PONDD Workshop – 4 December, 2018

Lepton-Number-Charged Scalars and Neutrino Beamstrahlung

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Virginia Tech; COFI Fellow

Based on *Phys. Rev. D97 (2018) no.7, 075030* with A. de Gouvêa, K. J. Kelly and Y. Zhang

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Orientation: *B–L*

- *B* and *L*: conserved at *renormalizable* level in the SM…but not in general!
- Their difference – *B-L* – is!
  - Signature of higher symmetry?
- Does this necessarily persist in higher-dimension operators?

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(NB: *even-dimension operators*)

$$(A, Z) \to (A, Z+2) e^- e^-$$

(NB: *odd-dimension operators*)

A New Scalar – *LeNCS*

- Let's assume *B-L* is a good symmetry – what new physics can we introduce?
  - Neutrinos must be *Dirac fermions*
  - We introduce a lepton-number-charged scalar ϕ (*LeNCS*) with *B-L* = +2

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$$\mathcal{L}_{\text{Yuk}} \supset y_\nu L H \nu^c + \text{h.c.}$$

$$\mathcal{L}_\phi \supset \frac{\lambda_c^{ij}}{2} \nu_i^c \nu_j^c \phi^* + \frac{(L_\alpha H)(L_\beta H)}{\Lambda_{\alpha\beta}^2} \phi + \text{h.c.}$$

$$\mathcal{L}_{\text{int}} \supset \frac{\lambda_c^{ij}}{2} \nu_i^c \nu_j^c \phi^* + \frac{\lambda_{\alpha\beta}}{2} \nu_\alpha \nu_\beta \phi + \frac{\lambda_{\alpha\beta}}{v} \nu_\alpha \nu_\beta \phi h + \text{h.c.} + \mathcal{O}(h^2)$$

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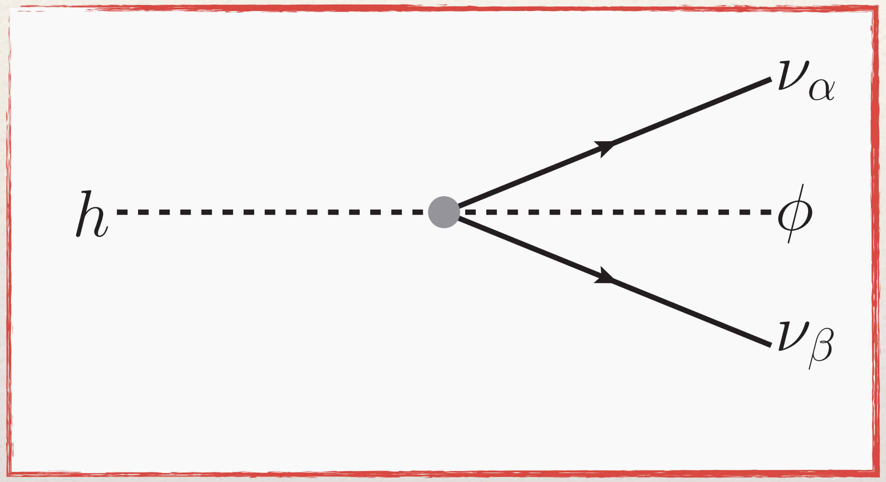
Assuming SM-gauge and Lorentz invariance, it is possible to show that

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

A. Kobach, *Phys. Lett. B758 (2016) 455-457*

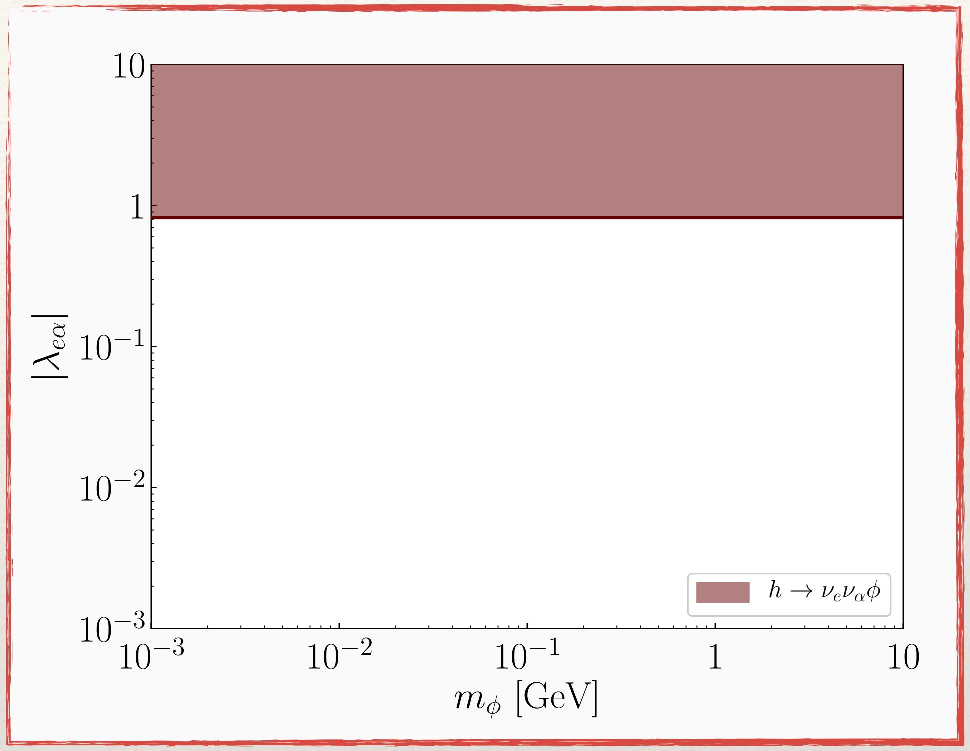
Bounds: Non-beam experiments

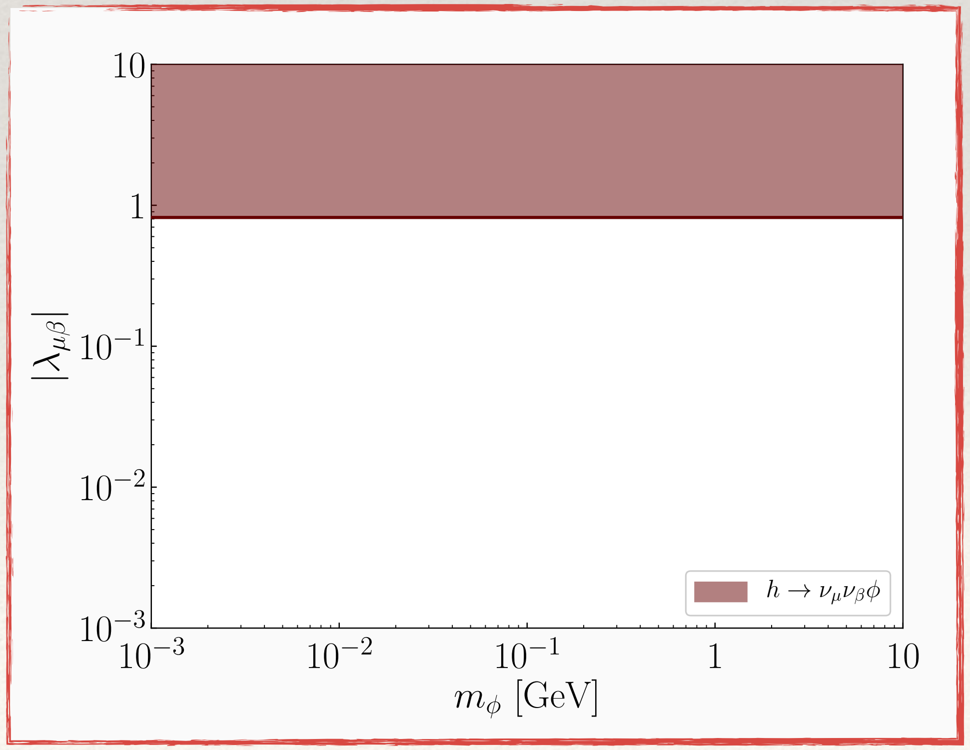
- Higgs decay:



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

$$\mathrm{Br}(h_{\rm inv}) = \frac{\Gamma(h \to \nu_\alpha \nu_\beta \phi) + \Gamma(h \to \bar\nu_\alpha \bar\nu_\beta \phi^*)}{\Gamma(h \to \nu_\alpha \nu_\beta \phi) + \Gamma(h \to \bar\nu_\alpha \bar\nu_\beta \phi^*) + \Gamma^h_{\rm SM}} < 0.34$$





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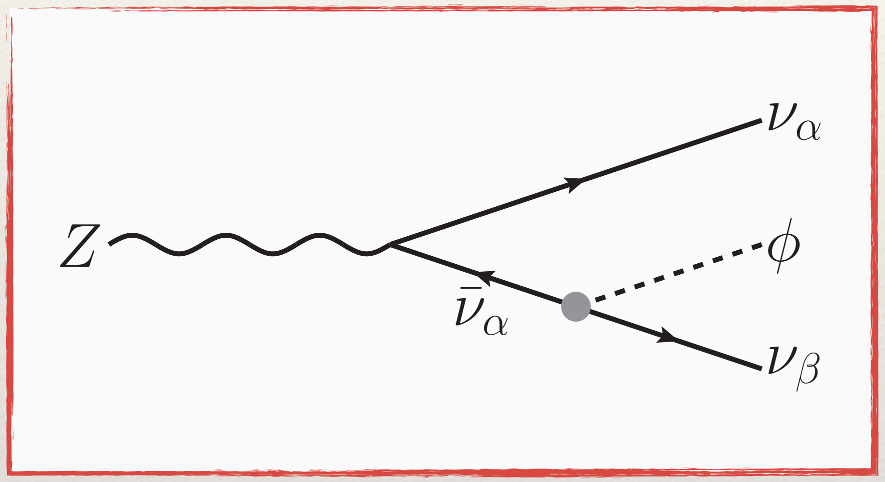
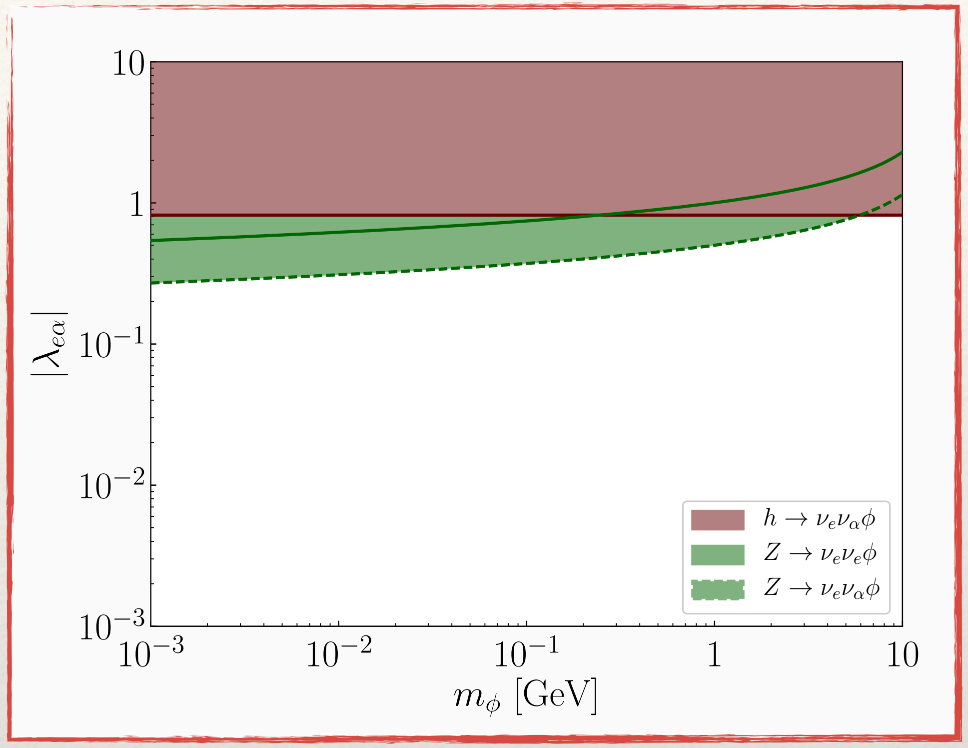
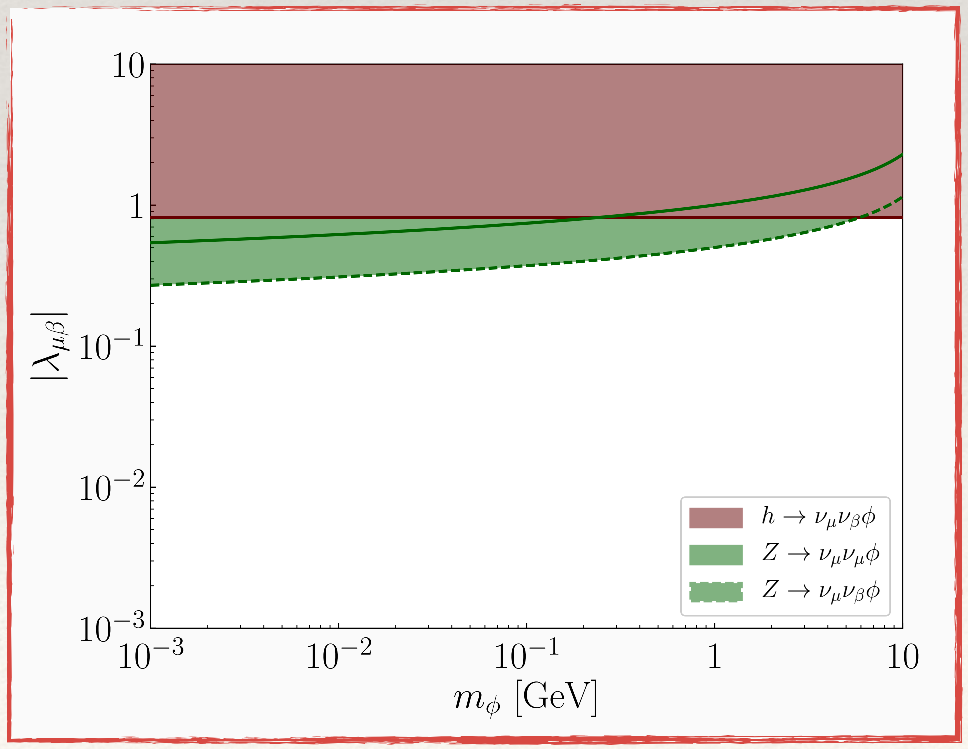


$$\Gamma(Z \to \nu_\alpha \nu_\beta \phi) \simeq \frac{G_F M_Z^3 |\lambda_{\alpha\beta}|^2 \left(\ln \frac{M_Z}{m_\phi} - \frac{5}{3} \right)}{288\sqrt{2}\pi^3 (1+\delta_{\alpha\beta})^2}$$

$$\mathrm{Br}(Z_{\mathrm{inv}}) = (20 \pm 0.06)\%$$

$$\Gamma_{Z,\,\mathrm{Tot}} = 2.495\,\mathrm{GeV}$$





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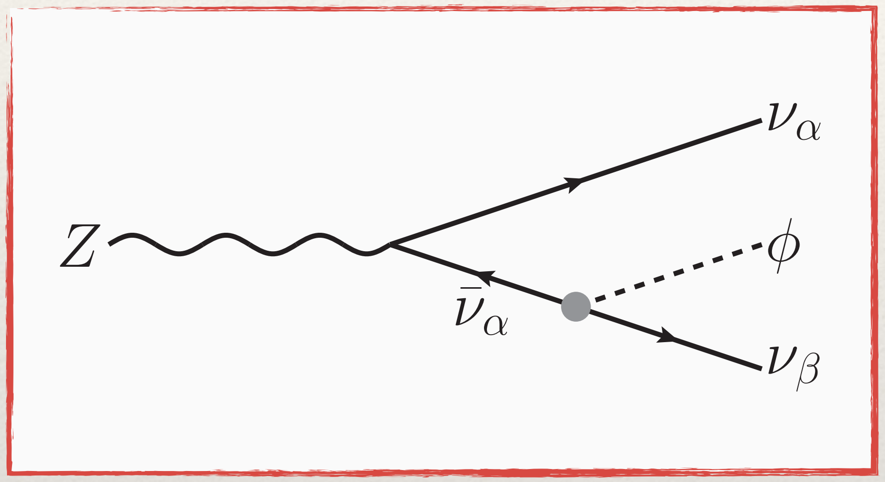

