Università di Pisa

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI PISA

Long-lived HNLs at the LHC: four-fermion operators

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BLED 2024 Breaking Lepton Number in High Energy Direct Searches

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. Phenomenological signatures of stable HNLs
4. Long-lived particle detectors at the high-luminosity LHC (HL-LHC)
5. Sensitivity to long-lived HNLs produced in partonic collisions
6. Sensitivity to long-lived HNLs produced in meson decays
7. 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:

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

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

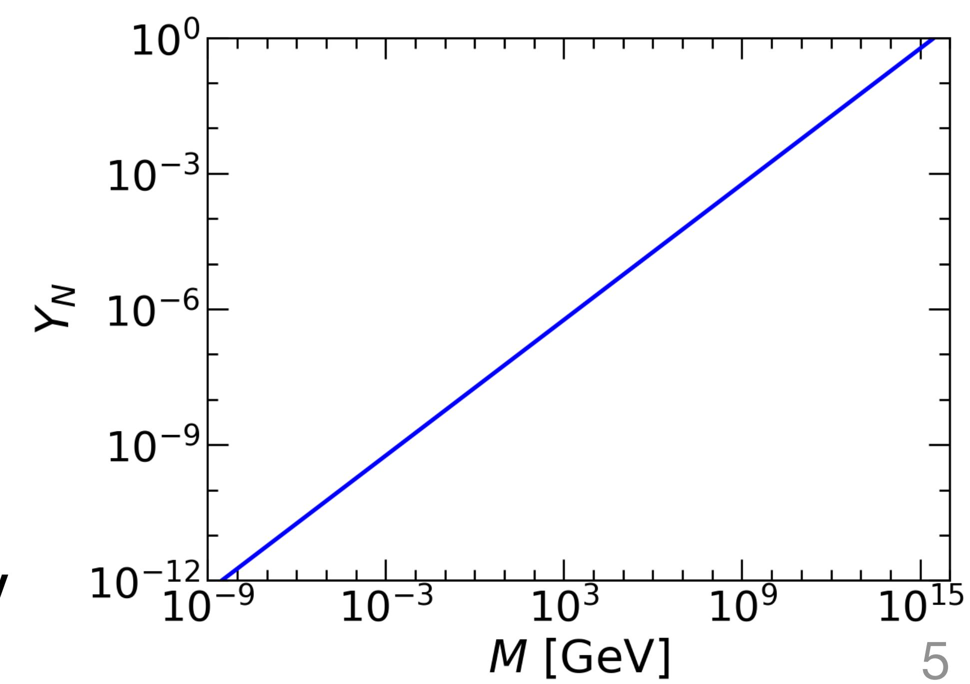
N is *heavy neutral lepton (HNL)*

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

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

Inverse seesaw mechanism

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

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

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

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

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

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 will assume

- lepton number conservation (LNC)

or

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

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

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

$\mathcal{O}_i^{(d)}$ 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)

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

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

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

$\mathcal{O}_{NNB}$ 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)

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

4-fermions 11 (16)

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

2 (4)

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

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

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

RRRR	$\mathcal{O}_{NN} = (\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma^\mu N_R)$ $\mathcal{O}_{eN} = (\overline{e_R}\gamma_\mu e_R)(\overline{N_R}\gamma^\mu N_R)$ $\quad \mathcal{O}_{uN} = (\overline{u_R}\gamma_\mu u_R)(\overline{N_R}\gamma^\mu N_R)$ $\mathcal{O}_{dN} = (\overline{d_R}\gamma_\mu d_R)(\overline{N_R}\gamma^\mu N_R)$ $\quad \mathcal{O}_{duNe} = (\overline{d_R}\gamma_\mu u_R)(\overline{N_R}\gamma^\mu e_R)$
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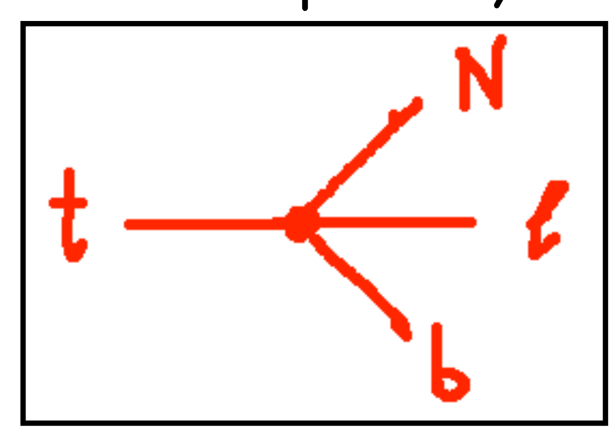
New top decay



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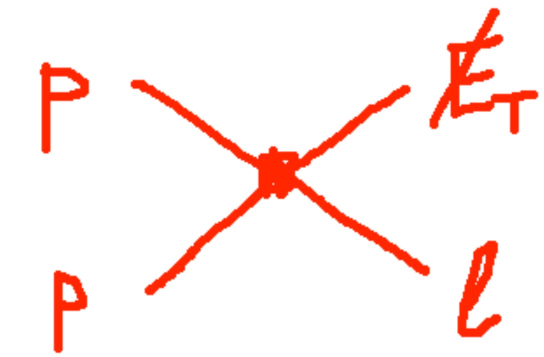

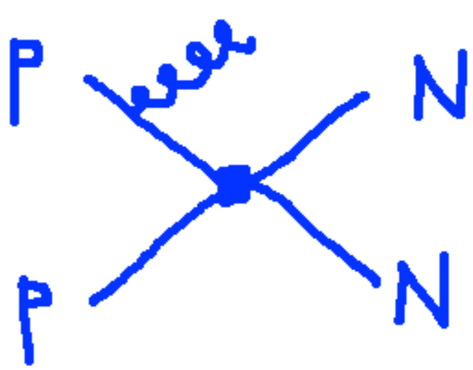

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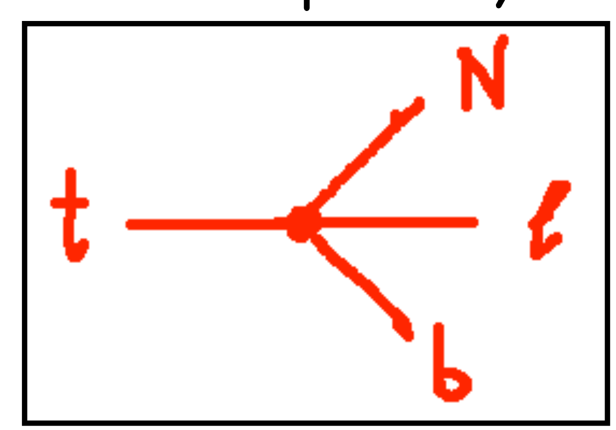

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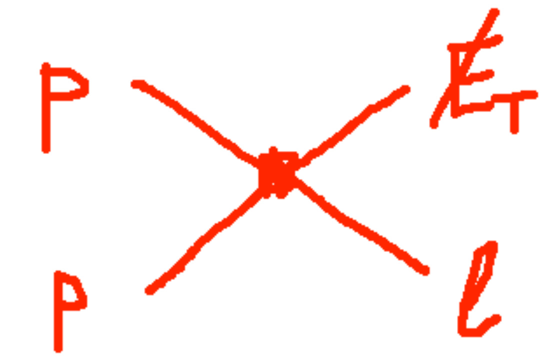
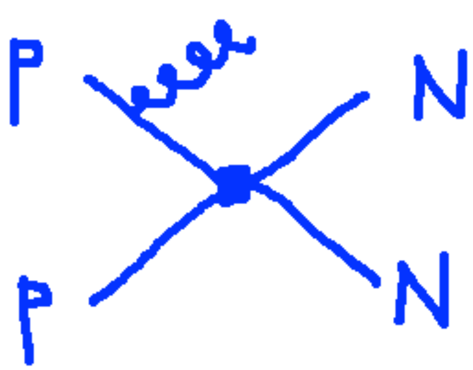
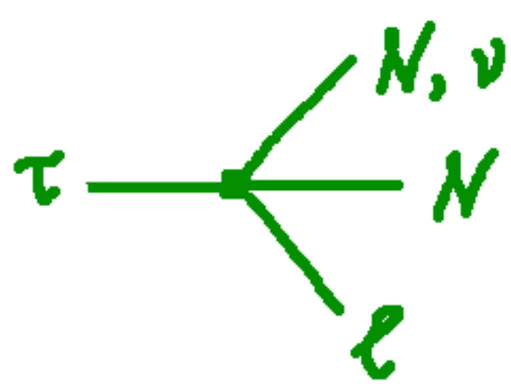
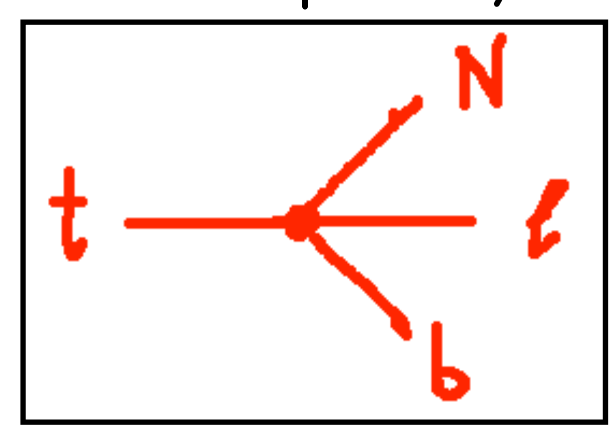


