Heavy neutral leptons

Lecture 4: frontier works

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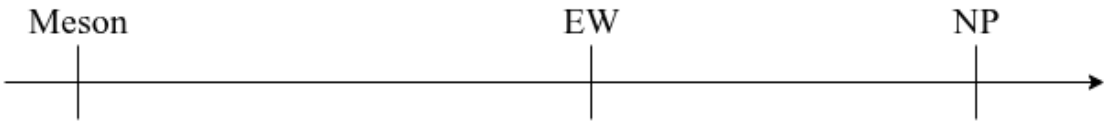
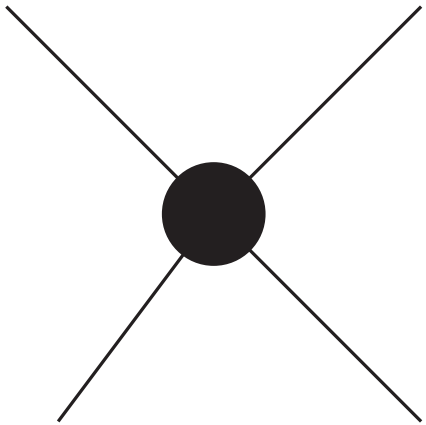
Minimal and non-minimal scenarios

- Dirac mass term and Majorana mass term (seesaw mechanisms)
- Sterile neutrinos, right-handed neutrinos, heavy neutrinos, heavy neutral leptons (HNLs)...
- Predicted not only in minimal scenarios but also in non-minimal scenarios: $\mathrm{U}(1)_{X(B-L)}$, leptoquarks, LRSM, ...
- If separation of scales $\Rightarrow$ use Effective Field Theories (EFTs)

Non-minimal scenarios and EFT

- N's appear sterile at lower energies, but interact at higher energies through the exchange of heavy BSM fields:
  LRSM, GUTs, Z', leptoquarks, ...
- Around the EW scale: N_R-extended SMEFT (N_RSMEFT)
- Example scenario:
  LRSM with heavy $\mathrm{SU}(2)_R$ gauge bosons and light HNLs
- Separation of scales: $m_N \ll v$ vs. $\Lambda \gg v$
  $\Rightarrow$ EFT framework: N_RSMEFT
- At even lower (meson) scales: N_R-extended low-energy EFT (N_RLEFT)





N_RSMEFT & N_RLEFT

- N_REFT framework construction:

  [Grzadkowski, Hioki, Ohkuma, Wudka 2004,
  Aguila, Bar-Shalom, Soni, Wudka 2009, Aparici, Kim, Santamaria, Wudka 2009,
  Bhattacharya, Wudka 2016, Liao, Ma 2017, Li, Ren, Xiao, Yu, Zheng 2021...]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{ren.}} + \sum_{d\geq 5} \sum_{i} c_i^{(d)} \mathcal{O}_i^{(d)}$$

- Focus on dim-6 and dim-7 operators
- Typical N_RSMEFT operators:
  - dim-6 (LNC): $(\bar{u}\gamma^\mu u)(\bar{N}\gamma_\mu N)$, $(\bar{L}d)\epsilon(\bar{Q}N)$, $(\bar{d}\gamma^\mu u)(\bar{N}\gamma_\mu e)$, $(\bar{N}\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$, ...
  - dim-7 (LNV): $(\bar{Q}N)(\overline{N^c}d)H$, $\tilde{H}^\dagger(\bar{u}Q)(\overline{N^c}N)$, ...
- RGE running, integrating out heavy fields
- Typical N_RLEFT operators:
  - dim-6 (LNC & LNV): $(\overline{u_R}\gamma^\mu u_R)(\bar{N}\gamma_\mu N)$, $(\bar{L}d_R)\epsilon(\bar{Q}N)$, $(\bar{d}\gamma^\mu u)(\bar{N}\gamma_\mu e)$, $(\overline{d_L}d_R)(\overline{N^c}N)$, $(\overline{u_L}u_R)(\overline{N^c}N)$, ...
- Mixing and operators $\Rightarrow$ prod. or decay of N

