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IFIC Institut de Física Corpuscular

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CSIC Consejo Superior de Investigaciones Científicas

Effective field theory of the Standard Model extended with right-handed neutrinos

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M. Chala and AT, 2001.07732, 2006.14596
J. Alcaide, S. Banerjee, M. Chala, AT, 1905.11375
J.M. Butterworth, M. Chala, C. Englert, M. Spannowsky, AT, 1909.04665

All *Things* EFT

25 November 2020

Outline

- Motivation
- NSMEFT operator basis
- One-loop renormalisation of dimension-6 operators
- Matching NSMEFT onto NLEFT
- Phenomenology
- Conclusions

Motivation: absence of New Physics

No New Physics signals at particle physics experiments (modulo several inconclusive anomalies), except for neutrino masses

New Physics

- very weakly coupled
  new degrees of freedom (dofs) below the electroweak (EW) scale v
  very likely singlets of the SM gauge group
- present at scales $\Lambda > v$
  SMEFT is appropriate description
- both
  "new dofs + SM" EFT (respecting SM gauge symmetry) required

What are these new dofs:

scalars, fermions, vectors?

Motivation: neutrino masses

In the SM neutrinos are massless

Neutrino oscillations show neutrinos are massive
(hypothesised by B. Pontecorvo in 1957, detected by Super-Kamiokande in 1998)

The minimal way to generate neutrino masses (at renormalisable level) is via Yukawa interaction (as for all other fermions in the SM)

This requires a new state — right-handed (RH) neutrino, $\nu_R \equiv N$

$$\mathscr{L}_{SM+N} = \mathscr{L}_{SM} + i\overline{N}\gamma^\mu \partial_\mu N - \left[\overline{L}\tilde{H} Y_N N + \text{h.c.}\right]$$

$\tilde{H} = i\sigma_2 H^*$

$\nu = (\nu_L, N)^T$ is Dirac neutrino, lepton number is conserved

$$m_\nu = Y_N \frac{\mathrm{v}}{\sqrt{2}} \sim 0.01 \text{ eV} \qquad \mathrm{v} = 246 \text{ GeV} \qquad \Rightarrow \qquad Y_N \sim 10^{-14}$$

$(Y_t \sim 1 \qquad Y_e \sim 10^{-6} \qquad \Rightarrow$ flavour problem)

Is lepton number a fundamental symmetry?

Motivation: neutrino masses

If lepton number is not a fundamental symmetry, then

$$-\mathscr{L}_{\text{mass}} = \overline{L}\tilde{H}Y_N N + \frac{1}{2}\overline{N^c}MN + \text{h.c.} \to \frac{1}{2}\left(\overline{\nu_L}\ \overline{N^c}\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N \end{pmatrix} + \text{h.c.}$$

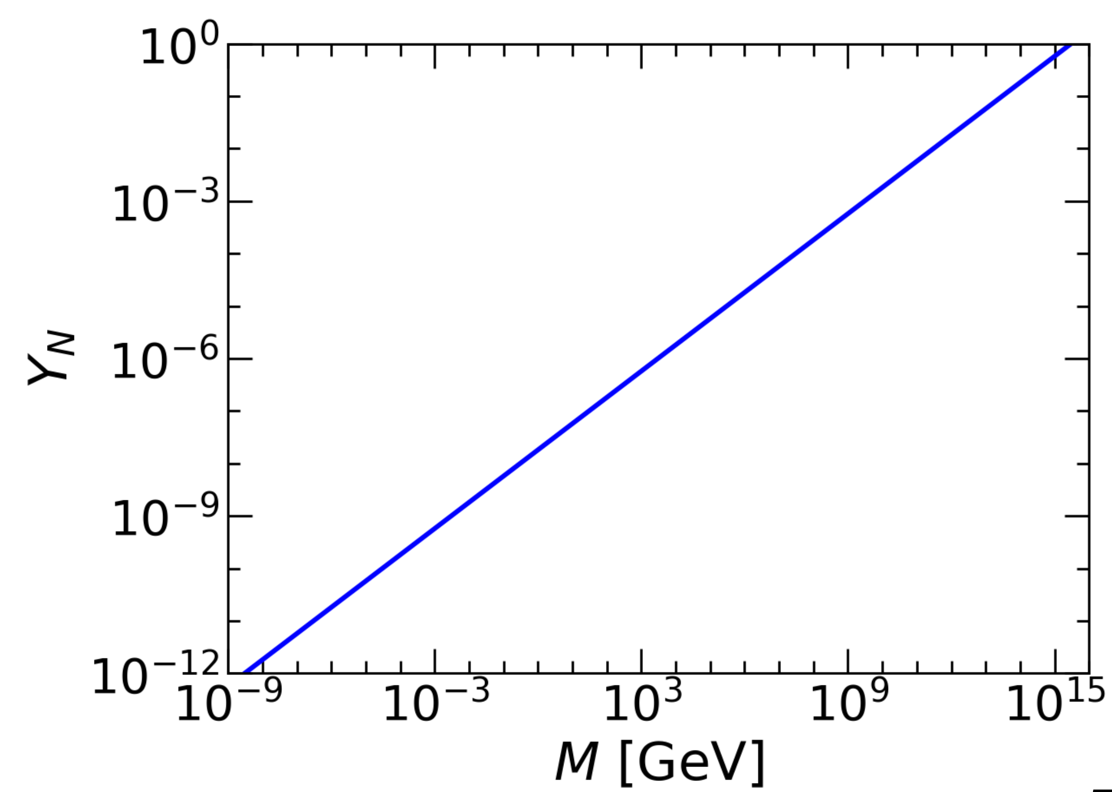
$$\psi^c = C\overline{\psi}^T \qquad C = i\gamma^2\gamma^0 \qquad m_D = Y_N \frac{\text{v}}{\sqrt{2}}$$

$\nu = (\nu_L, \nu_L^c)^T$ and $n = (N^c, N)^T$ are Majorana neutrinos

Type I seesaw mechanism: $m_D \ll M$

$$m_\nu = -m_D M^{-1} m_D^T \sim 0.01 \text{ eV}$$

Huge range of values for M, including $M \lesssim \text{v}$



Motivation: neutrino masses

(Of course, at non-renormalisable level, the minimal way to generate Majorana neutrino masses is via Weinberg dimension-5 operator

$$\mathcal{O}_{LH} = \left(\overline{L}\tilde{H}\right)\left(\tilde{H}^T L^c\right) + \text{h.c.}$$

SMEFT accommodates lepton number-violating neutrino masses)

In what follows, we assume

- lepton number conservation (LNC)

or

- lepton number violation (LNV) by $M \lesssim \mathrm{v}$

N should be present in the EFT ⇒ **NSMEFT**

NSMEFT: operator basis

$$\mathscr{L} = \mathscr{L}_{SM+N} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_{i}^{n_d} \alpha_i^{(d)} \mathscr{O}_i^{(d)}$$

$\mathscr{O}_i^{(d)}$ are invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$

Dimension 5 (LNV operators)

$$\mathscr{O}_{LH} = \left(\overline{L}\tilde{H}\right)\left(\tilde{H}^T L^c\right)$$

Weinberg, PRL **43** (1979) 1566

$$\mathscr{O}_{NNH} = \left(\overline{N^c}N\right)\left(H^\dagger H\right)$$

Aguila, Bar-Shalom, Soni, Wudka, 0806.0876
Aparici, Kim, Santamaria, Wudka, 0904.3244

$$\mathscr{O}_{NNB} = \left(\overline{N^c}\sigma^{\mu\nu}N\right)B_{\mu\nu}$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \qquad \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

$\mathscr{O}_{NNB} \equiv 0$ for $n_s = 1$ (n_s is # of Ns)

NSMEFT: operator basis

Dimension 6

Initial set of operators (redundant) Aguila, Bar-Shalom, Soni, Wudka, 0806.0876

Complete set of independent operators (basis) Liao and Ma, 1612.04527

Higgs-N operators # (+h.c.) = 5 (9)

$1H$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu} N \tilde{H} B_{\mu\nu}$	$\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu} N \sigma_I \tilde{H} W^I_{\mu\nu}$
$2H$	$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N (H^\dagger i \overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HNe} = \overline{N}\gamma^\mu e (\tilde{H}^\dagger i D_\mu H)$
$3H$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H} N (H^\dagger H)$	

4-fermions 11 (16)

RRRR	$\mathcal{O}_{NN} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	
	$\mathcal{O}_{eN} = (\overline{e}\gamma_\mu e)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN} = (\overline{u}\gamma_\mu u)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{dN} = (\overline{d}\gamma_\mu d)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{duNe} = (\overline{d}\gamma_\mu u)(\overline{N}\gamma^\mu e)$
LLRR	$\mathcal{O}_{LN} = (\overline{L}\gamma_\mu L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{QN} = (\overline{Q}\gamma_\mu Q)(\overline{N}\gamma^\mu N)$
LRLR	$\mathcal{O}_{LNLe} = (\overline{L}N)\epsilon(\overline{L}e)$	$\mathcal{O}_{LNQd} = (\overline{L}N)\epsilon(\overline{Q}d)$
	$\mathcal{O}_{LdQN} = (\overline{L}d)\epsilon(\overline{Q}N)$	
LRRL	$\mathcal{O}_{QuNL} = (\overline{Q}u)(\overline{N}L)$	

3 (6)

$\not{L}$	$\mathcal{O}_{NNNN} = (\overline{N^c}N)(\overline{N^c}N)$
$\not{L}$ & $\not{B}$	$\mathcal{O}_{QQdN} = (\overline{Q^c}\epsilon Q)(\overline{d^c}N)$
	$\mathcal{O}_{uddN} = (\overline{u^c}d)(\overline{d^c}N)$

$n_f = 1\ (3):\ \ 29\ (1614)$

operators including h.c.

NSMEFT: operator basis

Dimension 7 (LNV and BNV operators)

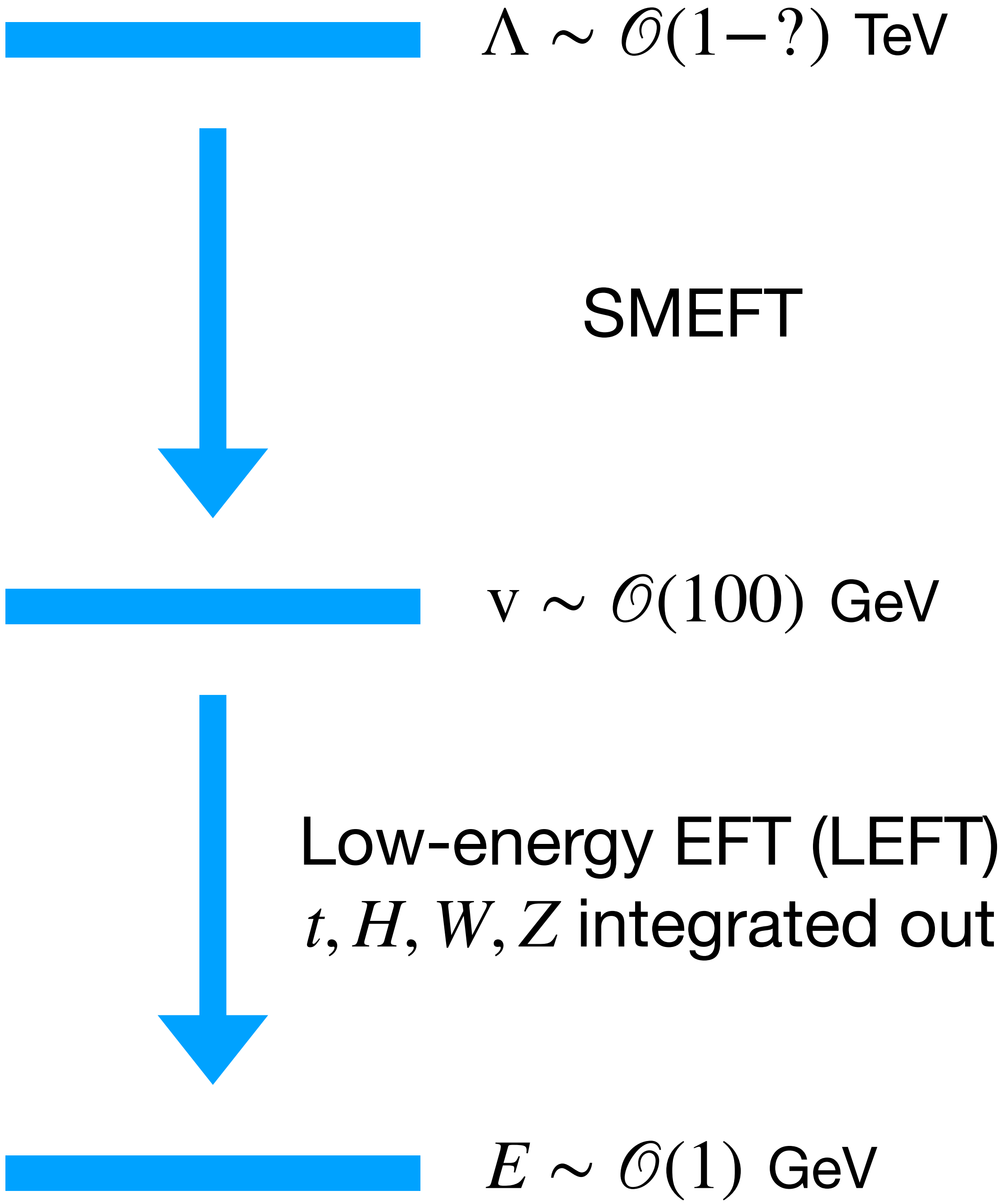
Initial set of operators (incomplete) Bhattacharya and Wudka, 1505.05264
Complete set of independent operators (basis) Liao and Ma, 1612.04527

$n_f = 1\ (3):\ \ 80\ (4206)$ operators including h.c.

The basis of operators involving N should be added to the basis of SMEFT operators derived in

- Dim 5 Weinberg, PRL **43** (1979) 1566
- Dim 6 Buchmüller and Wyler, NPB **268** (1986) 621
  Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884
- Dim 7 Lehman, 1410.4193
  Liao and Ma, 1607.07309

Hierarchy of scales: SM



Hierarchy of scales: SM

$\Lambda \sim \mathcal{O}(1-?)$ TeV

SMEFT

Renormalisation of dim-6 operators at 1 loop Jenkins, Manohar, Trott, 1308.2627
Jenkins, Manohar, Trott, 1310.4838
Alonso, Jenkins, Manohar, Trott, 1312.2014

$\mathrm{v} \sim \mathcal{O}(100)$ GeV

Matching of SMEFT onto LEFT at

- tree level
  Jenkins, Manohar, Stoffer, 1709.04486
- 1 loop Dekens, Stoffer, 1908.05295

Low-energy EFT (LEFT)
t, H, W, Z integrated out

Renormalisation of dim-6 operators at 1 loop
Jenkins, Manohar, Stoffer, 1711.05270

$E \sim \mathcal{O}(1)$ GeV

Hierarchy of scales: SM + N

$\Lambda \sim \mathcal{O}(1-?)$ TeV

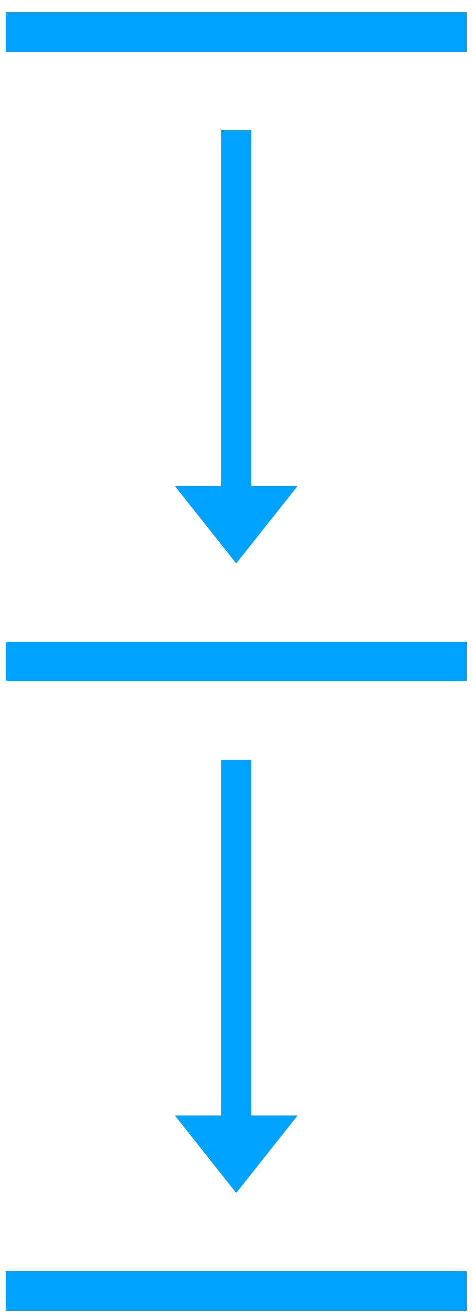
↓ NSMEFT

$\mathrm{v} \sim \mathcal{O}(100)$ GeV

↓ NLEFT

$E \sim \mathcal{O}(1)$ GeV

Hierarchy of scales: SM + N



$\Lambda \sim \mathcal{O}(1-?)$ TeV

NSMEFT

v $\sim \mathcal{O}(100)$ GeV

NLEFT

$E \sim \mathcal{O}(1)$ GeV

Renormalisation of dim-6 operators at 1 loop

- Higgs-N including gauge, lambda and Yukawa dependence
  Chala and AT, 2006.14596
- Higgs-N and 4-fermions including gauge dependence only
  Datta, Kumar, Liu, Marfatia, 2010.12109