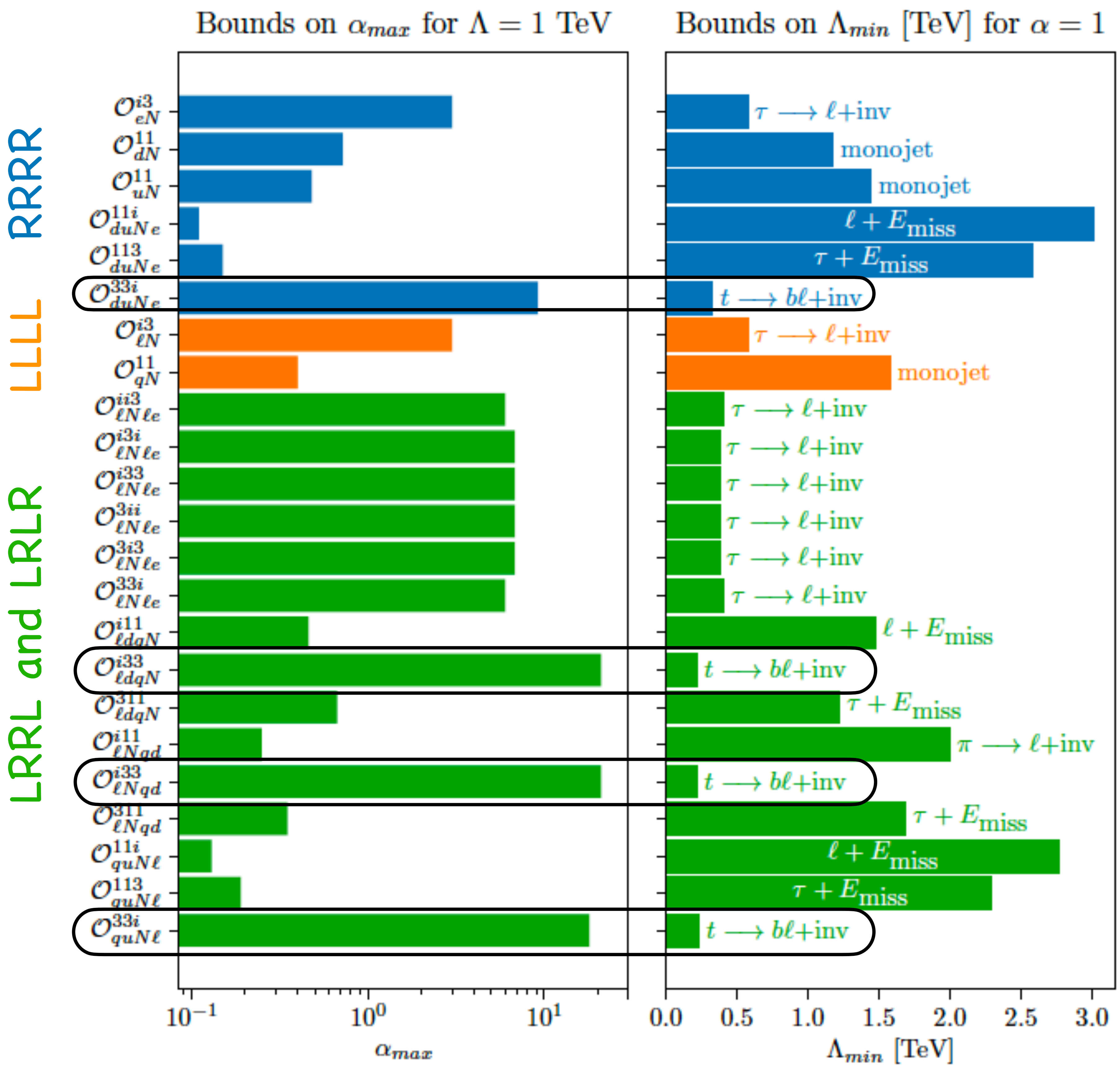




New top decay



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

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

CMS, 1712.02345

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

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

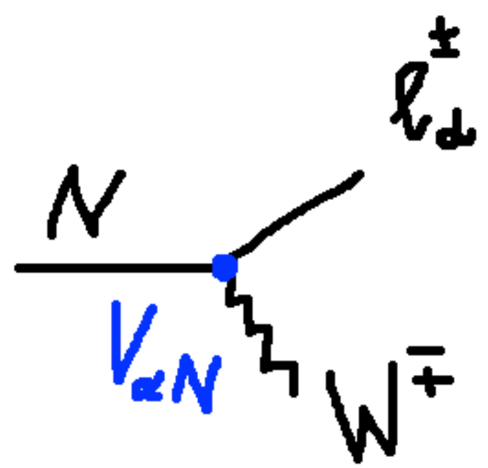
PDG, RPP 2018

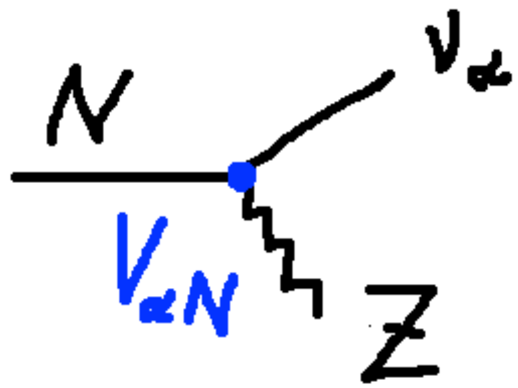
$t \to b\ell + {\rm inv}$ @ HL-LHC

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

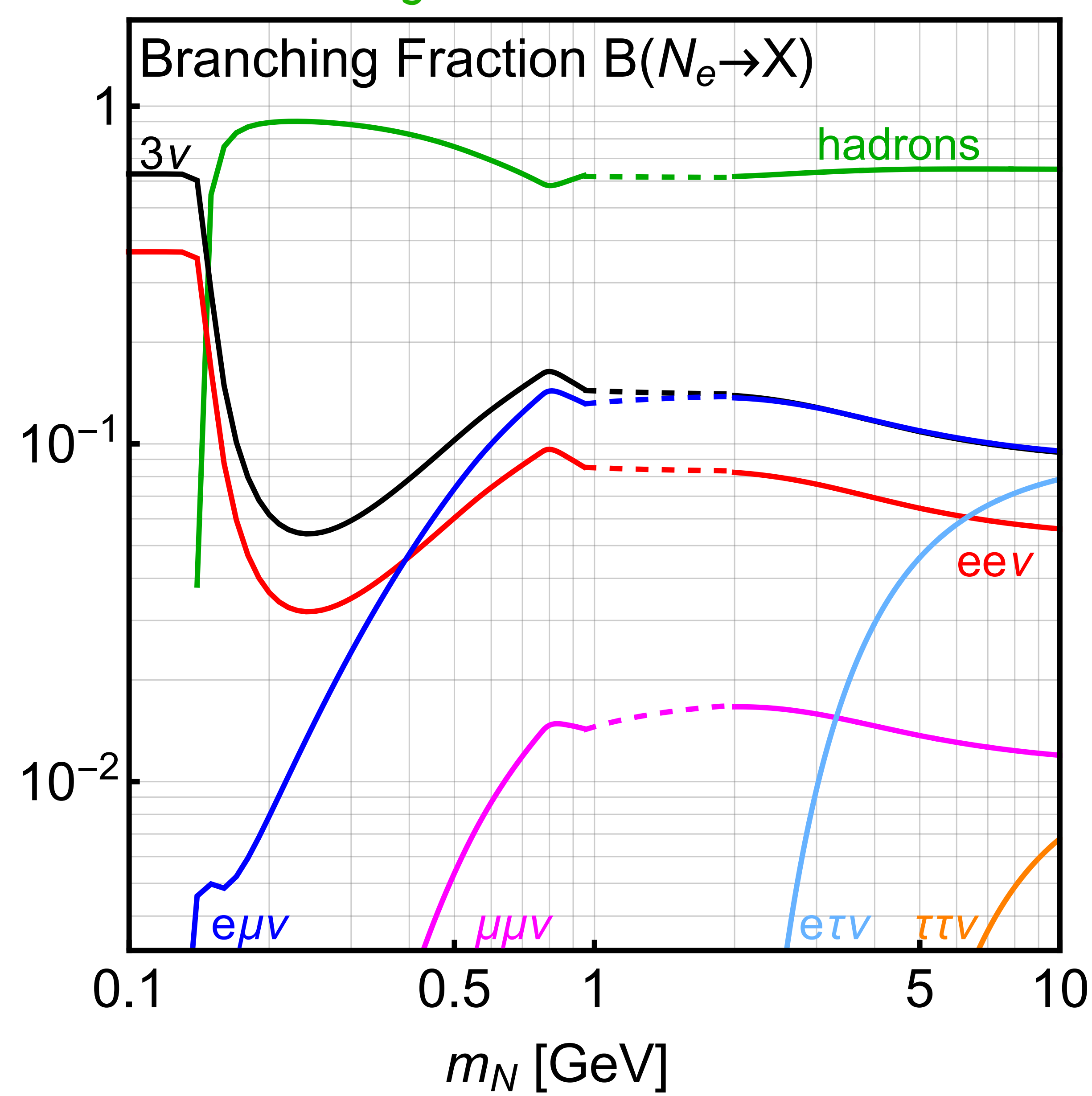
HNL decay via active-heavy mixing

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





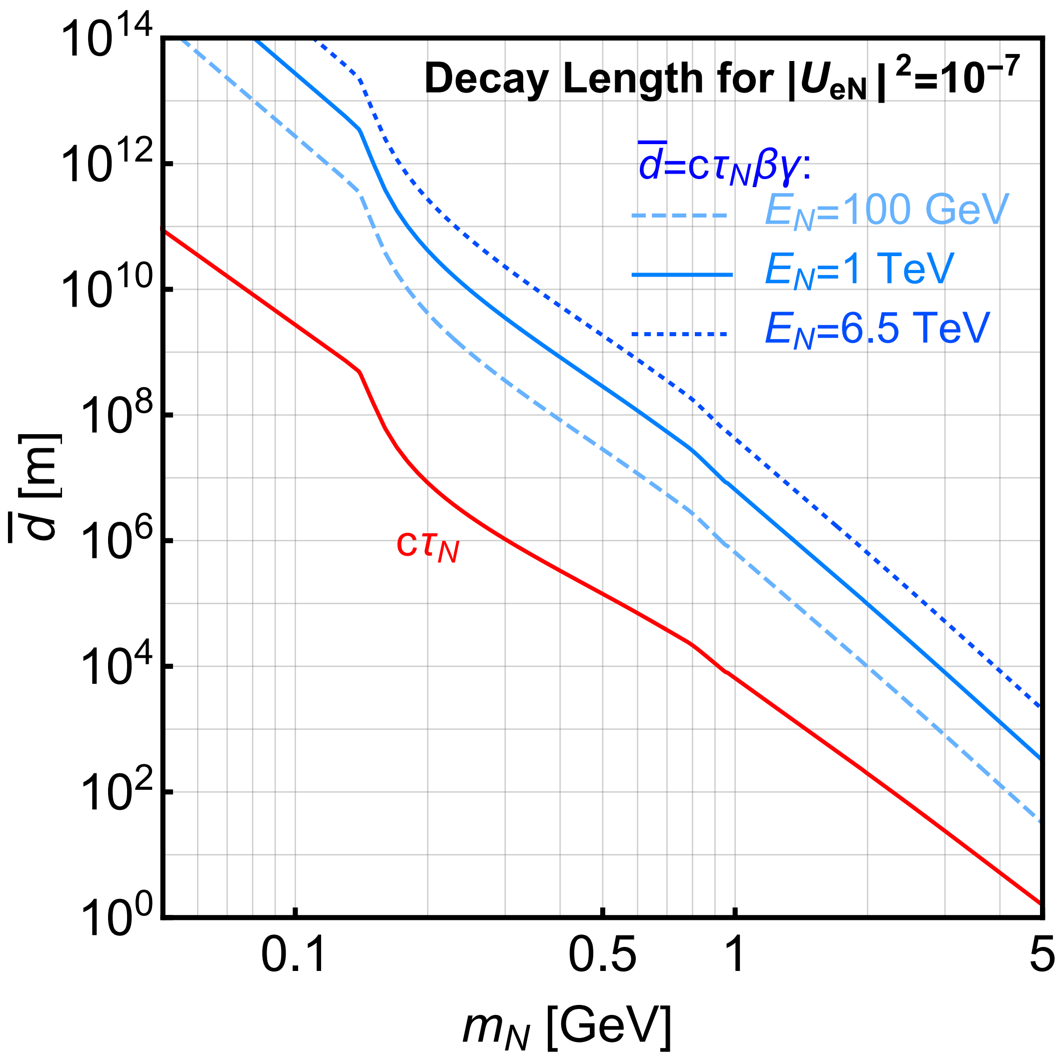
Kling and Trojanowski, 1801.08947

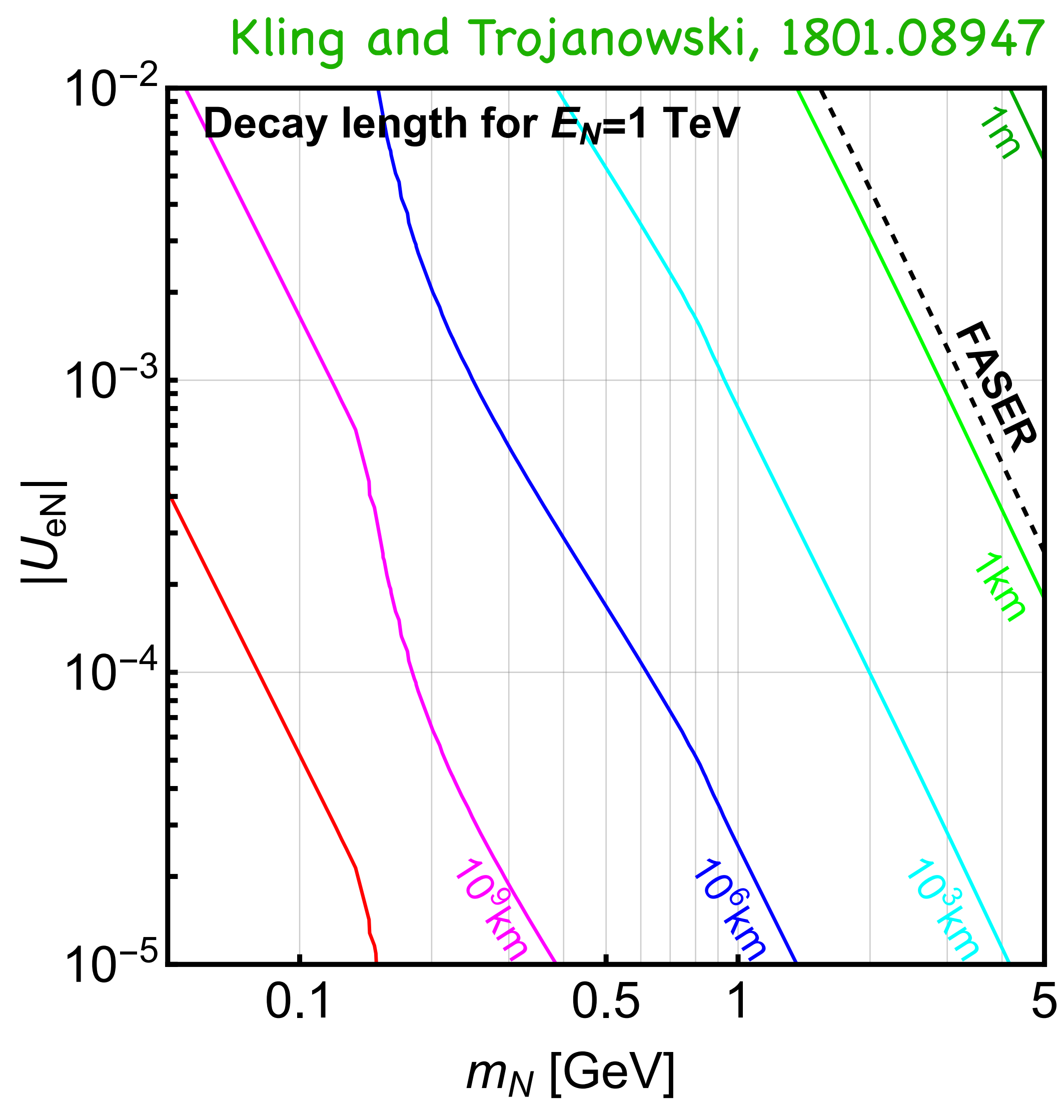


Long-lived HNLs

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

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





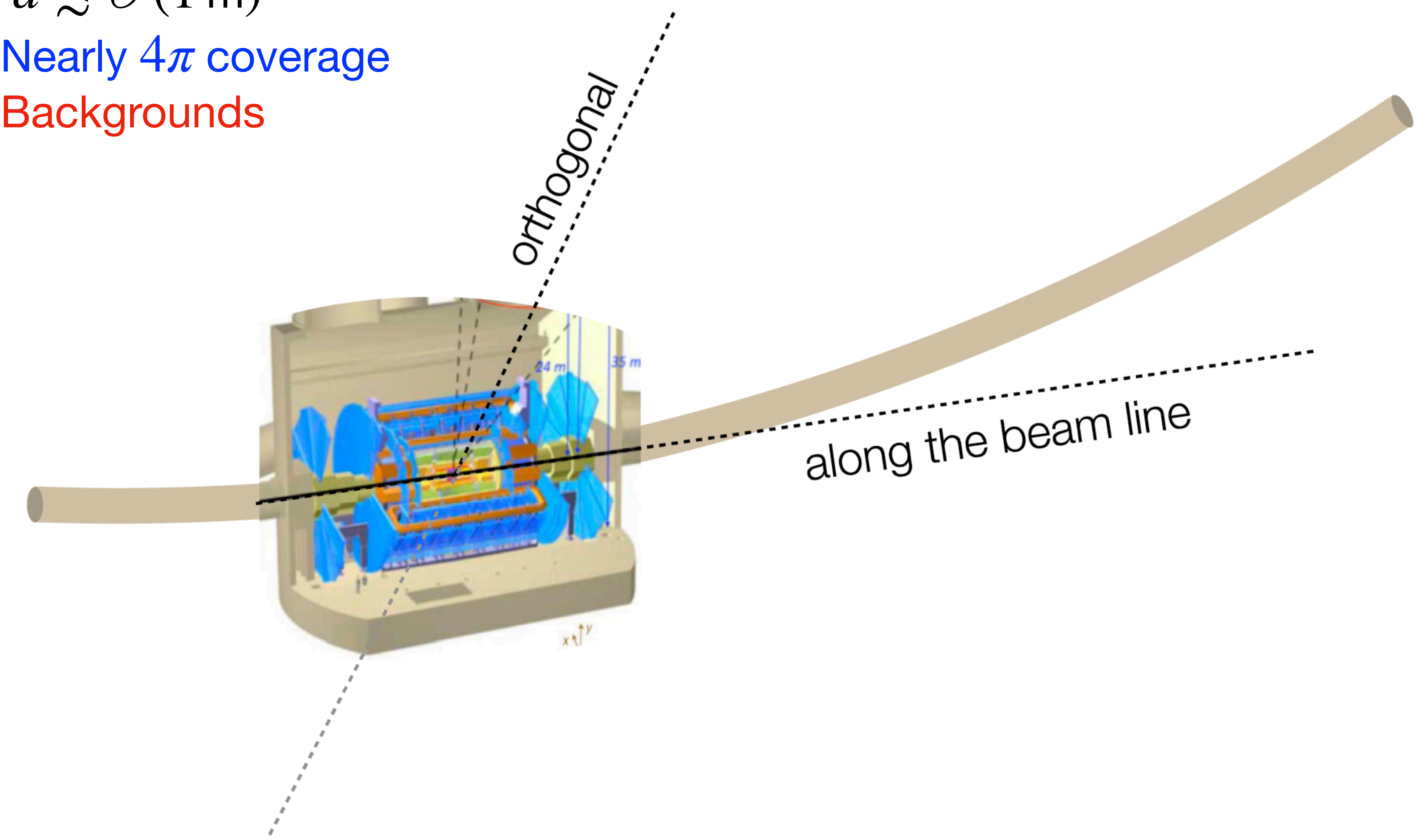
Local detectors at HL-LHC

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

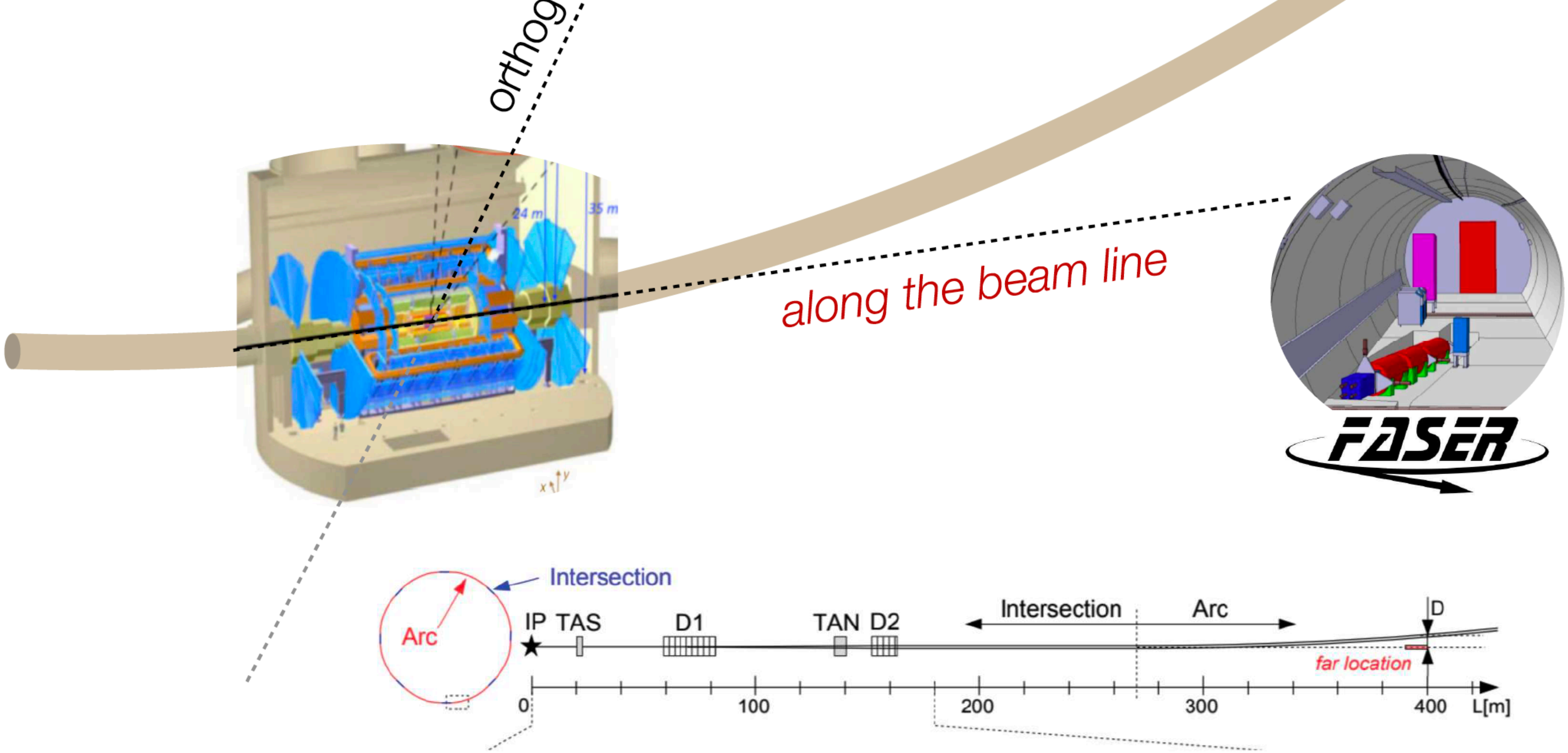
Cylinder with $r = 10$ cm and $\ell = 1.5$ m

$\bar{d} \sim 480$ 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

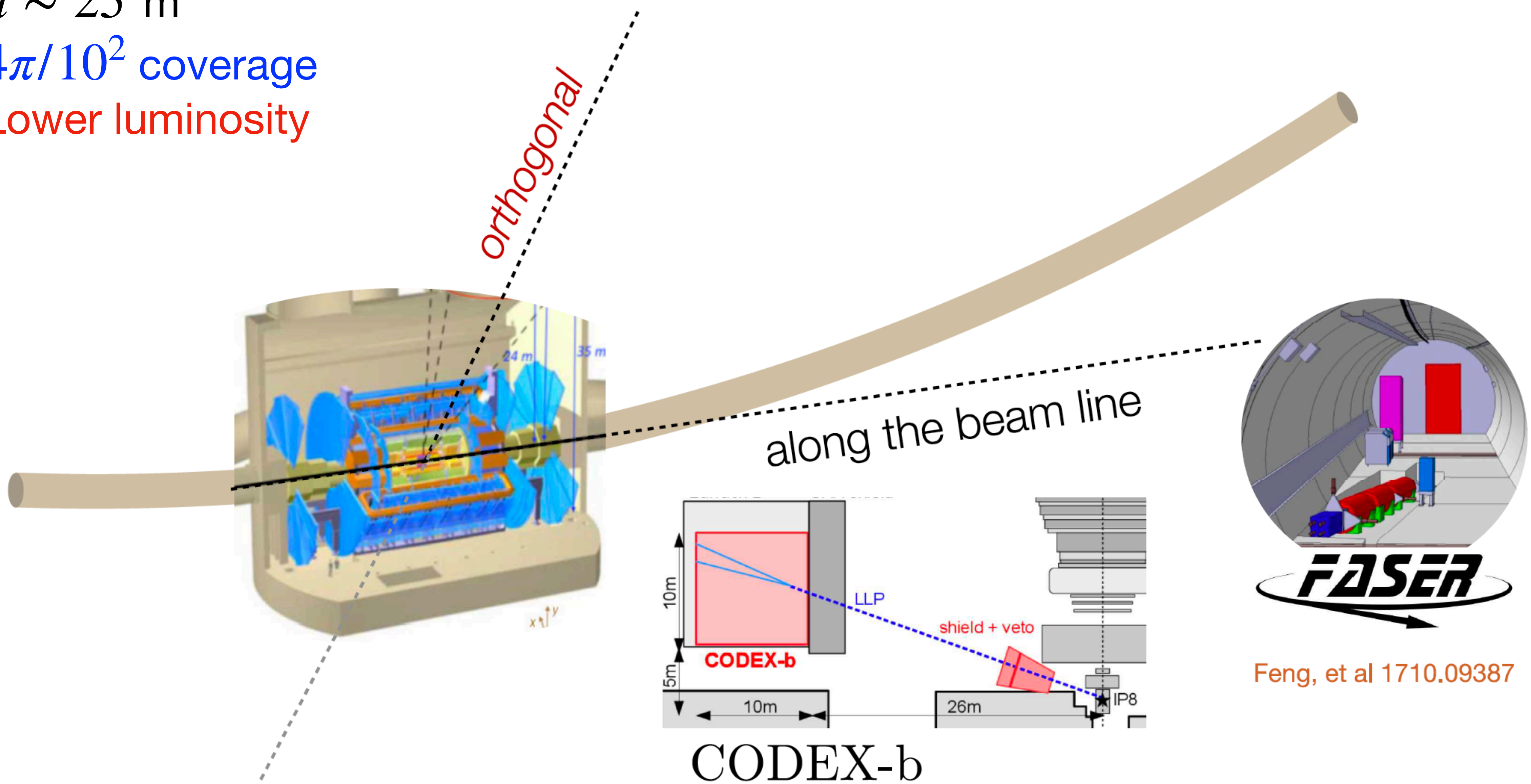
CODEX-b: COmpact Detector for EXotics at LHCb

