Lepton-Number-Charged Scalars and Neutrino Beamstrahlung

1802.00009 with Jeffrey M. Berryman, André de Gouvêa, and Yue Zhang
Phys. Rev. D97 (2018) no.7, 075030

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WG5, 16 August, 2018

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- $LeNCS$ in Neutrino Beams
- $LeNCS$ and Dark Matter

$LeNCS$: Lepton-Number-Charged Scalars

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Scalars with nonzero Lepton number that can only couple to the SM in ways that preserve $(B - L)$.

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If we construct higher-dimension (d) operators with SM fields and ν^c, they can have non-zero $(B-L)$ charge q_{B-L}.

$$(-1)^d = (-1)^{q_{B-L}/2}\,, \tag{1}$$

assuming $SU(3)\times SU(2)\times U(1)$ and Lorentz invariance [1604.05726].

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d is an integer $\implies$ q_{B-L} is even.
This means that if $(B-L)$ is conserved, odd-charged $LeNCS$ must appear in pairs.

Even-charged $LeNCS$

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Only renormalizable operator with one ϕ:

$$\mathcal{L}_{LeNCS} \supset \frac{\lambda_c^{ij}}{2} \nu_i^c \nu_j^c \phi^* . \tag{2}$$

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Since operators with $q_{B-L} = 2$ must be odd, the $(B-L)$-invariant operators with a ϕ then must be even. Lagrangian up to dimension-six:

$$\mathcal{L}_{LeNCS} \supset \frac{\lambda_c^{ij}}{2} \nu_i^c \nu_j^c \phi^\star + \frac{1}{\Lambda_{\alpha\beta}^2} \left(L_\alpha H\right) \left(L_\beta H\right) \phi + \mathrm{h.c.} \tag{3}$$

Extending the SM with ϕ

$$\mathcal{L}_{LeNCS} \supset \frac{\lambda_c^{ij}}{2}\nu_i^c\nu_j^c\phi^\star + \frac{1}{\Lambda_{\alpha\beta}^2}\left(L_\alpha H\right)\left(L_\beta H\right)\phi + \text{h.c.} \tag{4}$$

Post-Electroweak Symmetry Breaking, $H \to \frac{h+v}{\sqrt{2}}$:

$$\mathcal{L}_{LeNCS} \to \frac{\lambda_c^{ij}}{2}\nu_i^c\nu_j^c\phi^\star + \frac{\lambda_{\alpha\beta}}{2}\nu_\alpha\nu_\beta\phi + \frac{\lambda_{\alpha\beta}}{v}\nu_\alpha\nu_\beta\phi h + \text{h.c.} + \mathcal{O}(h^2), \tag{5}$$

where $\lambda_{\alpha\beta} \equiv v^2/\Lambda_{\alpha\beta}^2$.

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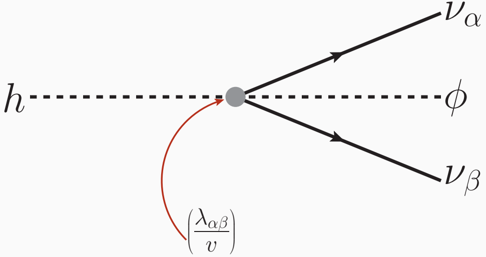
where $\lambda_{\alpha\beta} \equiv v^2/\Lambda_{\alpha\beta}^2$.

If $\Lambda_{\alpha\beta} \simeq$ electroweak scale, then we can have $\lambda_{\alpha\beta} \simeq 1$ and realizable interactions between ϕ and the active neutrinos ν_α.

Non-Neutrino Beam Experiment Constraints

Higgs boson decay

$$\mathcal{L}_{LeNCS} \supset \frac{\lambda_{\alpha\beta}}{v}\nu_\alpha\nu_\beta\phi h.$$



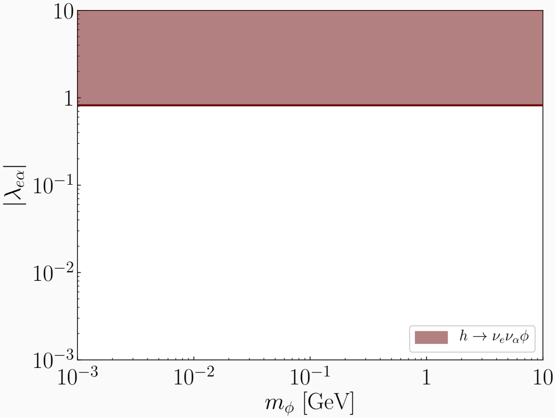
Since we're interested in $m_\phi < 10$ GeV, let's work in the limit $m_\phi \ll m_h$.

$$\Gamma(h \to \nu_\alpha\nu_\beta\phi) = \frac{|\lambda_{\alpha\beta}|^2 m_h^3}{384\pi^3 v^2}.$$