Matching of NSMEFT onto NLEFT at tree level
Chala and AT, 2001.07732
Li, Ma, Schmidt, 2005.01543
Bischer and Rodejohann, 1905.08699

Renormalisation of dim-6 operators at 1 loop

- partial results
  Chala and AT, 2001.07732
  Li, Ma, Schmidt, 2005.01543

Running of dim-6 Higgs-N operators

Green basis: set of operators independent off shell

Chala and AT, 2001.07732

$0H$	$1H$	$2H$
$\mathcal{O}^1_{DN} = \overline{N}\partial^2 \partial\!\!\!/ N$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu} N \tilde{H} B_{\mu\nu}$, $\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu} N \sigma_I \tilde{H} W^I_{\mu\nu}$	$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N (H^\dagger i D_\mu H)$
$\mathcal{O}^2_{DN} = i\tilde{B}_{\mu\nu}(\overline{N}\gamma^\mu \partial^\nu N)$	$\mathcal{O}^1_{LN} = \overline{L} N D^2 \tilde{H}$, $\mathcal{O}^2_{LN} = \overline{L}\partial_\mu N D^\mu \tilde{H}$	$\mathcal{O}^2_{NN} = \overline{N} i \partial\!\!\!/ N (H^\dagger H)$
$\mathcal{O}^3_{DN} = \partial^\nu B_{\mu\nu}(\overline{N}\gamma^\mu N)$	$\mathcal{O}^3_{LN} = i\overline{L}\sigma^{\mu\nu}\partial_\mu N D_\nu \tilde{H}$, $\mathcal{O}^4_{LN} = \overline{L}(\partial^2 N)\tilde{H}$	$\mathcal{O}_{HNe} = \overline{N}\gamma^\mu e (\tilde{H}^\dagger i D_\mu H)$
$3H$: $\mathcal{O}_{LNH} = \overline{L}\tilde{H} N (H^\dagger H)$		

The basis is obtained with the help of the package `BasisGen` Criado, 1901.03501

Operators in gray are redundant when evaluated on shell:

$$\mathcal{O}^1_{DN} = 0 \qquad \mathcal{O}^1_{LN} = \left(\mu_H^2 \overline{L}\tilde{H}N + \text{h.c.}\right) - \lambda_H \mathcal{O}_{LNH}$$

$$\mathcal{O}^2_{DN} = -\frac{g_1}{2}\mathcal{O}_{HN} \qquad \mathcal{O}^2_{LN} = -\left(\mu_H^2 \overline{L}\tilde{H}N + \text{h.c.}\right) - \frac{g_1}{8}\mathcal{O}_{NB} + \frac{g_2}{8}\mathcal{O}_{NW} - \frac{1}{2}Y_e \mathcal{O}_{HN} - \frac{\lambda_H}{2}\mathcal{O}_{LNH}$$

$$\mathcal{O}^3_{DN} = -\mathcal{O}^2_{DN} \qquad \mathcal{O}^3_{LN} = -\mathcal{O}^2_{LN}$$

$$\mathcal{O}^2_{NN} = 0 \qquad \mathcal{O}^4_{LN} = 0$$

(The equations hold up to Y_N suppressed operators and 4-fermions)

Running of dim-6 Higgs-N operators

Anomalous dimension matrix

$$16\pi^2 \mu \frac{\mathrm{d}\vec{\alpha}}{\mathrm{d}\mu} = \gamma \vec{\alpha}$$

Non-renormalisation theorems

Cheung and Shen, 1505.01844

$$\gamma = \begin{pmatrix} \gamma^{\text{SMEFT}}_{59\times 59} & & & & & \\ & \times & \times & 0 & 0 & 0 \\ & \times & \times & 0 & 0 & 0 \\ & \mathcal{O}(Y_e) & \mathcal{O}(Y_e) & \times & \mathcal{O}(Y_e) & \mathcal{O}(Y_e) \\ & \mathcal{O}(Y_e) & \mathcal{O}(Y_e) & \mathcal{O}(Y_e) & \times & \mathcal{O}(Y_e) \\ & \times & \times & \mathcal{O}(Y_e) & \mathcal{O}(Y_e) & \times \end{pmatrix} \begin{matrix} \\ \alpha_{NB} \\ \alpha_{NW} \\ \alpha_{HN} \\ \alpha_{HNe} \\ \alpha_{LNH} \end{matrix}$$

We set $Y_N = 0$ $\Rightarrow$ no mixing between Higgs-N and pure SMEFT operators

For $Y_{u,d,e} = 0$, $\mathscr{L}_{SM+N}$ is invariant under $N \to e^{i\theta_N} N\,,\ \ e \to e^{i\theta_e} e\,,\ \ H \to e^{i\theta_H} H$

$$\mathcal{O}_{NB,NW,LNH} \to e^{i(\theta_N - \theta_H)} \mathcal{O}_{NB,NW,LNH}\,, \quad \mathcal{O}_{HN} \to \mathcal{O}_{HN}\,, \quad \mathcal{O}_{HNe} \to e^{i(\theta_e - \theta_N + 2\theta_H)} \mathcal{O}_{HNe}$$

Running of dim-6 Higgs-N operators

Technicalities of the computation

- Background field method: $V_\mu \to V_\mu + \delta V_\mu$
- Feynman gauge
- To order $\mathcal{O}\left(1/\Lambda^2\right)$ any divergence can be mapped onto EFT's Green basis
- (Off-shell) 1PI amplitudes
- Dim reg: $d = 4 - 2\epsilon$

(Semi-)automatic computation using

`FeynRules` + `FeynArts` + `FormCalc`

Alloul et al., 1310.1921 — Hahn, hep-ph/0012260 — Hahn and Perez-Victoria hep-ph/9807565

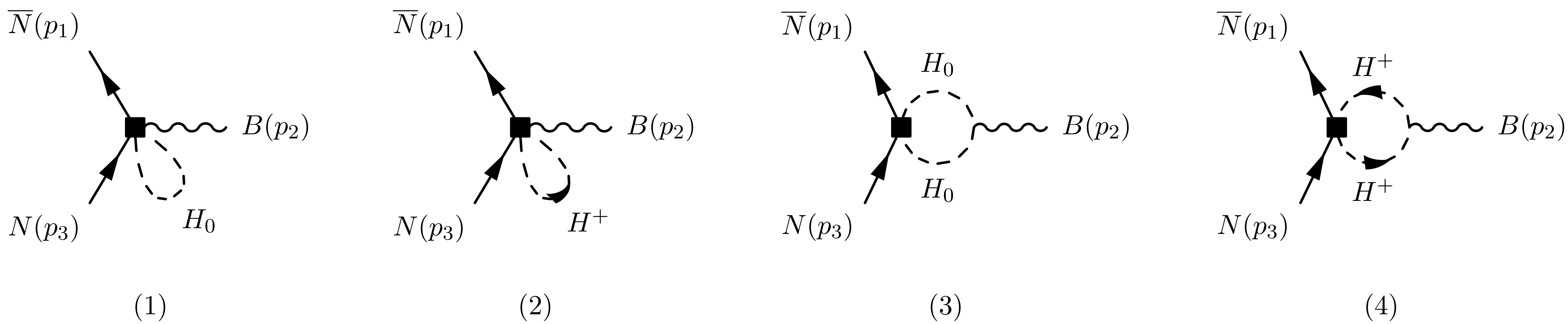
(Semi-)manual check using

`FeynRules` + `QGRAPH`

Nogueira, JCP **105** (1993) 279

Running of dim-6 Higgs-N operators

Example: $\overline{N}N \to B$ amplitude



$$i\mathcal{M}_{\rm loop} = \frac{i}{48\pi^2\Lambda^2\epsilon} g_1 \alpha_{HN} \overline{v_1} \left(p_2^2 \gamma^\mu - p_2^\mu \not{p}_2 \right) P_R u_3 \epsilon^*_\mu$$

$$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N (H^\dagger i D_\mu H)$$

$$i\mathcal{M}_{\rm div} = \frac{i}{\Lambda^2} \overline{v_1} \left[\widetilde{\alpha}^3_{DN} \left(p_2^\mu \not{p}_2 - p_2^2 \gamma^\mu \right) - 2\widetilde{\alpha}^2_{DN} \left(\gamma^\mu p_3 p_2 - \gamma^\mu \not{p}_2 \not{p}_3 + p_2^\mu \not{p}_3 - p_3^\mu \not{p}_2 \right) \right] P_R u_3 \epsilon^*_\mu$$

$$\widetilde{\alpha}^2_{DN} = 0$$

$$\widetilde{\alpha}^3_{DN} = -\frac{1}{48\pi^2\epsilon} g_1 \alpha_{HN}$$

$$\mathcal{O}^2_{DN} = i\tilde{B}_{\mu\nu}(\overline{N}\gamma^\mu \partial^\nu N)$$

$$\mathcal{O}^3_{DN} = \partial^\nu B_{\mu\nu}(\overline{N}\gamma^\mu N)$$

6 more amplitudes to fix all $\tilde{\alpha}_i$

Running of dim-6 Higgs-N operators

After removing the redundant (on shell) operators

$$\mathscr{L}_{\text{div}} = \frac{1}{32\pi^2\Lambda^2\epsilon}\overrightarrow{\mathscr{O}}^T \cdot \mathscr{C} \cdot \overrightarrow{\alpha}$$

$\mathscr{C}$ contains SM couplings

$$\mathscr{L}_6 = \frac{1}{\Lambda^2}\overrightarrow{\alpha}^T \cdot \overrightarrow{\mathscr{O}} + \mathscr{L}_{\text{c.t.}} \qquad \mathscr{L}_{\text{c.t.}} = -\mathscr{L}_{\text{div}}$$

$$\gamma = -\mathscr{C} - K_F \qquad K_F = 32\pi^2\epsilon\left(Z_F - \mathbf{1}\right)$$

Z_F contains wave-function renormalisation factors

Running of dim-6 Higgs-N operators

After removing the redundant (on shell) operators

$$\mathscr{L}_{\rm div} = \frac{1}{32\pi^2\Lambda^2\epsilon}\vec{\mathcal{O}}^T \cdot \mathscr{C} \cdot \vec{\alpha}$$

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Z_F contains wave-function renormalisation factors

Anomalous dimension matrix

Chala and AT, 2006.14596

$$\gamma_{5\times5} = \begin{pmatrix} \frac{91}{12}g_1^2 - \frac{9}{4}g_2^2 - \frac{3}{2}Y_e^2 + {\rm Tr}^2 & -\frac{9}{2}g_1 g_2 & 0 & 0 & 0 \\ -\frac{3}{2}g_1 g_2 & -\frac{3}{4}g_1^2 - \frac{11}{12}g_2^2 + \frac{5}{2}Y_e^2 + {\rm Tr}^2 & 0 & 0 & 0 \\ 3g_1 Y_e & -9g_2 Y_e & \frac{1}{3}g_1^2 + 2{\rm Tr}^2 & 2Y_e^2 & 0 \\ -3g_1 Y_e & 9g_2 Y_e & 0 & -3g_1^2 + Y_e^2 + 2{\rm Tr}^2 & 0 \\ -3g_1\left(g_1^2 + g_2^2\right) & 3g_2\left(g_1^2 + 3g_2^2 + 4Y_e^2\right) & 0 & Y_e\left(3g_2^2 - 2\lambda_H - 2Y_e^2\right) & -\frac{9}{4}g_1^2 - \frac{27}{4}g_2^2 + 12\lambda_H - \frac{3}{2}Y_e^2 + 3{\rm Tr}^2 \end{pmatrix} \begin{matrix} \alpha_{NB} \\ \alpha_{NW} \\ \alpha_{HN} \\ \alpha_{HNe} \\ \alpha_{LNH} \end{matrix}$$

$${\rm Tr}^2 \equiv 3\,{\rm Tr}\left(Y_u^2 + Y_d^2\right) + {\rm Tr}\left(Y_e^2\right)$$

Running of dim-6 Higgs-N operators

After removing the redundant (on shell) operators

$$\mathscr{L}_{\rm div} = \frac{1}{32\pi^2\Lambda^2\epsilon}\vec{\mathcal{O}}^T\cdot\mathscr{C}\cdot\vec{\alpha}$$

$\mathscr{C}$ contains SM couplings

$$\mathscr{L}_6 = \frac{1}{\Lambda^2}\vec{\alpha}^T\cdot\vec{\mathcal{O}} + \mathscr{L}_{\rm c.t.} \qquad \mathscr{L}_{\rm c.t.} = -\mathscr{L}_{\rm div}$$

$$\gamma = -\mathscr{C} - K_F \qquad K_F = 32\pi^2\epsilon\left(Z_F - \mathbf{1}\right)$$

Z_F contains wave-function renormalisation factors

Anomalous dimension matrix

Chala and AT, 2006.14596

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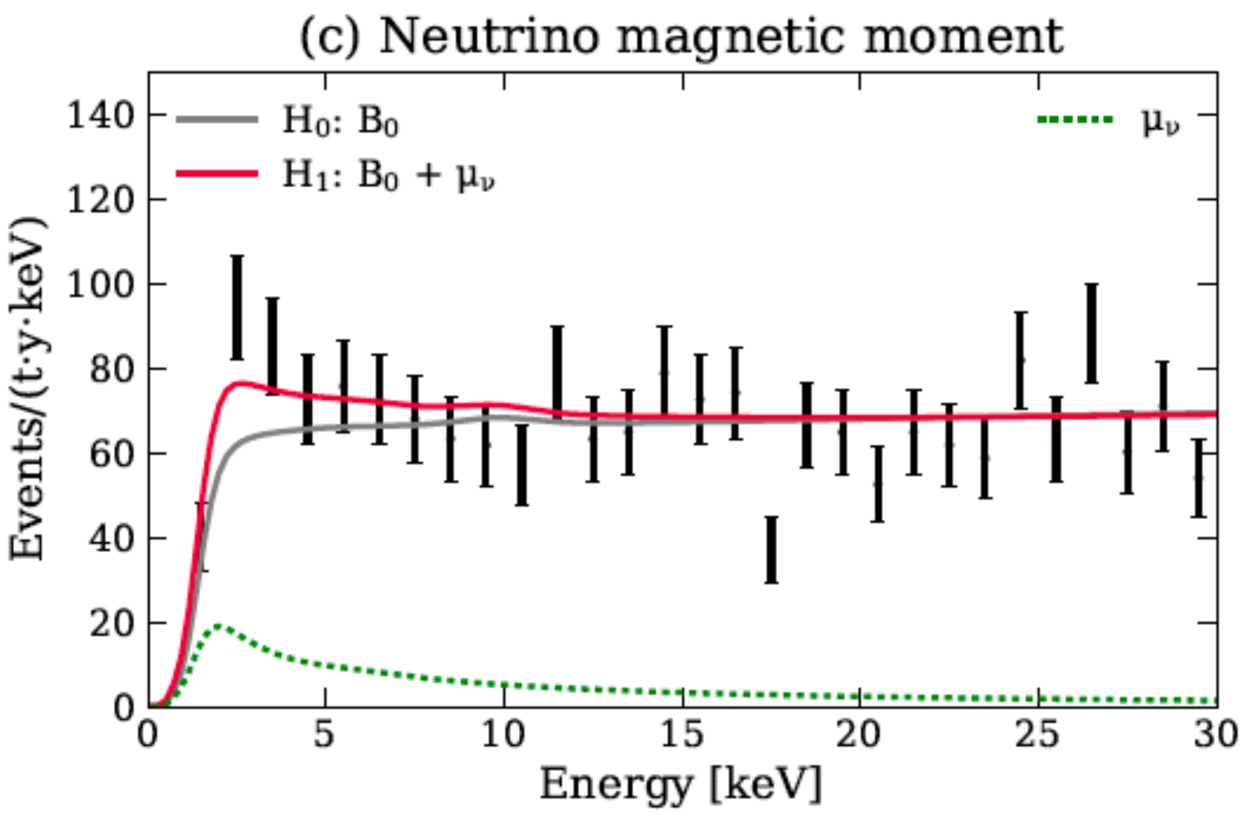
$${\rm Tr}^2 \equiv 3\,{\rm Tr}\left(Y_u^2 + Y_d^2\right) + {\rm Tr}\left(Y_e^2\right)$$

Gauge and lambda dependence of RGEs for α_{NB}, α_{NW}, α_{LNH} Bell et al., hep-ph/0504134