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

$\bar{d} \sim 25$ m

$4\pi/10^2$ coverage

Lower luminosity



Gligorov et al 1708.09395

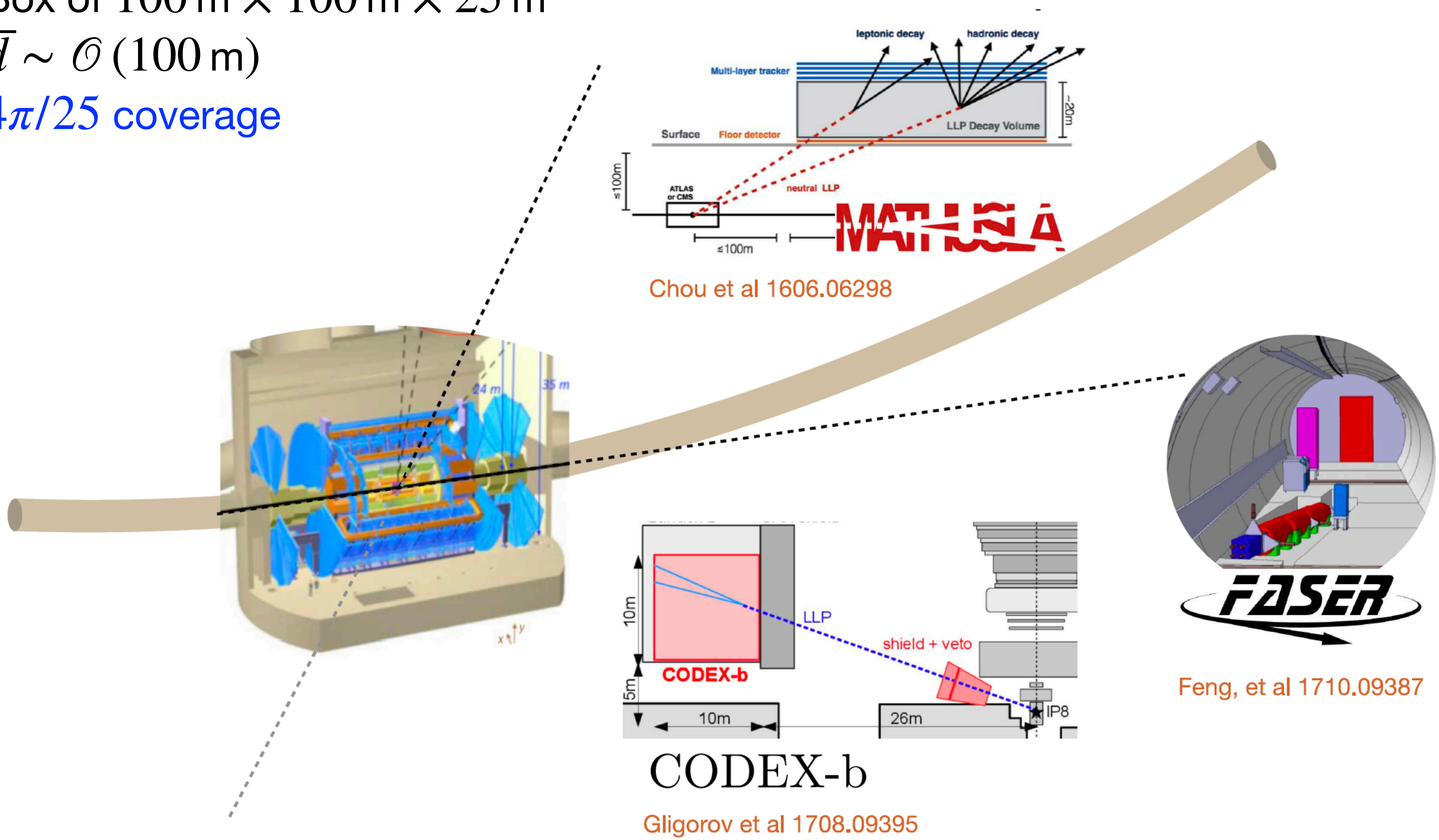
Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

MATHUSLA: MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

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

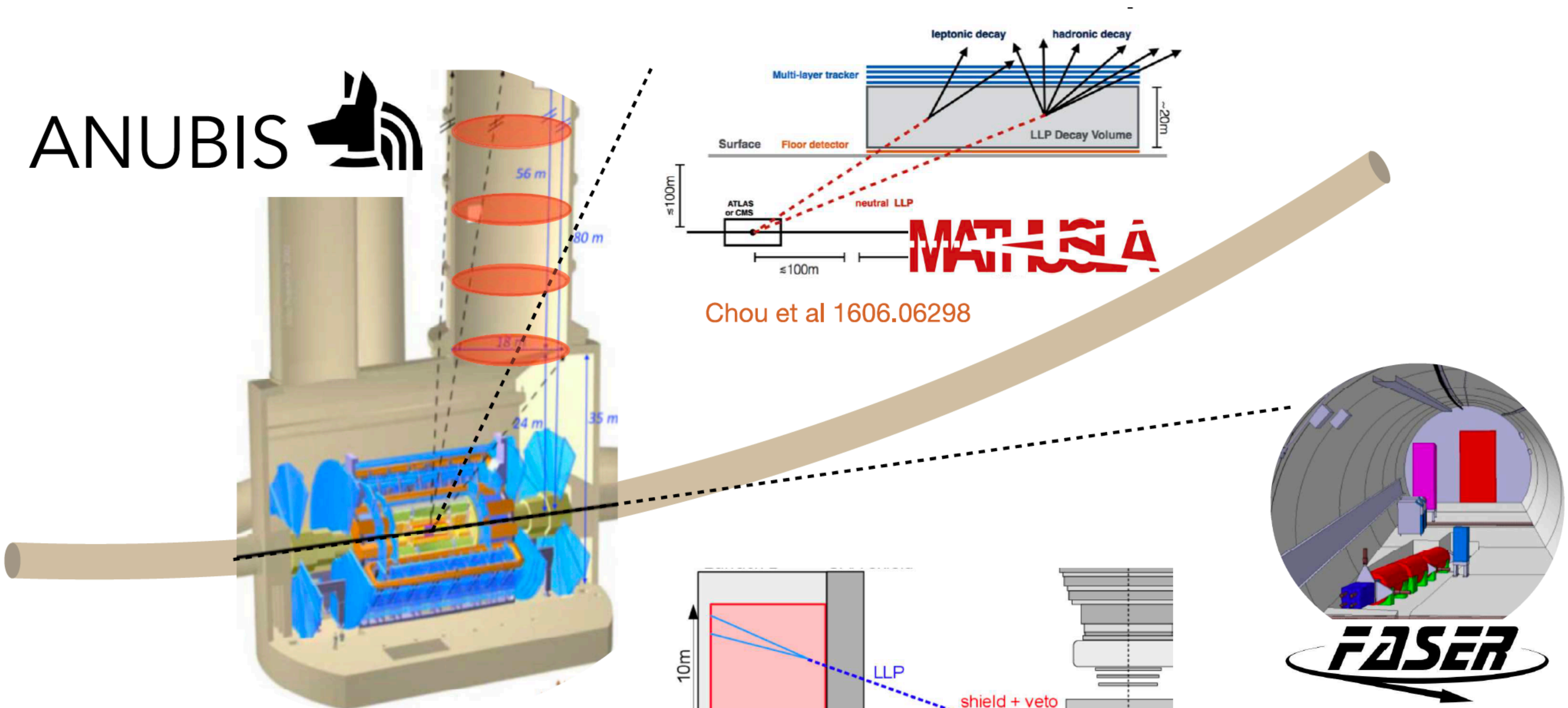
$\bar{d} \sim \mathcal{O}(100\,\text{m})$

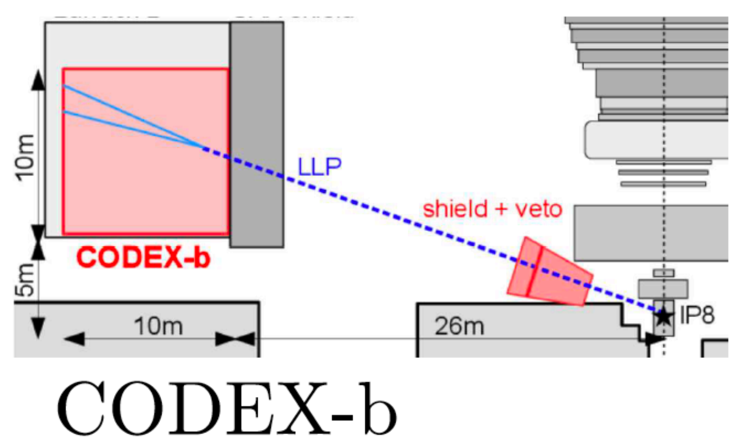
$4\pi/25$ coverage



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

ANUBIS: AN Underground Belayed In-Shaft search experiment





Feng, et al 1710.09387

Gligorov et al 1708.09395

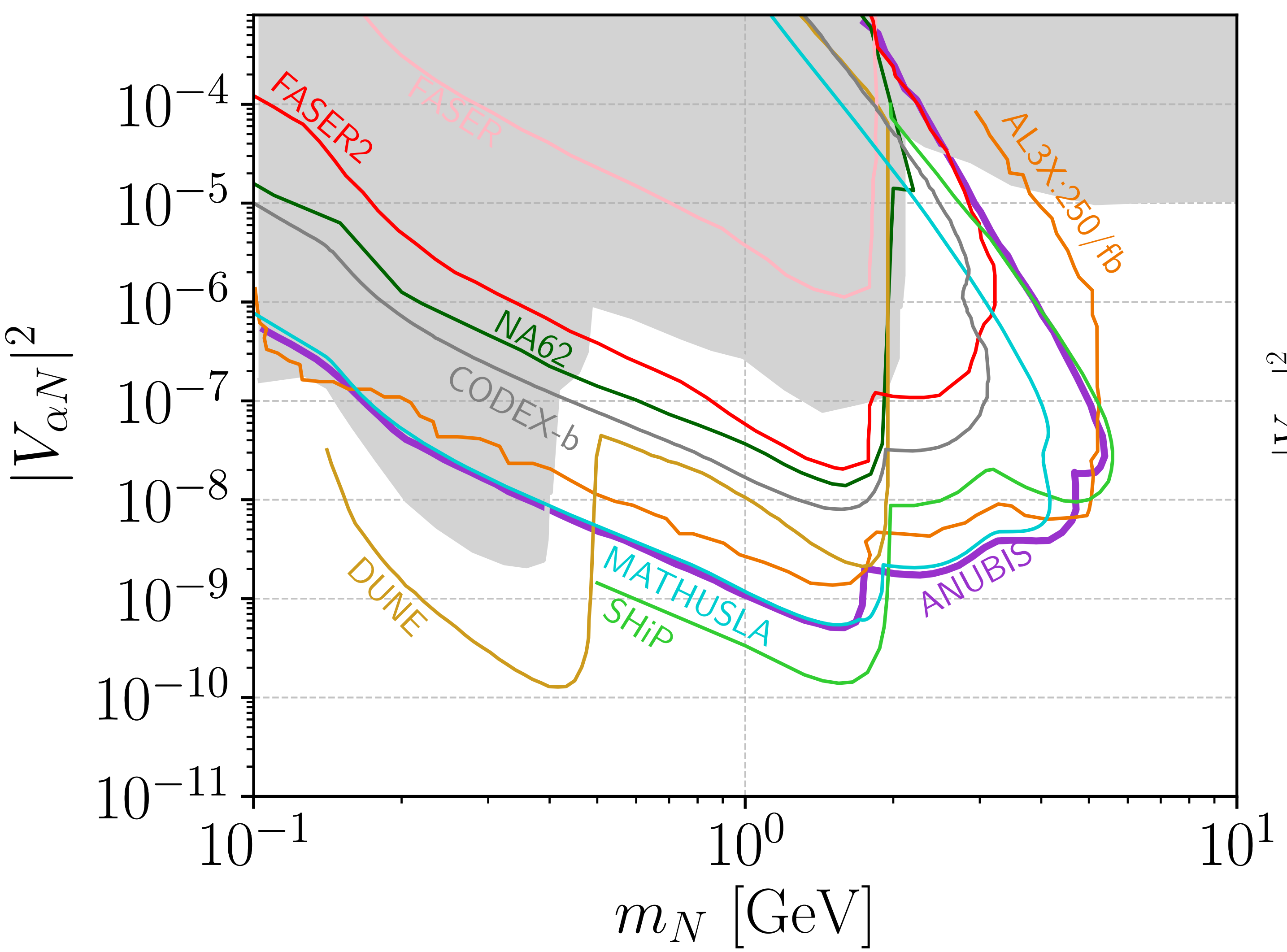
Cylinder with $r = 9$ m and $h = 56$ m
$\bar{d} \sim$ few 10 m
$4\pi/50$ coverage

Bauer, OB, Lee, Ohm 1909.13022

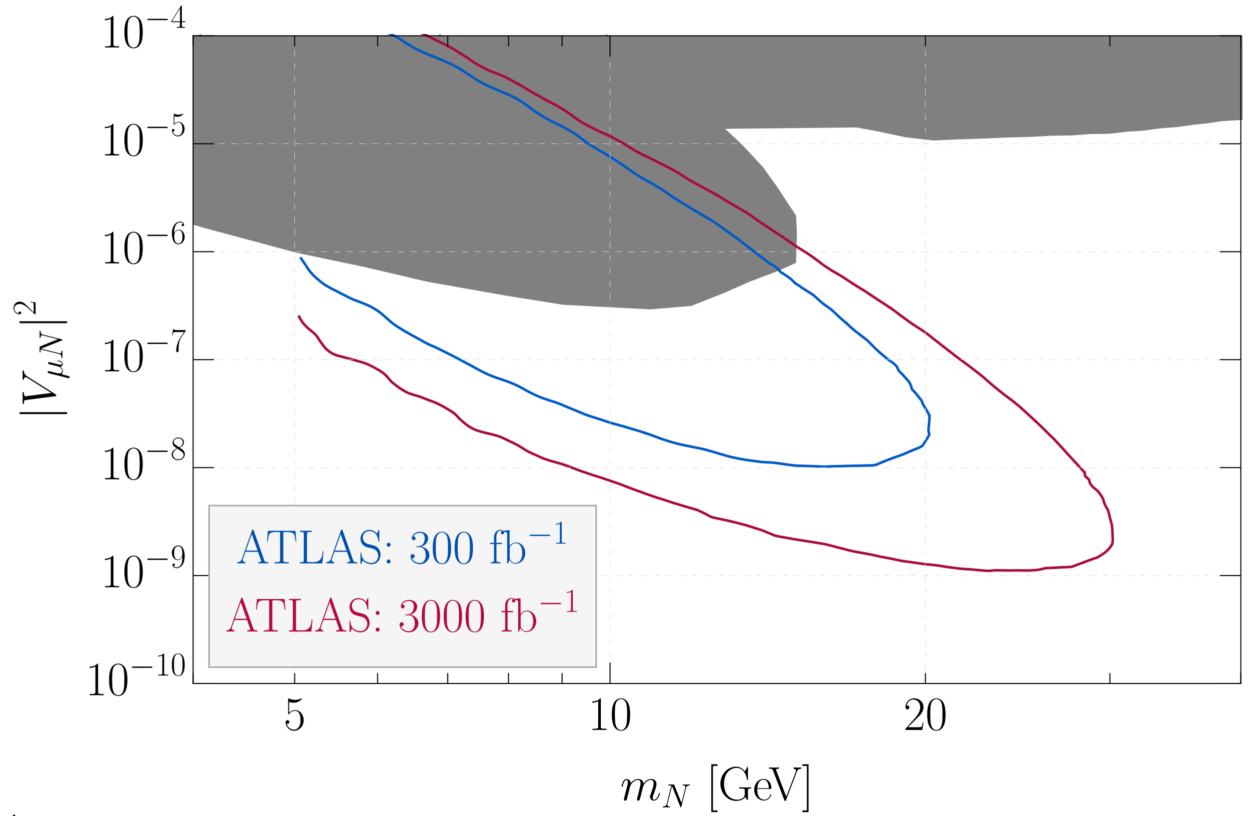
Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

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)



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

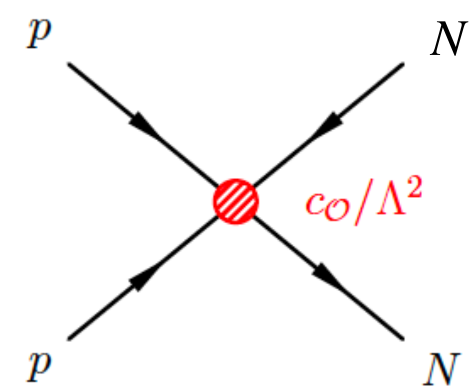
LQ state	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Coupling	Operator
S_d	**3**	**1**	$-1/3$	g_{dN}	$\mathcal{O}_{dN}$
S_u	**3**	**1**	$2/3$	g_{uN}	$\mathcal{O}_{uN}$
S_Q	**3**	**2**	$1/6$	g_{QN}	$\mathcal{O}_{QN}$

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

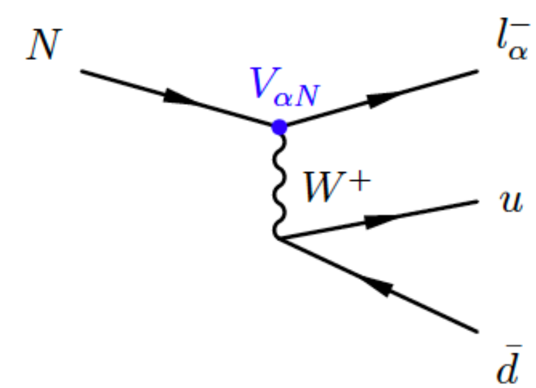
$$\mathcal{L}_{S_u} = g_{uN}\overline{u_R}N_R^c S_u + \text{h.c.}$$

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

- HNLs are pair produced via pair-N_R operators



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



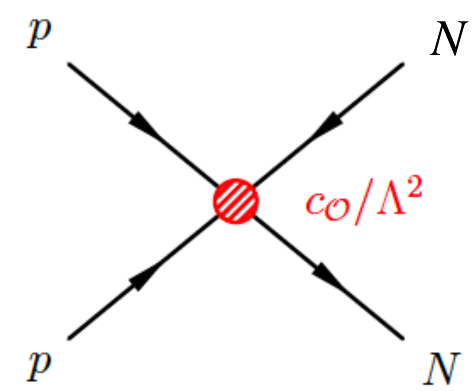
$$\frac{c_{qN}}{\Lambda^2} = \frac{g_{qN}^2}{2m_{S_q}^2}, \quad q = d, u, Q$$

