Heavy Neutral Leptons in Effective Field Theory and the High-Luminosity LHC

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Outline

- Motivation for heavy neutral leptons (HNLs)
- The effective field theory (EFT) of the Standard Model (SM) extended with HNLs
- Experimental prospects at the high-luminosity LHC (HL-LHC)
- Sensitivity to 4-fermion pair-N_R operators
- Sensitivity to 4-fermion single-N_R operators
- Conclusions

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:

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

N_R is *right-handed (RH) neutrino*; lepton number (LN) is conserved

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

Type I seesaw mechanism:

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

N_R is RH neutrino or *heavy neutral lepton (HNL)*; LN is violated

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

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

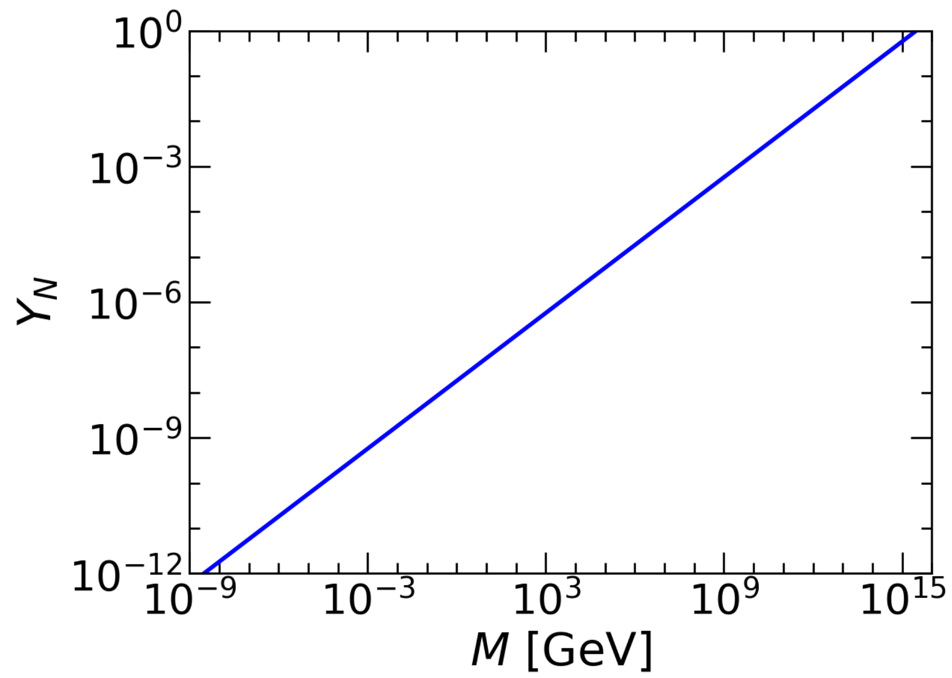
Motivation: neutrino masses

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

Active-heavy neutrino mixing

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

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



Inverse seesaw mechanism:

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

$$m_\nu = m_D M_R^{-1} \mu M_R^{-1T} m_D^T \sim 0.01 \text{ eV} \quad \text{and} \quad V_{\alpha N}^2 \sim \left(\frac{m_D}{M_R}\right)^2 \sim \frac{m_\nu}{\mu} \sim 10^{-2} \div 10^{-8}$$

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

Effective field theory approach

Assume that

- the HNL mass m_N is below or around the weak scale v
- new physics exists at scale $\Lambda \gg \mathrm{v}$

Then the most general description of physics at low energies is in terms of the EFT of the SM extended with HNLs (NSMEFT)

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

$\mathscr{O}_i^{(d)}$ are effective operators invariant under the SM gauge symmetry

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

NSMEFT at dimension 6

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)

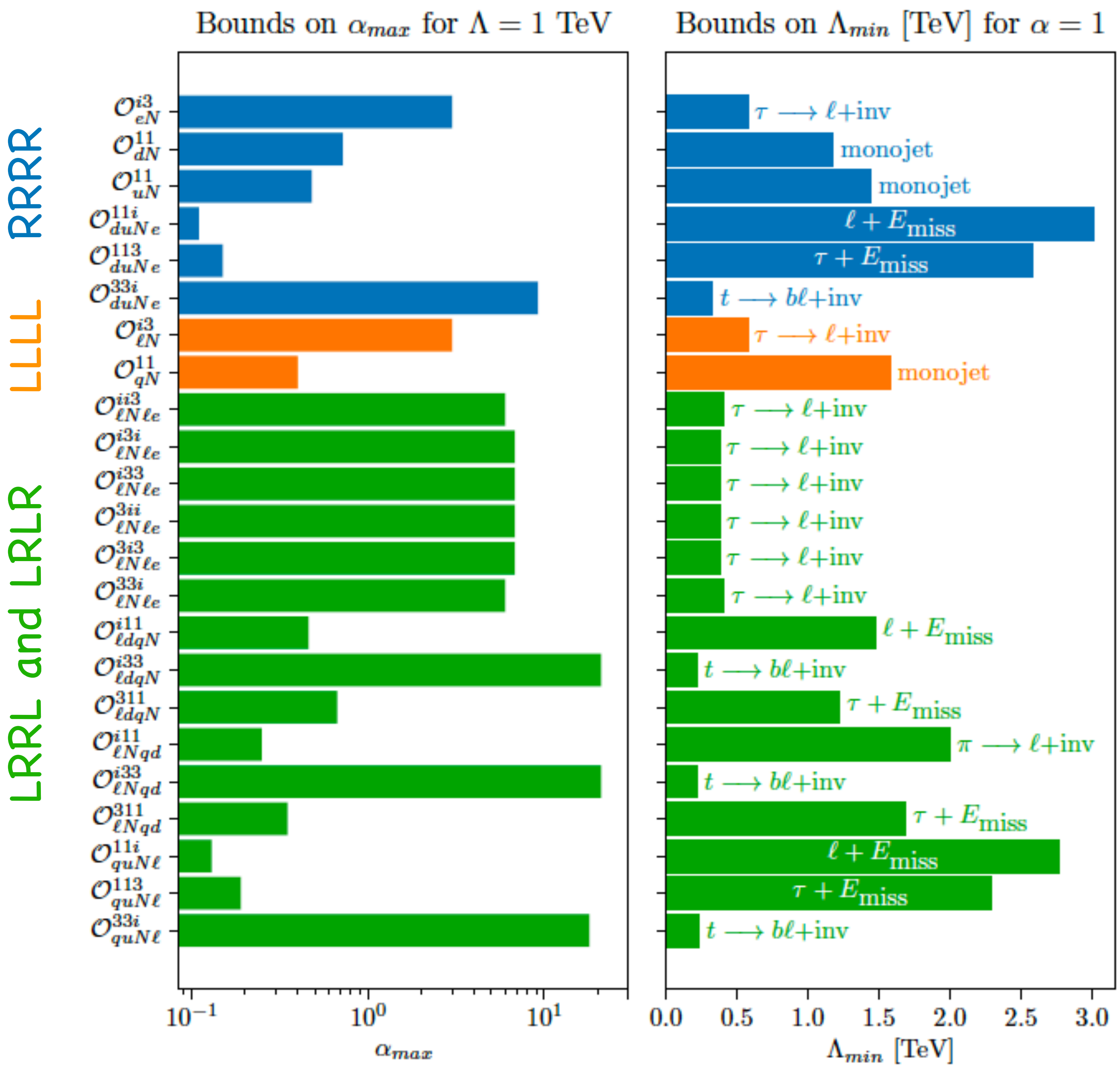
RRRR	$\mathcal{O}_{NN} = (\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma^\mu N_R)$	
	$\mathcal{O}_{eN} = (\overline{e_R}\gamma_\mu e_R)(\overline{N_R}\gamma^\mu N_R)$	$\mathcal{O}_{uN} = (\overline{u_R}\gamma_\mu u_R)(\overline{N_R}\gamma^\mu N_R)$
	$\mathcal{O}_{dN} = (\overline{d_R}\gamma_\mu d_R)(\overline{N_R}\gamma^\mu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