Higgs boson decay Bound

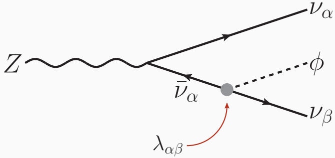
$\Gamma_h^{\text{tot.}} = 13$ MeV.

$$\Gamma(h \to \nu_\alpha \nu_\beta \phi) = \frac{|\lambda_{\alpha\beta}|^2 m_h^3}{384\pi^3 v^2}, \quad \text{Br}(h \to \text{invisibles}) \lesssim 28\%$$



Z-boson decay

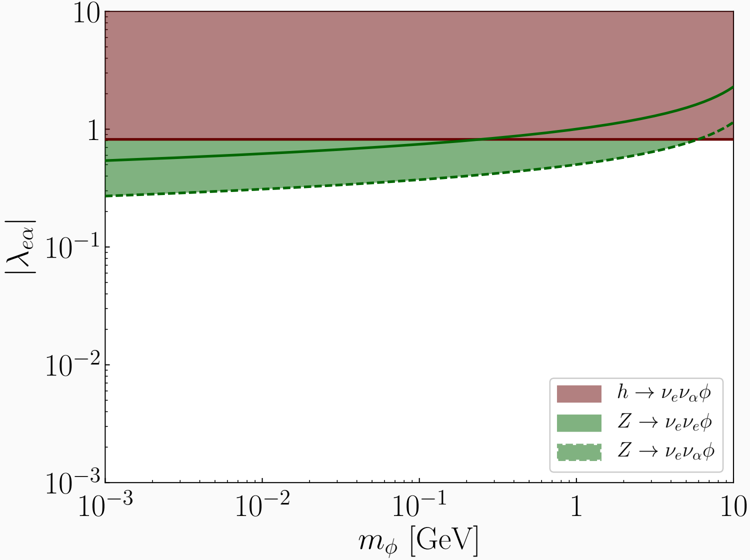
$$\mathcal{L}_{LeNCS} \supset \frac{\lambda_{\alpha\beta}}{2}\nu_\alpha\nu_\beta\phi$$



This decay will contribute to the Z-boson invisible decay width,
$\mathrm{Br}(Z \to \text{ invisibles}) = (20 \pm 0.06)\,\%$, and $\Gamma_Z^{\text{tot.}} = 2.495$ GeV.

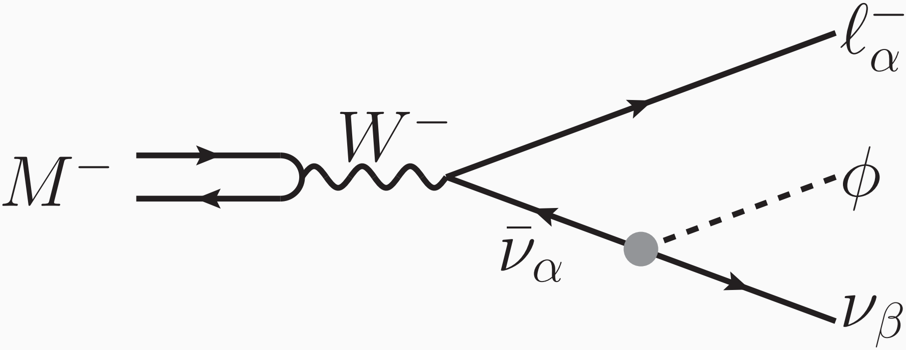
$$\Gamma(Z \to \nu_\alpha\nu_\beta\phi) \simeq \frac{G_F M_Z^3 |\lambda_{\alpha\beta}|^2 \left(\log\left(\frac{M_Z}{m_\phi}\right) - \frac{5}{3}\right)}{864\sqrt{2}\pi^3\left(1+\delta_{\alpha\beta}\right)^2}$$

Z-boson decay bound



Charged meson decays

Many charged mesons have the decay channel $M^- \to \ell_\alpha^- \bar{\nu}_\alpha$ (or $M^+ \to \ell_\alpha^+ \nu_\alpha$). With a nonzero $\lambda_{\alpha\beta}$ and $m_\phi < m_M$, Many charged mesons have the decay channel $M^- \to \ell_\alpha^- \bar{\nu}_\alpha$ (or $M^+ \to \ell_\alpha^+ \nu_\alpha$). With a nonzero $\lambda_{\alpha\beta}$ and $m_\phi < m_M$,



