Karlsruhe Institute of Technology

Deutscher Akademischer Austauschdienst
German Academic Exchange Service

Constraining neutrino transition magnetic moments at DUNE*

@ KSETA Plenary Workshop

Durbach

Albert Zhou

29 September 2021

*Work done in collaboration with Thomas Schwetz and Jing-Yu Zhu [arXiv:2105:09699]

Background: Neutrino oscillations

- Like quarks, the mass and (weak) interaction basis of neutrinos are not the same.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix converts mass to flavour basis

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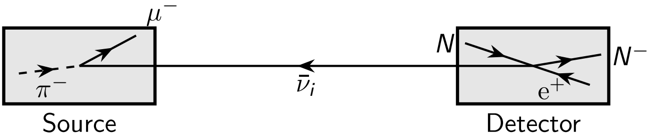
$\mathcal{A}_{e\mu} = \sum_i$ 

Figure: Another way to understand neutrino oscillations, is as the coherent sum of a Feynman diagram with neutrino mass eigenstates as internal lines.

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- For $E_\nu \sim 1\,\mathrm{GeV}$, the oscillation length is $L_{\mathrm{osc.}} \sim 1000\,\mathrm{km}$.
- Open question: is there a new fourth light "sterile neutrino", with a shorter oscillation baseline?

$$\nu_4?$$

Background: MiniBooNE excess

- MiniBooNE is a short-baseline accelerator neutrino experiment (no SM oscillations).

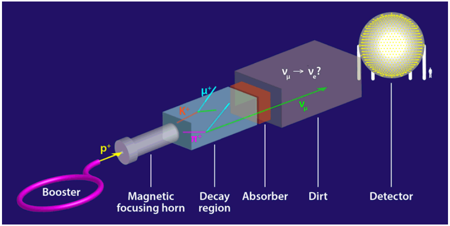

Figure: Made by Alan Stonebraker for the American Physical Society

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- The beam is mostly muon neutrinos with a small electron-neutrino background. Measuring electron-neutrino-like events, they found a 4.8σ excess.

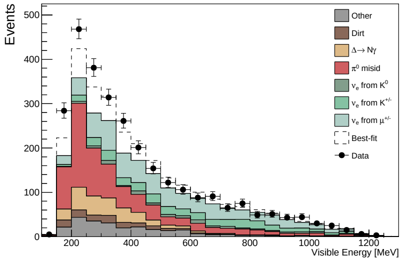

Figure: From [arXiv:2006.16883v3]

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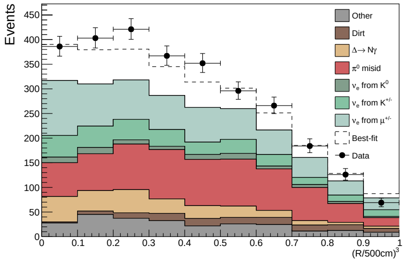

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- External background events and excess misreconstructed highly asymmetric π^0 decays were disfavoured.

Hypothesis	Factor	$\chi^2/9ndf$
NC $\Delta \to N\gamma$	3.18	10.0
External Event	5.98	44.9
ν_e from K_L^0 Decay	7.85	14.8
ν_e from $K^\pm$ Decay	2.95	16.3
ν_e from $\mu^\pm$ Decay	1.88	16.1
Other ν_e & $\bar{\nu}_e$	3.21	12.5
NC π^0 Background	1.75	17.2
Best Fit Oscillations	1.24	8.4

Table: From [arXiv:2006.16883v3]: *Log-likelihood shape-only fits to the radial distribution in neutrino mode, assuming only statistical errors, with arbitrary normalisation.*

Background: Possible explanations

- If excess were due to new $\nu_\mu \to \nu_e$ oscillations (via a fourth light neutrino), one should see a deficit in ν_μ flux in other beam experiments: not observed.

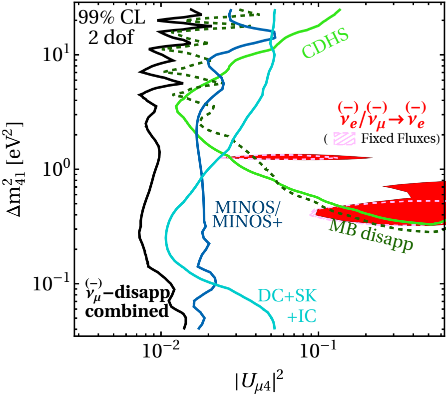

Figure: From [arXiv:1803.10661v1]. Right of black line is excluded region. Red islands are preferred regions from MiniBooNE

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- Gnienko [arXiv:0902.3802] first suggested that (in addition to a fourth light neutrino) sterile neutrino to single photon decay could explain the excess.