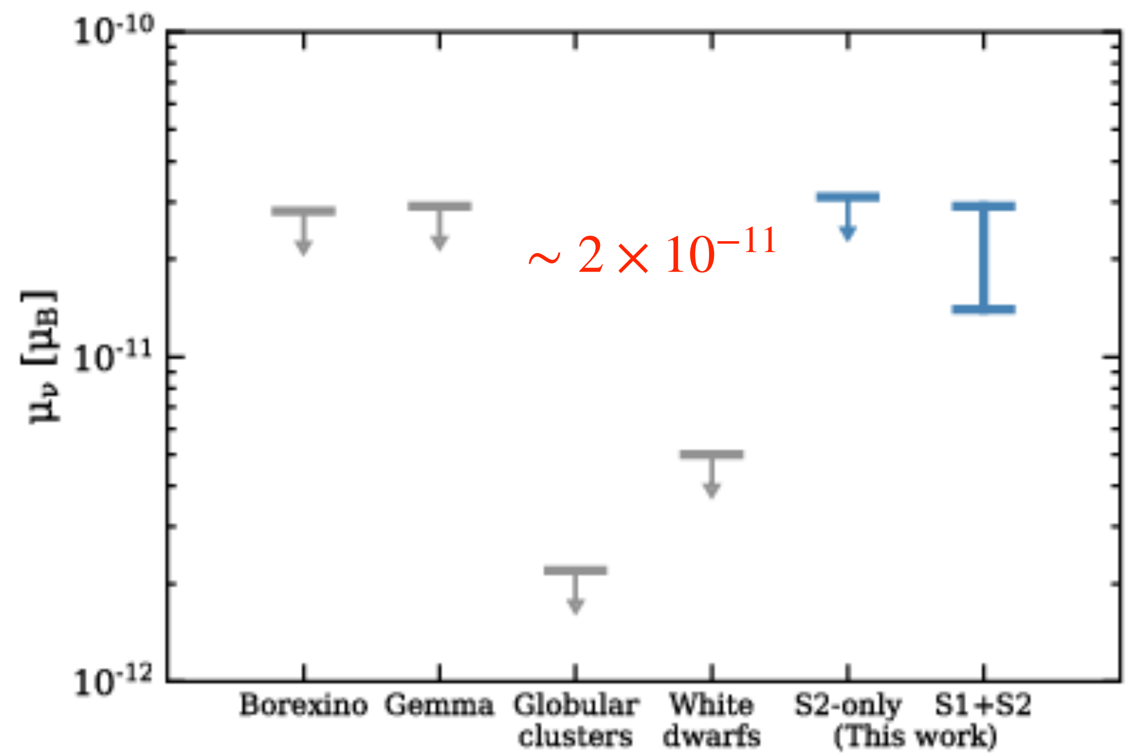
Applications

Dirac neutrino magnetic dipole moment and neutrino mass

$$\left|\frac{\mu_\nu}{\mu_B}\right| = \frac{4\sqrt{2}}{\mathrm{e}}\frac{m_e \mathrm{v}}{\Lambda^2}\alpha_{NA}(\mathrm{v})$$ Bell et al., hep-ph/0504134 $$\mathcal{O}_{NA} = c_W \mathcal{O}_{NB} + s_W \mathcal{O}_{NW}$$



XENON1T, 2006.09721



$\alpha_{NA} \sim 10^{-5}\ \left(10^{-1}\right)$ for $\Lambda = 1$ TeV $(100$ TeV$)$

$\alpha_{LNH}(v) \sim 10^{-7}\ \left(10^{-3}\right)$ $\quad \mathcal{O}_{LNH} = \bar{L}N\tilde{H}\left(H^\dagger H\right) \xrightarrow{\text{EWSB}} \delta m_\nu \sim \frac{\alpha_{LNH}\mathrm{v}^3}{2\sqrt{2}\Lambda^2}$

$\delta m_\nu \sim 10^2$ eV $\left(10^3 \text{ eV}\right)$ to be cancelled by Y_N — considerable fine-tuning

Applications

$\mathcal{O}_{HNe}$ and neutrino mass

$\mathcal{O}_{HNe} = \left(\overline{N}\gamma^{\mu}e\right)\left(\tilde{H}^{\dagger}iD_{\mu}H\right)$ also renormalises $\mathcal{O}_{LNH}$

For $\ell = \tau$, $Y_{\tau} \sim 10^{-2}$ and

$$\delta m_{\nu} \lesssim 1 \text{ eV} \quad \Rightarrow \quad \frac{\alpha_{HNe}}{\Lambda^2} \lesssim 10^{-6} \text{ TeV}^{-2}$$

Bound from $W \to \tau\nu$

$$\Delta\Gamma(W \to \tau\nu) = \frac{m_W^3 \mathrm{v}^2}{48\pi\Lambda^4}\alpha_{HNe}^2$$

$$\frac{\Delta\Gamma(W \to \tau\nu)}{\Gamma_W^{\text{total}}} < 2 \times 10^{-3} \quad \Rightarrow \quad \frac{\alpha_{HNe}}{\Lambda^2} \lesssim 4.5 \text{ TeV}^{-2}$$

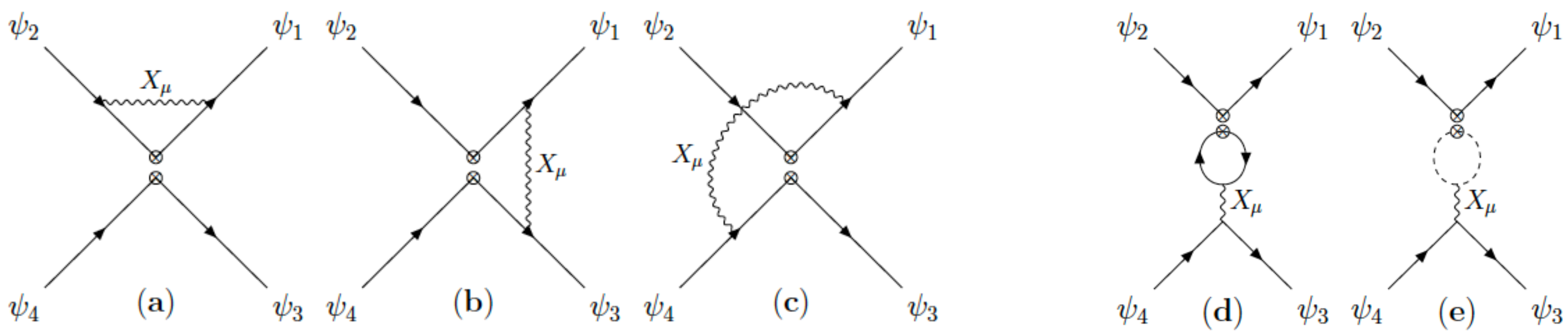
PDG, RPP 2020

6 orders of magnitude stronger bound from RGE!

Running of 4-fermions

Gauge dependence of anomalous dimension matrix

Datta, Kumar, Liu, Marfatia, 2010.12109



$$\gamma^{\rm NSMEFT}_{16\times16} = \begin{pmatrix} \gamma_{5\times5} & \gamma_{5\times11} \\ \gamma_{11\times5} & \gamma_{11\times11} \end{pmatrix}$$ Higgs-N / 4-fermions

The strong gauge coupling constant is in play

Sizeable mixing between certain 4-fermion operators, e.g.,

$\mathcal{O}_{LNQd} = (\overline{L}N)\,\epsilon\,(\overline{Q}d)$ and $\mathcal{O}_{LdQN} = (\overline{L}d)\,\epsilon\,(\overline{Q}N)$

NLEFT: operator basis

NLEFT is the EFT below the EW scale invariant under $SU(3)_c \times U(1)_{\rm em}$

LNC operators

Chala and AT, 2001.07732

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

Dipole: 1

4-fermions: 23

Matching NSMEFT onto NLEFT

Tree-level matching at EW scale (w/o Yukawas) Chala and AT, 2001.07732

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

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

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

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

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

$$\frac{\alpha^{V,LR}_{udeN}}{v^2} = -\frac{g^2 W_N}{2m_W^2}, \quad \text{(D.11)} \qquad \alpha^{S,RR}_{NN} = 0, \quad \text{(D.12)}$$

$$\frac{\alpha^{S,RR}_{eN}}{v^2} = \frac{3\alpha_{LNLe}}{2\Lambda^2}, \quad \text{(D.13)} \qquad \frac{\alpha^{T,RR}_{eN}}{v^2} = \frac{\alpha_{LNLe}}{8\Lambda^2}, \quad \text{(D.14)}$$

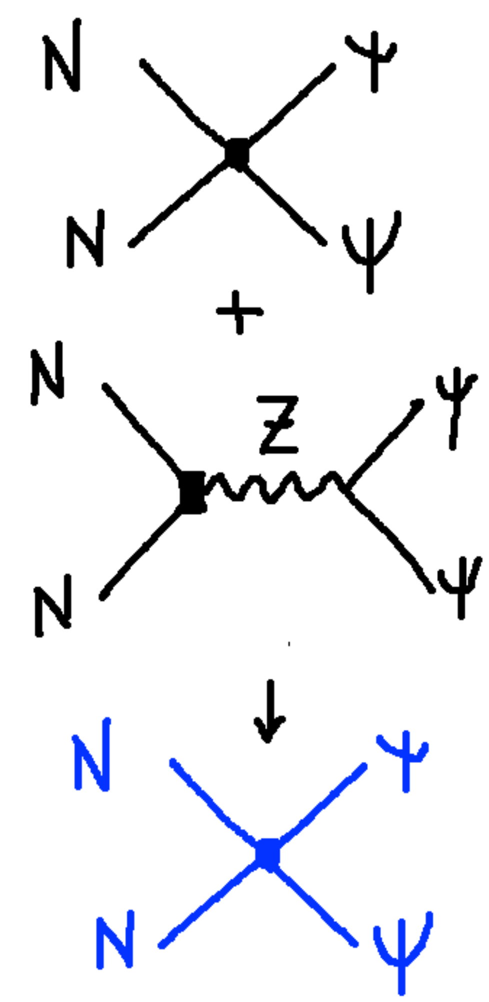
$$\alpha^{S,RR}_{uN} = 0, \quad \text{(D.15)} \qquad \alpha^{T,RR}_{uN} = 0, \quad \text{(D.16)}$$

$$\frac{\alpha^{S,RR}_{dN}}{v^2} = \frac{\alpha_{LNQd}}{\Lambda^2} - \frac{\alpha_{LdQN}}{2\Lambda^2}, \quad \text{(D.17)} \qquad \frac{\alpha^{T,RR}_{dN}}{v^2} = -\frac{\alpha_{LdQN}}{8\Lambda^2}, \quad \text{(D.18)}$$

$$\frac{\alpha^{S,RR}_{udeN}}{v^2} = \frac{\alpha_{LdQN}}{2\Lambda^2} - \frac{\alpha_{LNQd}}{\Lambda^2}, \quad \text{(D.19)} \qquad \frac{\alpha^{T,RR}_{udeN}}{v^2} = \frac{\alpha_{LdQN}}{8\Lambda^2}, \quad \text{(D.20)}$$

$$\frac{\alpha^{S,LR}_{eN}}{v^2} = \frac{g^2 W_N}{m_W^2}, \quad \text{(D.21)} \qquad \frac{\alpha^{S,LR}_{uN}}{v^2} = \frac{\alpha_{QuNL}}{\Lambda^2}, \quad \text{(D.22)}$$

$$\alpha^{S,LR}_{dN} = 0, \quad \text{(D.23)} \qquad \frac{\alpha^{S,LR}_{udeN}}{v^2} = \frac{\alpha_{QuNL}}{\Lambda^2}. \quad \text{(D.24)}$$



$$g_Z = \frac{e}{s_W c_W} \qquad Z_{\psi_{SM}} = T_3 - Q s_W^2$$

$$Z_N = -\frac{\alpha_{HN} v^2}{2\Lambda^2} \qquad W_N = \frac{\alpha_{HNe} v^2}{2\Lambda^2}$$

NLEFT: operator basis

There are also LNV operators

LNV operators

Chala and AT, 2001.07732

Dipole	$\mathcal{O}_{NN\gamma} = \overline{N}\sigma^{\mu\nu}N^c A_{\mu\nu}$	
LLLL	$\mathcal{O}^{V,LL}_{\nu N^c} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{\nu_L}\gamma^\mu N^c)$	$\mathcal{O}^{V,LL}_{eN^c} = (\overline{e_L}\gamma_\mu e_L)(\overline{\nu_L}\gamma^\mu N^c)$
	$\mathcal{O}^{V,LL}_{uN^c} = (\overline{u_L}\gamma_\mu u_L)(\overline{\nu_L}\gamma^\mu N^c)$	$\mathcal{O}^{V,LL}_{dN^c} = (\overline{d_L}\gamma_\mu d_L)(\overline{\nu_L}\gamma^\mu N^c)$
	$\mathcal{O}^{V,LL}_{udeN^c} = (\overline{u_L}\gamma_\mu d_L)(\overline{e_L}\gamma^\mu N^c)$	
RRLL	$\mathcal{O}^{V,RL}_{eN^c} = (\overline{e_R}\gamma_\mu e_R)(\overline{\nu_L}\gamma^\mu N^c)$	$\mathcal{O}^{V,RL}_{uN^c} = (\overline{u_R}\gamma_\mu u_R)(\overline{\nu_L}\gamma^\mu N^c)$
	$\mathcal{O}^{V,RL}_{dN^c} = (\overline{d_R}\gamma_\mu d_R)(\overline{\nu_L}\gamma^\mu N^c)$	$\mathcal{O}^{V,RL}_{udeN^c} = (\overline{u_R}\gamma_\mu d_R)(\overline{e_L}\gamma^\mu N^c)$
RLRL	$\mathcal{O}^{S,LL}_{eN^c} = (\overline{e_R}e_L)(\overline{N}N^c)$	$\mathcal{O}^{S,LL}_{uN^c} = (\overline{u_R}u_L)(\overline{N}N^c)$
	$\mathcal{O}^{S,LL}_{dN^c} = (\overline{d_R}d_L)(\overline{N}N^c)$	$\mathcal{O}^{S,LL}_{udeN^c} = (\overline{u_R}d_L)(\overline{e_R}N^c)$
	$\mathcal{O}^{T,LL}_{udeN^c} = (\overline{u_R}\sigma_{\mu\nu}d_L)(\overline{e_R}\sigma^{\mu\nu}N^c)$	
LRRL	$\mathcal{O}^{S,RL}_{\nu^c N^c} = (\overline{\nu_L}\nu_L^c)(\overline{N}N^c)$	$\mathcal{O}^{S,RL}_{NN^c} = (\overline{\nu_L}N)(\overline{N}N^c)$
	$\mathcal{O}^{S,RL}_{eN^c} = (\overline{e_L}e_R)(\overline{N}N^c)$	$\mathcal{O}^{S,RL}_{uN^c} = (\overline{u_L}u_R)(\overline{N}N^c)$
	$\mathcal{O}^{S,RL}_{dN^c} = (\overline{d_L}d_R)(\overline{N}N^c)$	$\mathcal{O}^{S,RL}_{udeN^c} = (\overline{u_L}d_R)(\overline{e_R}N^c)$

See also Li, Ma, Schmidt, 2005.01543, in particular, for tree-level matching

Phenomenology: Dirac neutrino

- What are the constraints on the NSMEFT operators involving N?
- What are the signatures of the unconstrained operators?

RRRR	$\mathcal{O}_{NN} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	
	$\mathcal{O}_{eN} = (\overline{e}\gamma_\mu e)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN} = (\overline{u}\gamma_\mu u)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{dN} = (\overline{d}\gamma_\mu d)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{duNe} = (\overline{d}\gamma_\mu u)(\overline{N}\gamma^\mu e)$
LLRR	$\mathcal{O}_{LN} = (\overline{L}\gamma_\mu L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{QN} = (\overline{Q}\gamma_\mu Q)(\overline{N}\gamma^\mu N)$
LRLR	$\mathcal{O}_{LNLe} = (\overline{L}N)\epsilon(\overline{L}e)$	$\mathcal{O}_{LNQd} = (\overline{L}N)\epsilon(\overline{Q}d)$
	$\mathcal{O}_{LdQN} = (\overline{L}d)\epsilon(\overline{Q}N)$	
LRRL	$\mathcal{O}_{QuNL} = (\overline{Q}u)(\overline{N}L)$	

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Alcaide, Banerjee, Chala, AT, 1905.11375

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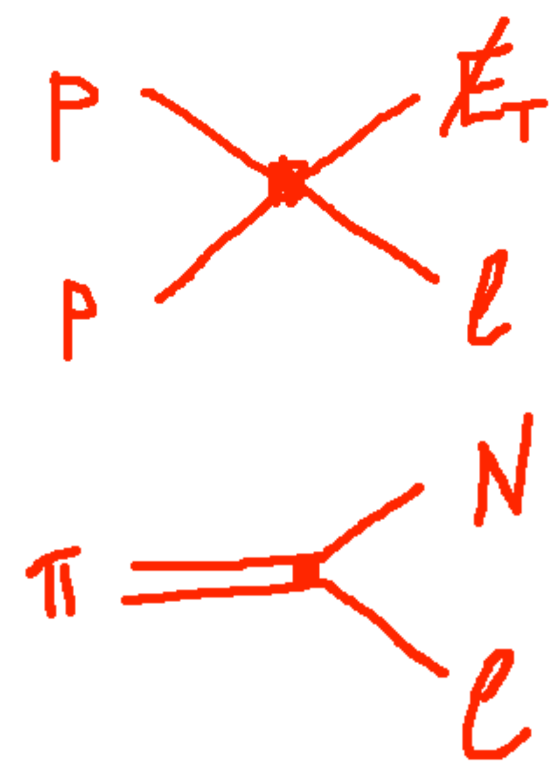

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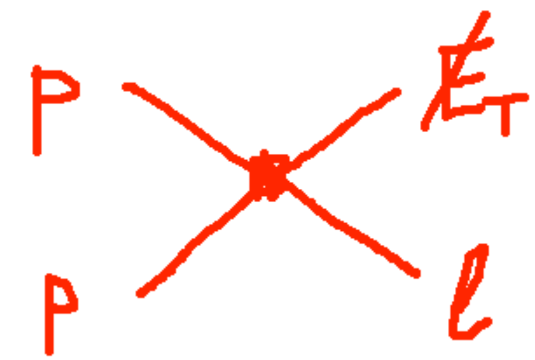