Meson decay bounds

The width of this process is

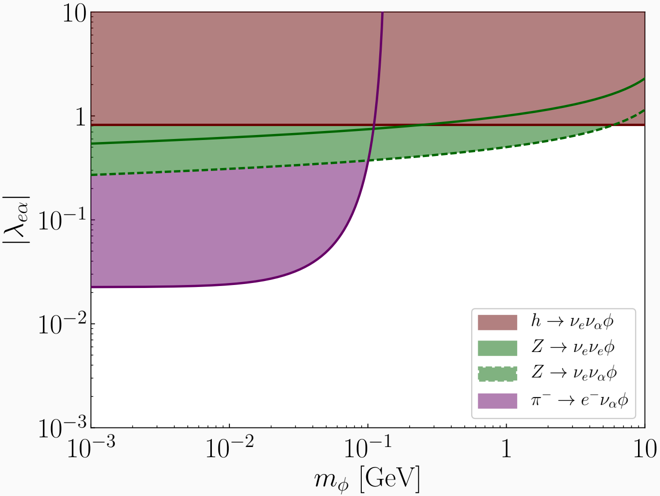
$$\Gamma(M^- \to \ell_\alpha^- \nu_\beta \phi) = \frac{|\lambda_{\alpha\beta}|^2 G_F^2 f_M^2}{768\pi^3 m_M^3} \times$$
$$\left[\left(m_M^2 - m_\phi^2\right)\left(m_M^4 + 10 m_M^2 m_\phi^2 + m_\phi^4\right) - 12 m_M^2 m_\phi^2 \left(m_M^2 + m\phi^2\right) \log \frac{m_M}{m_\phi}\right],$$

where f_M is the decay constant of M.

Pion decay

$\pi \to e\nu_\alpha\phi$ serves as a background for the search for $\pi \to e\bar{\nu}_e\nu\bar{\nu}$.

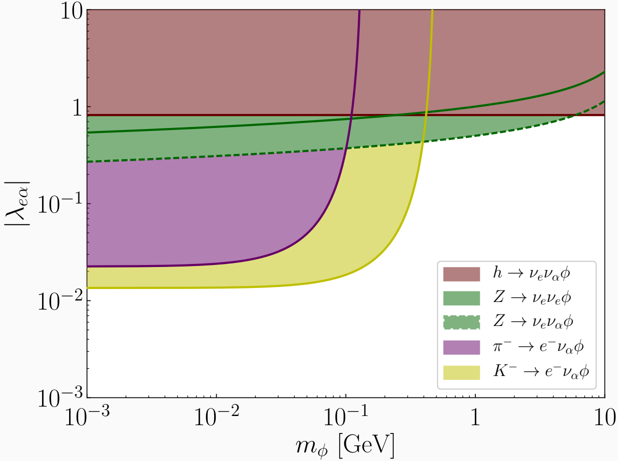
PDG: $\mathrm{Br}(\pi \to e\bar{\nu}_e\nu\bar{\nu}) < 5 \times 10^{-6}$, with $m_\pi = 137$ MeV, $f_\pi = 131$ MeV.



Kaon decay

Search for $K^- \to e^- \nu_\alpha \phi$ ($K^- \to \mu^- \nu_\beta \phi$) would contribute to $K \to e\bar{\nu}_e \nu\bar{\nu}$ ($K \to \mu\bar{\mu}_e \nu\bar{\nu}$). $m_K = 494$ MeV, $f_K = 160$ MeV.

PDG: $\mathrm{Br}(K \to e\bar{\nu}_e \nu\bar{\nu}) < 6 \times 10^{-5}$, $\mathrm{Br}(K \to \mu\bar{\mu}_e \nu\bar{\nu}) < 2.4 \times 10^{-6}$.



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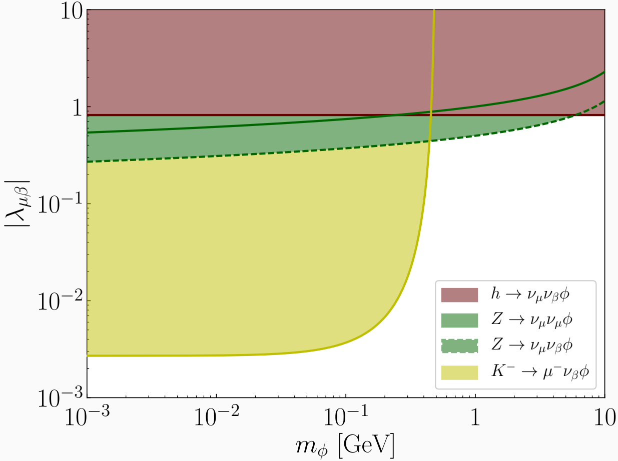
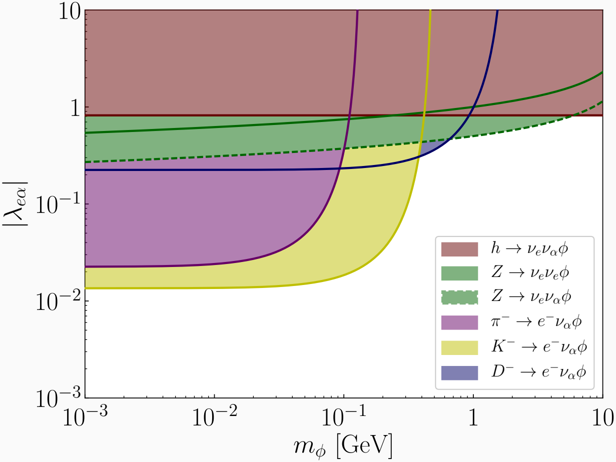