Bounds on 4-fermions for $m_N \lesssim 0.1$ GeV



Alcaide, Banerjee, Chala, AT, 1905.11375

Figure from J. Alcaide's PhD thesis

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

ATLAS, 1706.04786

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

CMS, 1712.02345

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

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

PDG, RPP 2018

$t \to b\ell + \text{inv}$

Alcaide, Banerjee, Chala, AT, 1905.11375

Long-lived HNLs

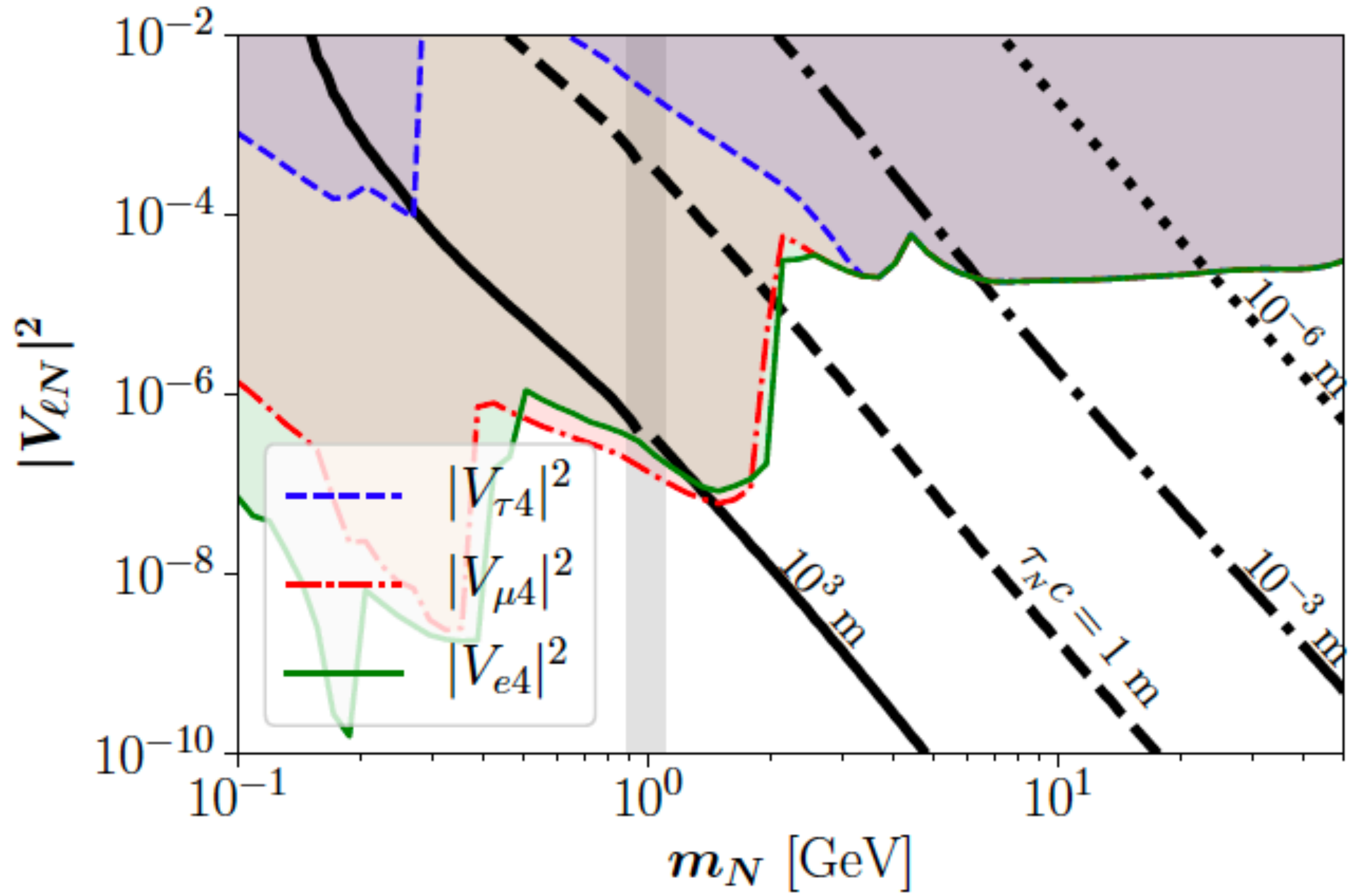


Figure from
Abada, Bernal, Losada, Marcano, 1807.10024

HNLs can be long-lived particles (LLPs)

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

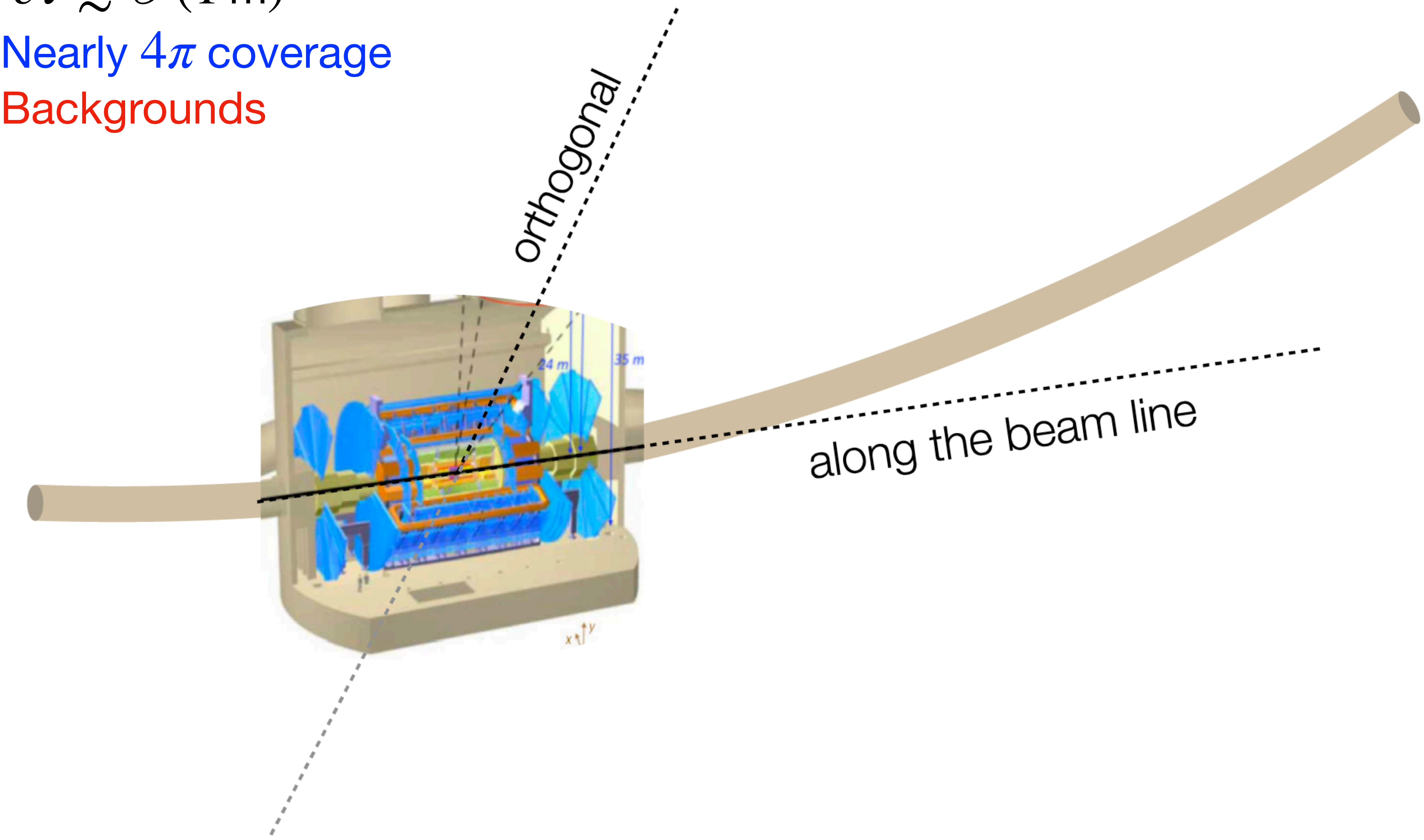
Experimental prospects at HL-LHC

ATLAS and CMS

$c\tau \lesssim \mathcal{O}(1\,\mathrm{m})$

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

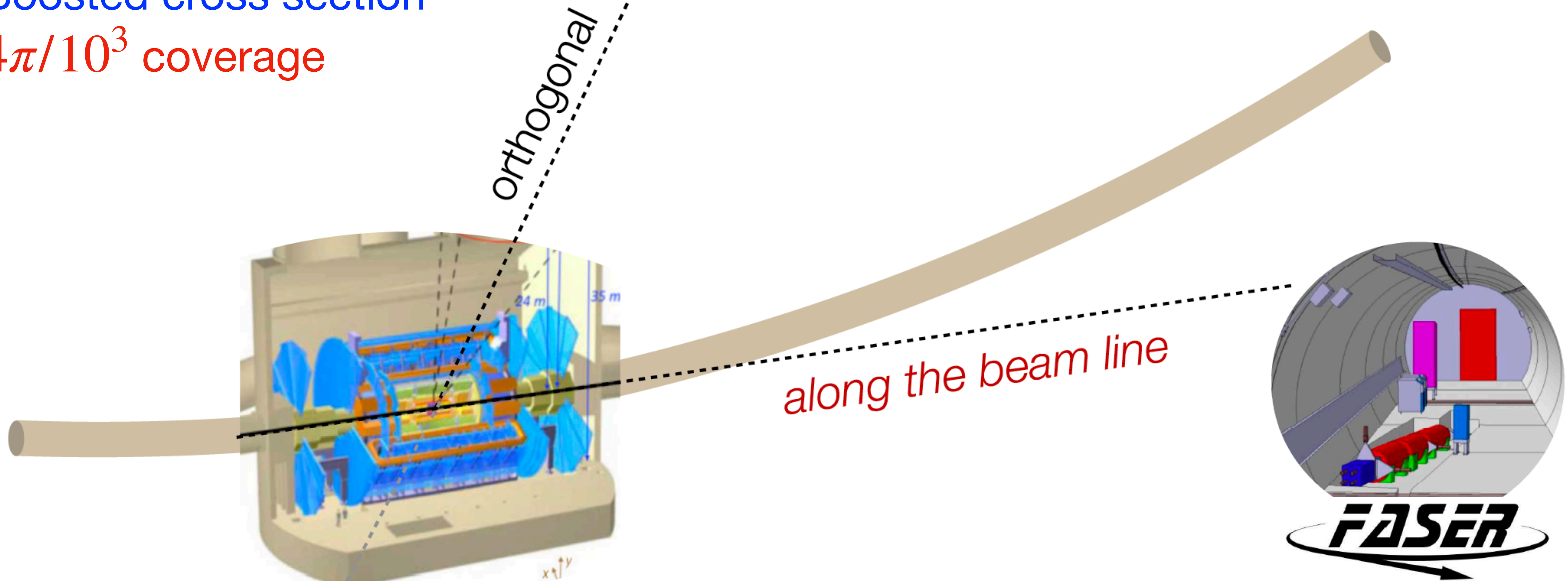
$c\tau \sim 480$ m

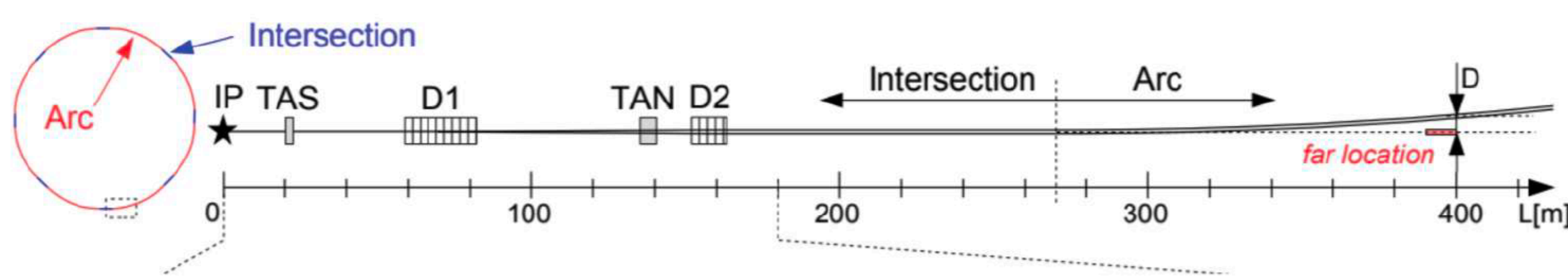
Boosted cross section

$4\pi/10^3$ coverage

Installed

Starts data taking this year!





