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The NSMEFT and its phenomenology

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New-ν Physics: From Colliders to Cosmology

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Outline

1. Motivation for right-handed (RH) neutrinos/heavy neutral leptons (HNLs)
2. NSMEFT: the effective field theory of the Standard Model extended with HNLs
3. Stable RH neutrinos
4. Promptly-decaying HNLs
5. Long-lived HNLs
6. Conclusions

Motivation: 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 $\Lambda \gg v$
  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 that (at least two) neutrinos have mass

Minimal renormalisable Lagrangian to accomodate neutrino masses:

$$\mathscr{L}_{\mathrm{SM}+N} = \mathscr{L}_{\mathrm{SM}} + i\,\overline{N_R}\,\partial\!\!\!/\,N_R - \left[\bar{L}\tilde{H}Y_N N_R + \text{h.c.}\right]$$

N_R is *right-handed (RH) neutrino*

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

$$Y_N \sim 10^{-13} \quad \Rightarrow \quad m_\nu = Y_N \mathrm{v}/\sqrt{2} \sim 0.01 \text{ eV}$$

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

Is LN a fundamental symmetry?

Motivation: neutrino masses

If LN is violated, then

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

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

N is *heavy neutral lepton (HNL)*

Type I seesaw mechanism

$$m_D = Y_N \mathrm{v}/\sqrt{2} \ll M \quad \Rightarrow \quad m_\nu = -m_D M^{-1} m_D^T$$

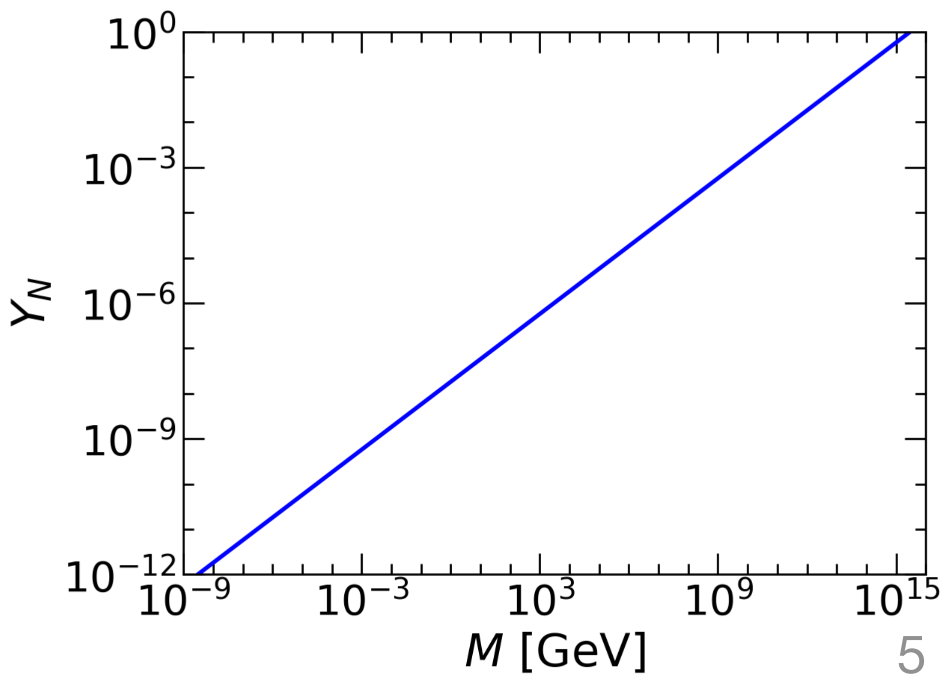
$$Y_N \sim 1\,, \quad M \sim 10^{15}\ \text{GeV} \quad \Rightarrow \quad m_\nu \sim 0.01\ \text{eV}$$

For $Y_N \ll 1$, huge range of values for M

Active-heavy neutrino mixing

$$V_{\alpha N}^2 \sim \left(\frac{m_D}{M}\right)^2 \sim \frac{m_\nu}{M}$$

$$V_{\alpha N}^2 \sim 10^{-11} \div 10^{-14} \quad \text{for} \quad M \sim 1 \div 10^3\ \text{GeV}$$



Motivation: neutrino masses

$\Big($ 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 $\Big)$

In what follows, we will assume

- lepton number conservation (LNC)

or

- lepton number violation (LNV) by $M \lesssim \mathrm{v}$
- new heavy physics exists at scale $\Lambda \gg \mathrm{v}$

Under these assumptions, N_R should be present in the EFT
$\Rightarrow$ **NSMEFT** (also called νSMEFT, N_RSMEFT, SMNEFT)

NSMEFT: dim-5 operators

The effective Lagrangian

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

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

Operators of $d = 5$ (all violate LN)

$\mathscr{O}_{LH} = \left(\overline{L}\tilde{H}\right)\left(\tilde{H}^T L^c\right)$ Weinberg, PRL **43** (1979) 1566

$\mathscr{O}_{NNH} = \left(\overline{N_R^c} N_R\right)\left(H^\dagger H\right)$ Aguila, Bar-Shalom, Soni, Wudka, 0806.0876

$\mathscr{O}_{NNB} = \left(\overline{N_R^c}\sigma^{\mu\nu} N_R\right) B_{\mu\nu}$ Aparici, Kim, Santamaria, Wudka, 0904.3244

$\mathscr{O}_{NNB}$ vanishes identically for one generation of N_R

NSMEFT: dim-6 operators

Aguila, Bar-Shalom, Soni, Wudka, 0806.0876
Liao and Ma, 1612.04527

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

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

4-fermions 11 (16)

RRRR	$\mathcal{O}_{NN} = (\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma^\mu N_R)$	
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2 (4)

$\cancel{L}$	$\mathcal{O}_{NNNN} = (\overline{N_R^c}N_R)(\overline{N_R^c}N_R)$
$\cancel{L}$ & $\cancel{B}$	$\mathcal{O}_{QQdN} = (\overline{Q^c}\epsilon Q)(\overline{d_R^c}N_R)$
	$\mathcal{O}_{uddN} = (\overline{u_R^c}d_R)(\overline{d_R^c}N_R)$

$n_f = 1\ [3]:\ \ 29\ [1614]$
operators including h.c.

Disclaimer

Many works on theoretical aspects and phenomenology of the NSMEFT, especially, over last few years (impossible to cover in 20 mins…)

Heavy Majorana Neutrinos in the Effective Lagrangian Description: Application to Hadron Colliders

Francisco del Aguila (Granada U., Theor. Phys. Astrophys. and CAFPE, Granada), Shaouly Bar-Shalom (Technion and UC, Irvine), Amarjit Soni (Brookhaven), Jose Wudka (Granada U., Theor. Phys. Astrophys. and CAFPE, Granada and UC, Riverside)

Jun, 2008

5 pages

Published in: *Phys.Lett.B* 670 (2009) 399-402

e-Print: 0806.0876 [hep-ph]

DOI: 10.1016/j.physletb.2008.11.031

Report number: UG-FT-230-08, CAFPE-100-08, UCI-TR-2008-21, BNL-HET-08-14

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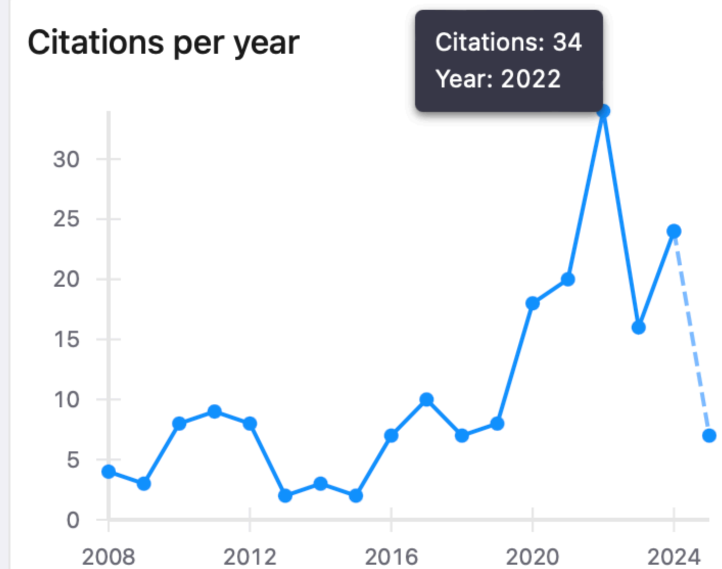
pdf cite claim reference search 190 citations



I will present a selection of results based mostly on my works

Apologies for missing your works

4-fermions and (almost) stable N

Dirac $\nu = (\nu_L, N_R)^T$ or Majorana $N = (N_R^c, N_R)^T$ with $m_N \lesssim 0.1$ GeV

Alcaide, Banerjee, Chala, **AT**, 1905.11375

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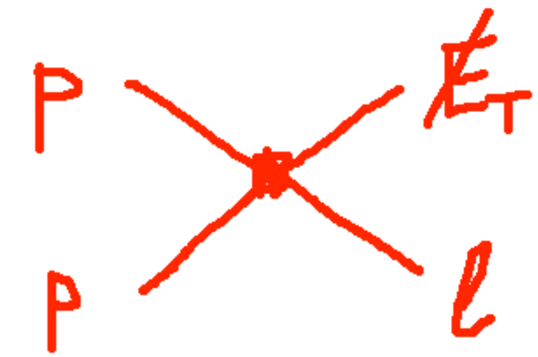
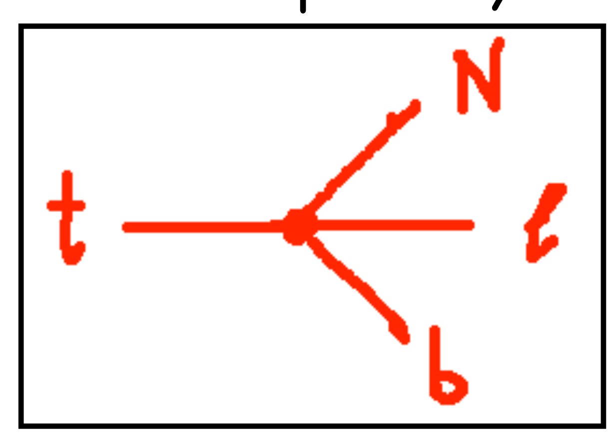


New top decay



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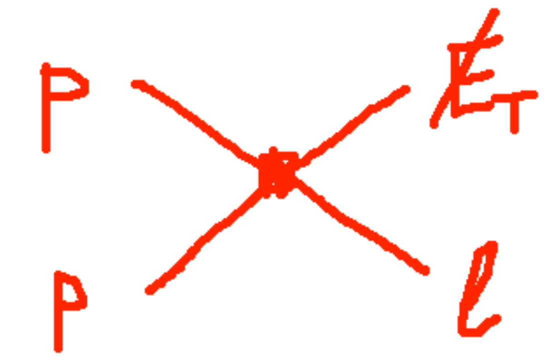

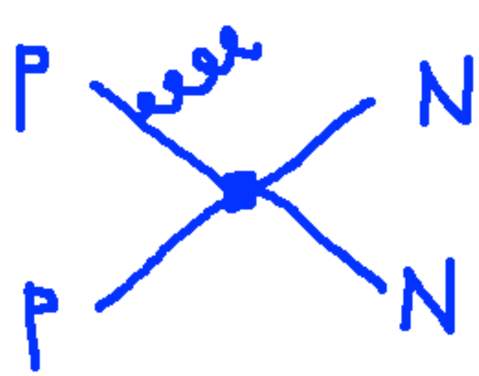

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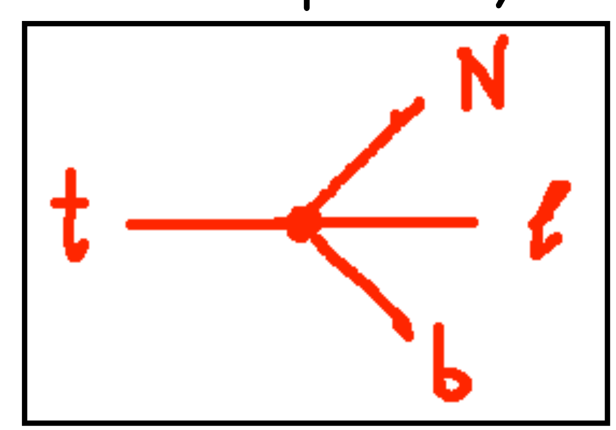

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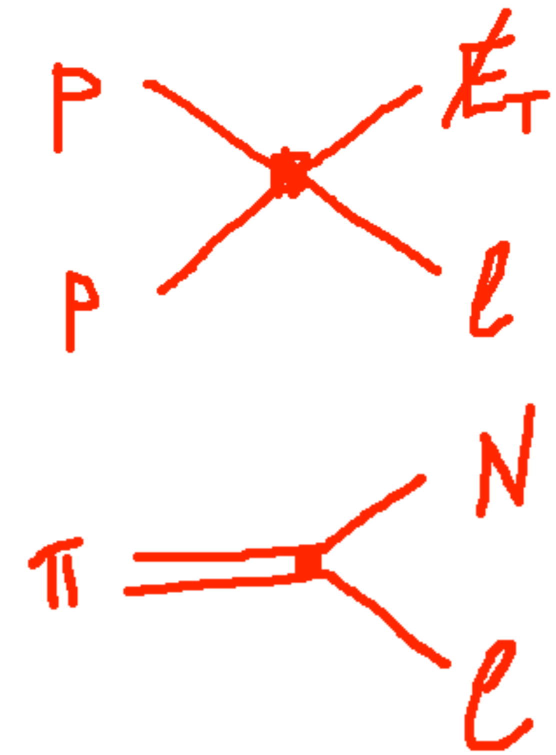

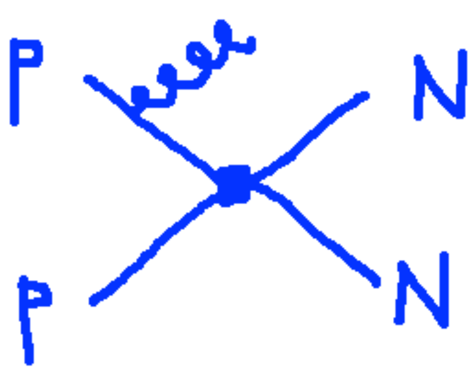

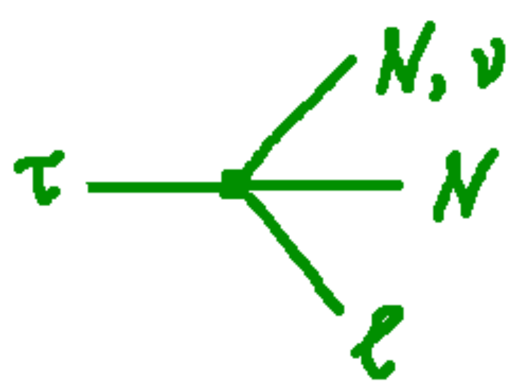

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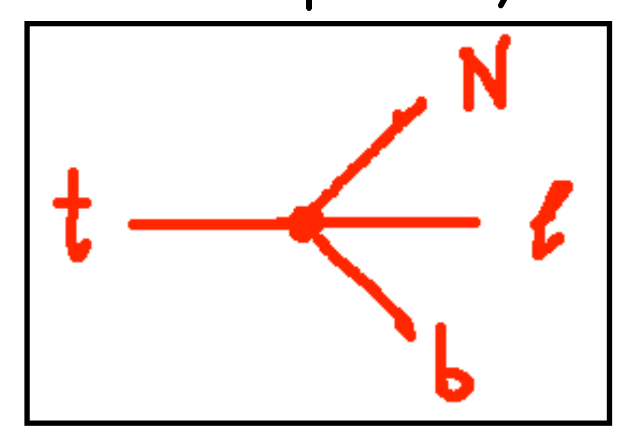
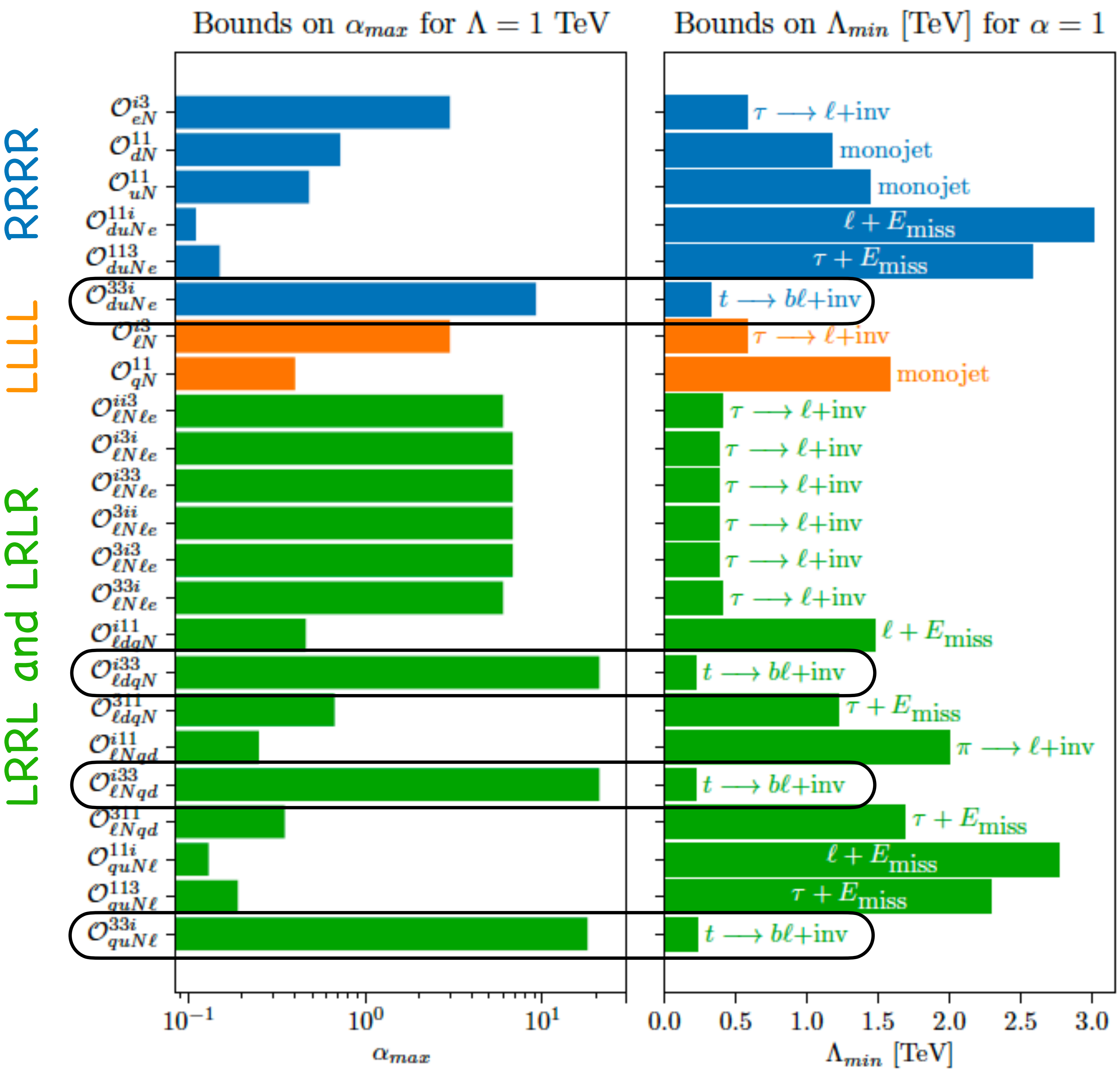


4-fermions and (almost) stable N



Alcaide, Banerjee, Chala, **AT**, 1905.11375

Figure from J. Alcaide's PhD thesis

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

ATLAS, 1706.04786

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

CMS, 1712.02345

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

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

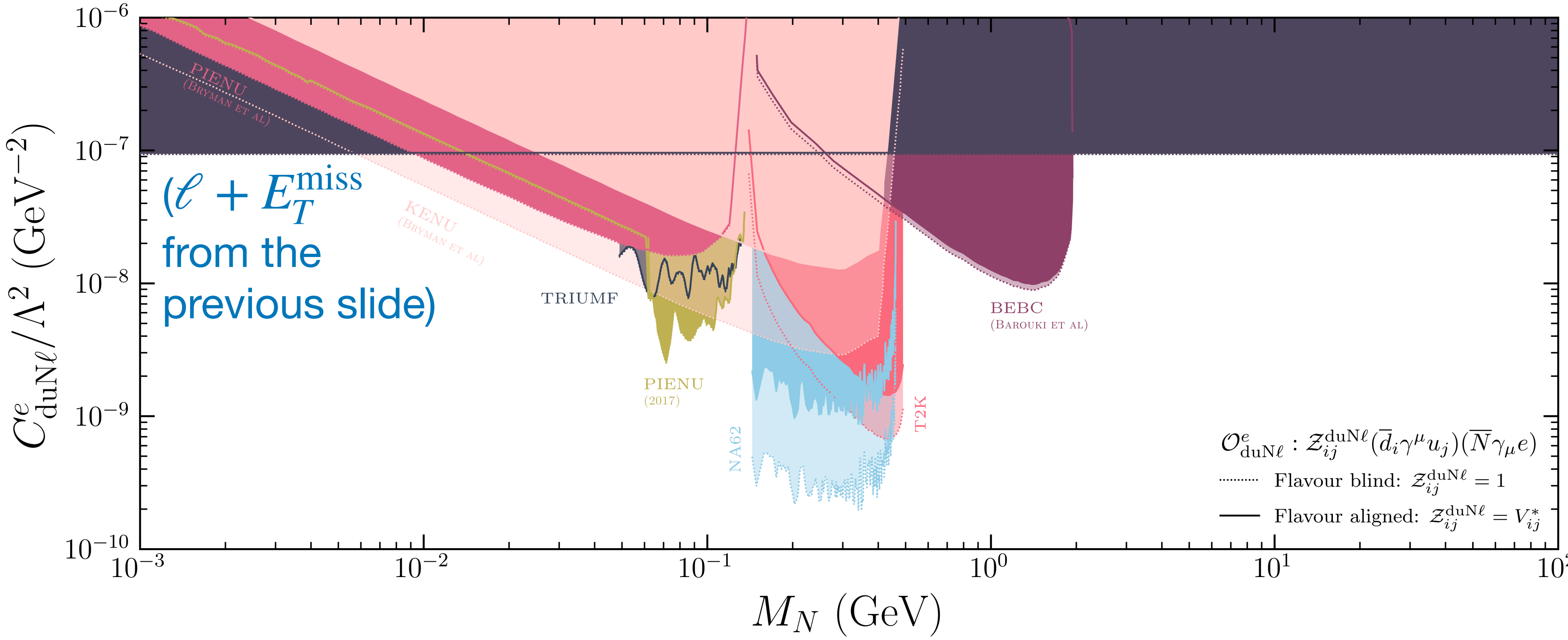
PDG, RPP 2018

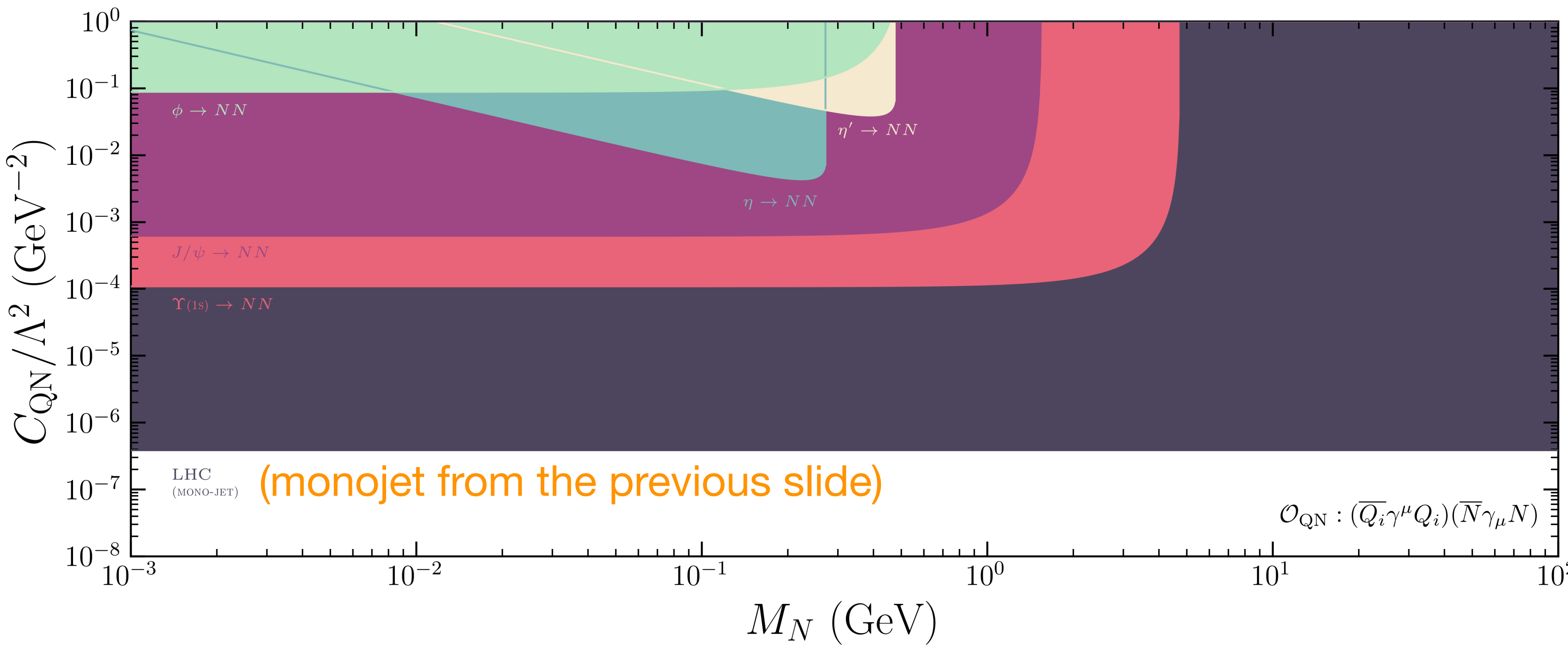
$t \to b\ell + {\rm inv}$ @ HL-LHC

Alcaide, Banerjee, Chala, **AT**, 1905.11375

Recast of existing limits

Fernandez-Martinez et al., 2304.06772 [https://github.com/mhostert/Heavy-Neutrino-Limits]





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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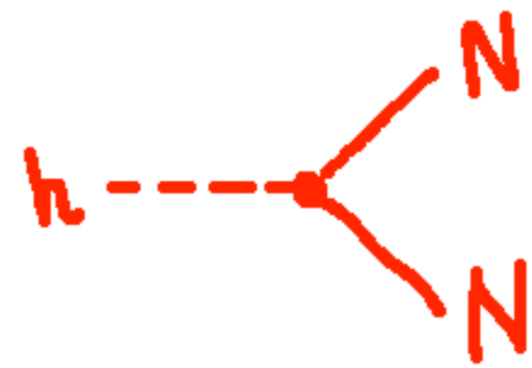

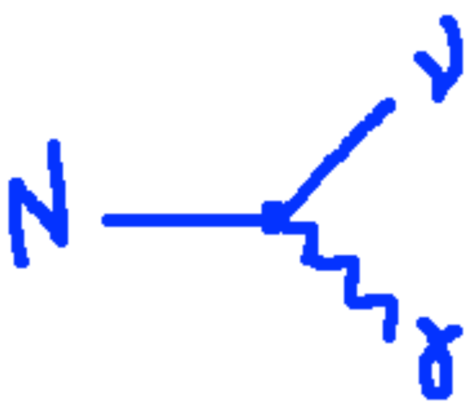

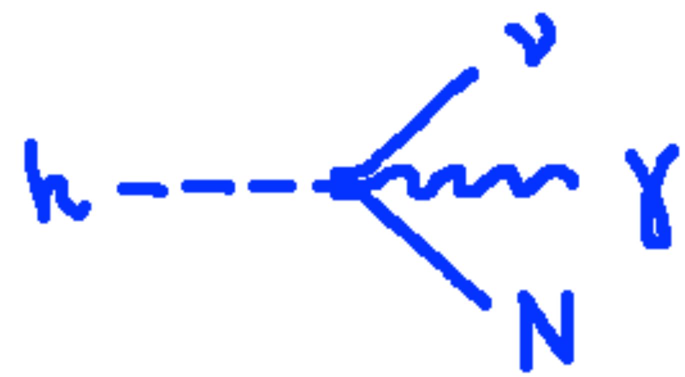

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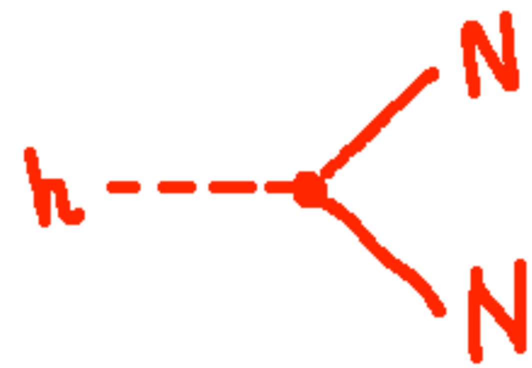