D decay

D Mesons: $m_D = 1869\ \mathrm{MeV}$, $f_D = 249\ \mathrm{MeV}$. Only an upper bound exists on searches for both $D \to e\bar{\nu}_e$ $(\mathrm{Br} < 8.8 \times 10^{-6})$ and $D \to \mu\bar{\nu}_\mu$ $(\mathrm{Br} < 3.4 \times 10^{-5})$.



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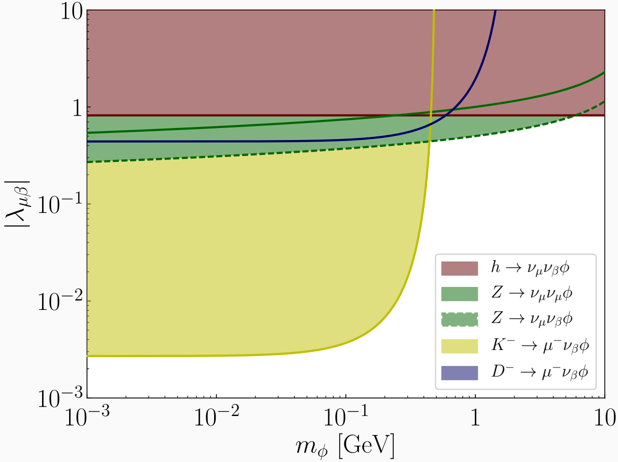
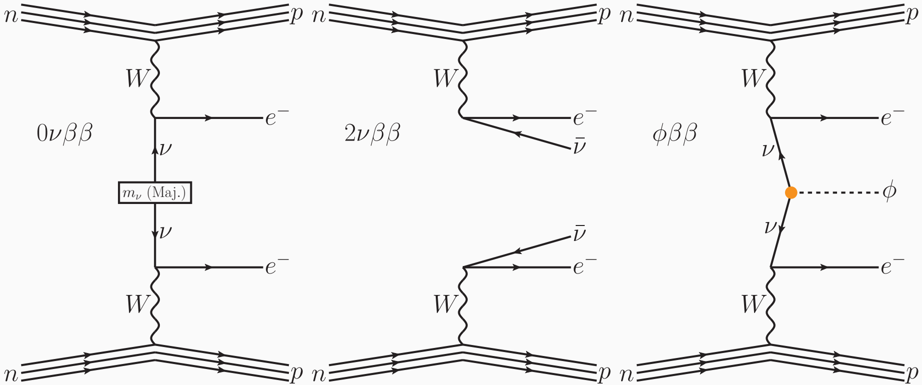


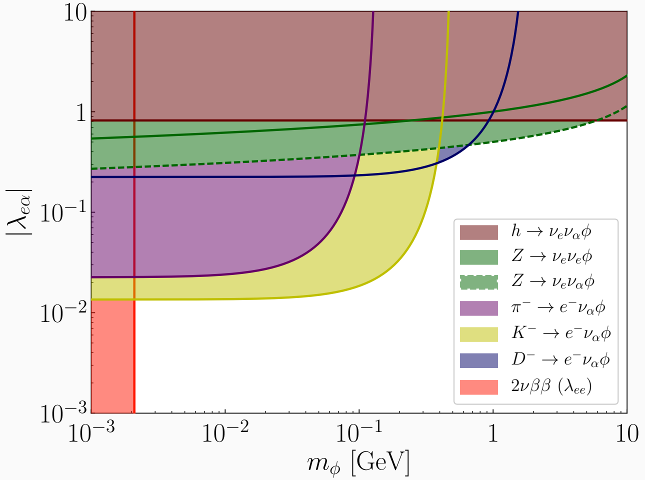
Double-beta decay

Neutrinoless double-beta decay is a process that only exists if neutrinos are Majorana fermions, and many experiments have searched for this process. One background is two-neutrino double-beta decay, in which the outgoing electrons have a spectrum of energies, not a sharp line.