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

- HNLs are pair produced via pair-N_R operators



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

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}	$\mathcal{O}_{QN}$

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

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

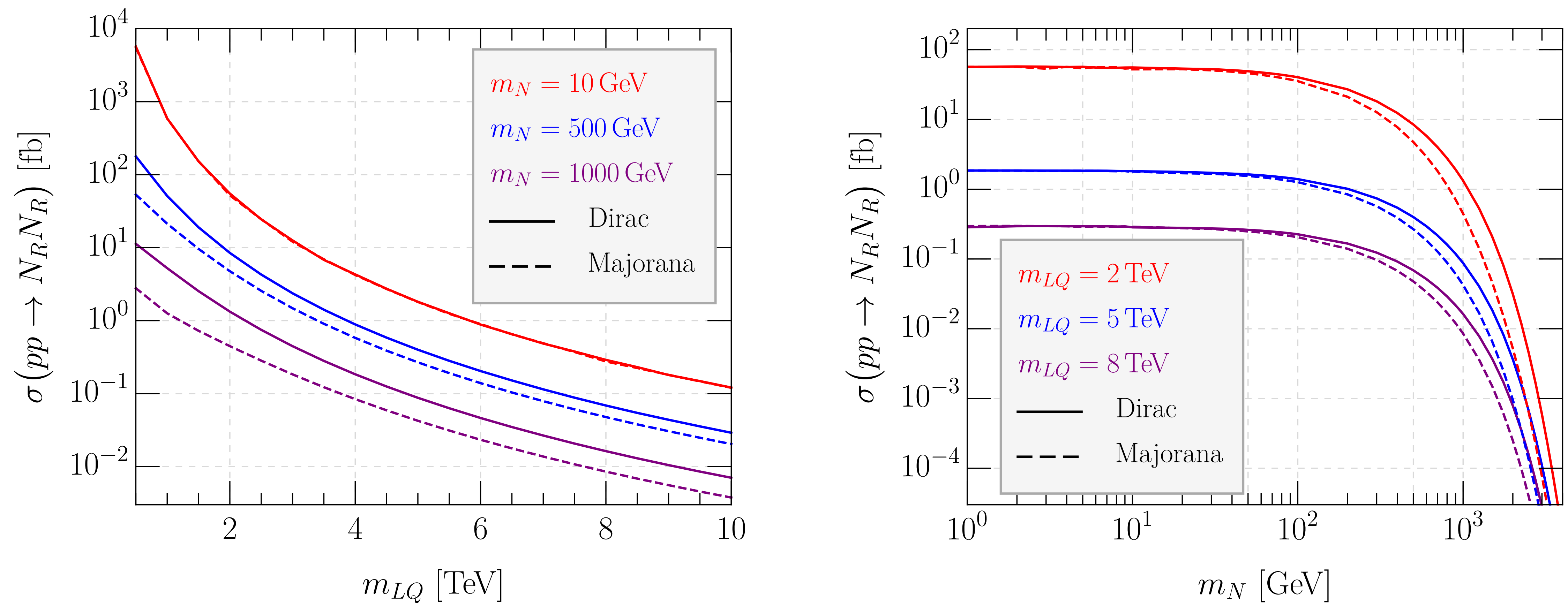
$$\mathcal{L}_{S_Q} = g_{QN}\overline{Q}N_R S_Q + g_{dL}\overline{d_R}L\epsilon S_Q + \text{h.c.}$$

- `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

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



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

$$\sigma_M(d\bar{d} \to NN) = \frac{c_{dN}^2}{144\pi\Lambda^4} s \left(1 - \frac{4m_N^2}{s}\right)^{3/2}$$

$\Rightarrow$ suppression for $m_N \gtrsim 100$ GeV

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

Number of events

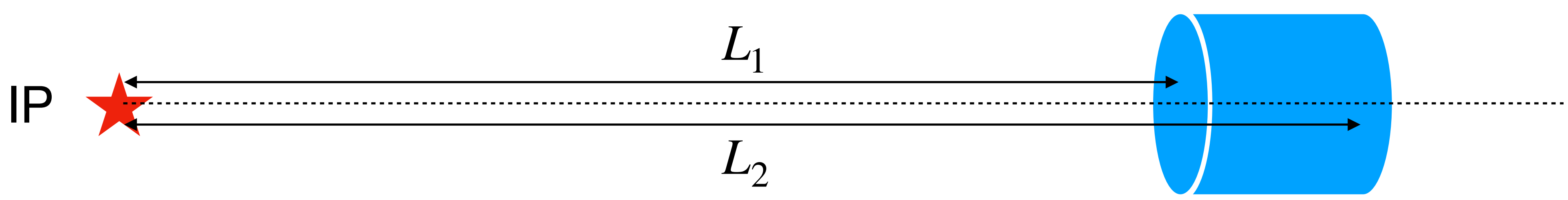
Projected number of signal events at ATLAS:

$$N_S^{\mathrm{ATLAS}} = \sigma(pp \to NN) \cdot \mathscr{L} \cdot \mathrm{BR}(N \to \ell jj) \cdot 2 \cdot \epsilon$$

`MadGraph5` `MadSpin+Pythia8`

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

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



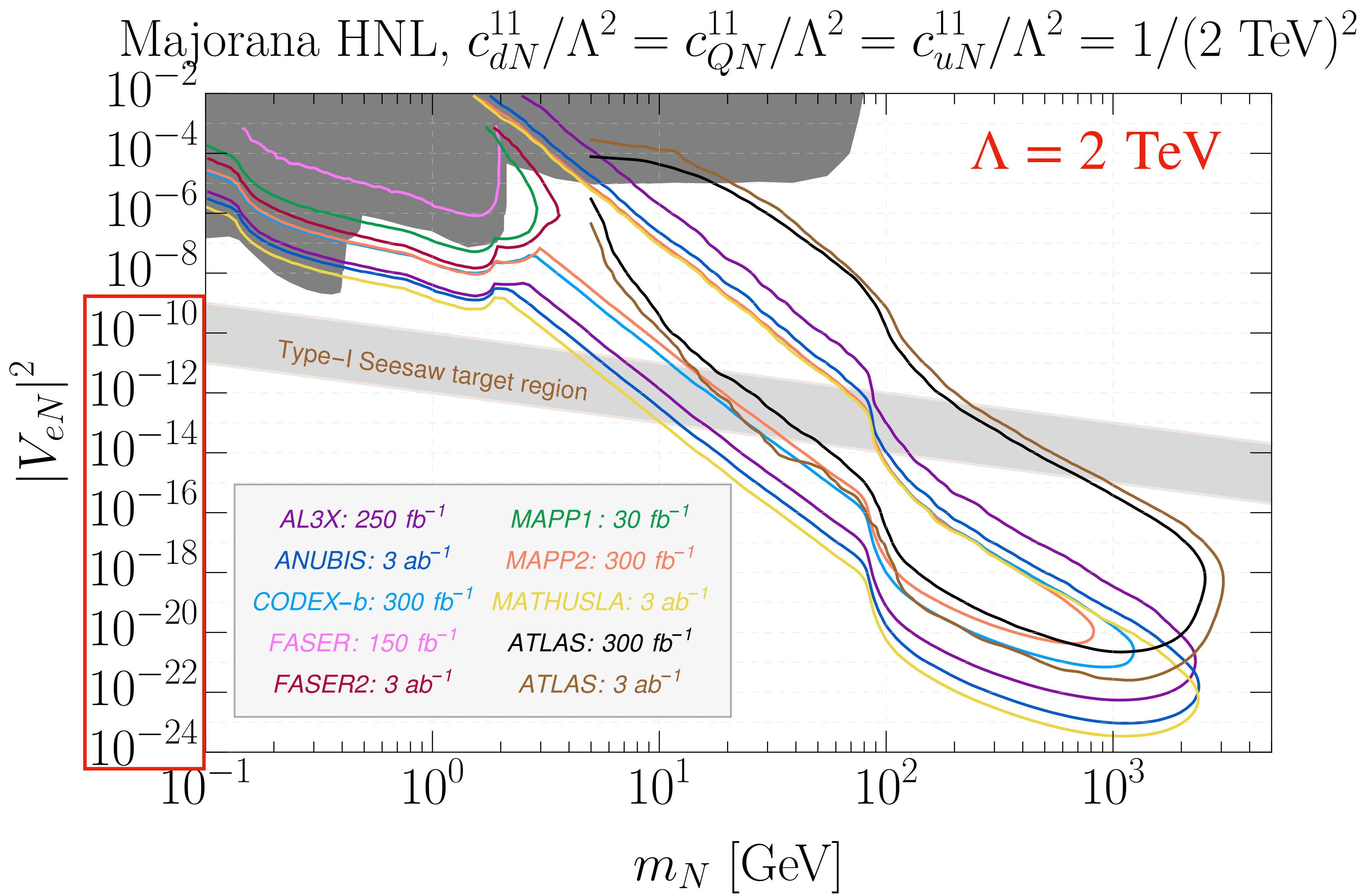
Projected number of signal events at a far detector:

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

`MadGraph5` `Pythia8` analytical

4-fermion pair-N operators at HL-LHC

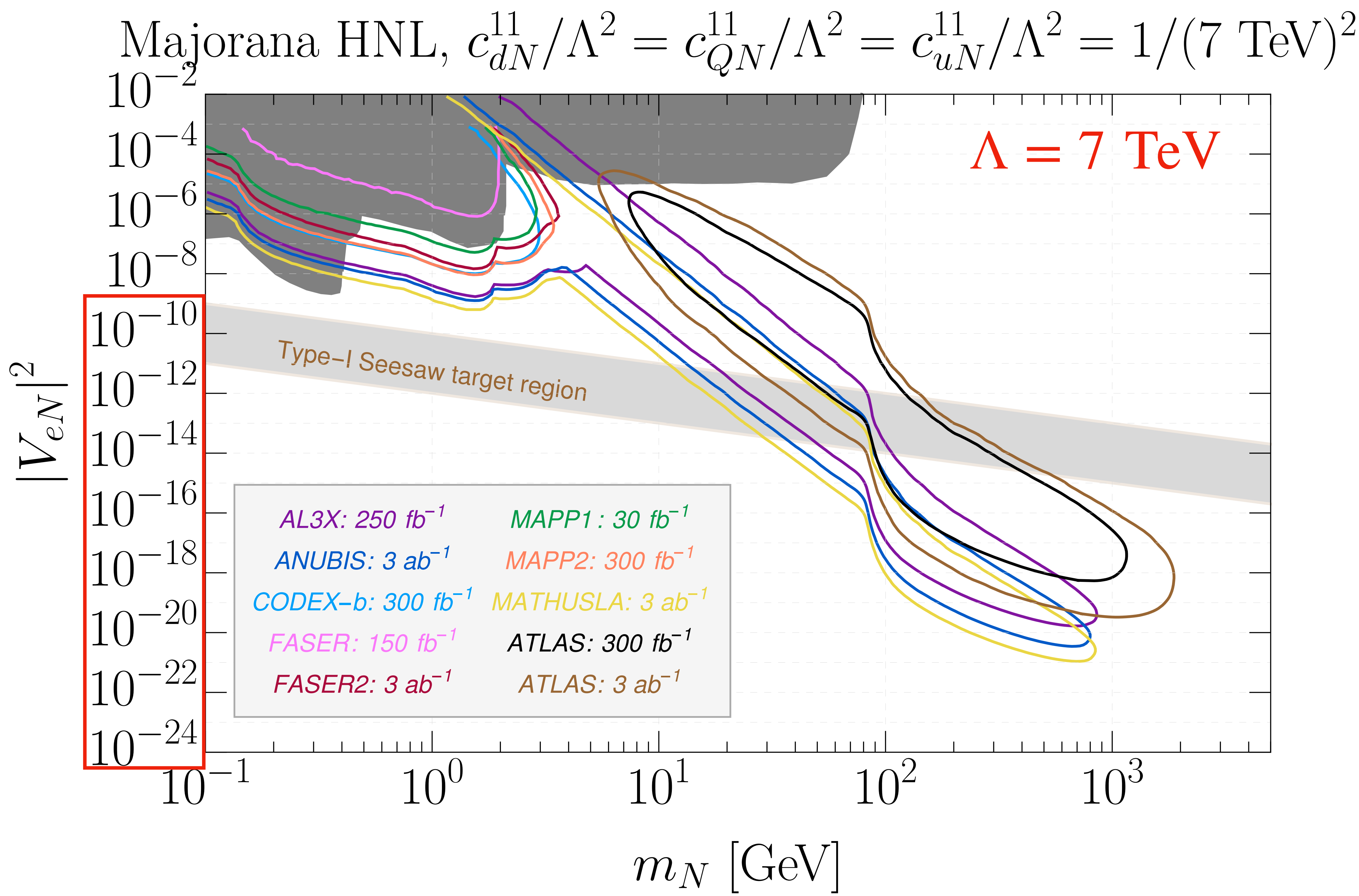
Reach on active-heavy neutrino mixing (for fixed new physics scale)



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

4-fermion pair-N operators at HL-LHC

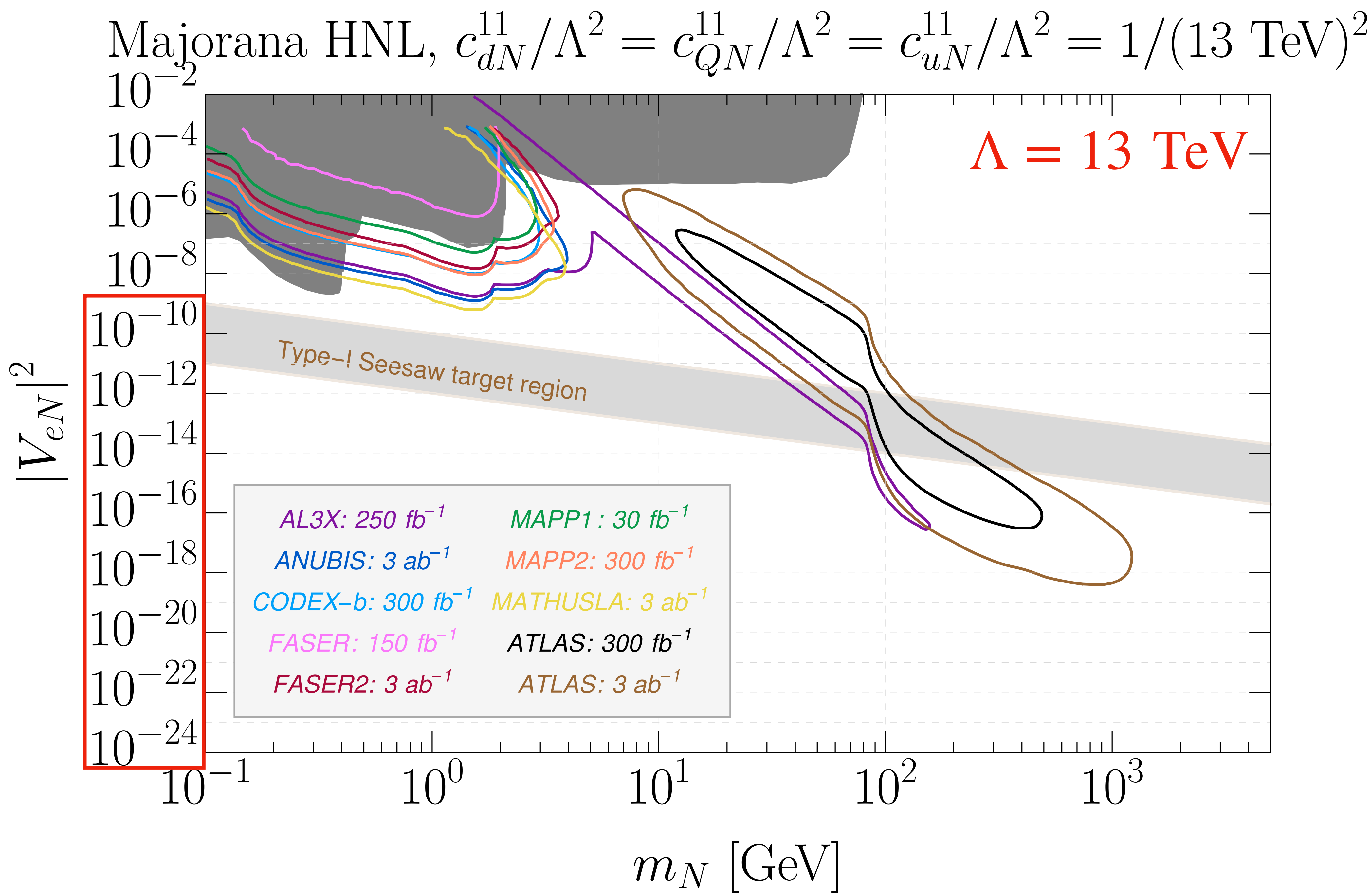
Reach on active-heavy neutrino mixing (for fixed new physics scale)



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

4-fermion pair-N operators at HL-LHC

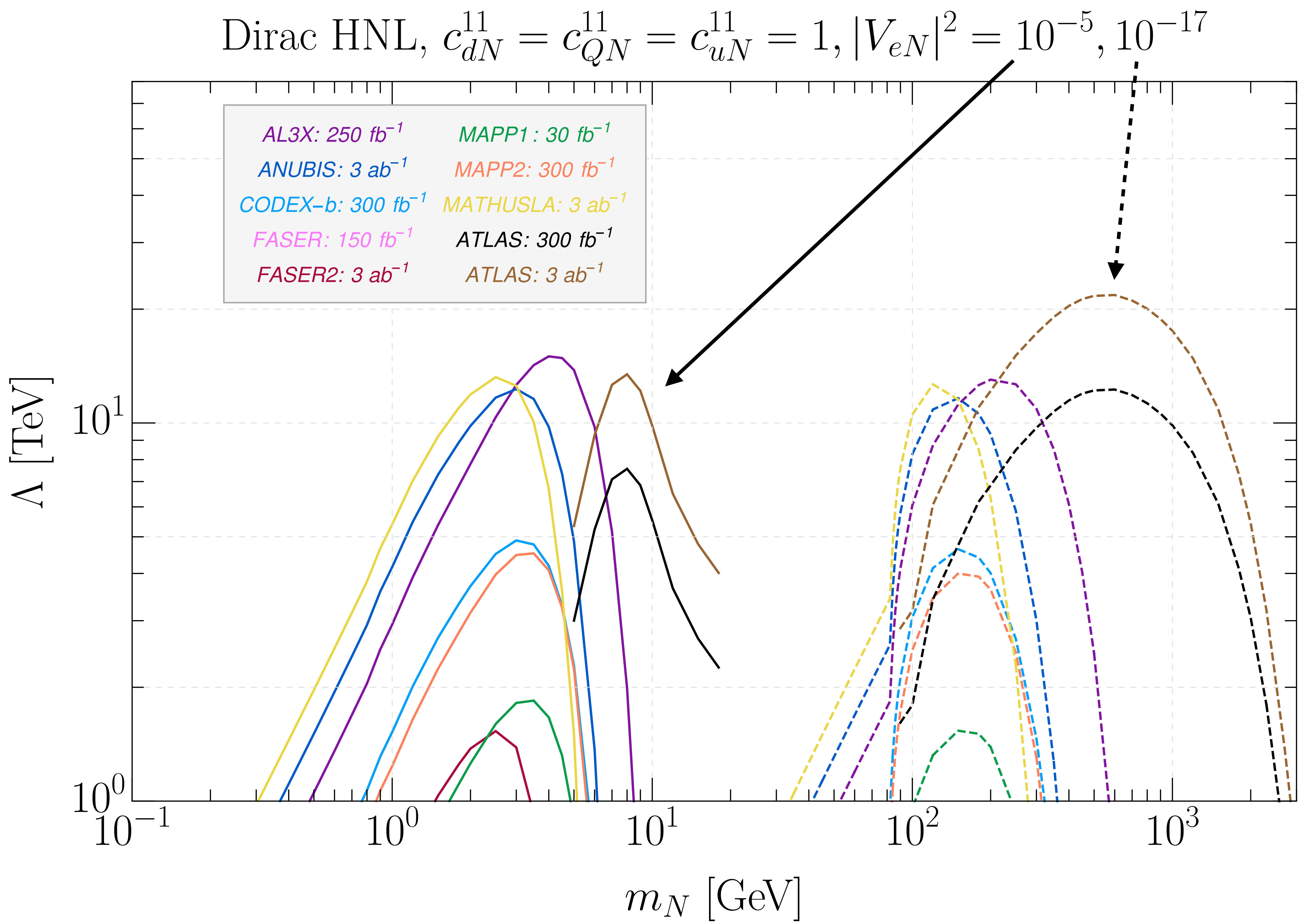
Reach on active-heavy neutrino mixing (for fixed new physics scale)