Sensitivities in the minimal scenario

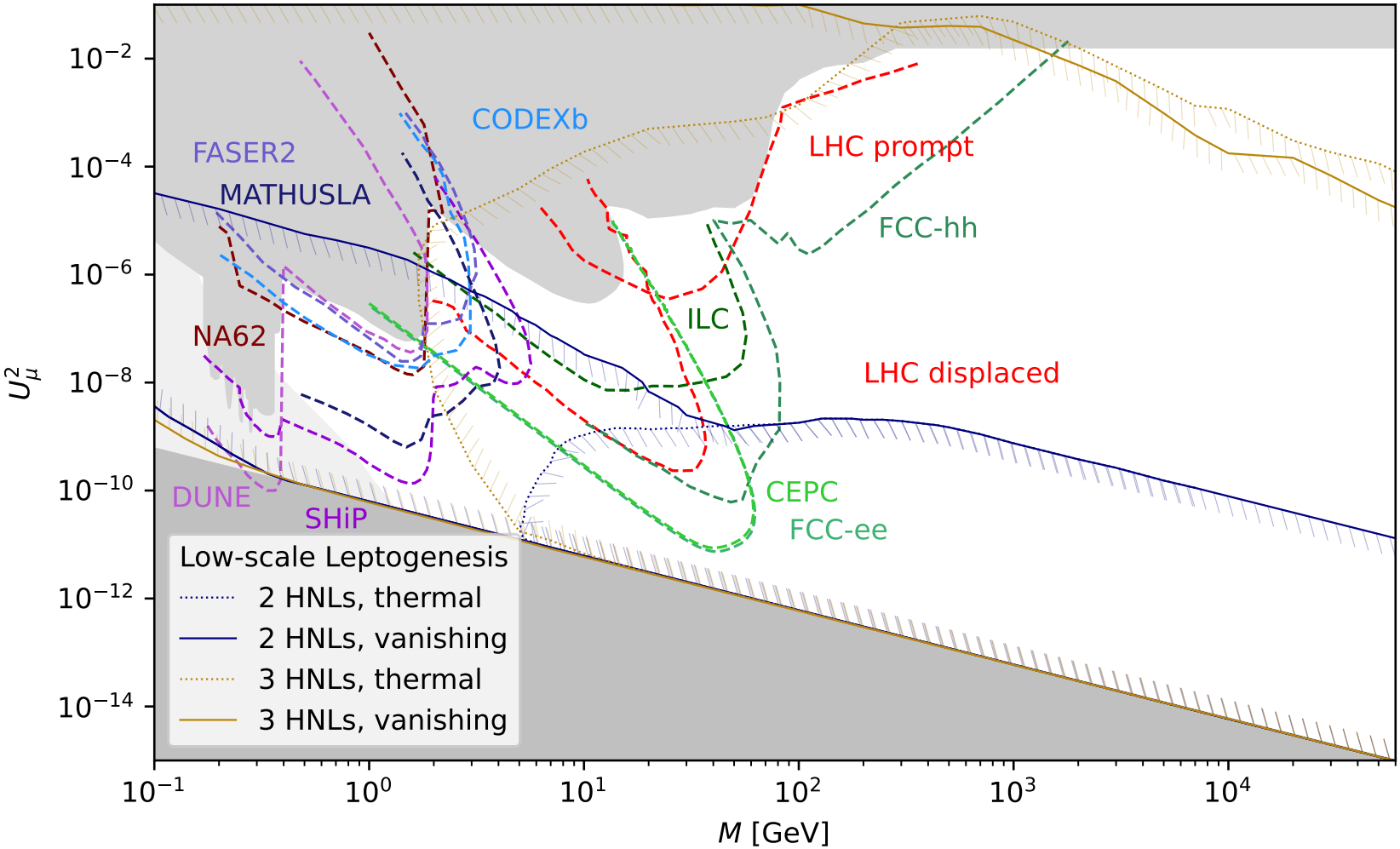
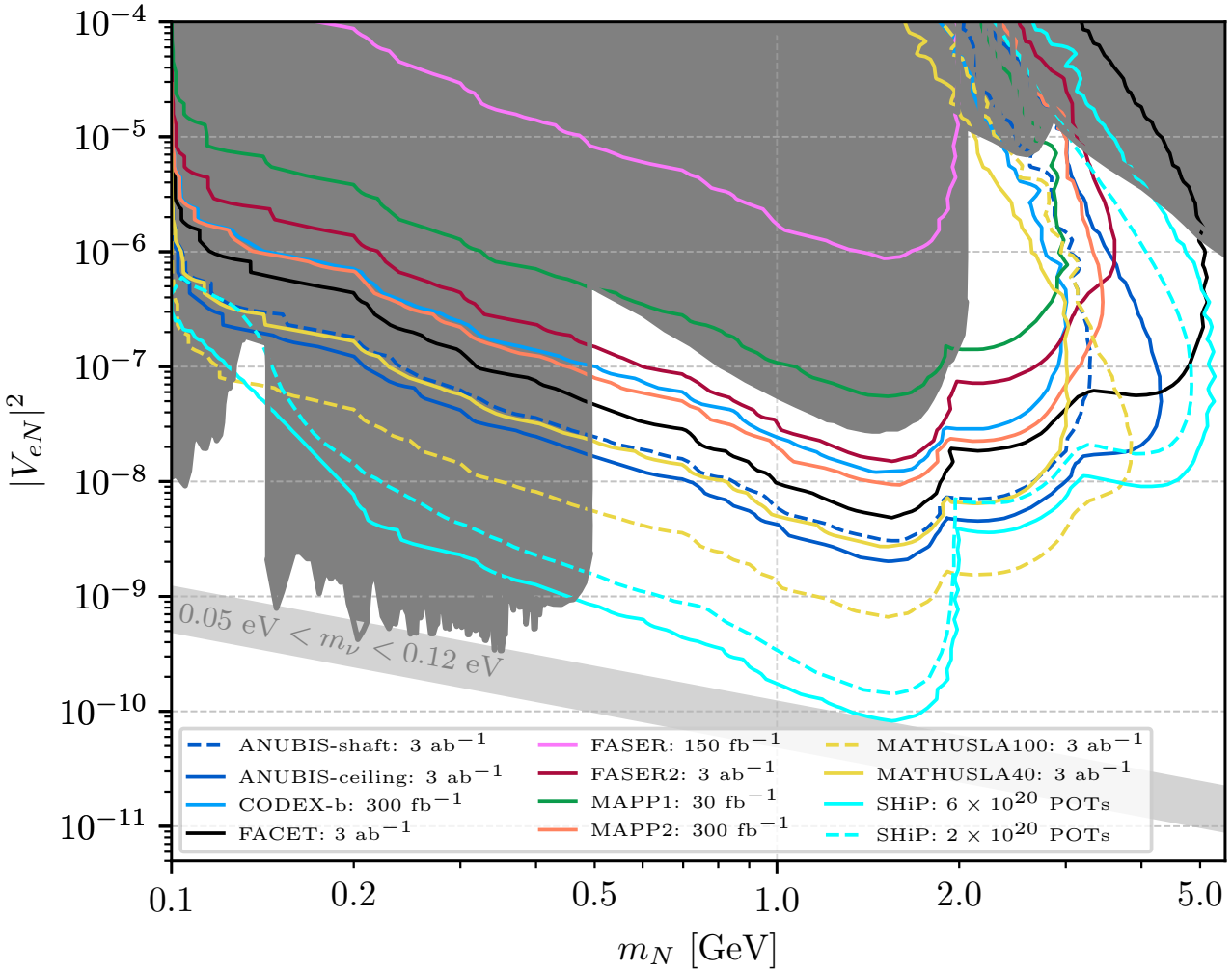