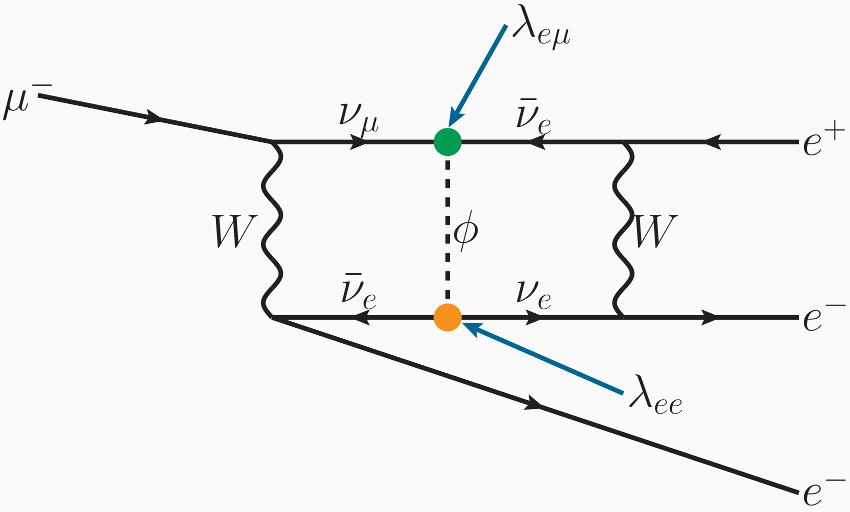


Bounds from double-beta decay

[1501.02345] analyzed Majoron emission impacting $2\nu\beta\beta$ measurements, which is identical to ϕ emission as long as $m_\phi < Q_{\beta\beta}$.



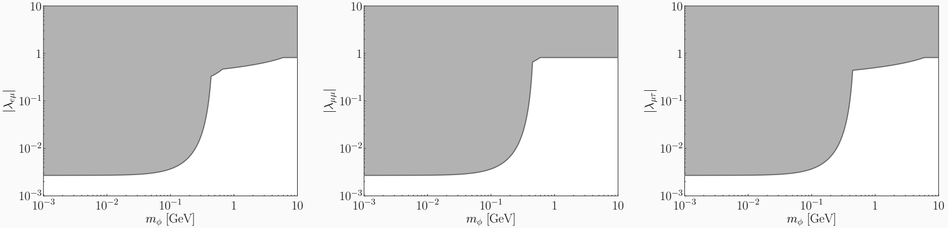
Charged-lepton Flavor Violation



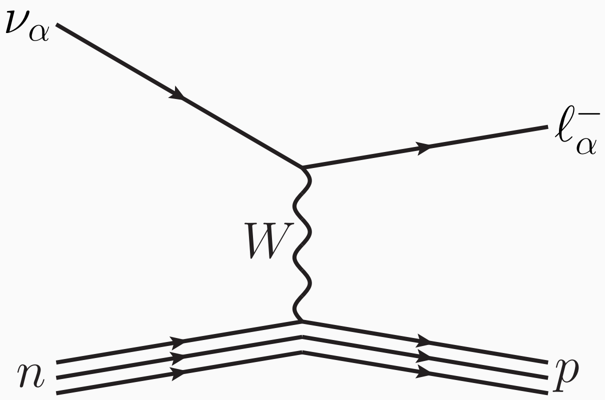
$LeNCS$ in Neutrino Beams

Parameters of Interest

We will be interested in ν_μ beams, so the parameters $\lambda_{\mu\alpha}$:



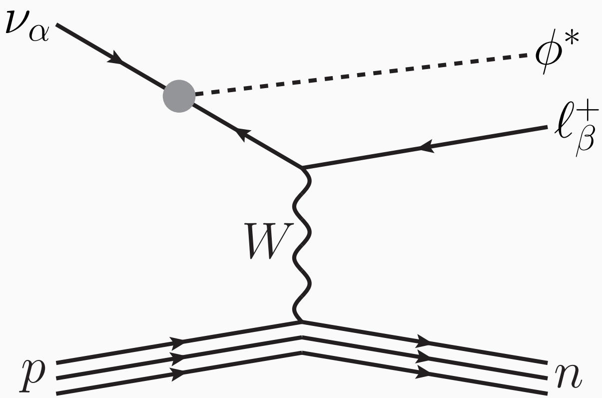
Standard ν Charged-Current Interaction:



$\mathcal{A}_{CC}$

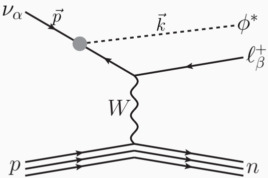
The process of interest

Charged-Current Interaction with ϕ Emission:



$\mathcal{A}_\phi$

Features of ϕ-emission



- Wrong-sign lepton – neutrino beam generates ℓ^+, antineutrino beam generates ℓ^-.