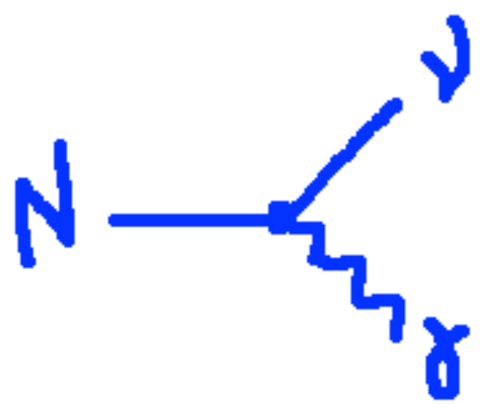

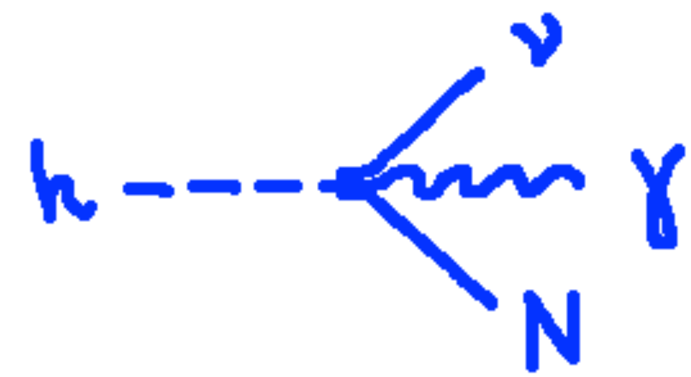

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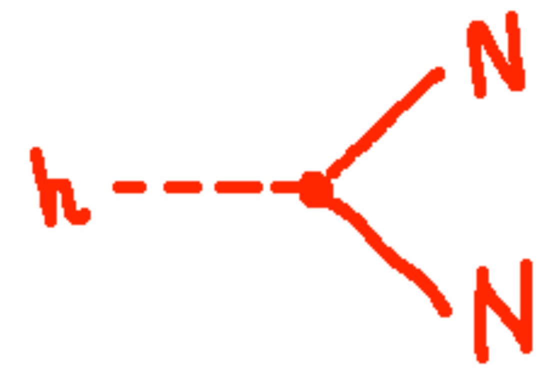

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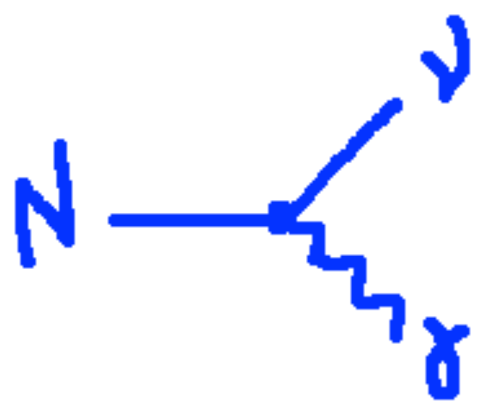
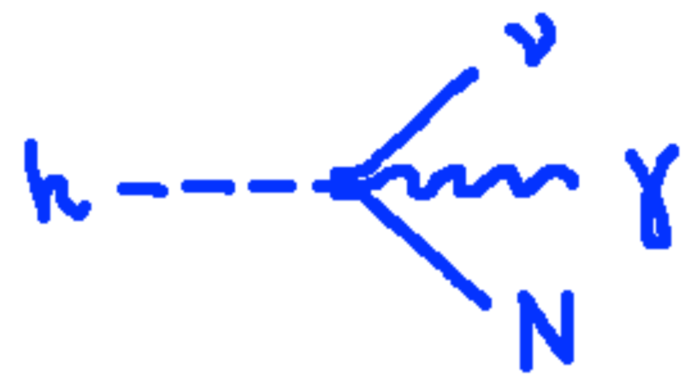
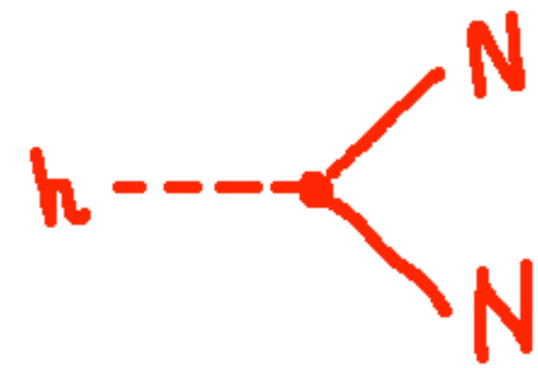


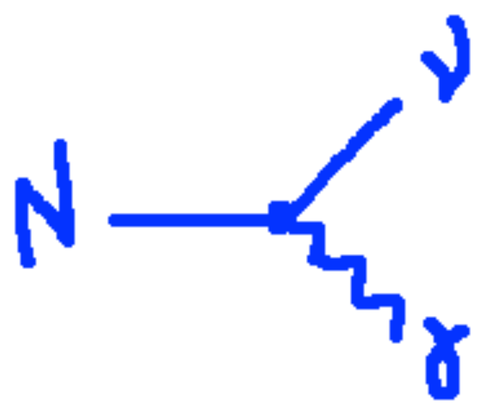


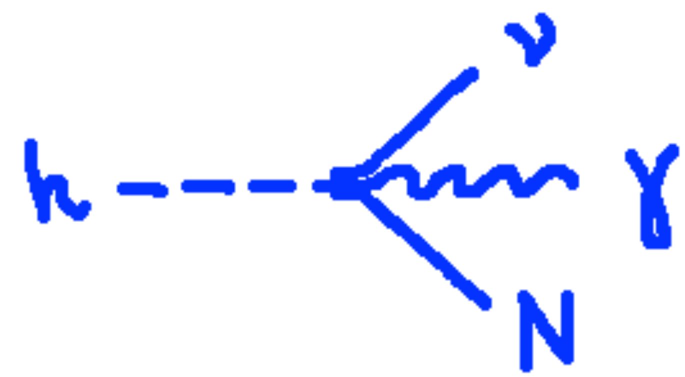
Higgs-N operators

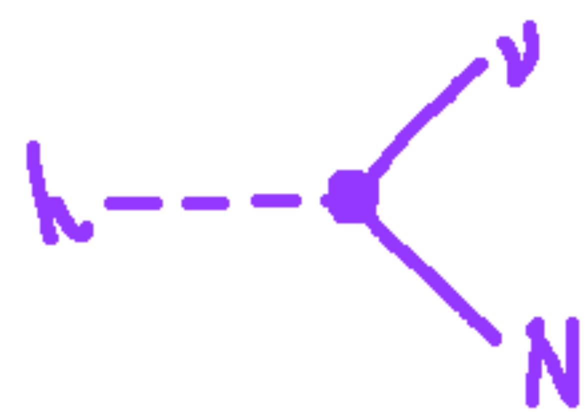
$$\mathcal{O}_{NNH} = \left(\overline{N^c} N\right)\left(H^\dagger H\right)$$

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



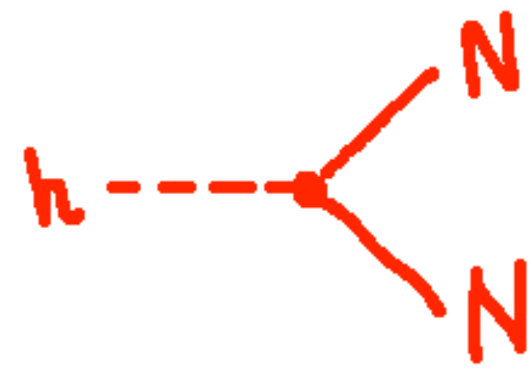




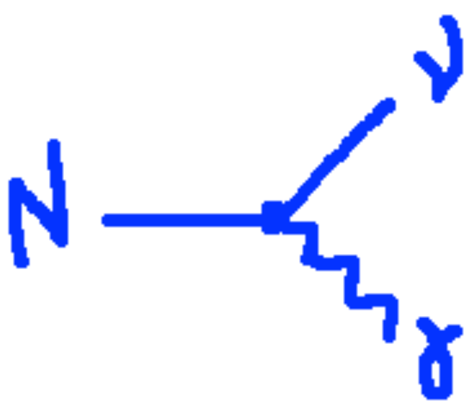


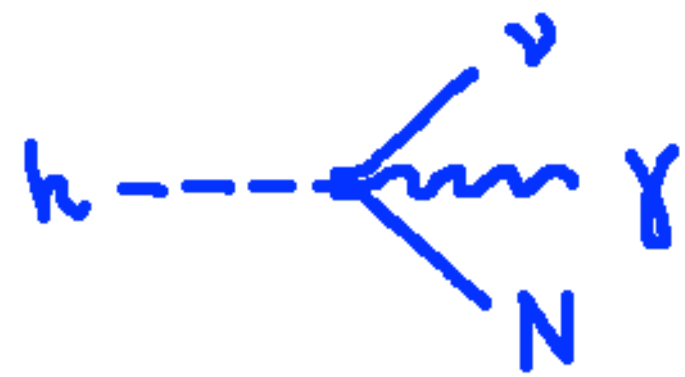
Higgs-N operators

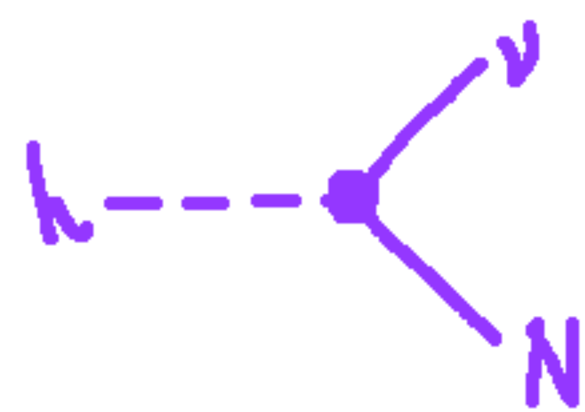
$$\boxed{\mathcal{O}_{NNH} = \left(\overline{N^c} N\right)\left(H^\dagger H\right)}$$



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







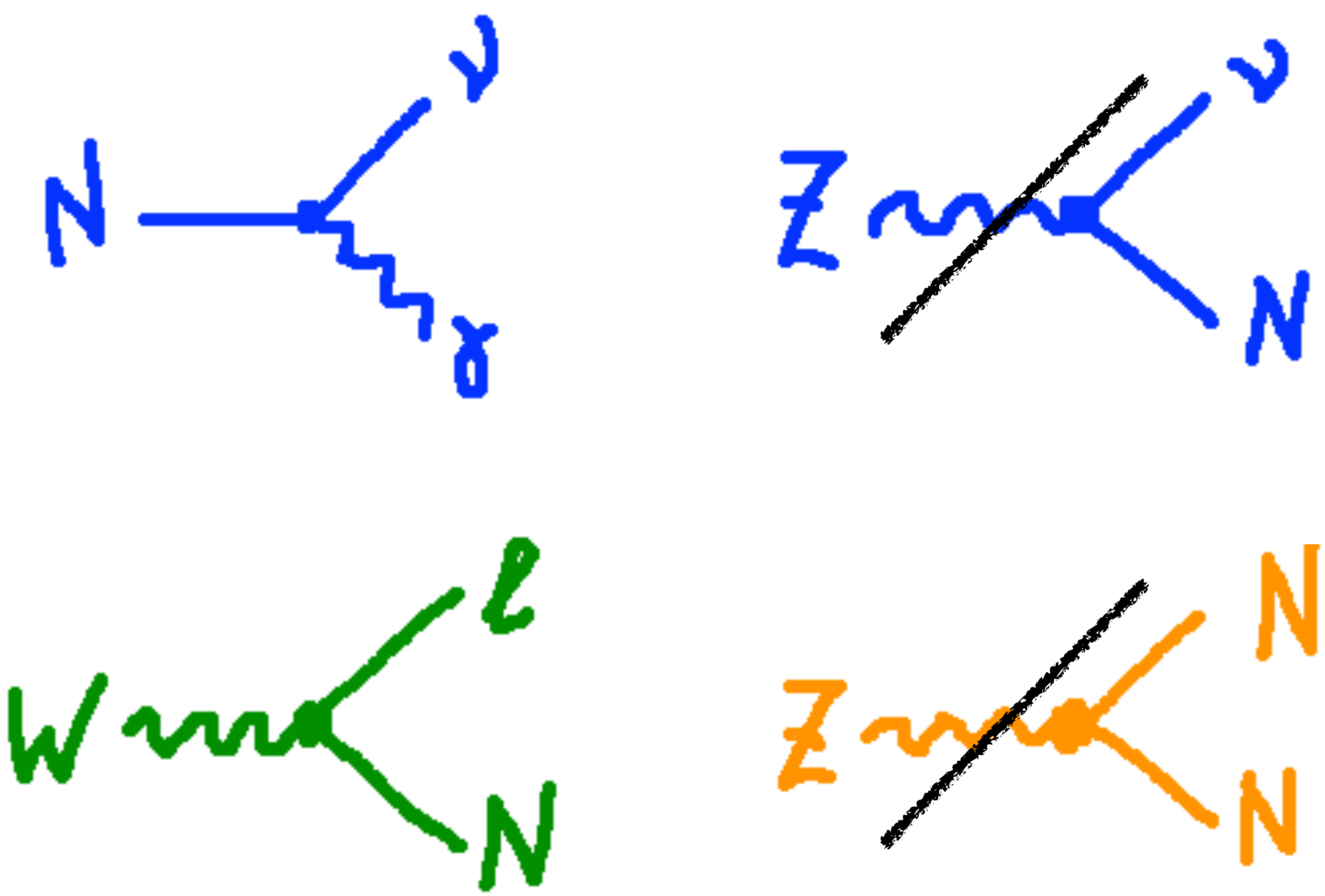
$\mathscr{B}(Z \to \nu\nu\gamma(\gamma)) \lesssim 3 \times 10^{-6} \quad \Rightarrow \quad$ set $\quad \alpha_{NZ} = \alpha_{HN} = 0 \quad$ (for simplicity)

LEP, 90's; PDG, RPP 2018

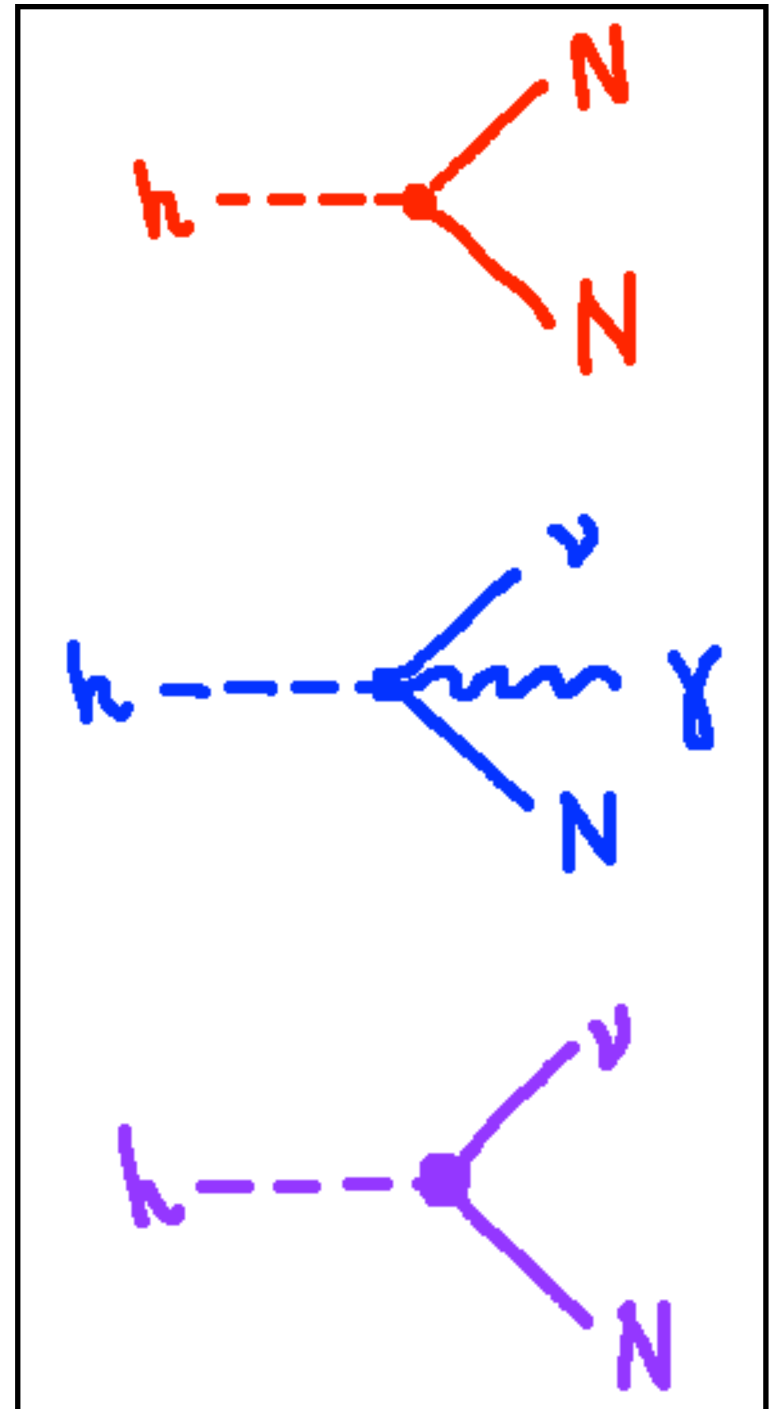
Higgs-N operators

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

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



New Higgs decays



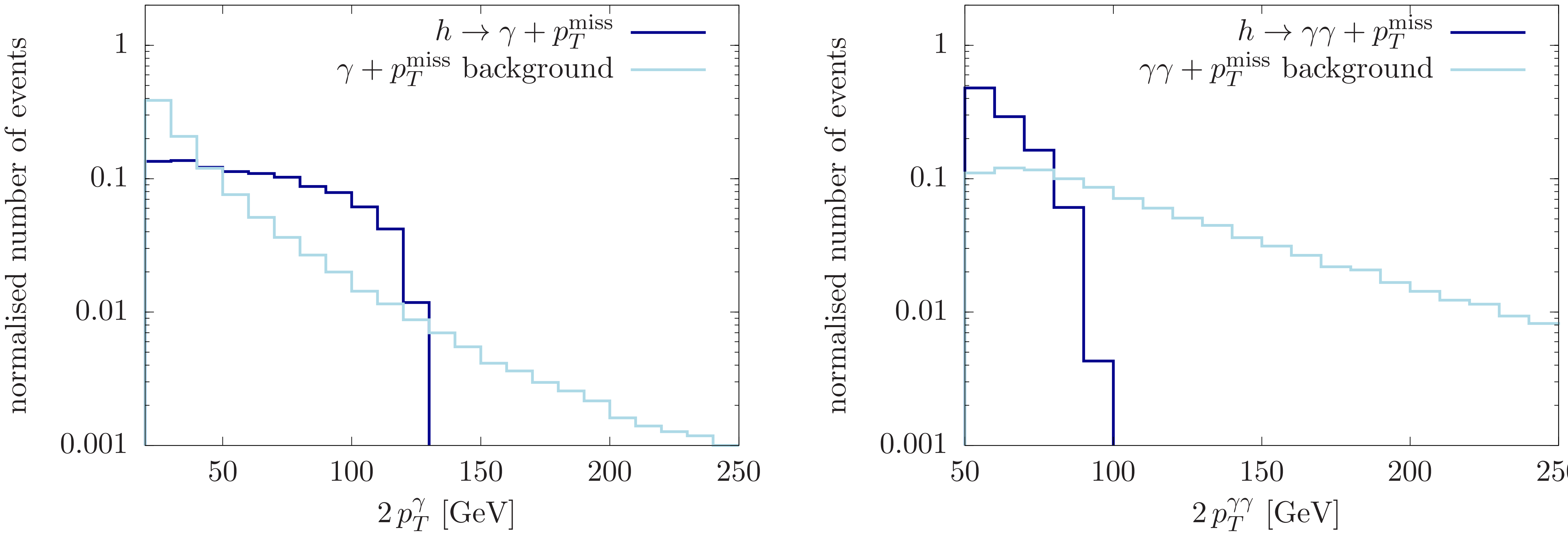
$\mathscr{B}(Z \to \nu\nu\gamma(\gamma)) \lesssim 3 \times 10^{-6}$ $\Rightarrow$ set $\alpha_{NZ} = \alpha_{HN} = 0$ (for simplicity)

LEP, 90's; PDG, RPP 2018

Higgs searches in $h \to \gamma(\gamma)$ + inv

Shape analysis: small signal on top of large background

Butterworth, Chala, Englert, Spannowsky, **AT**, 1909.04665



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

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

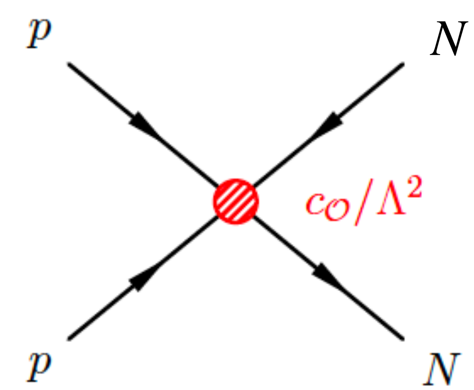
@ HL-LHC with $\mathscr{L} = 3$ ab^{-1}

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	$h \to \gamma\gamma + p_T^{\rm miss}$

4-fermion pair-N operators

Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)\,(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)\,(\overline{N_R}\gamma_\mu N_R)$	9	81

- HNLs are pair produced via pair-N_R operators



Examples of UV completions

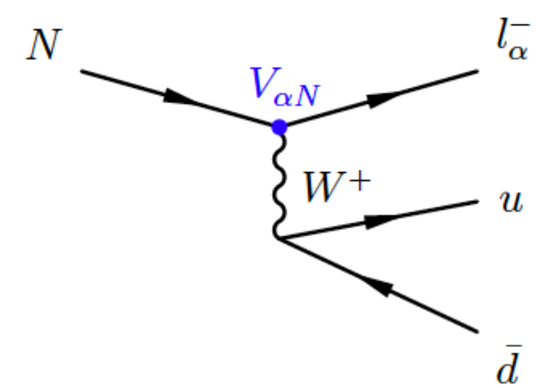
LQ state	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Coupling	Operator
S_d	**3**	**1**	$-1/3$	g_{dN}	$\mathcal{O}_{dN}$
S_u	**3**	**1**	$2/3$	g_{uN}	$\mathcal{O}_{uN}$
S_Q	**3**	**2**	$1/6$	g_{QN}	$\mathcal{O}_{QN}$

$$\mathscr{L}_{S_d} = g_{dN}\overline{d_R}N_R^c S_d + g_{ue}\overline{u_R}e_R^c S_d + g_{QL}\overline{Q}\epsilon L^c S_d + \text{h.c.}$$

$$\mathscr{L}_{S_u} = g_{uN}\overline{u_R}N_R^c S_u + \text{h.c.}$$

$$\mathscr{L}_{S_Q} = g_{QN}\overline{Q}N_R S_Q + g_{dL}\overline{d_R}L\epsilon S_Q + \text{h.c.}$$

- Lightest HNL cannot decay via these operators; it decays via mixing



$$\frac{c_{qN}}{\Lambda^2} = \frac{g_{qN}^2}{2m_{S_q}^2}, \qquad q = d, u, Q$$

Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

4-fermion pair-N operators

Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)\,(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)\,(\overline{N_R}\gamma_\mu N_R)$	9	81

Examples of UV completions

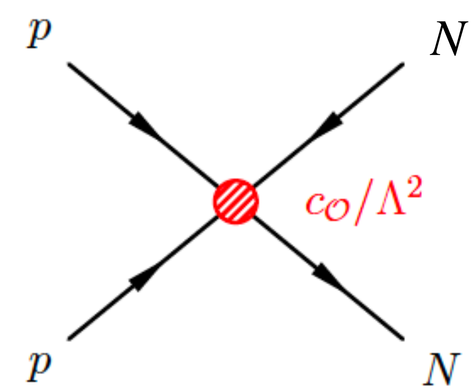
LQ state	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Coupling	Operator
S_d	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	g_{dN}	$\mathcal{O}_{dN}$
S_u	$\mathbf{3}$	$\mathbf{1}$	$2/3$	g_{uN}	$\mathcal{O}_{uN}$
S_Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$	g_{QN}	$\mathcal{O}_{QN}$

$$\mathcal{L}_{S_d} = g_{dN}\overline{d_R}N_R^c S_d + g_{ue}\overline{u_R}e_R^c S_d + g_{QL}\overline{Q}\epsilon L^c S_d + \text{h.c.}$$

$$\mathcal{L}_{S_u} = g_{uN}\overline{u_R}N_R^c S_u + \text{h.c.}$$

$$\mathcal{L}_{S_Q} = g_{QN}\overline{Q}N_R S_Q + g_{dL}\overline{d_R}L\epsilon S_Q + \text{h.c.}$$

- HNLs are pair produced via pair-N_R operators



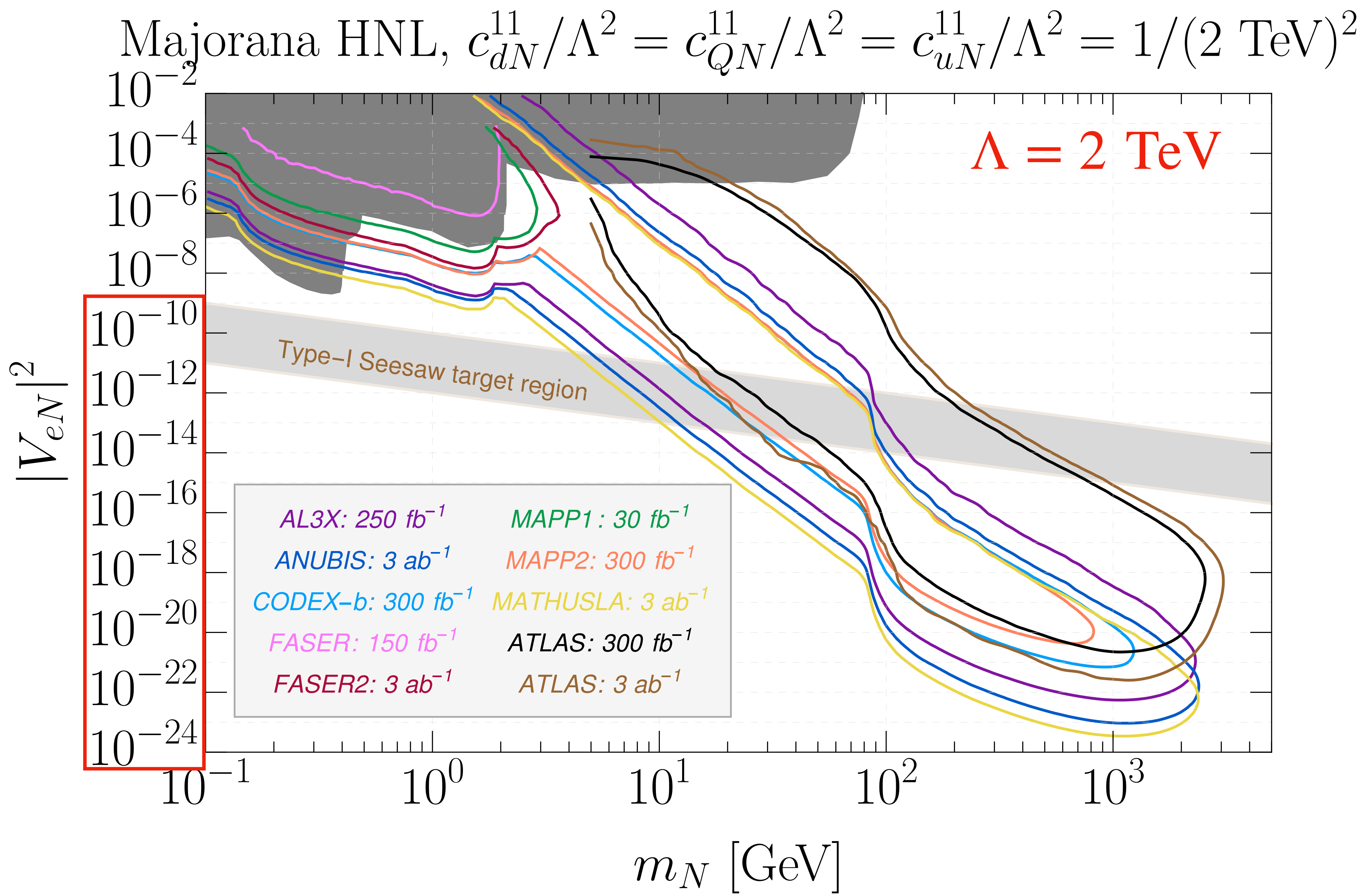
- Lightest HNL cannot decay via these operators; it decays via mixing

- MadGraph5 cannot handle Majorana fermions in operators with more than 2 fermions; renormalisable completions are needed to effectively implement such operators

Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

4-fermion pair-N operators at HL-LHC

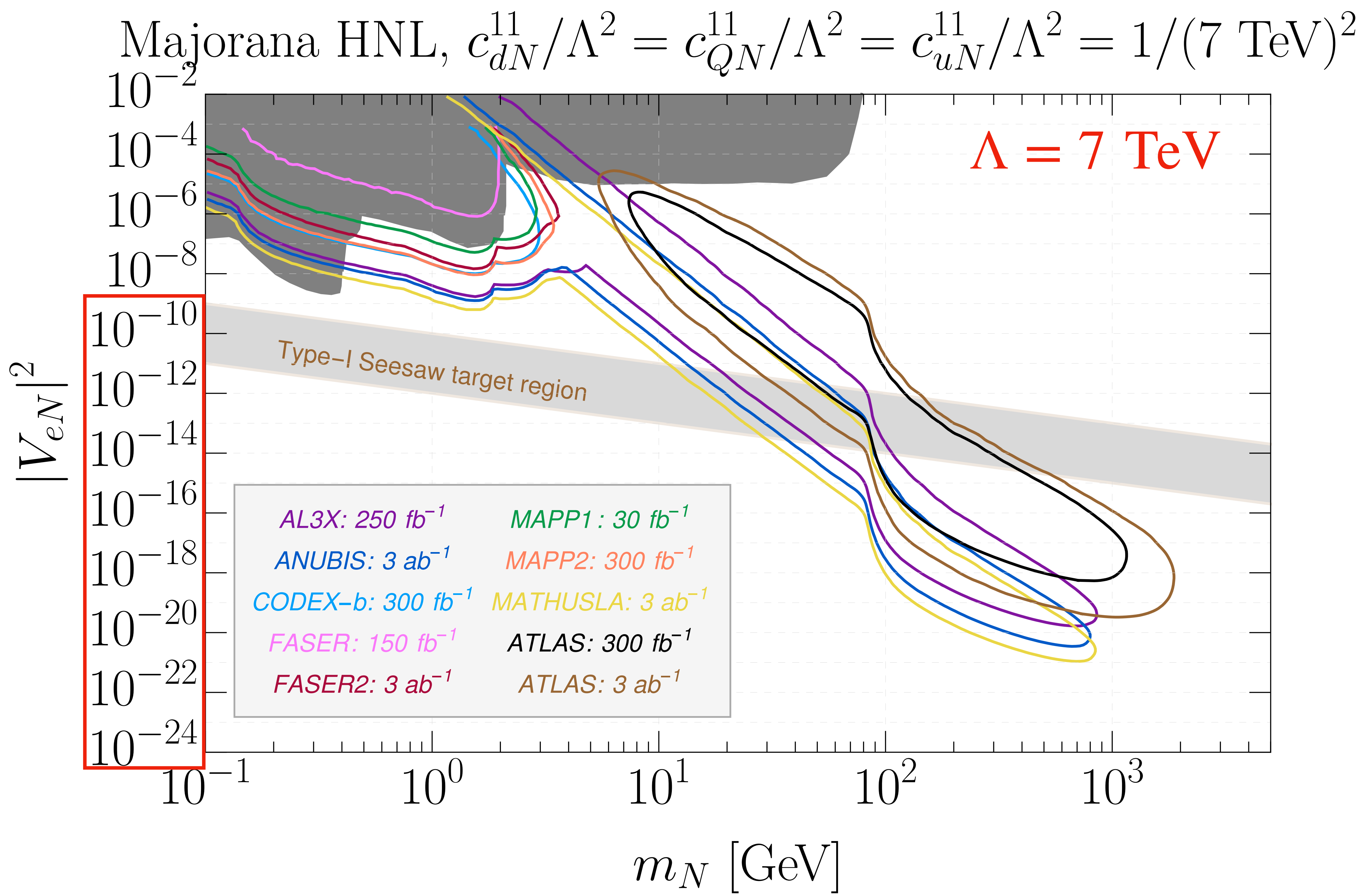
Reach on active-heavy neutrino mixing (for fixed new physics scale)



Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

4-fermion pair-N operators at HL-LHC

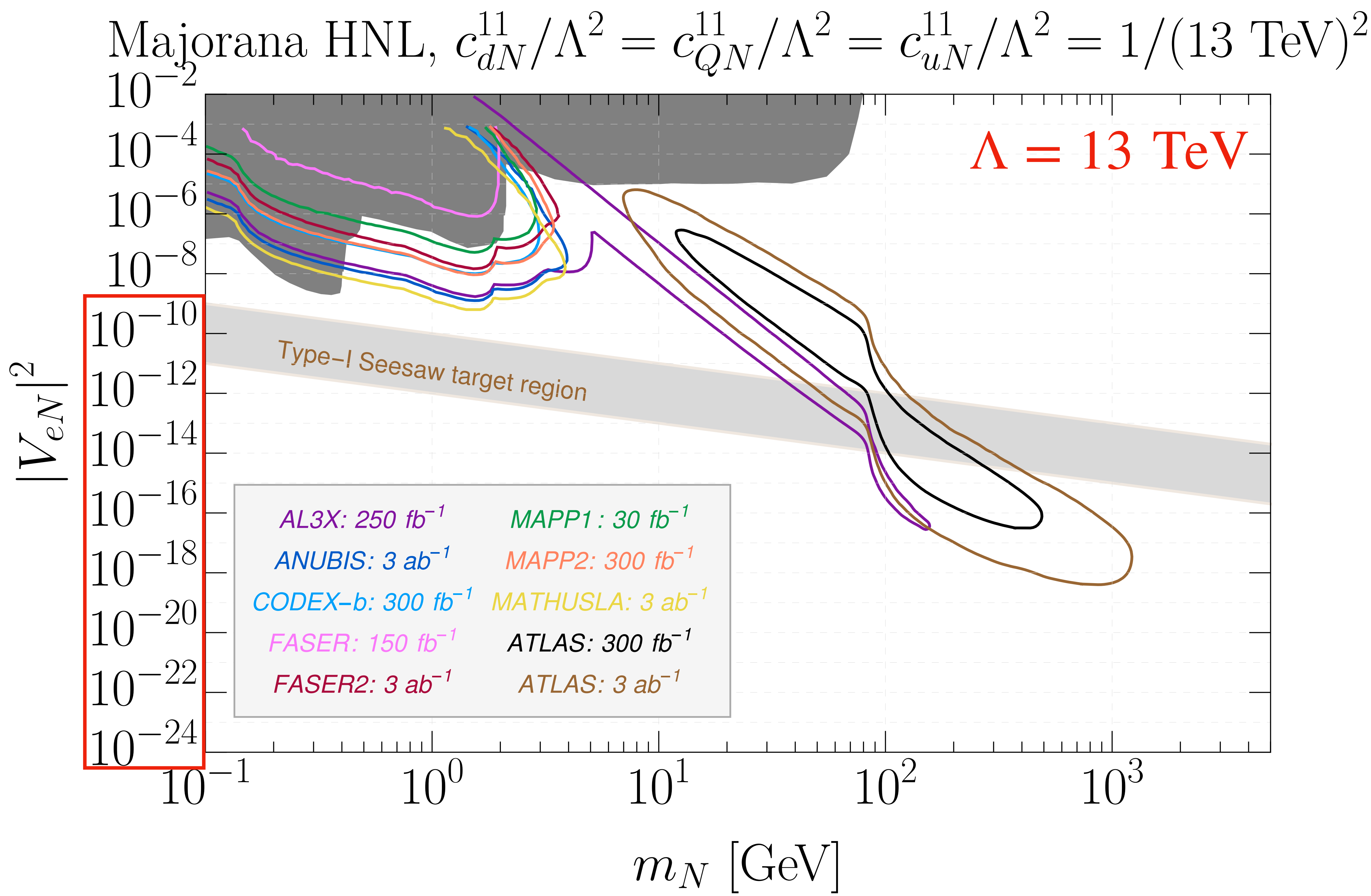
Reach on active-heavy neutrino mixing (for fixed new physics scale)



Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

4-fermion pair-N operators at HL-LHC

Reach on active-heavy neutrino mixing (for fixed new physics scale)

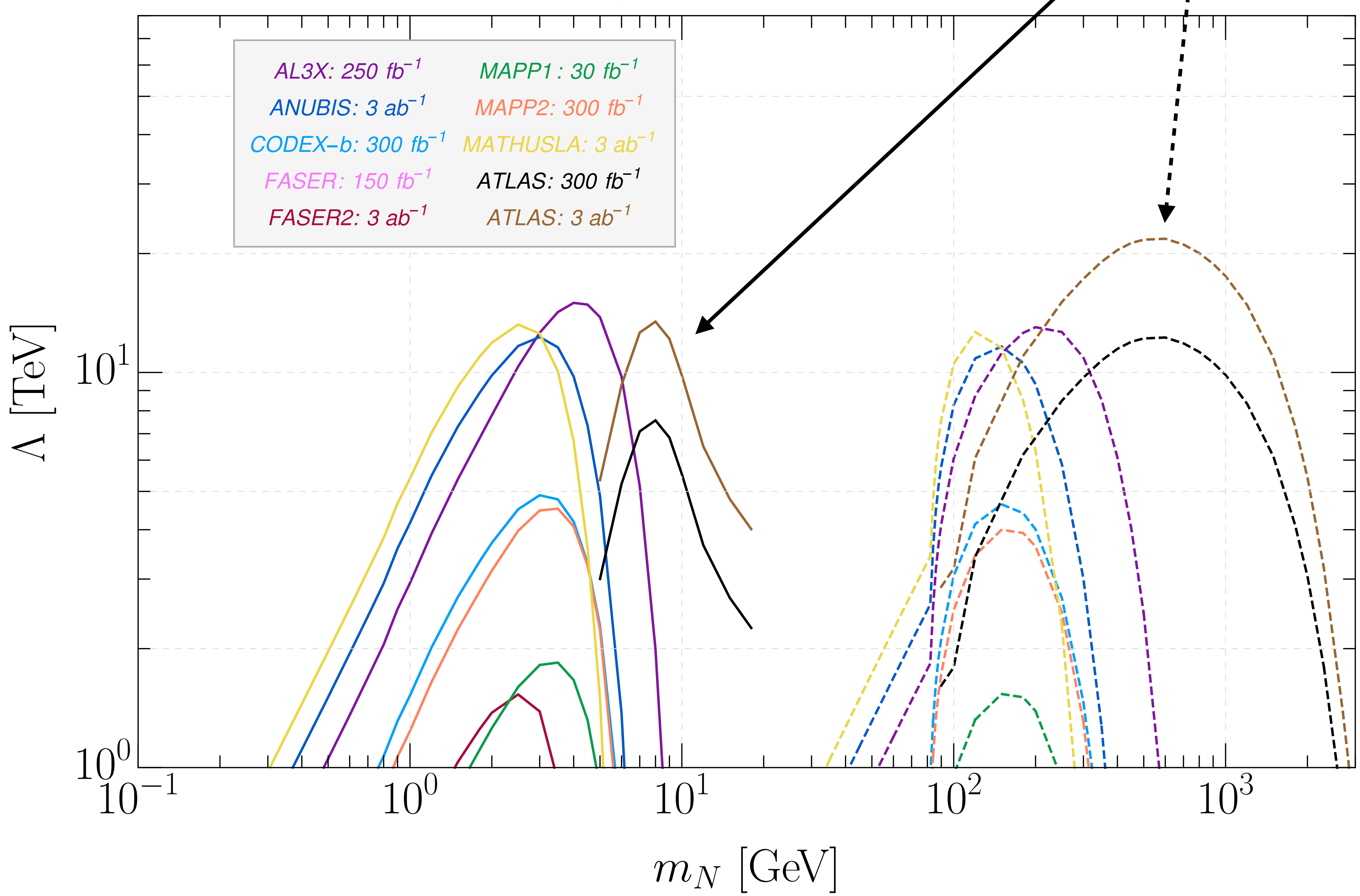


Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

4-fermion pair-N operators at HL-LHC

Reach on new physics scale (for fixed active-heavy neutrino mixing)

Dirac HNL, $c^{11}_{dN} = c^{11}_{QN} = c^{11}_{uN} = 1, |V_{eN}|^2 = 10^{-5}, 10^{-17}$

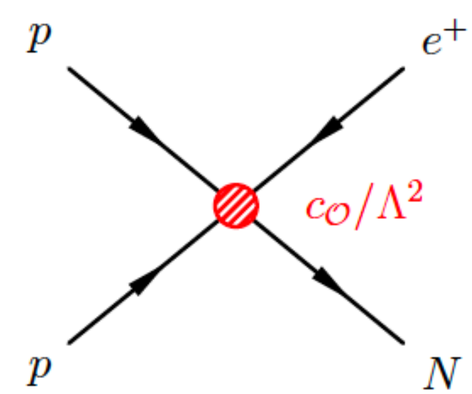


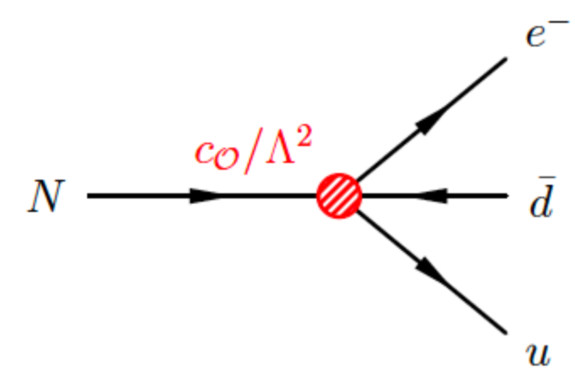
Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

4-fermion single-N operators

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$	54	162
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\epsilon(\overline{Q}d_R)$	54	162
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\epsilon(\overline{Q}N_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)(\overline{N_R}L)$	54	162
$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\epsilon(\overline{L}e_R)$	54	162

- Both HNL production and decay can be dominated by the operator





Examples of UV completions

Heavy scalar	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Operator	Matching relation
Leptoquark S_d	**3**	**1**	$-1/3$	$\mathcal{O}_{duNe}$	$\frac{c_{duNe}}{\Lambda^2} = \frac{g_{dN}g_{ue}}{2m_{S_d}^2}$
Leptoquark S_Q	**3**	**2**	$1/6$	$\mathcal{O}_{LdQN}$	$\frac{c_{LdQN}}{\Lambda^2} = \frac{g_{dL}g_{QN}}{m_{S_Q}^2}$
Inert doublet Φ	**1**	**2**	$1/2$	$\mathcal{O}_{LNQd}$	$\frac{c_{LNQd}}{\Lambda^2} = \frac{g_{LN}g_{Qd}}{m_\Phi^2}$
				$\mathcal{O}_{QuNL}$	$\frac{c_{QuNL}}{\Lambda^2} = \frac{g_{Qu}g_{LN}}{m_\Phi^2}$

$$\mathcal{L}_\Phi = g_{Qd}\overline{Q}\Phi d_R + g_{Qu}\overline{Q}\tilde{\Phi}u_R + g_{LN}\overline{L}\tilde{\Phi}N_R + \text{h.c.}$$

Beltrán, Cottin, Helo, Hirsch, **AT**, Wang, 2110.15096

4-fermion single-N operators

Example of HNL single production cross sections

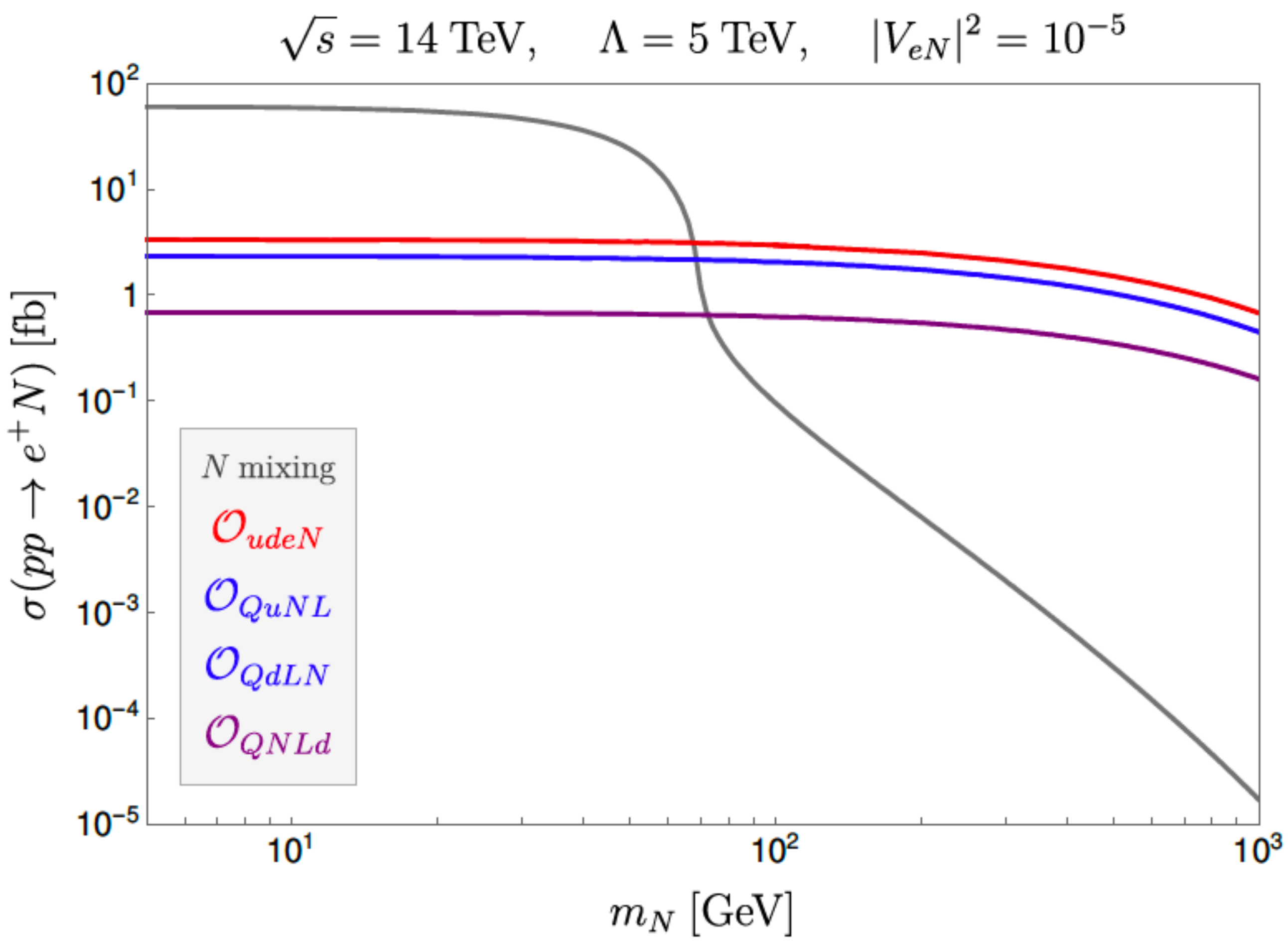


Figure from R. Beltrán's master thesis

$$\sigma^{\text{mix}} \propto |V_{eN}|^2$$

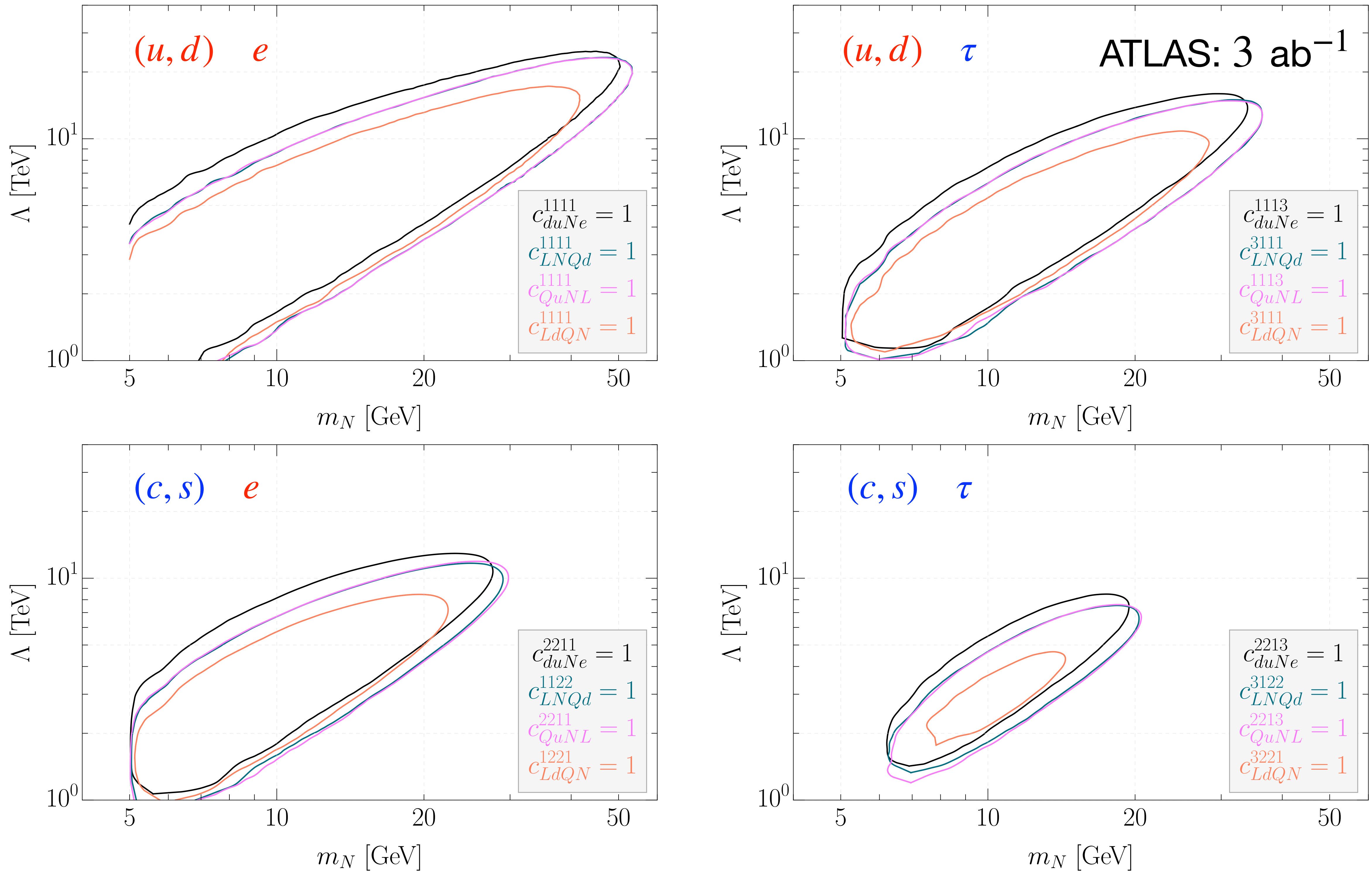
$$\sigma^{\mathcal{O}} \propto \Lambda^{-4}$$

Partial decay width of HNL

$$\Gamma(N \to \ell q q') = \frac{c_{\mathcal{O}}^2 m_N^5}{f_{\mathcal{O}}\, 512\, \pi^3 \Lambda^4}, \quad f_{\mathcal{O}} = 1\ (4) \quad \text{for} \quad \mathcal{O}_{duNe}\ \text{(3 remaining operators)}$$

Beltrán, Cottin, Helo, Hirsch, **AT**, Wang, 2110.15096

4-fermion single-N operators at HL-LHC



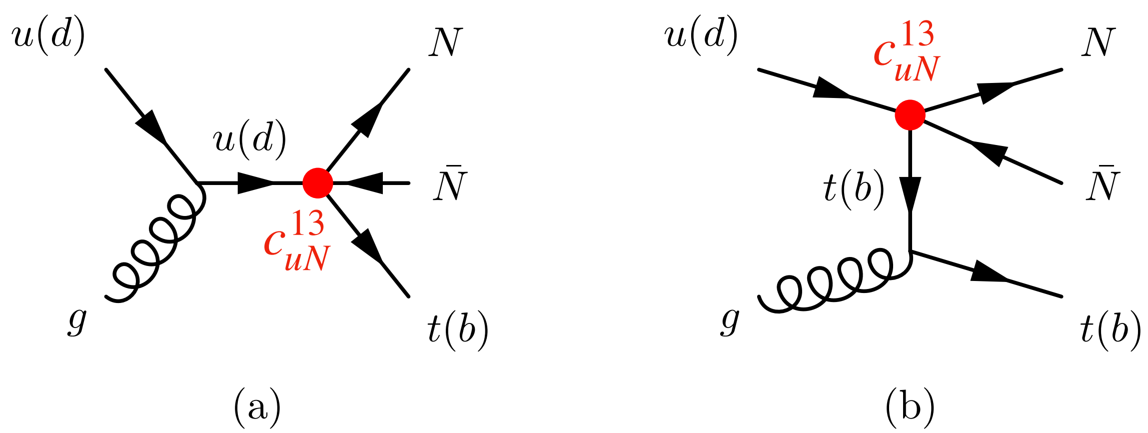
Assumption: both HNL production and decay are dominated by the operator
(fulfilled everywhere in the plots if $|V_{\alpha N}|^2 \lesssim 10^{-9}$)

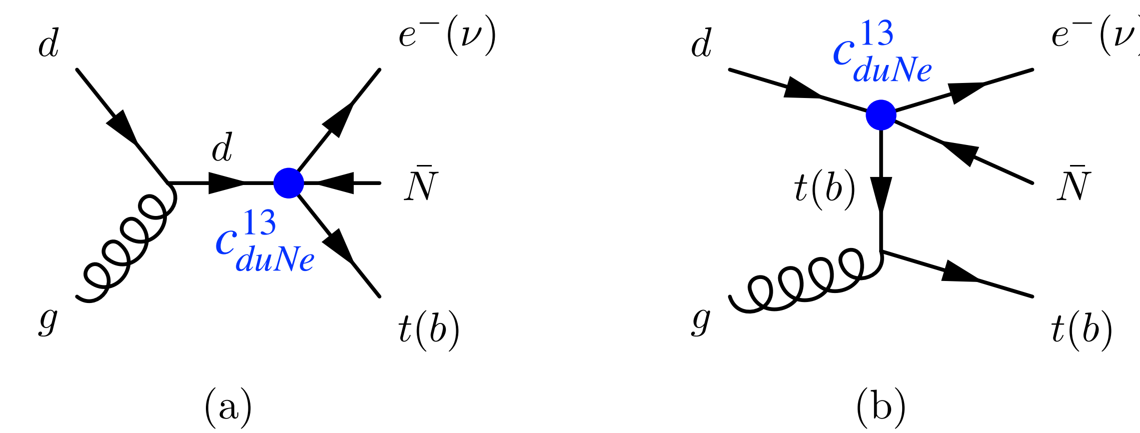
Beltrán, Cottin, Helo, Hirsch, **AT**, Wang, 2110.15096