Figure 35 in J.Phys.G 50 (2023)2,020501

Sensitivities in the minimal scenario – low mass



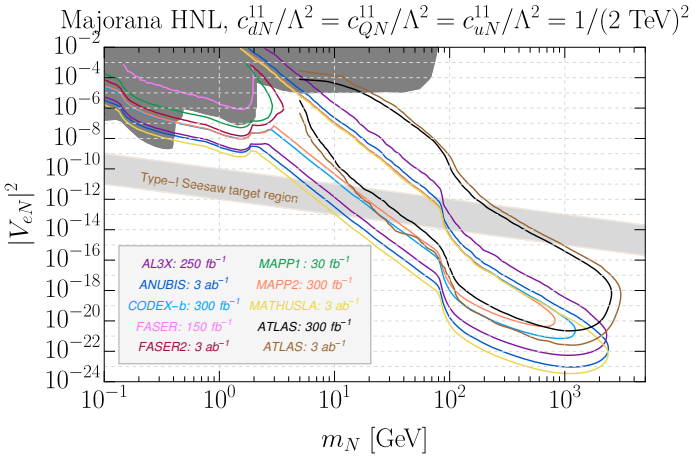
arXiv:2512.13011 (PRD accepted)

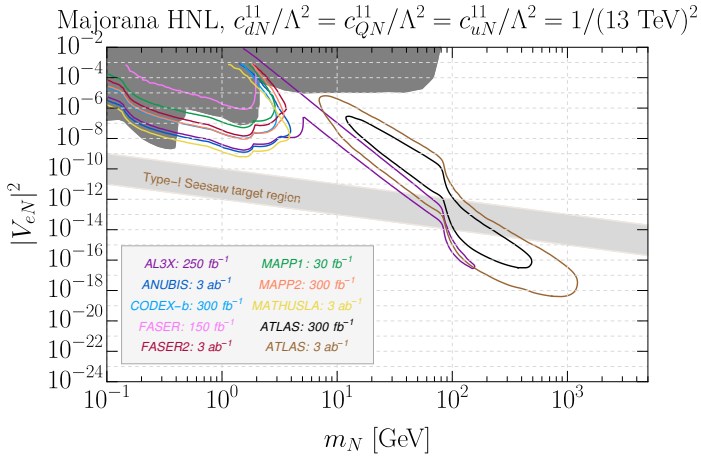
- There is still a lot of unexplored parameter space

Direct production from pp collisions at the LHC

- JHEP09(2021)039: $pp \xrightarrow{\text{Op.}} NN$ with N decaying via $|V_{eN}|^2$, double-N

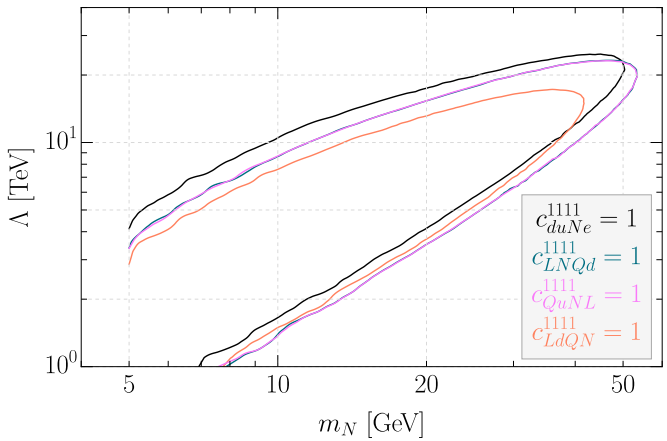
dim-6 op. $(m_N, \frac{c}{\Lambda^2}, |V_{eN}|^2)$

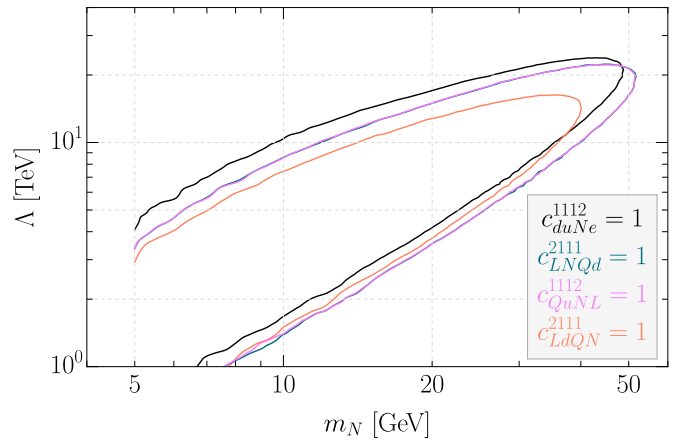




- JHEP01(2022)044: $pp \xrightarrow{\text{Op.}} Nl, N \xrightarrow{\text{Op.}} lqq'$, single-$N$, ATLAS