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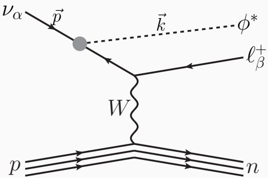

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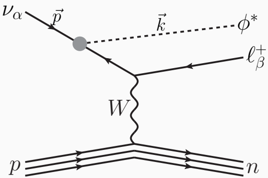

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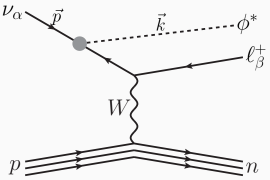

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- Need $m_\phi < E_\nu$ – high-energy neutrino beams open up more m_ϕ phase space.
- Events tend to peak in forward-going ϕ region.
- If we look where $m_\phi \to E_\nu$, the ϕ can be radiated at large angles, giving large missing transverse momentum $\not{p}_T$.

Existing constraint: MINOS

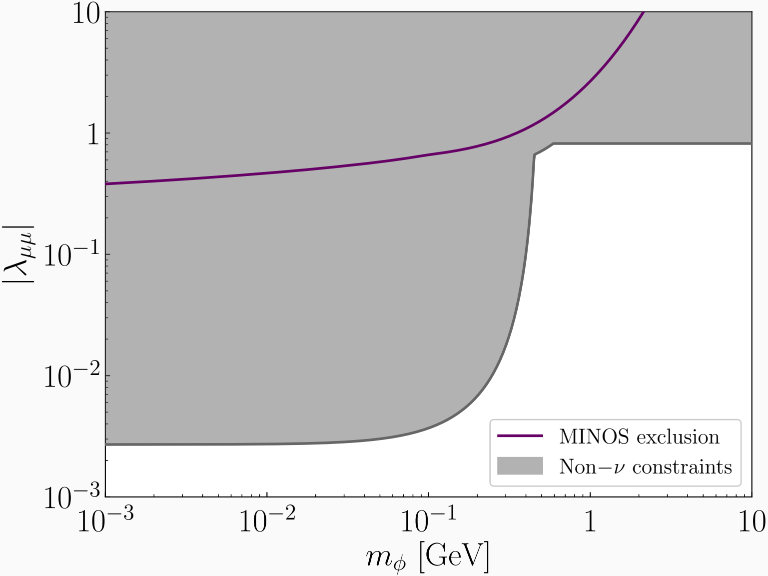
MINOS Beam: 91.7% ν_μ, 7% $\bar{\nu}_\mu$, nearly monochromatic $E_\nu \simeq 3$ GeV.

Collaboration measured the rate of $\bar{\nu}_\mu + p \to \mu^+ + n$ to be 3.84 ± 0.05 events/10^{15} protons on target.

Existence of ϕ (with nonzero $\lambda_{\mu\mu}$) adds to this apparent rate via $\nu_\mu + p \to \mu^+ + \phi + n$.

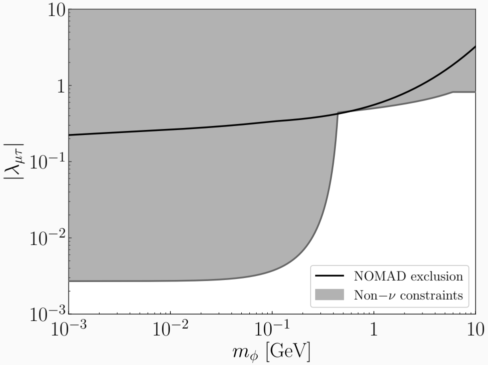
$$\mathcal{R} \equiv \frac{\sigma(\nu_\mu + p \to \mu^+ + \phi + n)}{\sigma(\bar{\nu}_\mu + p \to \mu^+ + n)}, \quad \mathcal{R} \lesssim 0.002.$$

Resulting bound from MINOS



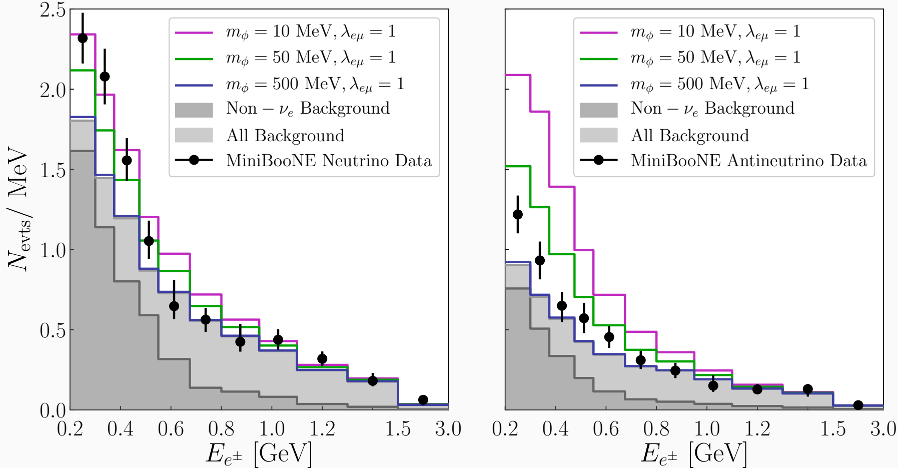
Existing constraints: NOMAD

Searched for $\nu_\mu \to \nu_\tau$ oscillations in the 1990s. If $LeNCS$ exists with nonzero $\lambda_{\mu\tau}$, there would be a contribution that seemed like this oscillation. NOMAD: $P(\nu_\mu \to \nu_\tau) < 2.2 \times 10^{-4}$. Since we know $\sigma(\nu_\mu p \to \tau^+ n \phi) \propto |\lambda_{\mu\tau}|^2$, we can solve for where the bound is saturated as a function of m_ϕ:

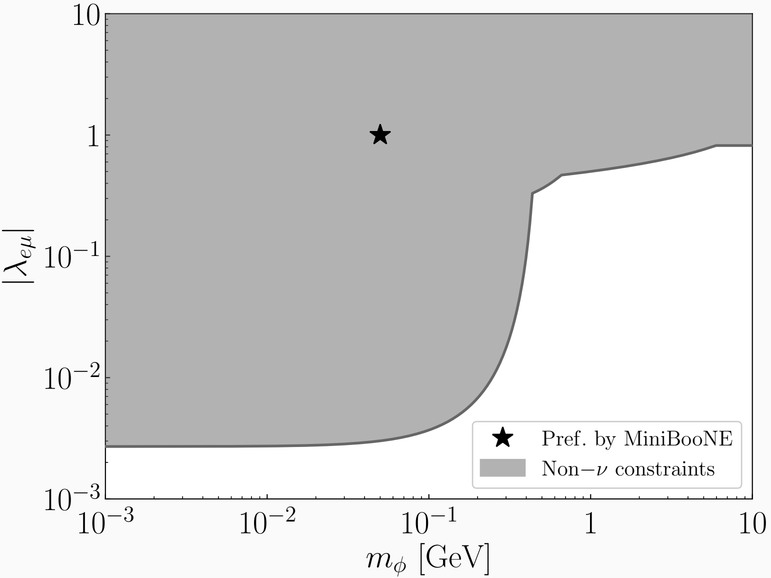


Existing constraint*: MiniBooNE [1310.0076]

MiniBooNE: Predominantly ν_μ beam (some ν_e contamination) searching for short-baseline $P(\nu_\mu \to \nu_e)$ oscillation. Famous low-energy excess. Can Φ_μ and $\lambda_{e\mu}$ explain?

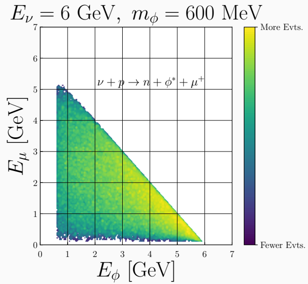


Preferred region of $LeNCS$ parameter space



Looking ahead: DUNE

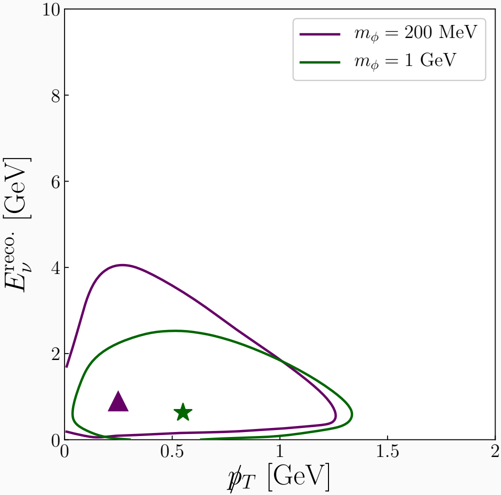
Assuming a $2 \to 2$ scattering event like $\nu_\alpha n \to \ell_\alpha^- p$, with perfect knowledge of outgoing ℓ_α^n and nucleon, we can calculate the neutrino energy exactly. $E_\nu \simeq E_\ell$.



If, however, we assume an event was $2 \to 2$, but it was actually $2 \to 3$ like $\nu_\alpha p \to \ell_\beta^+ n \phi$ with a particle not identified, then the calculated E_ν is wrong.

Exploiting $LeNCS$ Kinematics

$LeNCS$ signal at near detector: $\nu_\mu + p \to \mu^+ + \phi + n$. Large apparent missing transverse momentum in reconstructed μ^+/n final state.