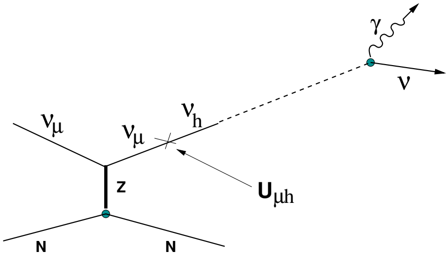

Figure: From [arXiv:0902.3802v1]

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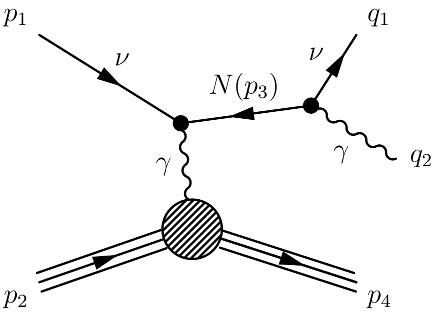
- G. Magill, R. Plestid, M. Pospelov and Y.-D. Tsai [arXiv:1803.03262] did the first systematic study into constraints on the neutrino dipole portal. (Production and detection via dipole operator).



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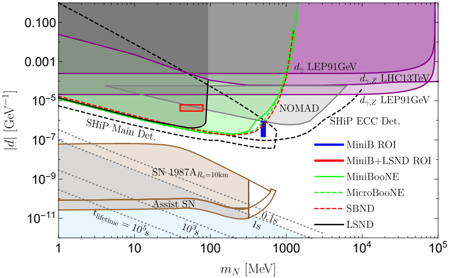

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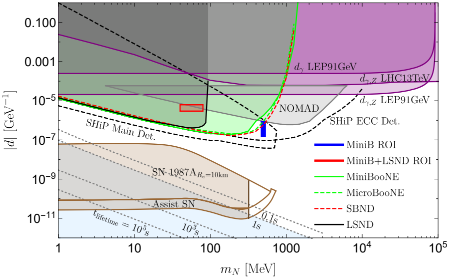

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- Note: purple collider bounds depend on electroweak UV completion.
- My work investigates the neutrino-dipole signal at DUNE.

Effective neutrino dipole operator

- Effective operator:

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

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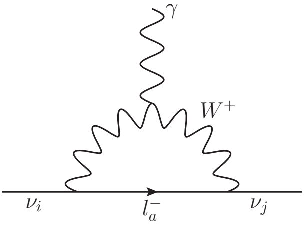

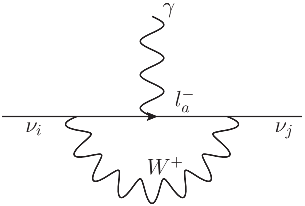

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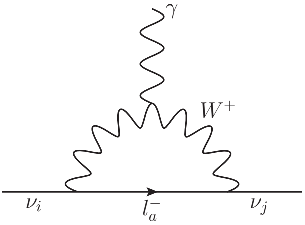

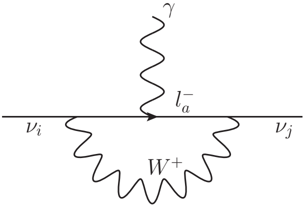

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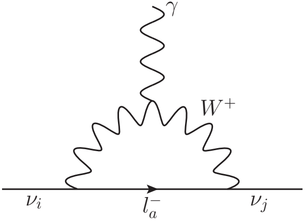

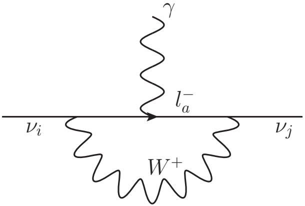

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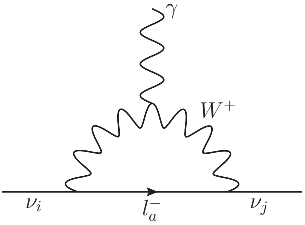