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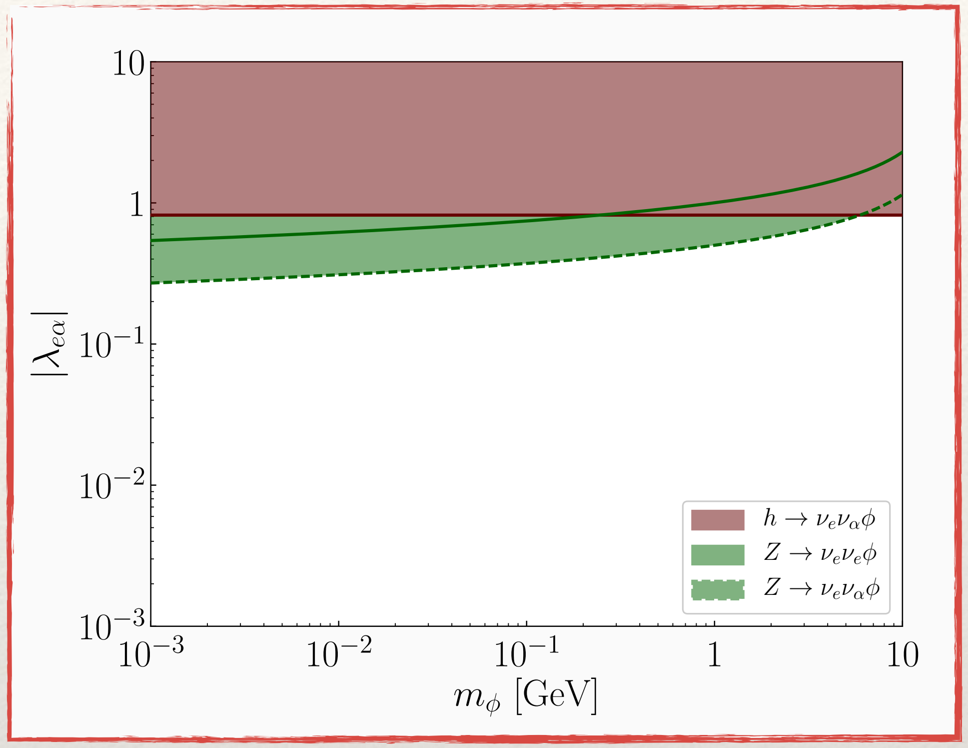
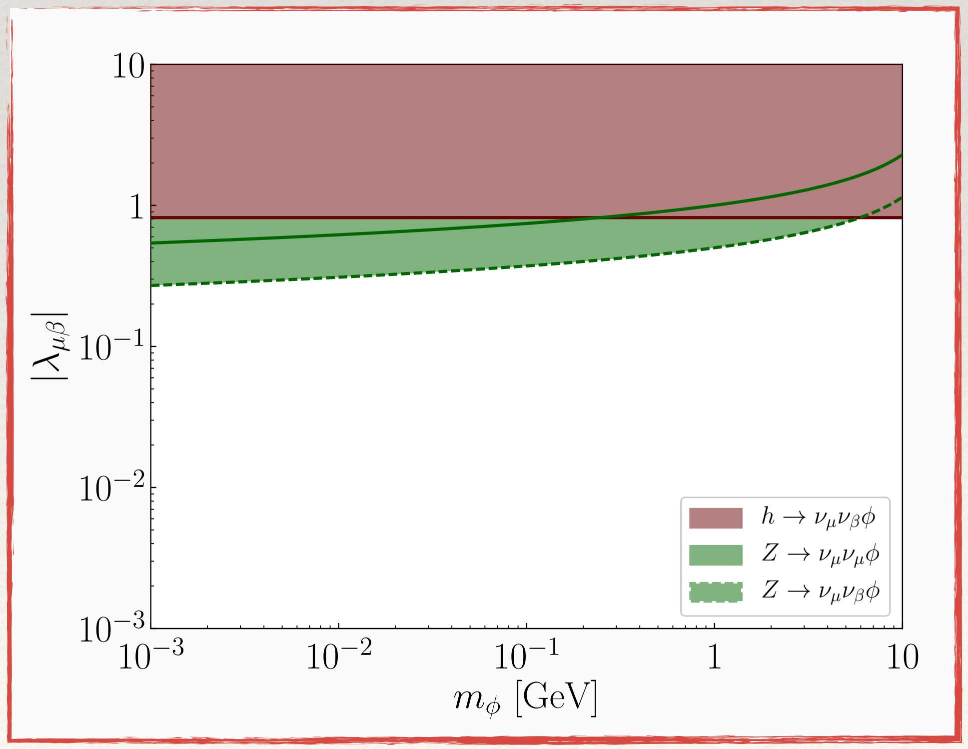
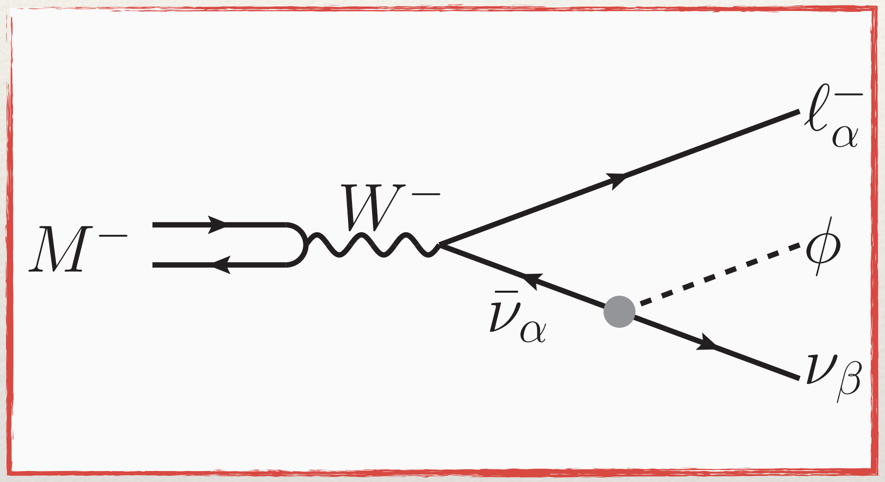
This log comes from collinear singularity; cancelled by one-loop correction!



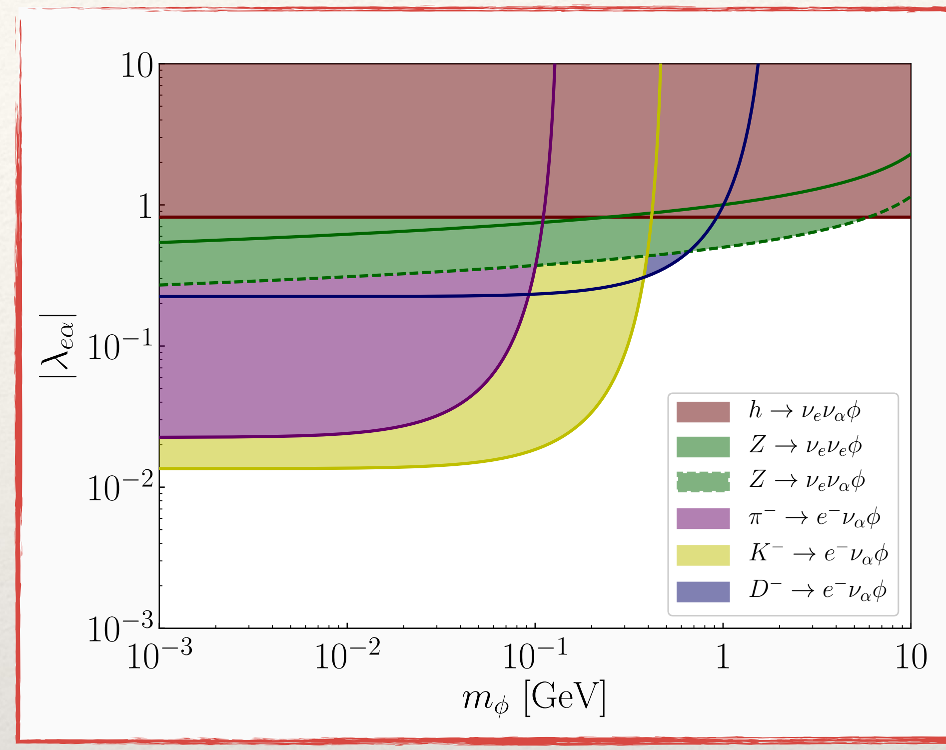


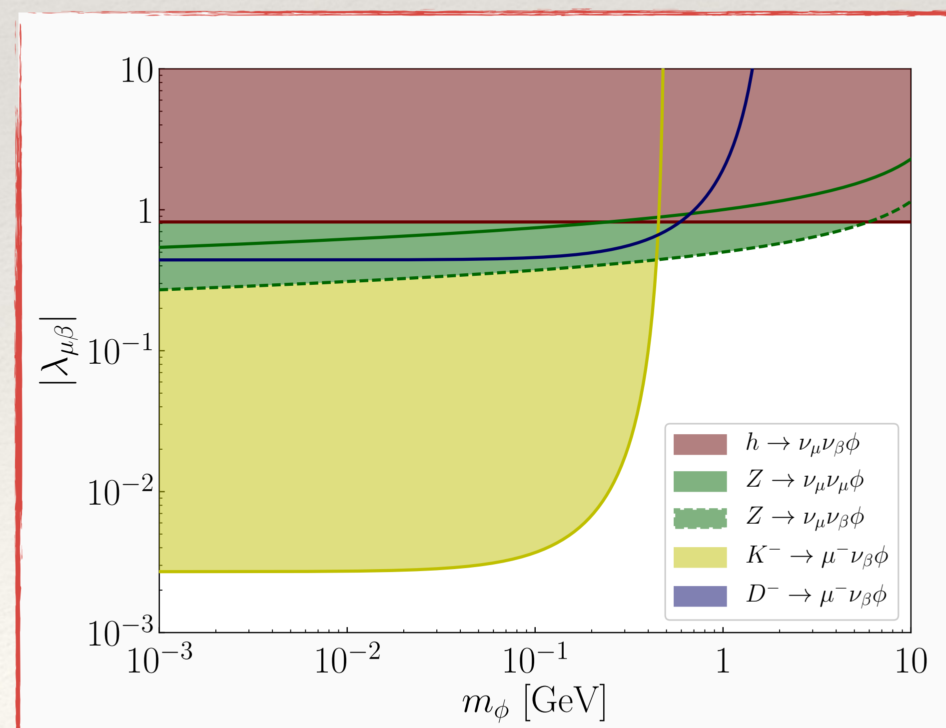
Bounds: Non-beam experiments

- Meson decays:



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





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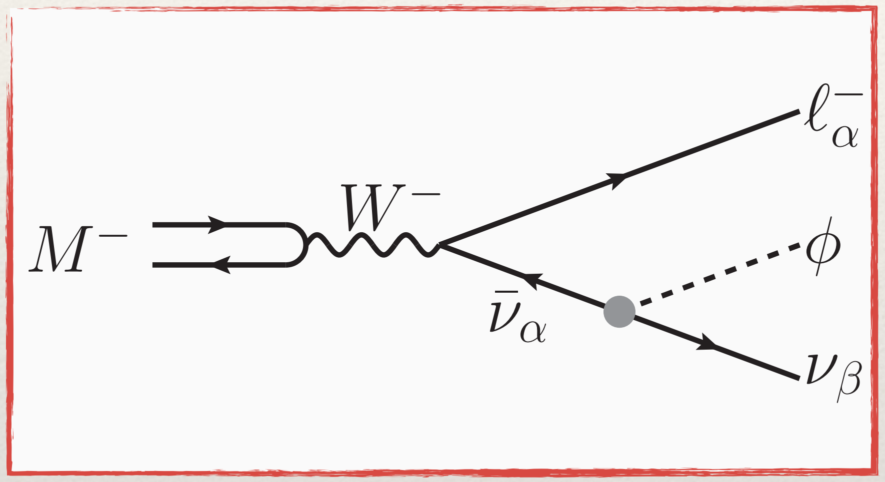
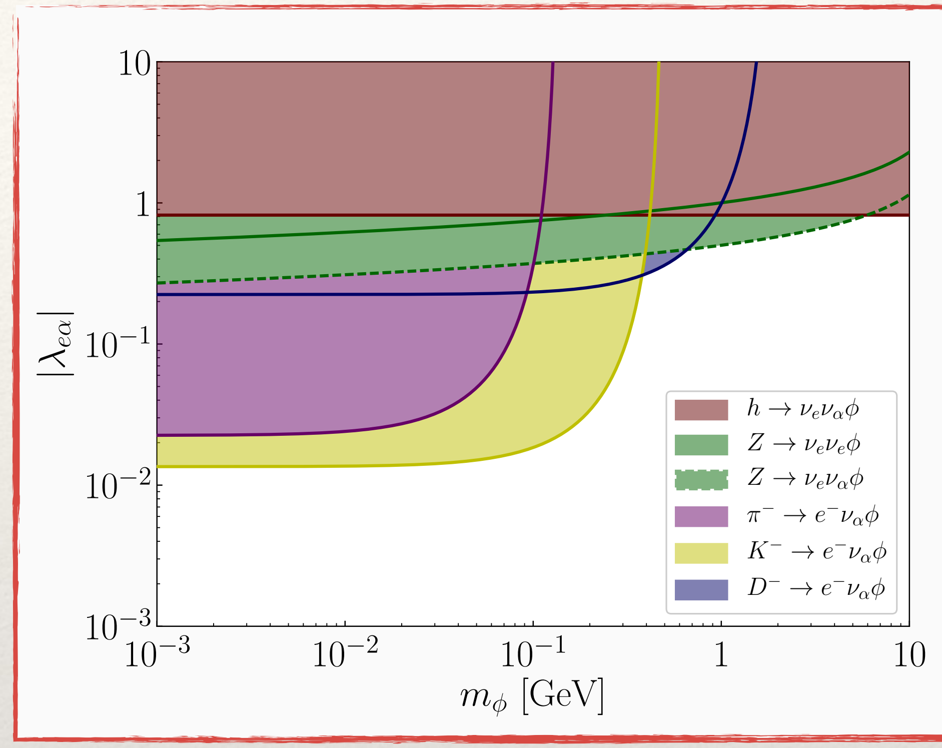
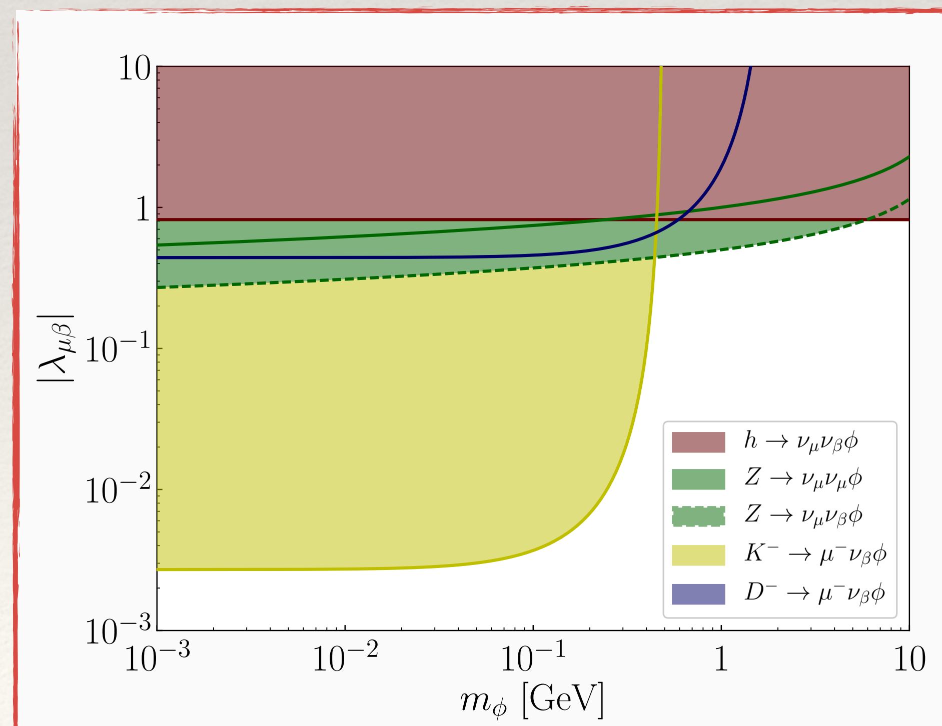


