amounts to cutoff of about 20 TeV



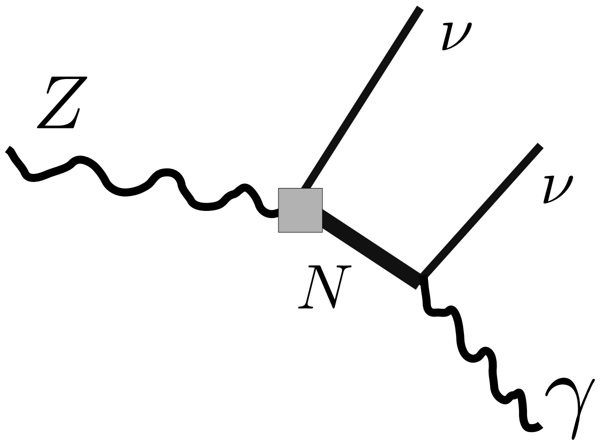


A variety of Z boson decays

Some decays explicitly ignored, e.g. mixed channels or Z → ννqq or pure invisible (see final slides)



$\mathbf{Z \to \nu\nu\gamma}$



$$\Gamma \sim \frac{m_Z^3 v^2}{\pi \Lambda^4} \alpha_{NZ}^2$$

$$\mathcal{B}^{\rm the} \sim 10^{-3}$$

$$\mathcal{B}^{\rm exp} < 3.2 \times 10^{-6}$$

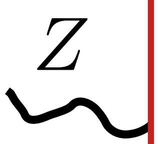
[PLB 412 (1997) 201-209]

Theoretical estimates hold for $\Lambda = 1$ TeV and O(1) couplings; I assume Z width is dominated by Standard Model

Naive estimate, based on 5×10^{12} Z bosons, requiring about 10 observed events and efficiency or order 0.2:
(0.85 exp. ref.)

$$\mathcal{B}^{\rm exp} \sim 10^{-11} \;(\Lambda \sim 100\,\text{TeV})$$

$\mathbf{Z \to \nu\nu\gamma}$



Γ_{58}	$e^+ e^- \gamma$		[f]	< 5.2	$\times 10^{-4}$	CL=95%
Γ_{59}	$\mu^+ \mu^- \gamma$		[f]	< 5.6	$\times 10^{-4}$	CL=95%
Γ_{60}	$\tau^+ \tau^- \gamma$		[f]	< 7.3	$\times 10^{-4}$	CL=95%
Γ_{61}	$\ell^+ \ell^- \gamma\gamma$		[g]	< 6.8	$\times 10^{-6}$	CL=95%

https://pdg.lbl.gov Page 4 Created: 8/11/2022 09:39

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022)

Γ_{62}	$q\overline{q}\gamma\gamma$		[g]	< 5.5	$\times 10^{-6}$	CL=95%
Γ_{63}	$\nu\overline{\nu}\gamma\gamma$		[g]	< 3.1	$\times 10^{-6}$	CL=95%
Γ_{64}	$e^\pm \mu^\mp$	LF	[d]	< 7.5	$\times 10^{-7}$	CL=95%
Γ_{65}	$e^\pm \tau^\mp$	LF	[d]	< 5.0	$\times 10^{-6}$	CL=95%
Γ_{66}	$\mu^\pm \tau^\mp$	LF	[d]	< 6.5	$\times 10^{-6}$	CL=95%
Γ_{67}	pe	L,B		< 1.8	$\times 10^{-6}$	CL=95%
Γ_{68}	$p\mu$	L,B		< 1.8	$\times 10^{-6}$	CL=95%

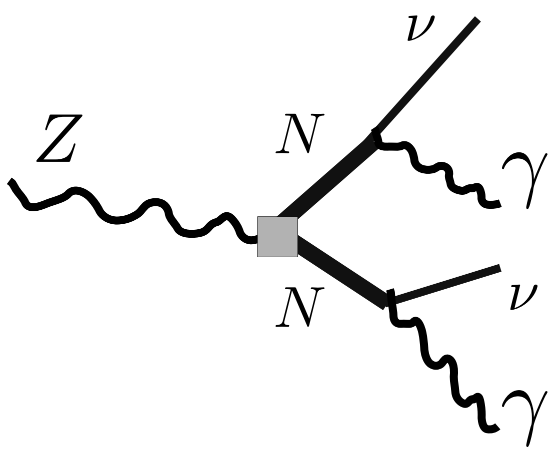
) 201-209]