dim-6 op. $(m_N, \frac{c}{\Lambda^2})$

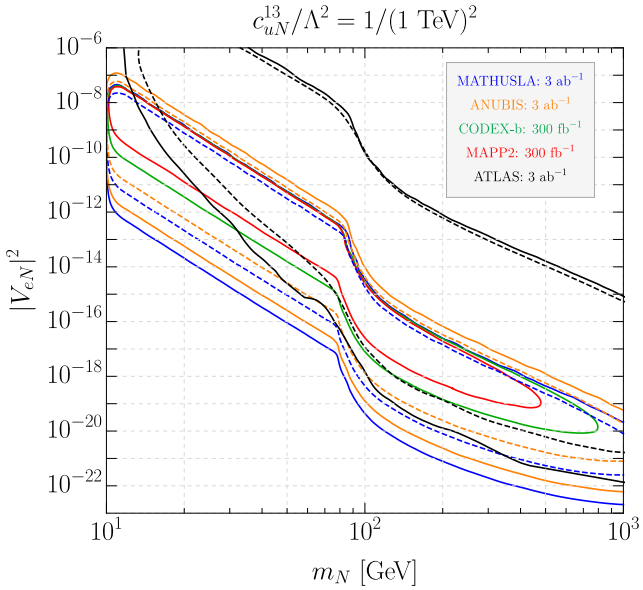


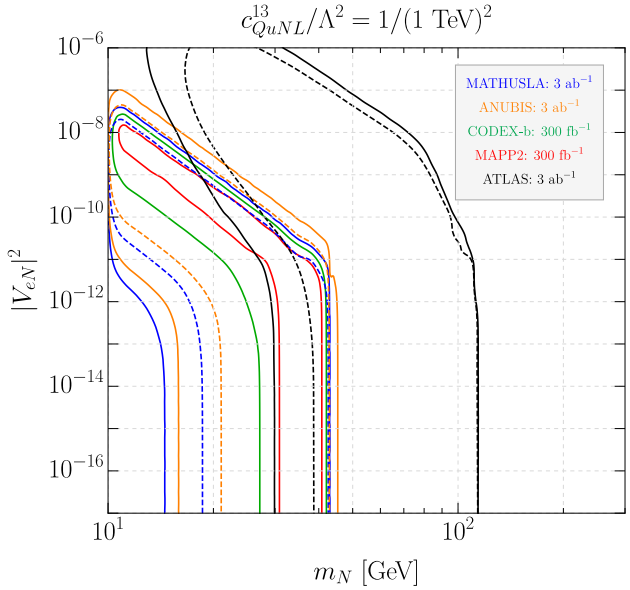


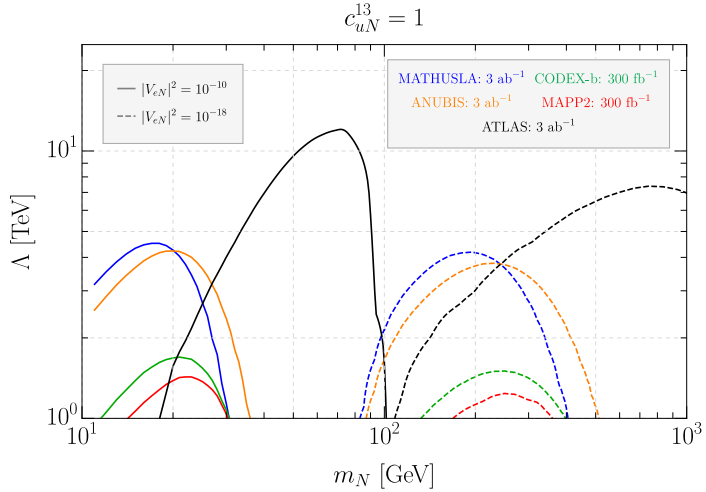
Direct production from pp collisions at the LHC in association with a top quark

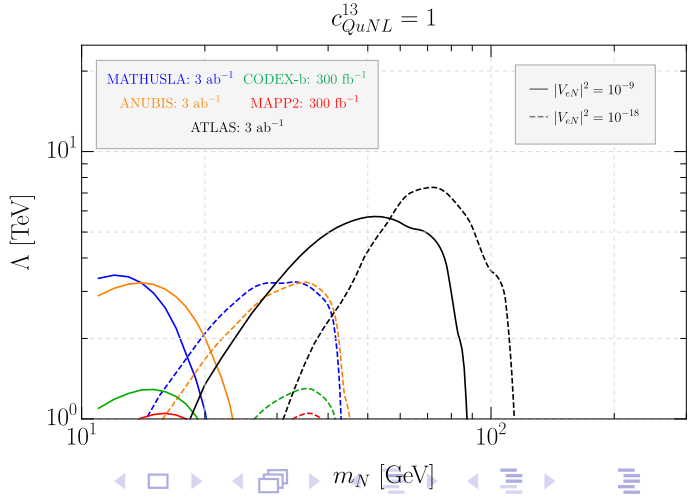
- JHEP05(2025)238: Ops. with a top quark incl. single-N and double-N

dim-6 op.
$(m_N, \frac{c}{\Lambda^2}, |V_{eN}|^2)$





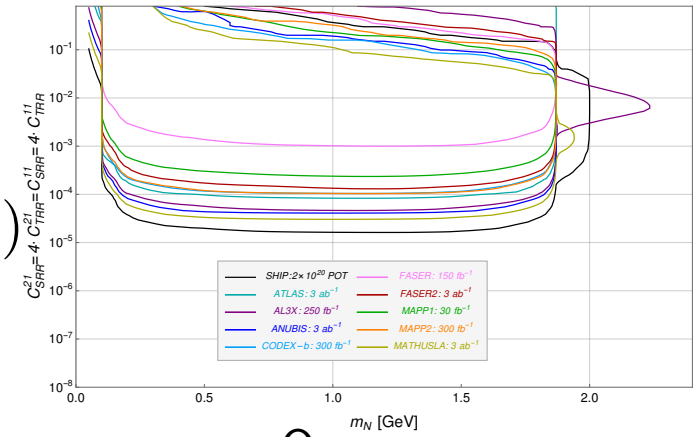


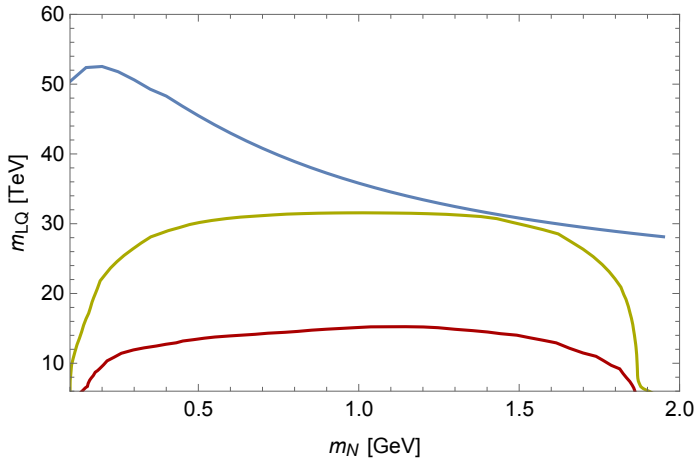


Production from heavy-meson decays at the LHC

- JHEP03(2021)148: $D/B \xrightarrow{\text{Op.}} N + e(+M), N \xrightarrow{\text{Op.}} e + M$, single-$N$