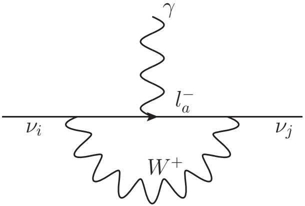

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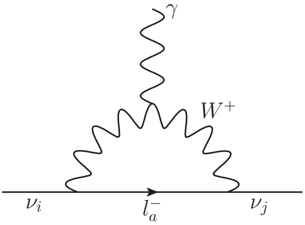
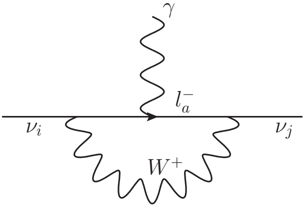
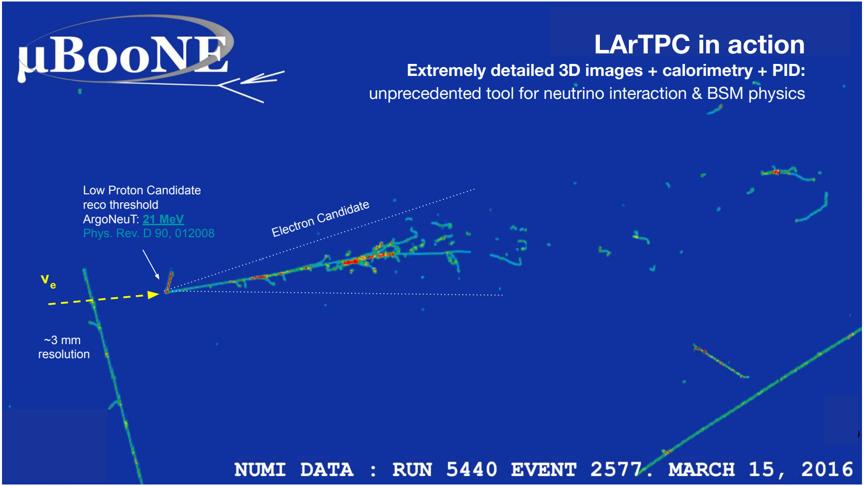
- See however [K.S. Babu, S. Jana and M. Lindner arXiv:2007.04291].





Signal generation at DUNE

- DUNE: 70kt of cryogenic (88 K or −185 °C) liquid Argon: good resolution and discrimination.



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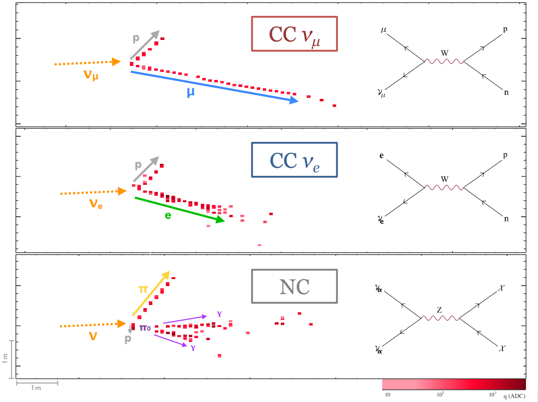
To compare with tracks from NOvA ND (courtesy of A. Himmel's 2018 presentation)

Neutrino Candidates from ND Data



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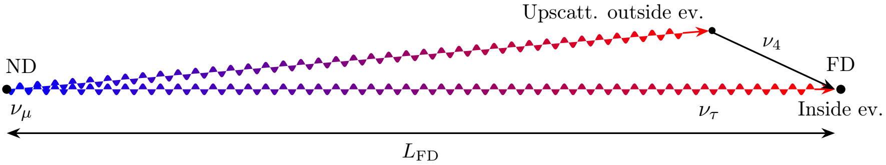

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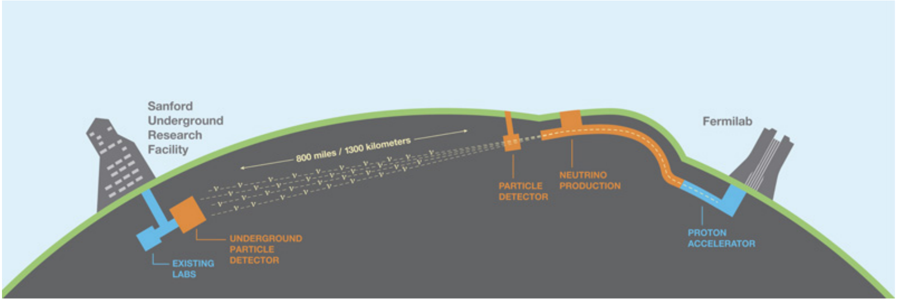
From [arXiv:2002.02967v3]. Cartoon illustrating the configuration of the LBNF beamline at Fermilab, in Illinois, and the DUNE detectors in Illinois and South Dakota, separated by 1300 km.