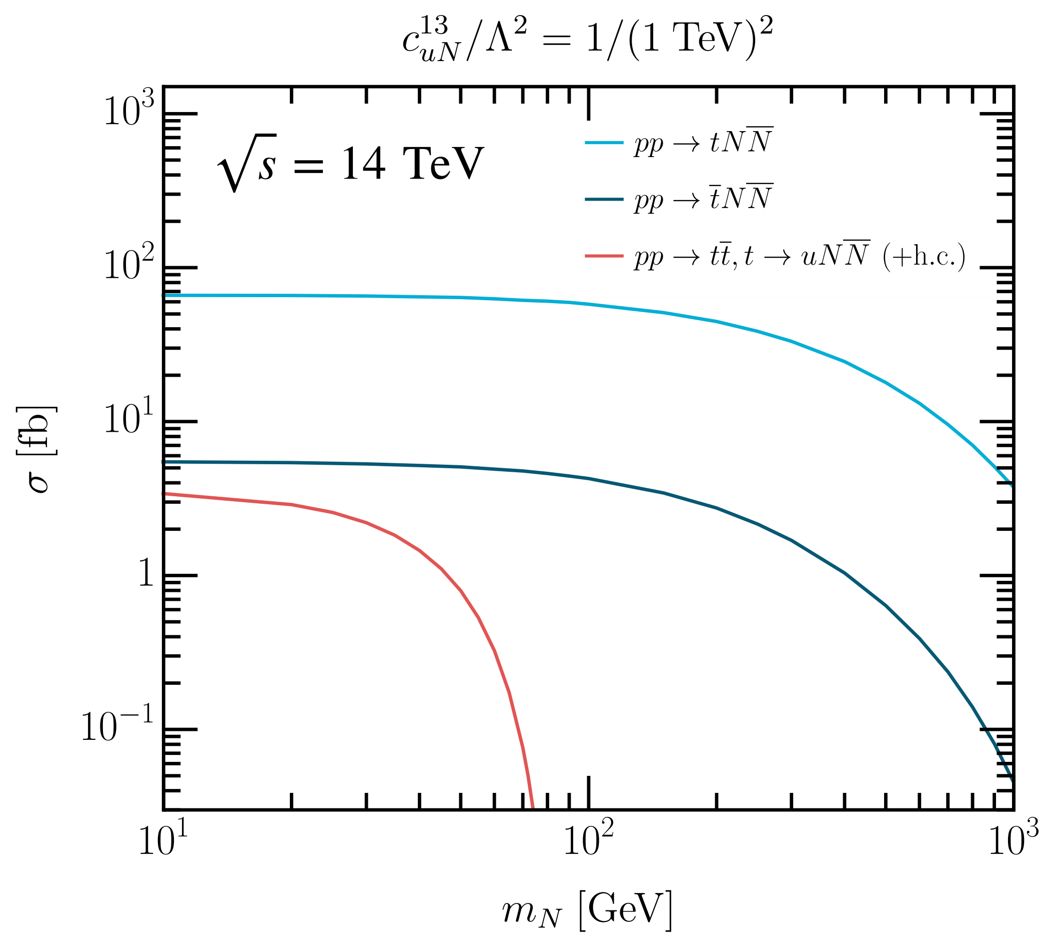
Top-N operators

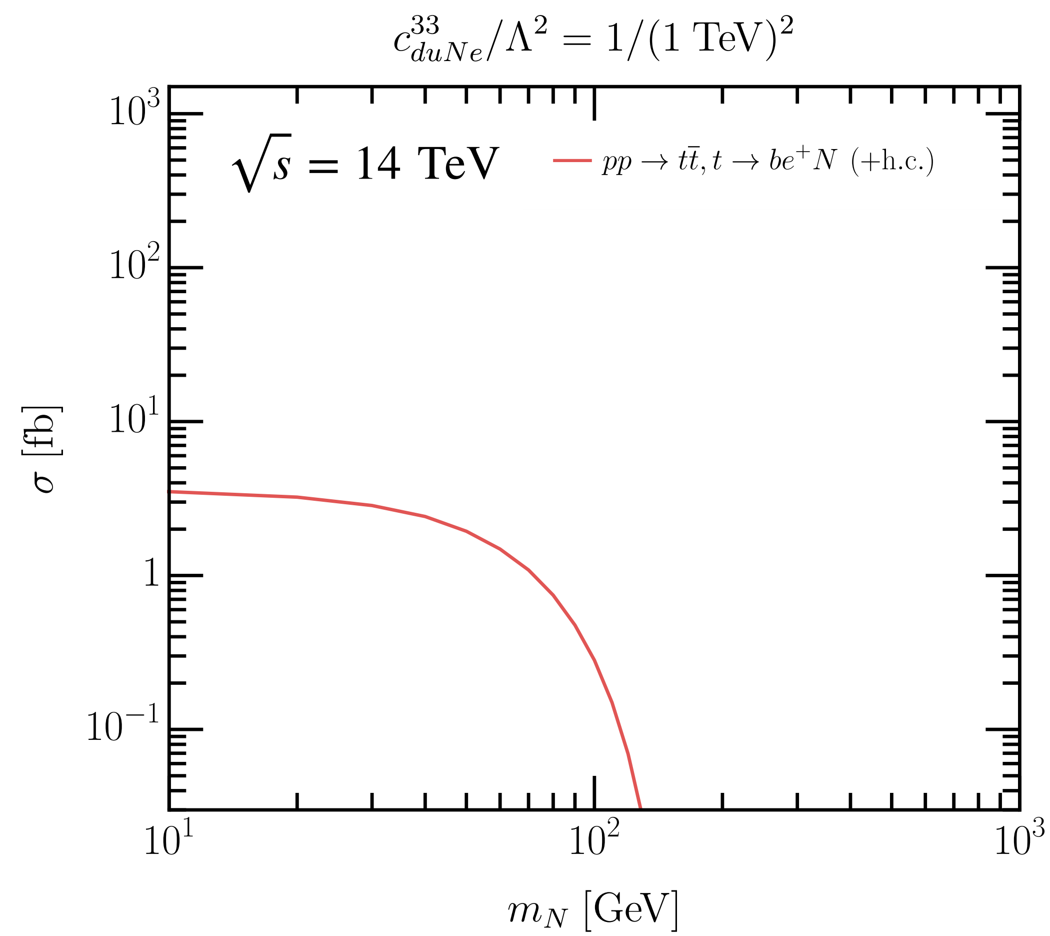
$\mathcal{O}_{uN}^{13}$	$(\overline{u_R}\gamma^\mu t_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{uN}^{33}$	$(\overline{t_R}\gamma^\mu t_R)\,(\overline{N_R}\gamma_\mu N_R)$

$\mathcal{O}_{duNe}^{13}$	$(\overline{d_R}\gamma^\mu t_R)\,(\overline{N_R}\gamma_\mu e_R)$
$\mathcal{O}_{duNe}^{33}$	$(\overline{b_R}\gamma^\mu t_R)\,(\overline{N_R}\gamma_\mu e_R)$



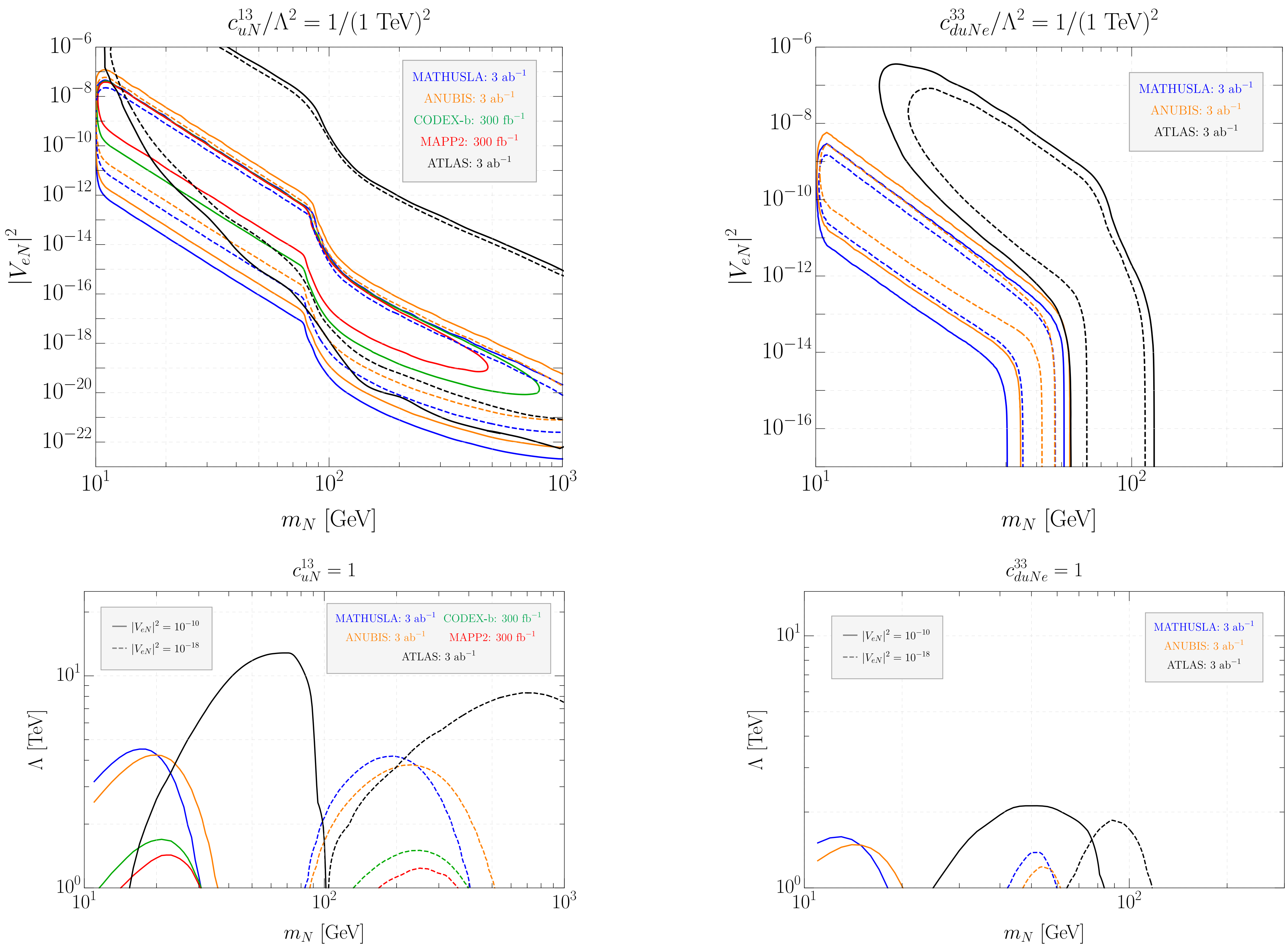






Beltrán, Cottin, Günther, Hirsch, **AT**, Wang, 2501.09065

Top-N operators



Beltrán, Cottin, Günther, Hirsch, **AT**, Wang, 2501.09065

Conclusions

- Neutrino masses may be pointing towards the existence of HNLs
- HNLs may have masses below the EW scale and new heavy physics may exist at scales $\Lambda \gg \mathrm{v}$, hence NSMEFT
- HNLs may be (effectively) stable, decaying promptly or long-lived
- In addition to active-heavy mixing, they can be produced through new effective interactions directly in partonic collisions or in meson decays*
- Rich programme for LLP searches at HL-LHC:
  - ATLAS, CMS
  - ANUBIS, CODEX-b, FACET, FASER, MATHUSLA, MoEDAL-MAPP
- HL-LHC will be sensitive to new physics scales up to
  - 20 TeV for quark-N_R operators with first generation quarks
  - a few TeV for top-N_R operators

Backup slides

Motivation: neutrino masses

There are variants of the seesaw mechanism with low M and large $V_{\alpha N}$ *e.g.*

Inverse seesaw mechanism

$$-\mathscr{L}_{\mathrm{mass}} = \frac{1}{2}\left(\overline{\nu_L}\ \overline{N_R^c}\ \overline{S_L}\right)\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \\ S_L^c \end{pmatrix} + \text{h.c.}$$

$$m_\nu = m_D\, M_R^{-1}\, \mu\, M_R^{-1T}\, m_D^T \quad \text{and} \quad V_{\alpha N}^2 \sim \left(\frac{m_D}{M_R}\right)^2 \sim \frac{m_\nu}{\mu}$$

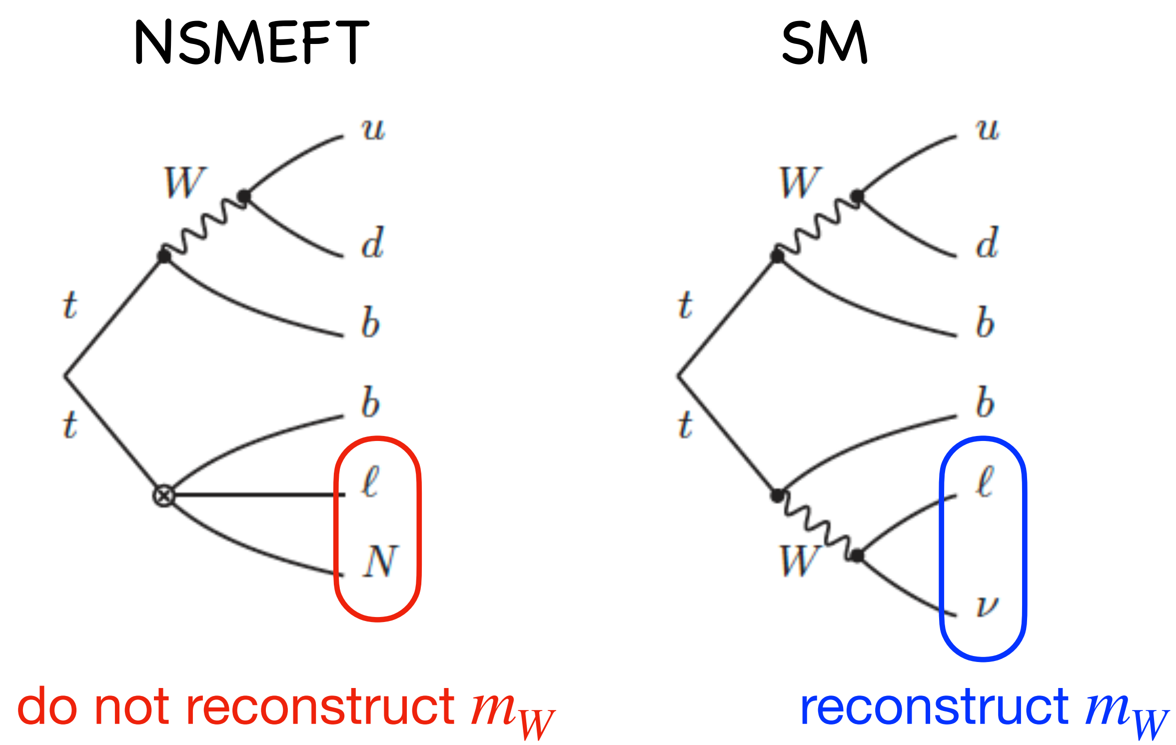
$m_\nu \sim 0.01$ eV and $|V_{\alpha N}|^2 \sim 10^{-2} \div 10^{-8}$

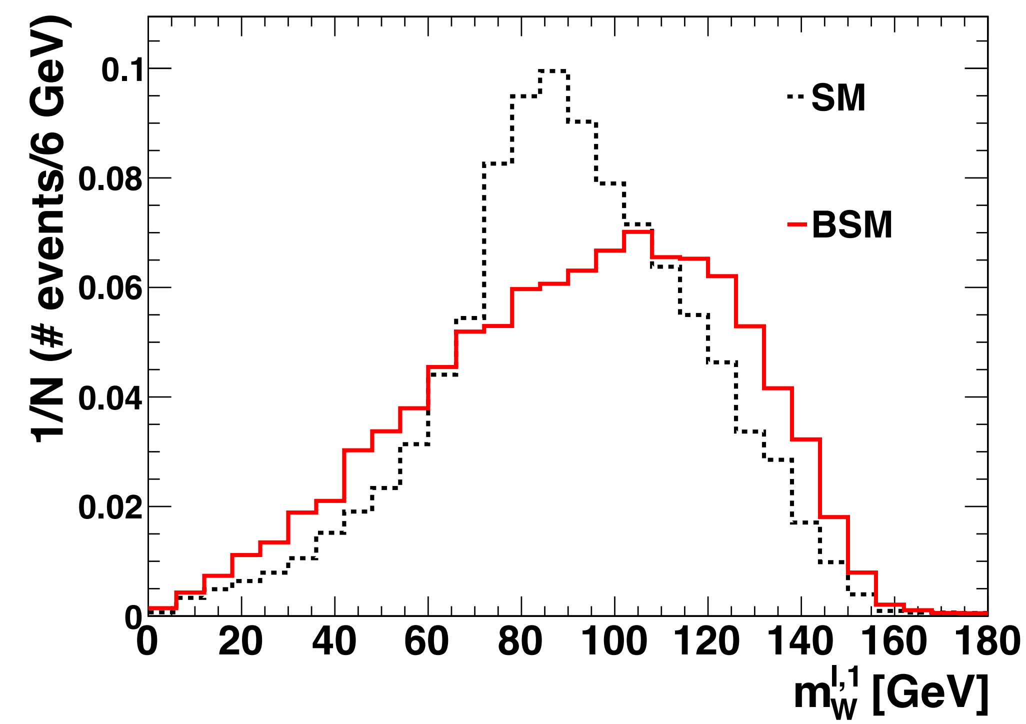
for $\quad Y_N \sim 10^{-3}, \quad M_R \sim 1 \div 10^3$ GeV, $\quad \mu \sim 10^{-9} \div 10^{-3}$ GeV

Small μ is technically natural, since for $\mu = 0$, LN symmetry is restored

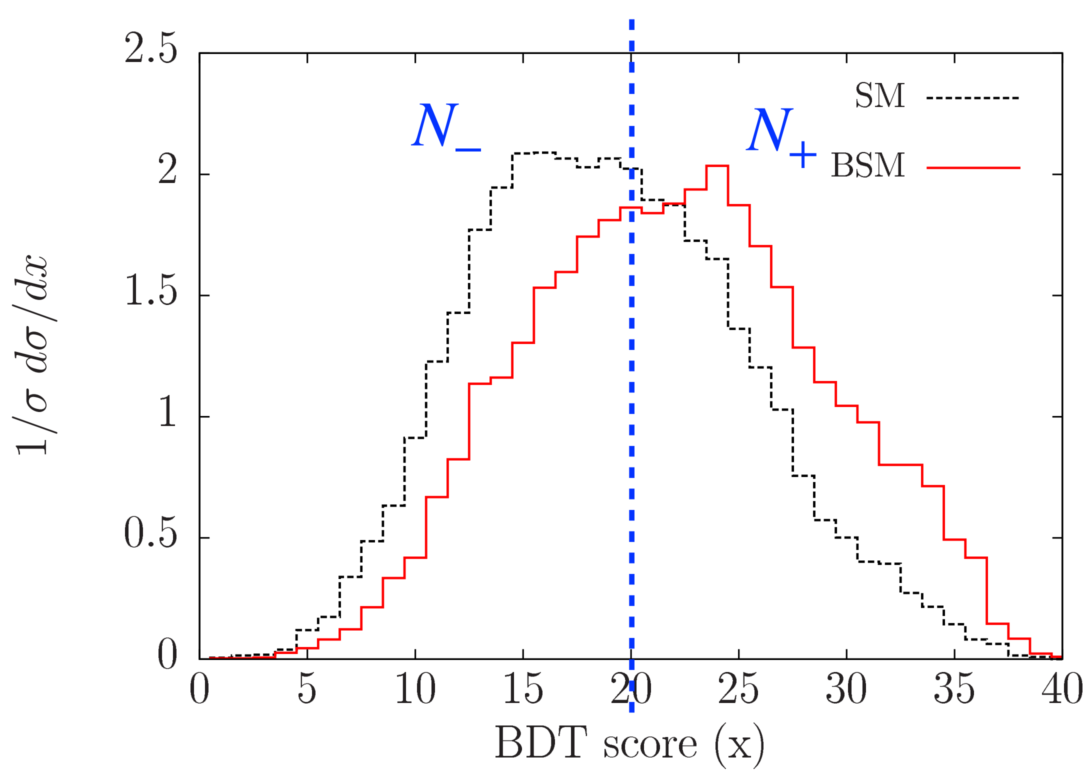
Novel LHC analysis for t → bl + inv

Alcaide, Banerjee, Chala, AT, 1905.11375





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



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

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

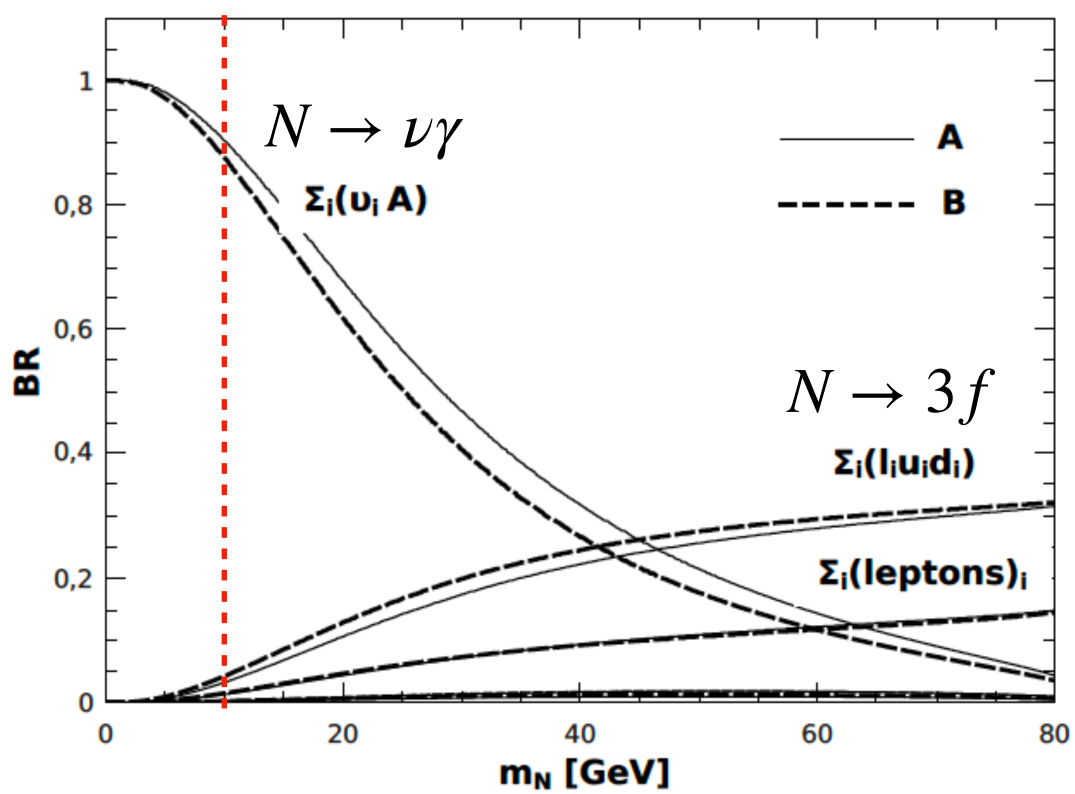
@ HL-LHC with $\mathscr{L} = 3\ \text{ab}^{-1}$

Majorana HNL

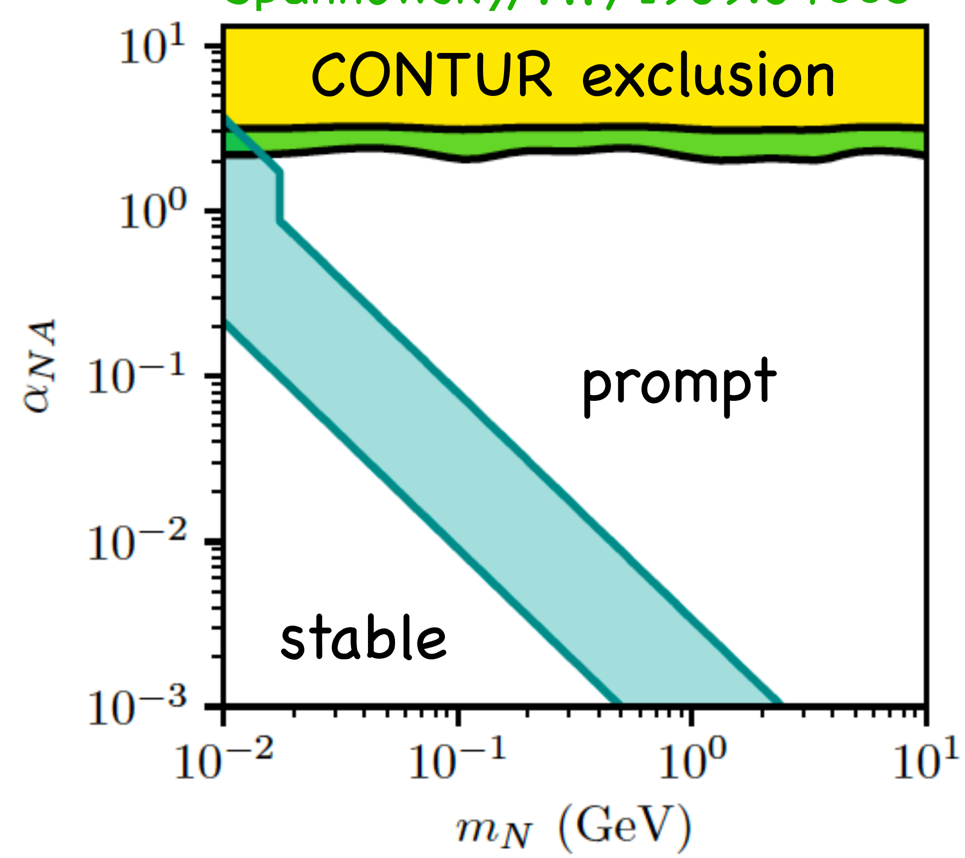
$$-\mathscr{L}_{\text{mass}} = \bar{L}\tilde{H}Y_N N + \frac{1}{2}\overline{N^c} m_N N + \text{h.c.} \quad \Rightarrow \quad N \text{ is Majorana}$$

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

Duarte, Peressutti, Sampayo, 1508.01588



Butterworth, Chala, Englert, Spannowsky, **AT**, 1909.04665

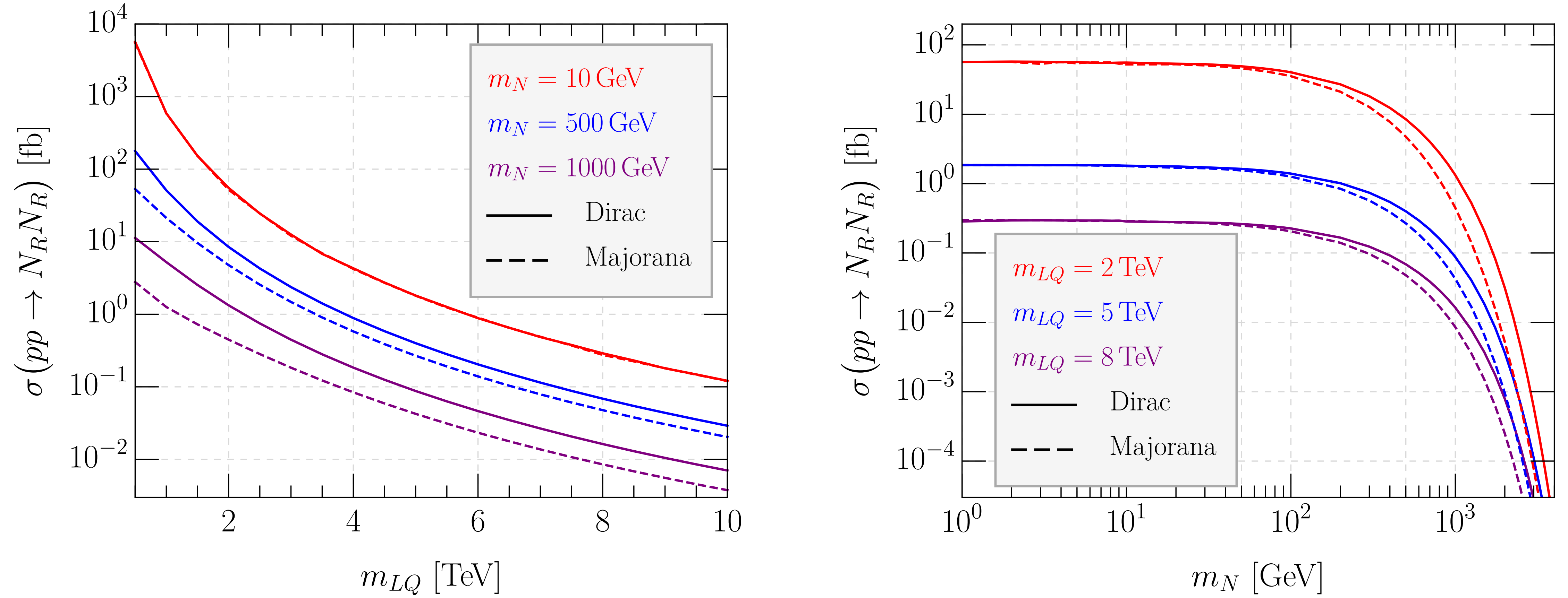


Let's restrict to Higgs-N operators

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

4-fermion pair-N operators

Examples of HNL pair production cross section for $\mathcal{O}_{dN}$ $(g_{dN} = \sqrt{2} \Leftrightarrow c_{dN}^{11} = 1)$



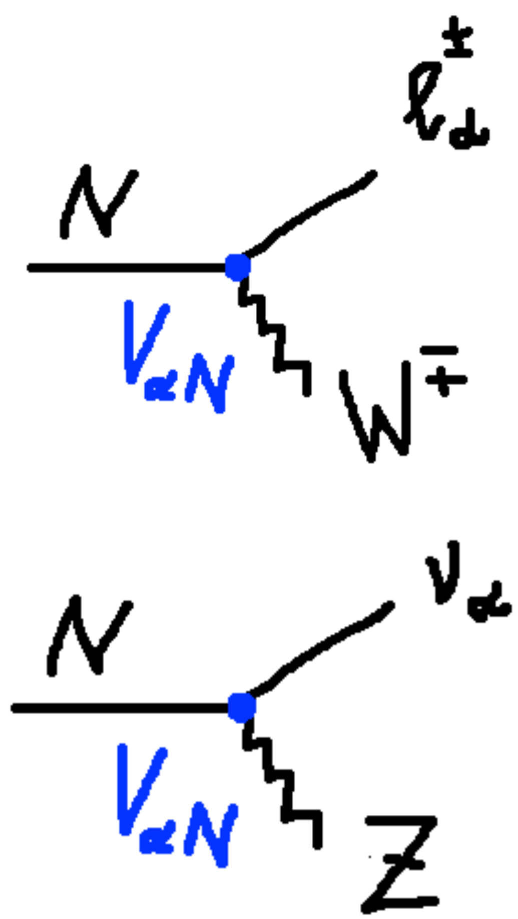
$$\sigma_D(d\bar{d} \to N\bar{N}) = \frac{c_{dN}^2}{192\pi\Lambda^4} s \sqrt{1 - \frac{4m_N^2}{s}} \left[1 + \frac{1}{3}\left(1 - \frac{4m_N^2}{s}\right)\right]$$

$$\sigma_M(d\bar{d} \to NN) = \frac{c_{dN}^2}{144\pi\Lambda^4} s \left(1 - \frac{4m_N^2}{s}\right)^{3/2} \quad \Rightarrow \quad \text{suppression for } m_N \gtrsim 100 \text{ GeV}$$

