Constraining tau neutrino transition magnetic moments at DUNE

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Based on the work JHEP 21 (2020) 200, in collaboration with Thomas Schwetz and Albert Zhou

29th September 2021, NuTau2021

Introduction

Neutrino oscillation → Neutrino mass → Heavy neutrino

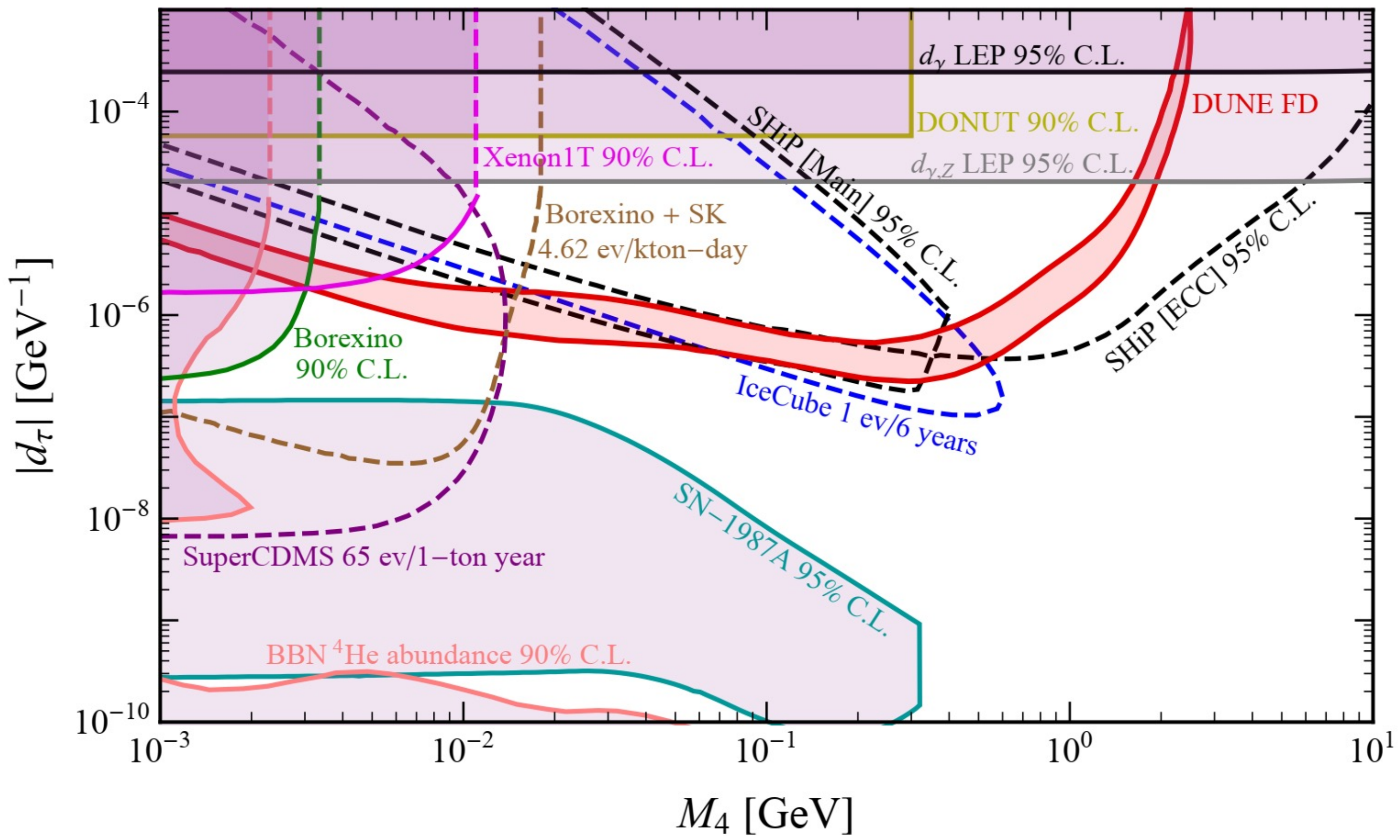
Heavy-neutrino dipole portal:

$$\mathcal{L} = d_\alpha \overline{\nu}_{\alpha L} \sigma^{\mu\nu} \nu_4 F_{\mu\nu} + \text{h.c.}$$

The bounds on d_α $(\alpha = e, \mu, \tau)$ come from various laboratory, astrophysical and cosmological observations, for example the ones from
solar neutrinos,
atmospheric neutrinos in IceCube,
short-baseline experiments,
current and future elastic neutrino-nucleus scattering or elastic neutrino-electron scattering experiments
and so on.