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)

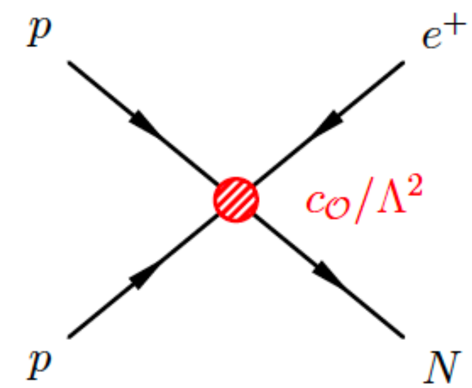


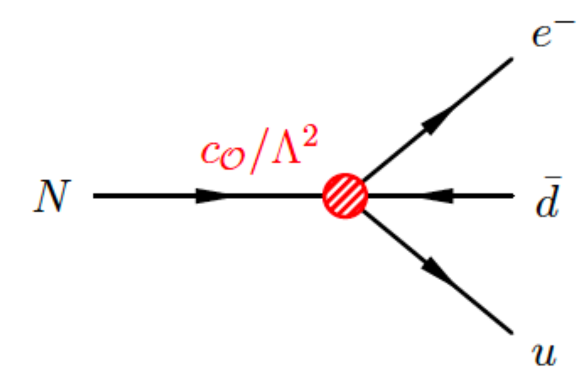
Cottin, Helo, Hirsch, **AT**, Wang, 2105.13851

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**	$1/2$	$\mathcal{O}_{LNQd}$	$\frac{c_{LNQd}}{\Lambda^2} = \frac{g_{LN}g_{Qd}}{m_\Phi^2}$
				$\mathcal{O}_{QuNL}$	$\frac{c_{QuNL}}{\Lambda^2} = \frac{g_{Qu}g_{LN}}{m_\Phi^2}$

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

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

4-fermion single-N operators

Example of HNL single production cross sections

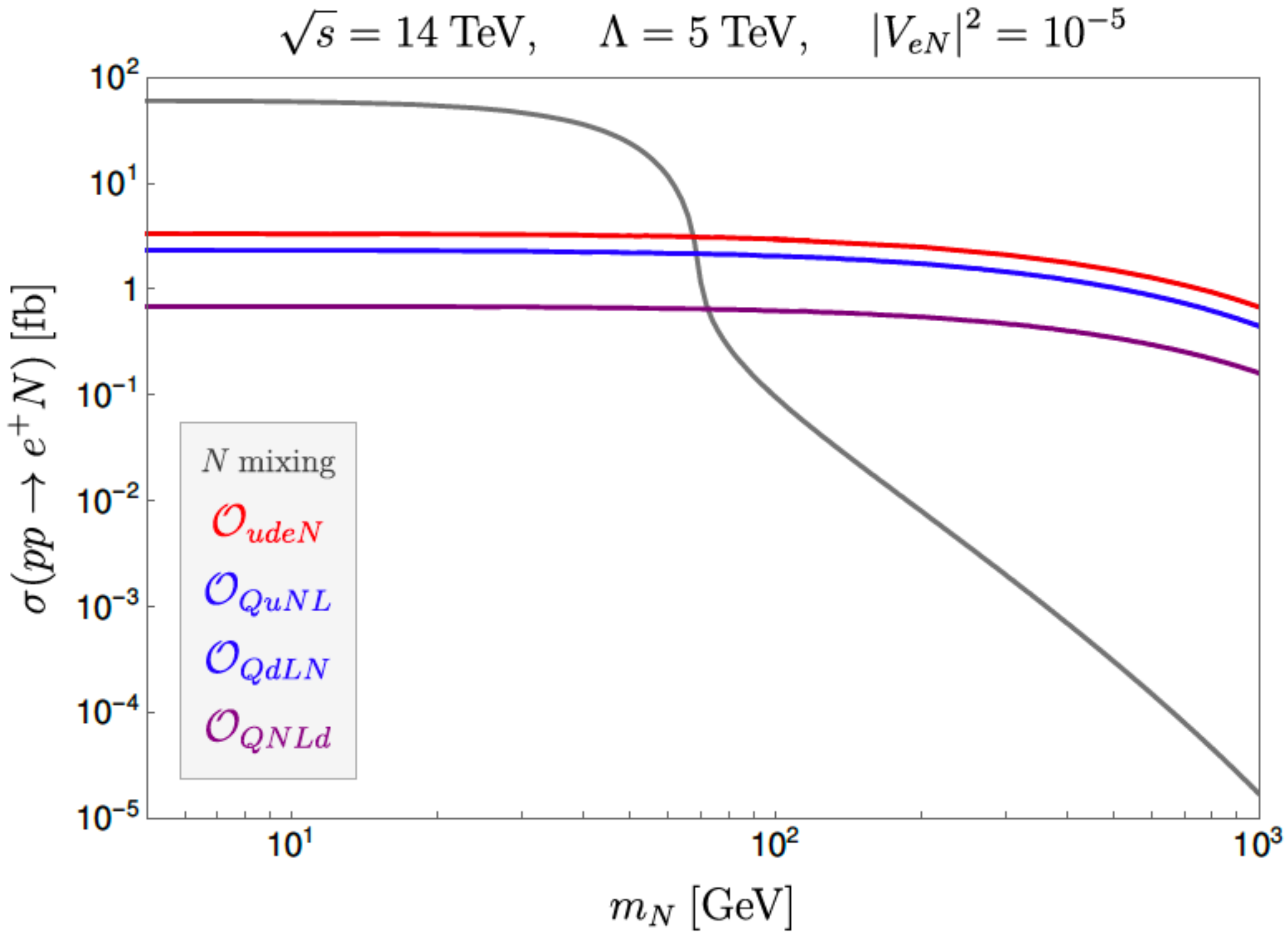


Figure from R. Beltrán's master thesis

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

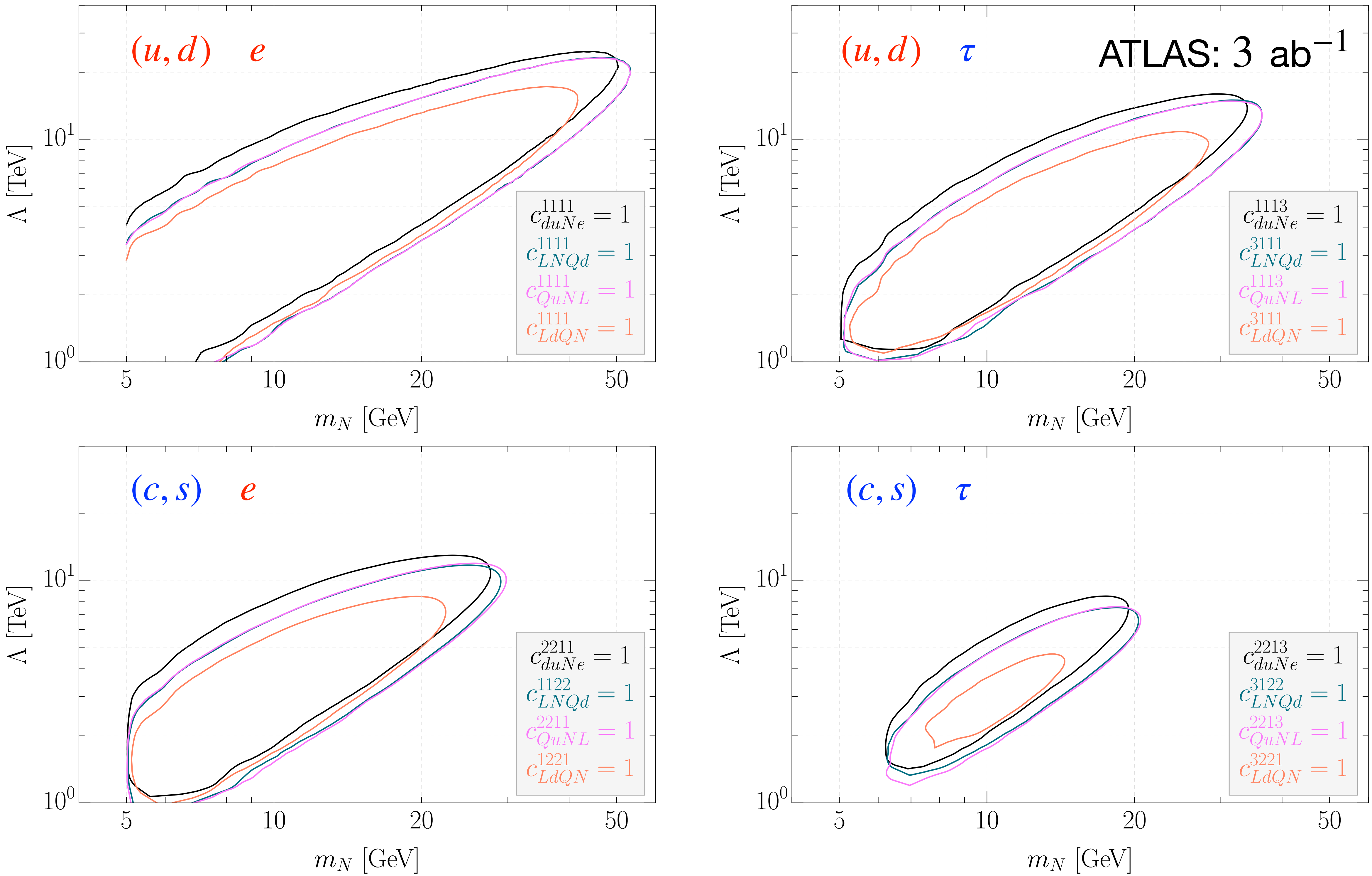
$$\sigma^{\mathcal{O}} \propto \Lambda^{-4}$$

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

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, $W^{\pm}$

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

$$\mathscr{L}_{\mathrm{ren}} = \mathscr{L}_{\mathrm{QCD+QED}} + i\,\overline{N_R} \not\partial N_R - \left[\frac{1}{2} \overline{\nu_L} M_\nu \nu_L^c + \frac{1}{2} \overline{N_R^c} M_N N_R + \overline{\nu_L} M_D N_R + \text{h.c.} \right]$$

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

$d \leq 6$ 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

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

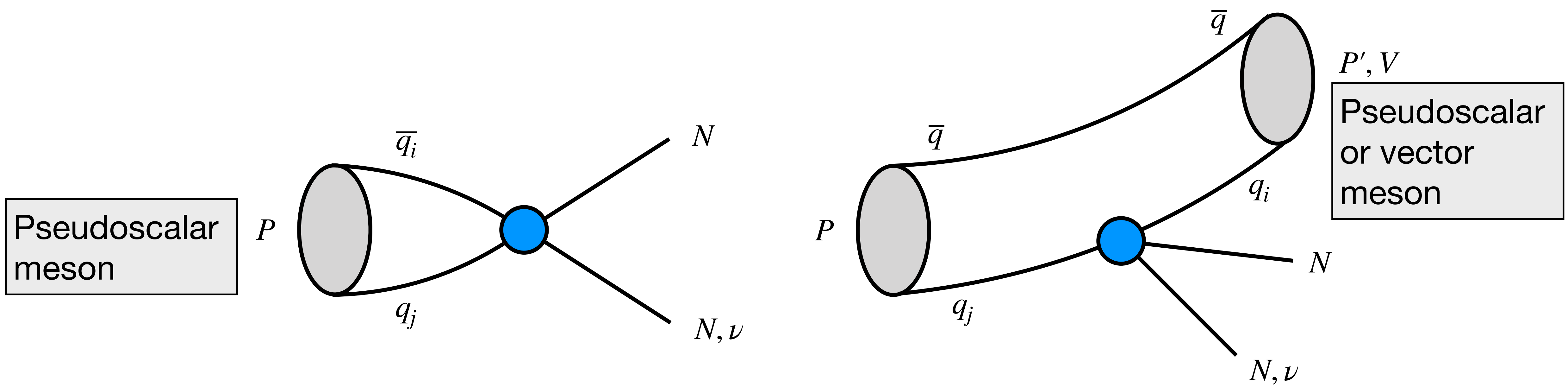
$$c^{S,LR}_{dN,ij} = \frac{\mathrm{v}}{\sqrt{2}} V_{kj} C^{ik}_{dQNH} \qquad c^{S,LR}_{uN,ij} = \frac{\mathrm{v}}{\sqrt{2}} C^{ij}_{uQNH}$$

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

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

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

HNL production in meson decays



• $c \to u$	$D^0 \to NN\ (\nu N)$	$D^0 \to \pi^0, \eta, \eta'\ (\rho^0, \omega)$	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 $q = b$
• $b \to d$	$B^0 \to NN\ (\nu N)$	…	
• $b \to s$	$B_s^0 \to NN\ (\nu N)$	…	
• $s \to d$	$K_{S/L} \to NN\ (\nu N)$	…	

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:

$$\Gamma(P \to NN) = \frac{m_P}{32\pi}\sqrt{1-\frac{4m_N^2}{m_P^2}}\Bigg[2\left|f_P\right|^2 \left|c_{qN,ij}^{V,RR} - c_{qN,ij}^{V,LR}\right|^2 m_N^2$$
$$+\left|f_P^S\right|^2\Bigg\{\left(\left|c_{qN,ij}^{S,RR} - c_{qN,ij}^{S,LR}\right|^2 + \left|c_{qN,ji}^{S,RR} - c_{qN,ji}^{S,LR}\right|^2\right)\left(1-\frac{2m_N^2}{m_P^2}\right)$$
$$+2\left[\left(c_{qN,ij}^{S,RR} - c_{qN,ij}^{S,LR}\right)\left(c_{qN,ji}^{S,RR} - c_{qN,ji}^{S,LR}\right) + \text{h.c.}\right]\frac{m_N^2}{m_P^2}\Bigg\}$$
$$+f_P f_P^S\left\{\left(c_{qN,ij}^{V,RR} - c_{qN,ij}^{V,LR}\right)\left(c_{qN,ij}^{S,RR\,*} - c_{qN,ij}^{S,LR\,*} + c_{qN,ji}^{S,RR} - c_{qN,ji}^{S,LR}\right) m_N + \text{h.c.}\right\}\Bigg]$$

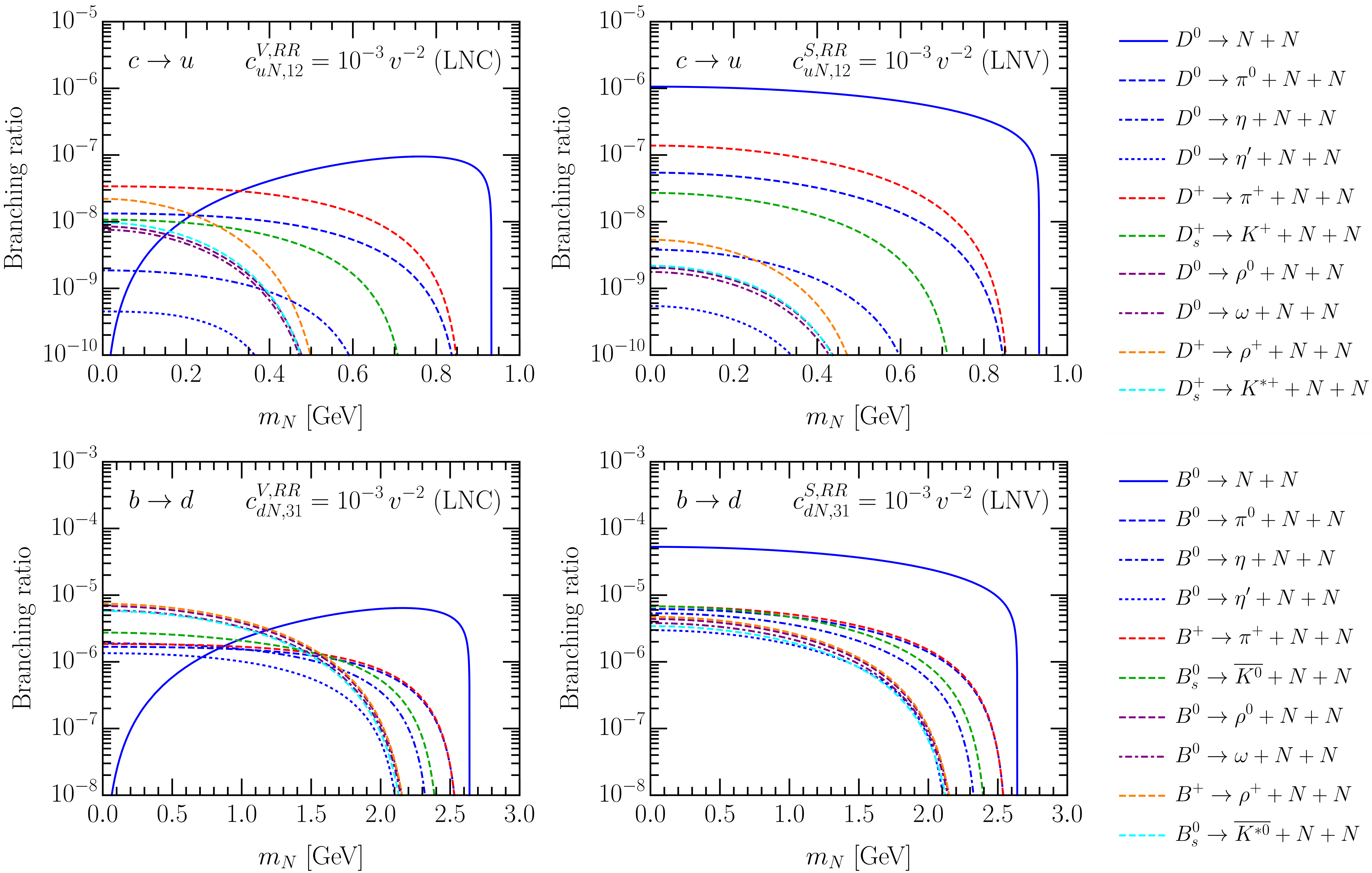
$$\langle 0|\overline{q}_i\gamma^\mu\gamma_5 q_j|P(p)\rangle = i f_P p^\mu \qquad\qquad \langle 0|\overline{q}_i\gamma_5 q_j|P(p)\rangle = i\frac{m_P^2}{m_{q_i}+m_{q_j}} f_P \equiv i f_P^S$$