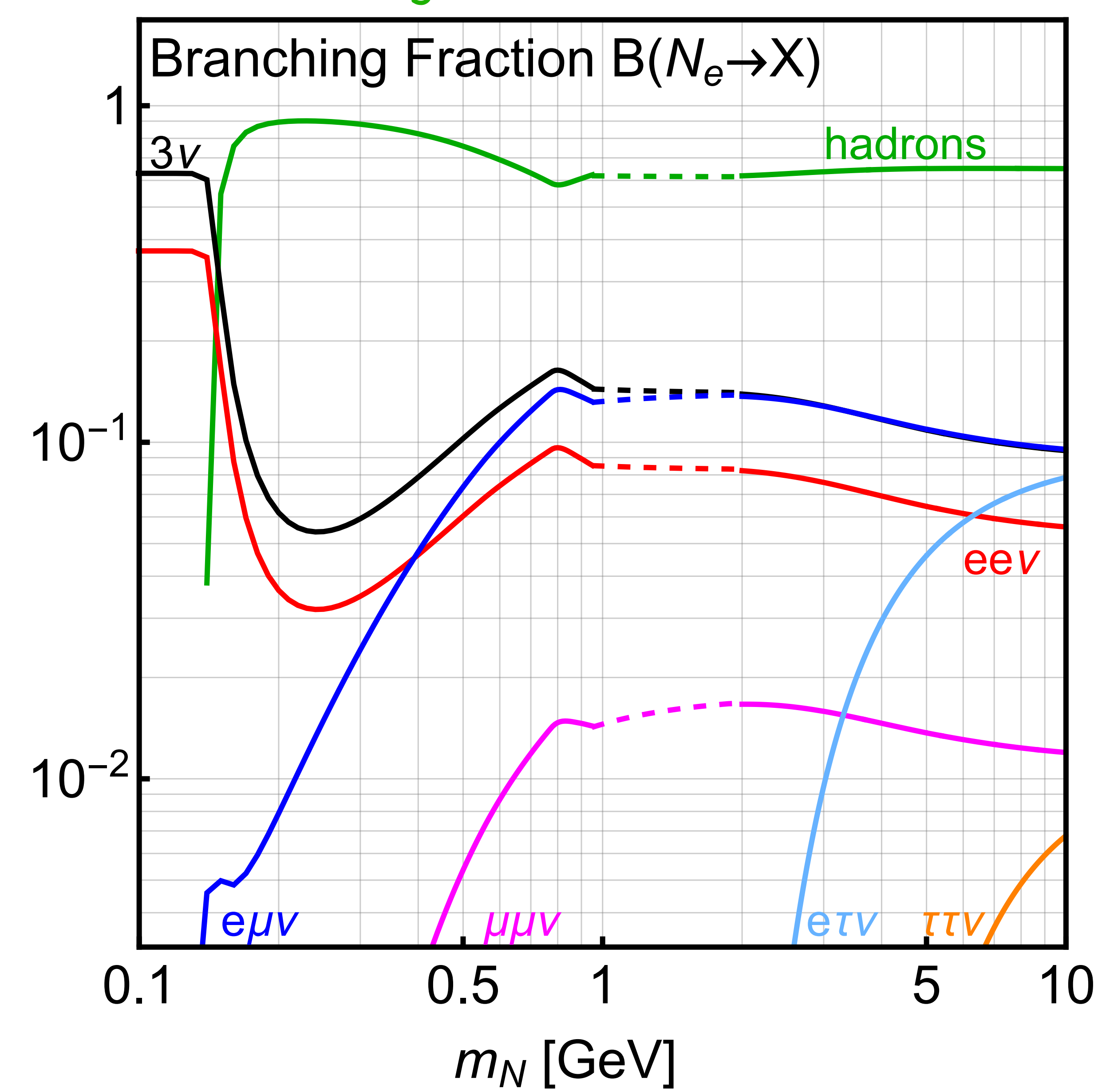
Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

HNL decay via active-heavy mixing

$$\mathscr{L}_{\min} = -\frac{g}{\sqrt{2}} V_{\alpha N} \overline{\ell_\alpha} \gamma^\mu P_L N\, W_\mu - \frac{g}{2\cos\theta_W} V_{\alpha N} \overline{\nu_\alpha} \gamma^\mu P_L N\, Z_\mu + \text{h.c.}$$



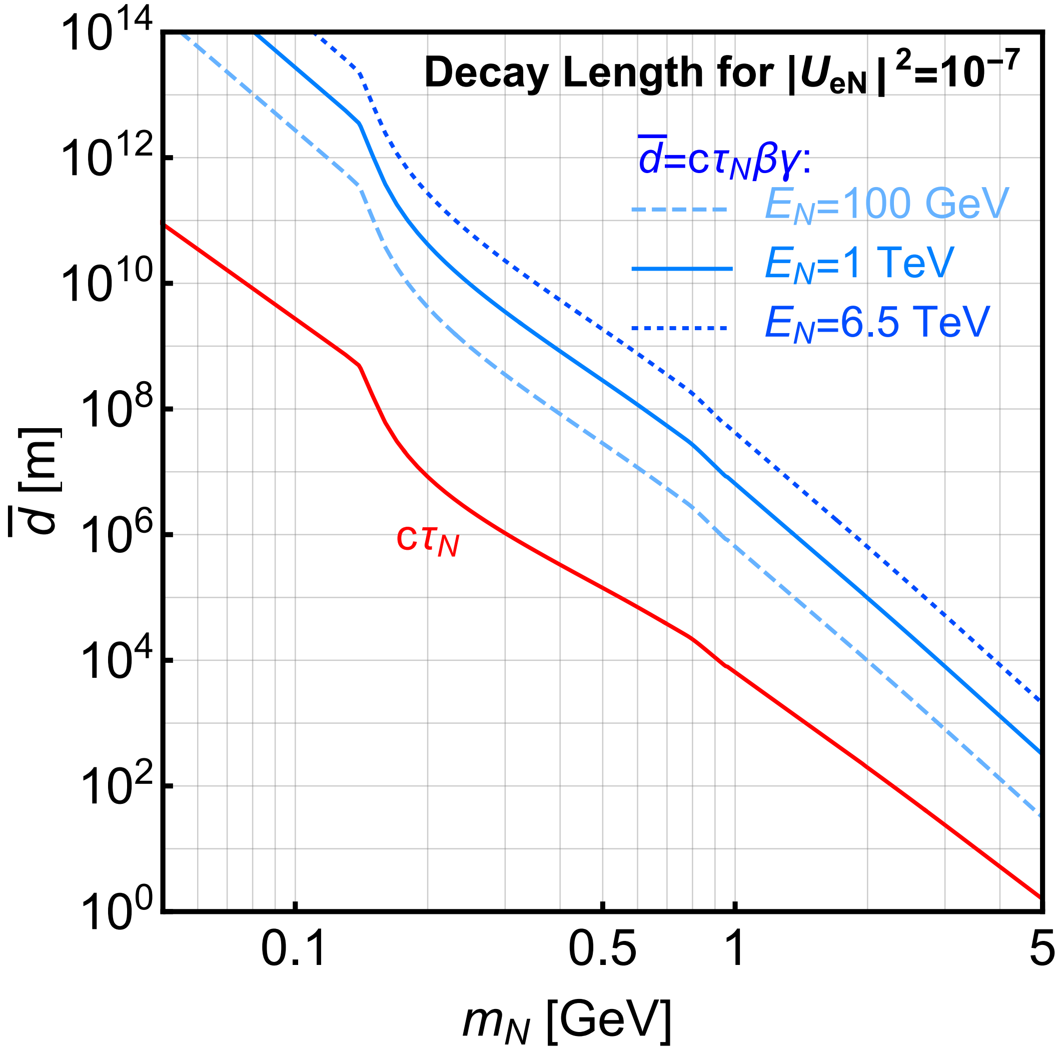
Kling and Trojanowski, 1801.08947



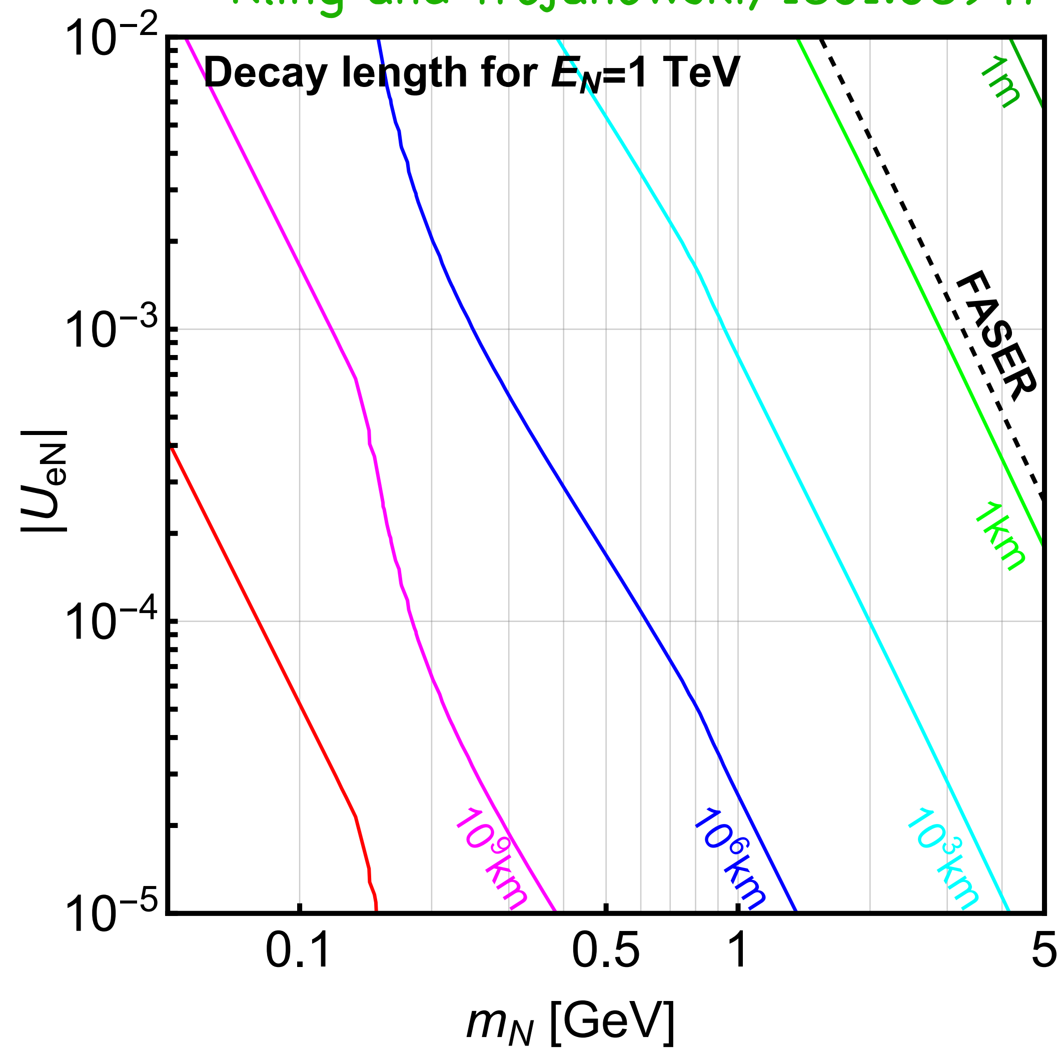
Long-lived HNLs

Proper decay length: $c\tau_N = \frac{1}{\Gamma_N} \propto \frac{1}{|V_{\alpha N}|^2}$

Decay length in the *lab frame*: $\bar{d} = \beta\gamma c\tau_N$



Kling and Trojanowski, 1801.08947



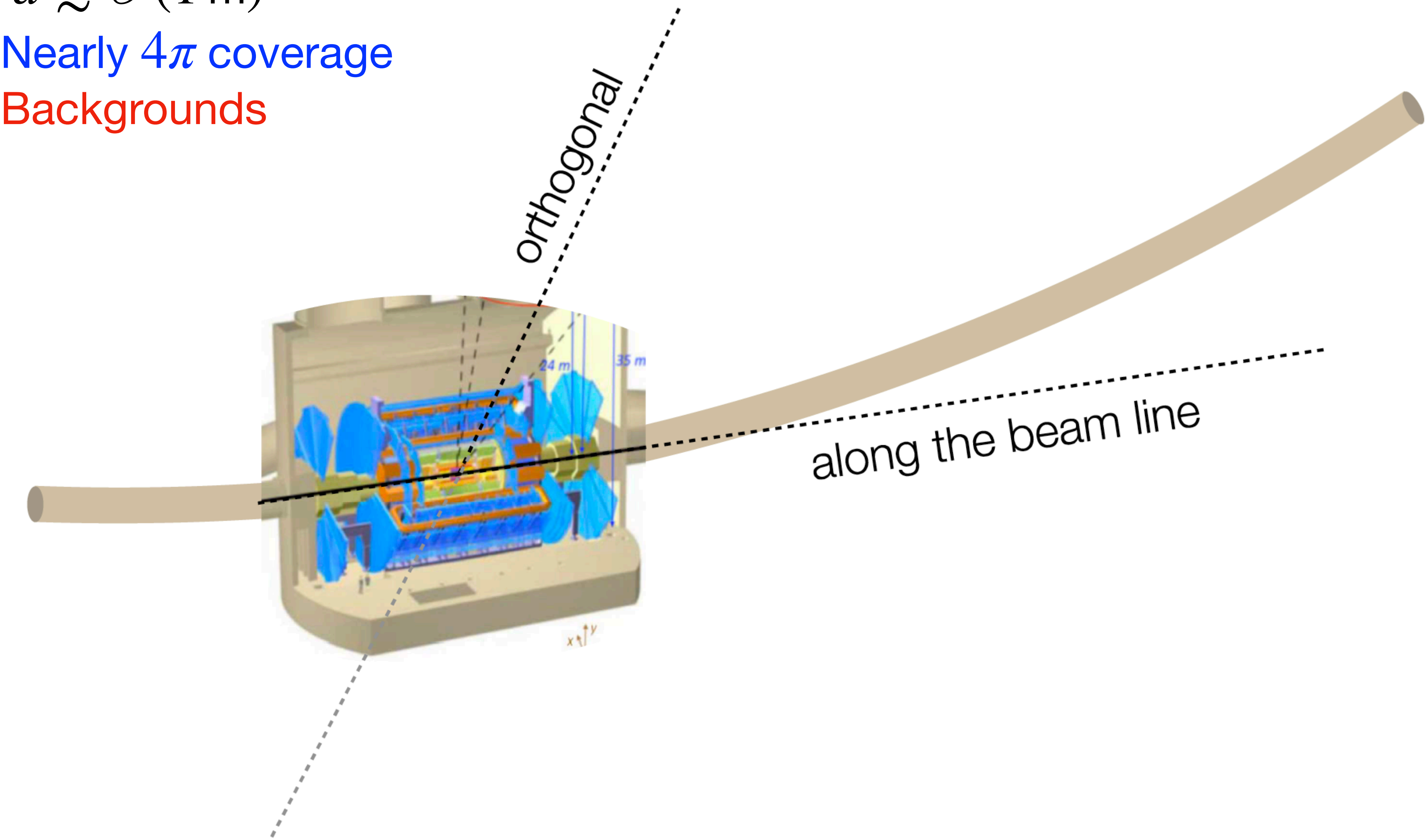
Local detectors at HL-LHC

ATLAS and CMS

$\bar{d} \lesssim \mathcal{O}(1\,\mathrm{m})$

Nearly 4π coverage

Backgrounds



Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

FASER: ForwArd Search ExpeRiment

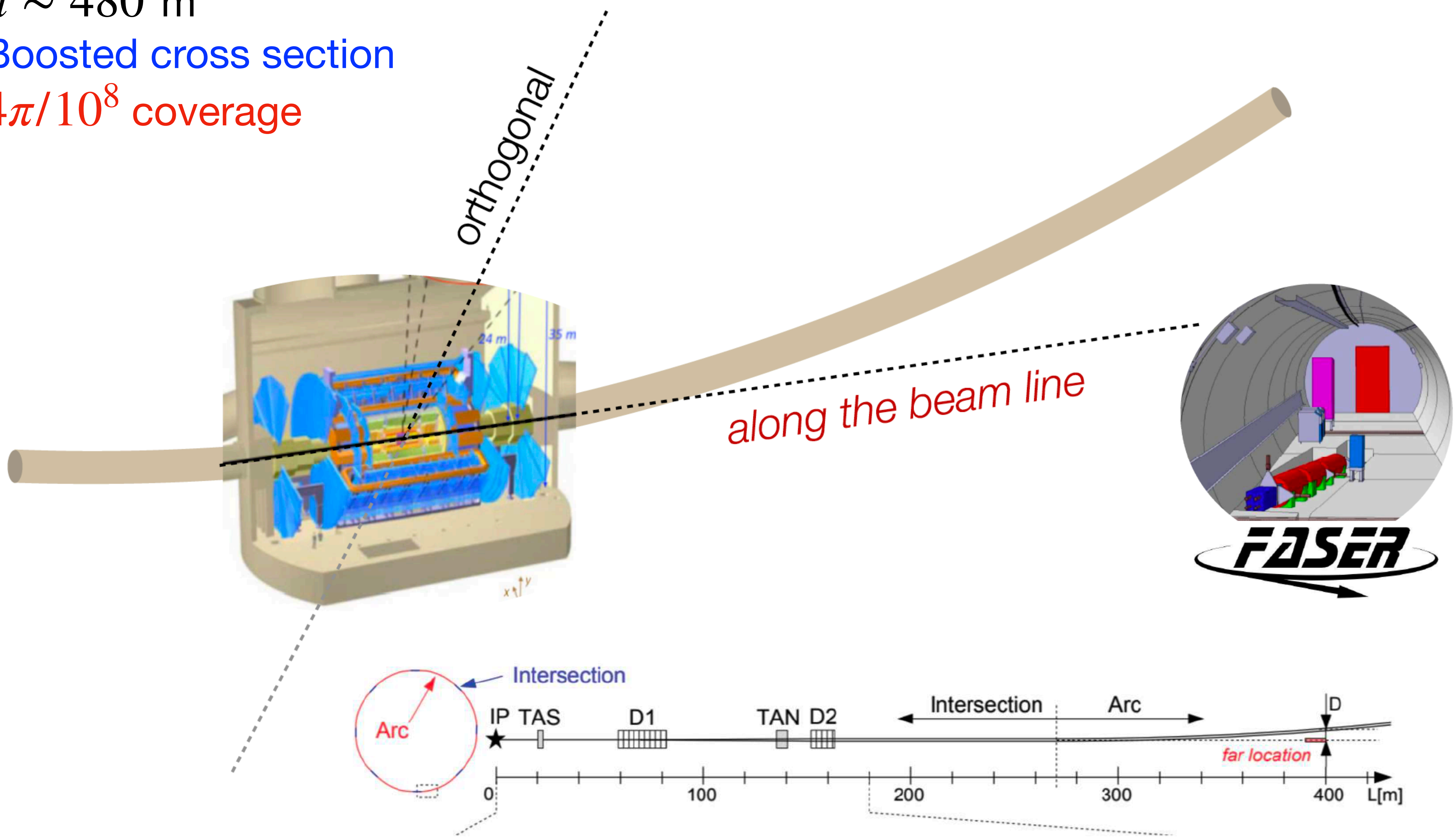
Cylinder with $r = 10$ cm and $\ell = 1.5$ m

$\bar{d} \sim 480$ m

Boosted cross section

$4\pi/10^8$ coverage

Started data taking in 2022



Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

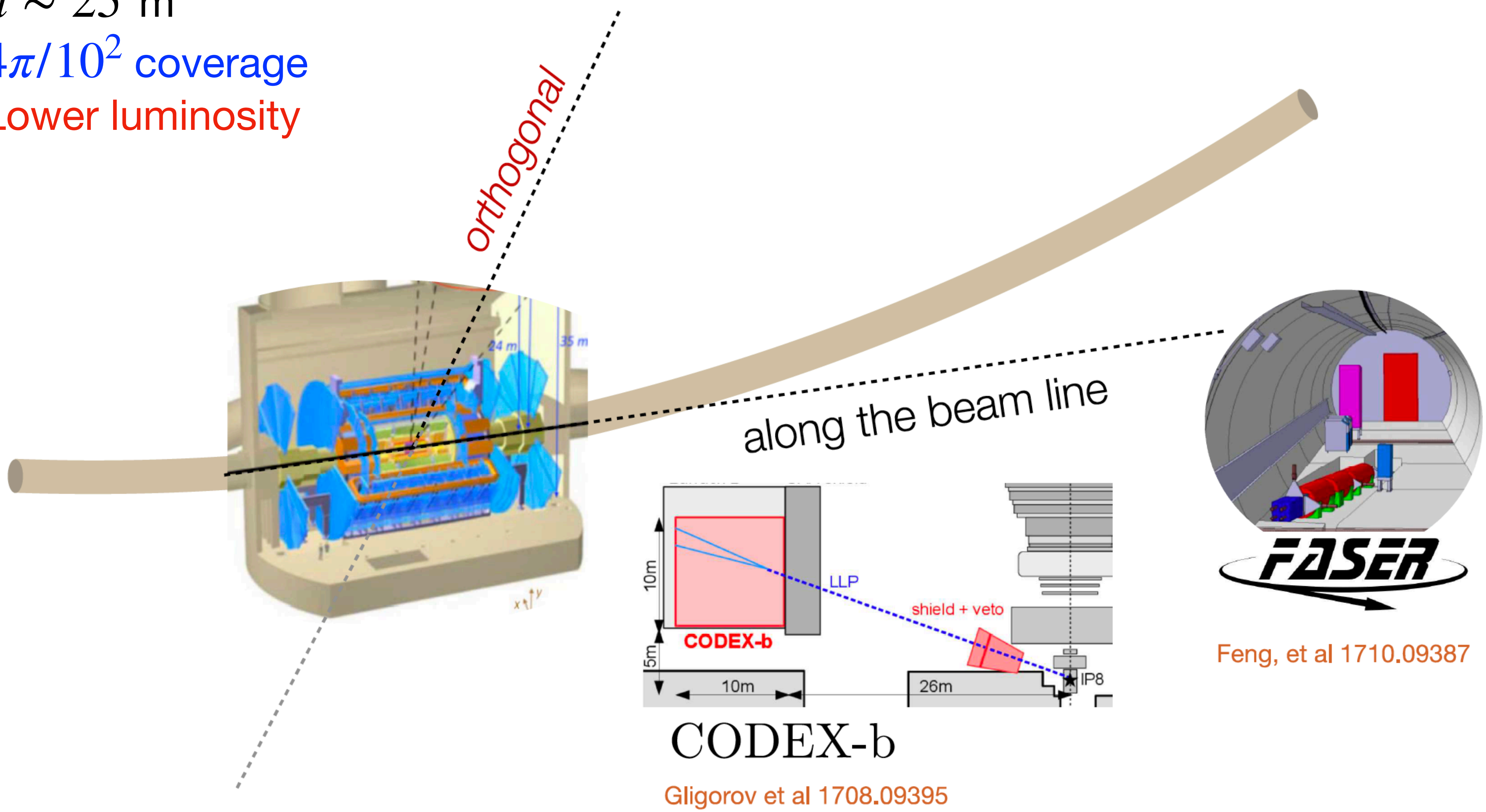
CODEX-b: COmpact Detector for EXotics at LHCb

Box of $10\,\mathrm{m} \times 10\,\mathrm{m} \times 10\,\mathrm{m}$

$\bar{d} \sim 25$ m

$4\pi/10^2$ coverage

Lower luminosity



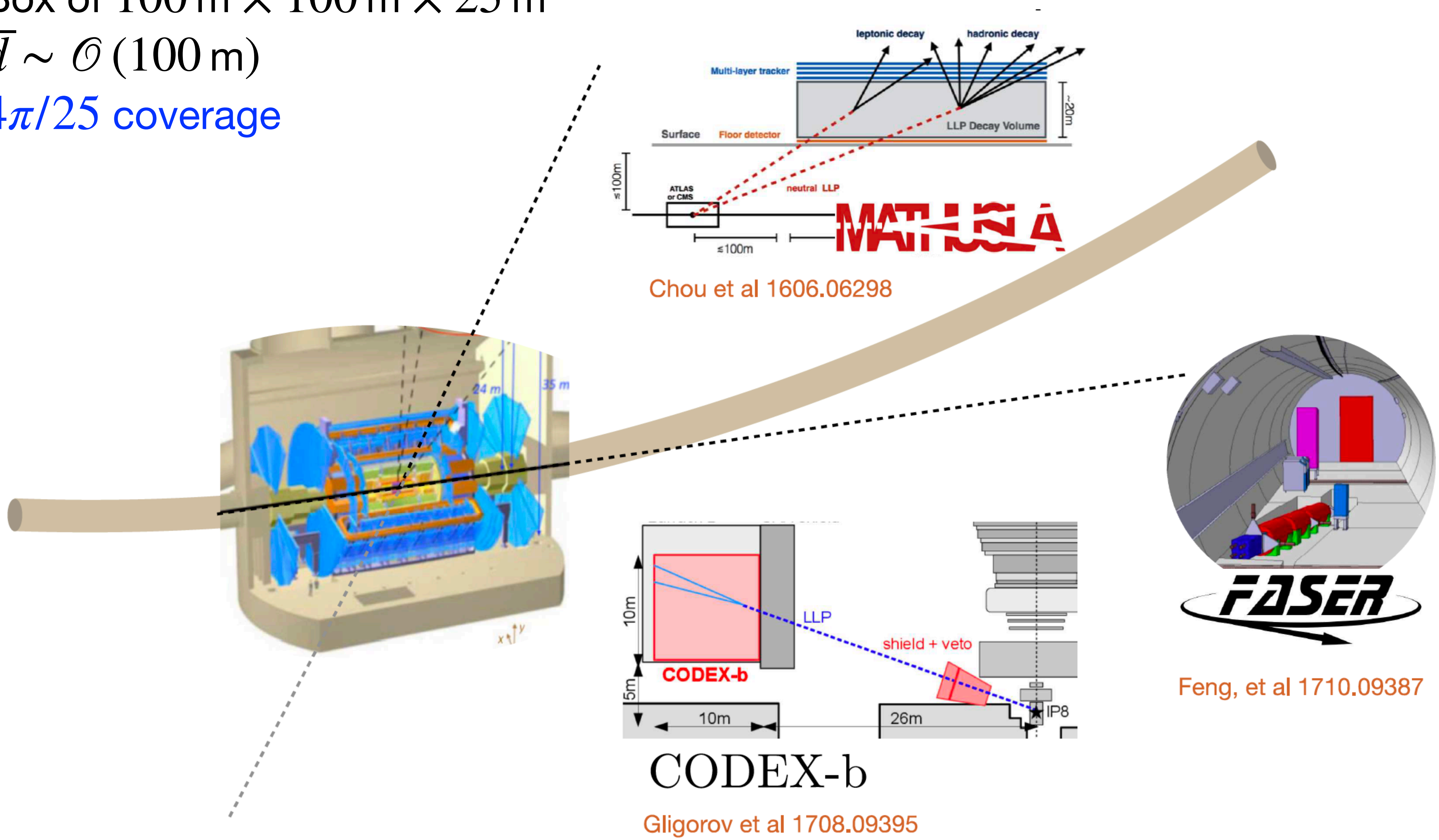
Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