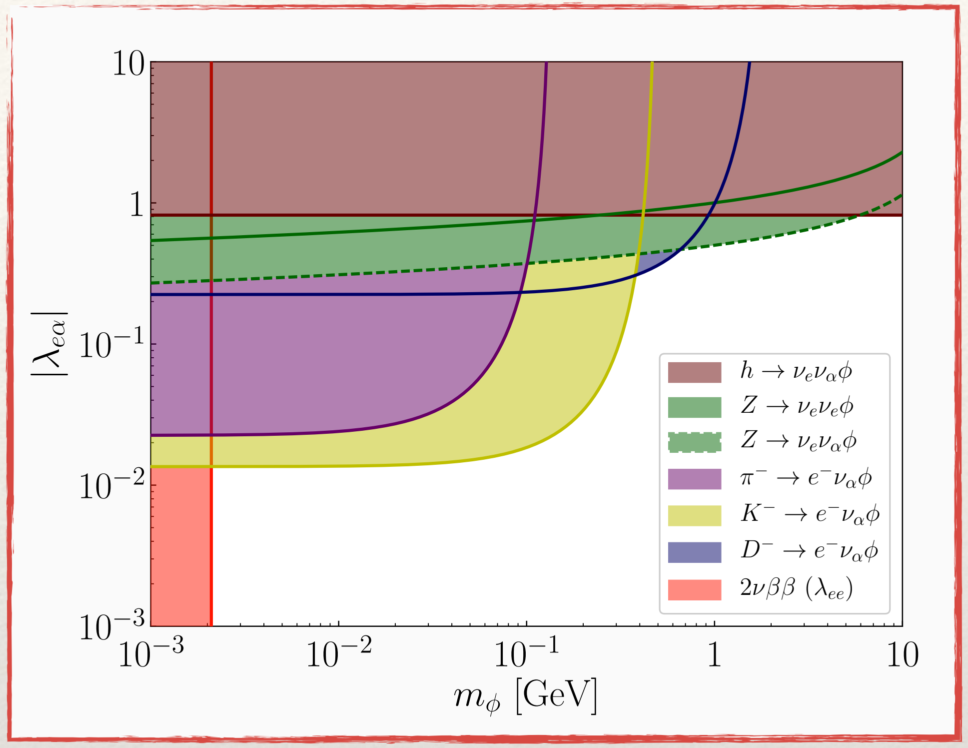
Decay channels from PDG	Decay channels in our model	Upper bound on Br
$\pi \to e\bar{\nu}_e\nu\bar{\nu}$	$\pi \to e\nu_\alpha\phi$	5×10^{-6}
$K \to e\bar{\nu}_e\nu\bar{\nu}$	$K \to e\nu_\alpha\phi$	6×10^{-5}
$K \to \mu\bar{\nu}_\mu\nu\bar{\nu}$	$K \to \mu\nu_\alpha\phi$	2.4×10^{-6}
$D \to e\bar{\nu}_e$	$D \to e\nu_\alpha\phi$	8.8×10^{-6}
$D \to \mu\bar{\nu}_\mu$	$D \to \mu\nu_\alpha\phi$	3.4×10^{-5}

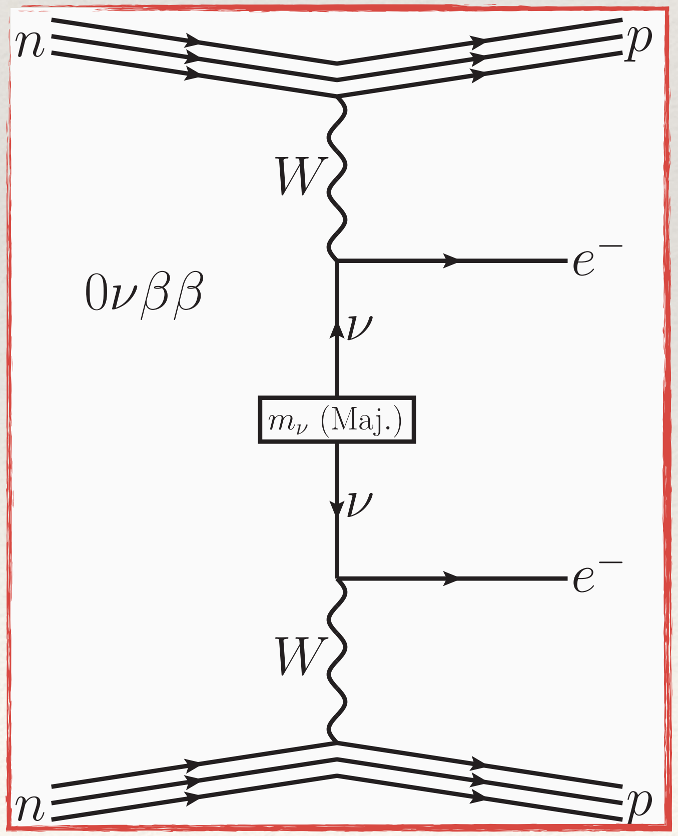


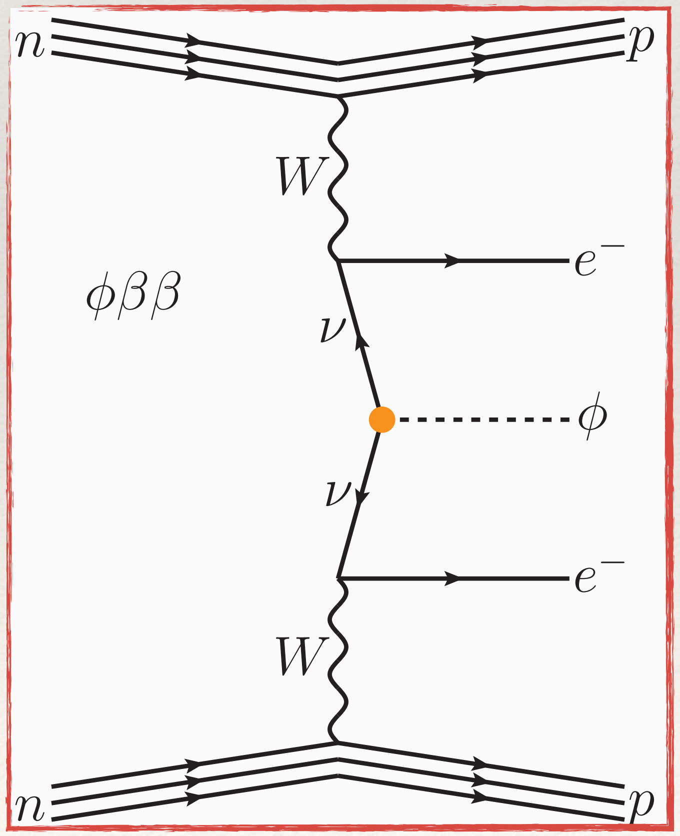


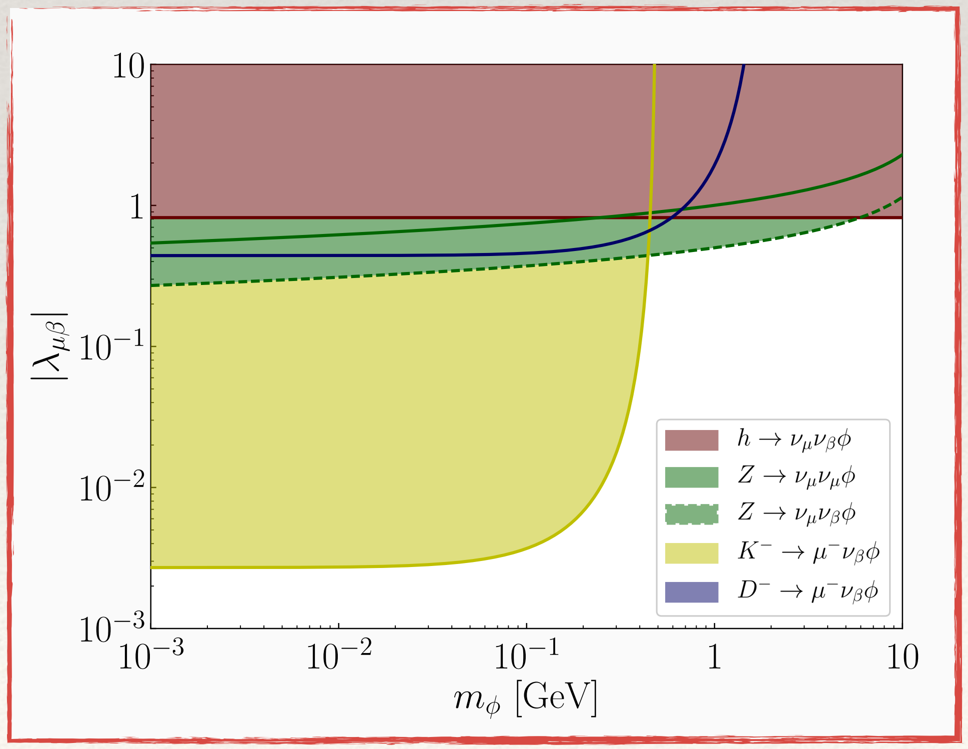
Bounds: Non-beam experiments

- Assorted Others:
  - Neutrinoless double beta decay: $|\lambda_{ee}| < 10^{-4}$, $m_\phi \lesssim Q$



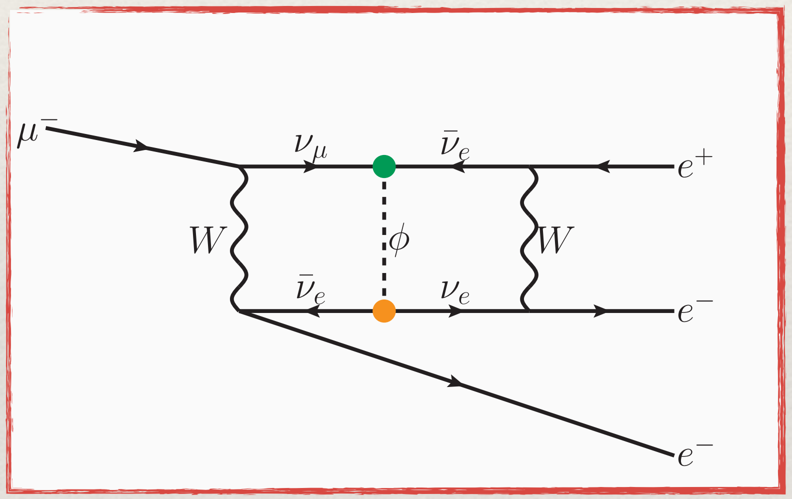




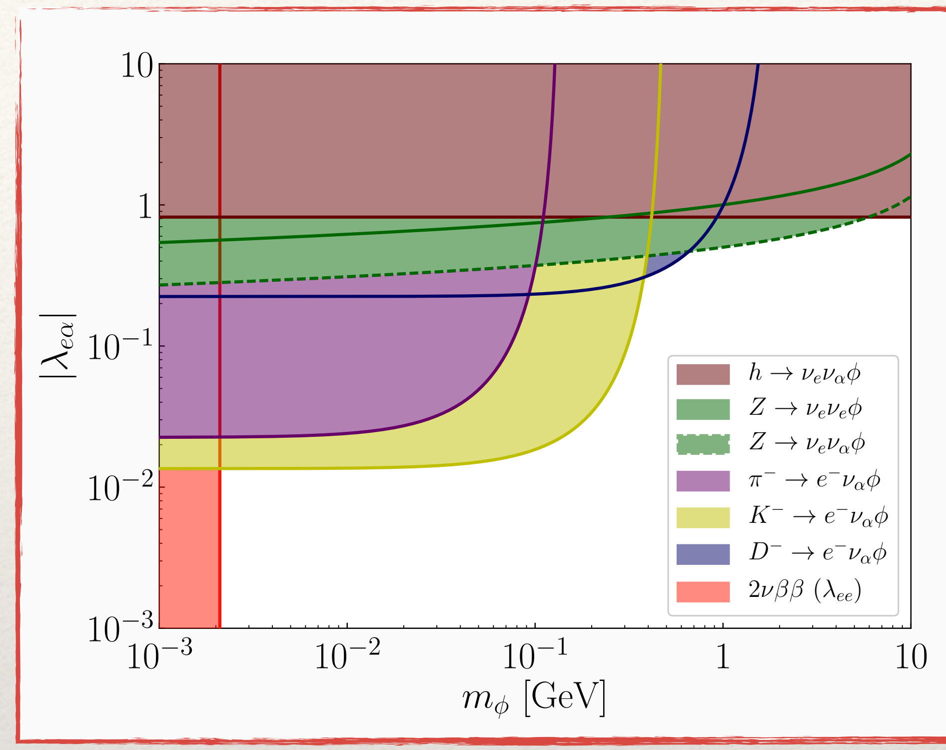


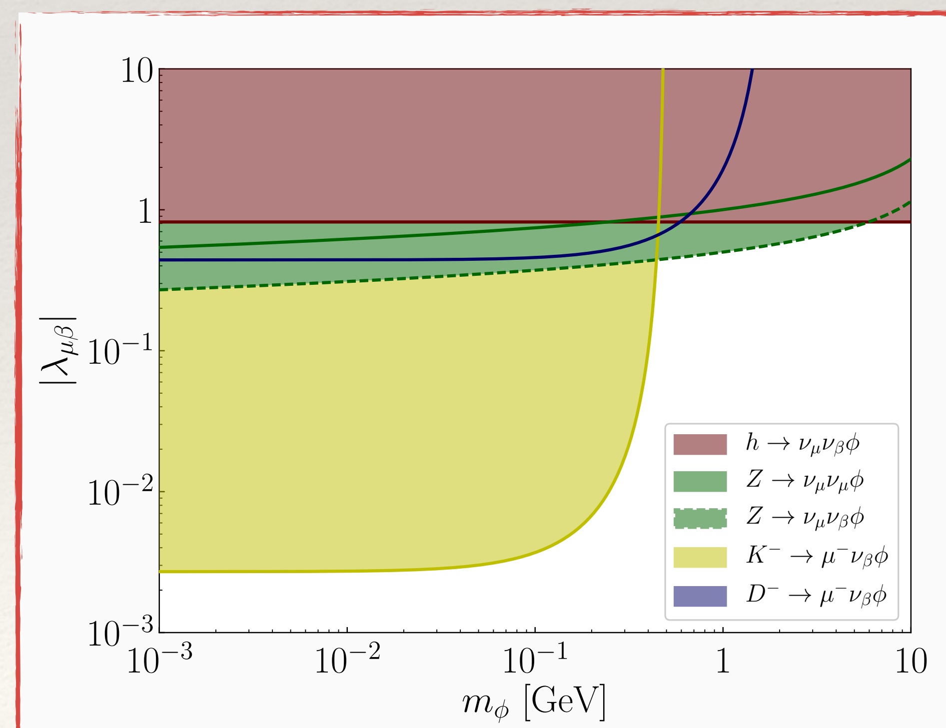
Bounds: Non-beam experiments

- Assorted Others:
  - $\mu \to 3e$: $|\lambda_{ee}\lambda_{e\mu}| \lesssim 10^{-2}$