See also the talk by Roshan Mammen Abraham later

Global picture of d_τ

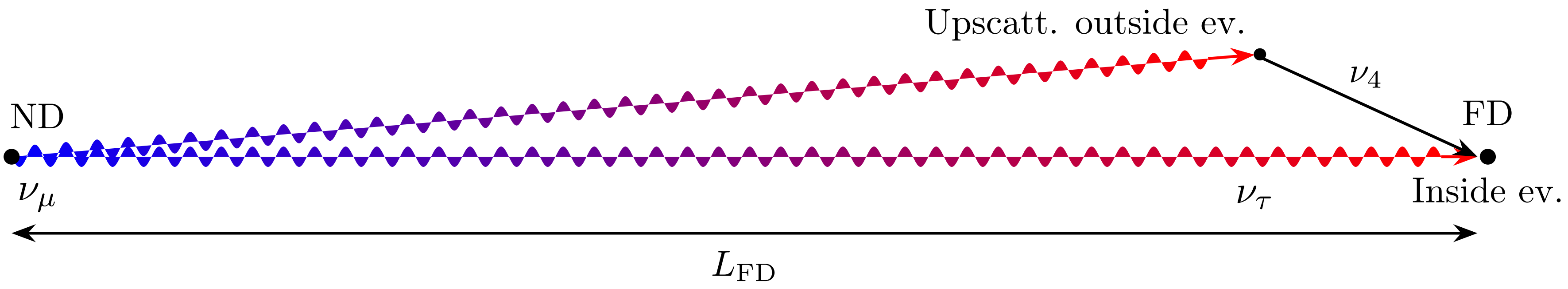


Most of the results come from Magill, Plestid, Pospelov and Tsai (PRD 2018), Brbar, Greljo, Kopp and Opferkuch (JCAP 2021), and Coloma, Machado, Martinez-Soler and Shoemaker (PRL 2017).

One can also refer to Atkinson et al. (2105.09357), Ismail et al. (2109.05032) and Miranda et al. (2109.09545) for recent discussion on this topic.

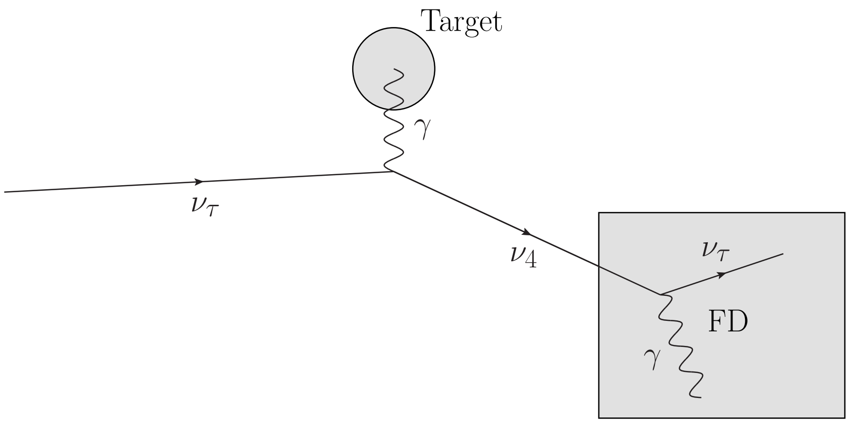
Methods at DUNE

We start with the tau neutrino flux generated by the neutrino oscillations and consider coherent scattering off nuclei and incoherent scattering off protons, neutrons and electrons.