MATHUSLA: MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

Box of $100\,\mathrm{m} \times 100\,\mathrm{m} \times 25\,\mathrm{m}$

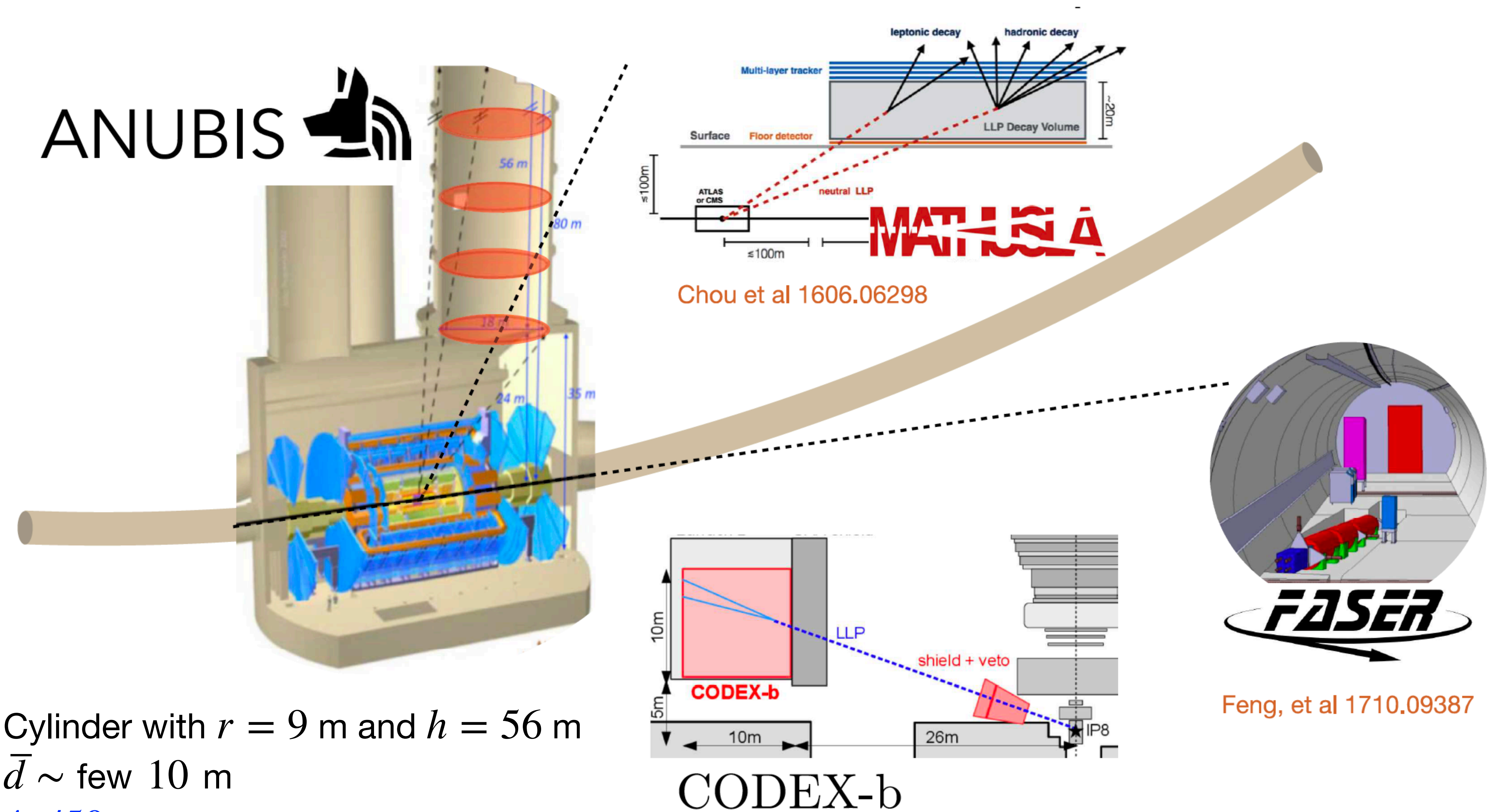
$\bar{d} \sim \mathcal{O}(100\,\mathrm{m})$

$4\pi/25$ coverage



Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

ANUBIS: AN Underground Belayed In-Shaft search experiment



Chou et al 1606.06298

Feng, et al 1710.09387

Gligorov et al 1708.09395

Cylinder with $r = 9$ m and $h = 56$ m
$\bar{d} \sim$ few 10 m
$4\pi/50$ coverage

Bauer, OB, Lee, Ohm 1909.13022

Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

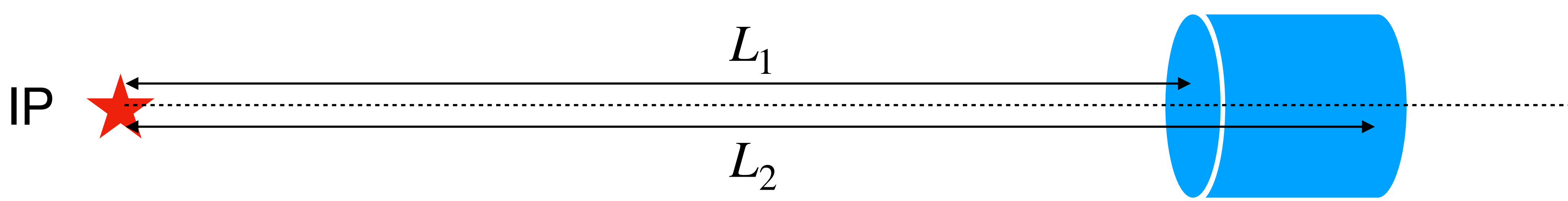
Number of events

Projected number of signal events at ATLAS:

$$N_S^{\text{ATLAS}} = \underbrace{\sigma(pp \to NN)}_{\texttt{MadGraph5}} \cdot \mathscr{L} \cdot \underbrace{\text{BR}(N \to \ell jj)}_{\texttt{MadSpin+Pythia8}} \cdot 2 \cdot \epsilon$$

Decay probability of an HNL in a far detector (approximately):

$$P[N \,\text{decay}] = e^{-L_1/\beta\gamma c\tau} - e^{-L_2/\beta\gamma c\tau}$$

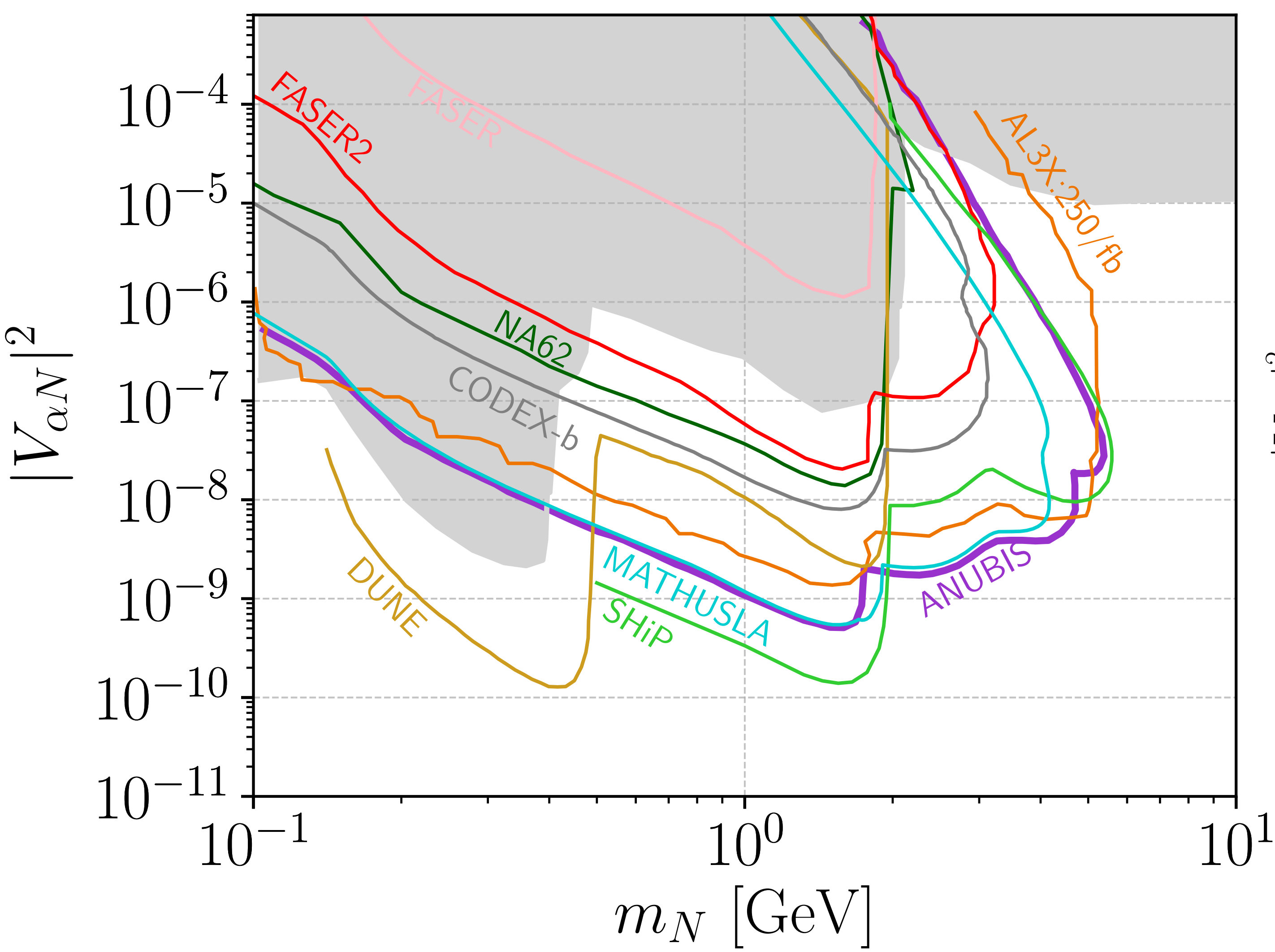


Projected number of signal events at a far detector:

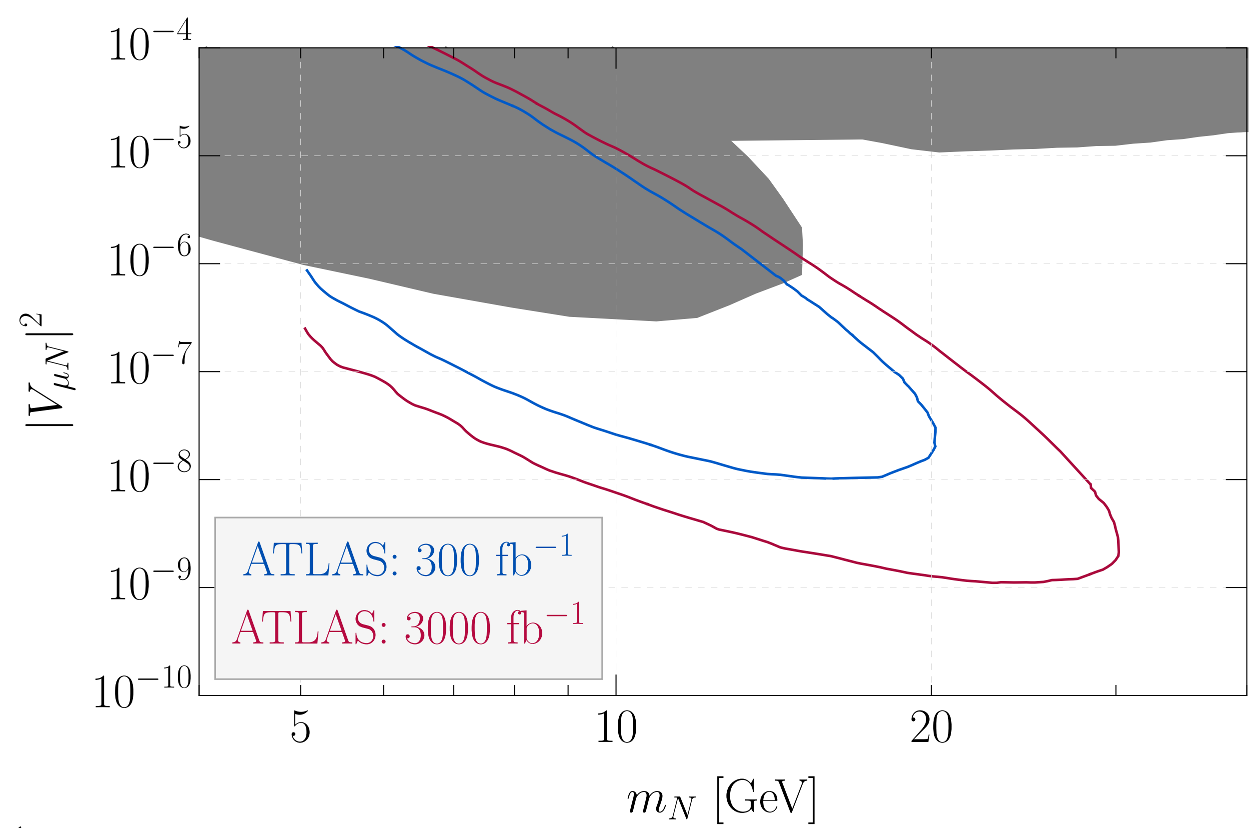
$$N_S^{\text{FD}} = 2 \cdot \underbrace{\sigma(pp \to NN)}_{\texttt{MadGraph5}} \cdot \mathscr{L} \cdot \underbrace{\langle P[N \,\text{decay in f.v.}]\rangle}_{\texttt{Pythia8}} \cdot \underbrace{\text{BR}(N \to \text{vis.})}_{\text{analytical}}$$

Minimal mixing scenario at HL-LHC

Hirsch and Wang, 1801.08947



Beltrán, Cottin, Helo, Hirsch, **AT**, Wang, 2110.15096
(update of Cottin, Helo, Hirsch, 1806.05191)



NLEFT: low-energy EFT with N

For low-energy processes at energies $E \ll \mathrm{v}$ and GeV-scale HNLs, the appropriate EFT is the low-energy EFT extended with N_R (NLEFT), which does not contain t, H, Z, $W^\pm$

$$\mathscr{L}_{\rm NLEFT} = \mathscr{L}_{\rm ren} + \sum_{d\geq 5}\sum_i c_i^{(d)}\mathcal{O}_i^{(d)}$$

$$\mathscr{L}_{\rm ren} = \mathscr{L}_{\rm QCD+QED} + i\,\overline{N_R}\partial\!\!\!/ N_R - \left[\frac{1}{2}\overline{\nu_L}M_\nu \nu_L^c + \frac{1}{2}\overline{N_R^c}M_N N_R + \overline{\nu_L}M_D N_R + \text{h.c.}\right]$$

$\mathcal{O}_i^{(d)}$ are effective operators invariant under $\mathrm{SU}(3)_C \times \mathrm{U}(1)_{\rm em}$

$d \leq 6$ operators with SM fields: Jenkins, Manohar, Stoffer, 1709.04486
$d \leq 6$ operators with N_R: Chala, **AT**, 2001.07732; Li, Ma, Schmidt, 2005.01543
$d \leq 9$ operators with N_R: Li et al., 2105.09329

Neutral current quark-N 4-fermion operators

NLEFT pair-N_R operators

	Name	Structure	$n_N=1$	$n_N=3$
LNC	$\mathcal{O}_{dN}^{V,RR}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{uN}^{V,RR}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$	4	36
	$\mathcal{O}_{dN}^{V,LR}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{uN}^{V,LR}$	$(\overline{u_L}\gamma_\mu u_L)\,(\overline{N_R}\gamma^\mu N_R)$	4	36
LNV	$\mathcal{O}_{dN}^{S,RR}$	$(\overline{d_L}d_R)\,(\overline{N_R^c}N_R)$	18	108
	$\mathcal{O}_{dN}^{T,RR}$	$(\overline{d_L}\sigma_{\mu\nu}d_R)\,(\overline{N_R^c}\sigma^{\mu\nu}N_R)$	0	54
	$\mathcal{O}_{uN}^{S,RR}$	$(\overline{u_L}u_R)\,(\overline{N_R^c}N_R)$	8	48
	$\mathcal{O}_{uN}^{T,RR}$	$(\overline{u_L}\sigma_{\mu\nu}u_R)\,(\overline{N_R^c}\sigma^{\mu\nu}N_R)$	0	24
	$\mathcal{O}_{dN}^{S,LR}$	$(\overline{d_R}d_L)\,(\overline{N_R^c}N_R)$	18	108
	$\mathcal{O}_{uN}^{S,LR}$	$(\overline{u_R}u_L)\,(\overline{N_R^c}N_R)$	8	48

NLEFT single-N_R operators

	Name	Structure	$n_N=1$	$n_N=3$
LNC	$\mathcal{O}_{d\nu N}^{S,RR}$	$(\overline{d_L}d_R)\,(\overline{\nu_L}N_R)$	54	162
	$\mathcal{O}_{d\nu N}^{T,RR}$	$(\overline{d_L}\sigma_{\mu\nu}d_R)\,(\overline{\nu_L}\sigma^{\mu\nu}N_R)$	54	162
	$\mathcal{O}_{u\nu N}^{S,RR}$	$(\overline{u_L}u_R)\,(\overline{\nu_L}N_R)$	24	72
	$\mathcal{O}_{u\nu N}^{T,RR}$	$(\overline{u_L}\sigma_{\mu\nu}u_R)\,(\overline{\nu_L}\sigma^{\mu\nu}N_R)$	24	72
	$\mathcal{O}_{d\nu N}^{S,LR}$	$(\overline{d_R}d_L)\,(\overline{\nu_L}N_R)$	54	162
	$\mathcal{O}_{u\nu N}^{S,LR}$	$(\overline{u_R}u_L)\,(\overline{\nu_L}N_R)$	24	72
LNV	$\mathcal{O}_{d\nu N}^{V,RR}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	54	162
	$\mathcal{O}_{u\nu N}^{V,RR}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	24	72
	$\mathcal{O}_{d\nu N}^{V,LR}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	54	162
	$\mathcal{O}_{u\nu N}^{V,LR}$	$(\overline{u_L}\gamma_\mu u_L)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	24	72

In the NLEFT, $n_d = 3$ and $n_u = 2$ (no top quark)

Charged current quark-N_R operators have been studied in De Vries et al., 2010.07305

Beltrán, Cottin, Helo, Hirsch, **AT**, Wang, 2210.02461

Matching to NSMEFT: pair-N operators

	NSMEFT pair-N_R operators			
	Name	Structure	$n_N = 1$	$n_N = 3$
$d=6$ (LNC)	$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{QN}$	$(\overline{Q}\gamma_\mu Q)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{HN}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)(\overline{N_R}\gamma^\mu N_R)$	1	9
$d=7$ (LNV)	$\mathcal{O}_{QNdH}$	$(\overline{Q}N_R)\,(\overline{N_R^c}d_R)\,H$	18	162
	$\mathcal{O}_{dQNH}$	$H^\dagger\,(\overline{d_R}Q)\,(\overline{N_R^c}N_R)$	18	108
	$\mathcal{O}_{QNuH}$	$(\overline{Q}N_R)\,(\overline{N_R^c}u_R)\,\tilde{H}$	18	162
	$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger\,(\overline{u_R}Q)\,(\overline{N_R^c}N_R)$	18	108

$d=6$ LNC in NLEFT ⇔ $d=6$ in NSMEFT

$$c^{V,RR}_{dN,ij} = C^{ij}_{dN} - \frac{g_Z^2}{m_Z^2} Z^{ij}_{d_R} Z_N$$

$$c^{V,RR}_{uN,ij} = C^{ij}_{uN} - \frac{g_Z^2}{m_Z^2} Z^{ij}_{u_R} Z_N$$

$$c^{V,LR}_{dN,ij} = V^*_{ki} V_{lj} C^{kl}_{QN} - \frac{g_Z^2}{m_Z^2} Z^{ij}_{d_L} Z_N$$

$$c^{V,LR}_{uN,ij} = C^{ij}_{QN} - \frac{g_Z^2}{m_Z^2} Z^{ij}_{u_L} Z_N$$

$d=6$ LNV in NLEFT ⇔ $d=7$ in NSMEFT

$$c^{S,RR}_{dN,ij} = -\frac{\mathrm{v}}{2\sqrt{2}} V^*_{ki} C^{kj}_{QNdH} \qquad c^{S,RR}_{uN,ij} = -\frac{\mathrm{v}}{2\sqrt{2}} C^{ij}_{QNuH}$$

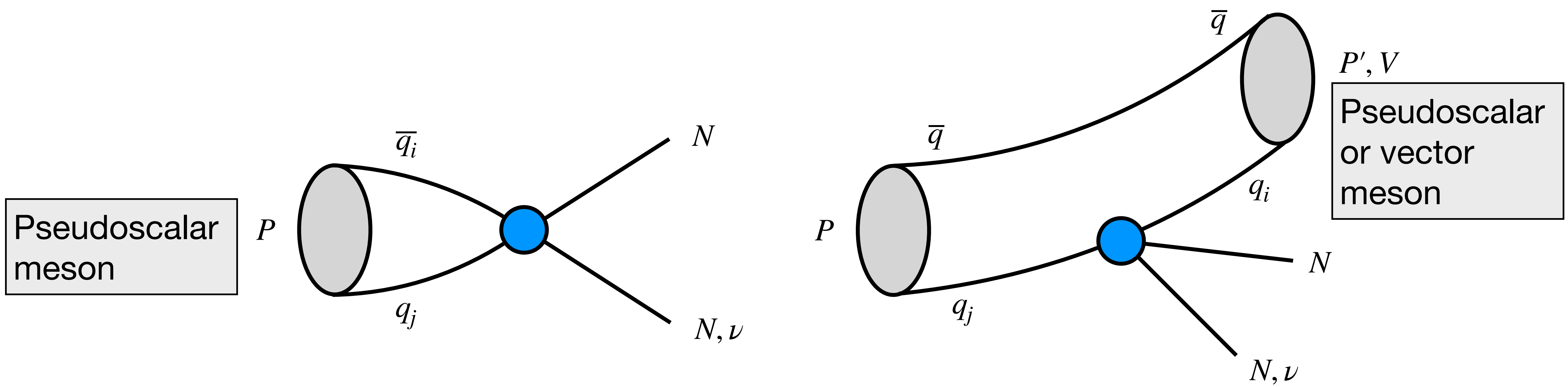
$$c^{S,LR}_{dN,ij} = \frac{\mathrm{v}}{\sqrt{2}} V_{kj} C^{ik}_{dQNH} \qquad c^{S,LR}_{uN,ij} = \frac{\mathrm{v}}{\sqrt{2}} C^{ij}_{uQNH}$$

$$g_Z \equiv \frac{e}{s_W c_W}$$

$$Z^{ij}_\psi \equiv \left(T^3_\psi - Q_\psi s_W^2\right)\delta^{ij}$$

$$Z_N \equiv -\frac{\mathrm{v}^2}{2} C_{HN}$$

HNL production in meson decays



- $c \to u$ $\quad D^0 \to NN\ (\nu N)$ $\quad D^0 \to \pi^0, \eta, \eta'\ (\rho^0, \omega)$ for $q = u$
  - $D^+ \to \pi^+\ (\rho^+)$ for $q = d$
  - $D_s^+ \to K^+\ (K^{*+})$ for $q = s$
  - $\eta_c \to \overline{D^0}\ (\overline{D^{*0}})$ for $q = c$
  - $B_c^+ \to B^+\ (B^{*+})$ for $q = b$
- $b \to d$ $\quad B^0 \to NN\ (\nu N)$ $\quad \ldots$
- $b \to s$ $\quad B_s^0 \to NN\ (\nu N)$ $\quad \ldots$
- $s \to d$ $\quad K_{S/L} \to NN\ (\nu N)$ $\quad \ldots$

HNLs from *D*- and *B*-meson decays: Beltrán, Cottin, Helo, Hirsch, **AT**, Wang, 2210.02461

HNLs from *K*-meson decays: Beltrán, Günther, Hirsch, **AT**, Wang, 2309.11546

Partial meson decay widths

Two-body decay:

$$\Gamma(P \to NN) = \frac{m_P}{32\pi}\sqrt{1 - \frac{4m_N^2}{m_P^2}}\Bigg[2\left|f_P\right|^2 \left|c_{qN,ij}^{V,RR} - c_{qN,ij}^{V,LR}\right|^2 m_N^2$$

$$+\left|f_P^S\right|^2\Bigg\{\left(\left|c_{qN,ij}^{S,RR} - c_{qN,ij}^{S,LR}\right|^2 + \left|c_{qN,ji}^{S,RR} - c_{qN,ji}^{S,LR}\right|^2\right)\left(1 - \frac{2m_N^2}{m_P^2}\right)$$

$$+2\left[\left(c_{qN,ij}^{S,RR} - c_{qN,ij}^{S,LR}\right)\left(c_{qN,ji}^{S,RR} - c_{qN,ji}^{S,LR}\right) + \text{h.c.}\right]\frac{m_N^2}{m_P^2}\Bigg\}$$

$$+f_P f_P^S\left\{\left(c_{qN,ij}^{V,RR} - c_{qN,ij}^{V,LR}\right)\left(c_{qN,ij}^{S,RR\,*} - c_{qN,ij}^{S,LR\,*} + c_{qN,ji}^{S,RR} - c_{qN,ji}^{S,LR}\right) m_N + \text{h.c.}\right\}\Bigg]$$

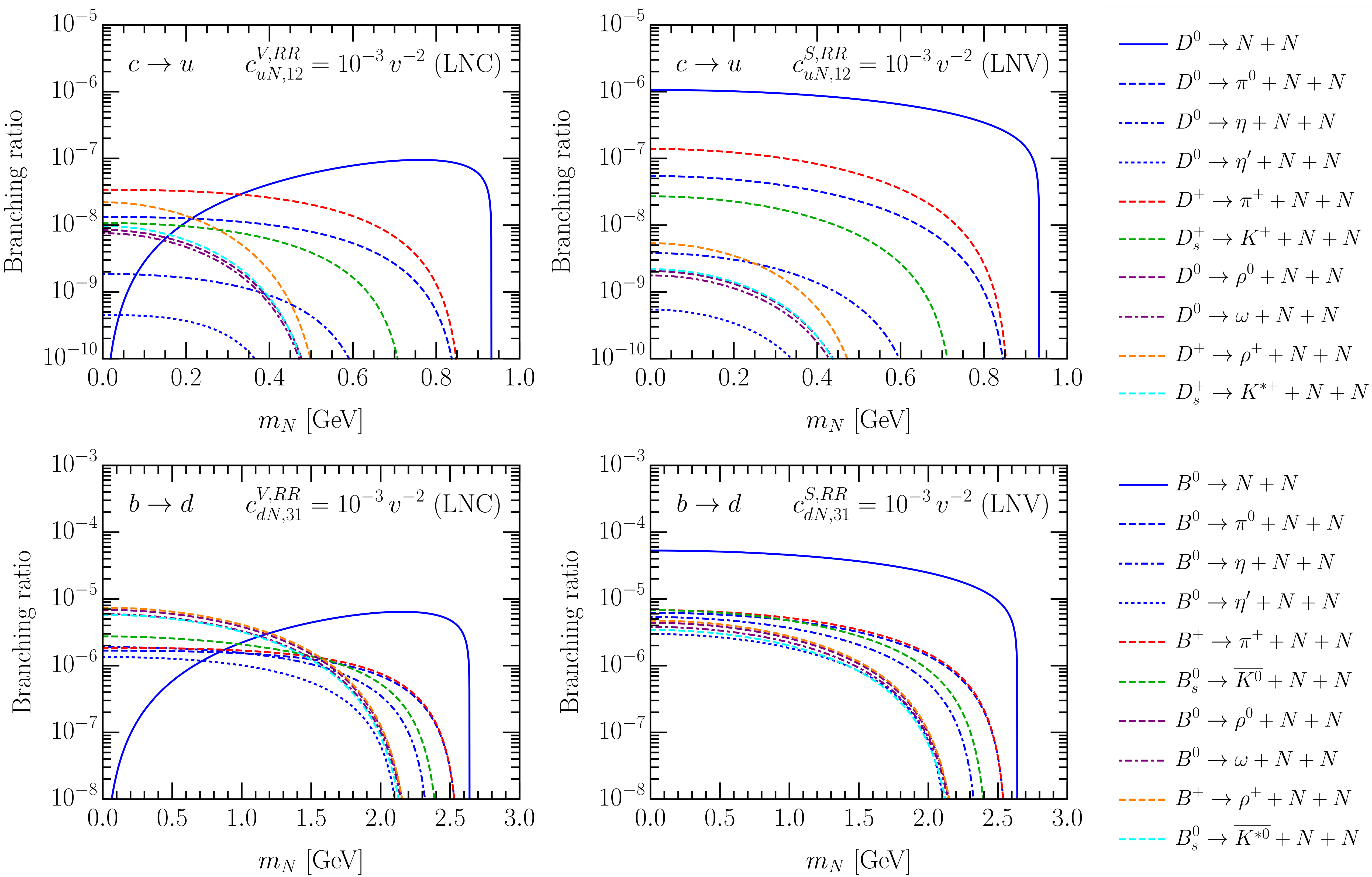
$$\langle 0|\overline{q}_i\gamma^\mu\gamma_5 q_j|P(p)\rangle = i f_P p^\mu \qquad\qquad \langle 0|\overline{q}_i\gamma_5 q_j|P(p)\rangle = i\frac{m_P^2}{m_{q_i} + m_{q_j}} f_P \equiv i f_P^S$$

Three-body decays require the knowledge of transition form factors:

$$\langle P'(p')|\mathcal{J}|P(p)\rangle \quad \text{and} \quad \langle V(p',\epsilon)|\mathcal{J}|P(p)\rangle$$

$$\mathcal{J} \in \{\overline{q}_i\gamma^\mu q_j\,,\ \overline{q}_i\gamma^\mu\gamma_5 q_j\,,\ \overline{q}_i q_j\,,\ \overline{q}_i\gamma_5 q_j\,,\ \overline{q}_i\sigma^{\mu\nu}q_j\}$$