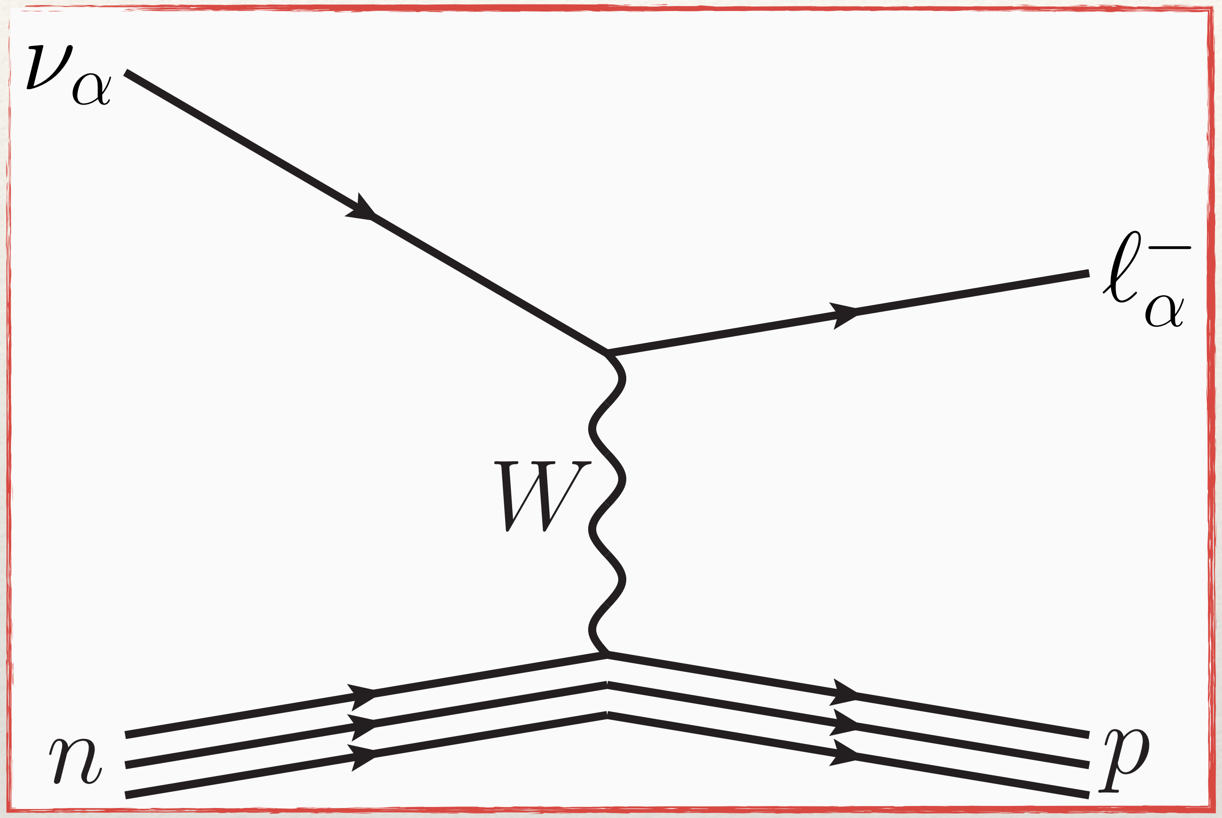


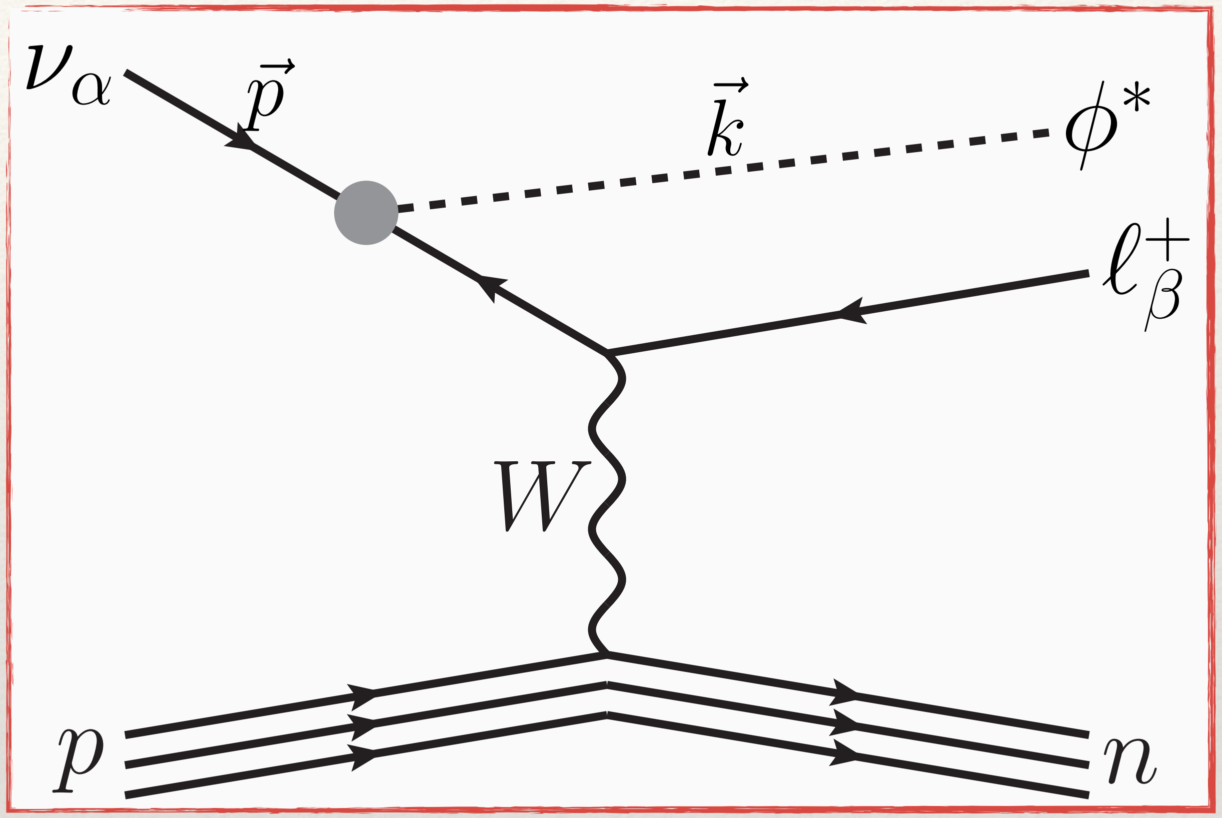
  - Cosmological constraints:
    - Free-streaming: $\lambda \lesssim \dfrac{m_\phi}{30\,\mathrm{MeV}}$
    - N_{eff}: $\lambda_c < 10^{-9}\left(\dfrac{1}{\lambda}\right)\left(\dfrac{m_\phi}{1\,\mathrm{GeV}}\right)^2$





Bounds: Beam Experiments





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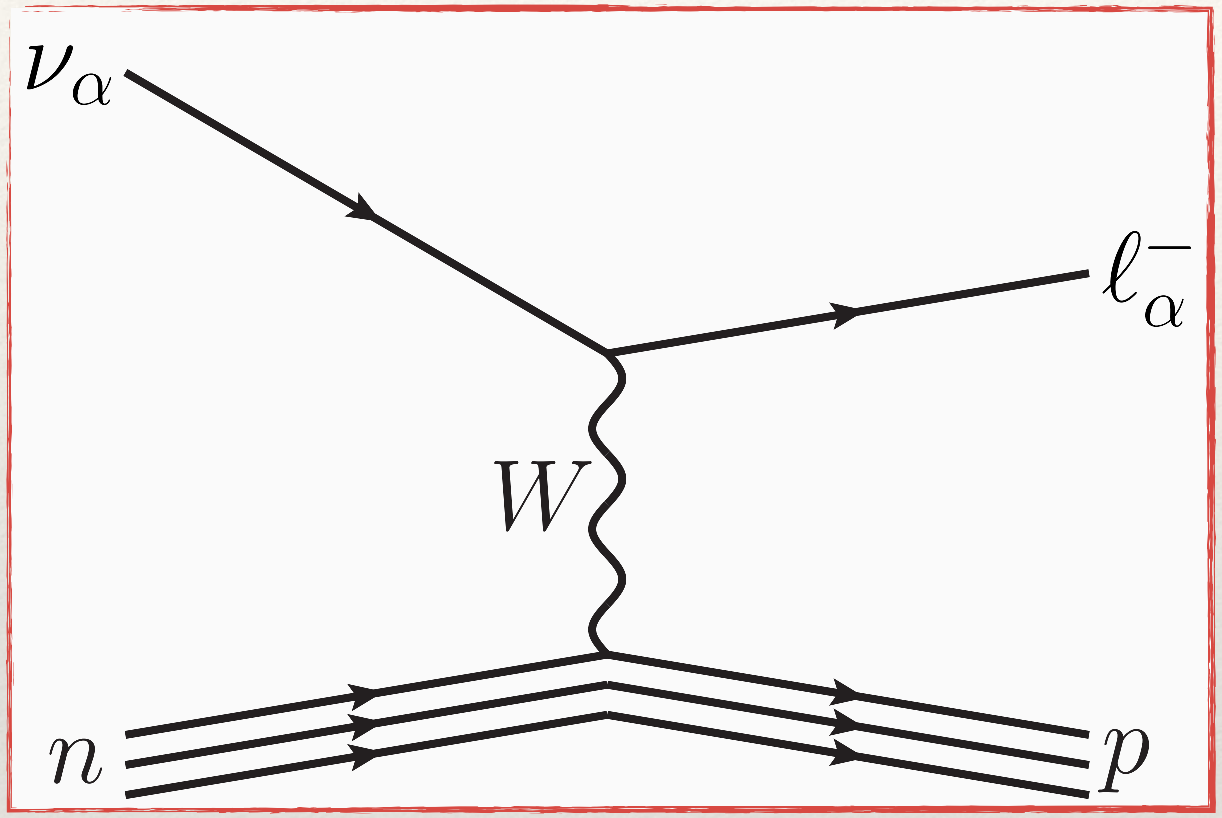
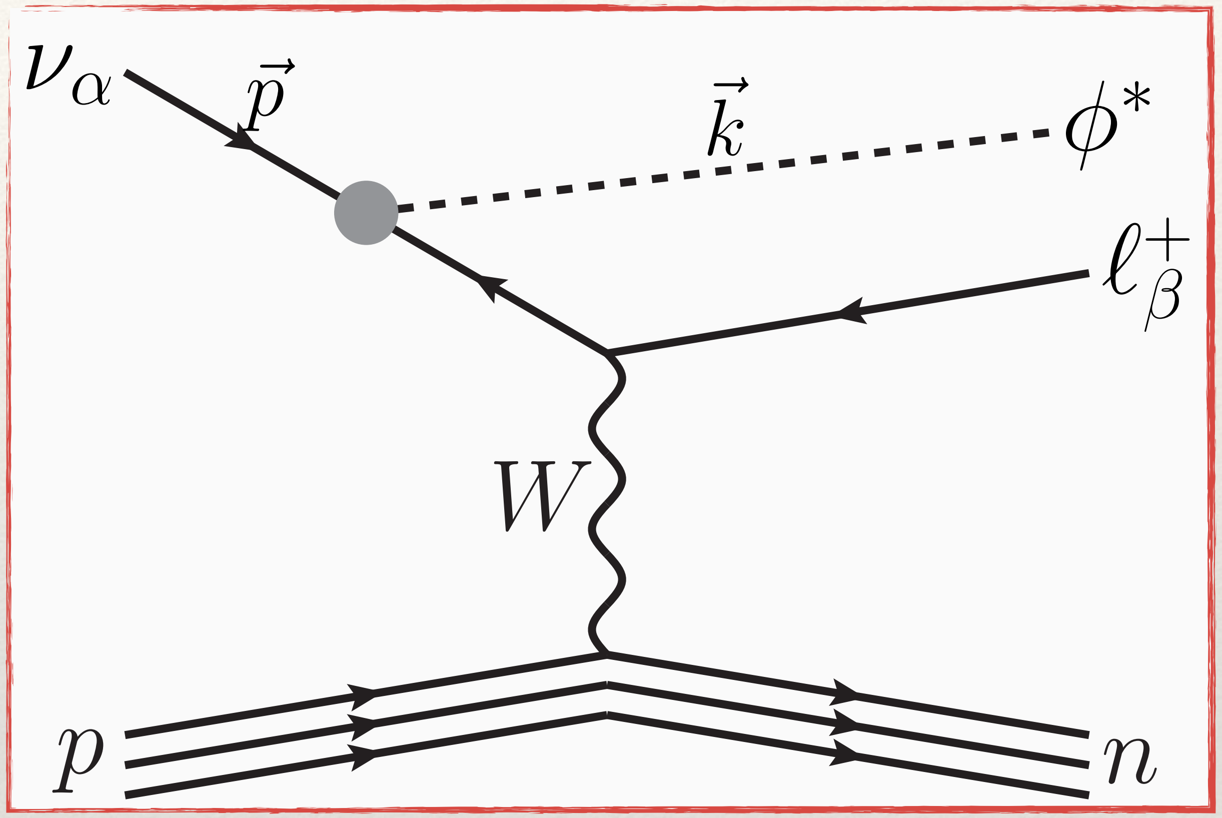




$$\mathcal{A}_{CC}$$

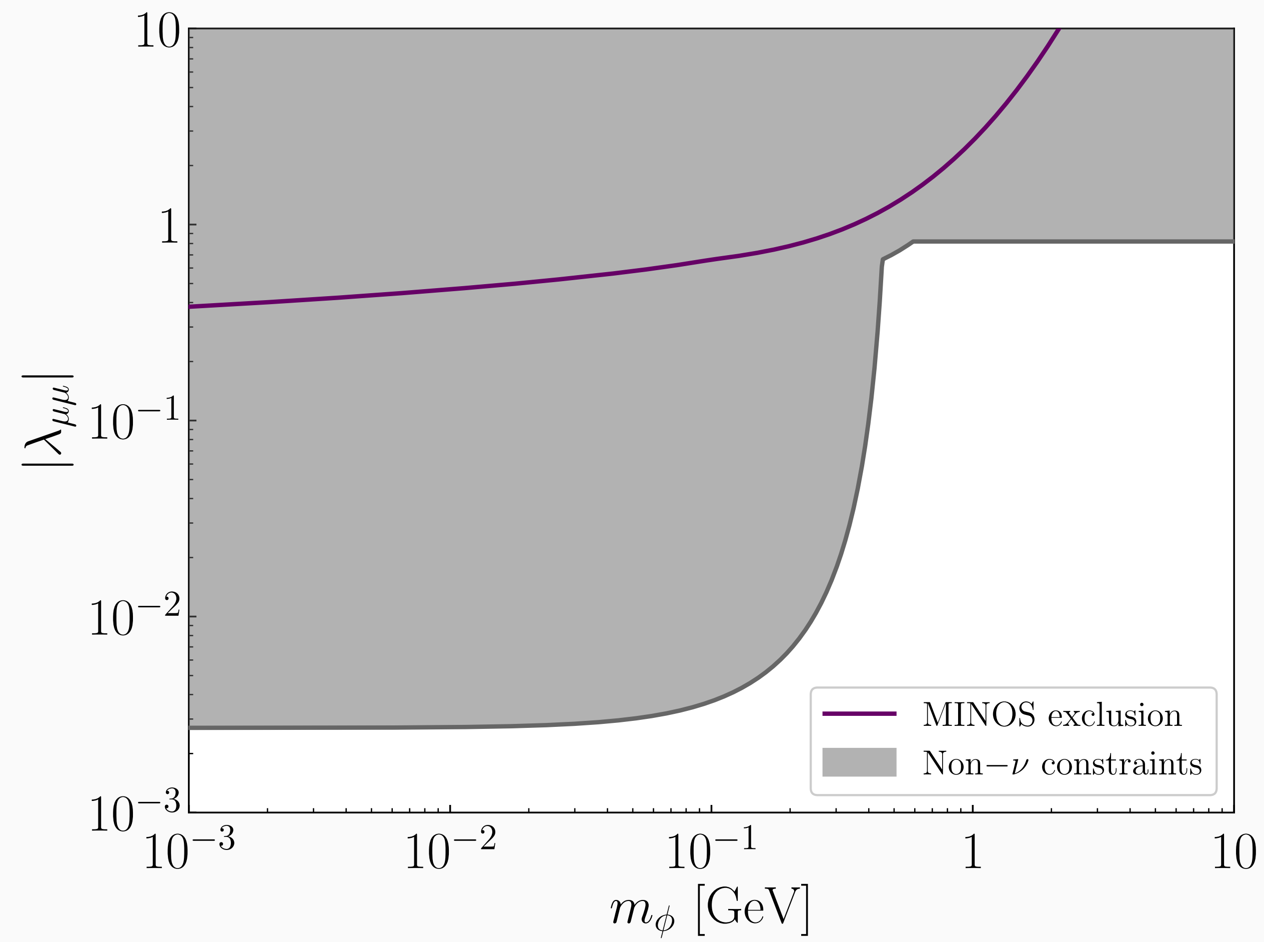
$$\begin{aligned} \mathcal{A} &= \widetilde{\mathcal{A}}_{CC} \frac{i}{\not{p} - \not{k} - m_\nu} (i\lambda_{\alpha\beta}) u_\nu(p) \\ &\simeq \lambda_{\alpha\beta} \mathcal{A}_{CC} \not{k} u_\nu(p) \frac{1}{2p \cdot k - m_\phi^2} \end{aligned}$$