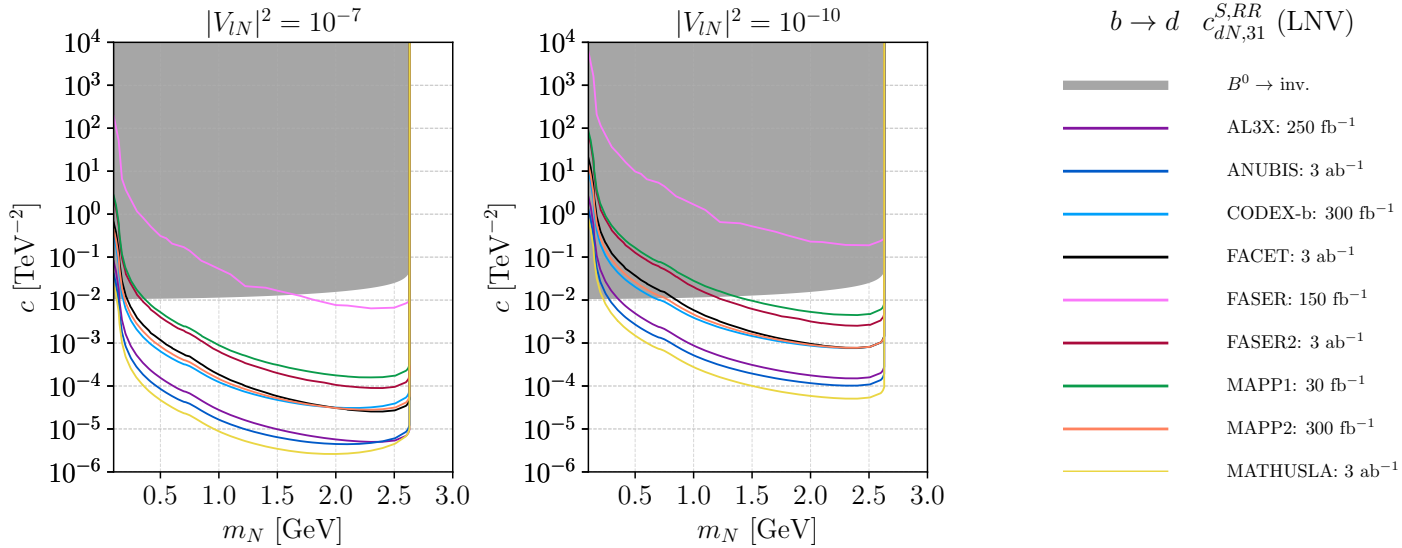
dim-6 op.
$(m_N, \frac{2G_F C}{\sqrt{2}}, |V_{eN}|^2)$





- JHEP01(2023)015: $D/B \xrightarrow{\text{Op.}} (M+)N + N$, double-$N$

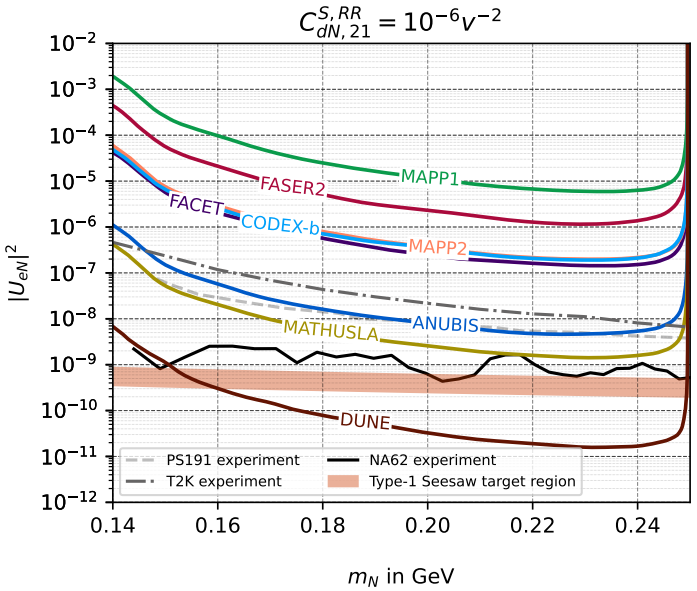
dim-6 op.
$(m_N, c, |V_{eN}|^2)$



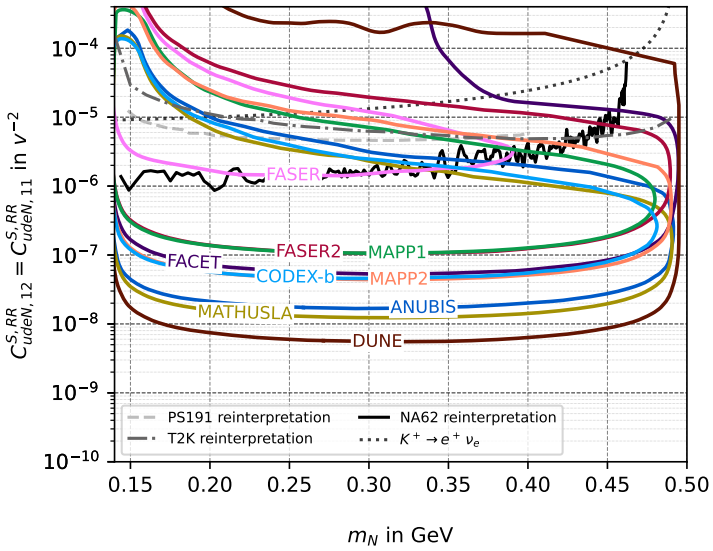
HNLs from kaon decays at the LHC and DUNE