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

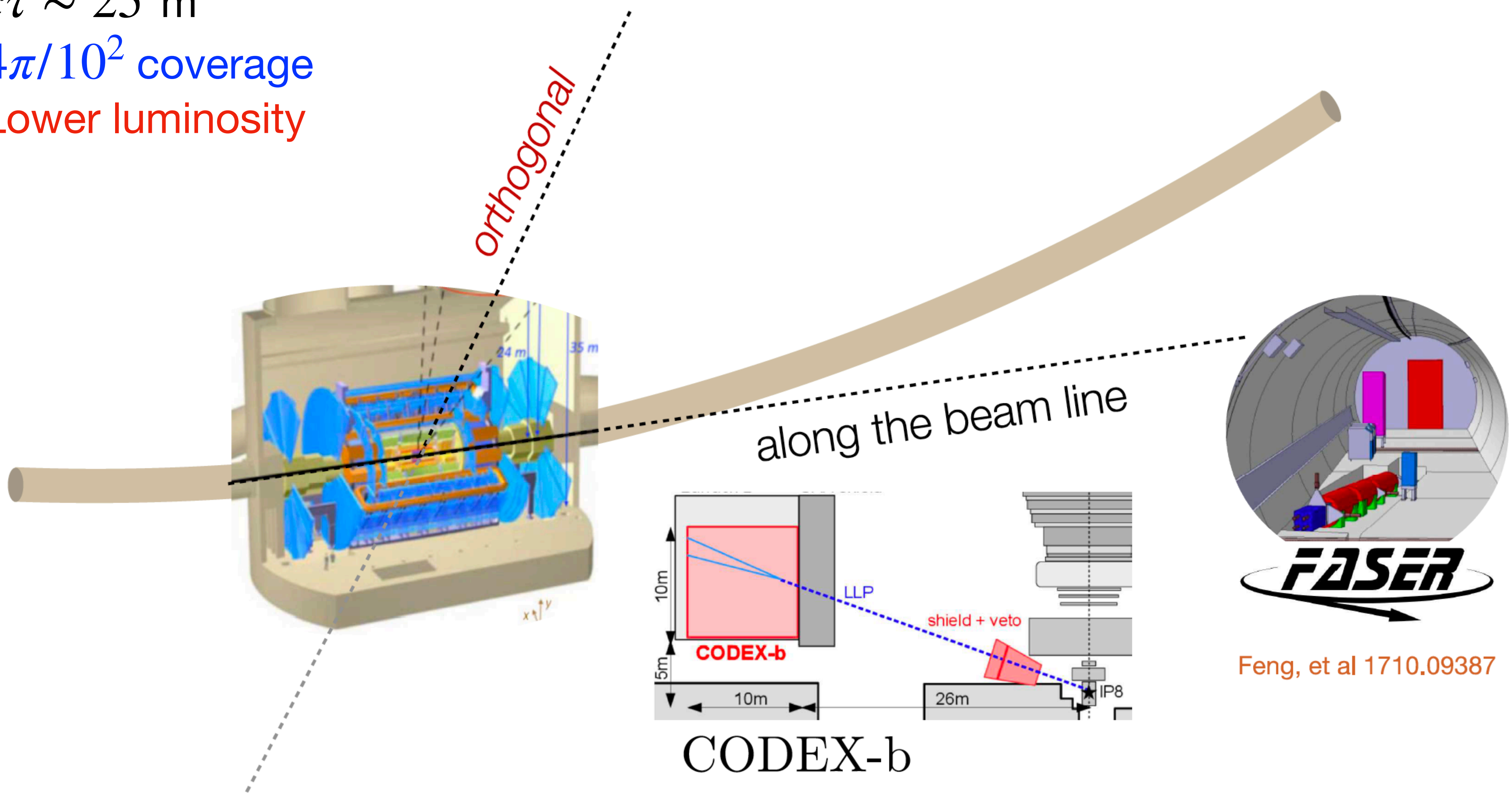
CODEX-b: COmpact Detector for EXotics at LHCb

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

$c\tau \sim 25$ m

$4\pi/10^2$ coverage

Lower luminosity



Gligorov et al 1708.09395

Feng, et al 1710.09387

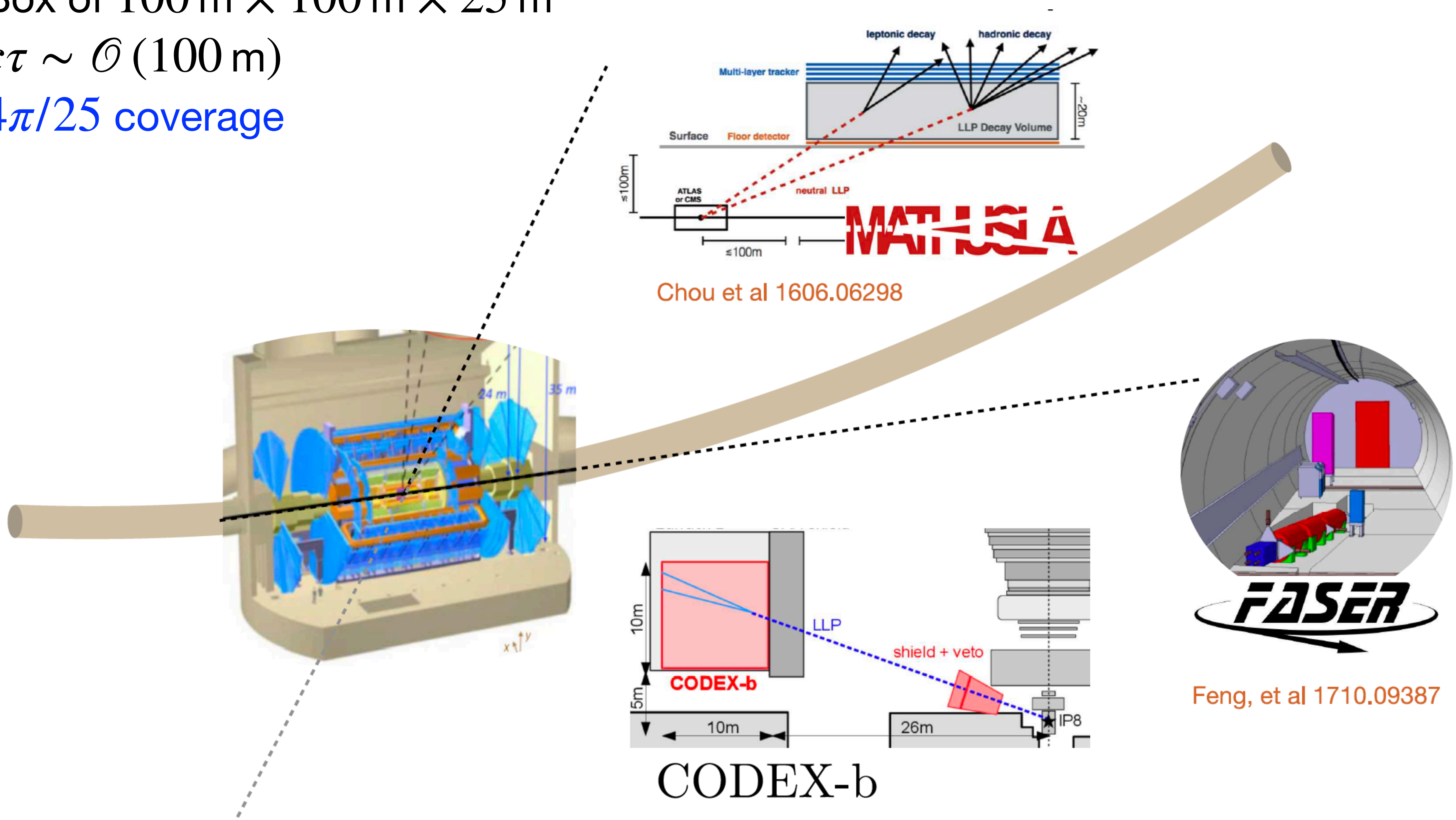
Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

MATHUSLA: MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

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

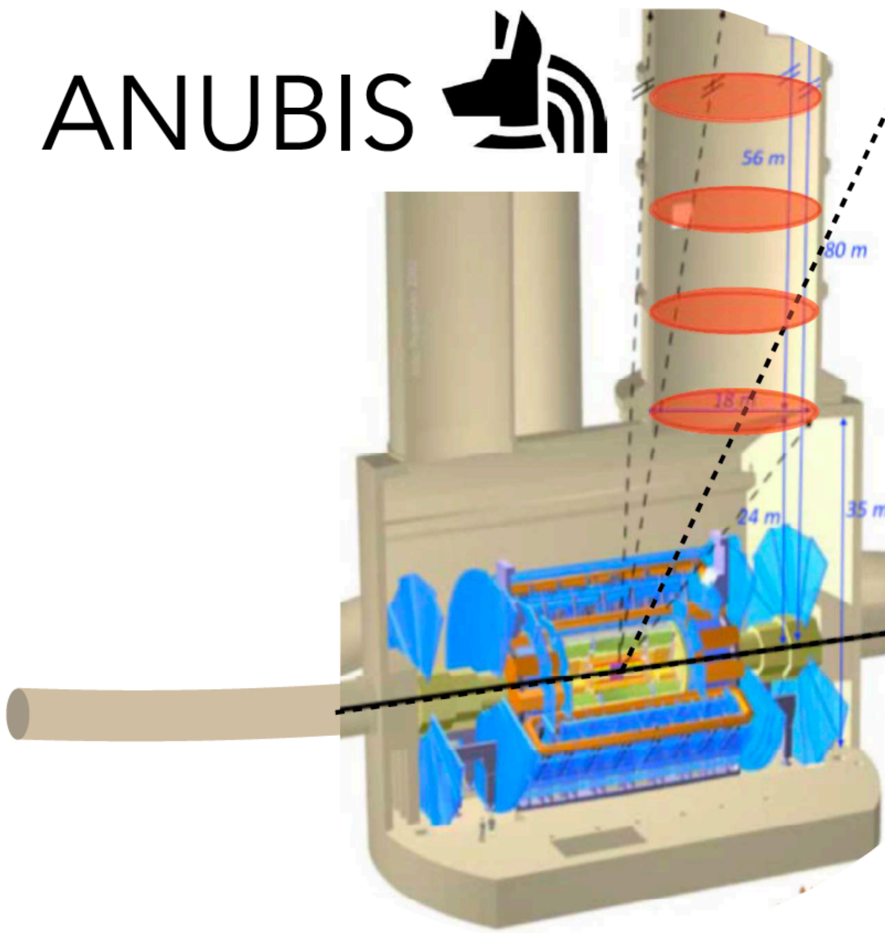
$c\tau \sim \mathcal{O}(100\,\mathrm{m})$