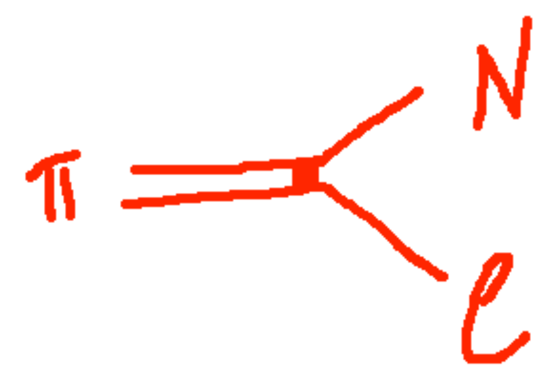

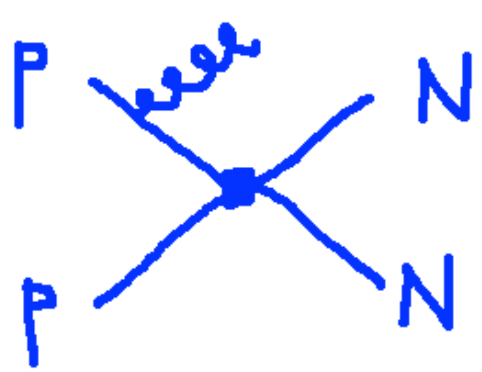

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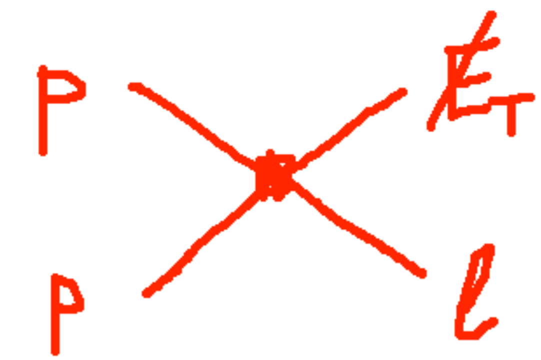

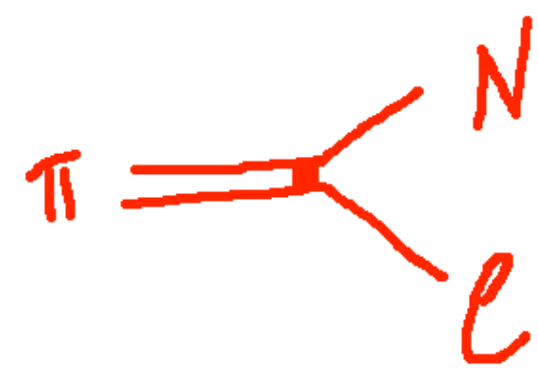

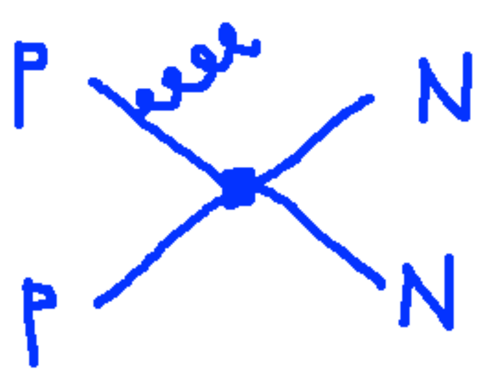

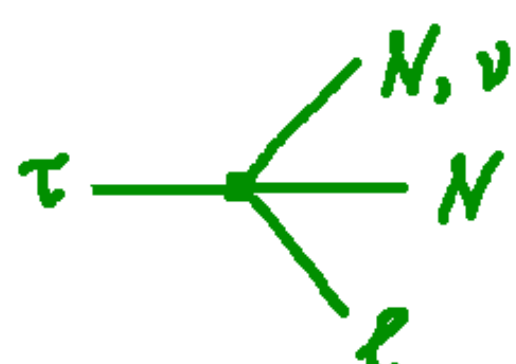

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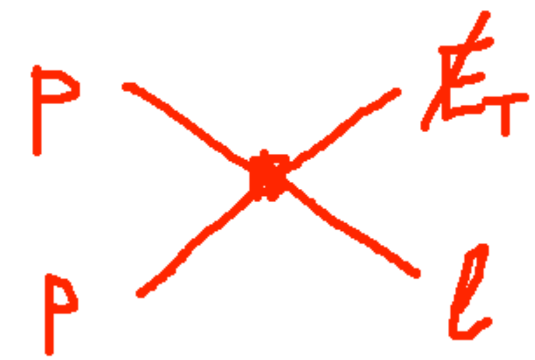
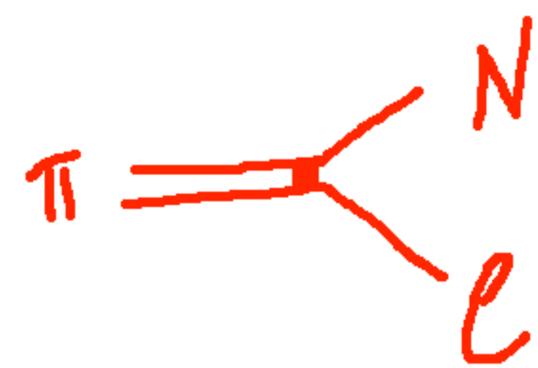
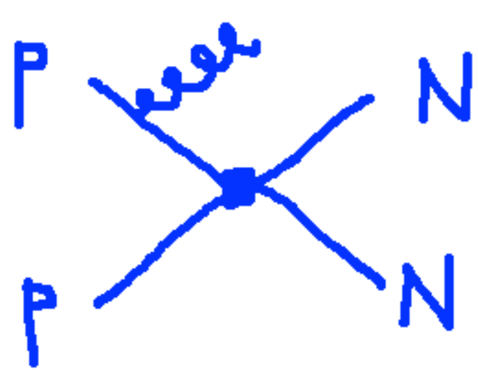
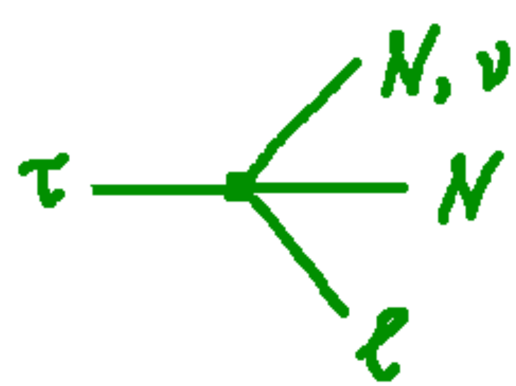
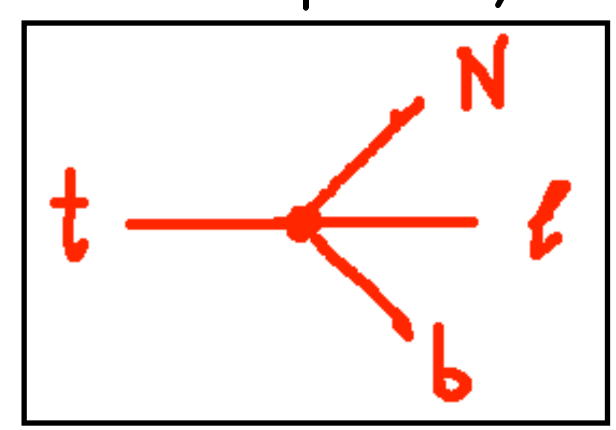




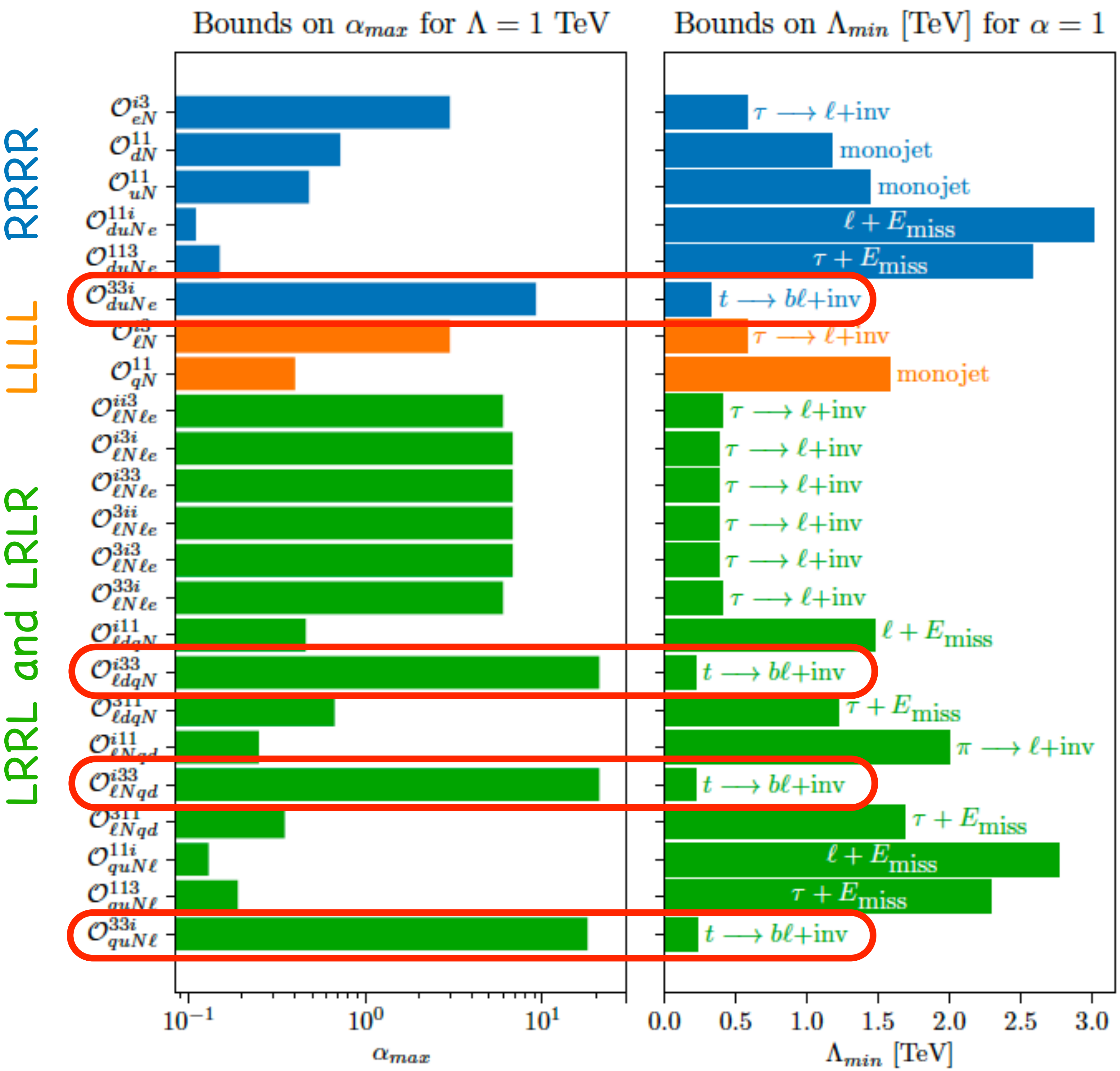




New top decay



Constraints on 4-fermions



Alcaide, Banerjee, Chala, AT, 1905.11375

Figure from Alcaide's PhD thesis

$pp \to \ell + E_T^{\text{miss}}$

ATLAS, 1706.04786

$pp \to j + E_T^{\text{miss}}$ (monojet)

CMS, 1712.02345

$\Gamma_{\pi\to e+\text{inv}} = (310 \pm 1) \times 10^{-23}$ GeV

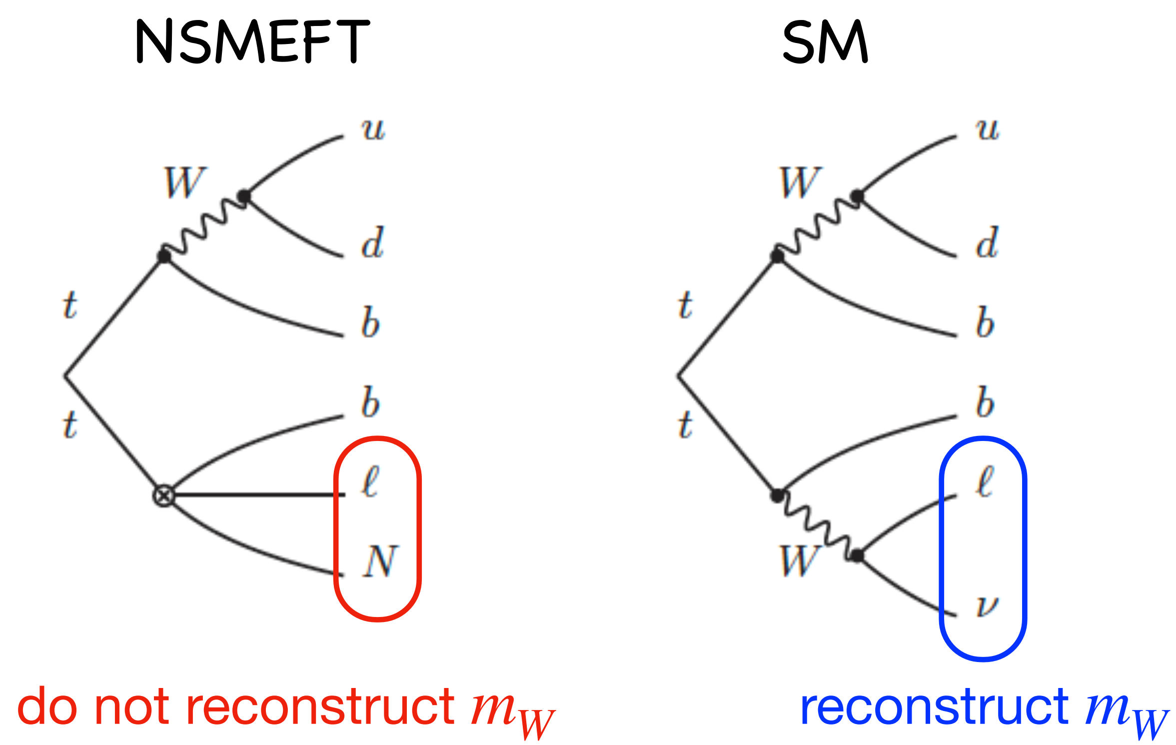
$\Gamma_{\tau\to e+\text{inv}} = (4.03 \pm 0.02) \times 10^{-13}$ GeV

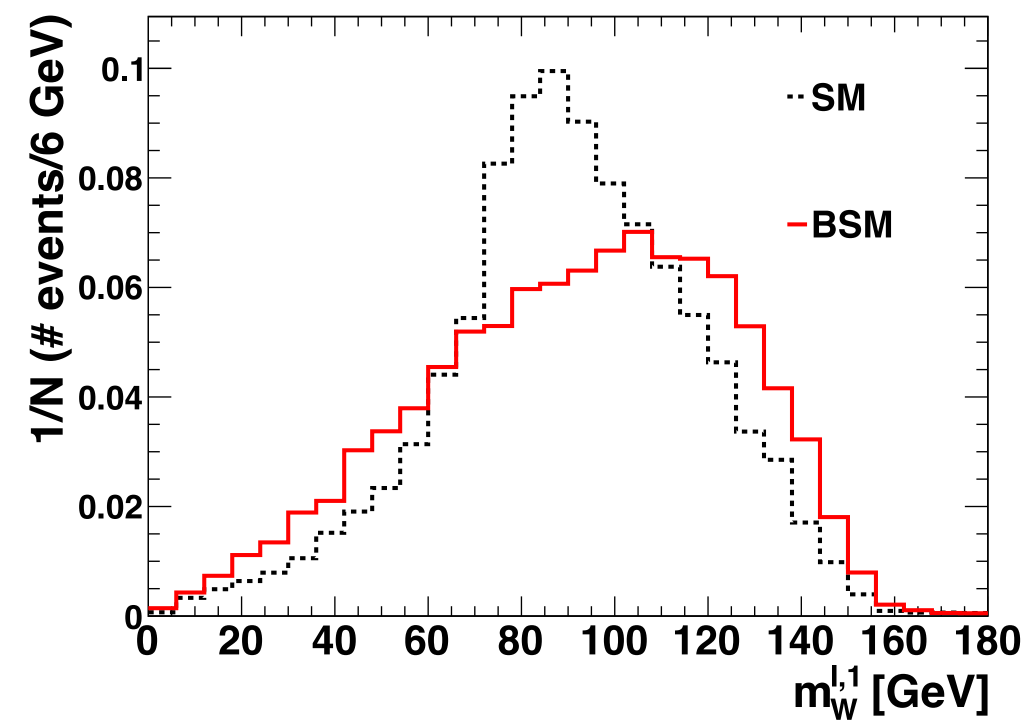
PDG, RPP 2018

Obtained with a novel analysis designed for HL-LHC

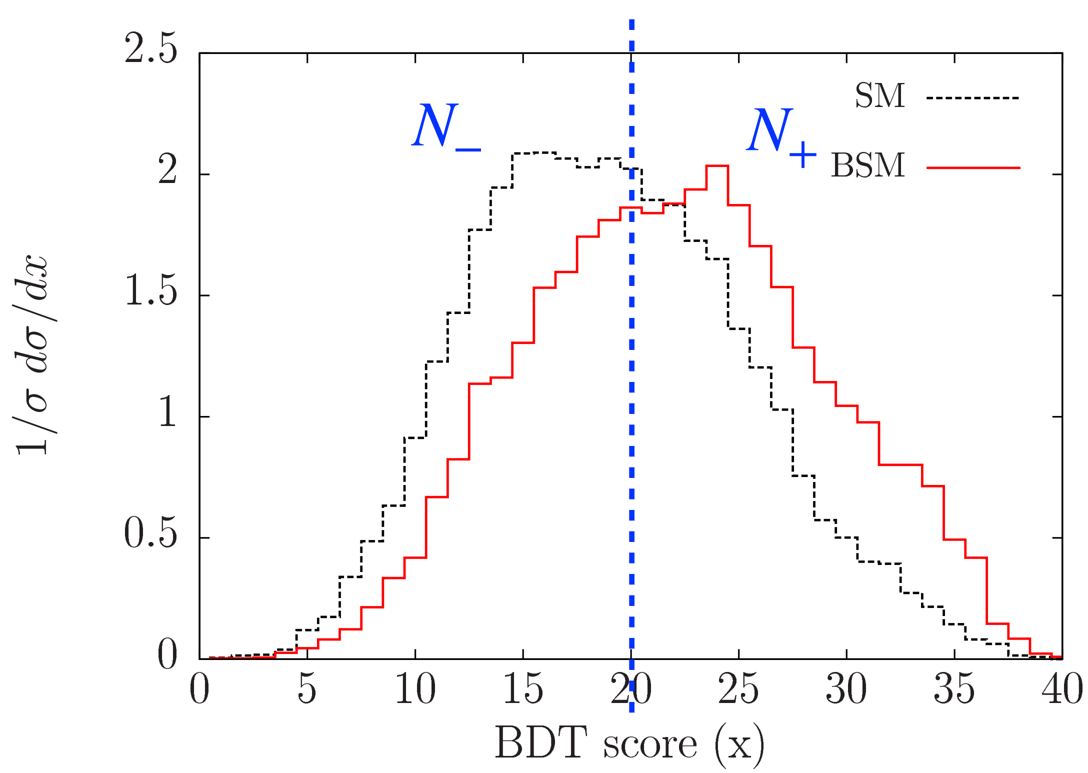
Novel LHC analysis for $t \to bl + inv$

Alcaide, Banerjee, Chala, AT, 1905.11375





A multivariate analysis based on a BDT classifier ($p_T^{b_i}, p_T^{j_i}, m_W, \Delta R_{ij}$)