- PRD109(2024)115014: $K \xrightarrow{\text{Op.}} NN(+\pi)$, $K \xrightarrow{\text{Op.}} e + N(+\pi)$

dim-6 op.
$(m_N, C, |V_{eN}|^2)$



one double-N operator

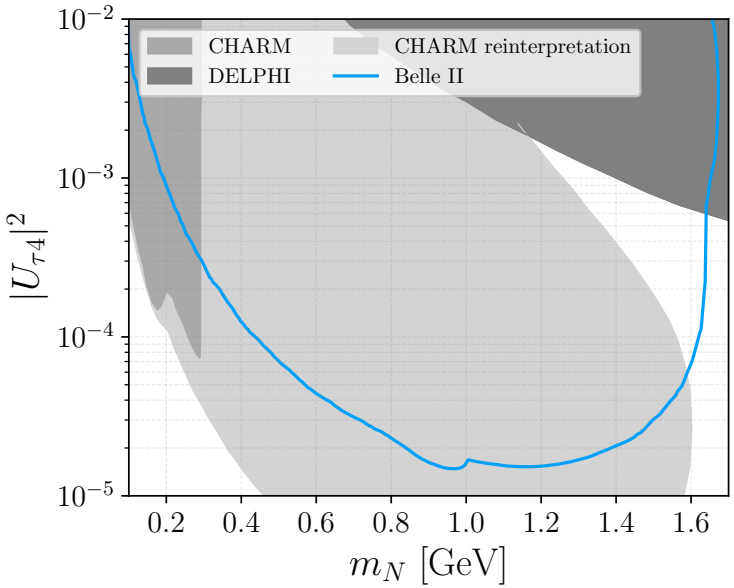


two single-N operators

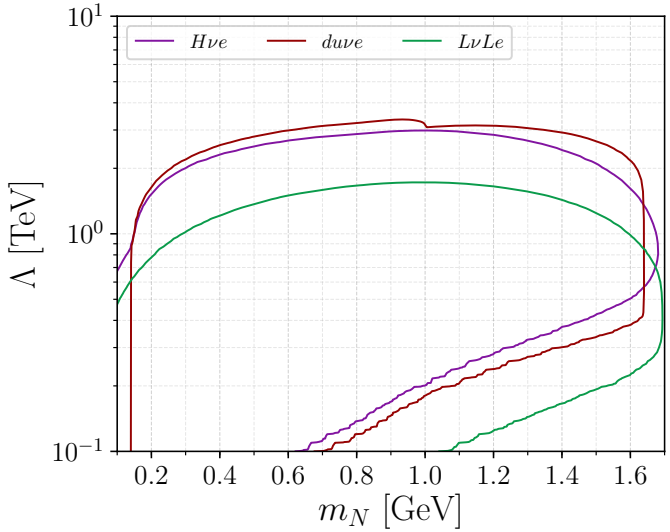
HNLs from τ-decays at Belle II

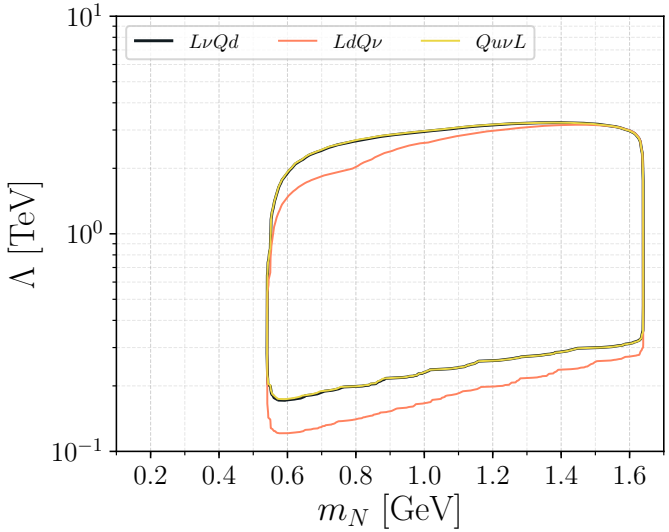
- JHEP04(2022)057: $\tau \xrightarrow{\text{Op.}} N + X, N \xrightarrow{\text{Op.}} Y$, single-$N$

Class 1	$\psi^2 H^3$	Class 4	ψ^4
$\mathcal{O}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{du\nu e}$	$(\bar{d}_R\gamma^\mu u_R)(\bar{\nu}_R\gamma_\mu e)$
Class 2	$\psi^2 H^2 D$	$\mathcal{O}_{Qu\nu L}$	$(\bar{Q}u_R)(\bar{\nu}_R L)$
$\mathcal{O}_{H\nu e}$	$(\bar{\nu}_R\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d_R)$
Class 3	$\psi^2 HF$	$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d_R)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e_R)$
$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$		