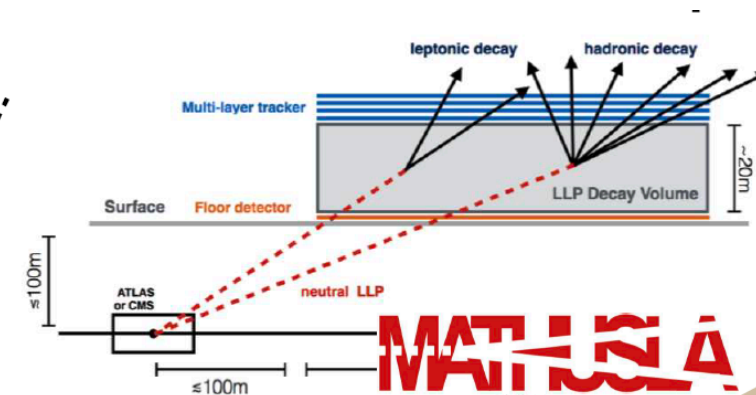
$4\pi/25$ coverage



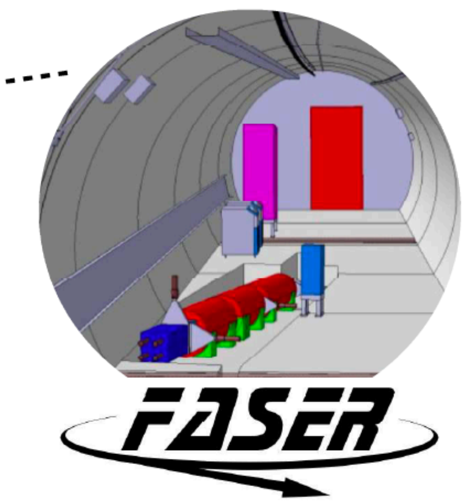
Images from O. Brandt's talk at Oxford Particle Physics Seminar on 9/6/2020

ANUBIS: AN Underground Belayed In-Shaft search experiment





Chou et al 1606.06298



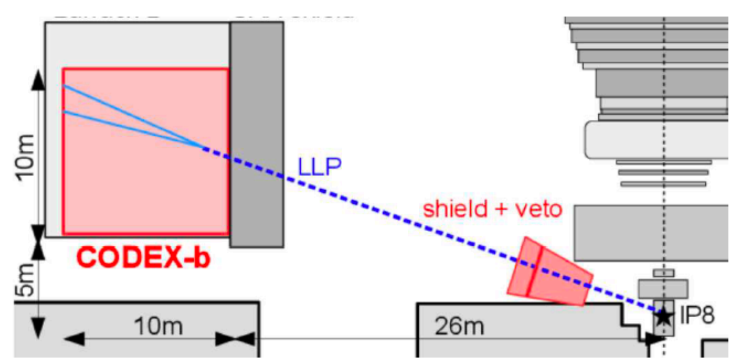
Feng, et al 1710.09387

Cylinder with $r = 9$ m and $h = 56$ m

$c\tau \sim$ few 10 m

$4\pi/50$ coverage

Bauer, OB, Lee, Ohm 1909.13022



CODEX-b

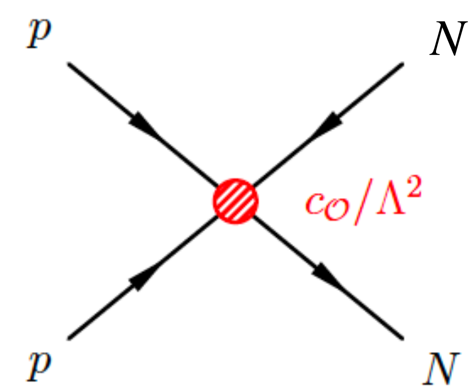
Gligorov et al 1708.09395

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

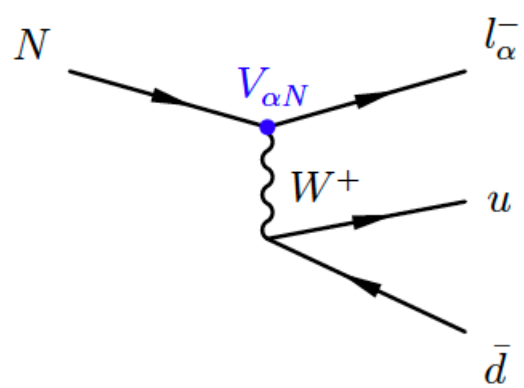
4-fermion pair-N_R operators

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

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

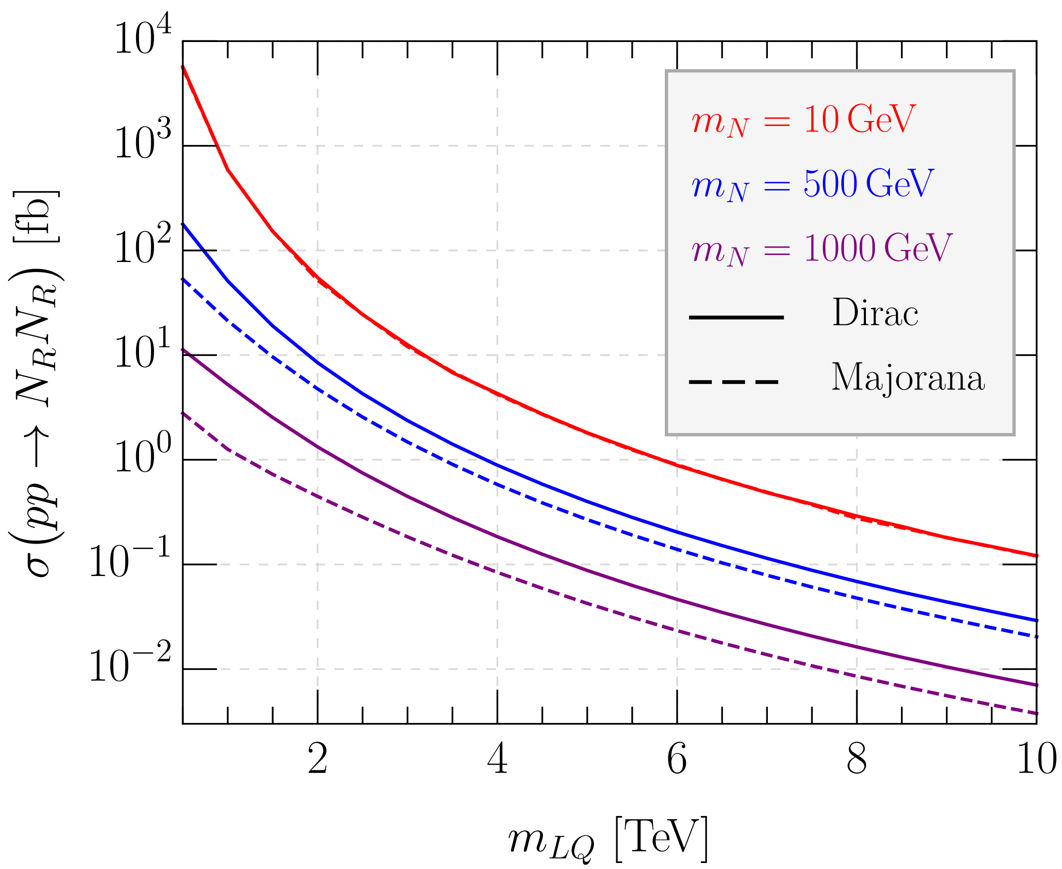
$$\mathscr{L}_{S_u} = g_{uN}\overline{u_R}N_R^c S_u + \text{h.c.}$$

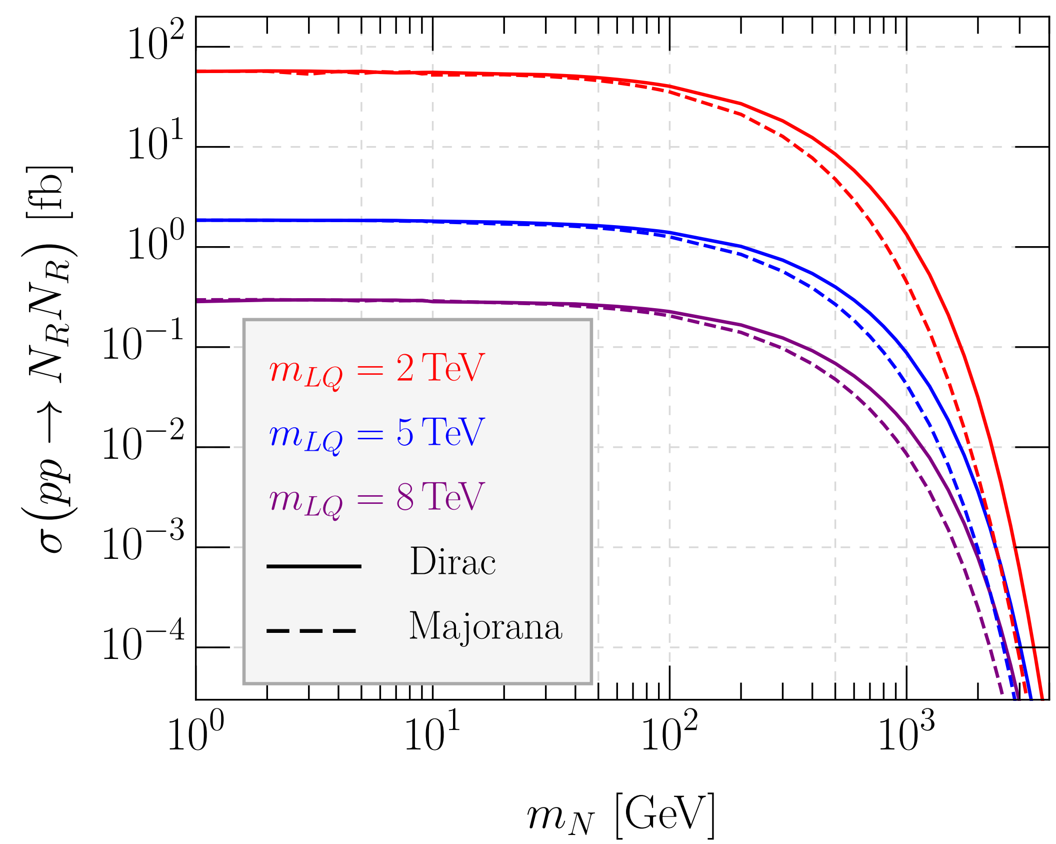
$$\mathscr{L}_{S_Q} = g_{QN}\overline{Q}N_R S_Q + g_{dL}\overline{d_R}L\epsilon S_Q + \text{h.c.}$$