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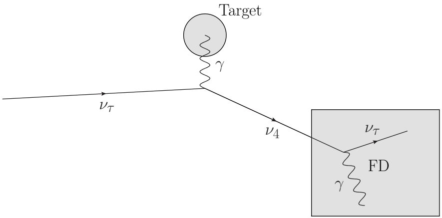
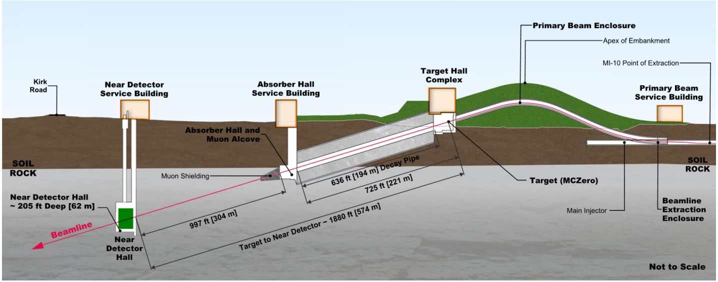
- Can also use intrinsic beam flux at near-detector.





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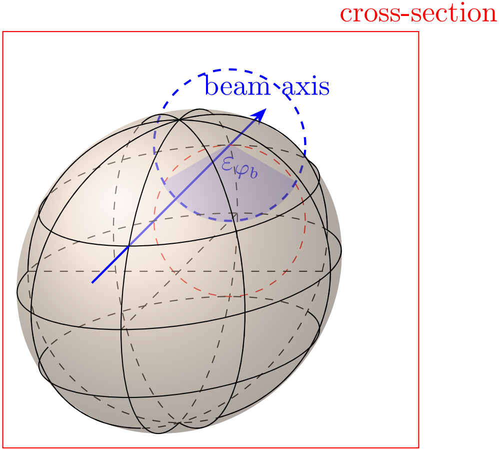
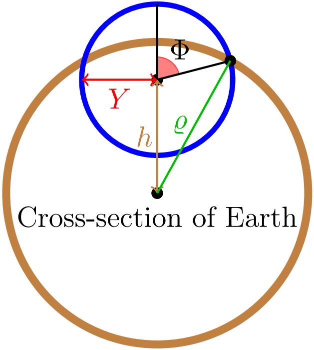
- **Inside events, coherent:** The coherent scattering on the nucleus leaves a nuclear recoil of low energy, which is difficult to observe in the detector. The decay leaves a single-photon signature.
- **Inside events, incoherent:** The incoherent scattering on nucleons leads to a signature similar to NC neutrino events, whereas the scattering on electrons results in a single electron. In addition, there is a coincidental displaced single-photon event from the heavy-neutrino decay.

Signal (approximations)

Outside events (no detector geometry):





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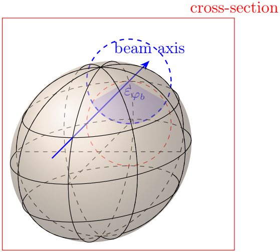
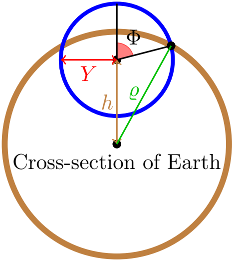
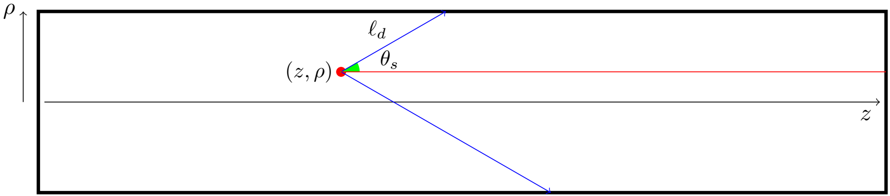


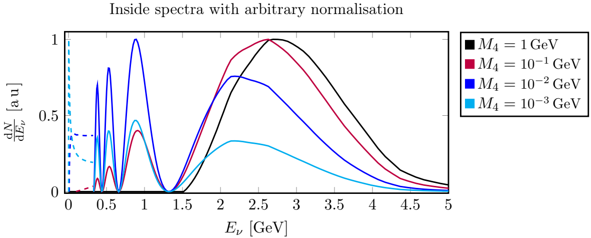


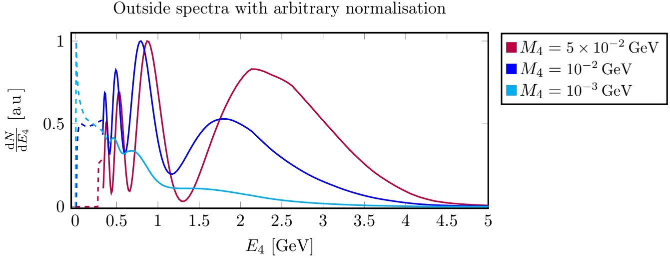
Inside events (only detector geometry, collimated beam):