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

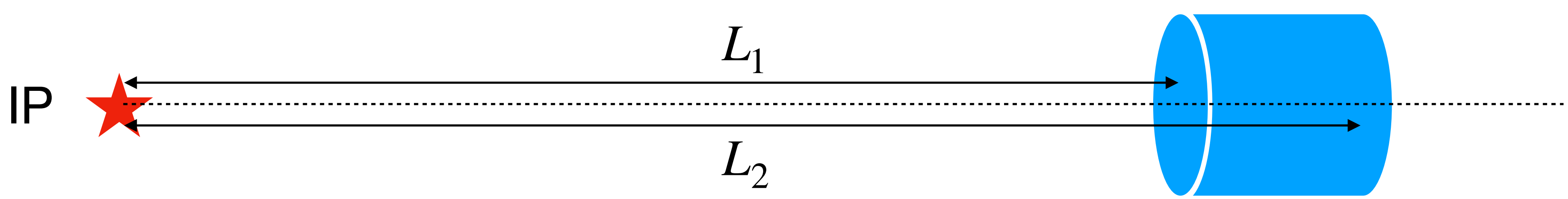
Projected number of signal events:

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

analytical Pythia8 analytical

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

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

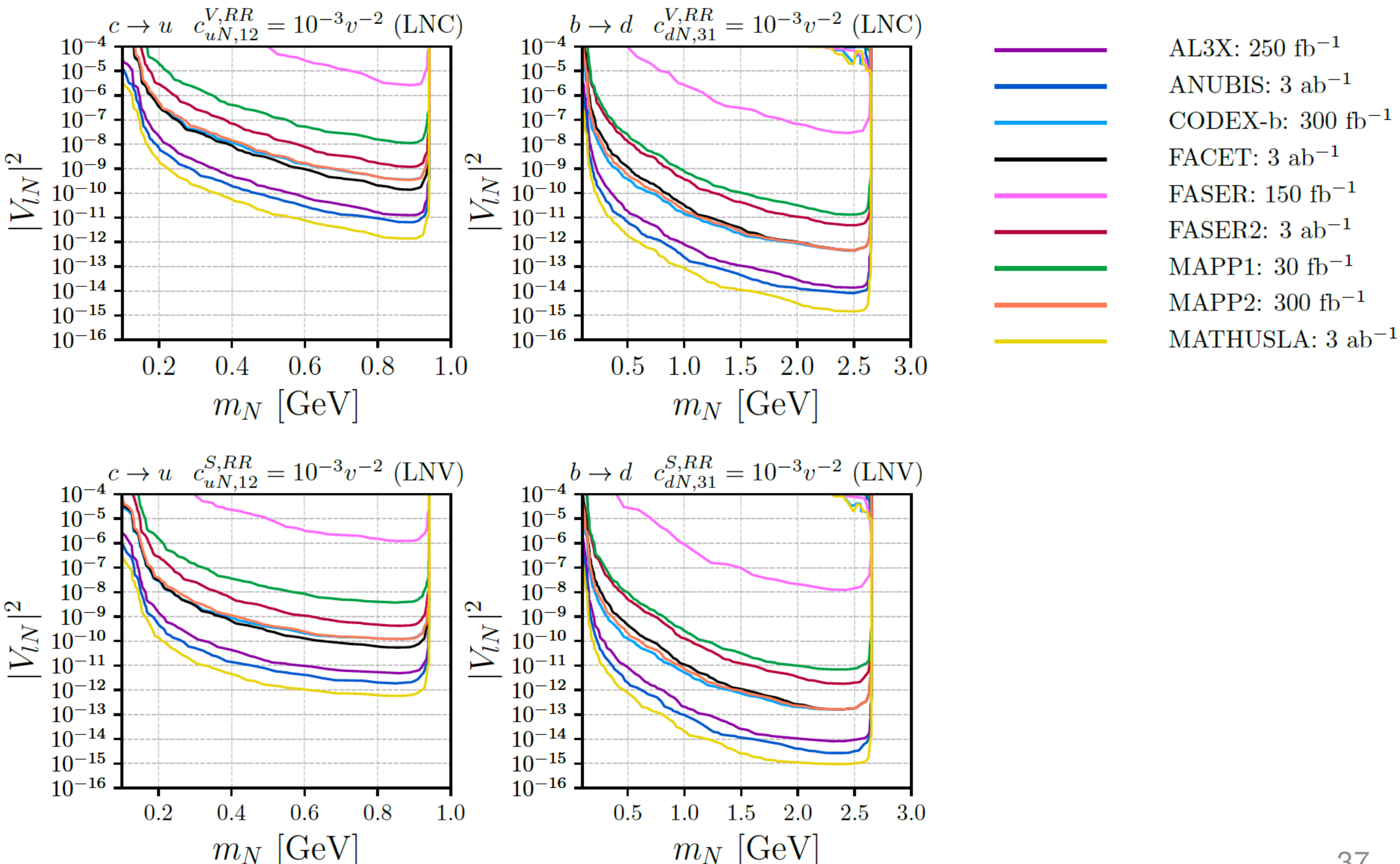


Inclusive production numbers of *D* and *B* mesons at the HL-LHC with $\sqrt{s} = 14$ TeV and $\mathscr{L} = 3$ ab^{-1}:

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}

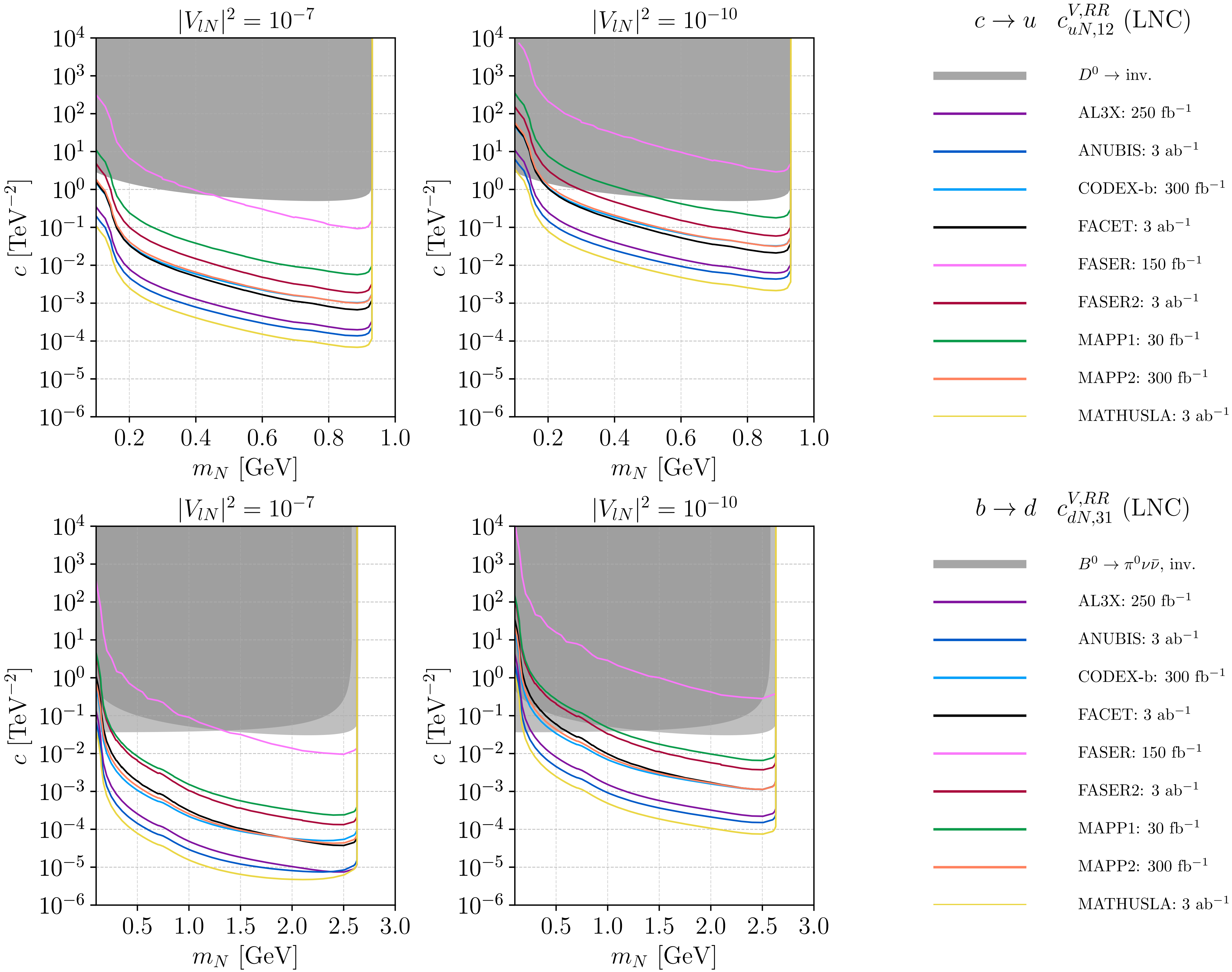
4-fermion NLEFT operators at HL-LHC

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



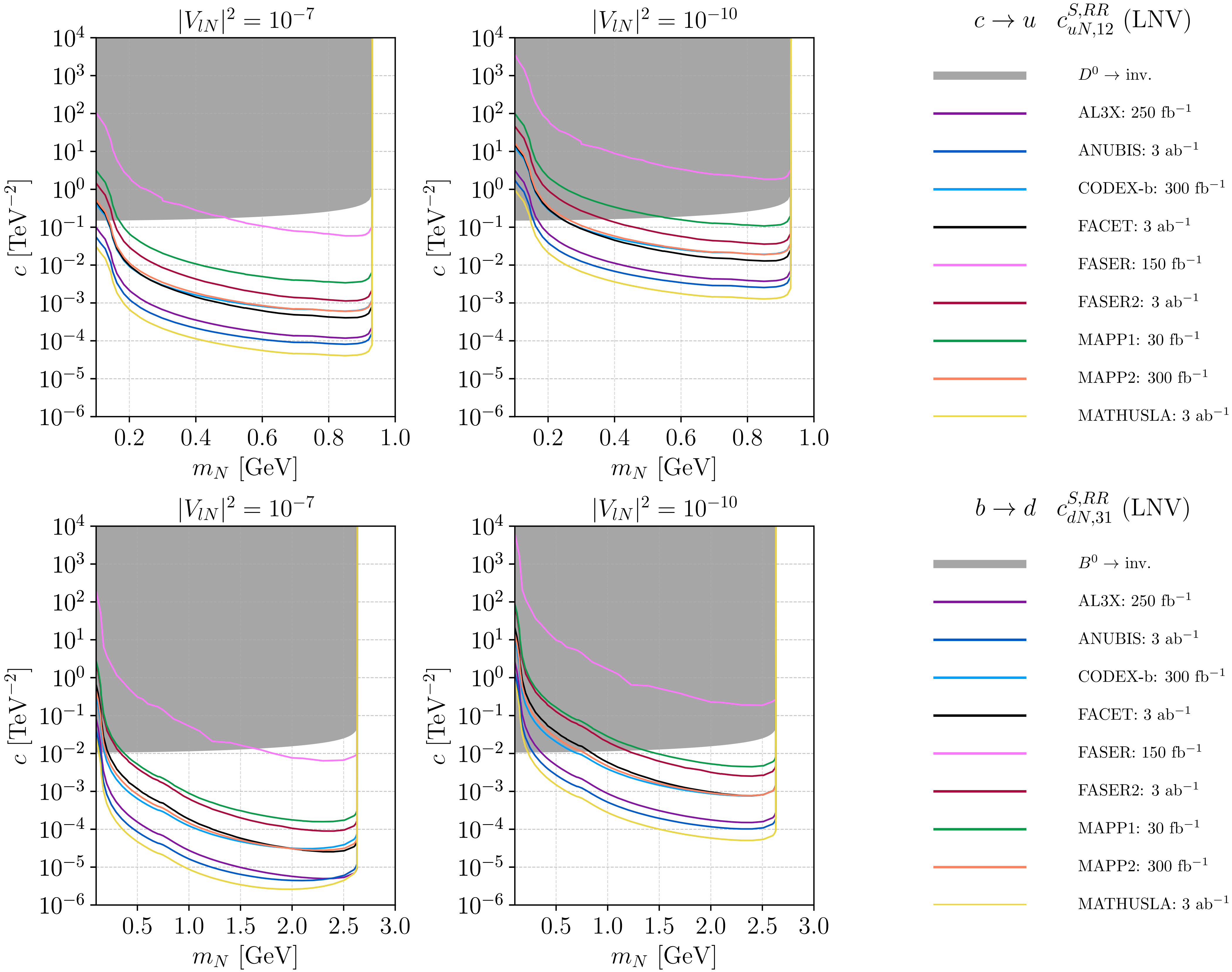
4-fermion NLEFT operators at HL-LHC

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:

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

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

LNV operators:

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

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

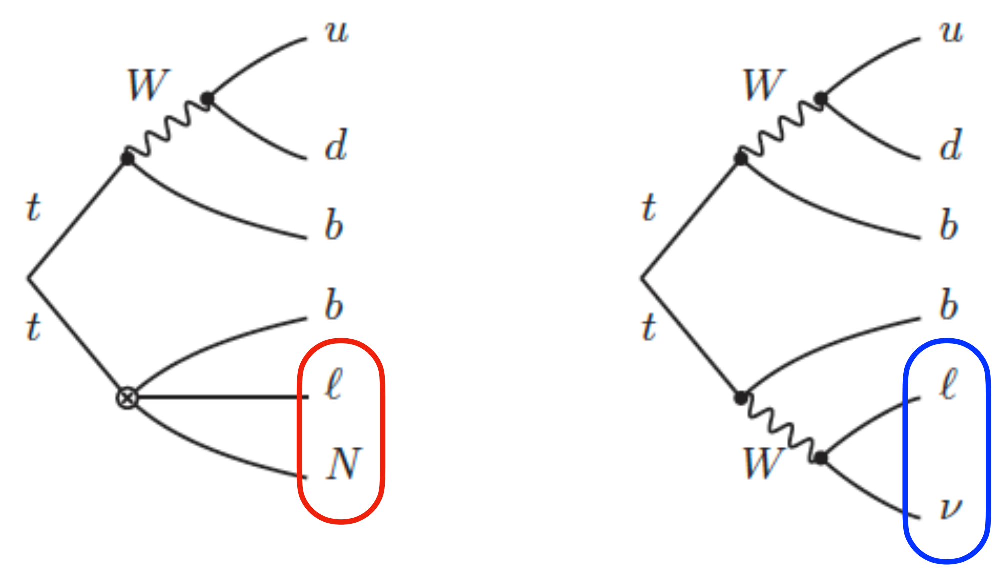
Conclusions

- 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 $\Lambda \gg v$, hence NSMEFT (NLEFT)
- HNLs may be long-lived (in a broad mass range)
- 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
  - AL3X, ANUBIS, CODEX-b, FACET, FASER, MATHUSLA, MoEDAL-MAPP
- New physics scales up to
  - 20 TeV for LNC operators could be probed through direct HNL production
  - 300 (20) TeV for LNC (LNV) operators via meson decays

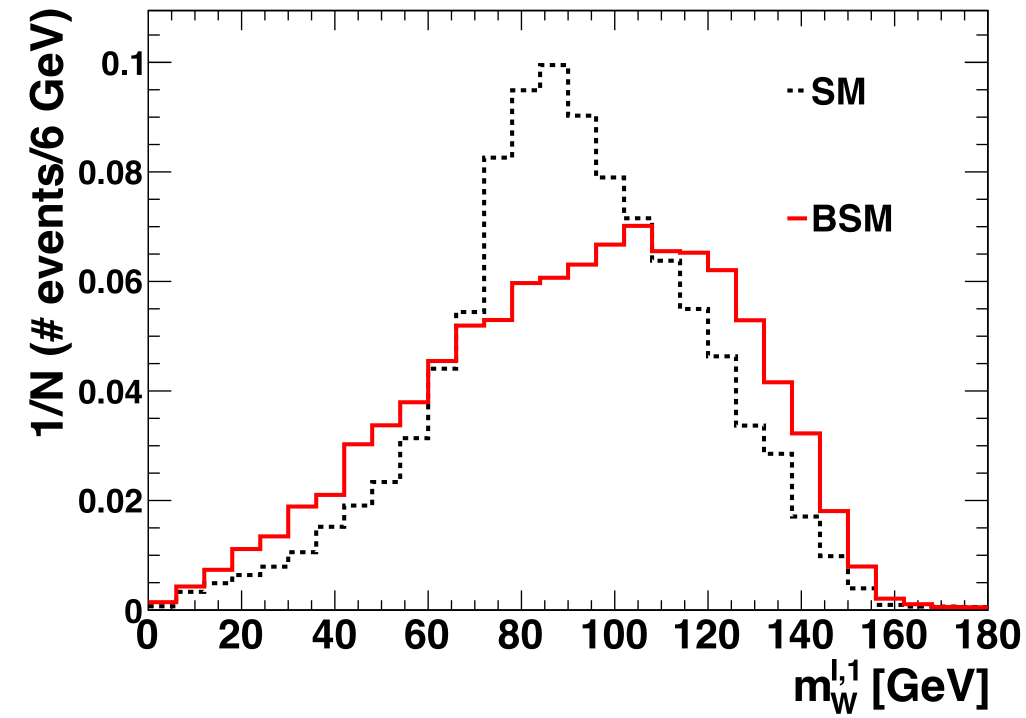
Backup slides

Novel LHC analysis for $t \to bl + \text{inv}$

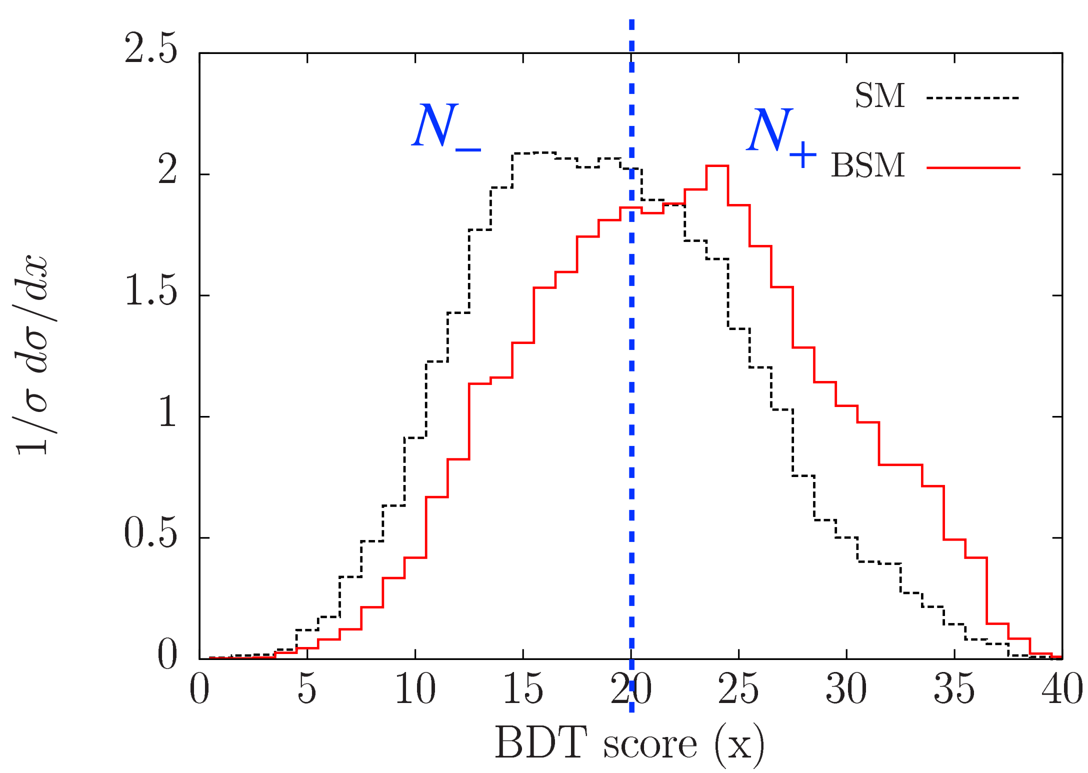
Alcaide, Banerjee, Chala, AT, 1905.11375



do not reconstruct m_W — reconstruct m_W



A multivariate analysis based on a BDT classifier ($p_T^{b_i}$, $p_T^{j_i}$, m_W, ΔR_{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 $\mathscr{L} = 3$ ab^{-1}