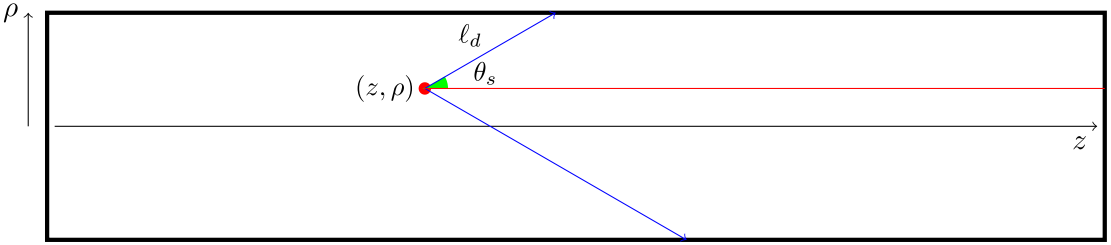
Assumptions:

- Dirac neutrinos
- The heavy neutrino flavor mixing with active neutrinos is negligible and the dipole interaction dominates.



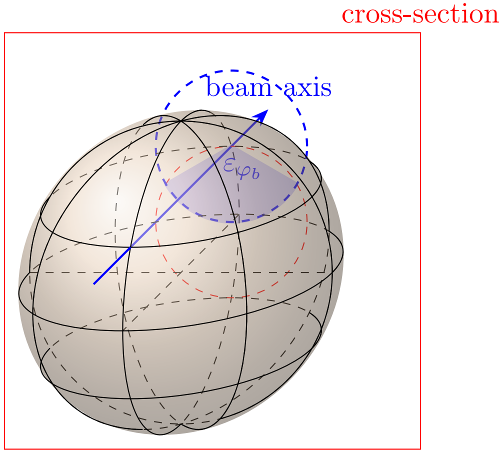
Inside events

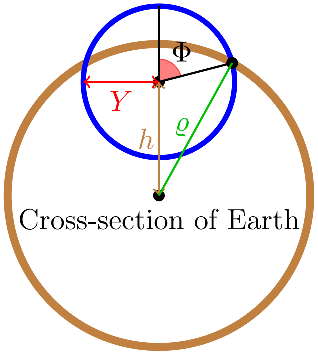
$$\frac{\mathrm{d}N}{\mathrm{d}E_\nu} = N_{\text{mod}} \frac{L_{\text{ND}}^2}{L_{\text{FD}}^2} \rho_N A_{\text{det}} \left.\frac{\mathrm{d}\Phi}{\mathrm{d}\Omega \mathrm{d}E_\nu}\right|_{\theta_b=0} P_{\text{osc}}\left(\frac{L_{\text{FD}}}{E_\nu}\right) \sum_{M_T} \int_0^{L_d} \mathrm{d}z \int_{-1}^{1} \mathrm{d}\cos\theta_s \frac{\mathrm{d}\sigma_T}{\mathrm{d}\cos\theta_s} \Pi\left(\ell_d^0\right) P_{\text{dec}}(\ell_d^0)\varepsilon(p_4)$$



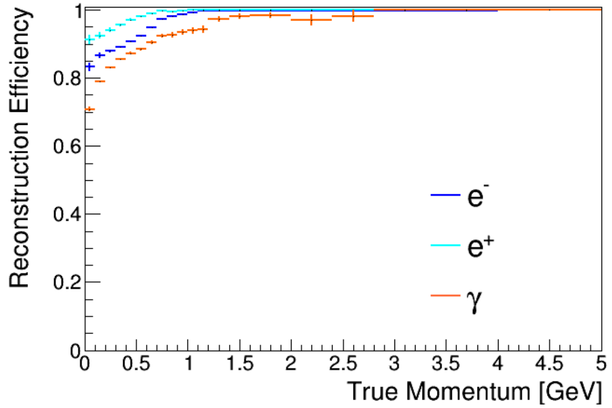
Outside events

$$\frac{\mathrm{d}N}{\mathrm{d}E_4} = N_{\text{mod}} \frac{\rho_N}{2\pi} \int_0^{\theta_b^{\text{max}}} \sin\theta_b \mathrm{d}\theta_b \int_{r_{\text{min}}}^{r_{\text{max}}} L_{\text{ND}}^2 \mathrm{d}r_p \sum_{M_T} \left[\frac{\mathrm{d}^2\Phi}{\mathrm{d}\Omega_b \mathrm{d}E_\nu}\frac{\mathrm{d}E_\nu}{\mathrm{d}E_4} P_{\text{osc}} \cdot \varepsilon_{\varphi_b} \cdot P_{\text{decay}}(\ell) \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_s} \Delta\Omega_s \cdot \varepsilon(p_4)\right]_T$$





Signal



Dune TDR, Vol. II

Outside events: The up-scattering happens outside detector, so the signature is a single-photon event.