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

4-fermion pair-N_R operators

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



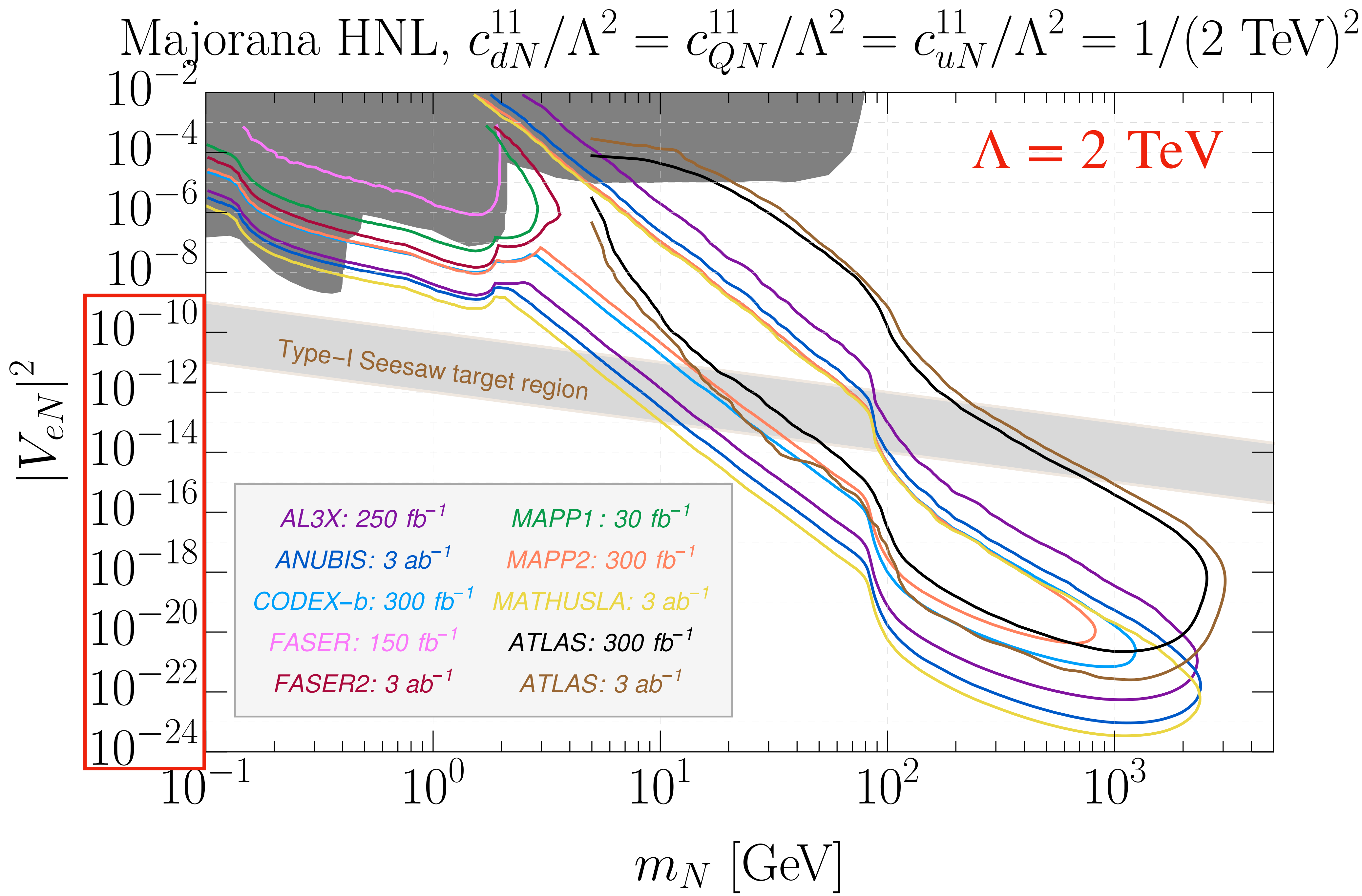


$$\sigma_D(d\bar{d} \to N\bar{N}) = \frac{c_{dN}^2}{192\pi\Lambda^4} s \sqrt{1 - \frac{4m_N^2}{s}} \left[1 + \frac{1}{3}\left(1 - \frac{4m_N^2}{s}\right)\right]$$

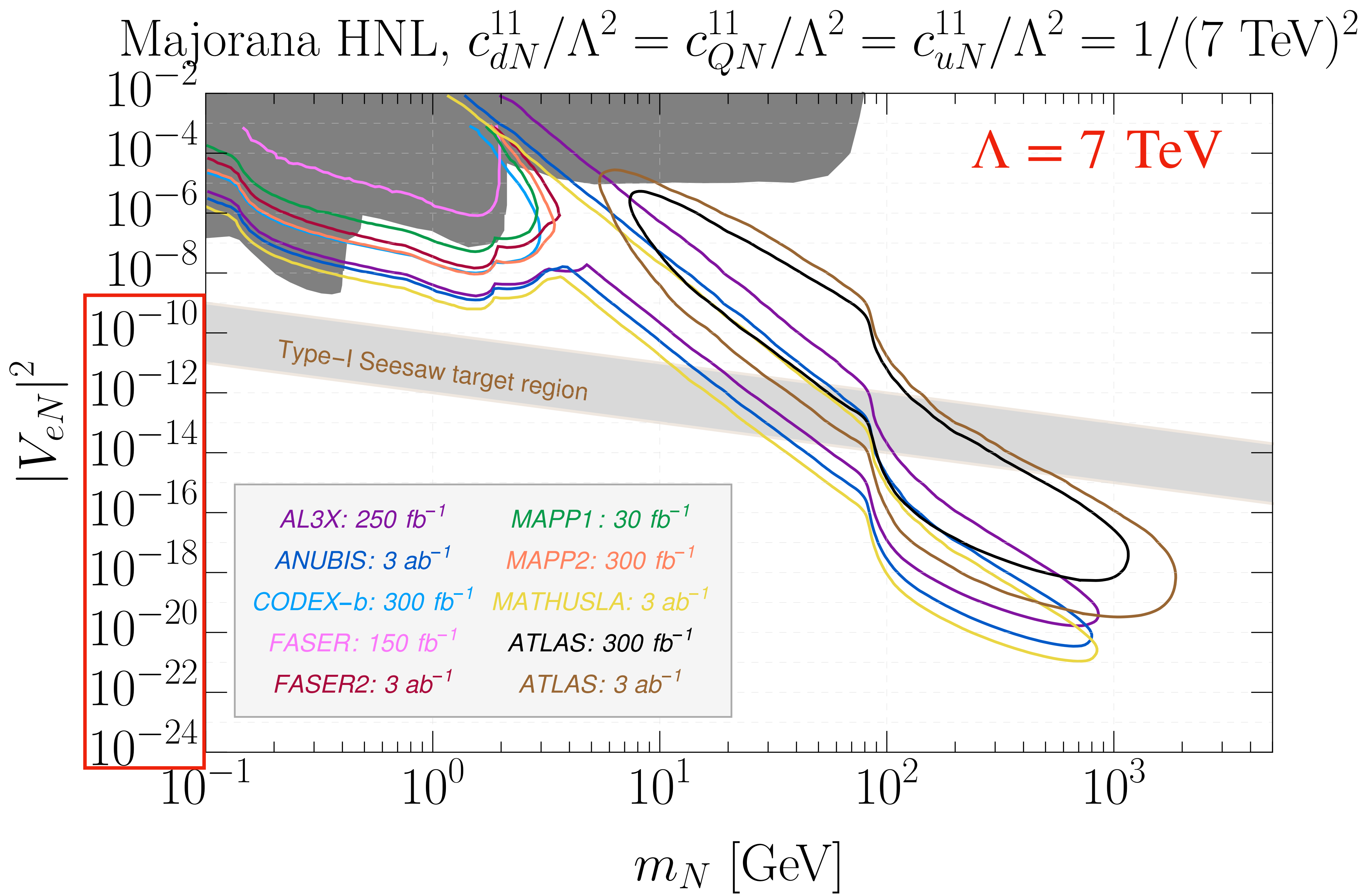
$$\sigma_M(d\bar{d} \to NN) = \frac{c_{dN}^2}{144\pi\Lambda^4} s \left(1 - \frac{4m_N^2}{s}\right)^{3/2}$$