Theoretic ... lings; I
assume Z

Naive est ... out 10
observed

$$\mathcal{B}^{\text{exp}} \sim 10^{-11} \; (\Lambda \sim 100\,\text{TeV})$$

$Z \to \nu\nu\gamma\gamma$



$$\Gamma \sim \frac{m_Z^3 v^2}{\pi \Lambda^4} \alpha_{HN}^2$$

$$\mathcal{B}^{\text{the}} \sim 10^{-3}$$

$$\mathcal{B}^{\text{exp}} < 3.1 \times 10^{-6}$$

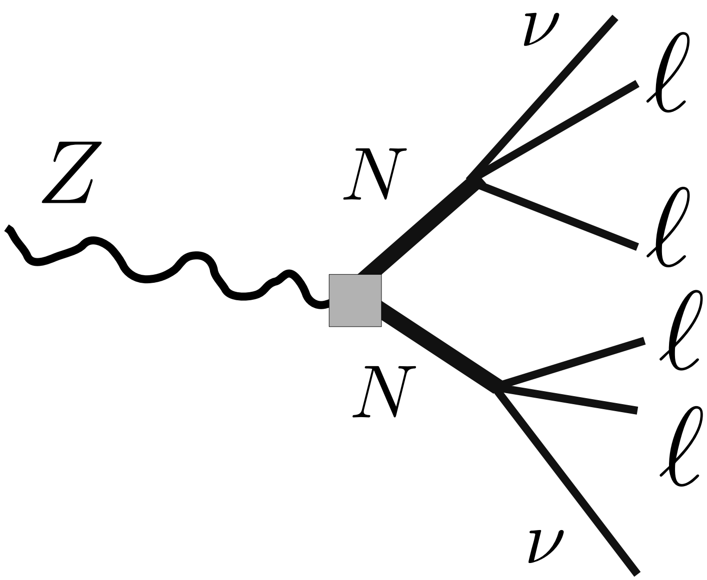
[PDG; PLB 311 (1993) 391-407]

Theoretical estimates hold for $\Lambda = 1$ TeV and O(1) couplings; I assume Z width is dominated by Standard Model

Naive estimate, based on 5×10^{12} Z bosons, requiring about 10 observed events and efficiency or order 0.2:
(0.56 exp. ref.)

$$\mathcal{B}^{\text{exp}} \sim 10^{-11} \; (\Lambda \sim 100\,\text{TeV})$$

$\mathbf{Z} \to \nu\nu llll$



$$\Gamma \sim \frac{m_Z^3 v^2}{\pi \Lambda^4} \alpha_{HN}^2$$

$$\mathcal{B}^{\text{the}} \sim 10^{-3}$$

$$\mathcal{B}^{\text{exp}} < 6 \times 10^{-7}$$

[PDG; 2103.01918, 1902.05892, 1709.08601, 1607.08834, 1403.5657]

I estimate the bound from the error on the current measurement of B(Z→llll)!

$(4.41 \pm 0.30)\times 10^{-6}$ [exp]

$(4.50 \pm 0.01) \times 10^{-6}$ [SM pred]

Hard to extrapolate results from LHC, but I would expect negligible background and therefore similar to previous bounds

Indirect sensitivity to other interactions (toy/out-of-fashioned example)

If neutrinos are Dirac particles, and they have a non-vanishing magnetic moment (like the one that explained the Xenon1T anomaly), then:

$$\gamma = \begin{pmatrix} \frac{91}{12}g_1^2 - \frac{9}{4}g_2^2 - \frac{3}{2}Y_e^2 + \mathrm{Tr}^2 & -\frac{9}{2}g_1 g_2 & 0 & 0 & 0 \\ -\frac{3}{2}g_1 g_2 & -\frac{3}{4}g_1^2 - \frac{11}{12}g_2^2 + \frac{5}{2}Y_e^2 + \mathrm{Tr}^2 & 0 & 0 & 0 \\ 3g_1 Y_e & -9g_2 Y_e & \frac{1}{3}g_1^2 + 2\,\mathrm{Tr}^2 & 2Y_e^2 & 0 \\ -3g_1 Y_e & 9g_2 Y_e & 0 & -3g_1^2 + Y_e^2 + 2\,\mathrm{Tr}^2 & 0 \\ -3g_1\left(g_1^2 + g_2^2\right) & 3g_2\left(g_1^2 + 3g_2^2 + 4Y_e^2\right) & 0 & Y_e\left(3g_2^2 - 2\lambda_H - 2Y_e^2\right) & -\frac{9}{4}g_1^2 - \frac{27}{4}g_2^2 + 12\lambda_H - \frac{3}{2}Y_e^2 + 3\,\mathrm{Tr}^2 \end{pmatrix} \begin{matrix} \alpha_{NB} \\ \alpha_{NW} \\ \alpha_{HN} \\ \alpha_{HNe} \\ \alpha_{LNH} \end{matrix}$$

$$\alpha_{NA} \sim 9 \times 10^{-6} \ \left(9 \times 10^{-2}\right) \quad \text{for} \quad \Lambda = 1\ \text{TeV}\ (100\ \text{TeV})$$

$$\mathcal{B}(h \to \text{inv}) \sim 2 \times 10^{-14} \ \left(4 \times 10^{-13}\right)$$
$$\mathcal{B}(Z \to \text{inv}) \sim 5 \times 10^{-19} \ \left(8 \times 10^{-18}\right)$$

Conclusions

The NSMEFT is a not-so-unreasonable description of the IR, with lot of different directions in parameter space still to be explored

Huge experimental program in Z decays, driven by the interplay between N production and decay modes

It might be worth exploring the topic first from simulation (with special attention to reconstruction of N). I might start this program myself :)

Although sensitivity to branching ratios is spectacular, it does not translate well to cutoff, because width scales with $1/\Lambda^4$ (no interference with SM)

Thank you!