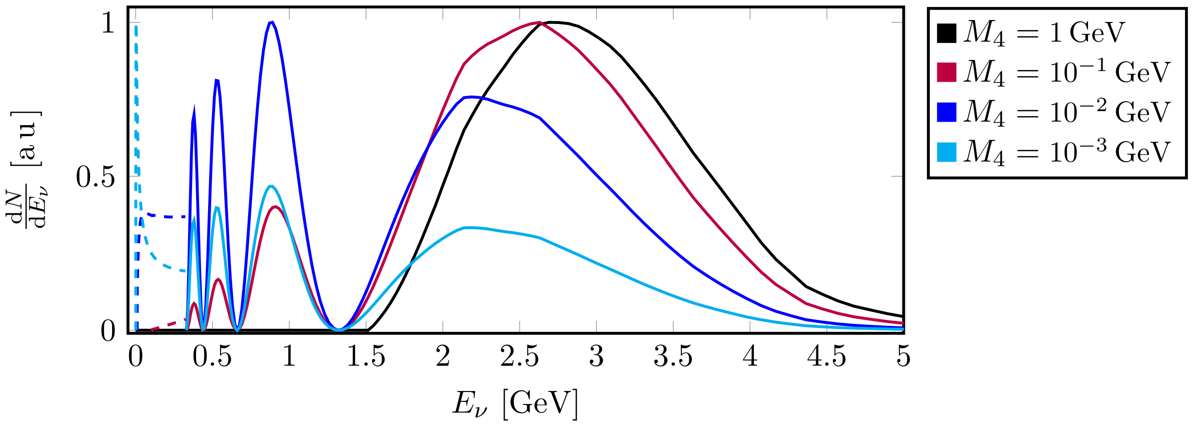
Inside events, coherent: The coherent up-scattering leaves a nuclear recoil of low energy, which is not easy to observe in the detector, so the signature is a single-photon event.

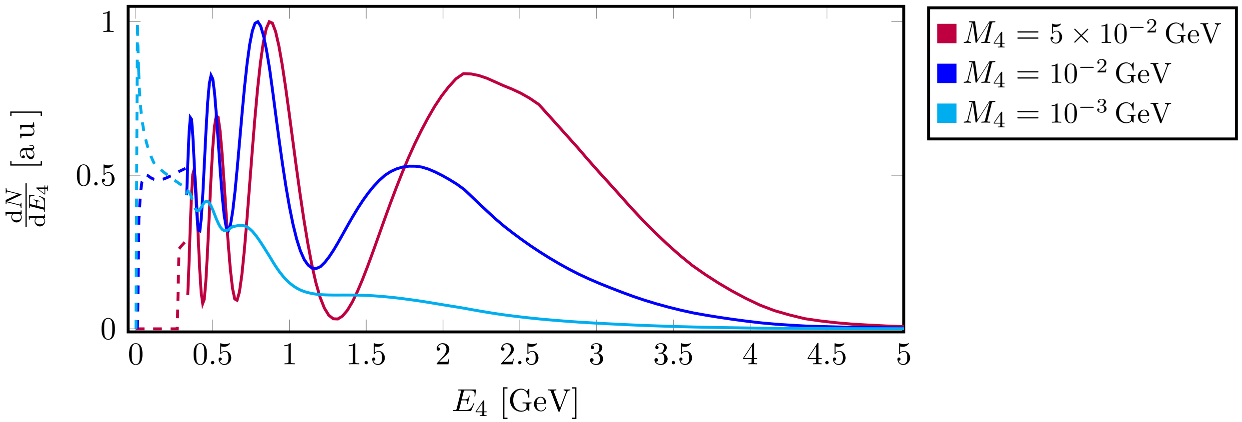
Inside events, incoherent: the signature will be either a NC-like (the up-scattering on nucleons) or single-electron type event (the up-scattering on electrons) together with the displaced single-photon event from the heavy-neutrino decay.