Branching ratios of D and B meson decays



Number of events

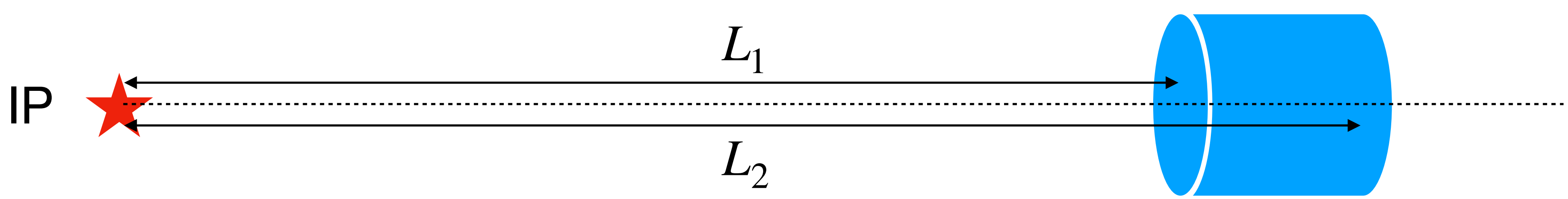
Projected number of signal events:

$$N_S = \sum_i 2 \cdot N_{M_i} \cdot \mathrm{BR}(M_i \to NN + \text{anything}) \cdot \langle P[N\,\text{decay}] \rangle \cdot \mathrm{BR}(N \to \text{vis.})$$

analytical Pythia8 analytical

Decay probability of an HNL in a far detector (approximately):

$$P[N\,\text{decay}] = e^{-L_1/\beta\gamma c\tau} - e^{-L_2/\beta\gamma c\tau}$$

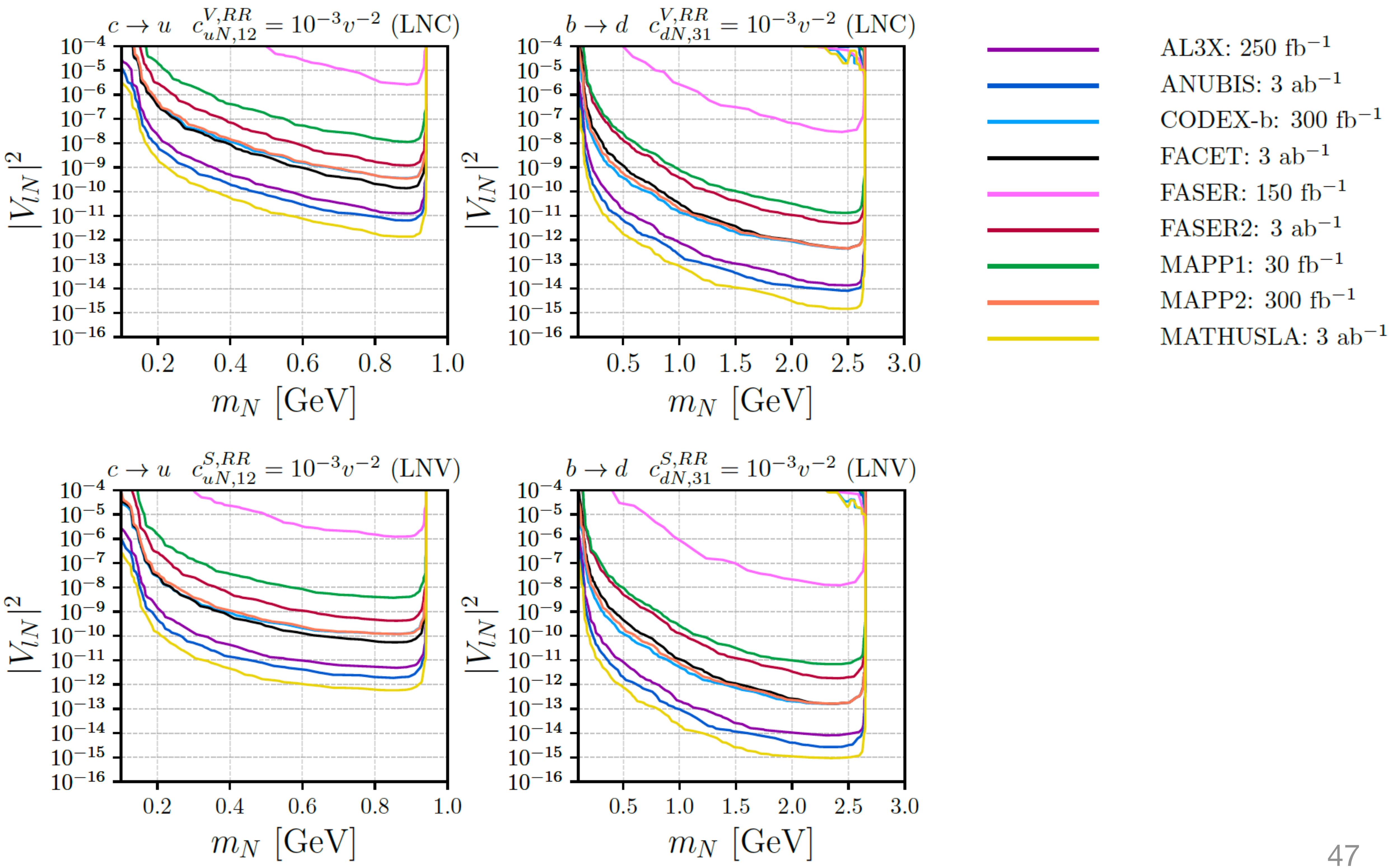


Inclusive production numbers of *D* and *B* mesons at the HL-LHC with $\sqrt{s} = 14$ TeV and $\mathscr{L} = 3$ ab^{-1}:

D^0	$D^\pm$	$D_s^\pm$	B^0	$B^\pm$	B_s^0
4.12×10^{16}	2.16×10^{16}	7.02×10^{15}	1.58×10^{15}	1.58×10^{15}	2.73×10^{14}

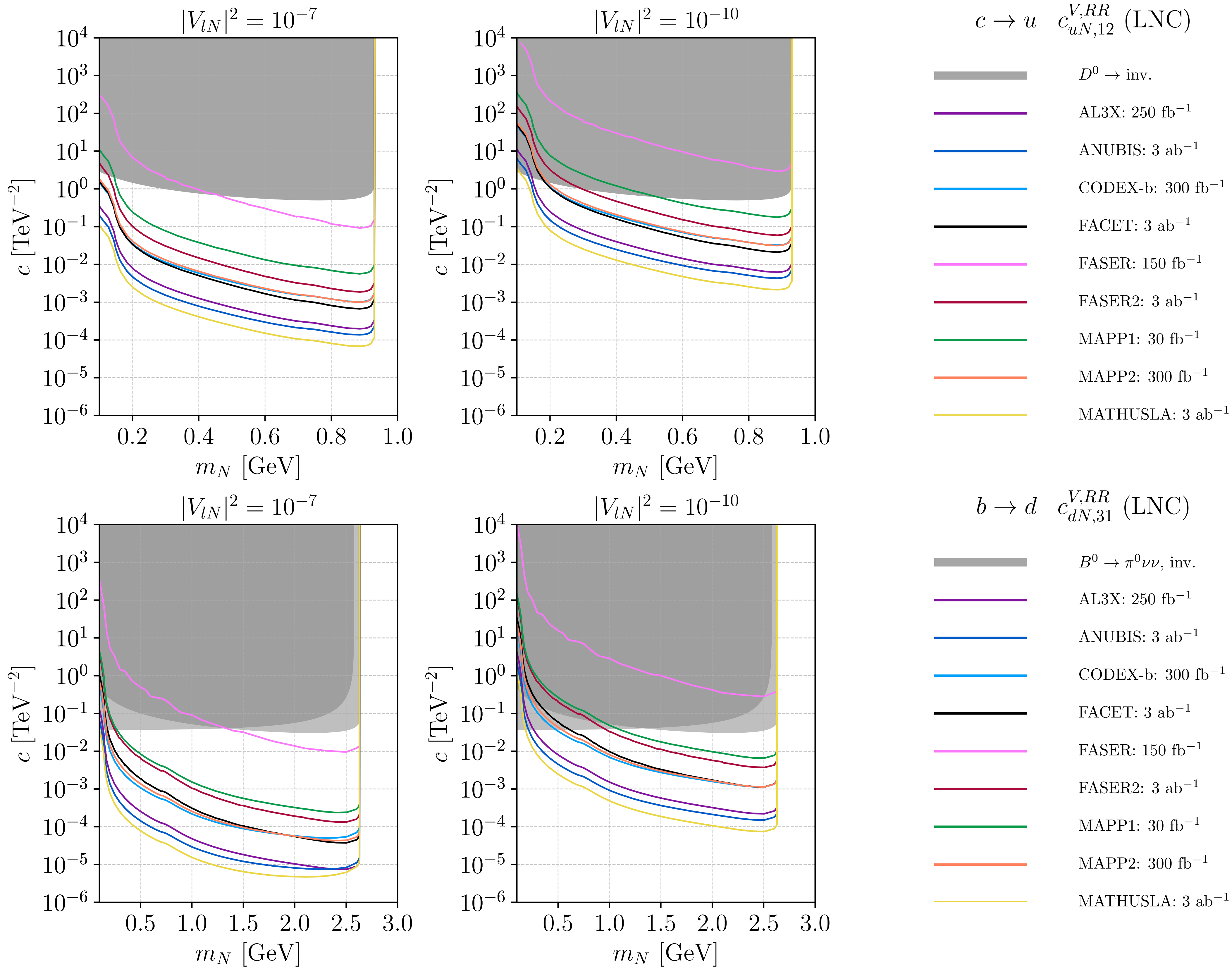
4-fermion NLEFT operators at HL-LHC

Reach on active-heavy neutrino mixing (for fixed Wilson coefficient)



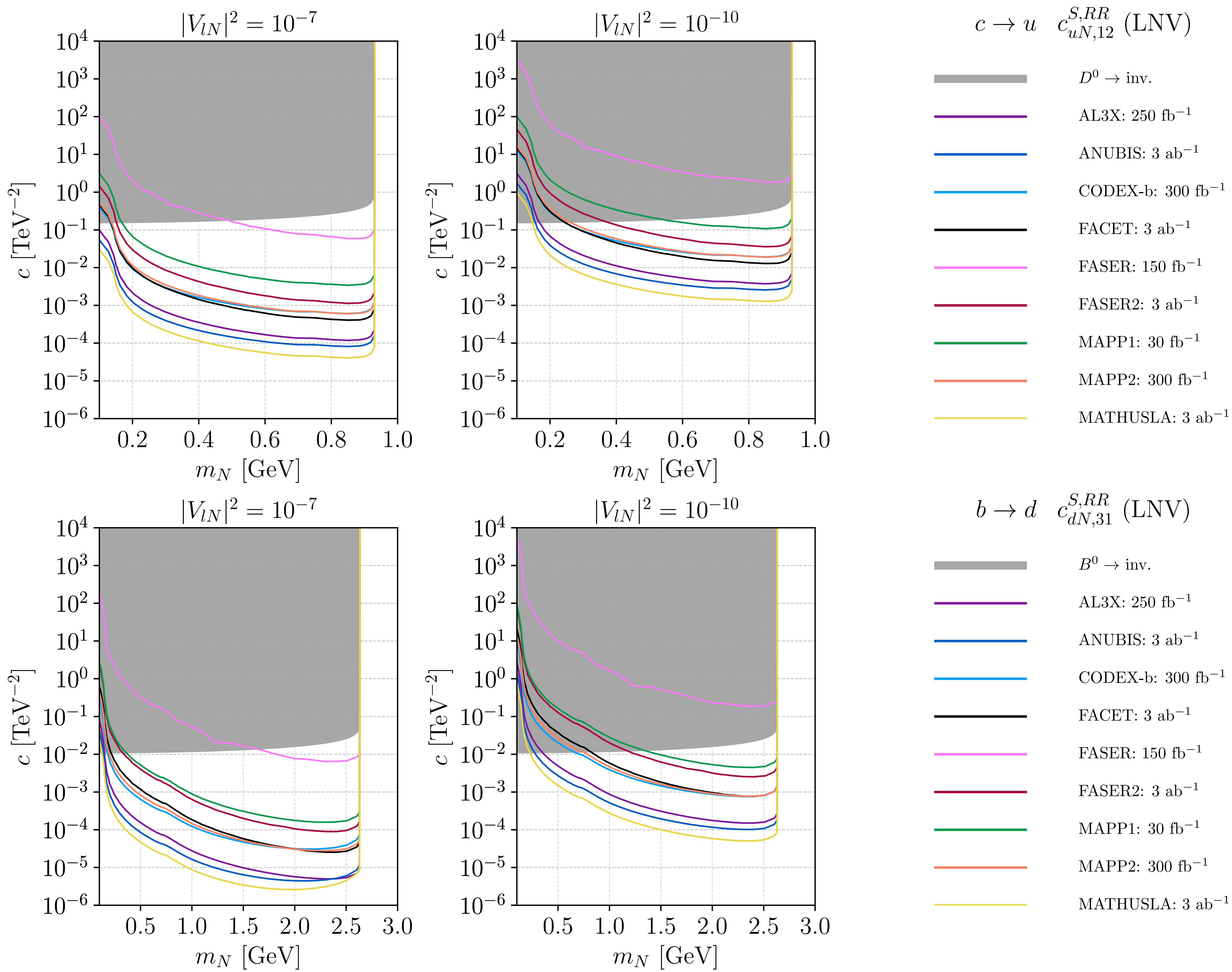
4-fermion NLEFT operators at HL-LHC

Reach on Wilson coefficients (for fixed active-heavy neutrino mixing)



4-fermion NLEFT operators at HL-LHC

Reach on Wilson coefficients (for fixed active-heavy neutrino mixing)



New physics scales

LNC operators:

$$c^{(6)}_{\rm NLEFT} \sim C^{(6)}_{\rm NSMEFT} \sim \frac{1}{\Lambda^2} \quad \Rightarrow \quad \Lambda \sim \left[\frac{1}{c^{(6)}_{\rm NLEFT}}\right]^{1/2}$$

$$c^{(6)}_{\rm NLEFT} \lesssim 10^{-4} \;\; \left(10^{-5}\right) \quad \Rightarrow \quad \Lambda \gtrsim 100 \;(316) \;\text{TeV}$$

LNV operators:

$$c^{(6)}_{\rm NLEFT} \sim \frac{\rm v}{2\sqrt{2}} C^{(7)}_{\rm NSMEFT} \sim \frac{1}{2\sqrt{2}} \frac{\rm v}{\Lambda^3} \quad \Rightarrow \quad \Lambda \sim \left[\frac{1}{2\sqrt{2}} \frac{\rm v}{c^{(6)}_{\rm NLEFT}}\right]^{1/3}$$

$$c^{(6)}_{\rm NLEFT} \lesssim 10^{-4} \;\; \left(10^{-5}\right) \quad \Rightarrow \quad \Lambda \gtrsim 10 \;(21) \;\text{TeV}$$

Matching to NSMEFT: single-N operators

NSMEFT single-N_R operators

	Name	Structure	$n_N=1$	$n_N=3$
$d=6$ (LNC)	$\mathcal{O}_{LNQd}$	$\epsilon_{ab}\left(\overline{L^a}N_R\right)\left(\overline{Q^b}d_R\right)$	54	162
	$\mathcal{O}_{LdQN}$	$\epsilon_{ab}\left(\overline{L^a}d_R\right)\left(\overline{Q^b}N_R\right)$	54	162
	$\mathcal{O}_{QuNL}$	$\left(\overline{Q}u_R\right)\left(\overline{N_R}L\right)$	54	162
$d=7$ (LNV)	$\mathcal{O}_{dNLH}$	$\epsilon_{ab}\left(\overline{d_R}\gamma_\mu d_R\right)\left(\overline{N_R^c}\gamma^\mu L^a\right)H^b$	54	162
	$\mathcal{O}_{uNLH}$	$\epsilon_{ab}\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{N_R^c}\gamma^\mu L^a\right)H^b$	54	162
	$\mathcal{O}_{QNLH1}$	$\epsilon_{ab}\left(\overline{Q}\gamma_\mu Q\right)\left(\overline{N_R^c}\gamma^\mu L^a\right)H^b$	54	162
	$\mathcal{O}_{QNLH2}$	$\epsilon_{ab}\left(\overline{Q}\gamma_\mu Q^a\right)\left(\overline{N_R^c}\gamma^\mu L^b\right)H$	54	162
	$\mathcal{O}_{NL1}$	$\epsilon_{ab}\left(\overline{N_R^c}\gamma_\mu L^a\right)\left(iD^\mu H^b\right)\left(H^\dagger H\right)$	6	18
	$\mathcal{O}_{NL2}$	$\epsilon_{ab}\left(\overline{N_R^c}\gamma_\mu L^a\right)H^b\left(H^\dagger i\overleftrightarrow{D^\mu}H\right)$	6	18

$d=6$ LNC in NLEFT $\Leftrightarrow$ $d=6$ in NSMEFT

$$c^{S,RR}_{d\nu N,ij\alpha} = V^*_{ki}\left(C^{\alpha kj}_{LNQd} - \frac{1}{2}C^{\alpha jk}_{LdQN}\right)$$

$$c^{T,RR}_{d\nu N,ij\alpha} = -\frac{1}{8}V^*_{ki}C^{\alpha jk}_{LdQN}$$

$$c^{S,RR}_{u\nu N,ij\alpha} = c^{T,RR}_{u\nu N,ij\alpha} = c^{S,LR}_{d\nu N,ij\alpha} = 0$$

$$c^{S,LR}_{u\nu N,ij\alpha} = C^{ji\alpha\,*}_{QuNL}$$

$d=6$ LNV in NLEFT $\Leftrightarrow$ $d=7$ in NSMEFT

$$c^{V,RR}_{d\nu N,ij\alpha} = -\frac{\mathrm{v}}{\sqrt{2}}C^{ij\alpha}_{dNLH} - \frac{g_Z^2}{m_Z^2}Z^{ij}_{d_R}Z^{\alpha}_{\nu N}$$

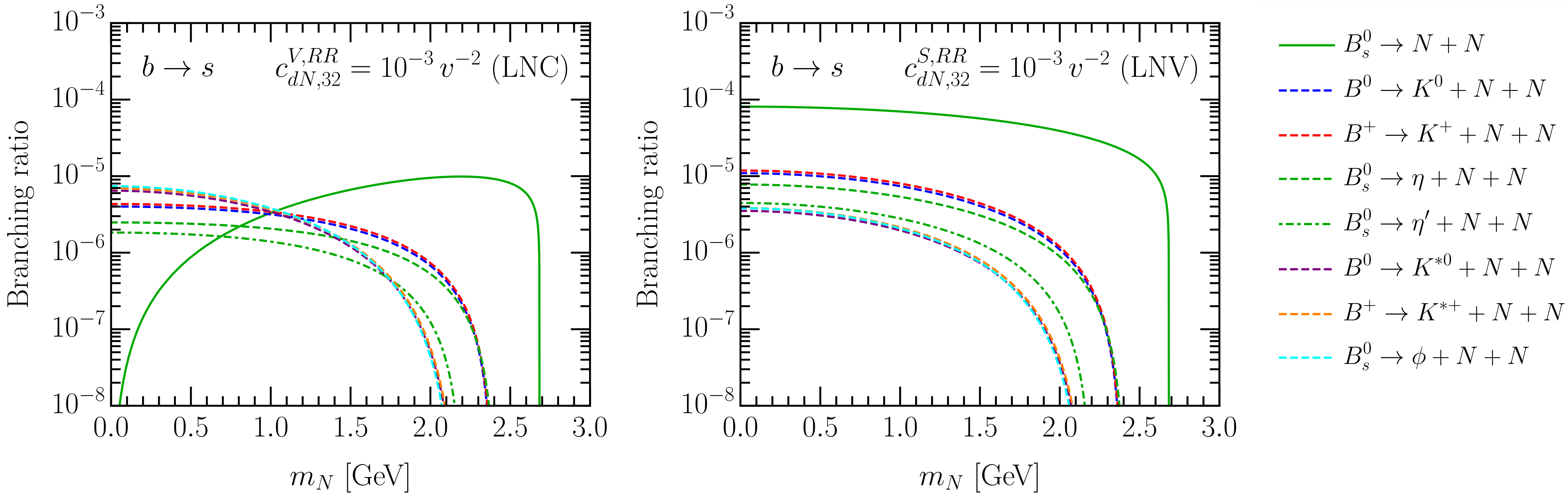
$$c^{V,RR}_{u\nu N,ij\alpha} = -\frac{\mathrm{v}}{\sqrt{2}}C^{ij\alpha}_{uNLH} - \frac{g_Z^2}{m_Z^2}Z^{ij}_{u_R}Z^{\alpha}_{\nu N}$$

$$c^{V,LR}_{d\nu N,ij\alpha} = -\frac{\mathrm{v}}{\sqrt{2}}V^*_{ki}V_{lj}\left(C^{kl\alpha}_{QNLH1} - C^{kl\alpha}_{QNLH2}\right) - \frac{g_Z^2}{m_Z^2}Z^{ij}_{d_L}Z^{\alpha}_{\nu N}$$

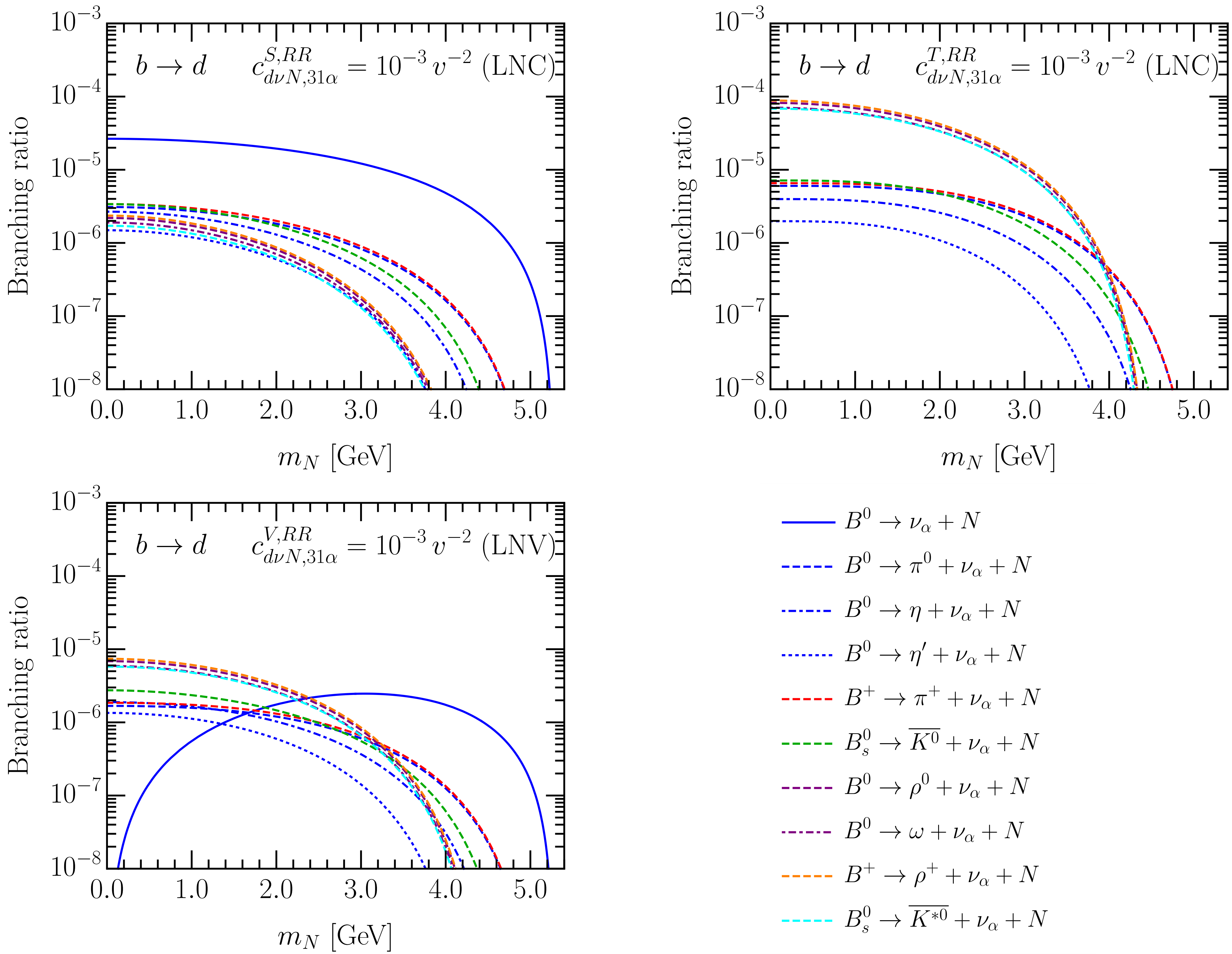
$$c^{V,LR}_{u\nu N,ij\alpha} = -\frac{\mathrm{v}}{\sqrt{2}}C^{ij\alpha}_{QNLH1} - \frac{g_Z^2}{m_Z^2}Z^{ij}_{u_L}Z^{\alpha}_{\nu N}$$

$$Z^{\alpha}_{\nu N} \equiv \frac{\mathrm{v}^3}{4\sqrt{2}}\left(C^{\alpha}_{NL1} + 2C^{\alpha}_{NL2}\right)$$

Branching ratios: b → s scenario



Branching ratios: single-N operators



Other experiments

AL3X: A Laboratory for Long-Lived eXotics
@ALICE
Cylinder with 0.85 m $< r < 5$ m and $\ell = 12$ m
$c\tau \sim 10$ m

FACET: Forward-Aperture CMS ExTension
@CMS
Cylinder with $r = 0.5$ m and $\ell = 18$ m
$c\tau \sim 100$ m

MoEDAL-MAPP: MoEDAL's Apparatus for Penetrating Particles
(MoEDAL: Monopole and Exotics Detector at the LHC)
@LHCb
MAPP1: ~ 130 m^3
MAPP2: ~ 430 m^3
$c\tau \sim 50$ m

Existing constraints on BRs

PDG 2022

Decay	Limit on BR	Decay	Limit on BR	Decay	Limit on BR
$D^0 \to \text{inv.}$	$\mathbf{9.4 \times 10^{-5}}$	$B^0 \to \text{inv.}$	$\mathbf{2.4 \times 10^{-5}}$	$B_s^0 \to \phi\nu\overline{\nu}$	5.4×10^{-3}
		$B^0 \to \pi^0\nu\overline{\nu}$	$\mathbf{9.0 \times 10^{-6}}$	$B^0 \to K^0\nu\overline{\nu}$	2.6×10^{-5}
		$B^0 \to \rho^0\nu\overline{\nu}$	4.0×10^{-5}	$B^0 \to K^{*0}\nu\overline{\nu}$	1.8×10^{-5}
		$B^+ \to \pi^+\nu\overline{\nu}$	1.4×10^{-5}	$B^+ \to K^+\nu\overline{\nu}$	$\mathbf{1.6 \times 10^{-5}}$
		$B^+ \to \rho^+\nu\overline{\nu}$	3.0×10^{-5}	$B^+ \to K^{*+}\nu\overline{\nu}$	4.0×10^{-5}

BELL'17

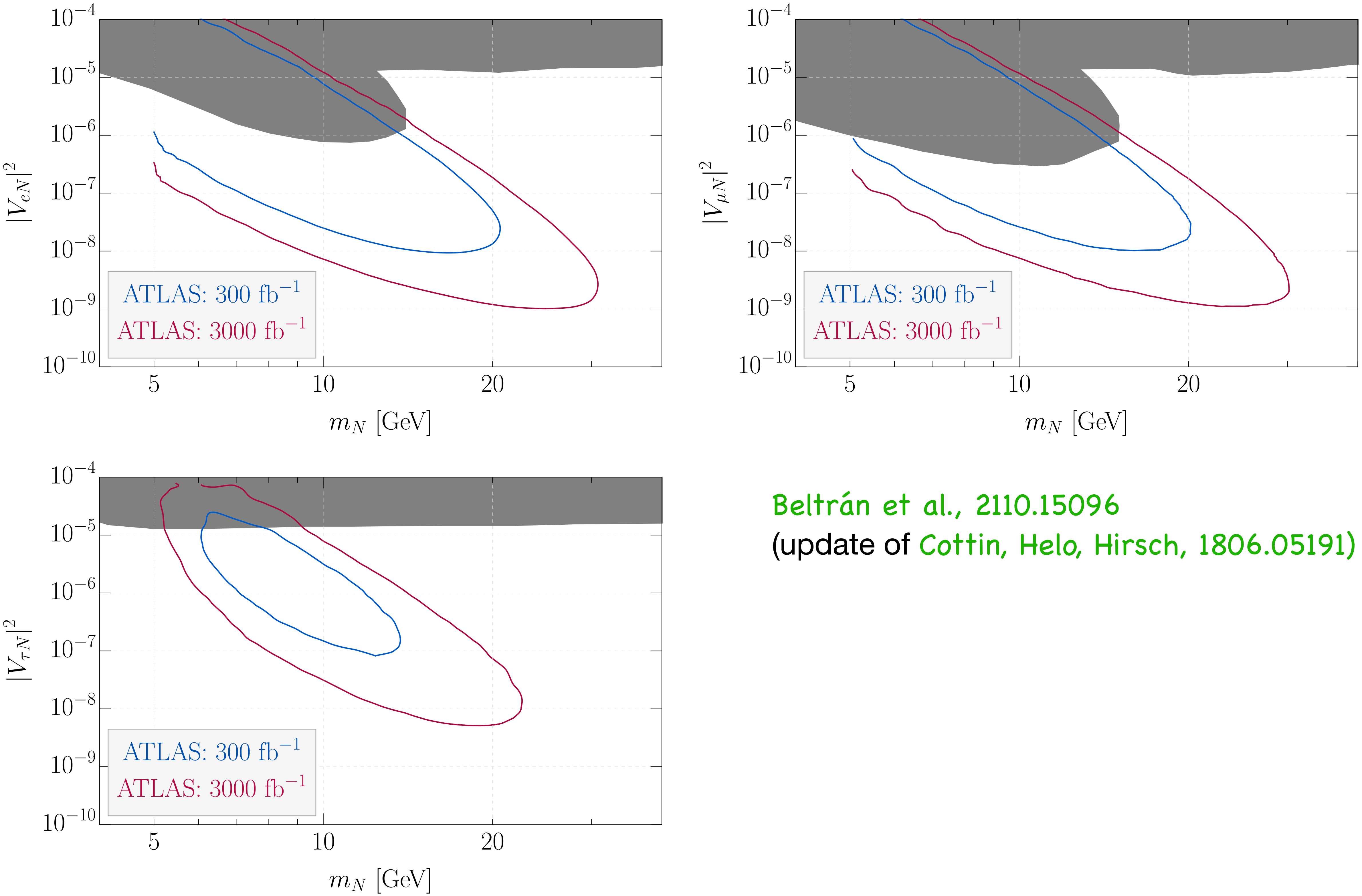
BABAR'12
BELL'17

BABAR'13

Decay	Branching ratio
$K_L \to \pi^0\nu\overline{\nu}$	$< 3.0 \times 10^{-9}$ at 90% C.L.
$K^+ \to \pi^+\nu\overline{\nu}$	$(1.14^{+0.40}_{-0.33}) \times 10^{-10}$