$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad \begin{cases} A < 0 & \text{in SM} \\ A > 0 & \text{in NSMEFT} \end{cases}$$

$$\mathscr{B}(t \to b\ell N) \sim 2 \times 10^{-4}$$

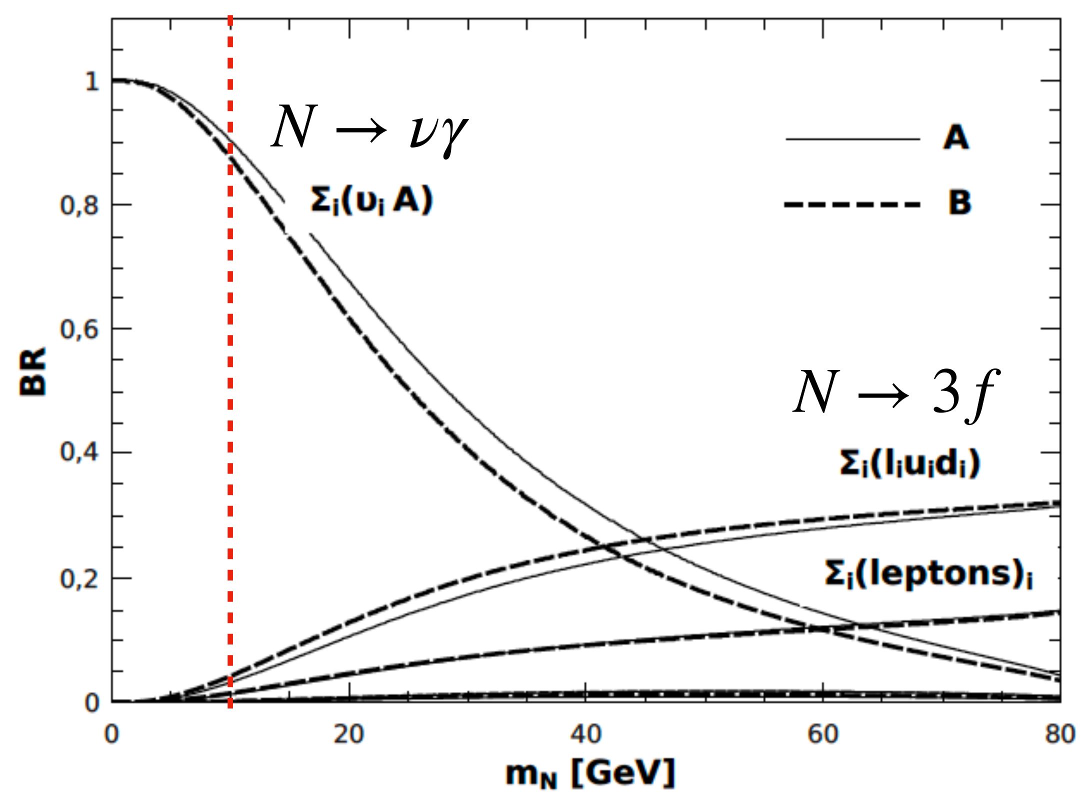
@ HL-LHC with $\mathscr{L} = 3$ ab^{-1}

Phenomenology: Majorana N

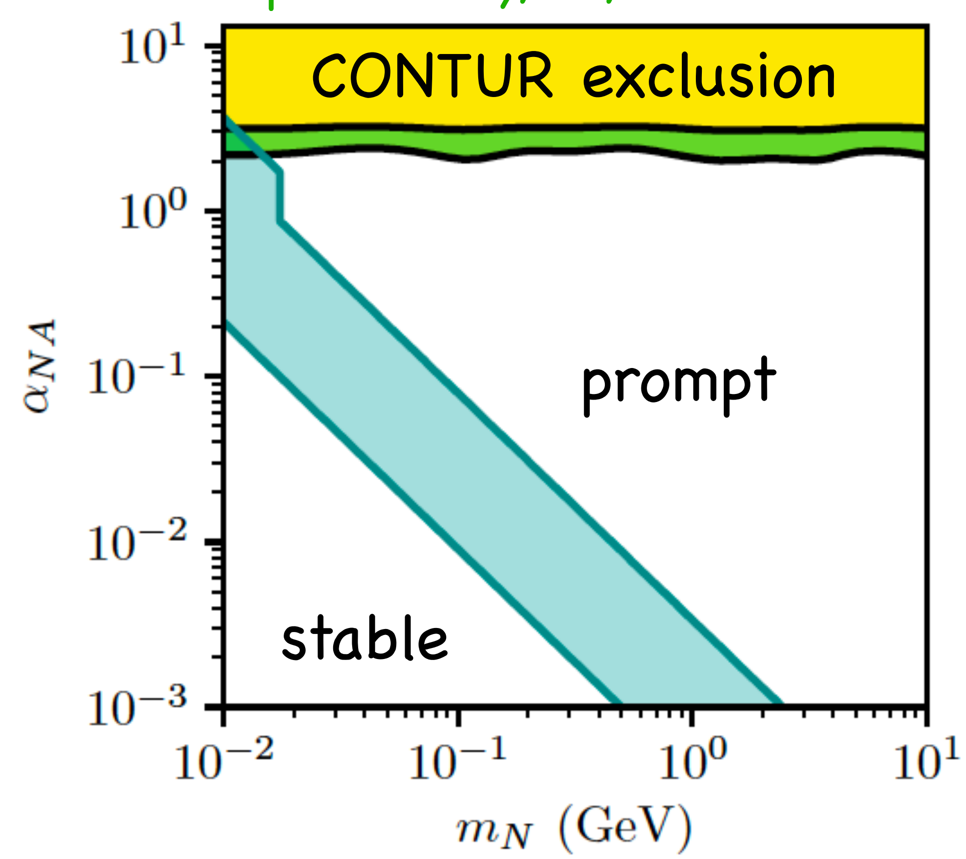
$$-\mathscr{L}_{\text{mass}} = \overline{L}\tilde{H}Y_N N + \frac{1}{2}\overline{N^c} m_N N + \text{h.c.} \quad \Rightarrow \quad N \text{ is Majorana}$$

$$\Gamma(N \to \nu\gamma) = \frac{m_N^3 v^2}{4\pi\Lambda^4}\alpha_{NA}^2 \qquad \alpha_{NA} = c_W \alpha_{NB} + s_W \alpha_{NW}$$

Duarte, Peressutti, Sampayo, 1508.01588



Butterworth, Chala, Englert, Spannowsky, AT, 1909.04665



Let's restrict to Higgs-N operators

For the analysis including 4-fermions in this regime see
Biekötter, Chala, Spannowsky, arXiv:2007.00673

Higgs-N operators

$$\mathcal{O}_{NNH} = \left(\overline{N^c} N\right)\left(H^\dagger H\right)$$

$1H$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu} N \tilde{H} B_{\mu\nu}$	$\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu} N \sigma_I \tilde{H} W^I_{\mu\nu}$
$2H$	$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N (H^\dagger i \overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HNe} = \overline{N}\gamma^\mu e (\tilde{H}^\dagger i D_\mu H)$
$3H$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H} N (H^\dagger H)$	

Higgs-N operators

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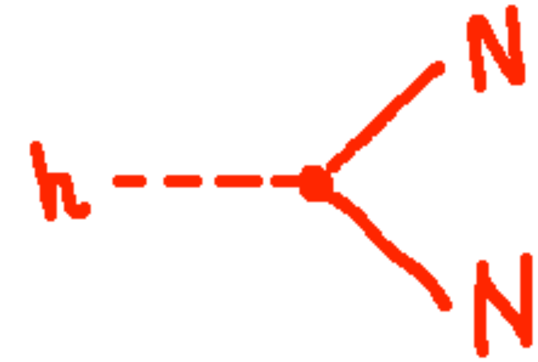
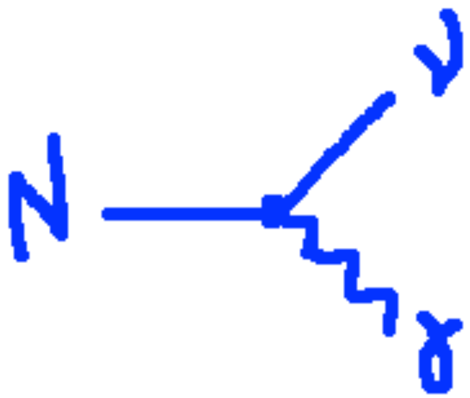
$3H$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H}N(H^\dagger H)$	

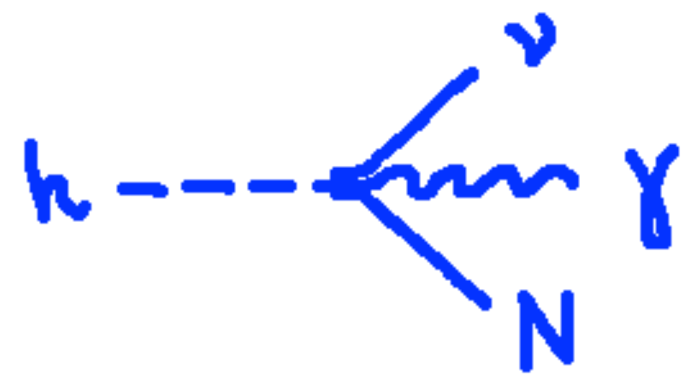
Higgs-N operators

$$\mathcal{O}_{NNH} = \left(\overline{N^c} N\right) \left(H^\dagger H\right)$$



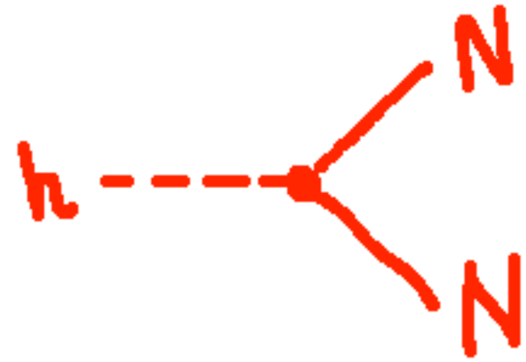
$1H$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu} N \tilde{H} B_{\mu\nu}$	$\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu} N \sigma_I \tilde{H} W^I_{\mu\nu}$
$2H$	$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N (H^\dagger i \overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HNe} = \overline{N}\gamma^\mu e (\tilde{H}^\dagger i D_\mu H)$
$3H$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H} N (H^\dagger H)$	





Higgs-N operators

$$\mathcal{O}_{NNH} = \left(\overline{N^c}N\right)\left(H^\dagger H\right)$$



$1H$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu}N\tilde{H}B_{\mu\nu}$	$\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu}N\sigma_I\tilde{H}W^I_{\mu\nu}$
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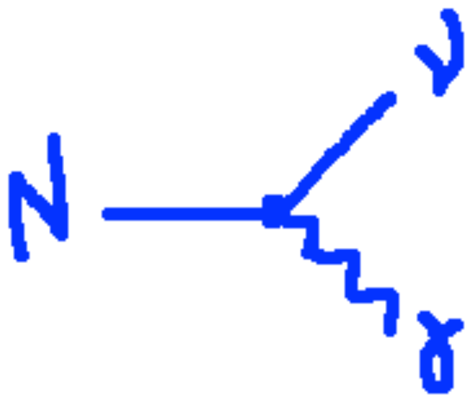

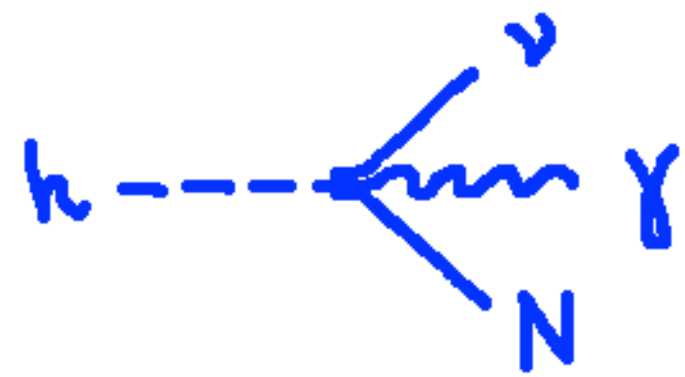

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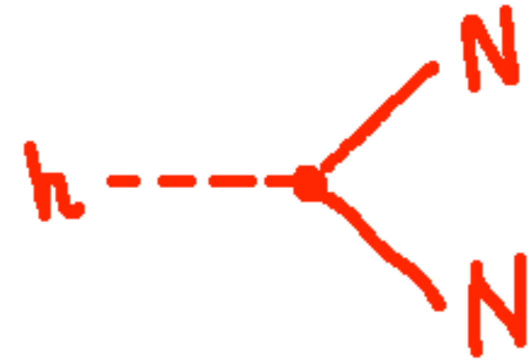

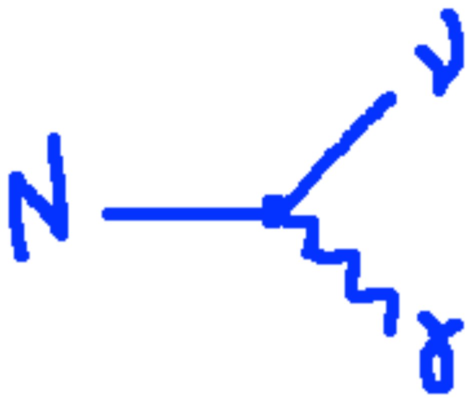

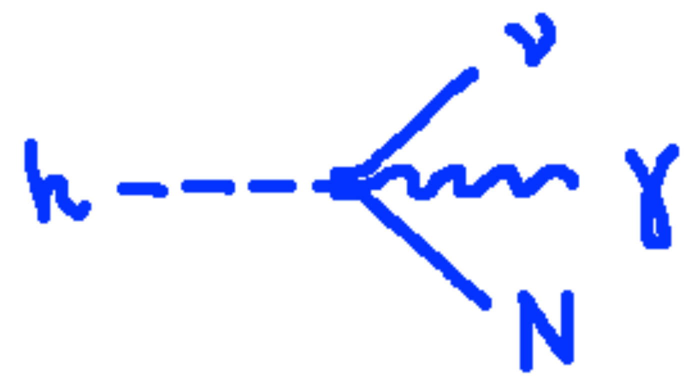

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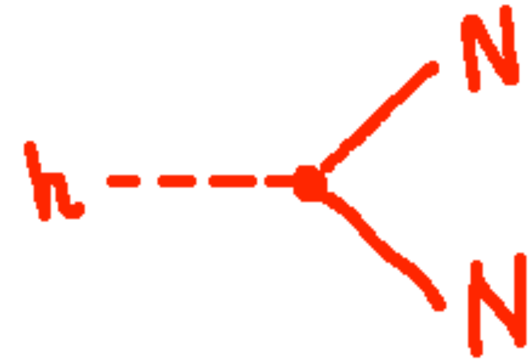

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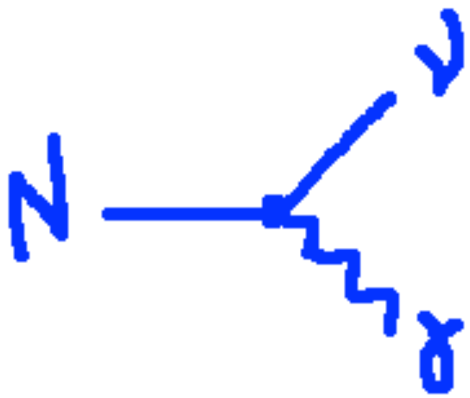