Background

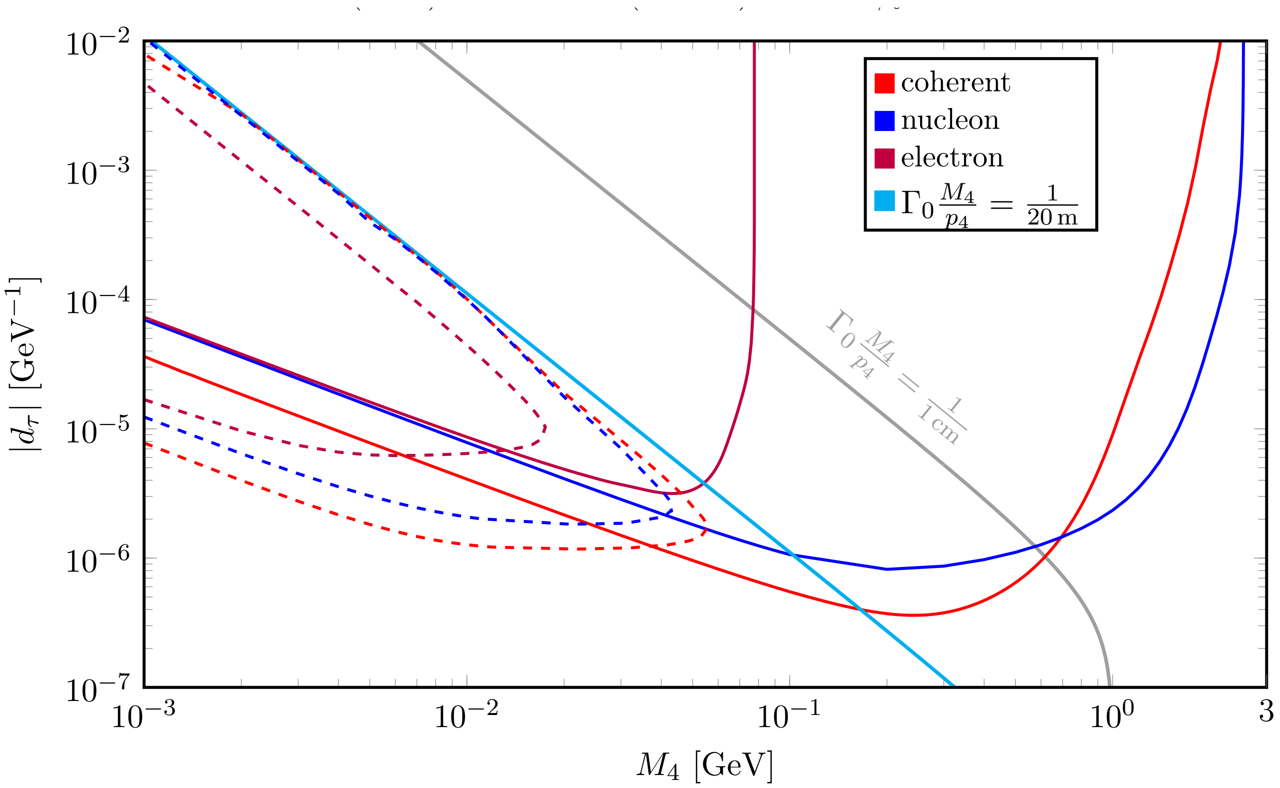
The relevant backgrounds for the dipole signal are the single photon process NC1γ and highly asymmetric NCπ0-decays, where the two photons from the pion decay cannot be distinguished.