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 ⇔ $d = 6$ 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 ⇔ $d = 7$ in NSMEFT

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

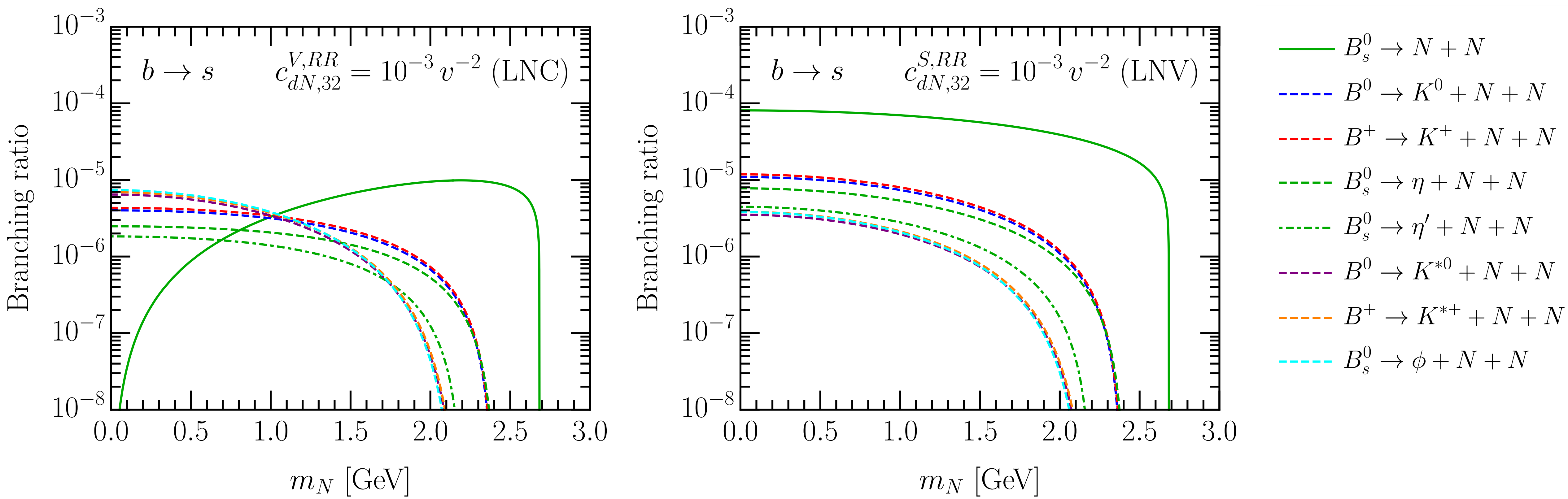
$$c^{V,RR}_{u\nu N,ij\alpha} = -\frac{\mathrm{v}}{\sqrt{2}}C^{ij\alpha}_{uNLH} - \frac{g_Z^2}{m_Z^2}Z^{ij}_{u_R}Z^\alpha_{\nu N}$$

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

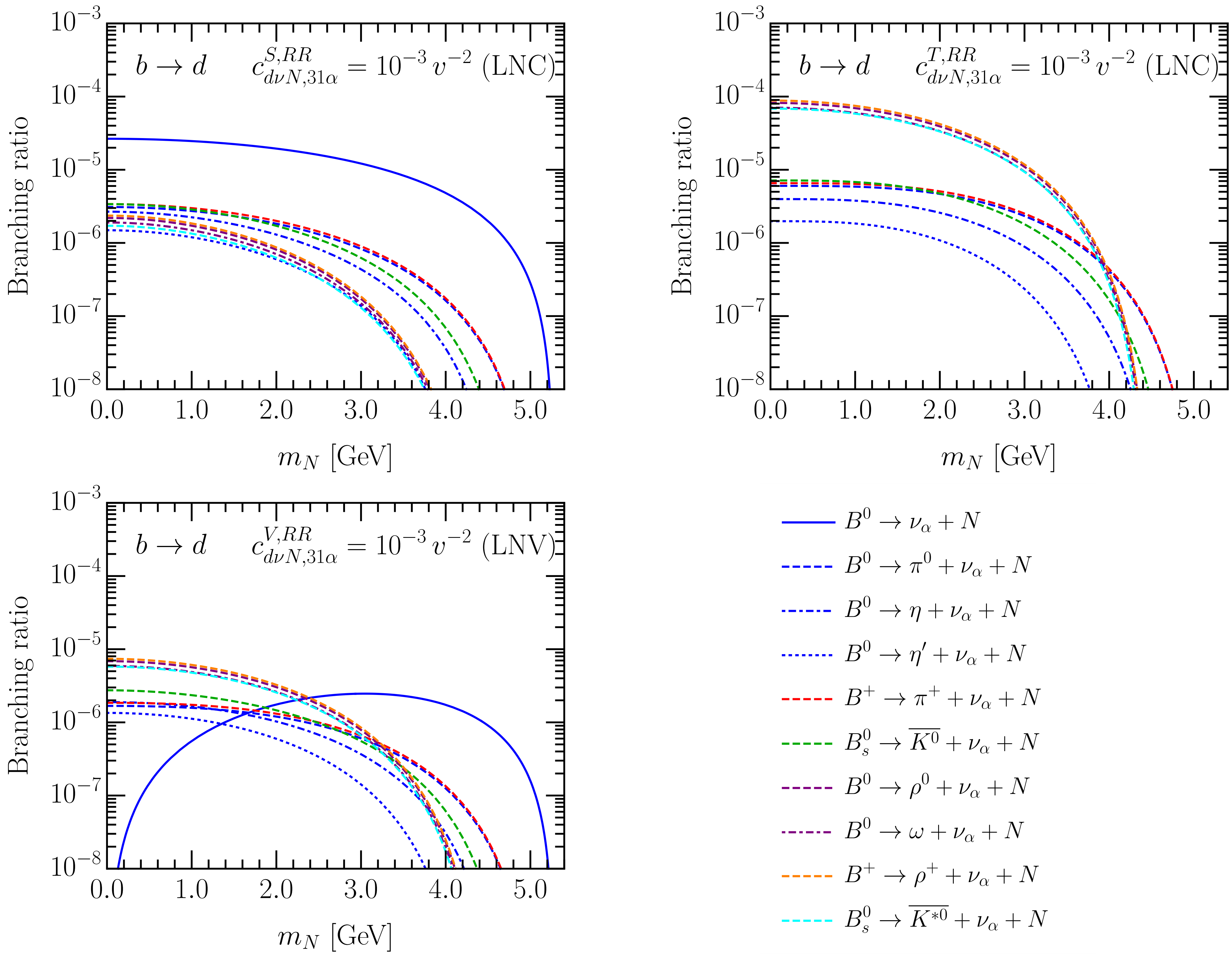
$$c^{V,LR}_{u\nu N,ij\alpha} = -\frac{\mathrm{v}}{\sqrt{2}}C^{ij\alpha}_{QNLH1} - \frac{g_Z^2}{m_Z^2}Z^{ij}_{u_L}Z^\alpha_{\nu N}$$

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

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

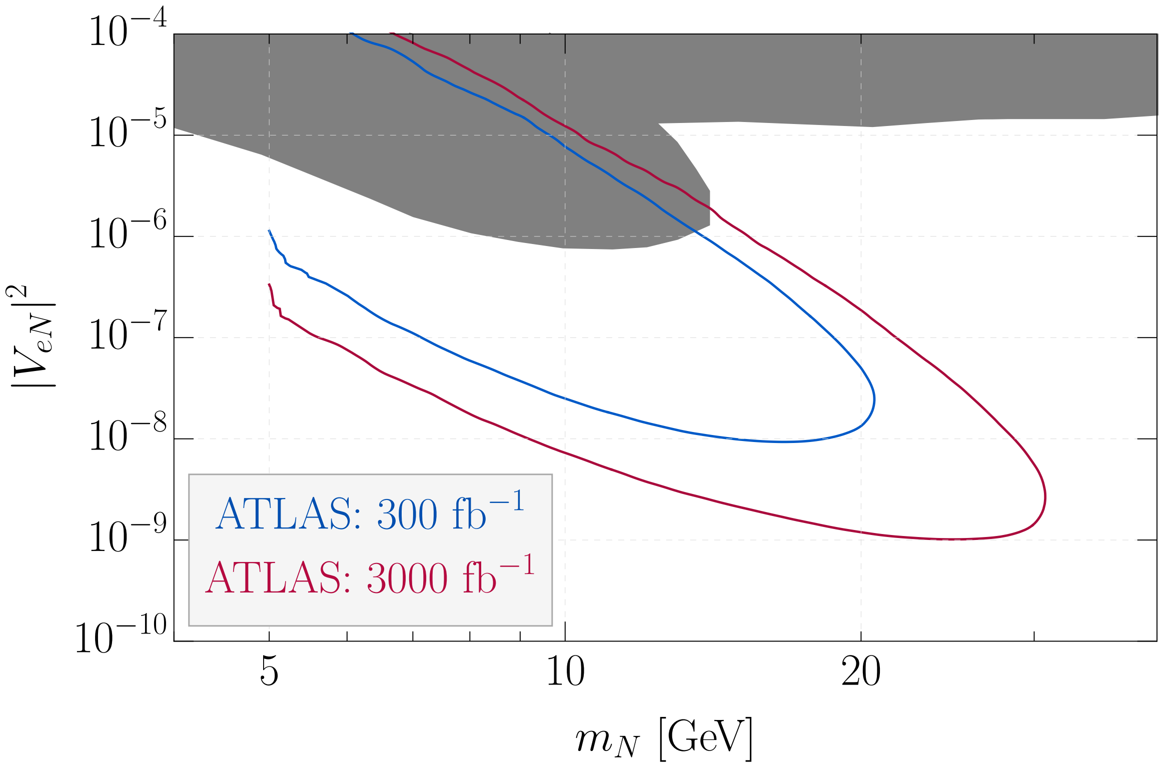
BABAR'12
BELL'17

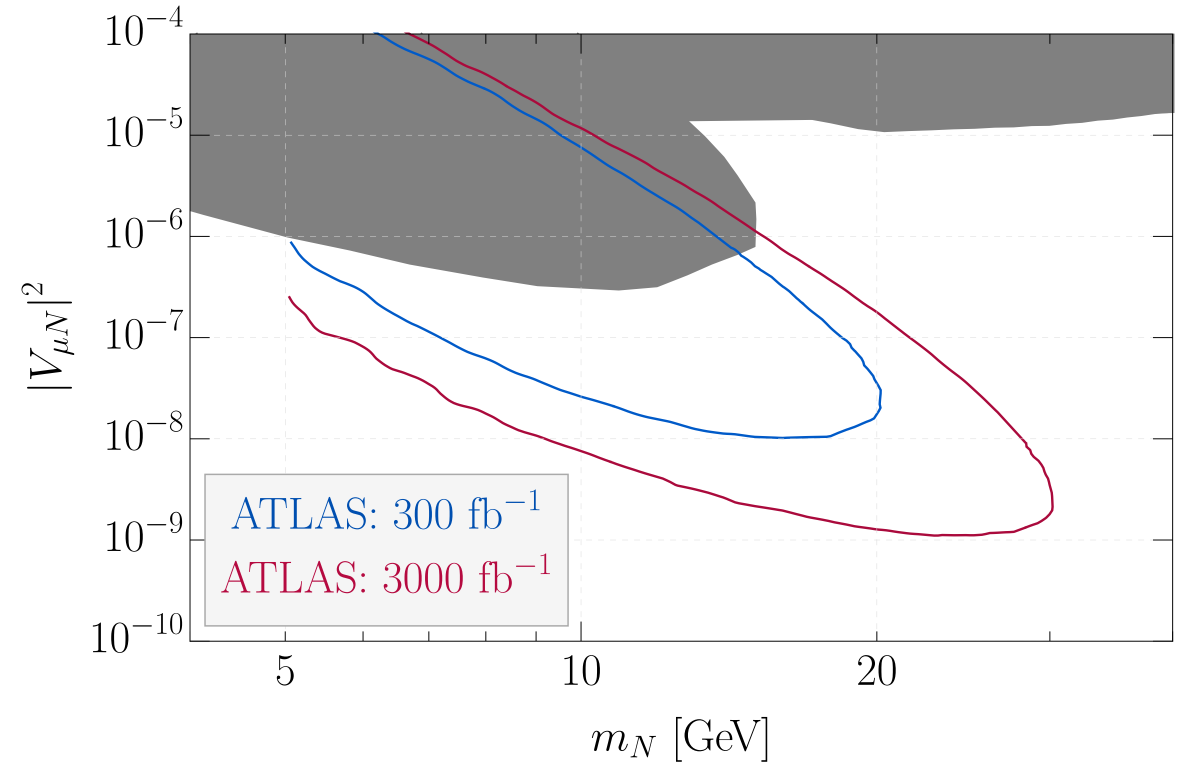
BABAR'13

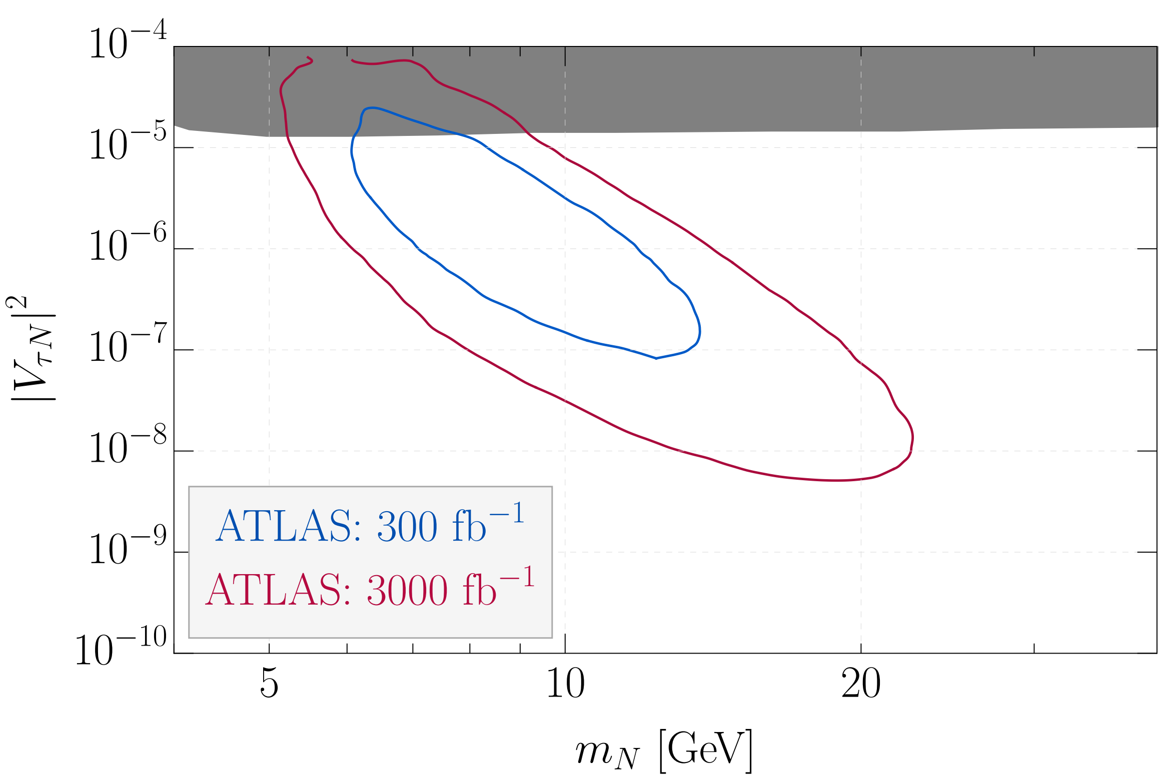
Decay	Branching ratio
$K_L \to \pi^0\nu\overline{\nu}$	$< 3.0 \times 10^{-9}$ at 90% C.L.
$K^+ \to \pi^+\nu\overline{\nu}$	$(1.14^{+0.40}_{-0.33}) \times 10^{-10}$