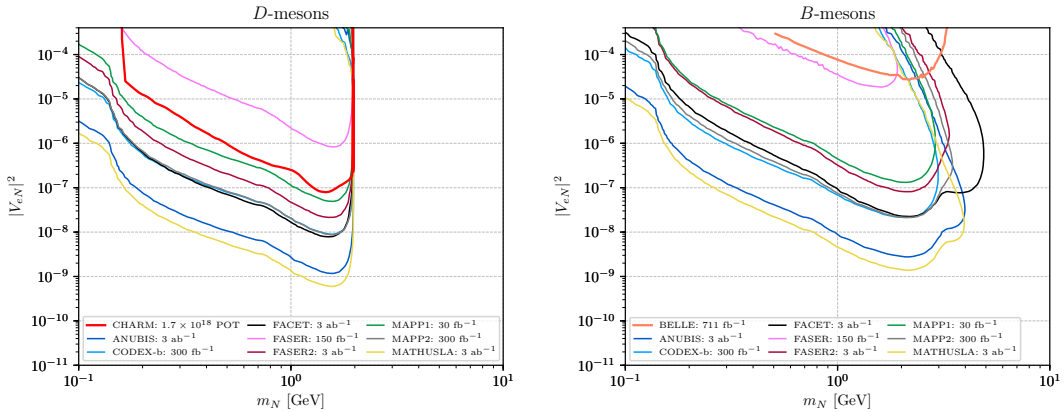
dim-6 op. $(m_N, \frac{C}{\Lambda^2})$

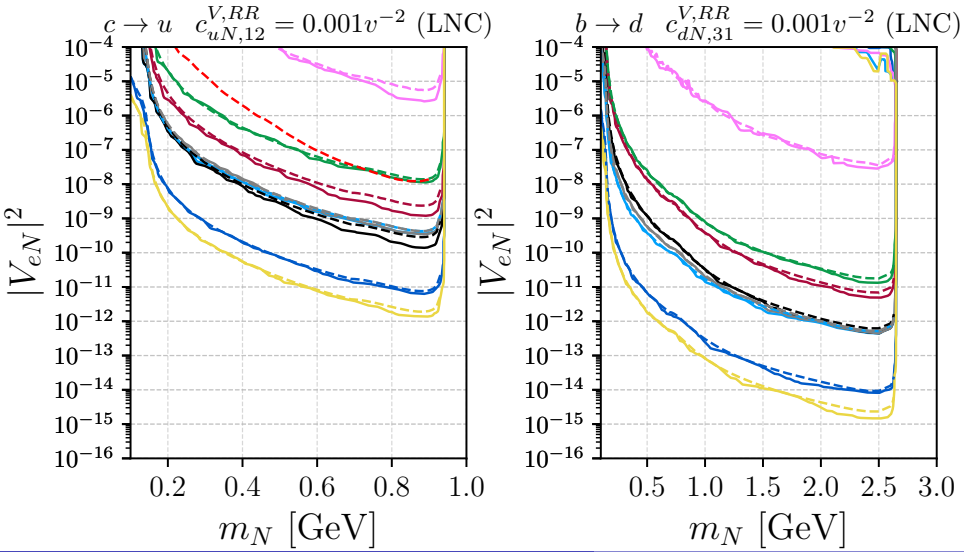




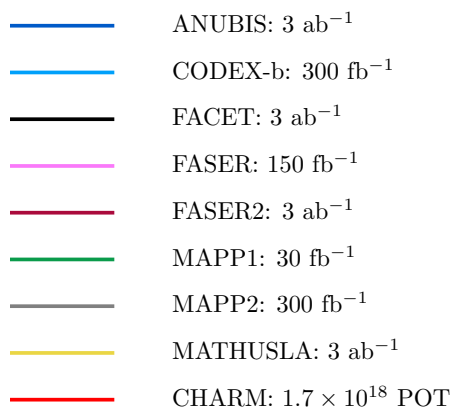
A quick reinterpretation method

- JHEP05(2023)031: using re-scaling to reinterpret sensitivities in the minimal-HNL scenario in terms of EFT-HNL scenarios
- Key: in the *large-decay-length* limit, the expon. decay function can be expanded to the linear order: $N_S \propto N_{\text{prod.}} \cdot \Gamma_{\text{HNL}}$
- No MC simulation is needed