Example spectra


Inside spectra with arbitrary normalisation

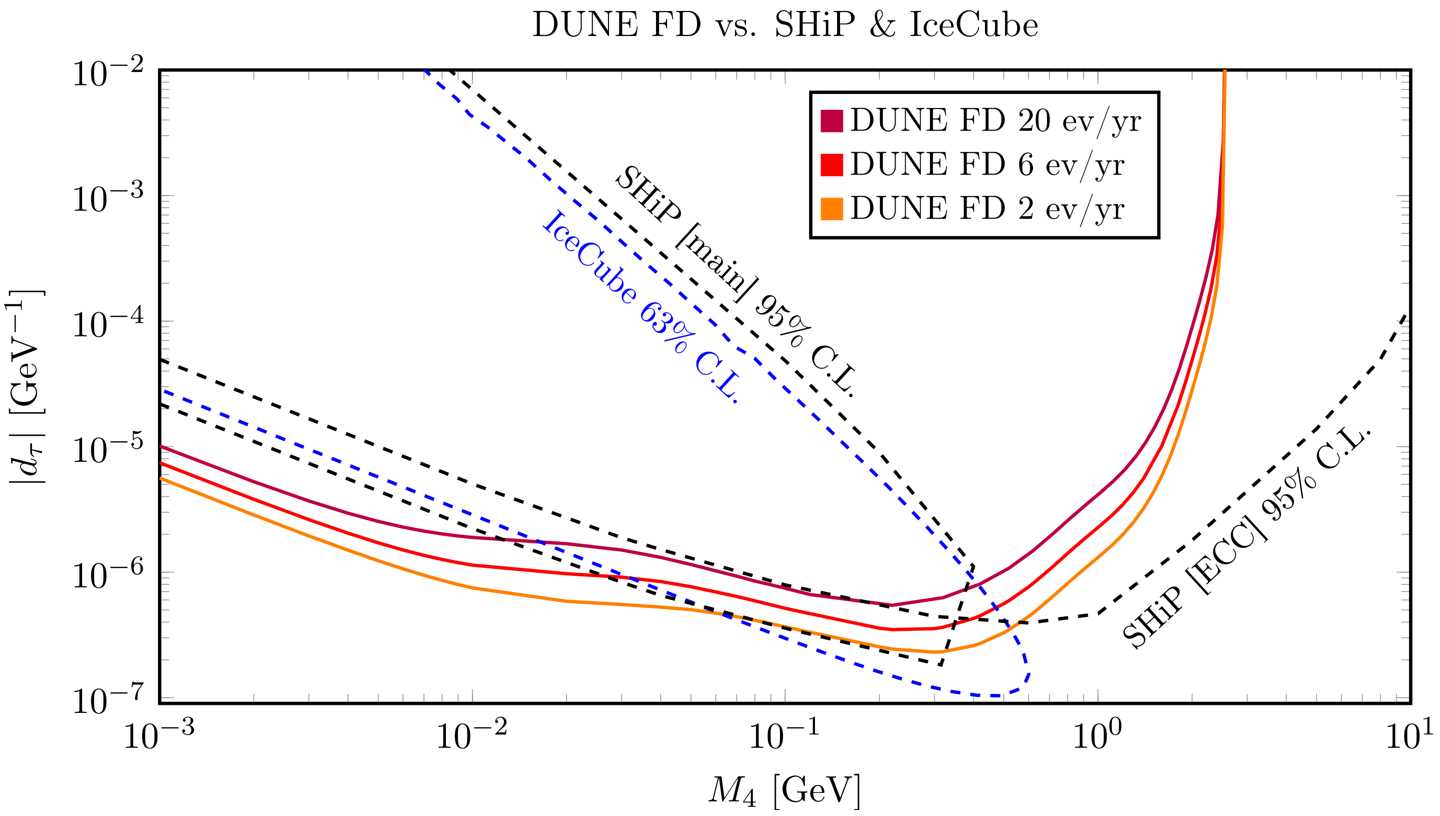

Outside spectra with arbitrary normalisation