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

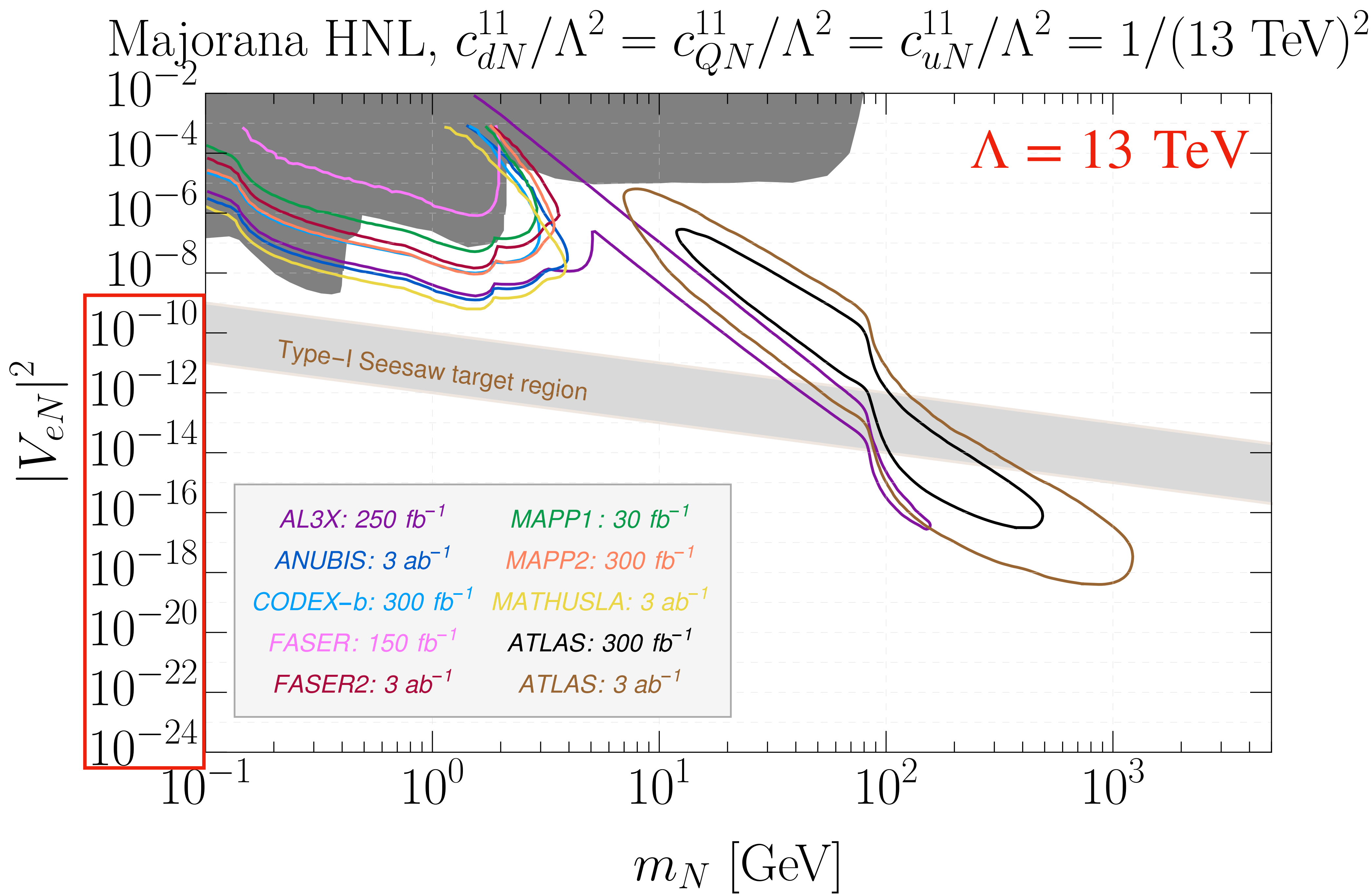
4-fermion pair-N_R operators: results



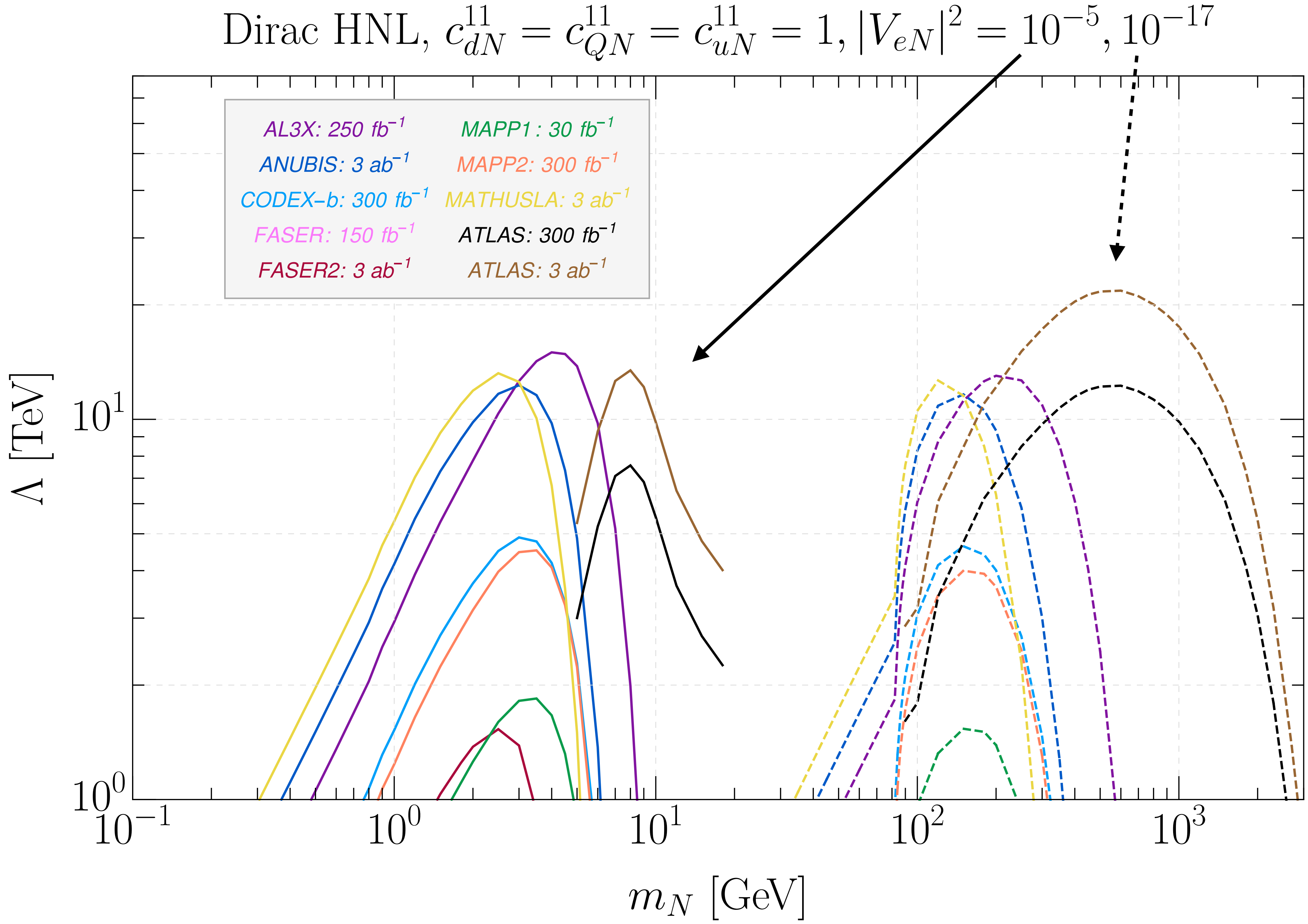
4-fermion pair-N_R operators: results



4-fermion pair-N_R operators: results



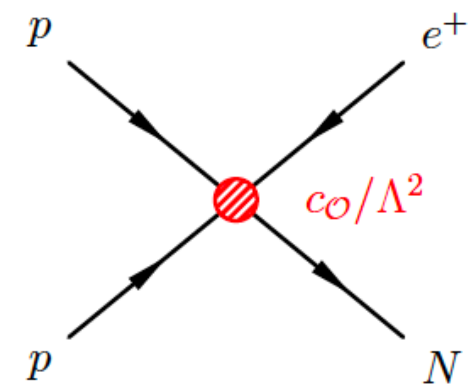
4-fermion pair-N_R operators: results

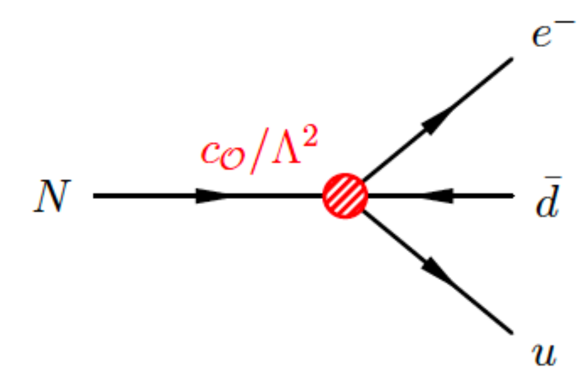


4-fermion single-N_R operators

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**	$-1/3$	$\mathcal{O}_{duNe}$	$\frac{c_{duNe}}{\Lambda^2} = \frac{g_{dN}g_{ue}}{2m^2_{S_d}}$
Leptoquark S_Q	**3**	**2**	$1/6$	$\mathcal{O}_{LdQN}$	$\frac{c_{LdQN}}{\Lambda^2} = \frac{g_{dL}g_{QN}}{m^2_{S_Q}}$
Inert doublet Φ	**1**	**2**	$1/2$	$\mathcal{O}_{LNQd}$ $\mathcal{O}_{QuNL}$	$\frac{c_{LNQd}}{\Lambda^2} = \frac{g_{LN}g_{Qd}}{m^2_\Phi}$ $\frac{c_{QuNL}}{\Lambda^2} = \frac{g_{Qu}g_{LN}}{m^2_\Phi}$