Bounds: Beam Experiments

- MINOS:
  - Charge identification!
  - 91.7% ν_μ & 7% $\overline{\nu}_\mu$
  - Background:

$$\overline{\nu}_\mu + p \to \mu^+ + n$$

$$3.84 \pm 0.05 \,\text{events}/10^{15}\,\text{p.o.t.}$$



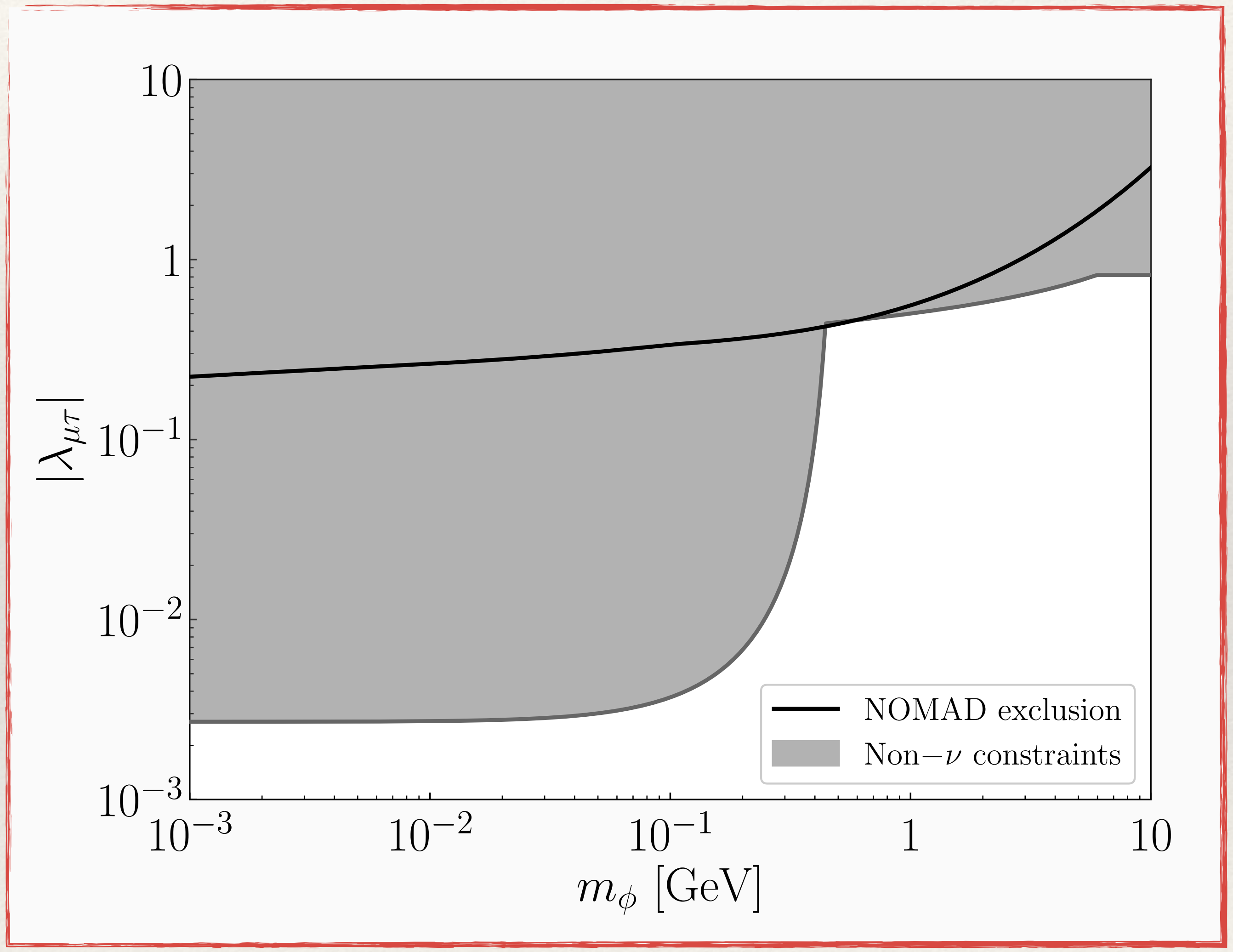
$$\mathcal{R} = \frac{\sigma(\nu_\mu + p \to \mu^+ + \phi + n)}{\sigma(\overline{\nu}_\mu + p \to \mu^+ + n)} \lesssim 0.002$$

Bounds: Beam Experiments

- NOMAD:
  - Search for $\nu_\mu \to \nu_\tau$ in the ~100 eV^2 region
  - Bound:

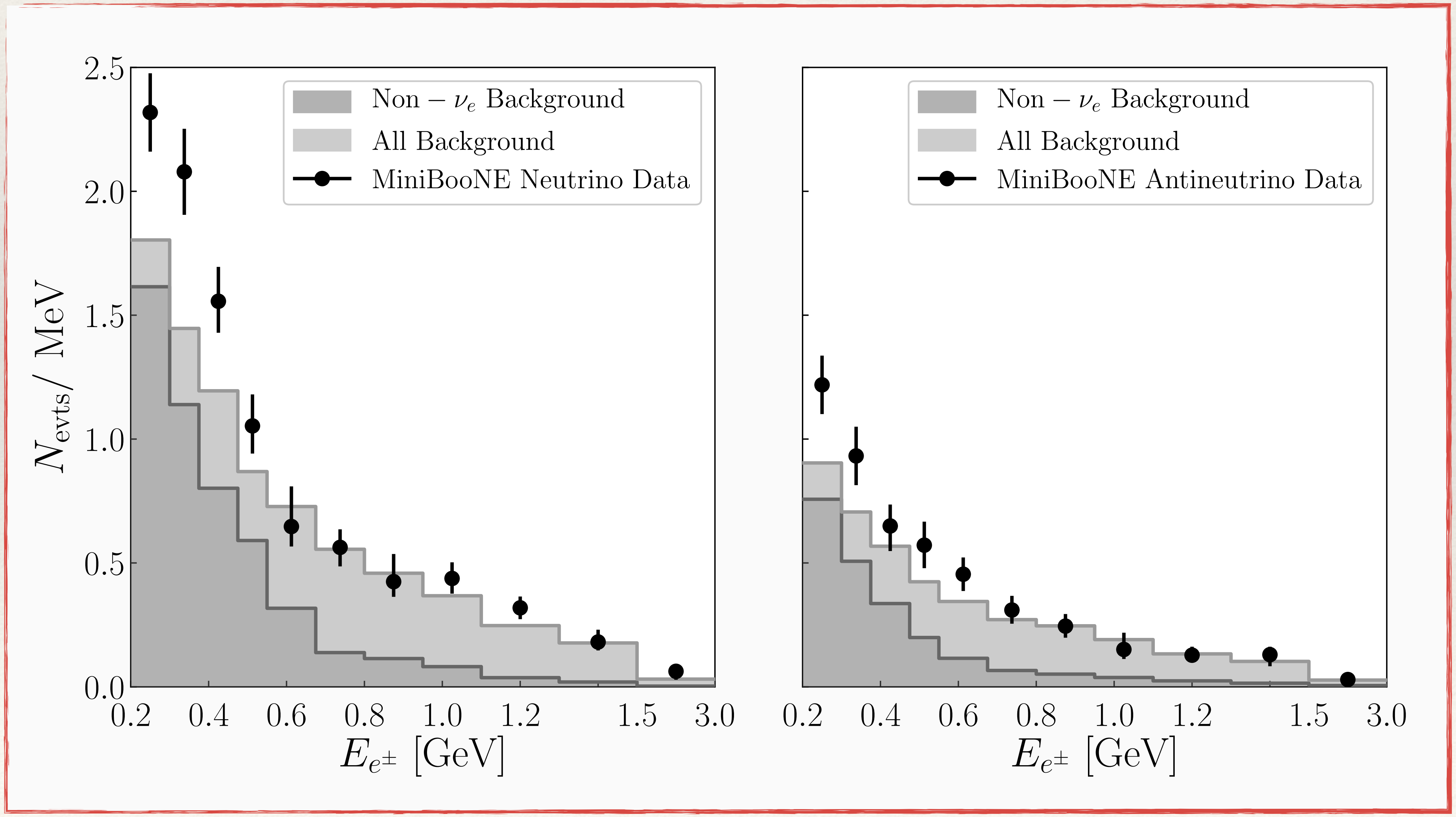
$$P\left(\nu_\mu \to \nu_\tau\right) < 2.2 \times 10^{-4}$$

  - Weaker constraint from CHORUS
  - Also weak constraint on $\lambda_{e\tau}$



Bounds: Beam Experiments

- MiniBooNE: Can this mechanism explain the (in)famous low-energy excess via $\nu_\mu + p \to e^+ + \phi^* + n$?



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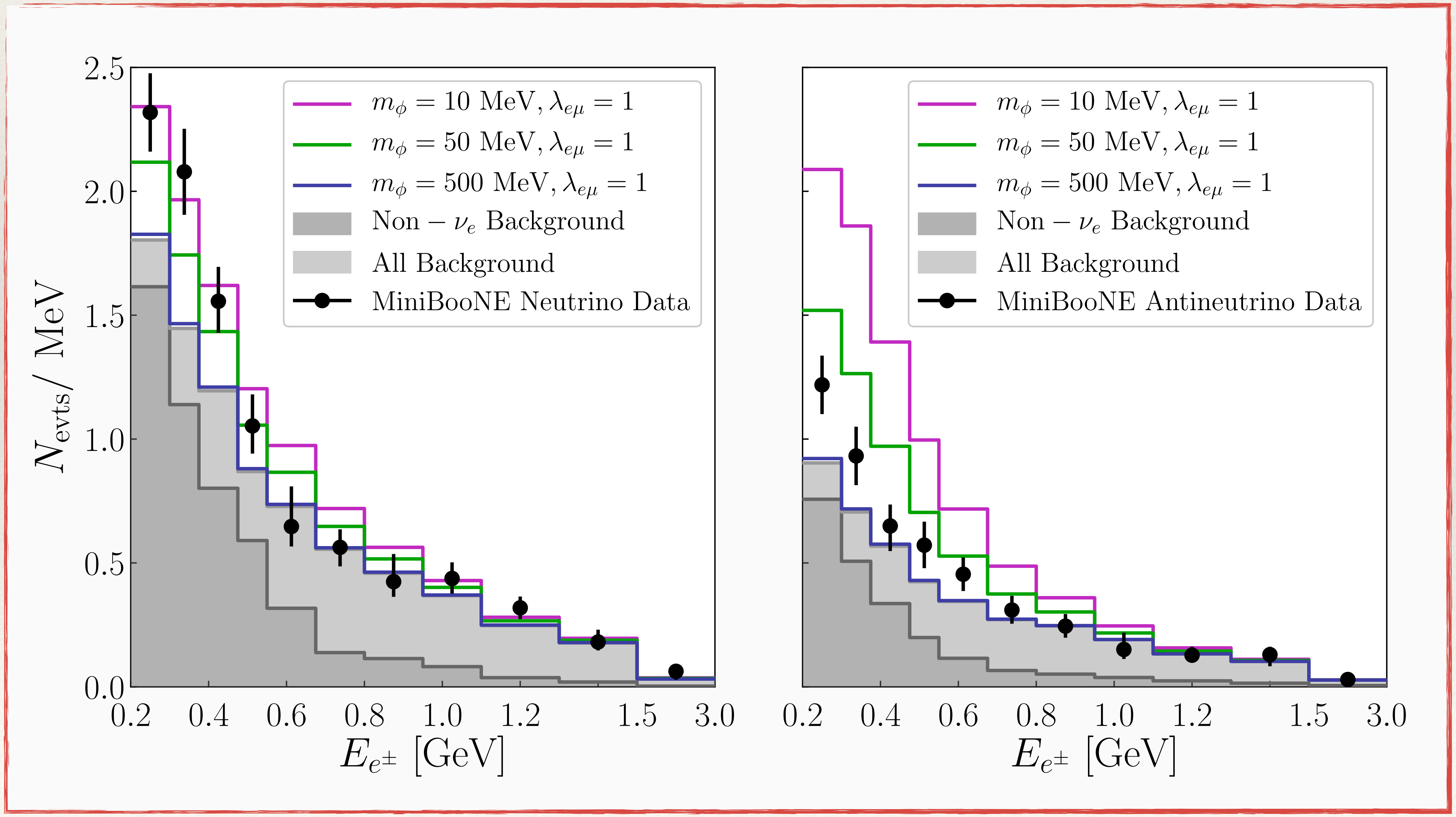