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

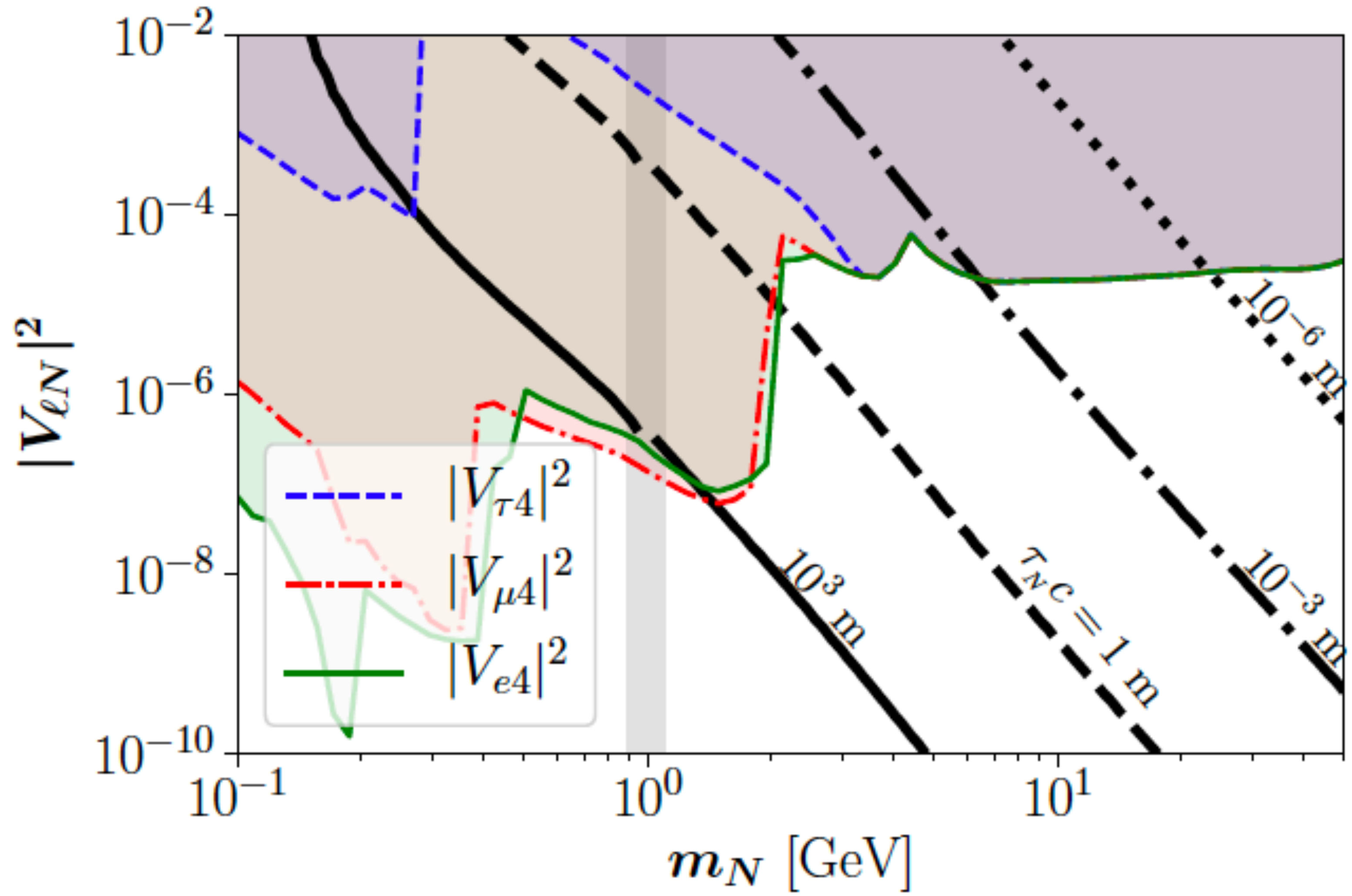


Figure from
Abada, Bernal, Losada, Marcano, 1807.10024

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

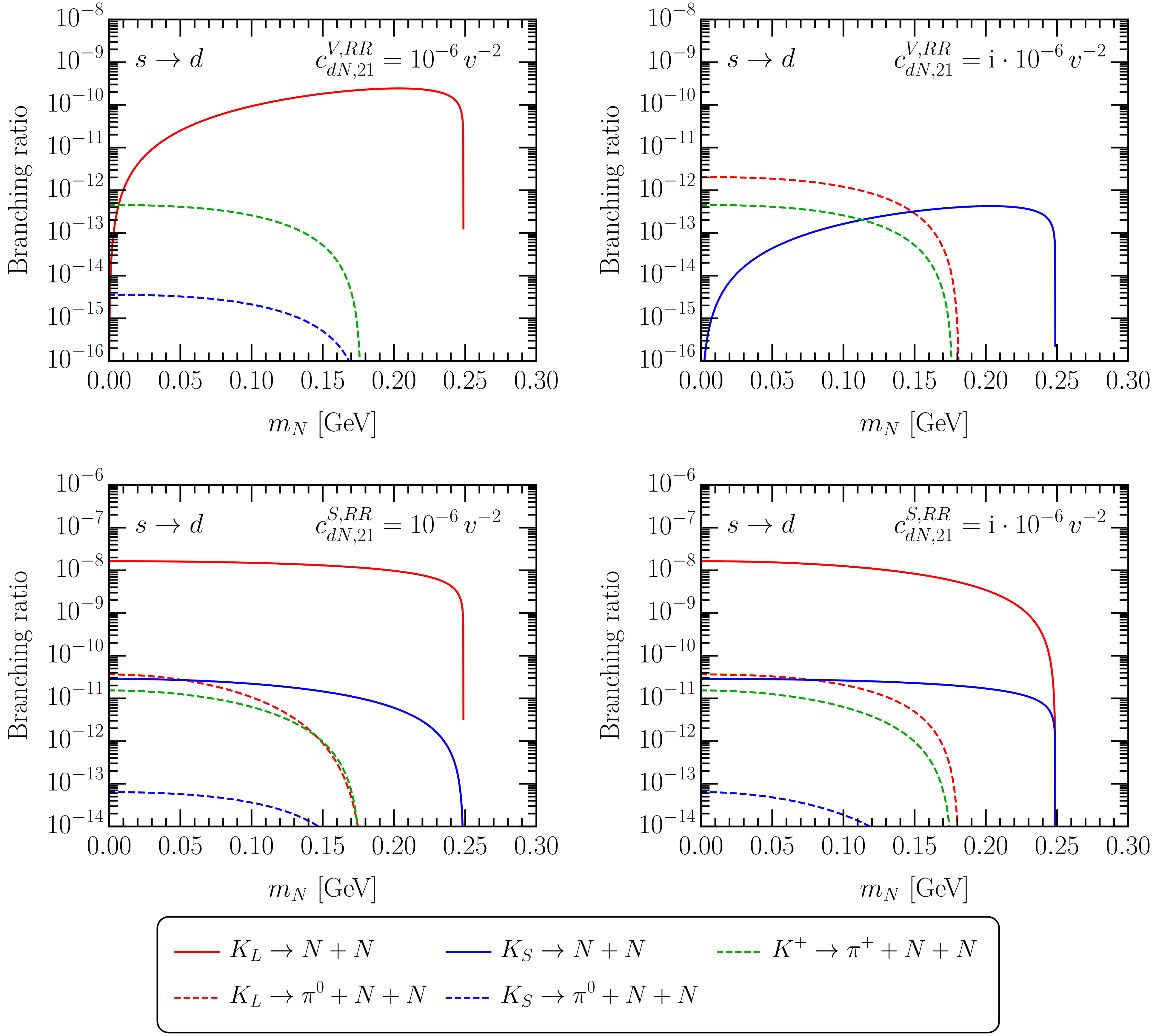
LNV operators		
Name	Structure	N_{pars}
$\mathcal{O}_{dN}^{S,RR}$	$(\overline{d_L}d_R)\,(\overline{N_R^c}N_R)$	18
$\mathcal{O}_{uN}^{S,RR}$	$(\overline{u_L}u_R)\,(\overline{N_R^c}N_R)$	8
$\mathcal{O}_{dN}^{S,LR}$	$(\overline{d_R}d_L)\,(\overline{N_R^c}N_R)$	18
$\mathcal{O}_{uN}^{S,LR}$	$(\overline{u_R}u_L)\,(\overline{N_R^c}N_R)$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

NLEFT single-N_R operators (CC)

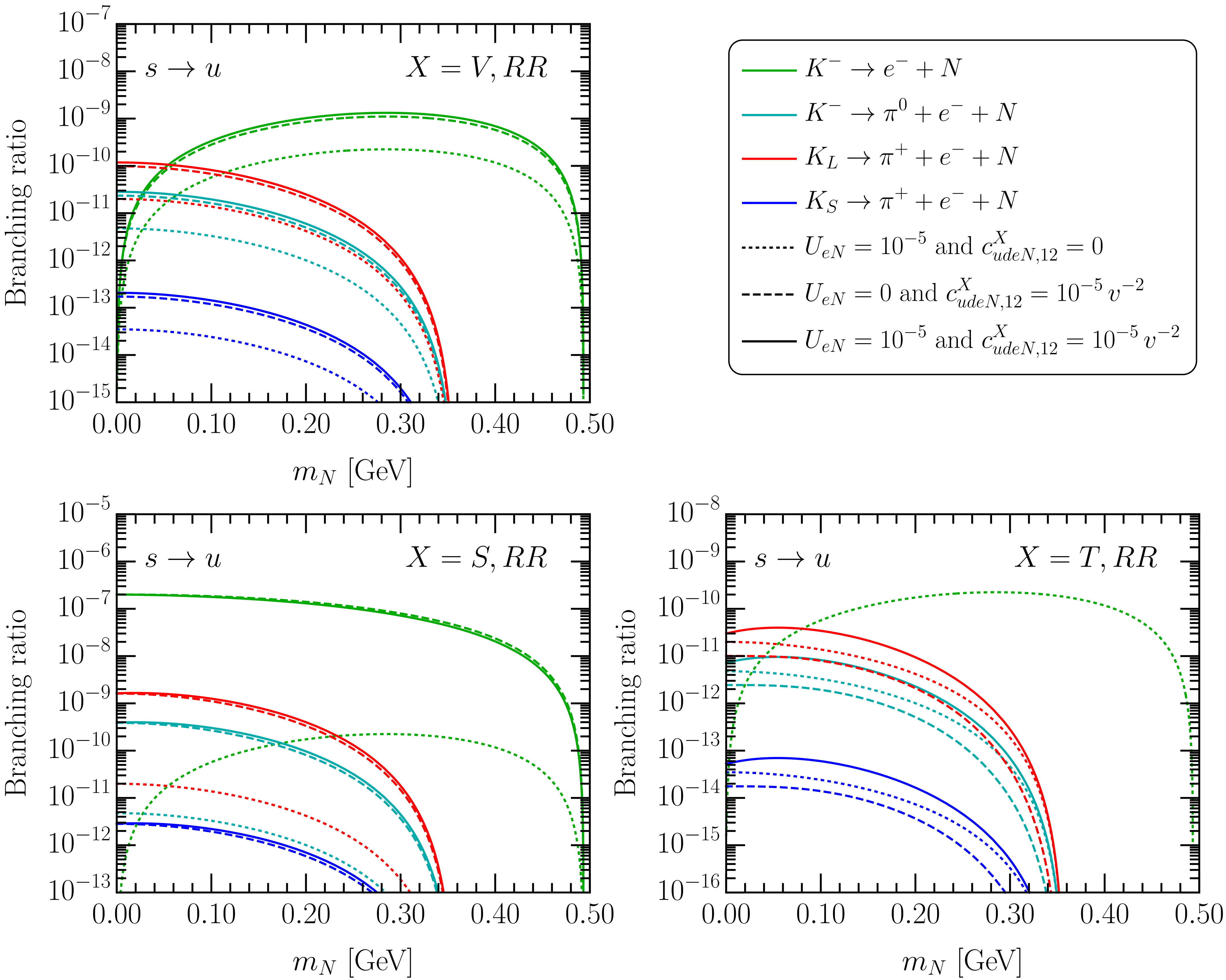
LNC operators	
Name	Structure
$\mathcal{O}_{udeN}^{V,RR}$	$(\overline{u_R}\gamma_\mu d_R)\,(\overline{e_R}\gamma^\mu N_R)$
$\mathcal{O}_{udeN}^{V,LR}$	$(\overline{u_L}\gamma_\mu d_L)\,(\overline{e_R}\gamma^\mu N_R)$
$\mathcal{O}_{udeN}^{S,RR}$	$(\overline{u_L}d_R)\,(\overline{e_L}N_R)$
$\mathcal{O}_{udeN}^{T,RR}$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

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

Branching ratios: pair-N operators



Branching ratios: single-N operators

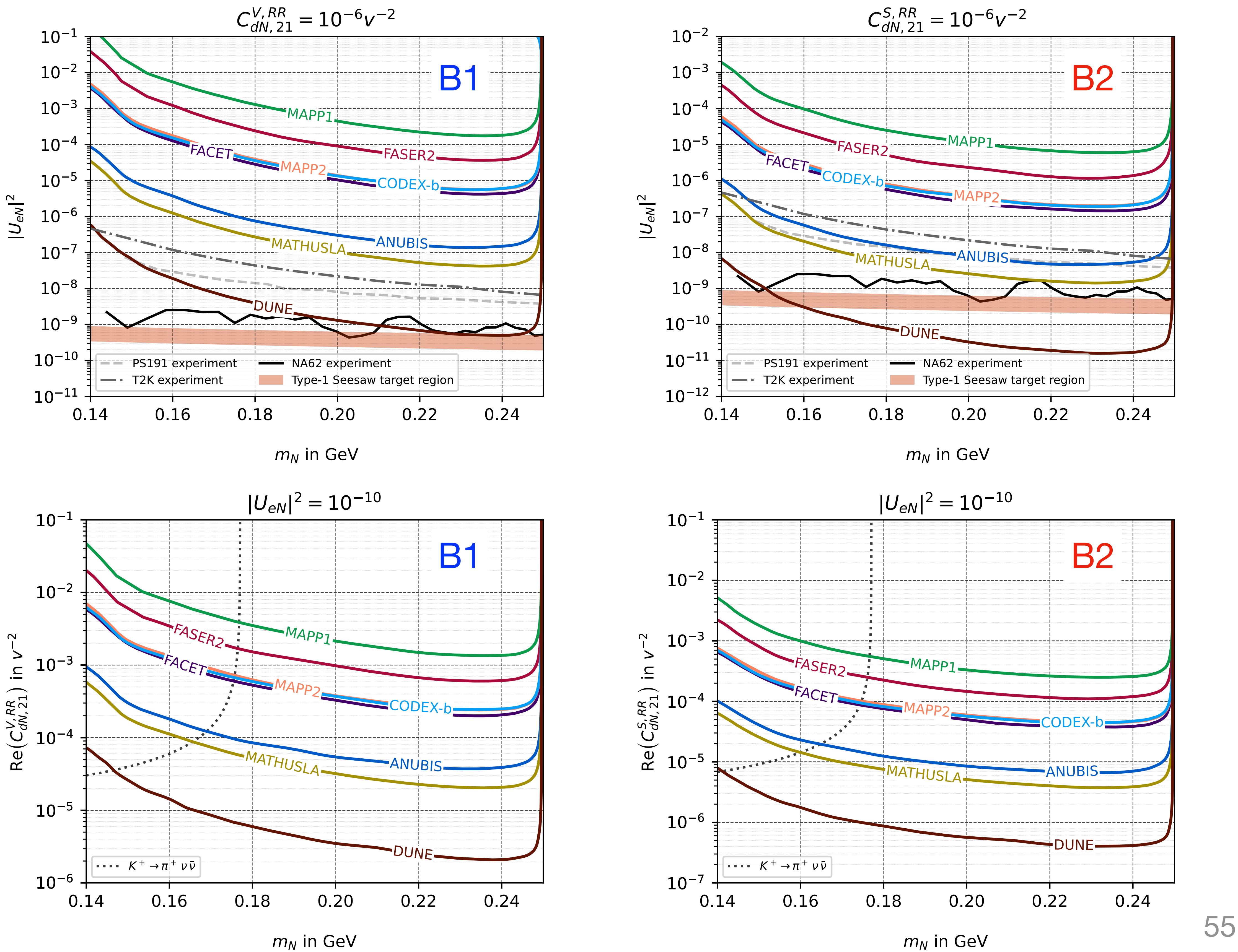


Benchmark scenarios

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}

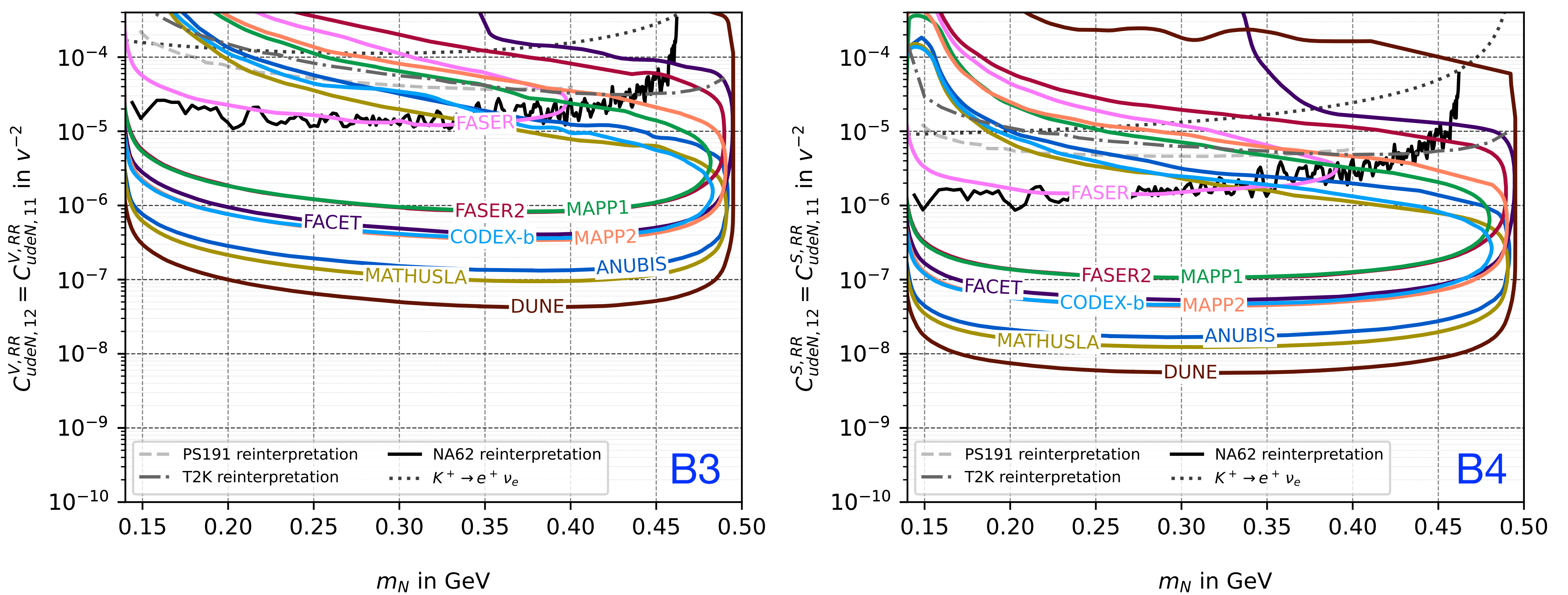
Benchmark	Production	Decay
B3	$c^{V,RR}_{udeN,12}$	$c^{V,RR}_{udeN,11}$
B4	$c^{S,RR}_{udeN,12}$	$c^{S,RR}_{udeN,11}$
B5	$c^{V,RR}_{udeN,12}$ and U_{eN}	U_{eN}
B6	$c^{S,RR}_{udeN,12}$ and U_{eN}	U_{eN}
B7	$c^{V,RL}_{udeN,12}$ and U_{eN}	U_{eN}
B8	$c^{S,RL}_{udeN,12}$ and U_{eN}	U_{eN}

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