Results

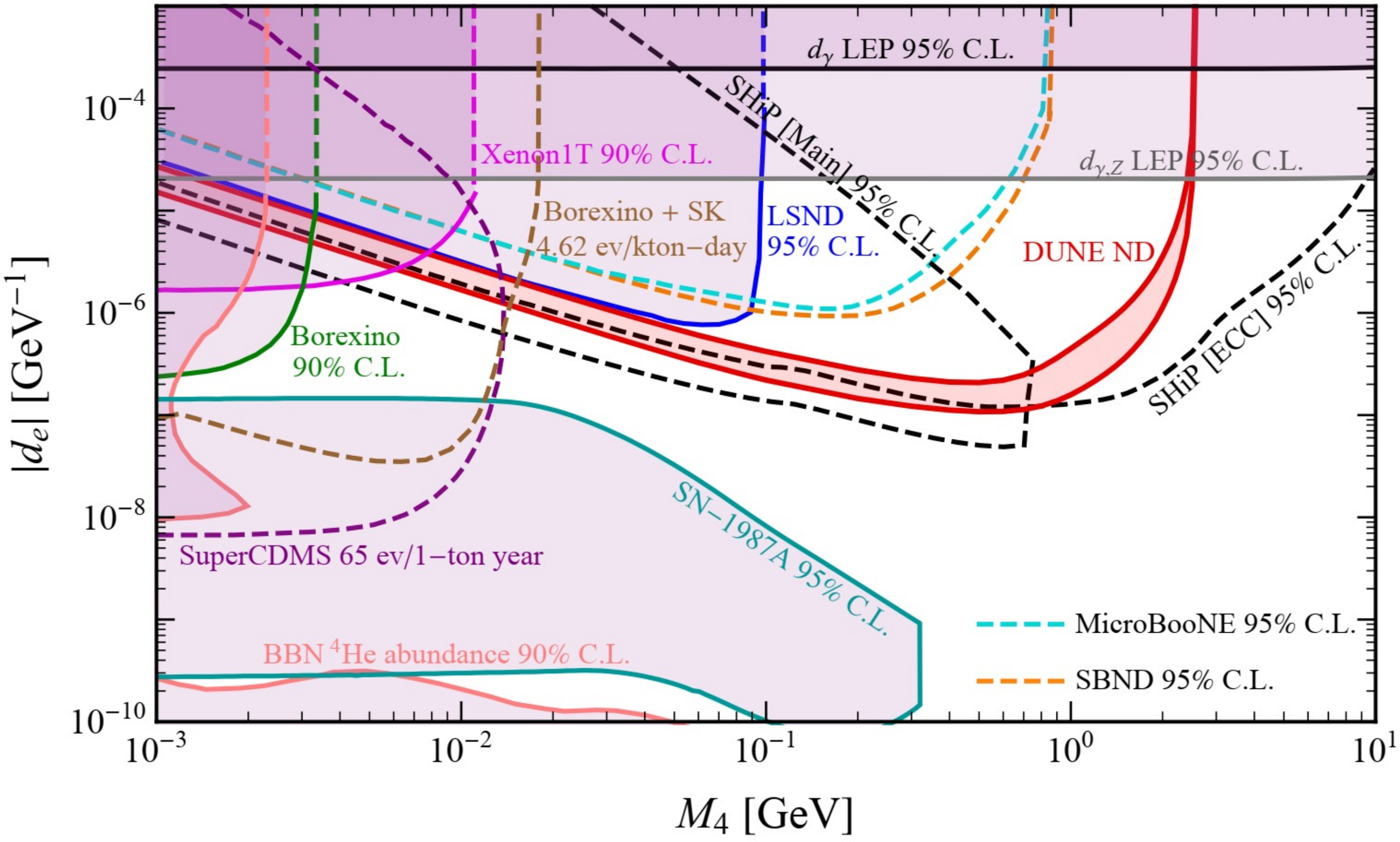


The 6-events/year curve for inside (solid) and outside (dashed) events at the DUNE FD.