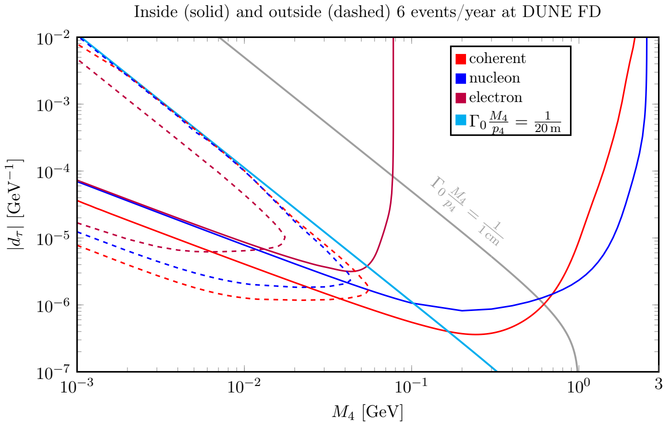
Signal for d_τ (example differential spectra)

Spectra for inside, outside events at various masses, normalised so that the peak is 1. At low energies (dashed), we replace the oscillation probability with $1/2$ to account for the averaging of fast oscillations. This is purely cosmetic for inside events.



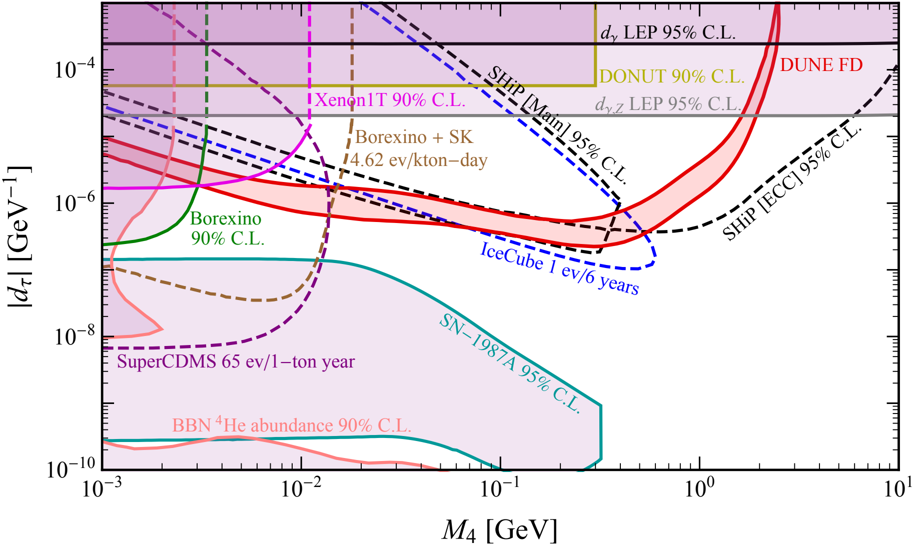


Results (decomposition by target and event-type)