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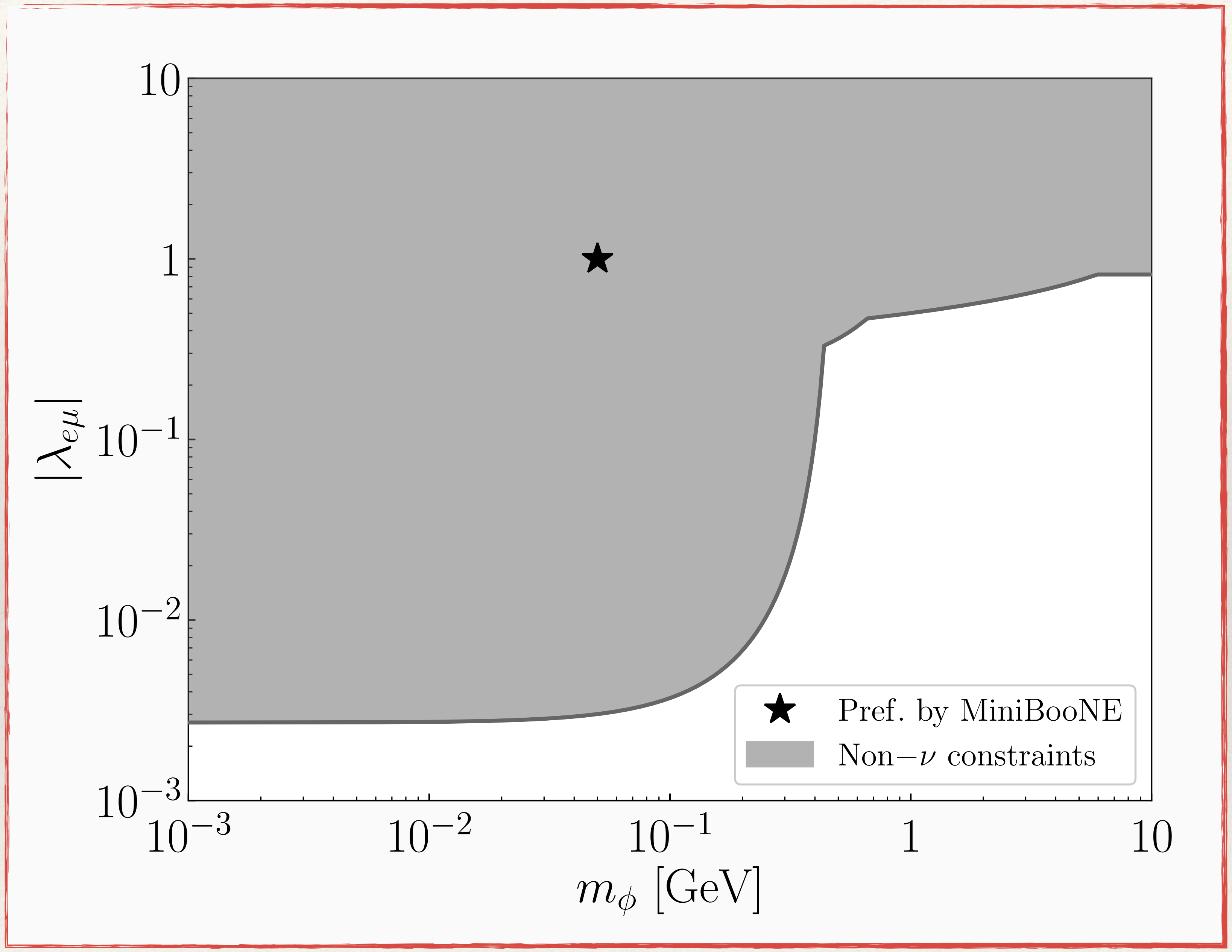

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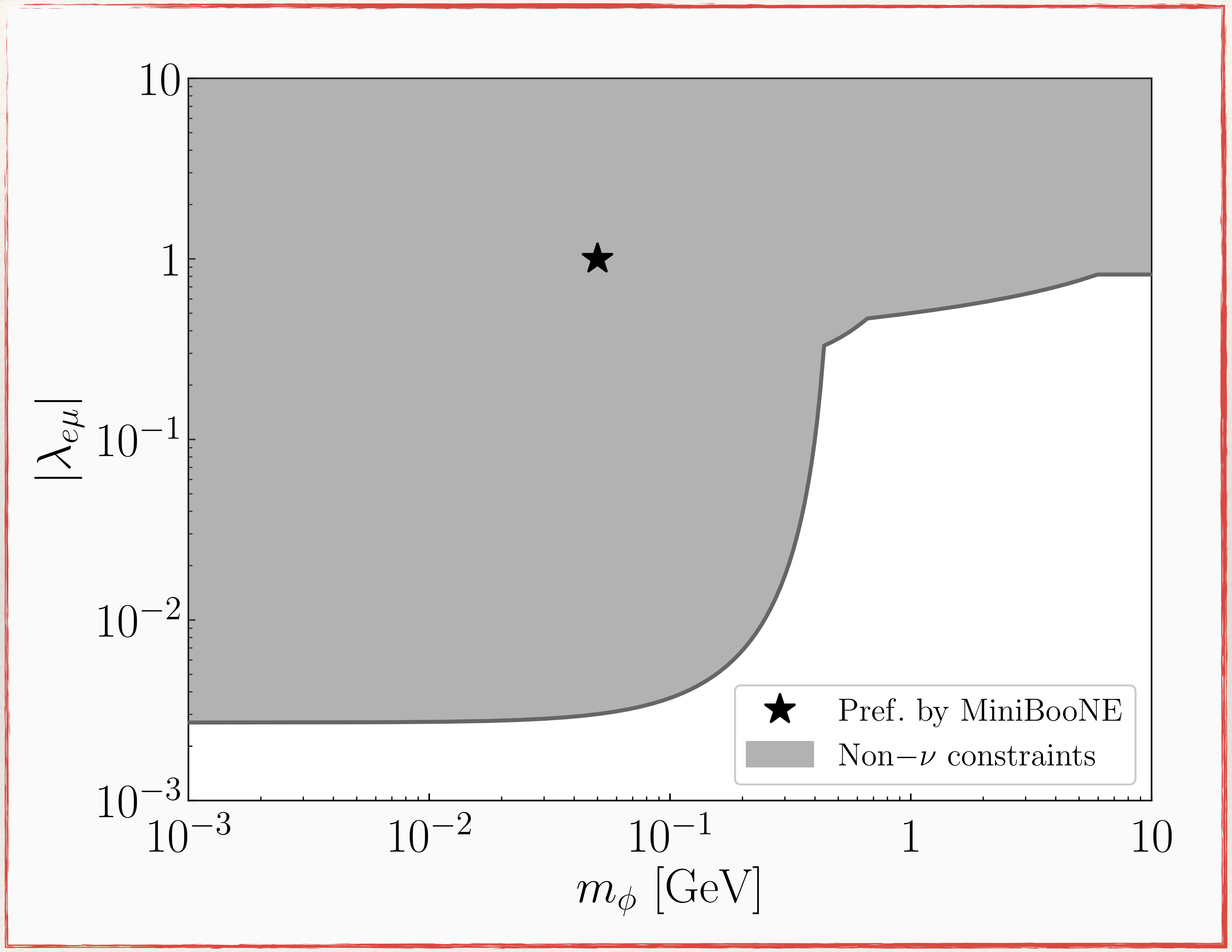
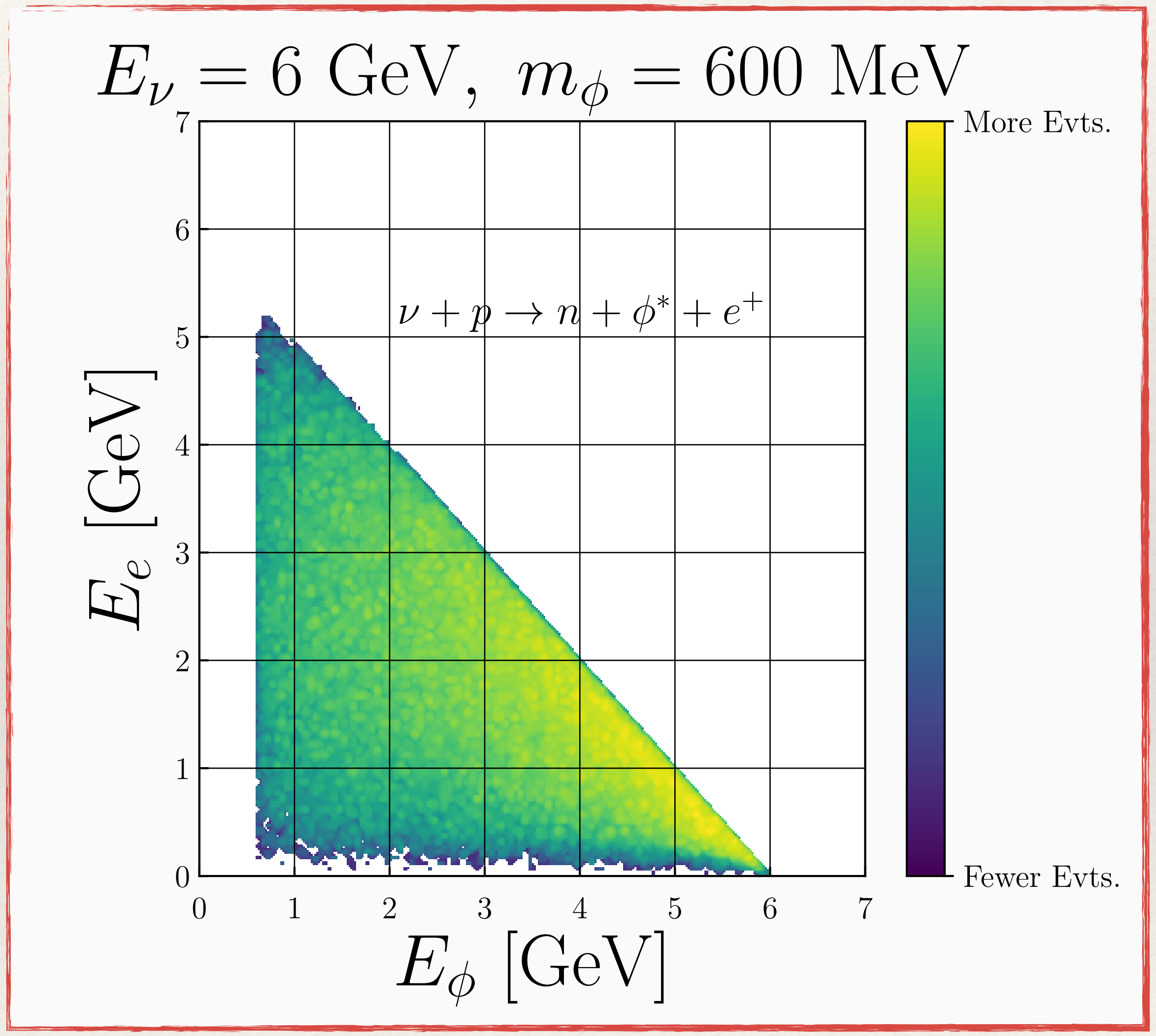


NB: Things are even hairier at LSND!

Prospects at DUNE

- *Near detector* will see ~10^5 CC events per year
  - No charge identification; account for wrong-sign backgrounds
  - Exploit kinematics of (thee-body) final state to separate!



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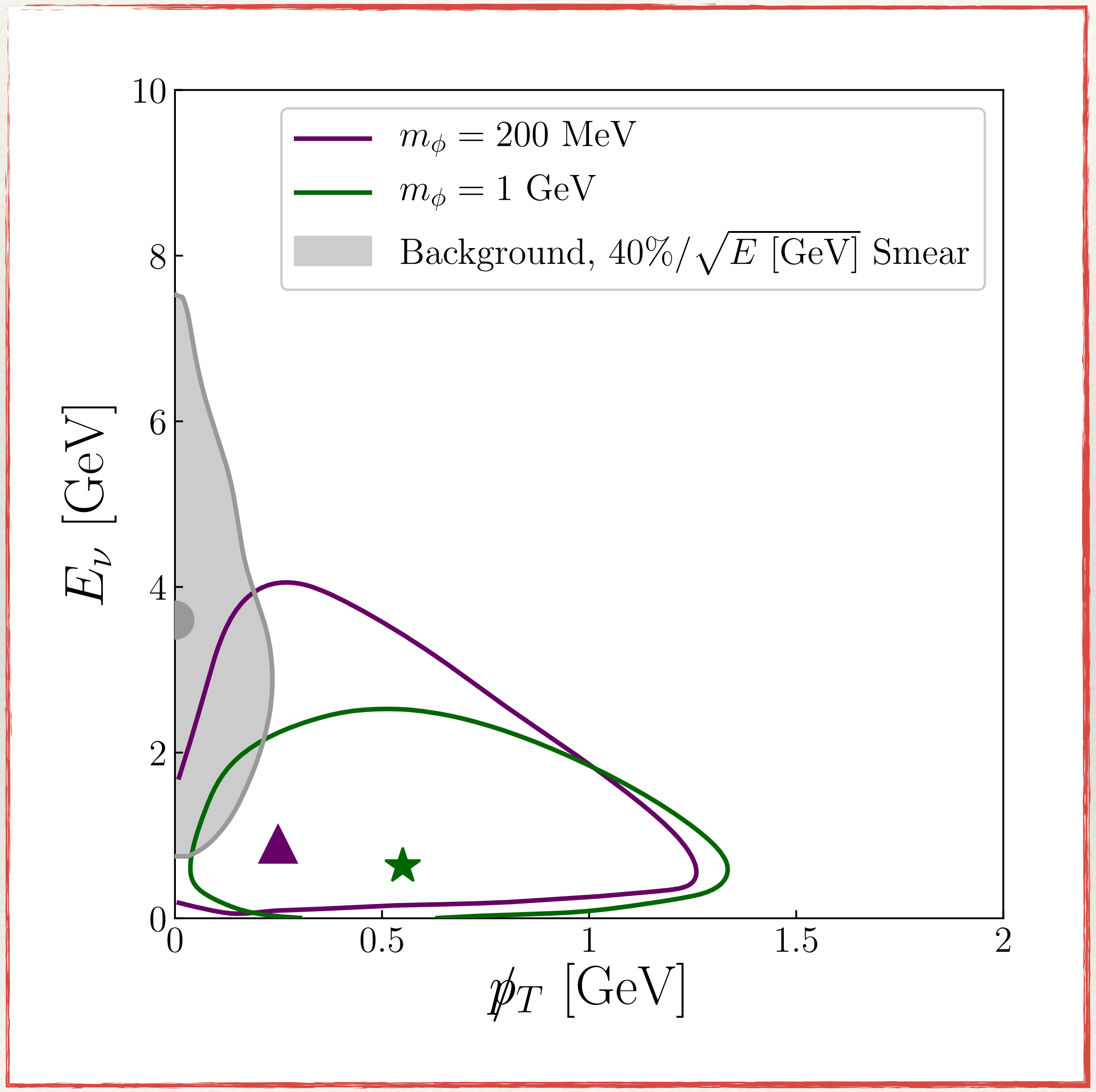