Results

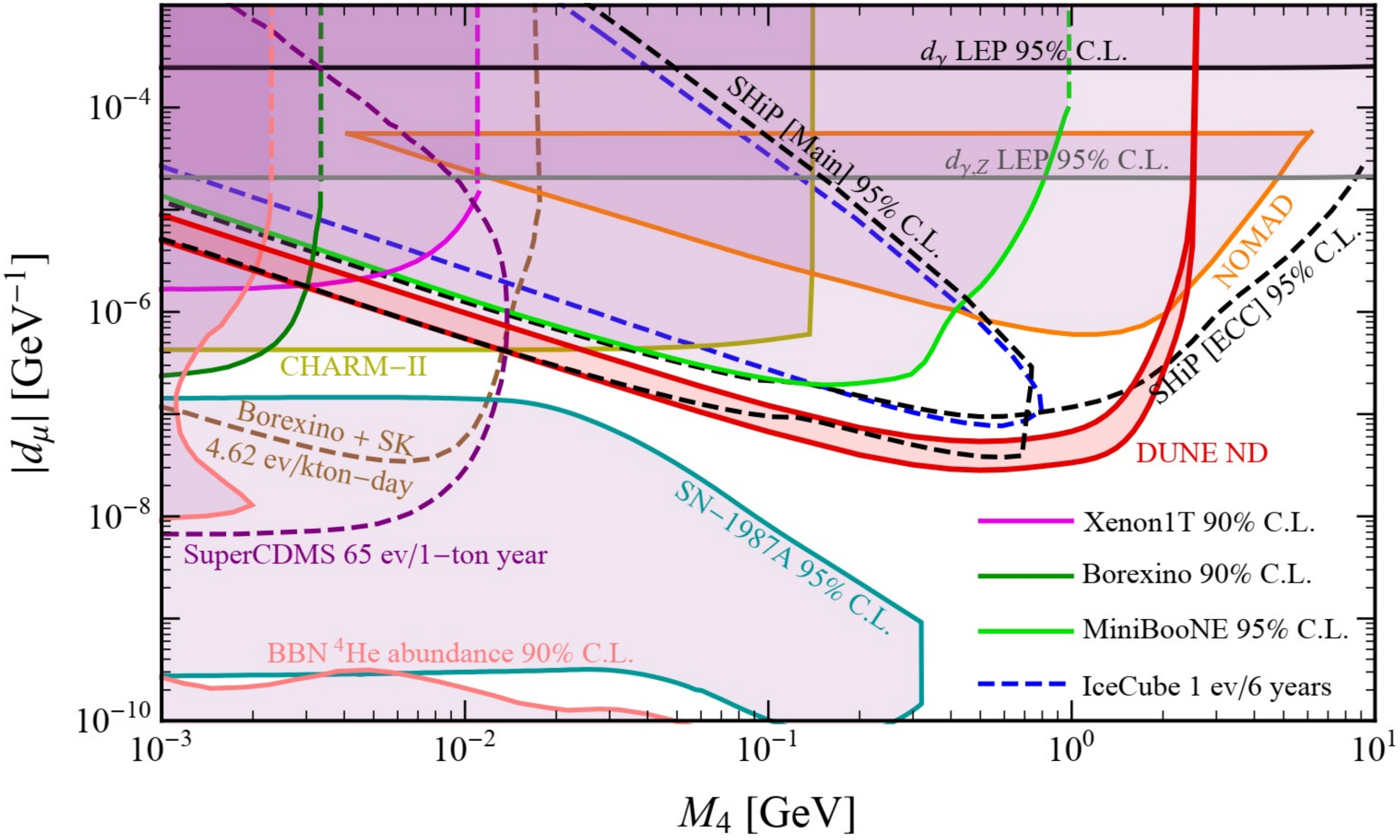

DUNE FD vs. SHiP & IceCube
DUNE FD 20 ev/yr
DUNE FD 6 ev/yr
DUNE FD 2 ev/yr
SHiP [main] 95% C.L.
IceCube 63% C.L.
SHiP [ECC] 95% C.L.
$|d_\tau|$ [GeV^{-1}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
M_4 [GeV]

Global picture of d_e



Due to the sizeable primary v_e and v_μ fluxes, the HNL transition moments d_e and d_μ are more efficiently probed at the near detector in the same way.

Global picture of d_μ



The primary flux of tau neutrinos in the beam has been estimated in the literature, from which we can estimate that the sensitivity of the d_τ-induced event rate in the ND is much smaller than the one in the FD.

Conclusions

- DUNE will be able to explore large regions of currently unconstrained parameter space and has competitive sensitivities compared with other relevant experiments, such as SHiP.

- A systematic detector simulation is further needed by taking into account a detailed background analysis and making use of event discrimination abilities in the liquid argon detector.

- The meson decays via virtual-neutrino or –photon exchange due to the same interaction may also contribute. This requires a detailed simulation of the meson production and decay in the beam target and decay pipe, which is beyond the scope of this work.

Thank you for your attention! 😀