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

4-fermion single-N_R operators

Example of HNL single production cross sections

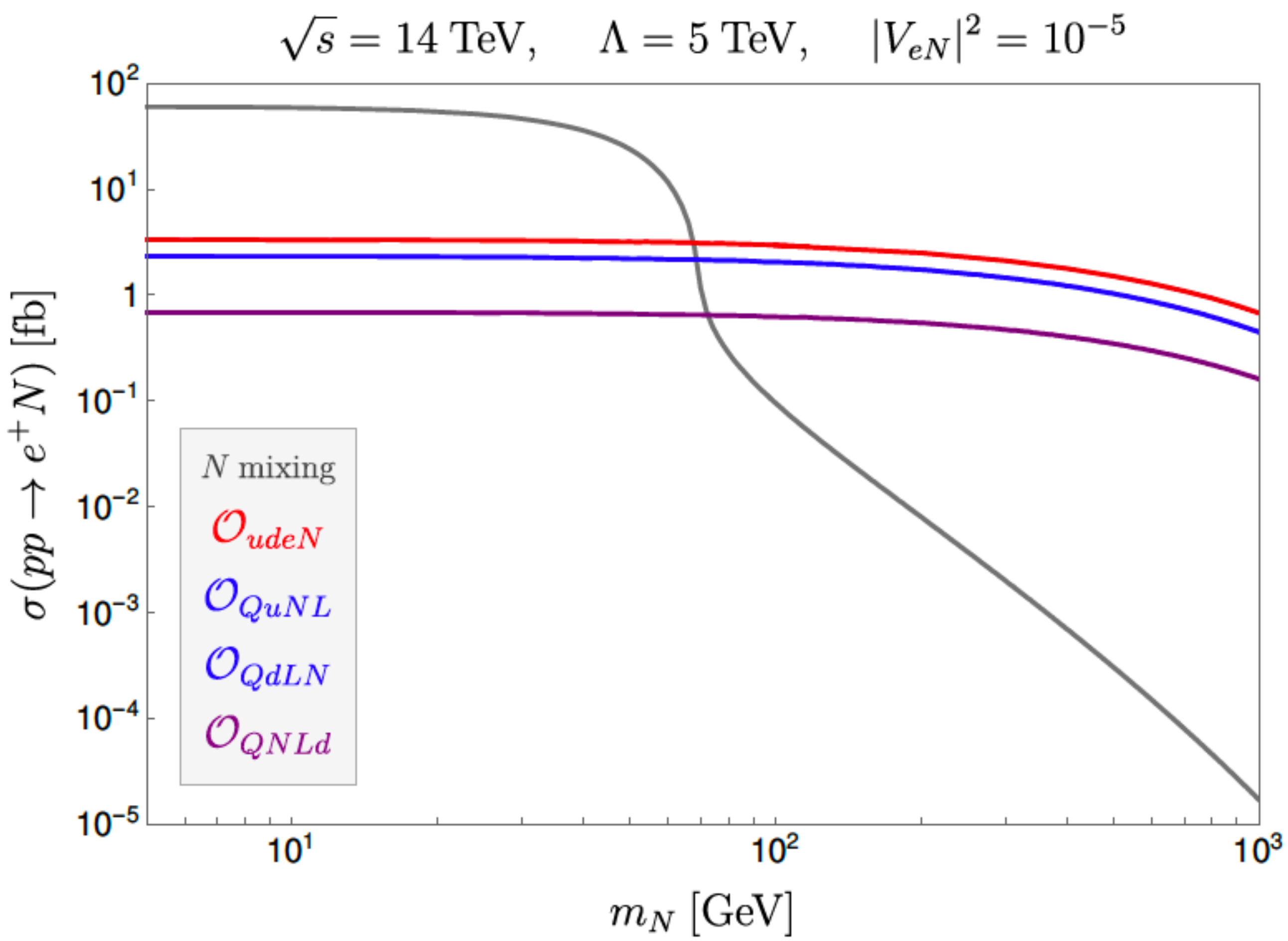


Figure from R. Beltrán's master thesis

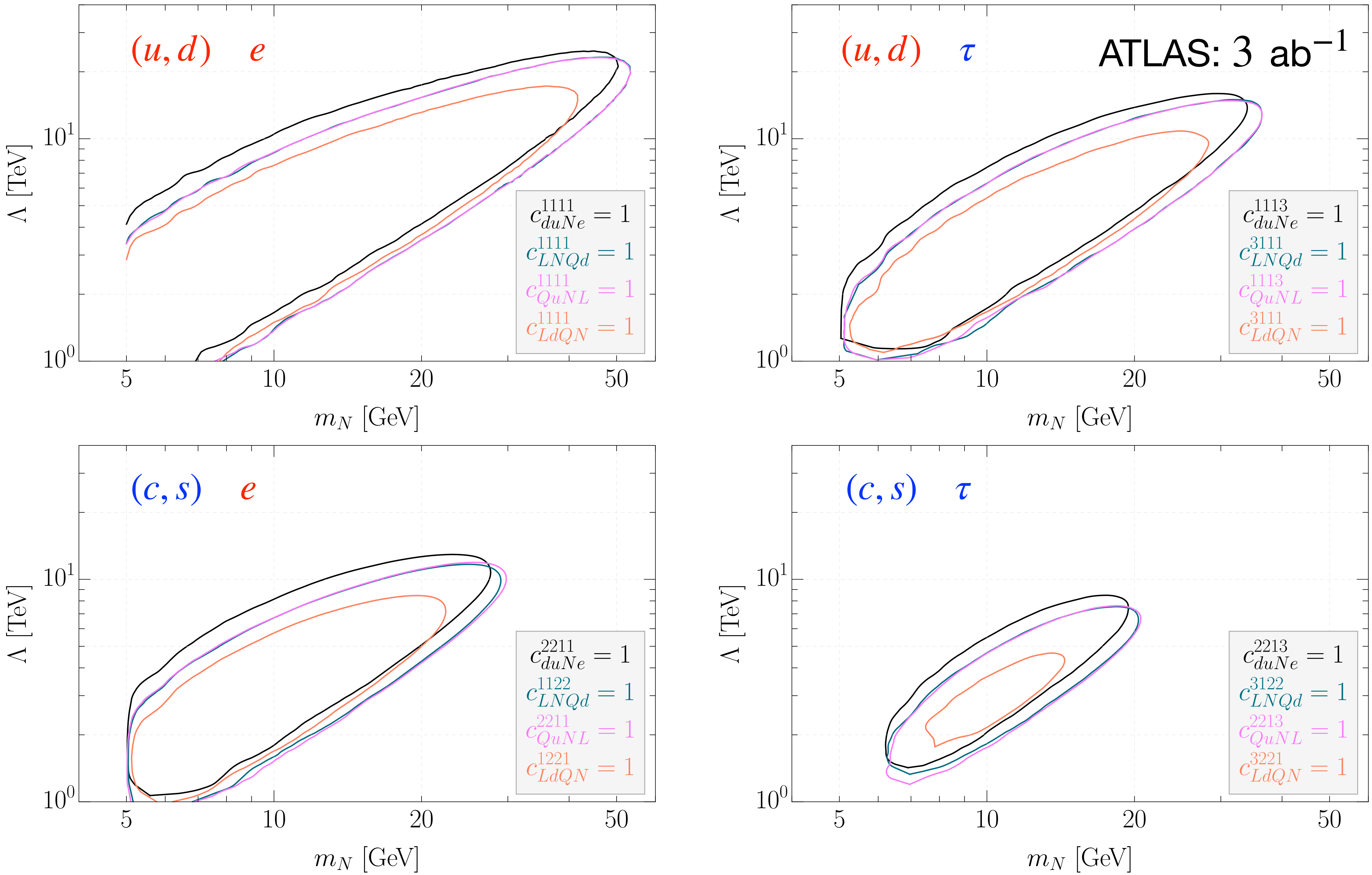
$$\sigma^{\text{mix}} \propto |V_{eN}|^2$$

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

Partial decay width of HNL

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

4-fermion single-N_R operators: results



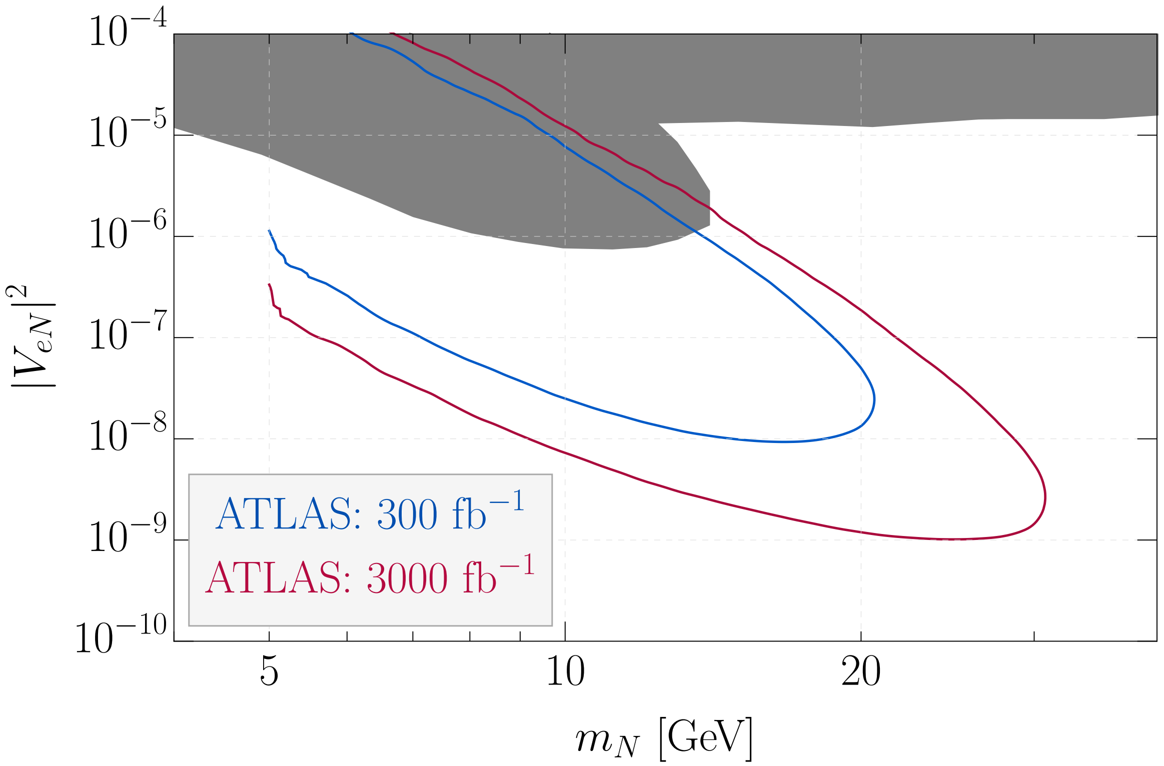
Assumption: both HNL production and decay are dominated by the operator (fulfilled everywhere in the plots if $|V_{\alpha N}|^2 \lesssim 10^{-9}$)