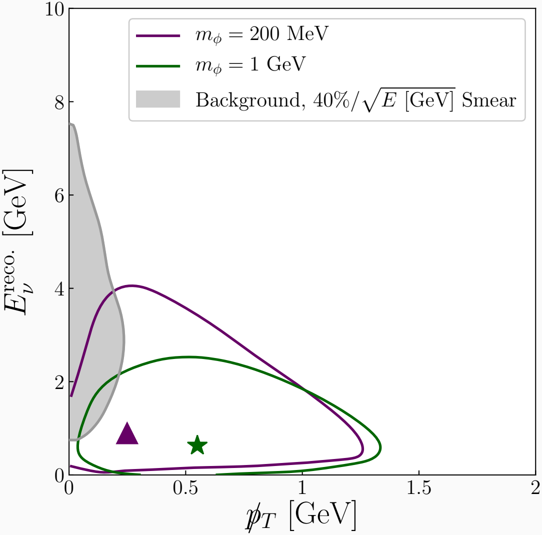
SM background:

$\nu_\mu + n \to \mu^- + p$

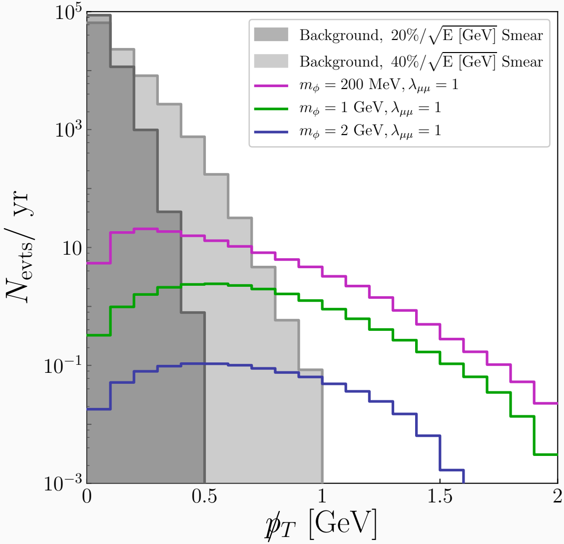
should be reconstructed as known flux as a function of energy, $\not{p}_T = 0$ for all events.

Smeared SM Background at DUNE

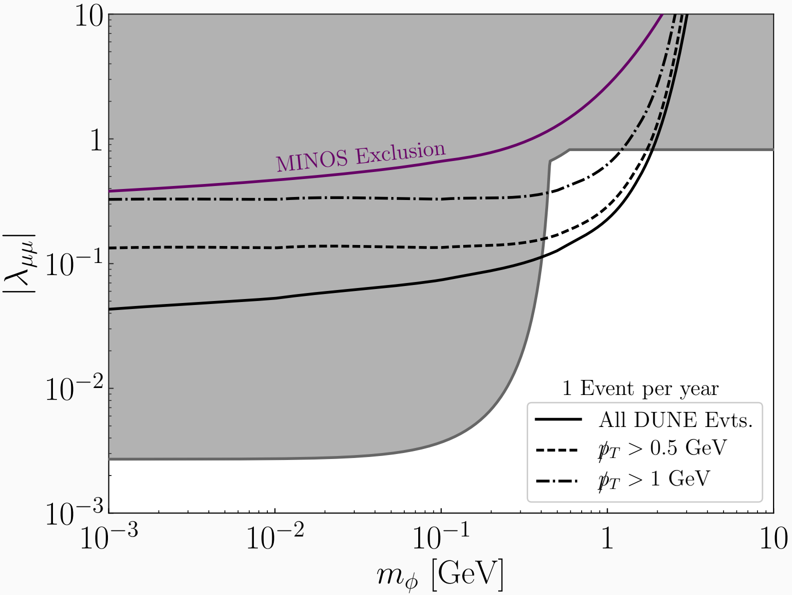
Smeared $\nu_\mu + n \to \mu^- + p$ events.



Projecting $\not{p}_T - E_\nu$ down to just $\not{p}_T$:



DUNE Sensitivity



$LeNCS$ and Dark Matter

Possible DM Scenarios with χ

$$\mathcal{L} \supset \left(\mu_{\phi\chi}\phi\chi^2 + \mathrm{h.c.}\right) + c_{\phi\chi}|\phi|^2|\chi|^2 + c_{H\chi}|H|^2|\chi|^2 + \left(\chi^2\hat{O}_{B-L=2} + \mathrm{h.c.}\right) + \ldots$$

- **Neutrinophilic Dark Matter with ϕ portal to χ** – if $\mu_{\phi\chi}$ and $c_{\phi\chi}$ are the most significant terms, ϕ-mediated interaction between neutrinos and χs.

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- **Dark Matter triggered Nucleon Decay** – If the $\chi^2\hat{O}_{B-L=2}$ terms dominate, then we could have reactions such as $\chi + (Z,A) \to \chi^* + (Z, A-1) + \nu$, where detectable hadronic activity could be a signal of an interaction.

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- We explored one new physics extension, in which $(B - L)$ is preserved in nature, and new scalar fields are charged under $(B - L)$.
- The parameter space is already constrained by a number of sources, both related to neutrino beams and not.

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- These $LeNCS$ may serve as a portal to a stable Dark Matter candidate.