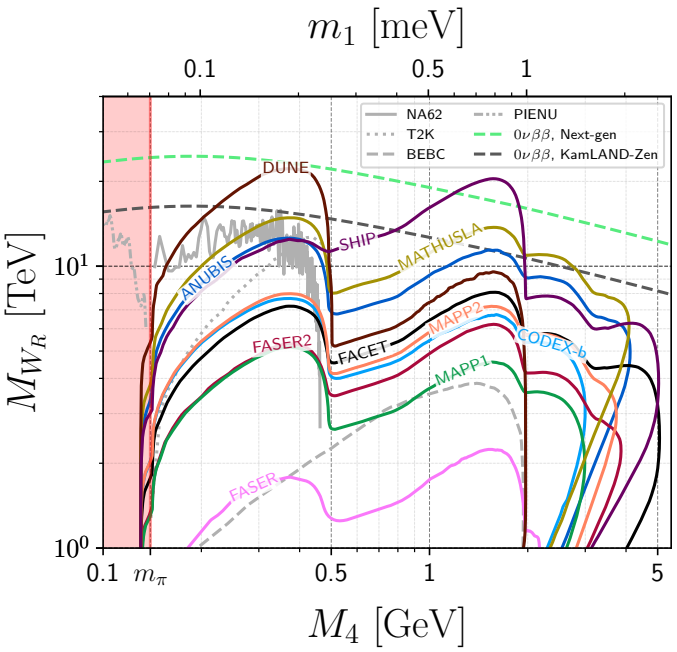
dim-6 double-N $(M_N, c, |V_{eN}|^2)$



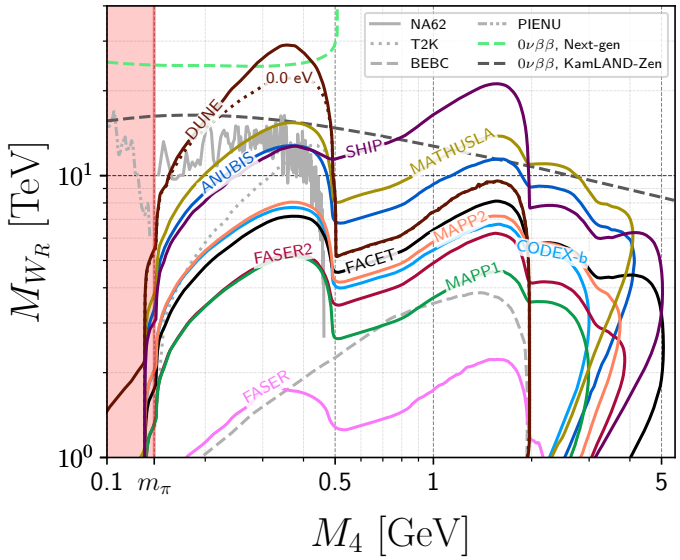
Matching to UV – LRSM

- JHEP04(2025)007: matching N_RSMEFT and N_RLEFT to mLRSM
- Complementarity between displaced-vertex and $0\nu\beta\beta$ searches
- Light: HNL; Heavy: W_R

dim-6 op.
$(m_N, \frac{C}{\Lambda^2}, |V_{eN}|^2)$



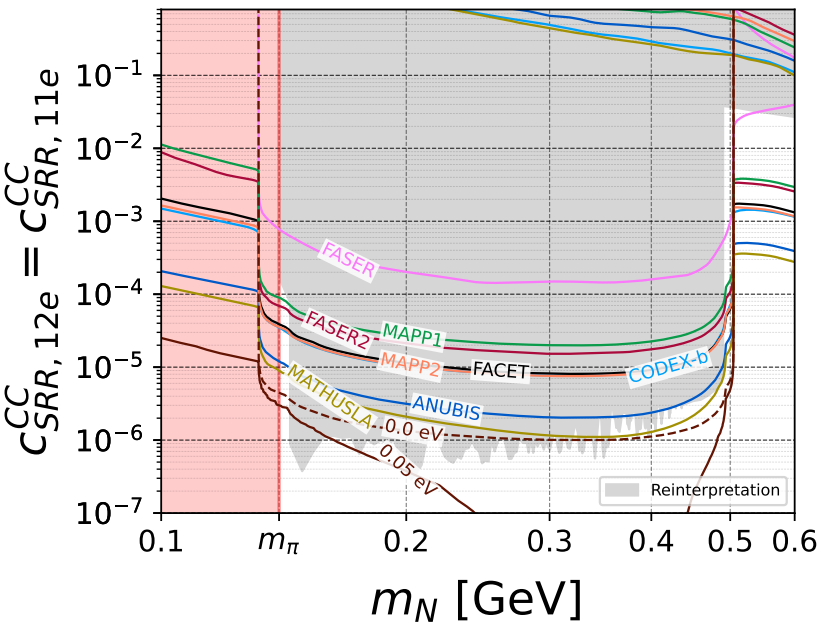
type-II seesaw,
$W_L - W_R$ mixing $\xi = 0.0$



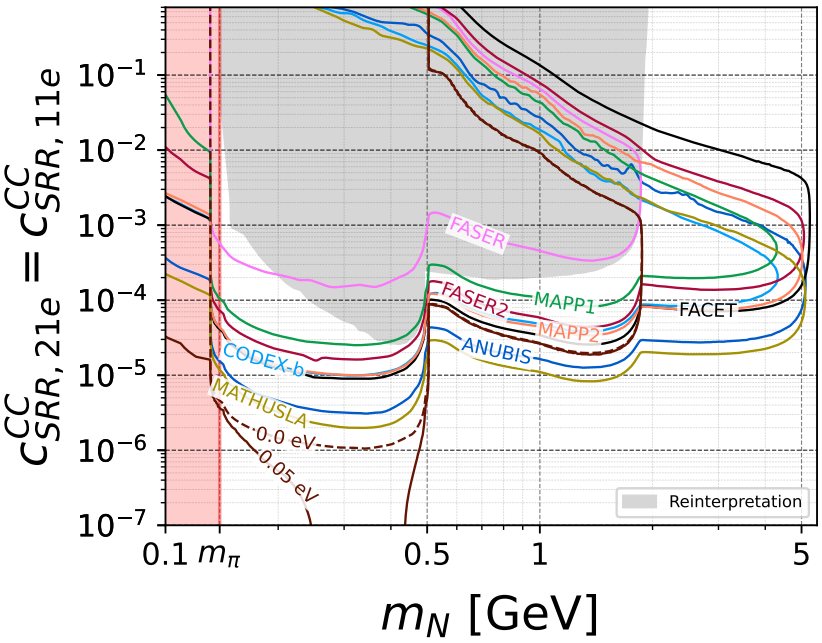
type-I seesaw,
$m_1 = 0.03$ eV,
$W_L - W_R$ mixing $\xi = 0.0$

Matching to UV – $\tilde{\chi}_1^0$ in RPV-SUSY

- JHEP01(2024)108: N_RSMEFT/LEFT can describe other SM singlets, too, e.g. the bino-like lightest neutralino
- Light: neutralino; Heavy: sfermions



N from kaon and *B*-meson decays



N from *D*-meson, kaon, and *B*-meson decays

Conclusions

- HNLs both in the minimal scenario and extended scenarios
- Separation of scales $\Rightarrow$ EFT framework suitable
- Effective field theories: N_RSMEFT and N_RLEFT
- Multiple pheno studies:
  - Direct production from pp collisions at the LHC
  - Production from meson decays at the LHC, DUNE, and SHiP
  - Production from τ decays at Belle II
  - A quick reinterpretation method
  - Matching to UV: HNLs in the mLRSM & a light $\tilde{\chi}_1^0$ in the RPV-SUSY
- Outlook and final remarks:
  - phenomenology: interface between theory and experiment
  - In addition, coding and tools
  - LLP is an ongoing opportunity window to look for BSM physics
  - LLP study: interdisciplinary field of theory, experiment, and tools

Thank You! 谢谢!