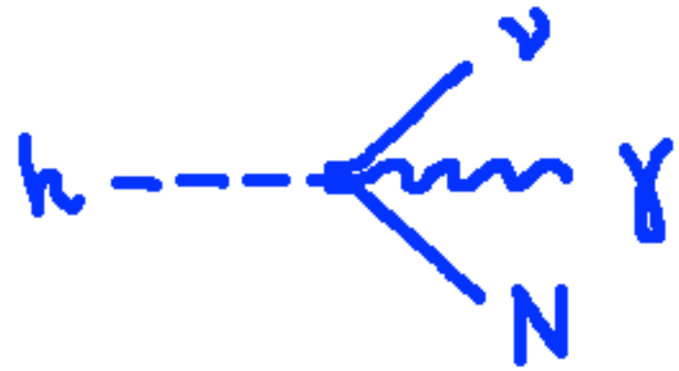

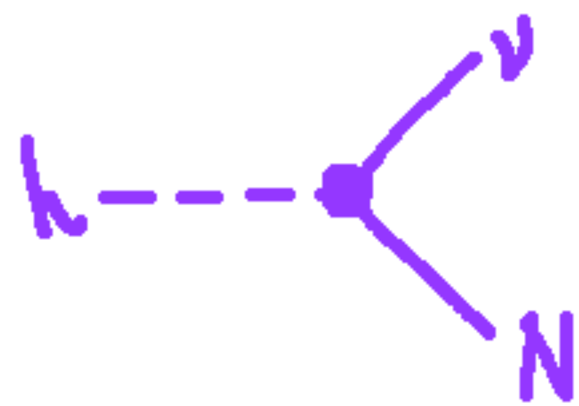

Higgs-N operators

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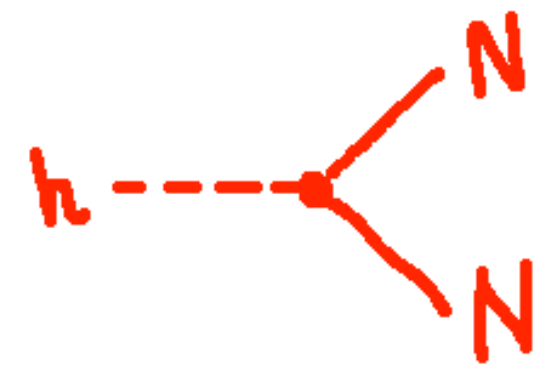

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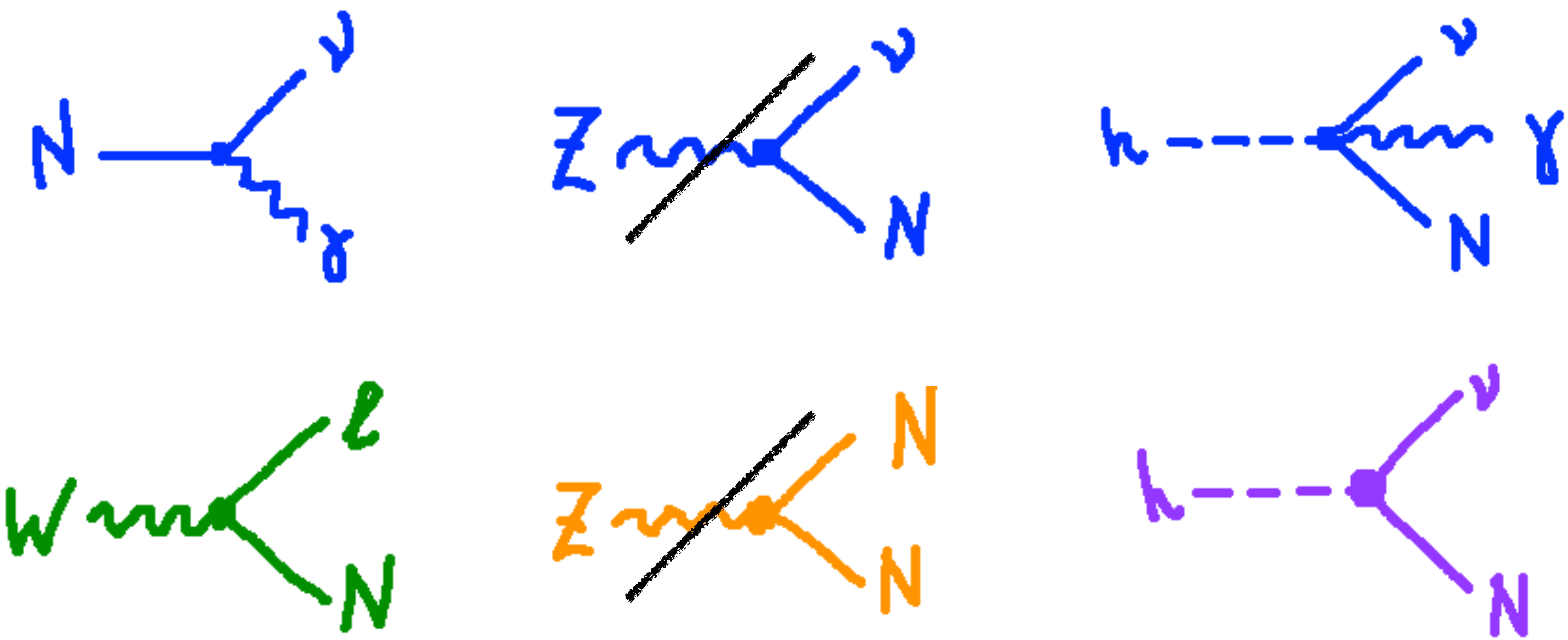

$\mathcal{B}(Z \to \nu\nu\gamma(\gamma)) \lesssim 3 \times 10^{-6}$ $\Rightarrow$ set $\alpha_{NZ} = \alpha_{HN} = 0$ (for simplicity)

LEP, 90's; PDG, RPP 2018

Higgs-N operators

$$\mathcal{O}_{NNH} = \left(\overline{N^c}N\right)\left(H^\dagger H\right)$$

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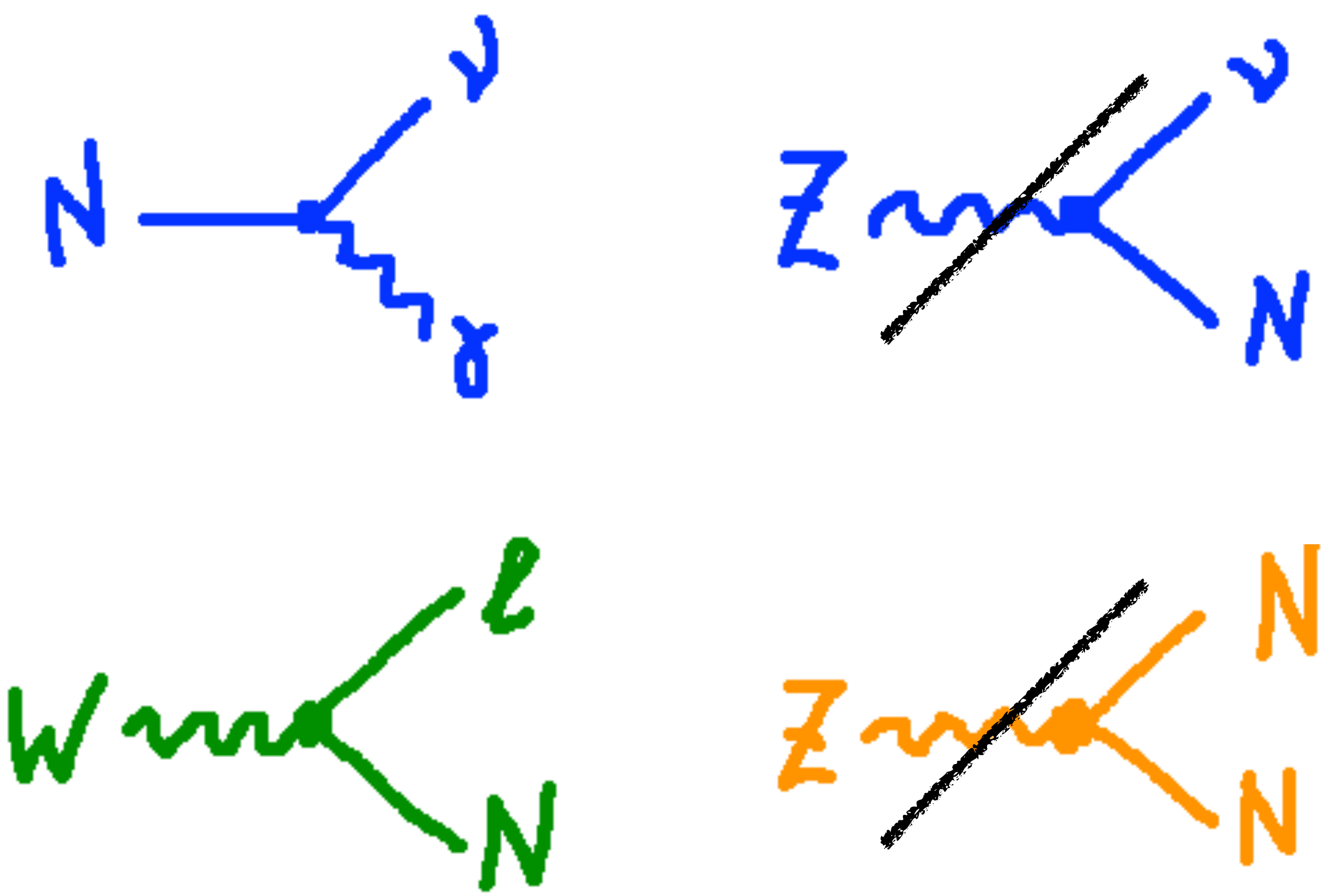
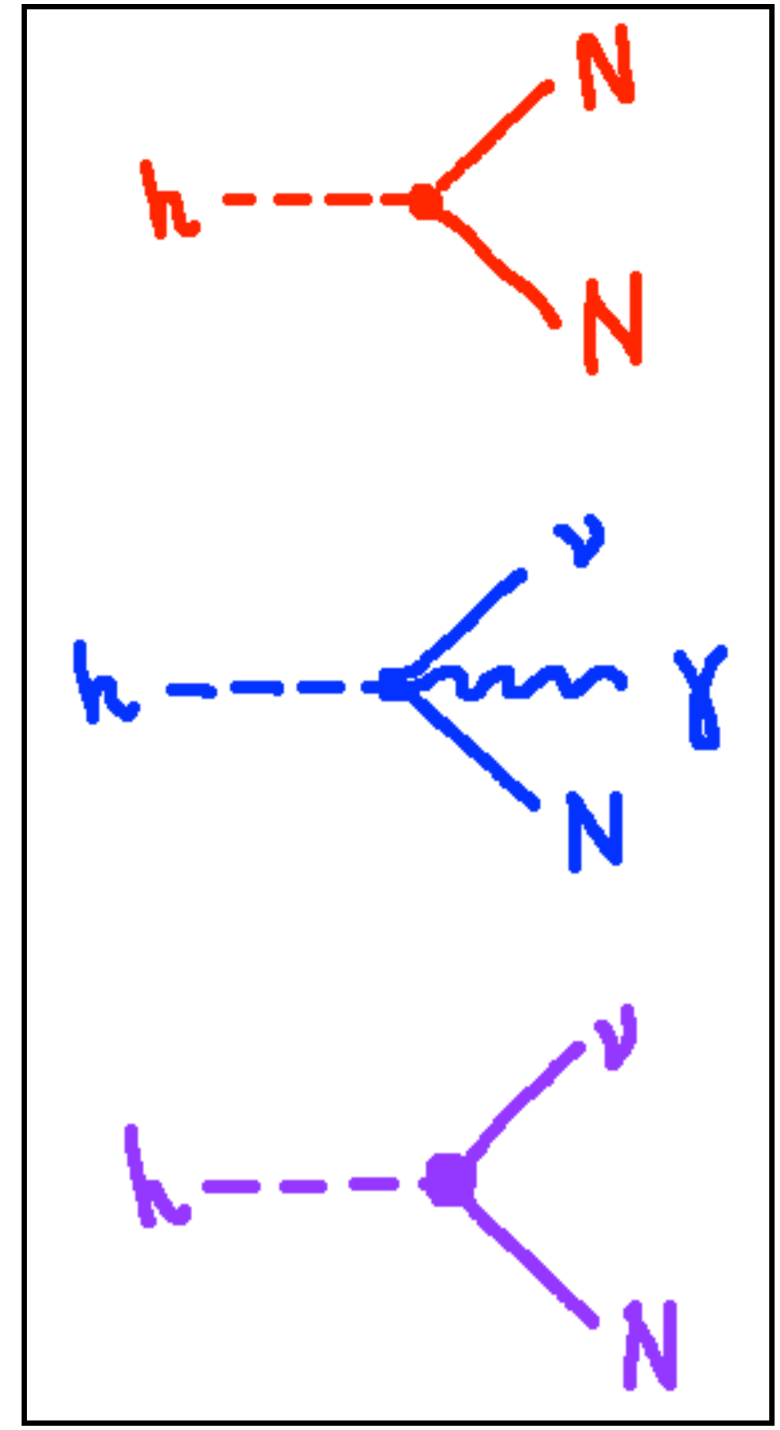


New Higgs decays



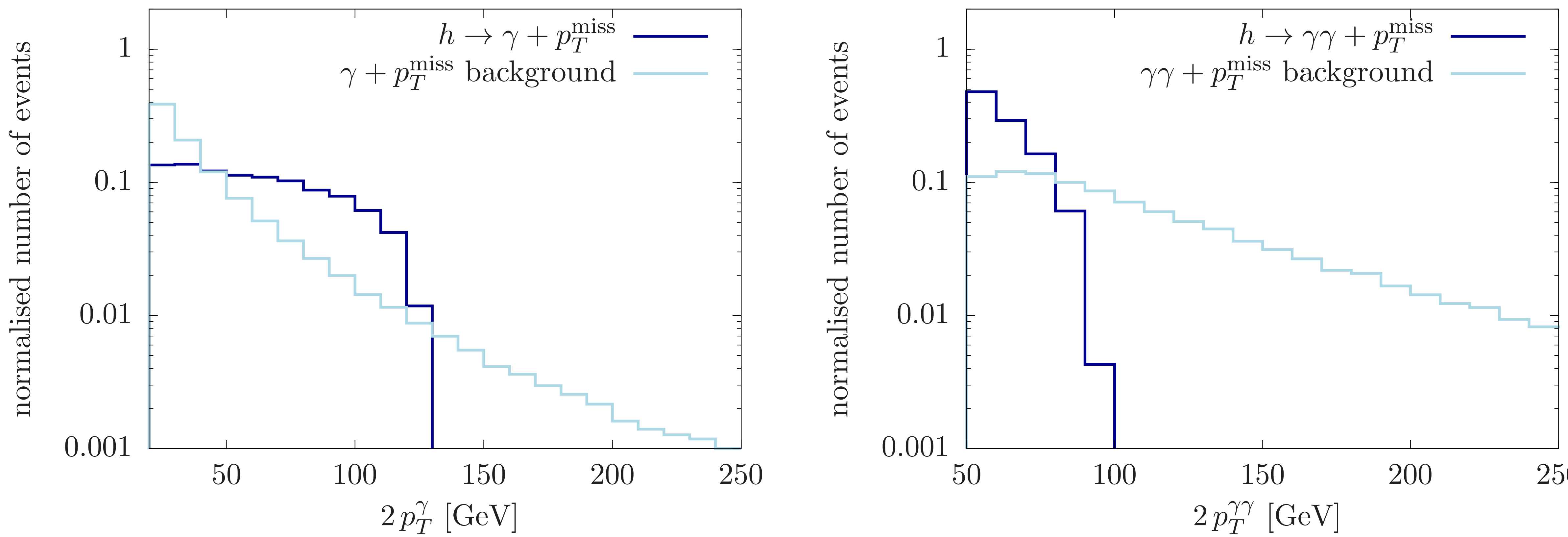
$\mathcal{B}(Z \to \nu\nu\gamma(\gamma)) \lesssim 3\times10^{-6}$ $\Rightarrow$ set $\alpha_{NZ} = \alpha_{HN} = 0$ (for simplicity)

LEP, 90's; PDG, RPP 2018

Higgs searches in h → γ(γ) + inv

Shape analysis: small signal on top of large background

Butterworth, Chala, Englert, Spannowsky, AT, 1909.04665



$$\mathscr{B}(h \to \gamma + p_T^{\rm miss}) \sim 1.2 \times 10^{-4}$$

$$\mathscr{B}(h \to \gamma\gamma + p_T^{\rm miss}) \sim 4.2 \times 10^{-5}$$

@ HL-LHC with $\mathscr{L} = 3$ ab^{-1}

Operator	$\alpha_{\rm max}$ for $\Lambda = 1$ TeV	$\Lambda_{\rm min}$ [TeV] for $\alpha = 1$	Channel
$\mathcal{O}_{LNH}$	4.2×10^{-3}	15	$h \to \gamma + p_T^{\rm miss}$
$\mathcal{O}_{NNH}$	5.3×10^{-4}	1900	$h \to \gamma\gamma + p_T^{\rm miss}$
$\mathcal{O}_{NA}$	0.21	2.2	$h \to \gamma\gamma + p_T^{\rm miss}$

Further probes of NSMEFT / NLEFT

- CEvNS, beta and meson decays
  Bischer and Rodejohann, 1905.08699
  Han, Liao, Liu, Marfatia, 2004.13869 -> also collider constraints
  Li, Ma, Schmidt, 2005.01543, 2007.15408

- Displaced vertices from long-lived sterile neutrinos
  de Vries et al., 2010.07305

- Neutrinoless double beta decay
  Dekens et al., 2002.07182

- Long-range neutrino interactions
  Bolton, Deppisch, Hati, 2004.08328

Conclusions

- If massive neutrinos are Dirac particles, or light sterile Majorana neutrinos exist, SM should be extended with RH neutrino N
- If New Physics exists at $\Lambda > \mathrm{v}$, EFT is the appropriate description
  SMEFT → NSMEFT,   LEFT → NLEFT
- Renormalisation of dim-6 NSMEFT operators at 1 loop
- Matching NSMEFT onto NLEFT at tree level
- Phenomenological consequences of new operators:
  new rare top and Higgs decays to be probed at HL-LHC