Decay	Branching ratio
$K^+ \to e^+\nu_e$	$(1.582 \pm 0.007) \times 10^{-5}$
$K^+ \to \pi^0 e^+\nu_e$	$(5.07 \pm 0.04) \times 10^{-2}$
$K_S \to \pi^\pm e^\mp\nu_e$	$(7.04 \pm 0.08) \times 10^{-4}$
$K_L \to \pi^\pm e^\mp\nu_e$	$(40.55 \pm 0.11) \times 10^{-2}$

Minimal 3+1 scenario



Beltrán et al., 2110.15096
(update of Cottin, Helo, Hirsch, 1806.05191)

Long-lived HNLs

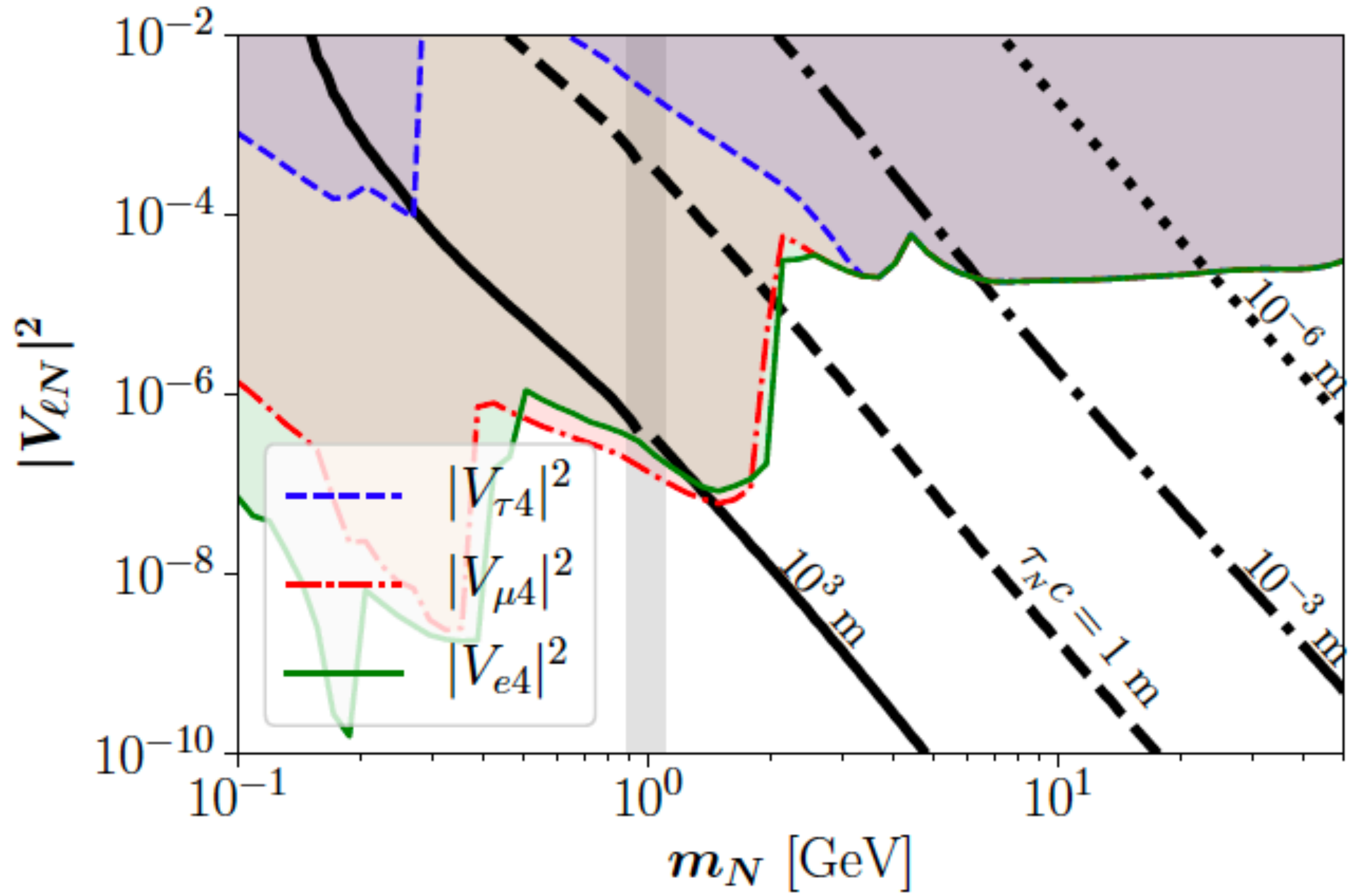


Figure from
Abada, Bernal, Losada, Marcano, 1807.10024

HNLs can be long-lived particles (LLPs)

HNL decay width calculation:
Atre, Han, Pascoli, Zhang, 0901.3589
Bondarenko, Boyarsky, Gorbunov, Ruchayskiy, 1805.08567

4-fermion quark-N operators (kaons)

NLEFT pair-N_R operators (NC)

LNC operators		
Name	Structure	N_{pars}
$\mathcal{O}^{V,RR}_{dN}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$	9
$\mathcal{O}^{V,RR}_{uN}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$	4
$\mathcal{O}^{V,LR}_{dN}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{N_R}\gamma^\mu N_R)$	9
$\mathcal{O}^{V,LR}_{uN}$	$(\overline{u_L}\gamma_\mu u_L)\,(\overline{N_R}\gamma^\mu N_R)$	4

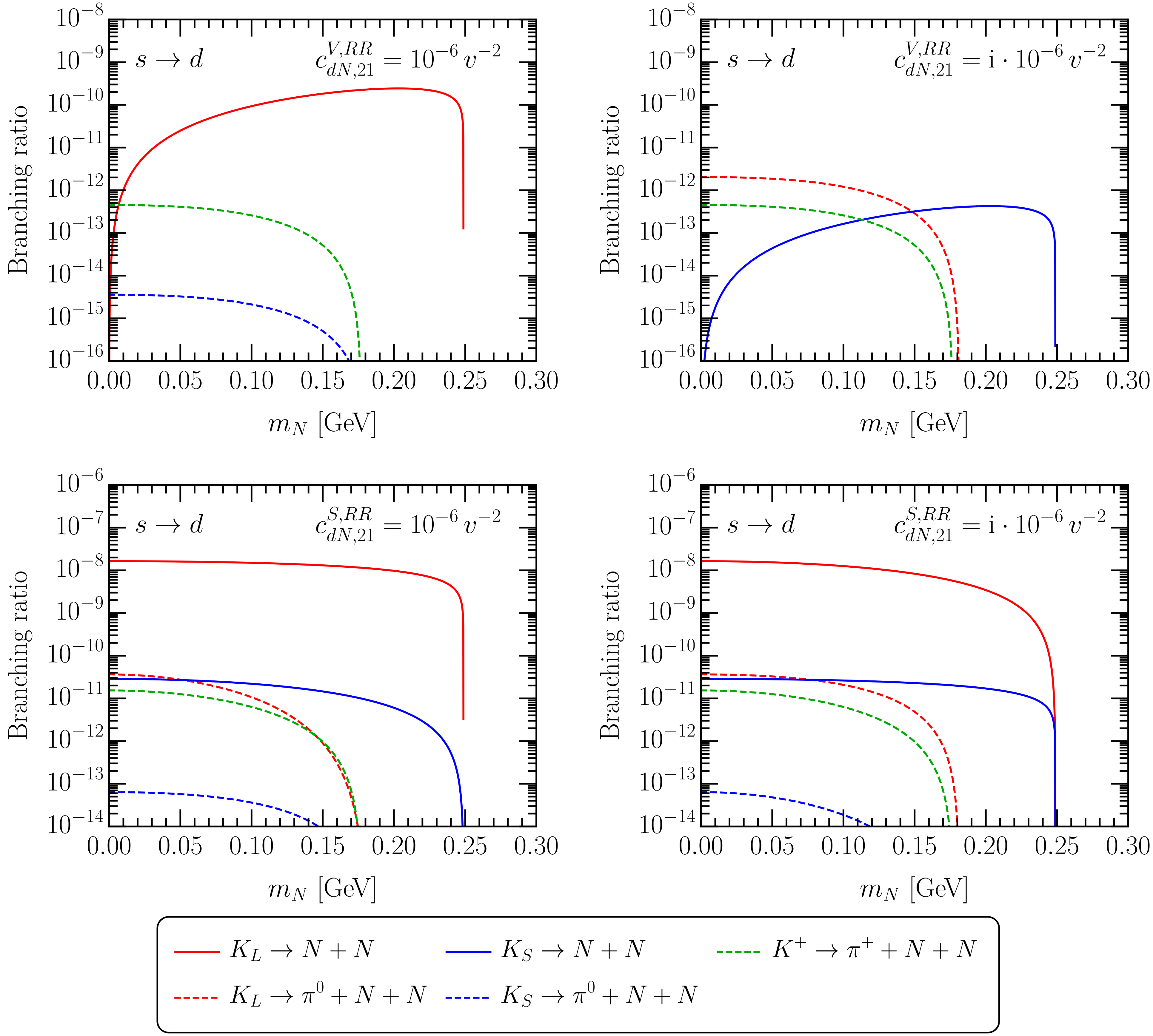
LNV operators		
Name	Structure	N_{pars}
$\mathcal{O}^{S,RR}_{dN}$	$(\overline{d_L}d_R)\,(\overline{N_R^c}N_R)$	18
$\mathcal{O}^{S,RR}_{uN}$	$(\overline{u_L}u_R)\,(\overline{N_R^c}N_R)$	8
$\mathcal{O}^{S,LR}_{dN}$	$(\overline{d_R}d_L)\,(\overline{N_R^c}N_R)$	18
$\mathcal{O}^{S,LR}_{uN}$	$(\overline{u_R}u_L)\,(\overline{N_R^c}N_R)$	8

NLEFT single-N_R operators (CC)

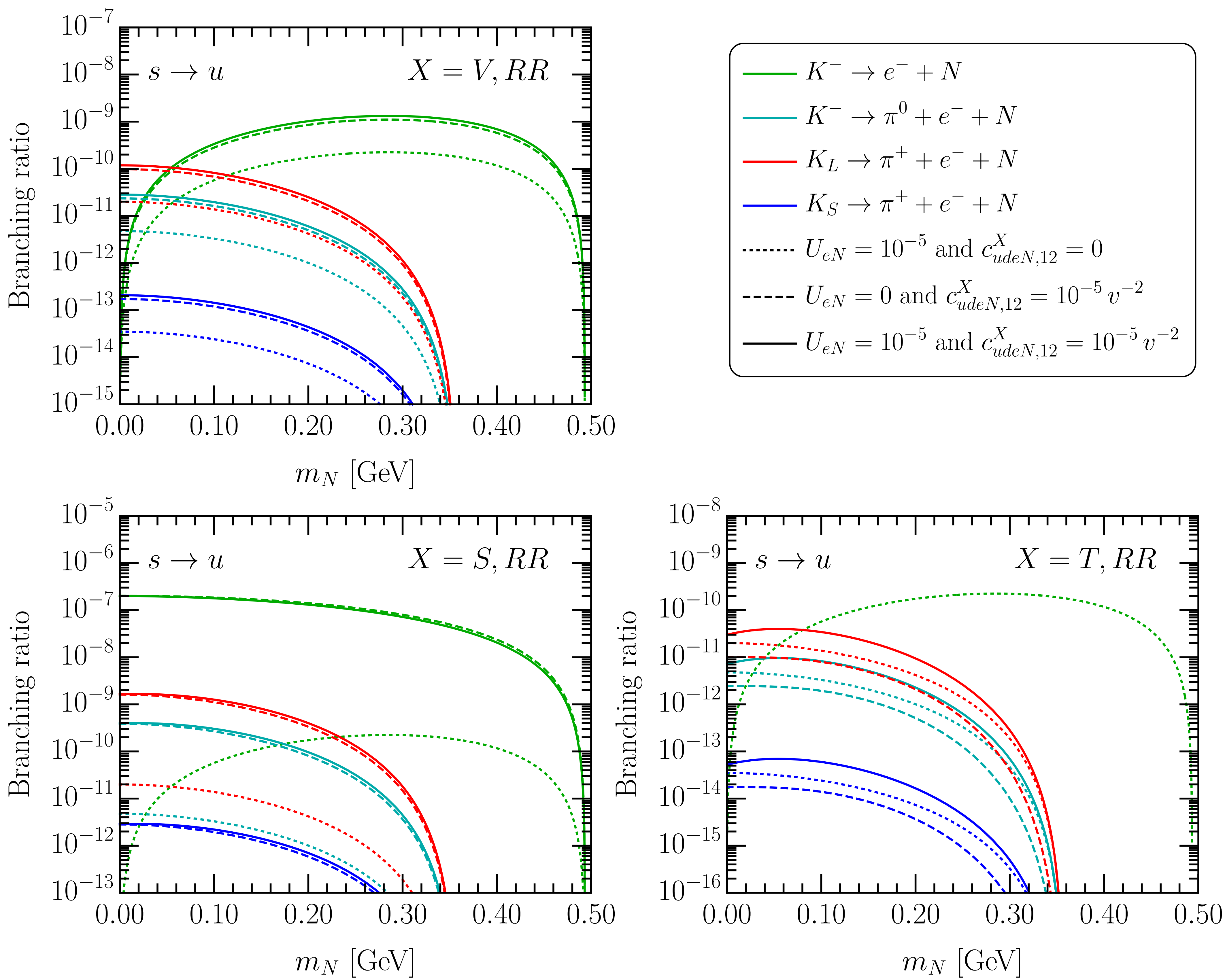
LNC operators	
Name	Structure
$\mathcal{O}^{V,RR}_{udeN}$	$(\overline{u_R}\gamma_\mu d_R)\,(\overline{e_R}\gamma^\mu N_R)$
$\mathcal{O}^{V,LR}_{udeN}$	$(\overline{u_L}\gamma_\mu d_L)\,(\overline{e_R}\gamma^\mu N_R)$
$\mathcal{O}^{S,RR}_{udeN}$	$(\overline{u_L}d_R)\,(\overline{e_L}N_R)$
$\mathcal{O}^{T,RR}_{udeN}$	$(\overline{u_L}\sigma_{\mu\nu}d_R)\,(\overline{e_L}\sigma^{\mu\nu}N_R)$
$\mathcal{O}^{S,LR}_{udeN}$	$(\overline{u_R}d_L)\,(\overline{e_L}N_R)$

LNV operators	
Name	Structure
$\mathcal{O}^{V,LL}_{udeN}$	$(\overline{u_L}\gamma_\mu d_L)\,(\overline{e_L}\gamma^\mu N_R^c)$
$\mathcal{O}^{V,RL}_{udeN}$	$(\overline{u_R}\gamma_\mu d_R)\,(\overline{e_L}\gamma^\mu N_R^c)$
$\mathcal{O}^{S,LL}_{udeN}$	$(\overline{u_R}d_L)\,(\overline{e_R}N_R^c)$
$\mathcal{O}^{T,LL}_{udeN}$	$(\overline{u_R}\sigma_{\mu\nu}d_L)\,(\overline{e_R}\sigma^{\mu\nu}N_R^c)$
$\mathcal{O}^{S,RL}_{udeN}$	$(\overline{u_L}d_R)\,(\overline{e_R}N_R^c)$

Branching ratios: pair-N operators



Branching ratios: single-N operators

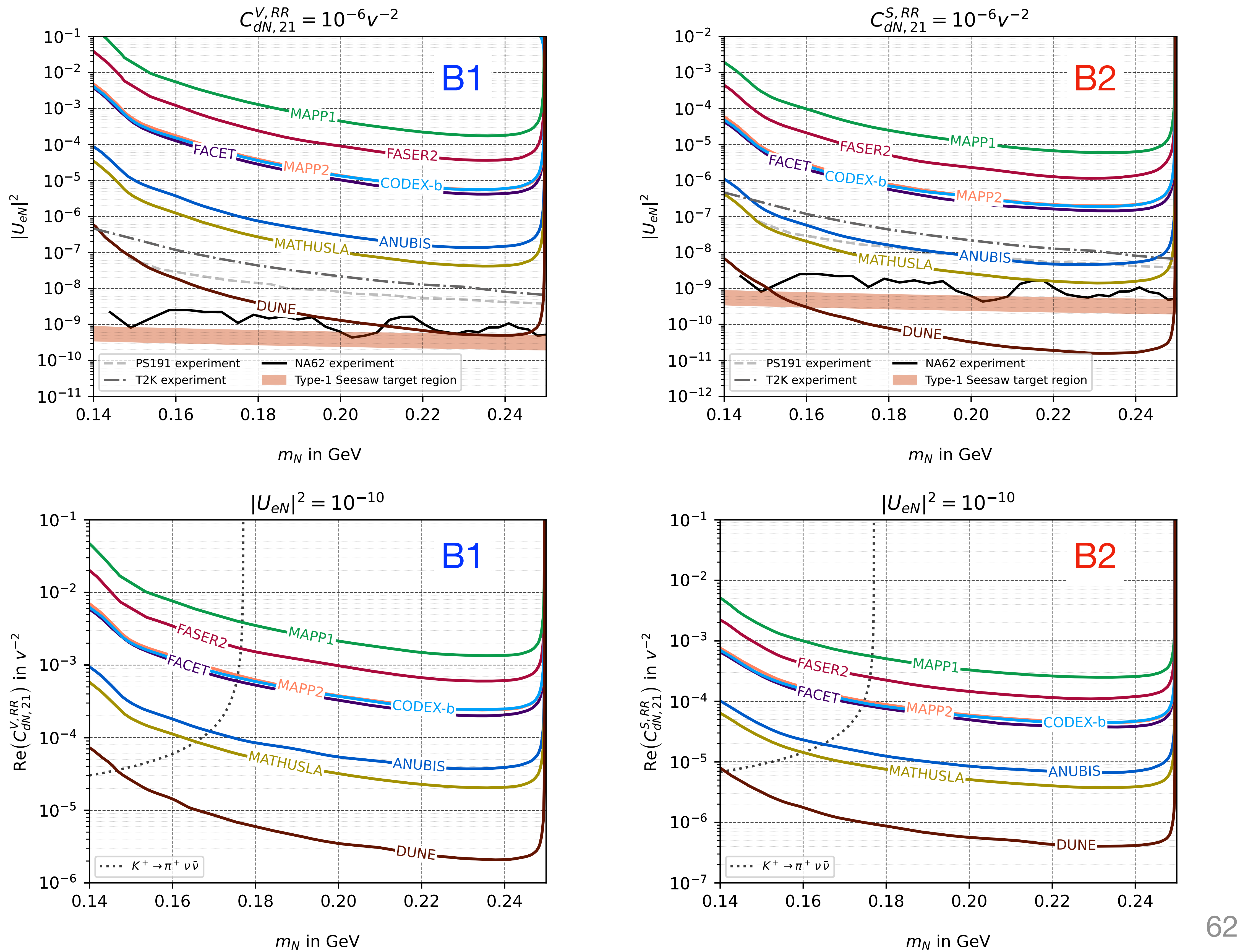


Benchmark scenarios

Benchmark	Production	Decay
B1.1	$c^{V,RR}_{dN,21} \in \mathbb{R}$	U_{eN}
B1.2	$c^{V,RR}_{dN,21} \in i\,\mathbb{R}$	U_{eN}
B2.1	$c^{S,RR}_{dN,21} \in \mathbb{R}$	U_{eN}
B2.2	$c^{S,RR}_{dN,21} \in i\,\mathbb{R}$	U_{eN}

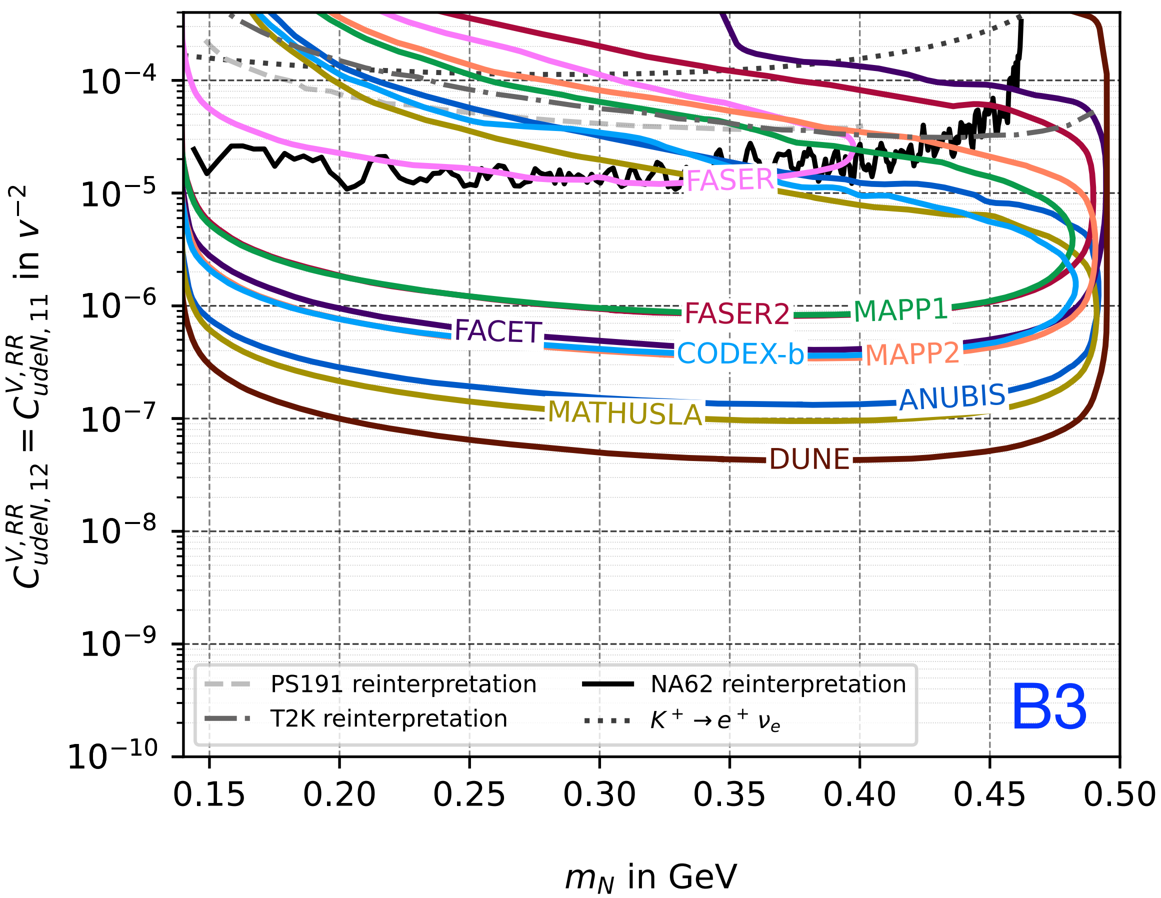
Benchmark	Production	Decay
B3	$c^{V,RR}_{udeN,12}$	$c^{V,RR}_{udeN,11}$
B4	$c^{S,RR}_{udeN,12}$	$c^{S,RR}_{udeN,11}$
B5	$c^{V,RR}_{udeN,12}$ and U_{eN}	U_{eN}
B6	$c^{S,RR}_{udeN,12}$ and U_{eN}	U_{eN}
B7	$c^{V,RL}_{udeN,12}$ and U_{eN}	U_{eN}
B8	$c^{S,RL}_{udeN,12}$ and U_{eN}	U_{eN}

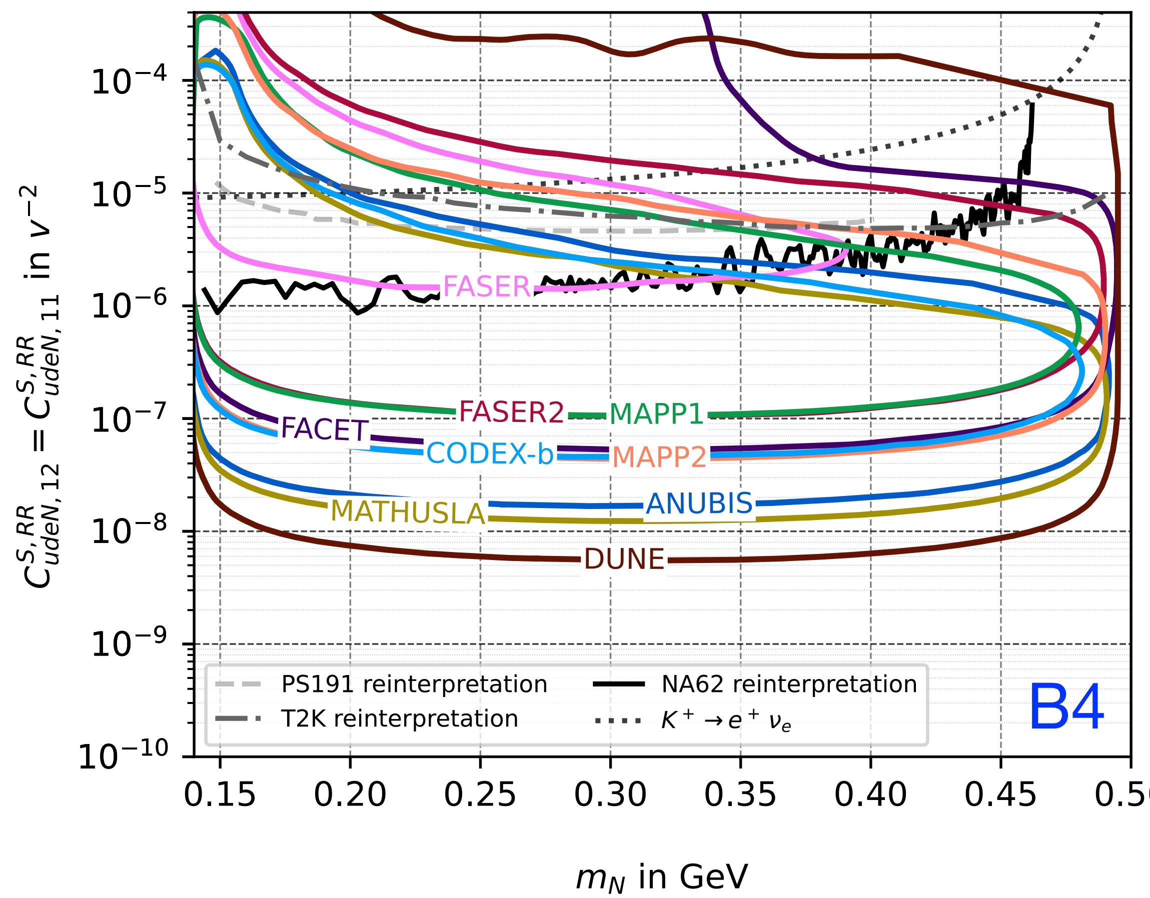
Pair-N benchmarks B1 and B2



Single-N benchmarks B3 and B4

Production and decay of N through the same operator structure $\mathcal{O}_{udeN}^{V/S,RR}$, but with different quark flavour indices: 12 (for production) vs. 11 (for decay)





Single-N benchmarks B5 and B7