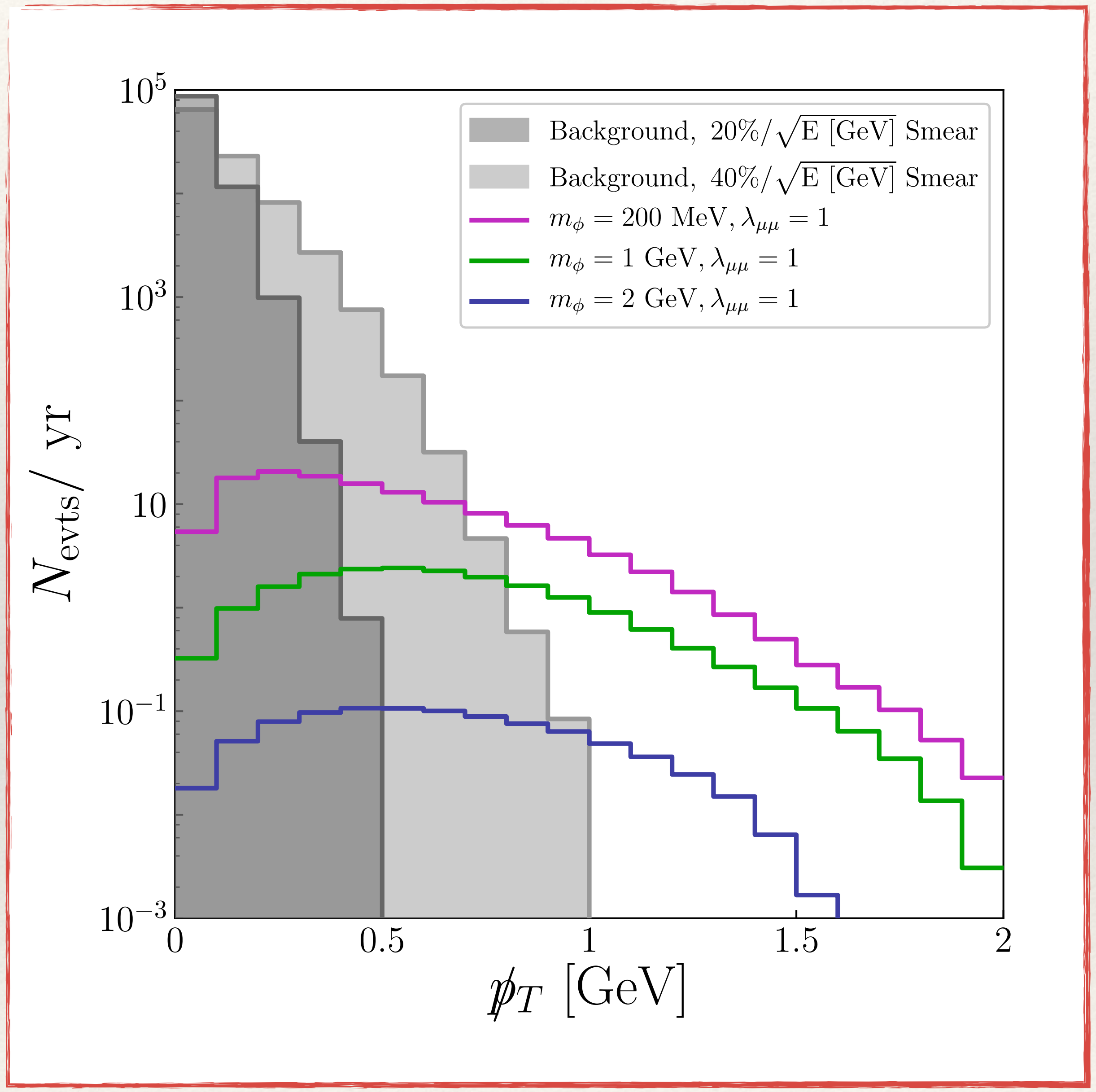

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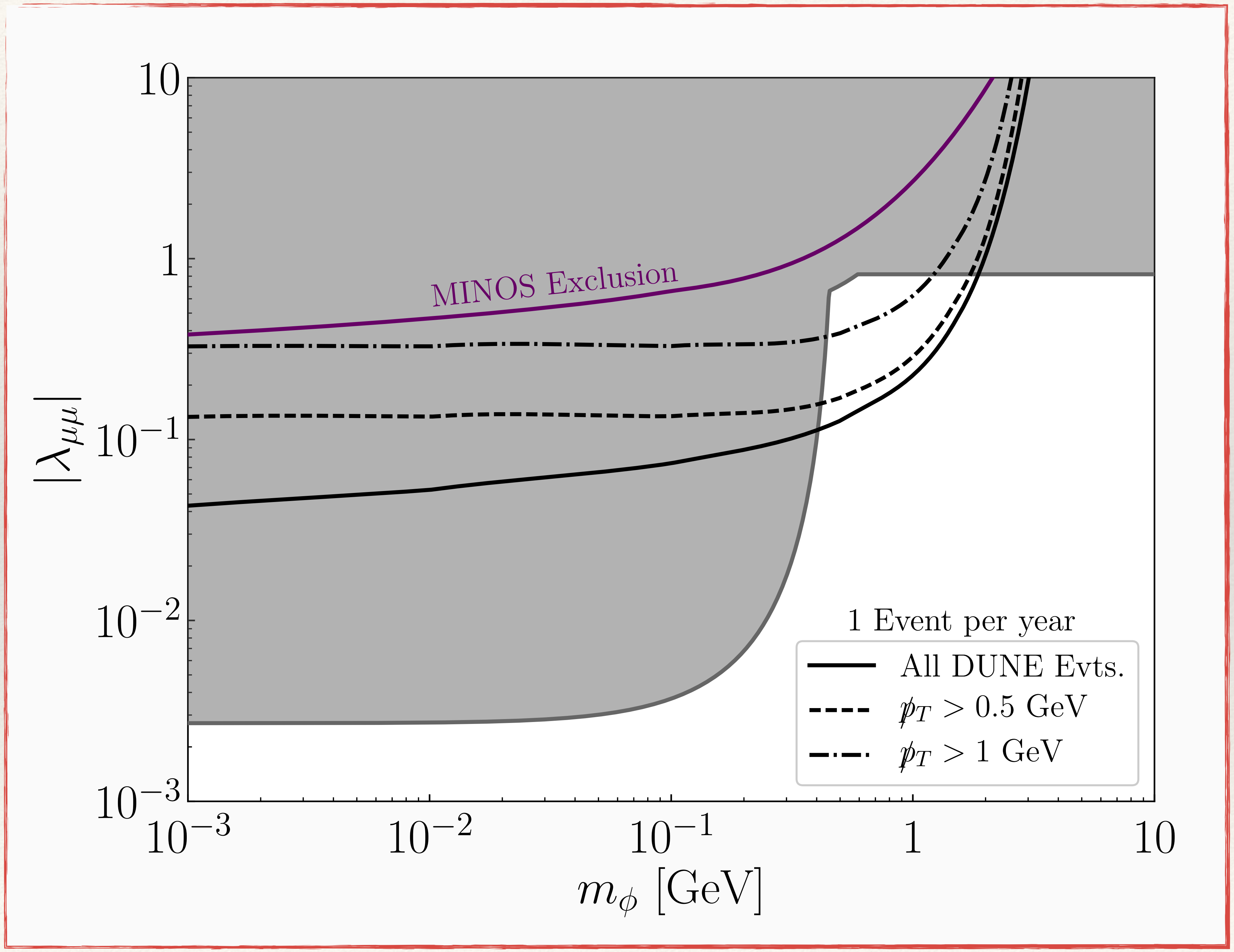
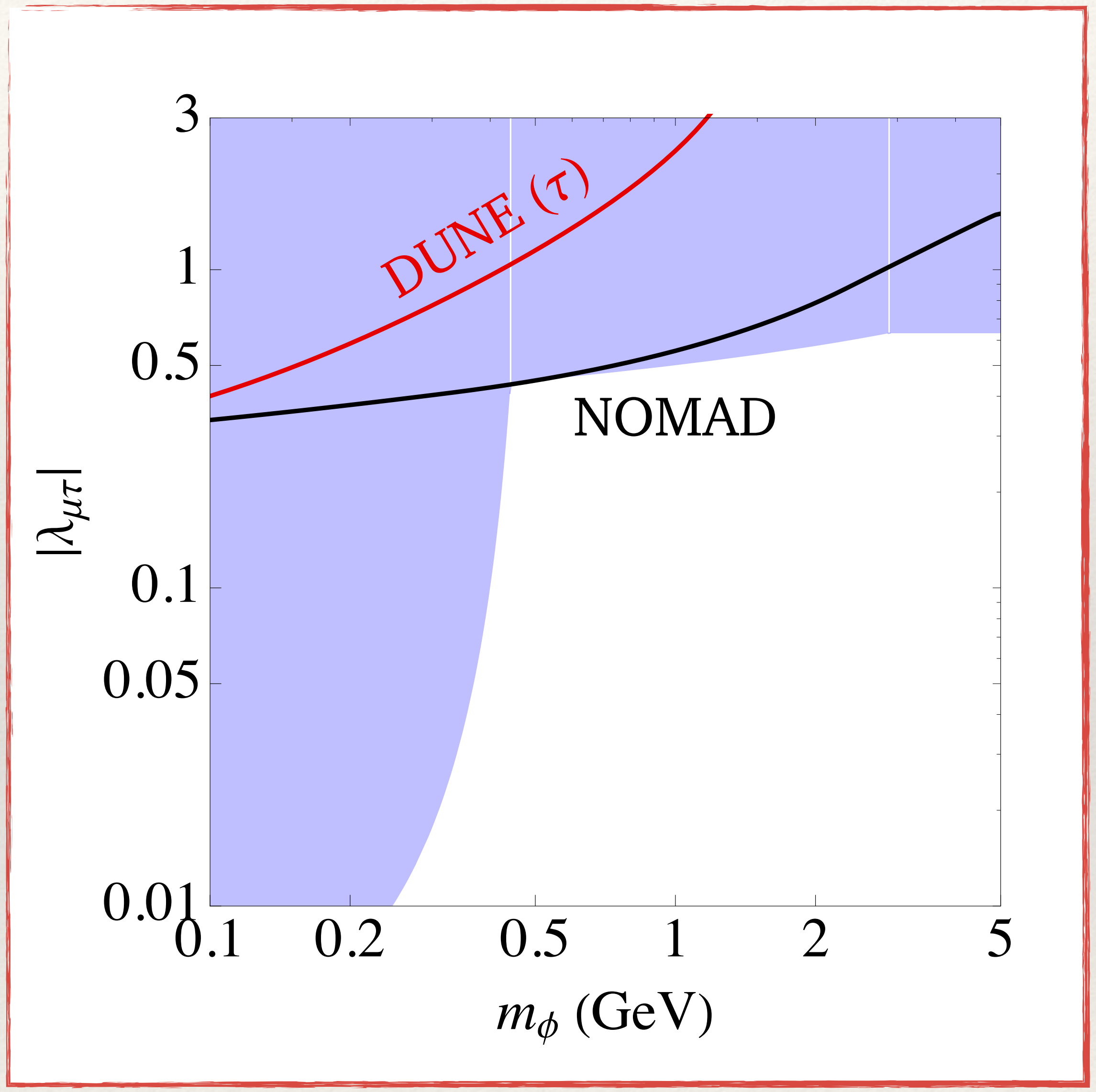


Prospects at DUNE

- Harder time with taus:
  - Need higher energy neutrinos, and more difficult to reconstruct.
- In *far detector*, oscillated neutrinos are major background – completely dominate potential signal



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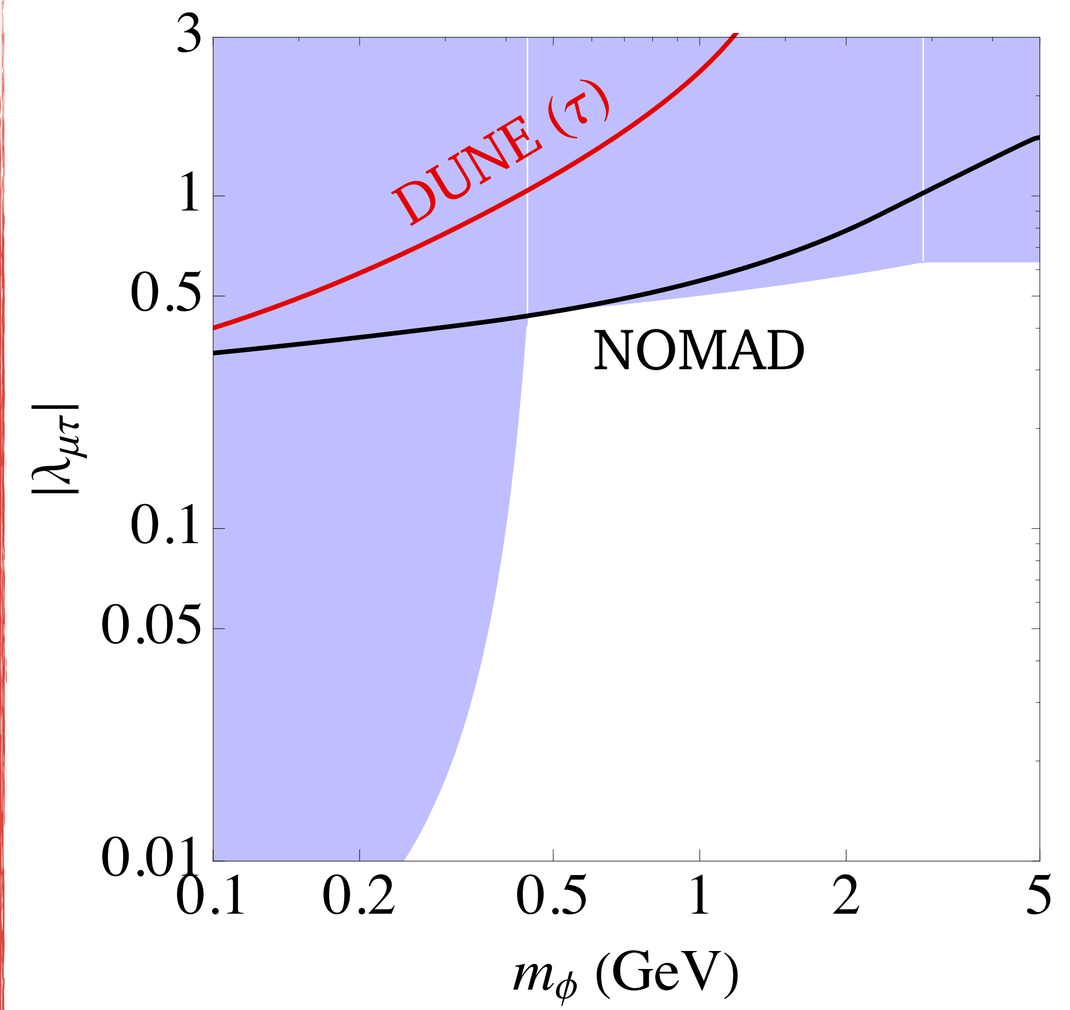


The near detector is the best tool DUNE has to search for this kind of new physics!

LeNCS as Dark Matter

- Introduce a new *LeNCS* field χ with B-L = –1

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

- Neutrinophilic: ϕ mediates interactions between ν and χ
- Higgs Portal: indistinguishable from standard Higgs portal
- Nucleon Portal: dark matter may induce nuclear decays:

$$\chi + (Z, A) \to \chi^* + (Z, A-1) + \nu$$

Sneak Preview – Mono-neutrinos

- Focus on neutrinophilic χ:

$$\mathcal{L} \supset \left(\mu_{\phi\chi}\phi\chi^2 + \text{h.c.}\right)$$

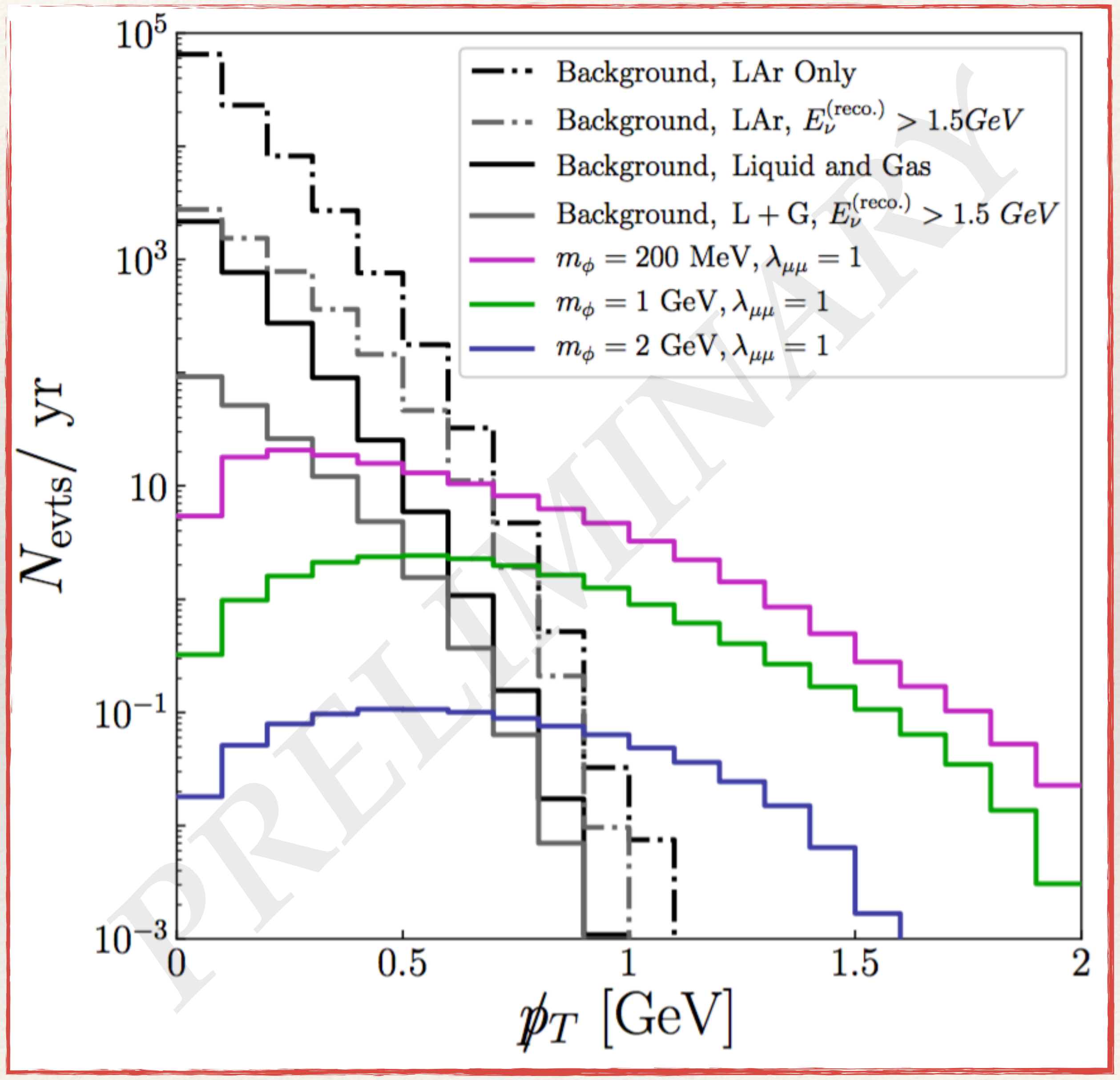
- Consider near detector with *charge identification*