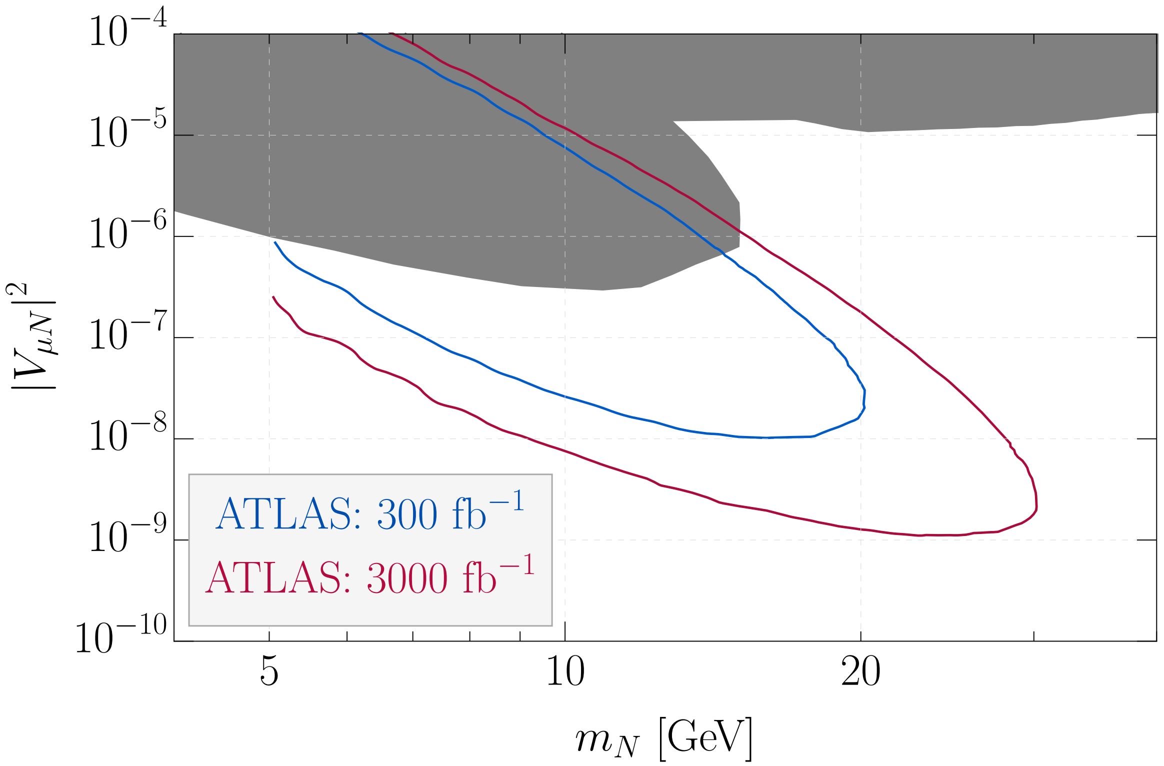
Conclusions

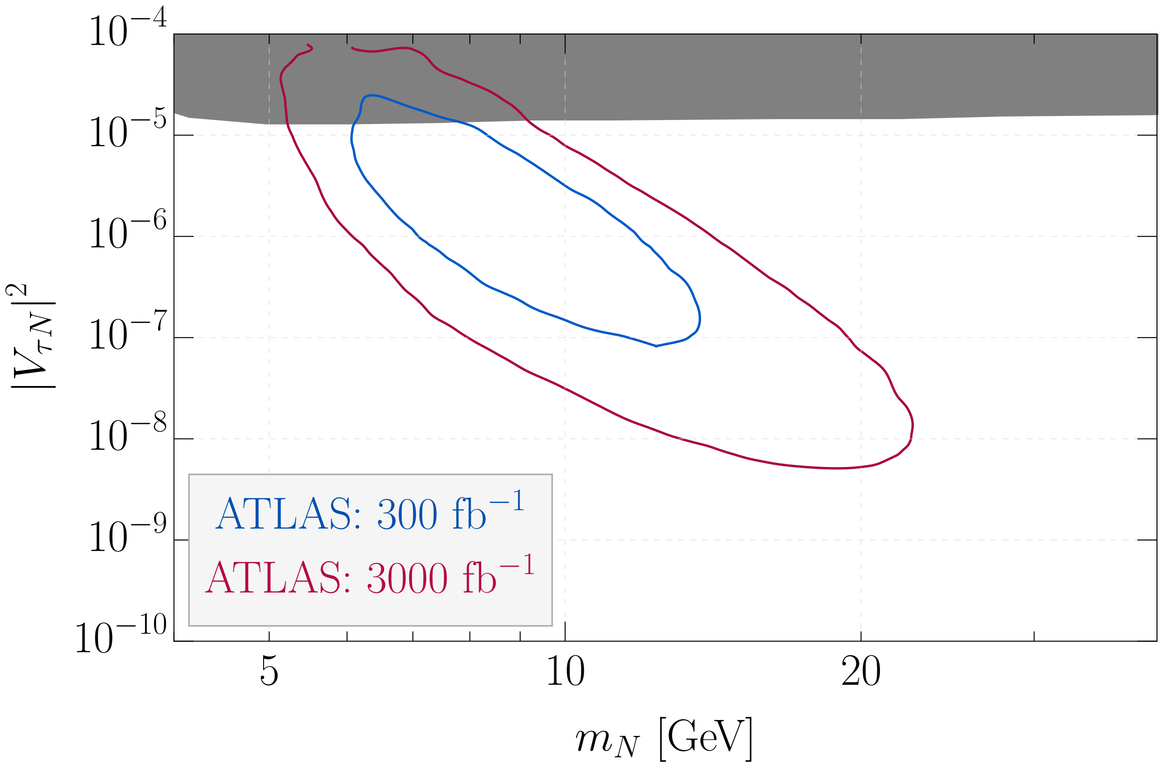
- Neutrino masses may be pointing to the existence of HNLs
- HNLs may be long-lived
- Interesting experimental prospects at the HL-LHC
  with ATLAS/CMS and future detectors:
  AL3X, ANUBIS, CODEX-b, FASER, MATHUSLA and MoEDAL-MAPP
- NSMEFT represents an excellent physics case!
- New physics scales in excesses of 20 TeV could be probed at the HL-LHC

Backup slides

Minimal 3+1 scenario







Update of Cottin, Helo, Hirsch, 1806.05191

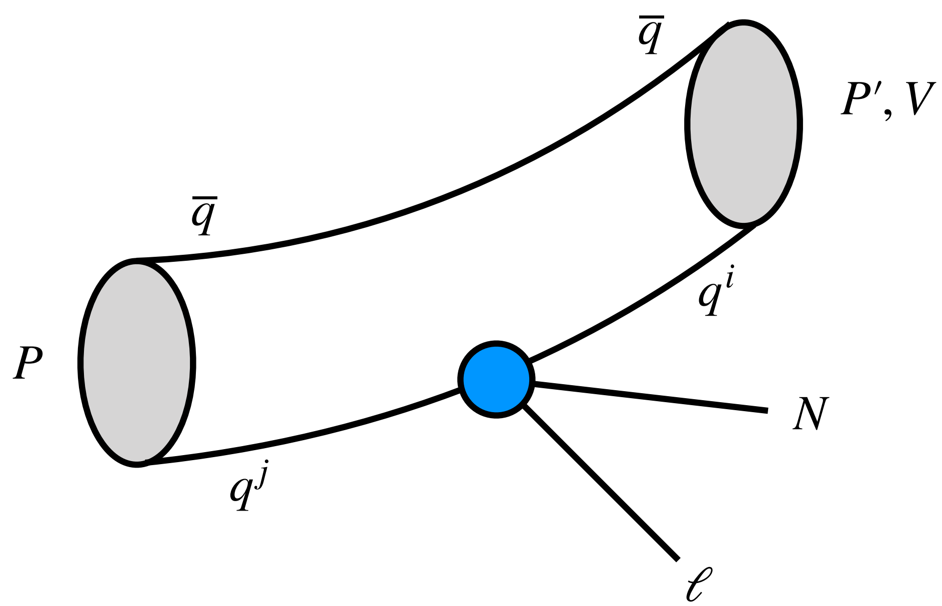
Other experiments

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

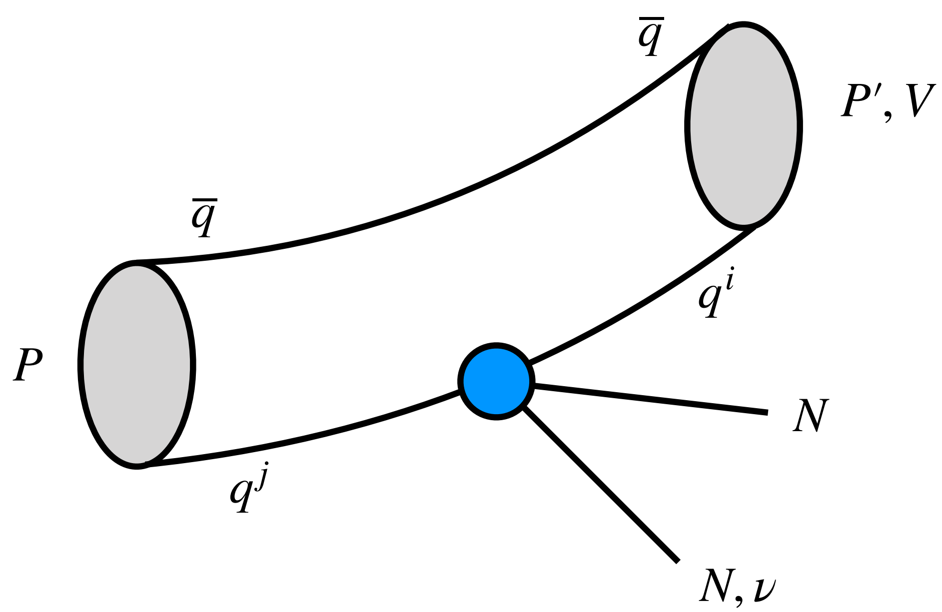
MoEDAL-MAPP: MoEDAL's Apparatus for Penetrating Particles
(MoEDAL: Monopole and Exotics Detector at the LHC)
@LHCb
MAPP1: ~ 130 m^3
MAPP2: ~ 430 m^3
$c\tau \sim 50$ m

HNL production in meson decays

HNLs with $m_N \lesssim 5$ GeV can be produced in meson decays



- "Charged current" single-N_R operators
  De Vries et al., 2010.07305



- "Neutral current" pair- and single-N_R operators
  Beltrán et al., 22XX.YYYY