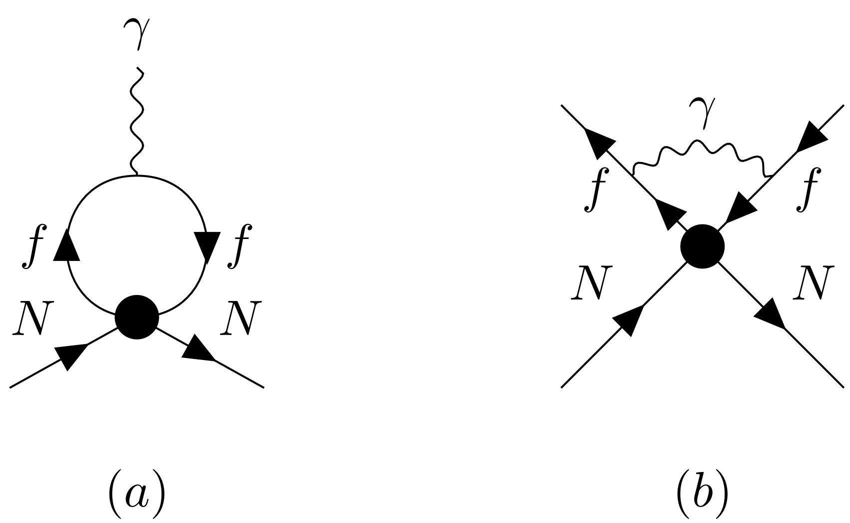
Further directions

- Completing RGEs in NSMEFT and NLEFT taking into account dependence on all Yukawas and full flavour structure
- Matching NSMEFT onto NLEFT at 1 loop
- Phenomenological studies of NSMEFT / NLEFT in different regimes

Backup slides

Running of some operators in NLEFT

Chala and AT, 2001.07732



$$\dot{\alpha} \equiv 16\pi^2\mu\frac{\mathrm{d}\alpha}{\mathrm{d}\mu}$$

$$\dot{\alpha}_{N\gamma} = \frac{4}{3}\left(3q_e^2 + 3N_c q_d^2 + 2N_c q_u^2\right)e^2\alpha_{N\gamma}$$

$$\dot{\alpha}_{\psi N}^{V,RR} = \frac{4}{3}e^2 q_\psi\left[N_c q_u\left(\alpha_{uN}^{V,RR} + \alpha_{uN}^{V,LR}\right) + N_c q_d\left(\alpha_{dN}^{V,RR} + \alpha_{dN}^{V,LR}\right) + q_e\left(\alpha_{eN}^{V,RR} + \alpha_{eN}^{V,LR}\right)\right]$$

$$\dot{\alpha}_{\psi N}^{V,LR} = \frac{4}{3}e^2 q_\psi\left[N_c q_u\left(\alpha_{uN}^{V,RR} + \alpha_{uN}^{V,LR}\right) + N_c q_d\left(\alpha_{dN}^{V,RR} + \alpha_{dN}^{V,LR}\right) + q_e\left(\alpha_{eN}^{V,RR} + \alpha_{eN}^{V,LR}\right)\right]$$

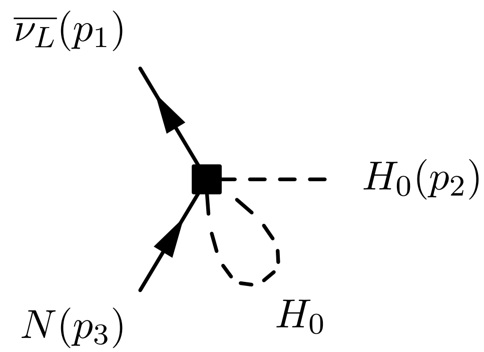
$$\psi = \nu\,,\, N\,,\, e\,,\, u\,,\, d$$

$$\dot{\alpha}_{NN}^{V,RR} = \dot{\alpha}_{\nu N}^{V,LR} = 0$$

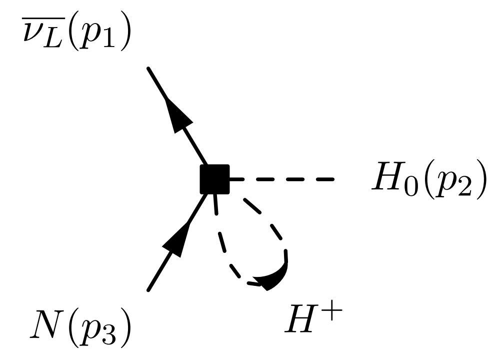
Amplitudes for RGEs in NSMEFT

$\overline{\nu_L} N \to H_0$

Chala and AT, 2006.14596

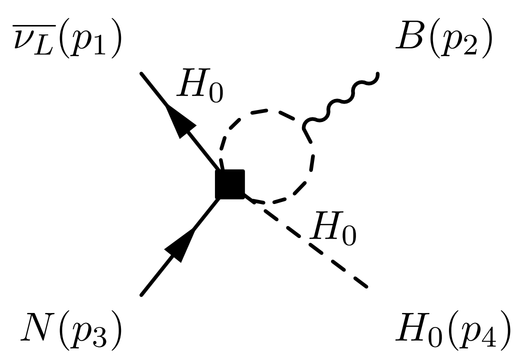


(2)

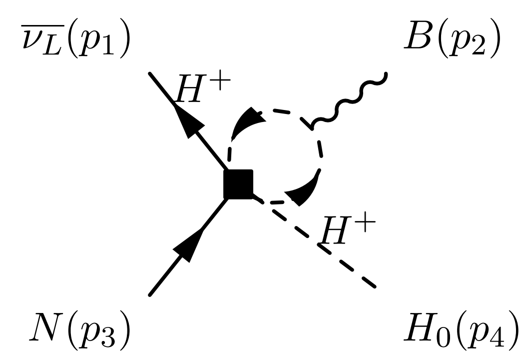


(3)

$\overline{\nu_L} N \to B H_0$

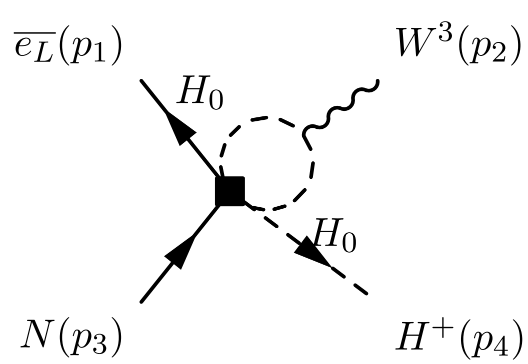


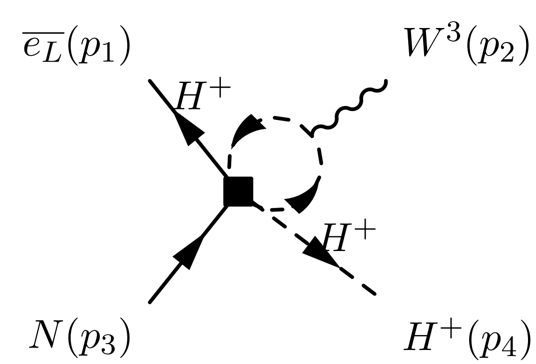
(1)



(2)

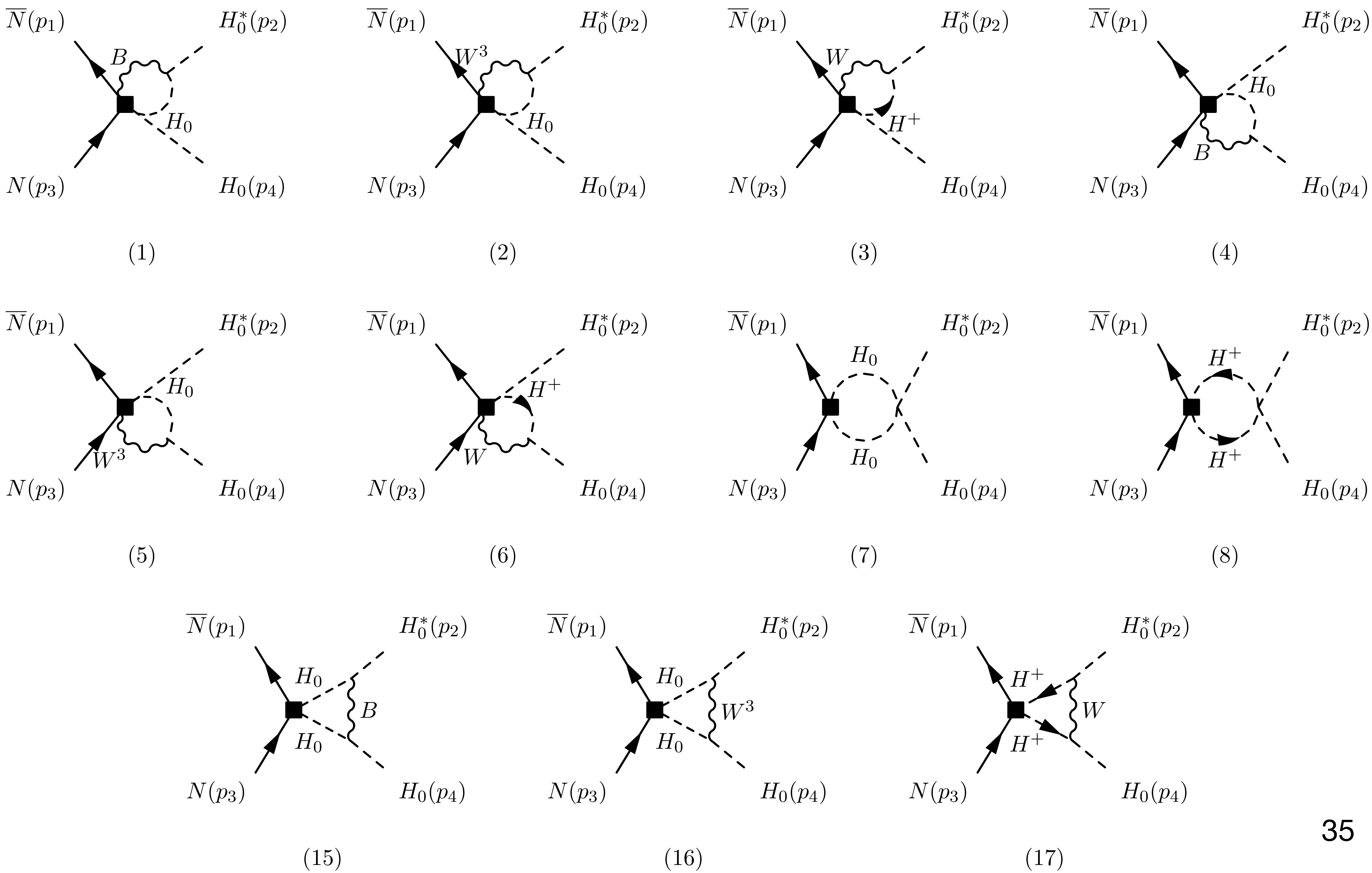
$\overline{e_L} N \to W^3 H^+$





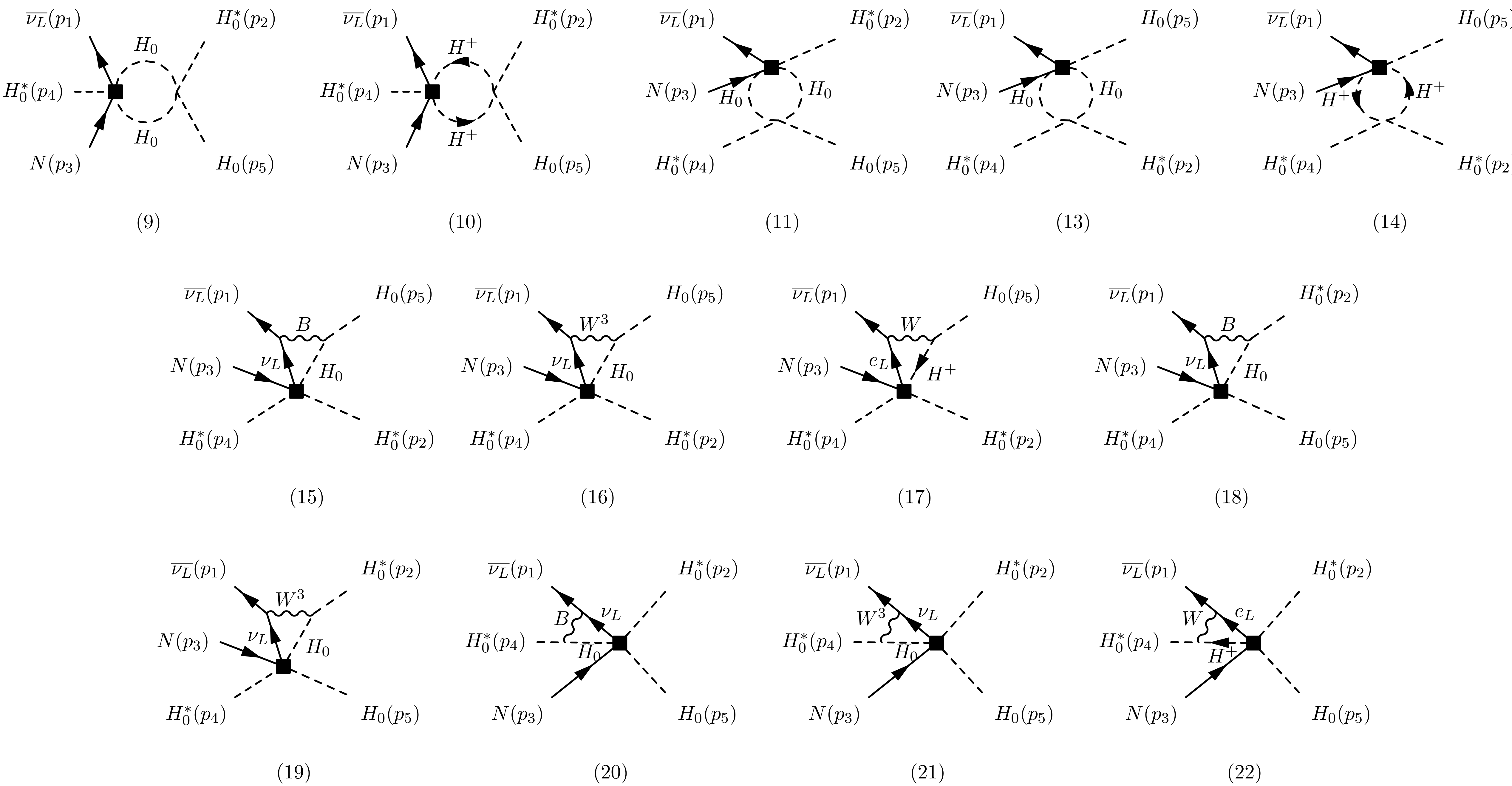
Amplitudes for RGEs in NSMEFT

$\overline{N}N \to H_0^* H_0$



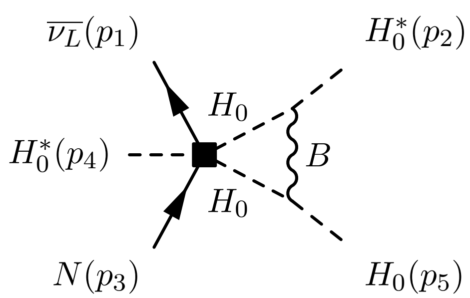
Amplitudes for RGEs in NSMEFT

$\overline{\nu_L} N H_0^* \rightarrow H_0^* H_0$ (I)

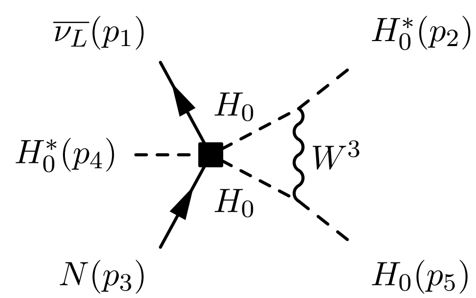


Amplitudes for RGEs in NSMEFT

$\overline{\nu_L} N H_0^* \to H_0^* H_0$ (II)



(24)



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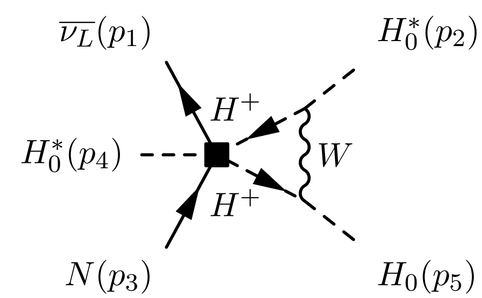

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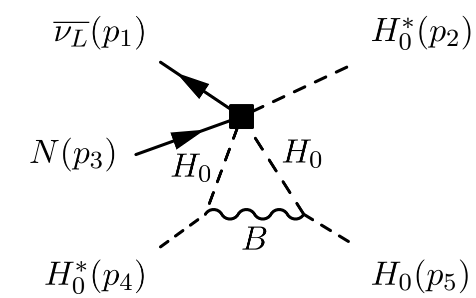

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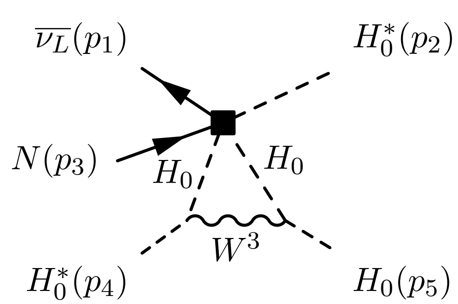

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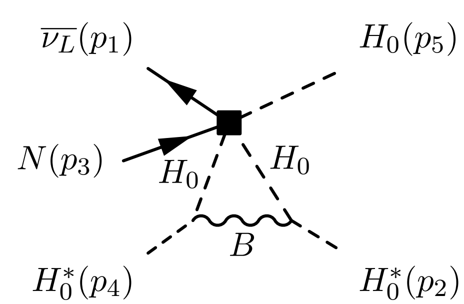