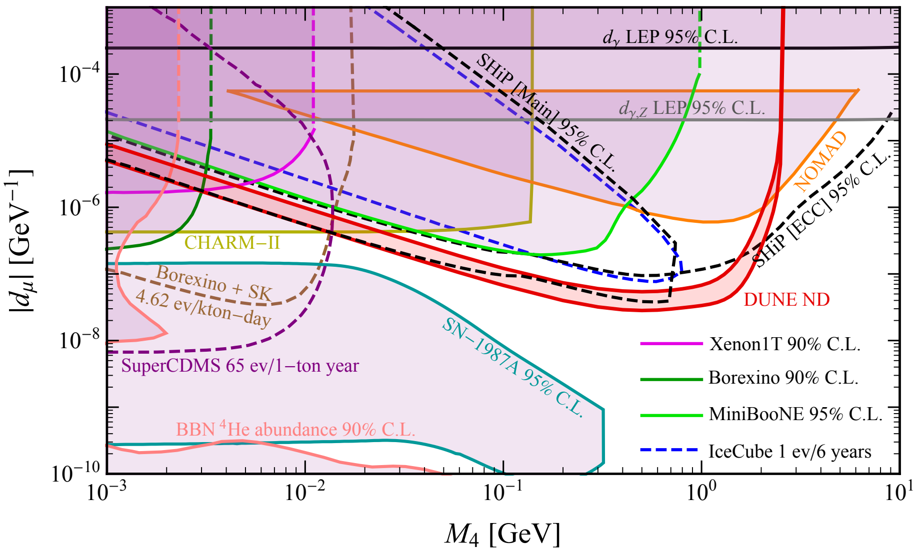


6-events/year curves for inside (solid) and outside (dashed) events at the DUNE FD for coherent scattering on nuclei (red), incoherent scattering on nucleons (blue) as well as electrons (purple). Our approximations for outside events break down at the upper curve, as decays occur very close to the detector (cyan line). This effect is negligible as inside-events will dominate. In grey is indicated when the decay-length is of the order of DUNE's spatial resolution.

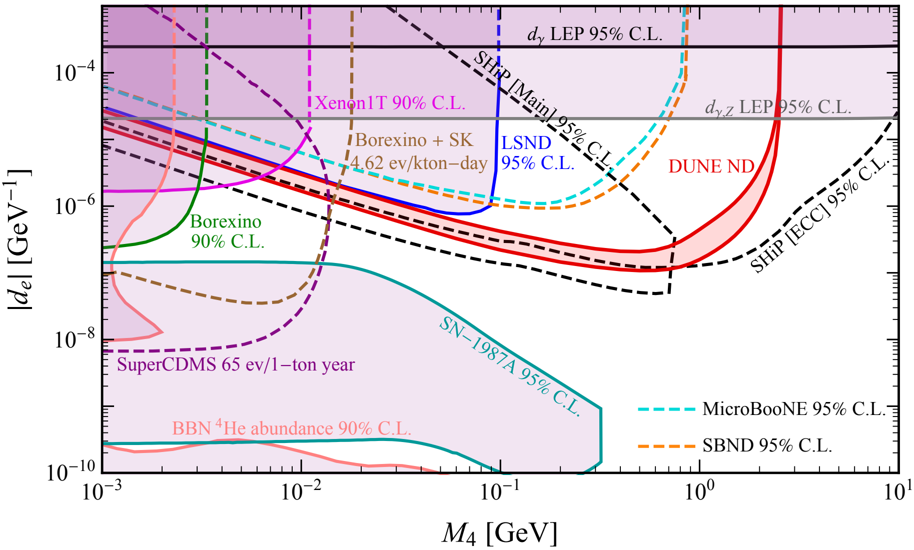
Global picture (d_τ)



Global picture (d_μ)



Global picture (d_e)



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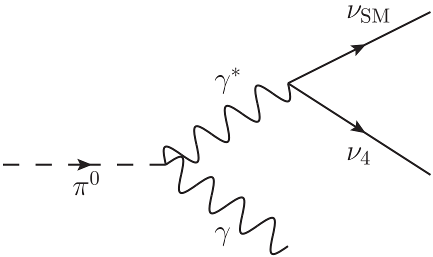

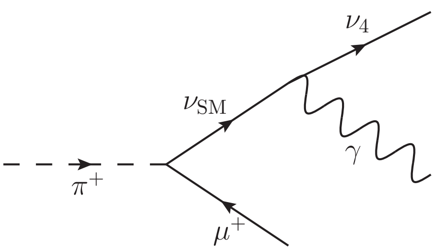

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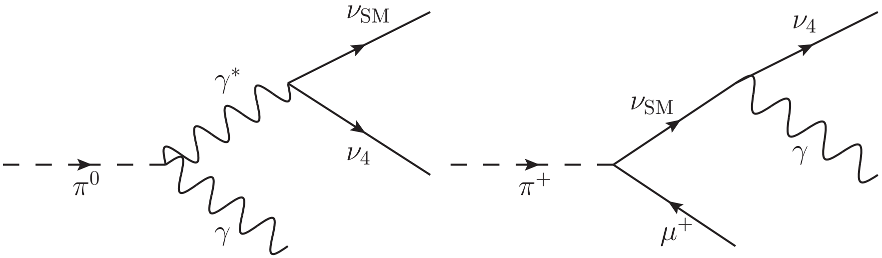
- Background studies needed for proper sensitivity curve.



Thanks for your attention!

Signal (equations)

Outside events (no detector geometry):

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

Signal (equations)

Outside events (no detector geometry):

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

Inside events (only detector geometry, collimated beam):

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