- Relic density constraint:

$$\langle \sigma v_{\rm rel} \rangle_{\chi\chi\to\nu_\alpha\nu_\beta} \approx \frac{|\lambda_{\alpha\beta}\mu_{\phi\chi}|^2}{8\pi(4m_\chi^2 - m_\phi^2)^2(1+\delta_{\alpha\beta})}$$

- Self-interaction constraint:

$$\sigma_{\chi\chi\to\chi\chi} = \frac{1}{2}\sigma_{\chi\overline{\chi}\to\chi\overline{\chi}} = \frac{\mu_{\phi\chi}^4}{128\pi m_\chi^2 m_\phi^4}$$



K.J. Kelly & Y. Zhang, *in preparation*

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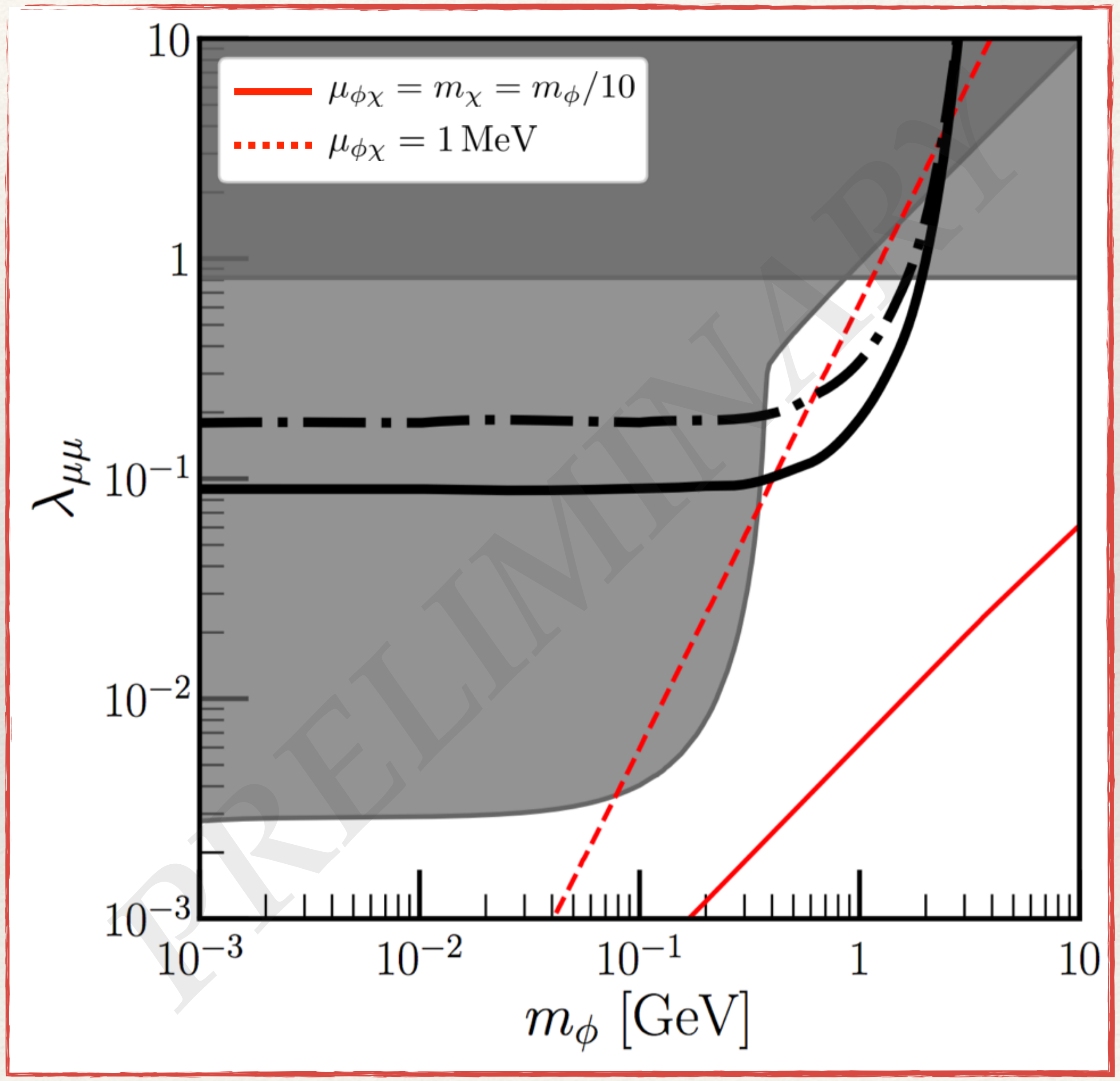

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Conclusions

- *B-L* is an attractive candidate for a fundamental symmetry of Nature – but it means neutrinos must be *Dirac fermions*!
- New scalars with *B-L* charge – *LeNCS* – can lead to varied interesting phenomena: new decays, beamstrahlung, dark matter, etc.
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Thank you!

Back-Up Slides

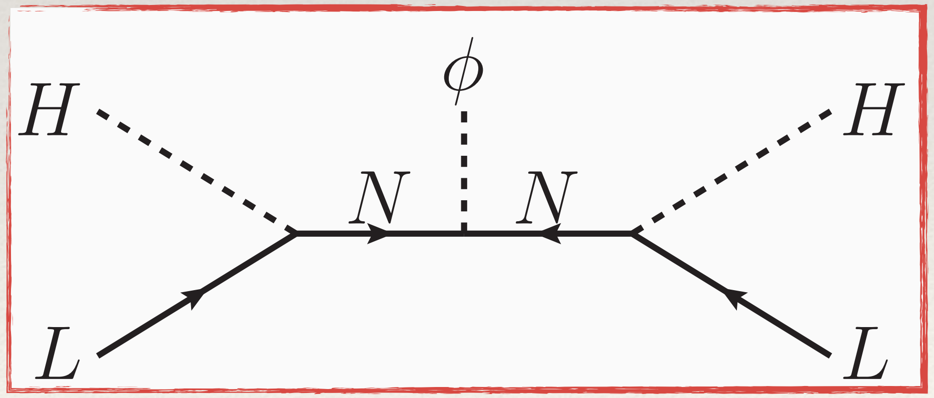
Possible UV Completions

- Type I Seesaw: $N \sim (\mathbf{1}, \mathbf{1}, 0, -1) \quad N^c \sim (\mathbf{1}, \mathbf{1}, 0, +1)$

$$\mathcal{L}_{\rm UV} \supset \tilde{y}_{\alpha i} L_{\alpha i} H N_i^c + M_{N,i} N_i N_i^c + \lambda_{N,ij} \phi N_i N_j$$
$$+\lambda^c_{N,ij} \phi^* N_i^c N_j^c + \tilde{\lambda}^c_{N\nu,ij} \phi^* N_i^c \nu_j^c + \text{h.c.}$$

$$\lambda_{\alpha\beta} = \sum_{i,j} \tilde{y}_{\alpha i} \frac{v}{M_{N_i}} \lambda_{N,ij} \frac{v}{M_{N_j}} \tilde{y}_{\beta j}$$

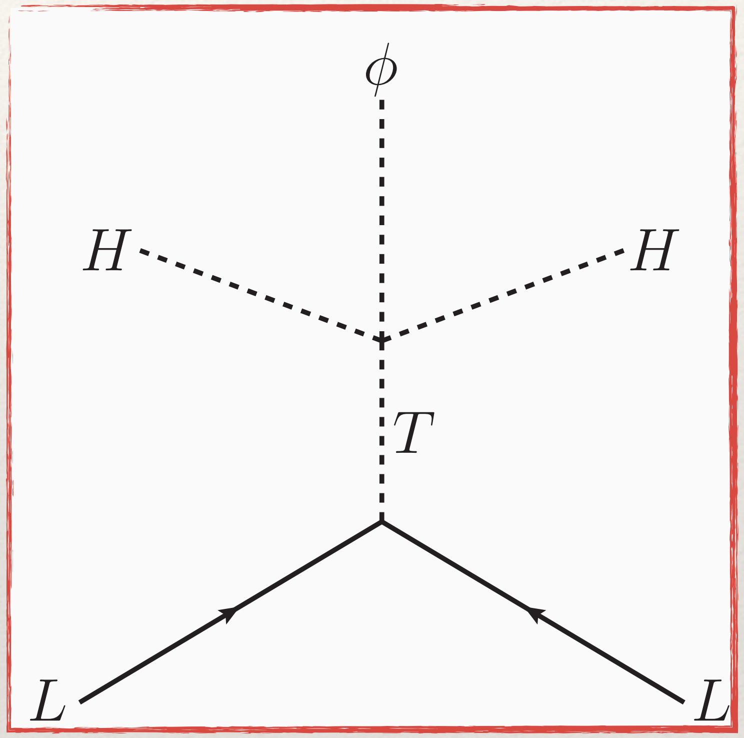
$$\theta_{as} \sim \tilde{y} v / M_N$$



Possible UV Completions

- Type II Seesaw: $T \sim (\mathbf{1}, \mathbf{3}, +1, +2)$

$$\mathcal{L}_{\rm UV} \supset \tilde{y}_{\alpha\beta} L_\alpha T L_\beta + \lambda_T H T^\dagger H \phi$$
$$-M_T^2 {\rm Tr}(T^\dagger T) + {\rm h.c.}$$



$$\lambda_{\alpha\beta} \approx \tilde{y}_{\alpha\beta} \lambda_T \frac{v^2}{M_T^2} \qquad \theta_{\phi T^0} \simeq \lambda_T v^2/(2M_T^2)$$
$$\lambda_c^{ij} \approx 0$$

Z width: $\Gamma_{Z\to 2\phi} = e^2 \theta^4_{\phi T^0} M_Z/(24\pi \sin^2 2\theta_W) \implies M_T > (350\,{\rm GeV}) \times \sqrt{|\lambda_T|}$

Muon g-2: $M_T \gtrsim (500 \text{ GeV}) \times |\tilde{y}_{\mu\mu}|$

$\mu \to 3e$: ${\rm Br}(\mu \to 3e) \leq 10^{-12} \implies M_T \gtrsim (150 \text{ TeV}) \times \sqrt{\tilde{y}_{\mu e} \tilde{y}_{ee}}$

SM+*LeNCS* Effective Field Theory

Number	Operator	Associated Phenomena
1*	$e^c(LL)(LH)\phi$	$\overline{\nu}e^\pm \to \nu e^\pm\phi$; $\ell \to \ell'\nu\nu\phi$
2*	$d^c(QL)(LH)\phi$	$\nu p \to \ell^+ n\phi^*$; quark/meson decays
3	$\overline{u}^c(L\overline{Q})(LH)\phi$	$\nu p \to \ell^+ n\phi^*$, quark/meson decays
4	$\overline{\nu}^c(L\overline{L})(LH)\phi$	$\ell \to \ell'\nu\nu\phi$; $\nu\nu \to \nu\overline{\nu}\phi^*$; C$\nu$B
5a	$\overline{\nu}^c(Q\overline{Q})(LH)\phi$	$\overline{\nu}N \to \nu N^{(\prime)}\phi$; quark/meson decays
5b	$\overline{\nu}^c(L\overline{Q})(QH)\phi$	$\overline{\nu}N \to \nu N^{(\prime)}\phi$; $\ell \to M\nu\nu\phi$; quark/meson decays
6	$d^c(L\overline{Q})(\overline{Q}H)\phi$	$n \to \nu\phi$; $p \to \nu\pi^+\phi$; $\tau^- \to n\pi^-\phi^*$
7	$\overline{\nu}^c(\overline{QQ})(\overline{Q}H)\phi$	$n \to \nu\phi$; $p \to \nu\pi^+\phi$
8	$\overline{\nu}^c(\overline{QQ})(\overline{Q}H)\phi$	$n \to \nu\phi$; $p \to \nu\pi^+\phi$
9*	$\overline{u}^c\overline{e}^c\overline{\nu}^c(\overline{Q}H)\phi$	$\nu p \to \ell^+ n\phi^*$; $\ell \to M\nu\nu\phi$; quark/meson decays
10	$u^c d^c d^c(LH)\phi$	$n \to \nu\phi$; $p \to \nu\pi^+\phi$
11	$\overline{u}^c d^c\overline{e}^c(LH)\phi$	$\nu p \to \ell^+ n\phi^*$; quark/meson decays
12	$d^c\overline{d}^c\overline{\nu}^c(LH)\phi$	$\overline{\nu}N \to \nu N^{(\prime)}\phi$; b, s, meson decays
13	$u^c\overline{u}^c\overline{\nu}^c(LH)\phi$	$\overline{\nu}N \to \nu N^{(\prime)}\phi$; t, c, meson decays
14	$e^c\overline{e}^c\overline{\nu}^c(LH)\phi$	$\overline{\nu}e^\pm \to \nu e^\pm\phi$; $\ell \to \ell'\nu\nu\phi$
15	$d^c\overline{e}^c\overline{\nu}^c(QH)\phi$	$\nu p \to \ell^+ n\phi^*$; $\ell \to M\nu\nu\phi$; quark/meson decays
16	$u^c d^c\overline{\nu}^c(\overline{Q}H)\phi$	$n \to \nu\phi$; $p \to \nu\pi^+\phi$
17	$d^c d^c\overline{\nu}^c(\overline{Q}H^\dagger)\phi$	$n \to \nu K^0\phi$; $p \to \nu K^+\phi$
18	$d^c d^c\overline{e}^c(\overline{Q}H)\phi$	$n \to e^- K^+\phi$; $\tau^- \to nK^-\phi^*$
19	$d^c d^c d^c(LH^\dagger)\phi$	$n \to e^- K^+\phi$; $\tau^- \to nK^-\phi^*$
20	$\overline{\nu}^c\overline{\nu}^c\overline{e}^c(\overline{L}H)\phi$	$\overline{\nu}e^\pm \to \nu e^\pm\phi$; $\ell \to \ell'\nu\nu\phi$
21	$\overline{\nu}^c\overline{\nu}^c\overline{d}^c(\overline{Q}H)\phi$	$\overline{\nu}N \to \nu N^{(\prime)}\phi$; b, s, meson decays
22	$\overline{\nu}^c\overline{\nu}^c\overline{u}^c(\overline{Q}H^\dagger)\phi$	$\overline{\nu}N \to \nu N^{(\prime)}\phi$; t, c, meson decays
23	$\overline{\nu}^c\overline{\nu}^c\overline{\nu}^c(\overline{L}H^\dagger)\phi$	$\nu\nu \to \nu\overline{\nu}\phi^*$; C$\nu$B

- We show a subset of dimension-8 operators in the SM+*LeNCS* effective field theory
  - *NB*: These are simply dimension-7 operators in SM EFT with *LeNCS* attached!
- A whole host of interesting new things can happen!