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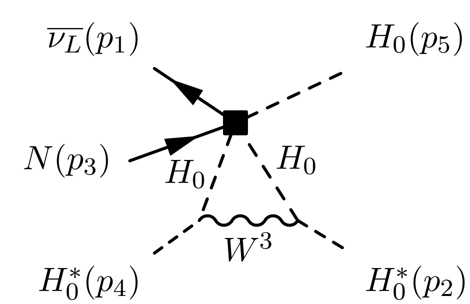

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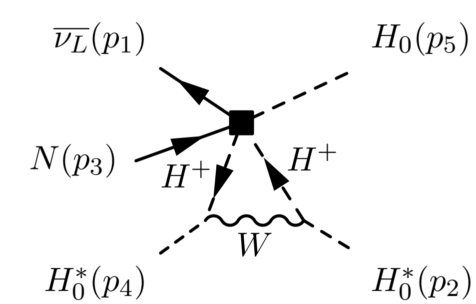
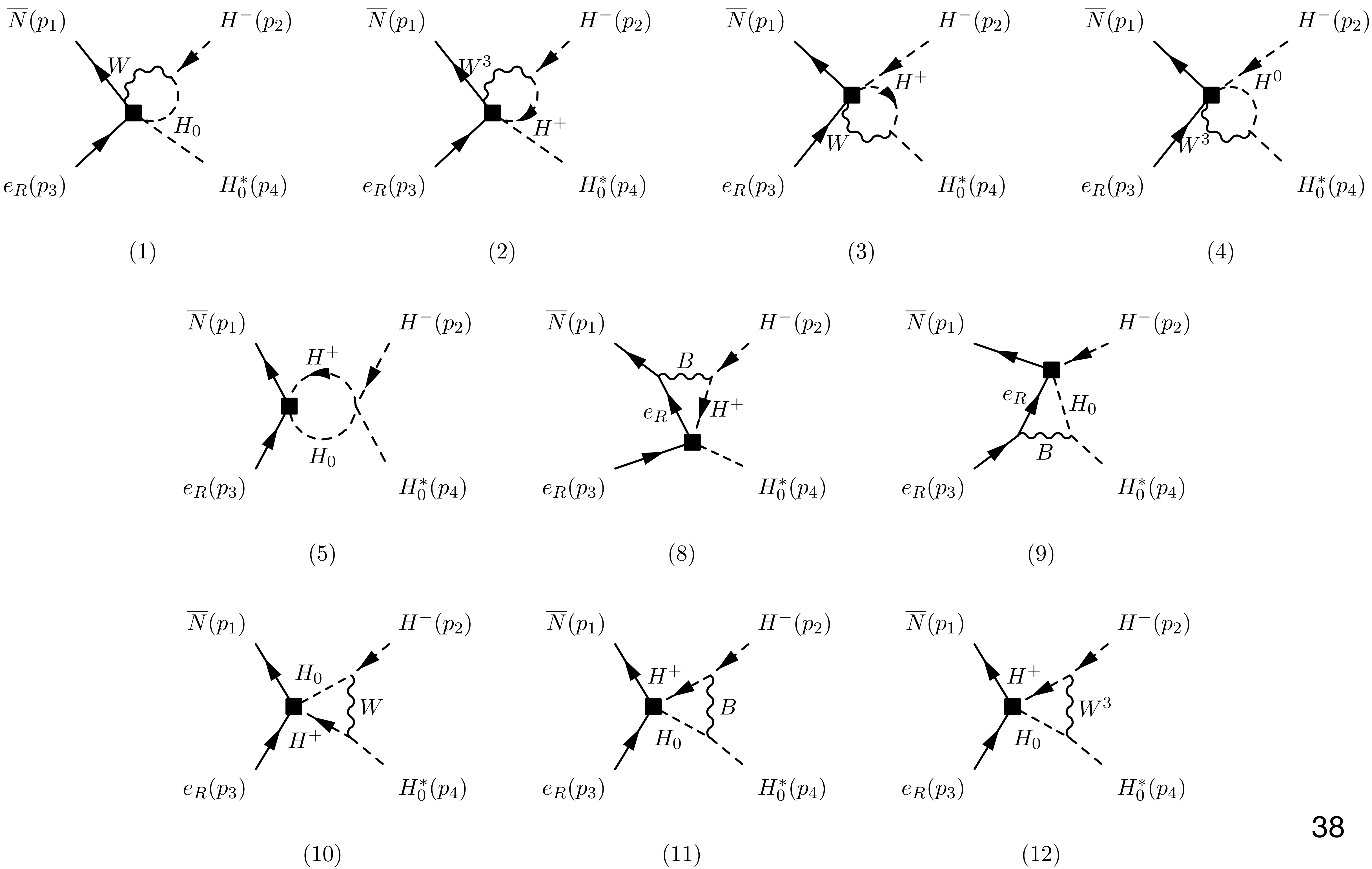


(32)

Amplitudes for RGEs in NSMEFT

$\overline{N} e_R \to H^- H_0^*$



UV complete model

Chala and AT, 2001.07732

SM + N + $X_E \sim (\mathbf{1},\mathbf{2})_{1/2}$ + $X_N \sim (\mathbf{1},\mathbf{1})_{1}$ + $\varphi \sim (\mathbf{1},\mathbf{1})_{-1}$

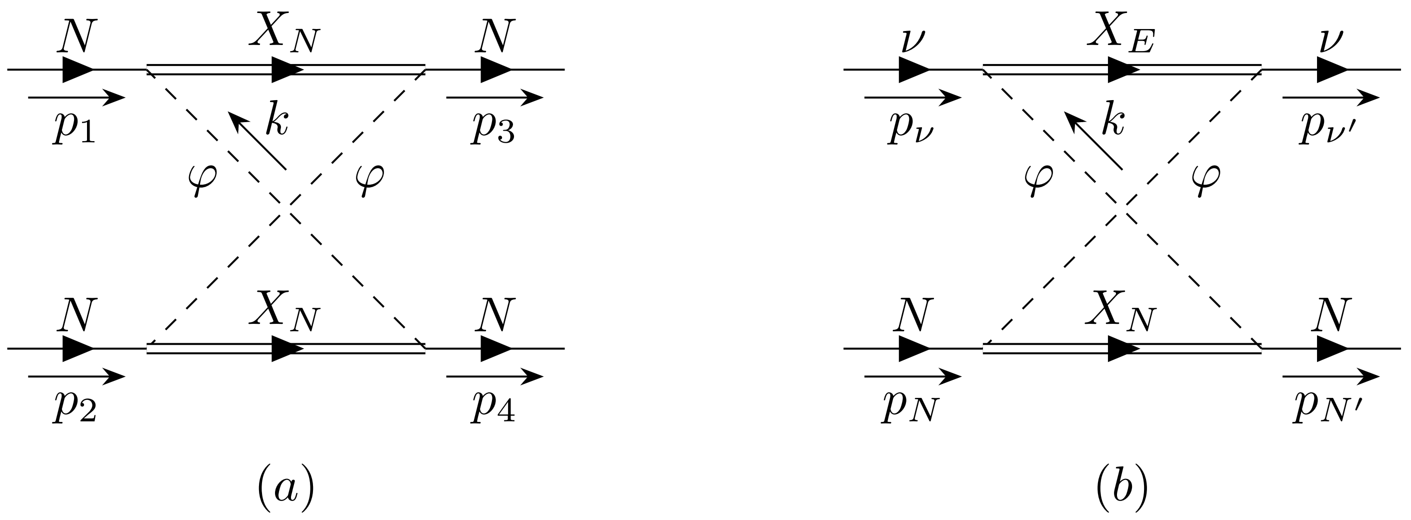
$$\mathcal{L} = \mathcal{L}_{SM+N} + \mathcal{L}_{\text{heavy}}$$

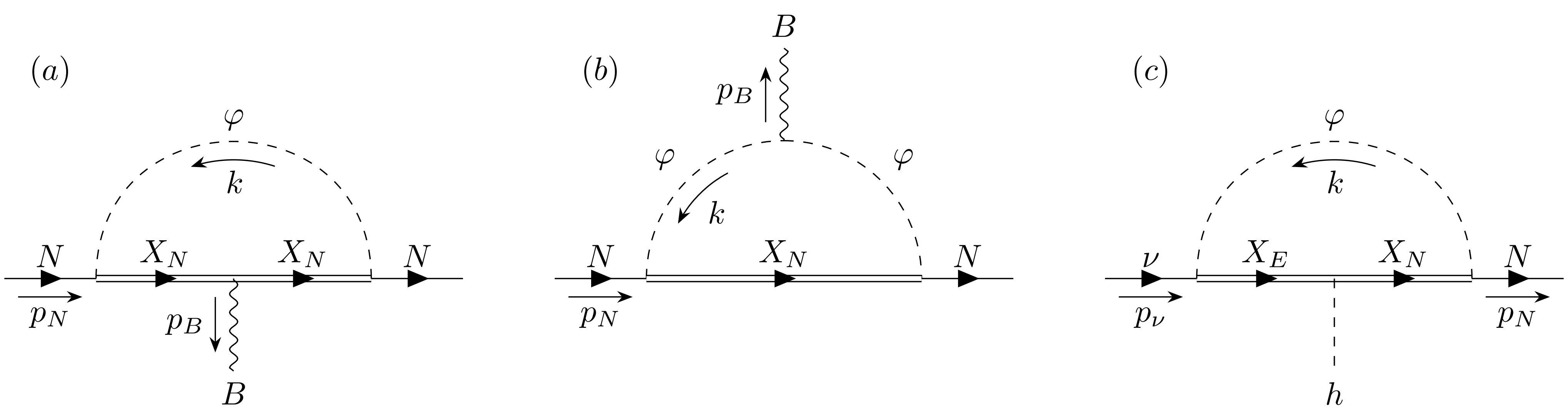
$$\begin{aligned}
\mathcal{L}_{SM+N} = & -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& + (D_\mu H)^\dagger (D^\mu H) + \mu_H^2 H^\dagger H - \frac{1}{2}\lambda_H \left(H^\dagger H\right)^2 \\
& + i\left(\overline{Q}\not{D}Q + \overline{u}\not{D}u + \overline{d}\not{D}d + \overline{L}\not{D}L + \overline{e}\not{D}e + \overline{N}\not{D}N\right) \\
& - \left[\frac{1}{2}m_N\overline{N^c}N + \overline{Q}Y_d H d + \overline{Q}Y_u\tilde{H}u + \overline{L}Y_e H e + \overline{L}Y_N\tilde{H}N + \text{h.c.}\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\text{heavy}} = & \overline{X_E}\left(i\not{D} - M_{X_E}\right)X_E + \overline{X_N}\left(i\not{D} - M_{X_N}\right)X_N \\
& + (D_\mu\varphi)^*(D^\mu\varphi) - M_\varphi^2\varphi^*\varphi - \lambda_{\varphi\varphi}\left(\varphi^*\varphi\right)^2 - \lambda_{\varphi H}\left(\varphi^*\varphi\right)\left(H^\dagger H\right) \\
& + \left[g_X\overline{X_E}\tilde{H}X_N + g_L\overline{X_E}\varphi^*L + g_N\overline{X_N}\varphi^*N + \text{h.c.}\right].
\end{aligned}$$

UV complete model

Matching at 1 loop

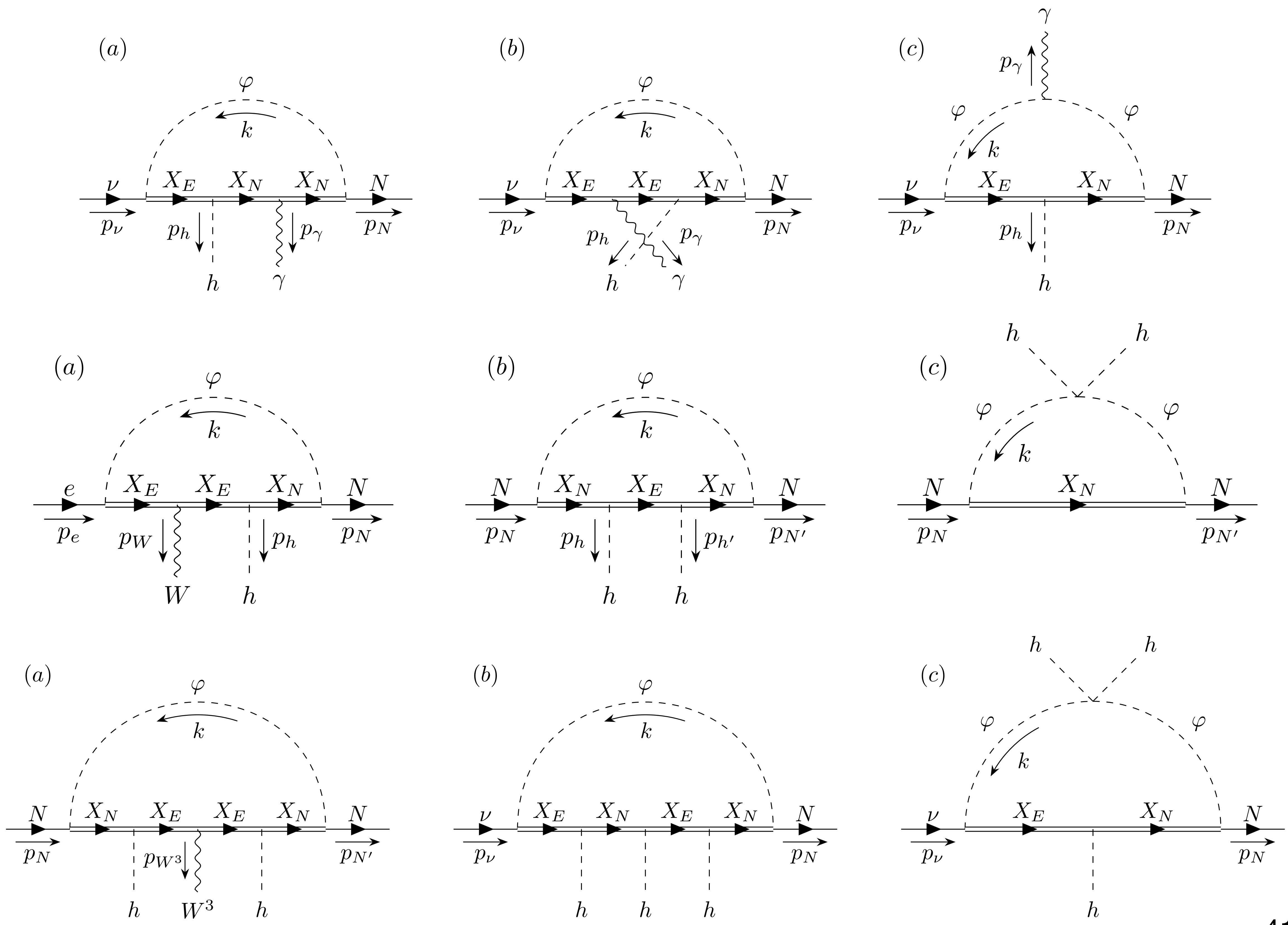




$$
i\mathcal{M}_{UV} = \frac{i g' g_N^2}{96\pi^2 M^2}\overline{u}(p_N - p_B) P_L \Big[\gamma^\mu \left(p_B^2 - p_B p_N + \not{p}_B \not{p}_N \right) - p_B^\mu \not{p}_B - p_B^\mu \not{p}_N + p_N^\mu \not{p}_B \Big] u(p_N) \epsilon^*_\mu(p_B)
$$

$$
i\mathcal{M}_{EFT} = \frac{i}{\Lambda^2}\overline{u}(p_N - p_B) P_L \Big[\gamma^\mu \left(\alpha^3_{DN} p_B^2 - 2\alpha^2_{DN} p_B p_N + 2\alpha^2_{DN} \not{p}_B \not{p}_N \right) - \alpha^3_{DN} p_B^\mu \not{p}_B - 2\alpha^2_{DN} p_B^\mu \not{p}_N + 2\alpha^2_{DN} p_N^\mu \not{p}_B \Big] u(p_N) \epsilon^*_\mu(p_B)
$$

UV complete model



UV complete model

10 Wilson coefficients in terms of 4 couplings of the UV model:

$$\frac{\alpha_{NB}}{\Lambda^2} = \frac{e g_L g_X g_N}{256\pi^2 c_W M^2}\,, \qquad \frac{\alpha_{NW}}{\Lambda^2} = \frac{e g_L g_X g_N}{768\pi^2 s_W M^2}\,,$$

$$\frac{\alpha_{HN}}{\Lambda^2} = \frac{g_N^2(e^2 - 4c_W^2 g_X^2)}{384\pi^2 c_W^2 M^2}\,, \qquad \frac{\alpha_{LNH}}{\Lambda^2} = -\frac{g_L g_X g_N}{192\pi^2 M^2}\left[\frac{m_h^2}{v^2} + 2(g_X^2 - \lambda_{\varphi H})\right]\,,$$

$$\frac{\alpha_{LN}}{\Lambda^2} = -\frac{g_N^2(e^2 + 2c_W^2 g_L^2)}{384\pi^2 c_W^2 M^2}\,, \qquad \frac{\alpha_{eN}}{\Lambda^2} = -\frac{e^2 g_N^2}{192\pi^2 c_W^2 M^2}\,,$$

$$\frac{\alpha_{NN}}{\Lambda^2} = -\frac{g_N^4}{384\pi^2 M^2}\,, \qquad \frac{\alpha_{QN}}{\Lambda^2} = \frac{e^2 g_N^2}{1152\pi^2 c_W^2 M^2}\,,$$

$$\frac{\alpha_{uN}}{\Lambda^2} = \frac{e^2 g_N^2}{288\pi^2 c_W^2 M^2}\,, \qquad \frac{\alpha_{dN}}{\Lambda^2} = -\frac{e^2 g_N^2}{576\pi^2 c_W^2 M^2}\,.$$

UV complete model

Prospect on α_{LNH} from the $h \to \gamma + p_T^{\text{miss}}$ analysis